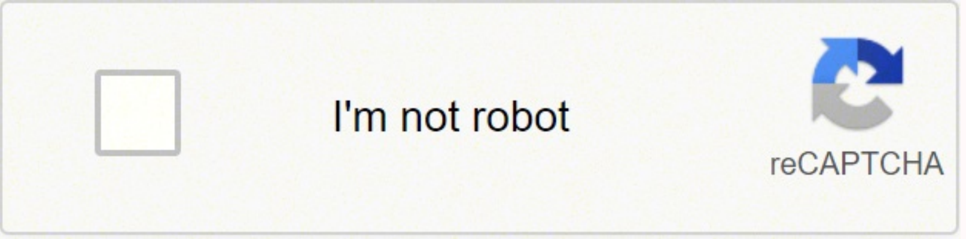

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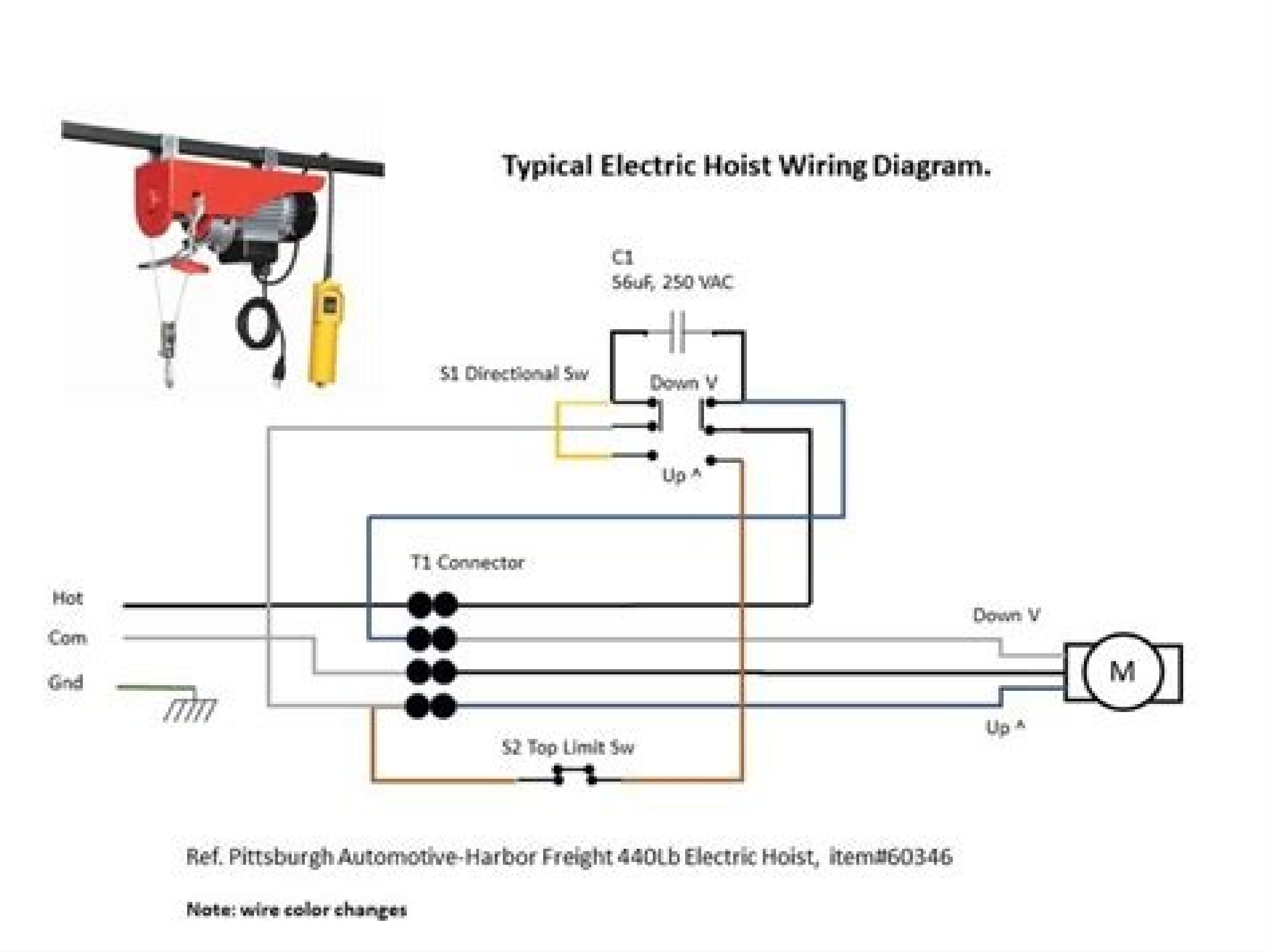

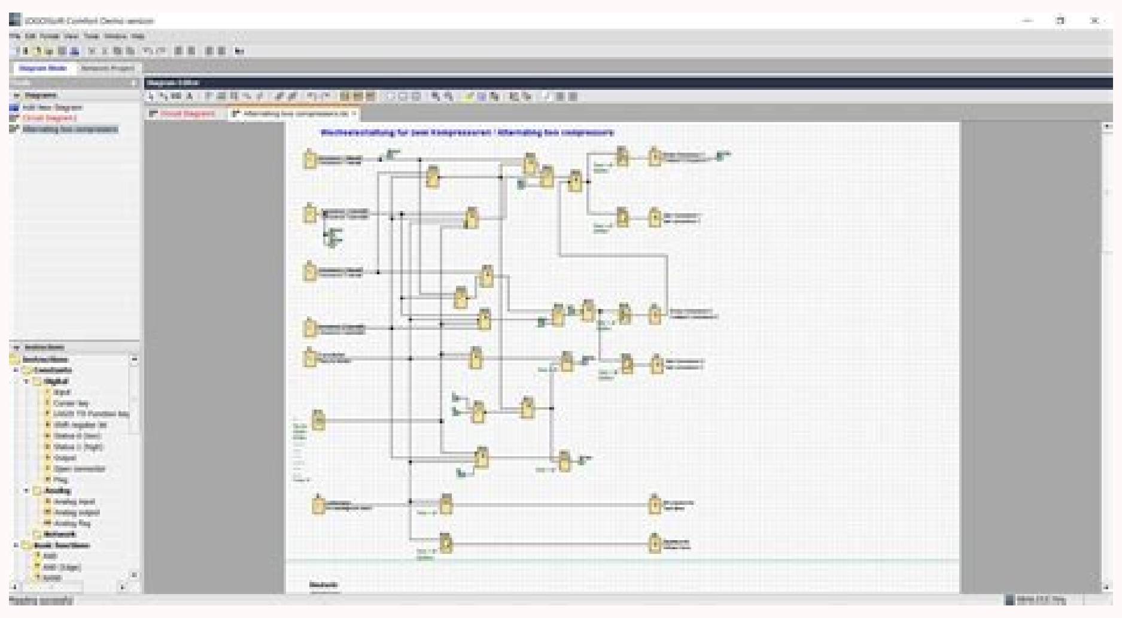

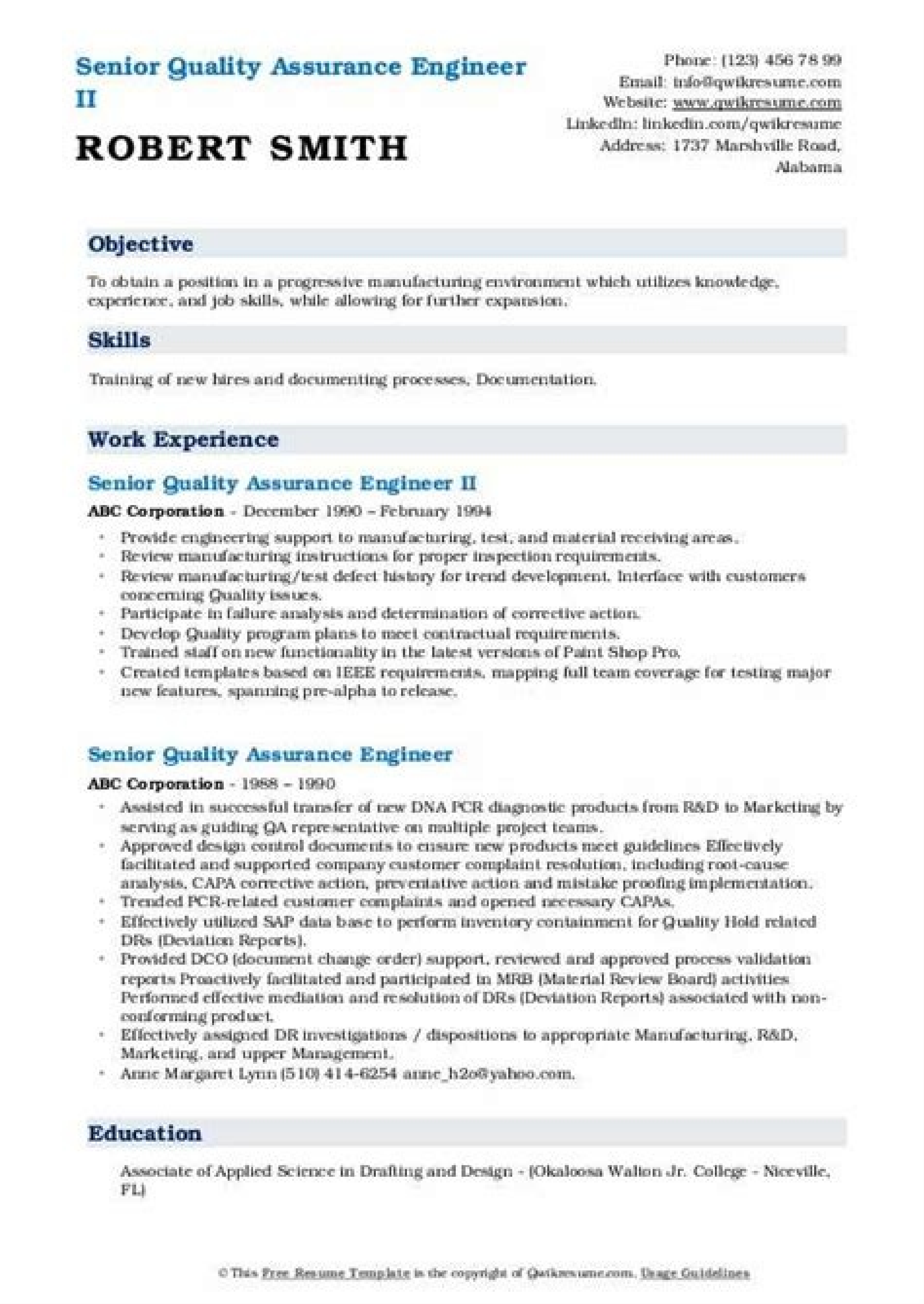

Senior Quality Assurance Engineer II

ROBERT SMITH

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Alabama

Objective

To obtain a position in a progressive manufacturing environment which utilizes knowledge, experience, and job skills, while allowing for further expansion.

Skills

Training of new hires and documenting processes, Documentation.

Work Experience

Senior Quality Assurance Engineer II

ABC Corporation - December 1990 – February 1994

- Provide engineering support to manufacturing, test, and material receiving areas.
- Review manufacturing instructions for proper inspection requirements.
- Review manufacturing/test defect history for trend development. Interface with customers concerning Quality issues.
- Participate in failure analysis and determination of corrective action.
- Develop Quality program plans to meet contractual requirements.
- Trained staff on new functionality in the latest versions of Paint Shop Pro.
- Created templates based on IEEE requirements, mapping full team coverage for testing major new features, spanning pre-alpha to release.

Senior Quality Assurance Engineer

ABC Corporation - 1988 – 1990

- Assisted in successful transfer of new DNA PCR diagnostic products from R&D to Marketing by serving as guiding QA representative on multiple project teams.
- Approved design control documents to ensure new products meet guidelines Effectively facilitated and supported company customer complaint resolution, including root-cause analysis, CAPA corrective action, preventative action and mistake proofing implementation.
- Trended PCR-related customer complaints and opened necessary CAPAs.
- Effectively utilized SAP data base to perform inventory containment for Quality Hold related DRs (Deviation Reports).
- Provided DCO (document change order) support, reviewed and approved process validation reports Proactively facilitated and participated in MRB (Material Review Board) activities Performed effective mediation and resolution of DRs (Deviation Reports) associated with non-conforming product.
- Effectively assigned DR investigations / dispositions to appropriate Manufacturing, R&D, Marketing, and upper Management.
- Anne Margaret Lynn (510) 414-6254 anne_h2o@yahoo.com.

Education

Associate of Applied Science in Drafting and Design - (Okaloosa Walton Jr. College - Niceville, FL)

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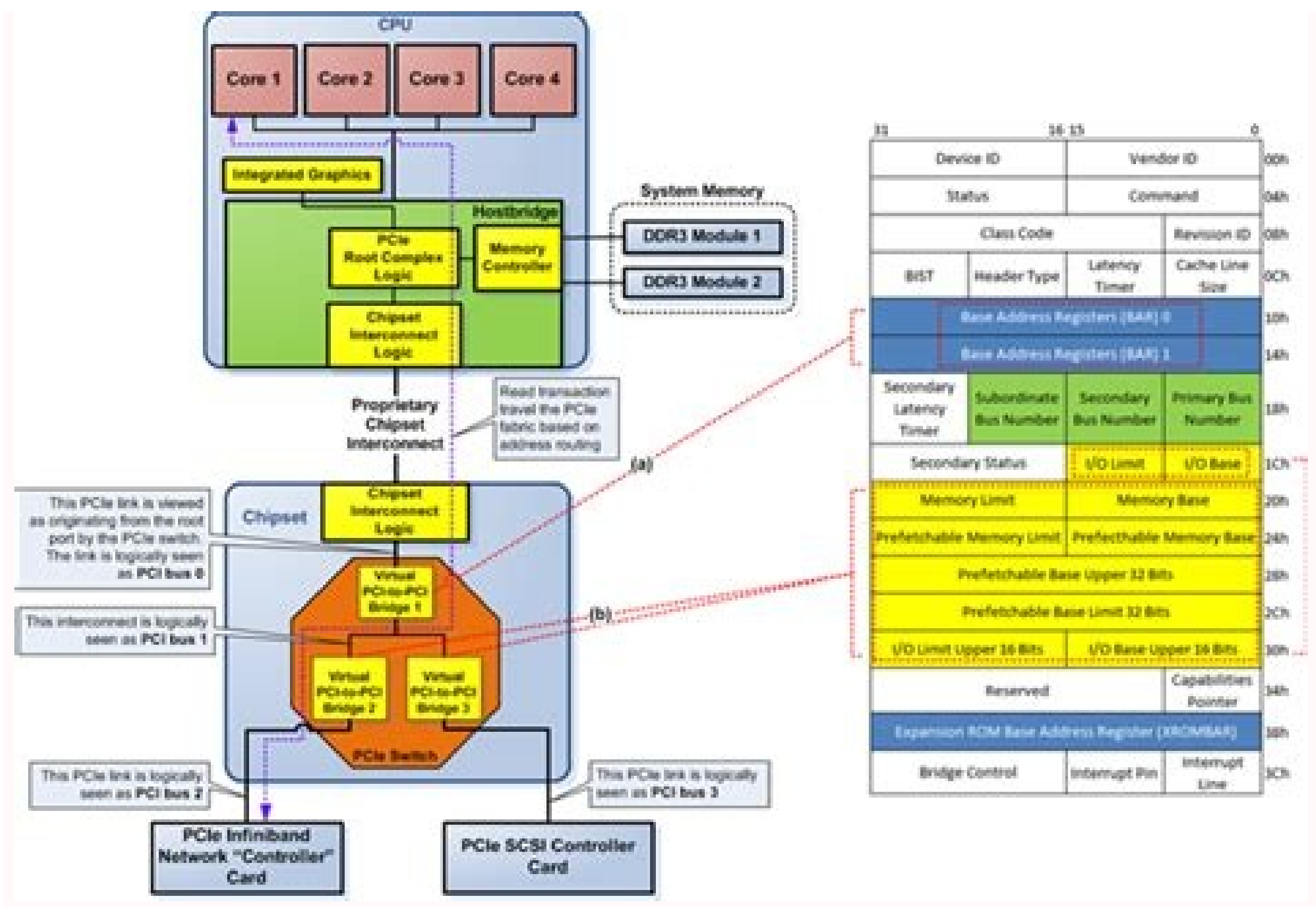
CPU
Core 1
Core 2
Core 3
Core 4
Integrated Graphics
Hostbridge
PCIe Root Complex Logic
Memory Controller
System Memory
DDR3 Module 1
DDR3 Module 2
Chipset Interconnect Logic
Proprietary Chipset Interconnect
Read transaction travel the PCIe fabric based on address routing
(a)
(b)
Chipset
Chipset Interconnect Logic
This PCIe link is viewed as originating from the root port by the PCIe switch. The link is logically seen as PCI bus 0
Virtual PCI-to-PCI Bridge 1
This interconnect is logically seen as PCI bus 1
Virtual PCI-to-PCI Bridge 2
Virtual PCI-to-PCI Bridge 3
PCIe Switch
This PCIe link is logically seen as PCI bus 2
This PCIe link is logically seen as PCI bus 3
PCIe Infiniband Network "Controller" Card
PCIe SCSI Controller Card
31
16 15
0
Device ID
Vendor ID
00h
Status
Command
04h
Class Code
Revision ID
08h
BIST
Header Type
Latency Timer
Cache Line Size
0Ch
Base Address Registers (BAR) 0
10h
Base Address Registers (BAR) 1
14h
Secondary Latency Timer
Subordinate Bus Number
Secondary Bus Number
Primary Bus Number
18h
Secondary Status
I/O Limit
I/O Base
1Ch
Memory Limit
Memory Base
20h
Prefetchable Memory Limit
Prefetchable Memory Base
24h
Prefetchable Base Upper 32 Bits
28h
Prefetchable Base Limit 32 Bits
2Ch
I/O Limit Upper 16 Bits
I/O Base Upper 16 Bits
30h
Reserved
Capabilities Pointer
34h
Expansion ROM Base Address Register (XROMBAR)
38h
Bridge Control
Interrupt Pin
Interrupt Line
3Ch

Thus, the state of the system is specified in terms of physically identifiable variables, and a nonzero initial state is freely implemented. Burl, Fahmida N. Techniques described as the Hurwitz criterion and the Routh criterion provide additional information. Chowdhury, Robert H. This home security panel is great for those who have used panels in the past and are comfortable with the one-touch monitoring for police, medical attention and the fire department. Problems 6.1 INTRODUCTION The dynamic stability of a control system is a critical property that is reflected in the character of the transient response. The Hurwitz criterion (reported by A. Thus, the generation of response functions is not necessarily coherent with respect to real time, and additional complexity is reflected in an increased computational time rather than an increased number of computational elements. The instantaneous power supplied to a mechanical element is equal to the product of instantaneous force and velocity, and instantaneous power supplied to an electrical element is equal to the product of instantaneous voltage and current. However, certain situations, such as the consideration of a small-signal model or a piecewise linear model, permit the adaptation of a linear technique to a system model that is not strictly linear. Although accurate models of induction and synchronous motors are not easily produced, these motors are similar to DC motors in the sense that they exhibit an inherent feedback operation. A common technique is to obtain desired control functions with circuit realizations that use operational amplifiers to provide summing, integrating, and other linear circuit functions. If the attive devices in the output stage of an operational amplifier are forced into cutoff or saturation, the feedback operation ceases at that point and limiting occurs. 4 Partitioning the Solution It is apparent that the solution as presented in Equation 4.33 is composed of two parts. When a system parameter changes, the roots of the characteristic equation move in the s-plane, and the root loci are the paths that describe the variation in root location. Considering the system using a trilevel controller with dead zone, the following program provides a phase-plane portrait of the state variables: clear a=[0 1;0 -2J; % A matrix of plant b=[0;lJ; % B matrix of plant ts=.005; N=900; % Numerical step size and number of steps t=0:ts:N*ts; % Time vector [ad,bdJ=c2d(a,b,ts);% Discrete-time plant model--ad and bd are discrete model A and B matrices x(:,1)=[0;0J; % Specify initial state (both rows, first column) for k=l:N e(k)=4-x(1,k); % Calculate error signal if e(k»=0.2, u(k)=10; elseif e(k) The gain is formed by the ratio of output amplitude Figure 7.11 A cross-section of the splane as viewed at the jw-axis. Controlling the rate of fluid flow to a hydraulic cylinder provides velocity control of the piston with respect to the cylinder. Tactile sensors or vision systems were developments that could provide this capability. This circuit is advantageous in a situation in which torque may be required without motion. As you turn the pages of this book, you are using your tactile (touch) and visual senses to provide feedback in a process that is continuous while turning the page. This condition is known as asymptotic stability. 10.11 Using MATLAB 305 Considering the application of frequency-response techniques, a script M-file can again be adapted to a variety of situations. Assuming that a successful control strategy can be realized, a controller with only two or three discrete output levels provides a relatively uncomplicated, efficient, and reliable method of controlling energy to the plant. Thus, if the number of poles and zeros to the right is odd, the angle criterion is satisfied. 8. A third technique is to use a set of rules that are based on miscellaneous properties of root loci. However, redesign of the controller function with the insertion of a cascaded integrator (Figure 7.24a) is not a viable procedure with this system. The Nyquist stability criterion is applied by evaluating the G(s)H(s) function along the Nyquist path in the s-plane and then plotting this result in the GH-plane. Another approach is to search for loci in the s-plane by checking graphical conditions that must be satisfied by points on the loci. Transfer-function parameters are readily related to the operational functions of specific parts of a physical system, and transfer-function parameters are also readily related to experimental data. The development of a model provides the opportunity to study variations of the proposed control strategy and the corresponding performance before implementing the system. With this objective in mind, it is not necessary to apply any physical significance to the transformed system model. The initial orientation of a vertical lift must be maintained by control of the horizontal component of thrust at the base of the rocket. 3 functions. Although this discussion is relatively brief, an increasingly intensive use of computer-aided analysis and design will be found in many of the following chapters. These devices dissipate energy and do not store energy. A frequency-response function can then be visualized by considering the cross section of the surface that is obtained by slicing through the plane along the jw-axis, as shown in Figure 7.11. Although there is an obvious disparity in application and notation (including the description of sinusoidal signals), there is a very important commonality: Either technique can be used to obtain a transfer function, and with the exception of the transformation variable, the transfer function is identical. The freedom to vary the natural response is not unlimited-limitations are imposed by practical considerations that include bounds on the validity of the linear model. The variation is commonly described by plotting the pole locations in the s-plane as a parameter is varied continuously (usually from zero to infinity). • Create the G2(s) = 100/(s(s + 2)) block by copying a Zero-Pole block from the Linear Library, double clicking on the block, and entering [ ] for Zeros, [0 - 2] for Poles, and 100 for Gain. If the plant exhibits a cluster of two or more dominant poles, or if the required change in type number is from type 1 to type 2 (or type 2 to type 3), the additional difficulty with stability considerations may impose an undesired encumbrance with respect to obtaining a fast response time. Models that Require Multiple Summations For an electrical circuit, the summation of voltages in a loop must be zero, and the summation of currents at a node must be zero. The PID tuning technique and Robust Control explanations have been updated, and where applicable, pictures have been added. Thus, the entire system or a critical part of the system requires the application of a continuous-signal model. 7.5 Steady-State Error 187 maintain zero error (assuming no disturbance inputs) is dependent only on the invariability of the unity feedback factor. 1.3 A Brief History 5 radar control systems. Assuming that the large error is a transient phenomenon, the error at some point in time will fall to zero and change sign. The diagram can be saved with an arbitrary name such as "blockmodel." This model can then be used in various ways. Considering a portion of the plot that is predominantly defined by a single term (a single power of w becomes dominant), the function 7.4 SPECTRAL SELECTIVITY AND NOISE BANDWIDTH Various interfering signals are present in all systems, and considerations of the distribution of signal and noise power versus frequency may become a factor in the determination of an optimal model. The input can be described using a piecewise-constant function or a piecewise-linear function. In other words, the signalflow graph replaces the matrix model, and the application of Mason's gain formula replaces a matrix inversion. Systems with digital control using sampled data 3. 11.7 Using MATLAB 337 This result can be checked by computing A - BK and then requesting the eigenvalues. Basic Control Systems Engineering p. 10.3 The PI Controller 279 initialization procedure. The activation of the integrator feedback loop creates a mode of operation in which the pole is temporarily moved from the origin into the LHP. The relationships provided by these transform pairs are easily verified by showing that the composition of the transformed functions is a linear combination of previously listed functions. To understand the relationship between polynomial inputs and steady-state error, it is helpful to consider several steady-state performance criteria, as defined in the next subsection. Transfer functions, as derived using Laplace or phasor algebra transformations, appear throughout the following chapters with application to a variety of techniques. With this particular combination of conditions, the steady-state equilibrium condition is obtained with the input to the integrator equal to zero and the output of the integrator equal to a nonzero constant value. A PID controller is often effective in a situation for which PI control is sufficient to produce the desired steady-state performance, but additional improvement is sought with regard to transient behavior. The effects of controller variations are, of course, easily studied by observing the performance with variations of the initially selected parameters. Using phasor representations of the input and the forced component of the output, the ratio of output over input is an algebraic function that is expressible at any frequency as a complex number. Slotine and W. It is important, however, to distinguish carefully between a pure time delay and the modification of a signal that is produced by the attenuation of high-frequency components. The units 1 are ohms, henrys, and farads, respectively. Although a frequency-response function is theoretically realizable with either a stable or unstable system, the phasor-algebra transfer function is not meaningful (as a physical measurement) if the system is unstable. The increase in open-loop gain increases the value of the velocity error constant by a factor of 1.58,but the response to a step input now exhibits about 10% overshoot. Thus, multiple system variables must be introduced despite the fact that the transfer function is expressed with reference to only one dependent variable. The application of Mason's gain formula [1,2] to the signal-flow graph model provides a solution for the dependent variables. Check out these top home security system control panels to learn more about which system suits your needs.The ADT PulseWith its seven-inch interactive touchscreen that looks similar to a tablet, the ADT Pulse makes managing your home security simple. Due to analytical difficulties, this is an area of study that is significantly aided by the presentation of simulation techniques using MATLABor SIMULINK. With regard to the operational characteristics of an integrator, an interruption in operation may require special attention. The generation of this plot is advantageous because a large range of gain and frequency values can be displayed, and certain portions of the plot will approach straight-line asymptotes. Another approach is to reconfigure the equations in a manner that produces a set of n first-order differential equations in terms of n variables. 316 Controller Design Variations Chap. The Laplace transformation can be used to obtain a general solution (the forced response plus the natural response) with a large class of input functions. Thus, if the model is nonlinear, the concept of performance evaluation is subject to an additional dimension that significantly complicates both perception and analysis. The operations may vary slightly for different computer platforms, and the reader should refer to the SIMULINK user's manual. In comparison to proportional control, the insertion of phase-lead control can offer an increase in bandwidth while maintaining a desired phase margin. In addition, a system may incorporate physical phenomena that elicit nonlinear behavior with small or midrange signals. If the waveforms are piecewise linear, additional periodic signals can be generated with the Repeating Sequence block. Since system theory is potentially applicable to a diverse set of phenomena, the definition of a system tends to be correspondingly equivocal. Figure 9.20 presents a Nichols chart with a curved grid that shows a set of fixed values of both closed-loop gain and closed-loop phase angle. A saturation phenomenon can also be observed with the use of electric motors, tachometers, and other devices that incorporate controlled magnetic fields. However, it is an uncommon procedure to sum velocities. A typical application of a phaselocked receiver involves the reception of signals from a satellite or a space probe, with the feedback action utilized to track automatically a variation in input frequency. Nothing is more important than the safety of your family, especially inside of your own home. The resistor dissipates energy, and the inductor and capacitor store energy in a magnetic or electric field, respectively. To obtain a conventional plot, select Graph. A reduced-order model can be obtained by carefully eliminating groups of poles and zeros that are placed far to the left in the s-plane with respect to the dominant poles and zeros. If the system is initially at rest and the magnitude of the applied force increases to exceed the breakaway value, the model will change from Equation 2.19 to either Equation 2.20 or 2.21 depending on whether the force is positive or negative. The ability to apply transient and steady-state performance criteria is utilized in almost all aspects of further work. New York: McGrawHill, 1993. Although the performance of a digital controller under some circumstances may imitate continuous control, the categories reflect basic differences with respect to inherent characteristics of the controller. Some of the major topics of further study that use transfer-function techniques include the considerations of linear system stability, transient and steady-state performance criteria, analysis and design techniques using root loci, frequency-response methods, and controller design. A discrete-event controller typically responds only to bilevel information, with control decisions dependent on considerations of combinational and sequential logic. The absence of time information is sometimes resolved by noting the corresponding time at certain discrete points on the trajectory. If a simulation is applied to this system to study timedomain performance characteristics, the assumption with regard to relative stability is corroborated. However, the controller is often designed to provide an operational function that imitates the action of a linear continuous-signal function. The modeling procedures described in Chapters 2 and 3 begin with the development of differential equations, but a possible variation in modeling procedure is to use experimental input/output data as a basis for determination of a system model. Since equally spaced combinations other than jw-axis pairs include RHP roots, the premature occurrence of a row of zeros indicates that there are either jw-axis roots or RHP roots. Since the feedback operation acts to reduce the error, the antenna angle follows changes in the reference angle. Although some commands allow introduction of the model using a transfer-function formulation, the transfer-function model is internally converted to an equivalent state model. The use of MATLABis considered briefly in Chapter 4 and extensively in Chapter 5 and most of the following chapters. A failure to exhibit controllability is evidence that the position of one or more plant poles is not responsive to the application of state feedback. The Growth of Aerospace Applications The use of automatic control techniques in the aerospace industry increased in many areas that can be only briefly described. 4If a digital simulation is utilized, the return of v to zero must be interpreted as the detection of v in a defined proximity of zero. The magnetic field is enhanced by utilizing a magnetic core material, but saturation occurs if the current is increased to a level for which all of the magnetic domains are aligned. Each of the plots depicts an unforced response with a nonzero initial state. The presence of the distributed parameters acts to extend the time required for a current to traverse the resistor or a force to traverse the spring. In addition, the trajectory displays infinite slope where it crosses the horizontal axis. Although defined in terms of the open-loop transfer function, the evaluation of stability applies to performance of the closed-loop system. However, instantaneous changes in dv/dt will be observed when the nonlinear frictional components change instantaneously. A general linear system solution can be obtained using lsim. Transfer functions are interchangeable between the two techniques by replacing jw by s (or s by jw). In this case, the equation can be simplified by placing the displacement reference (y = 0) to mark the static (at rest) position with the mass in place. Tests for controllability involve the A and B matrices, and a lack of controllability is observed as the inability to move at least one pole. Burke, Connections (Technology History). With careful placement of the zero and pole, however, the application of a practical PD controller can produce a notable reduction in response time while maintaining a satisfactory degree of relative stability. Figure 3.24 shows the main SIMULINK block library and four sublibraries used in the example discussed in this section. State Feedback: A Graphical Model An alternate approach to the development of a system model with state feedback is to construct a state diagram to represent the plant and then add the state feedback as required. Considering the stable limit cycle, note that the trajectories as shown converge to the stable limit cycle despite initial states that are both inside and outside the path. effect of the disturbance torque is apparent. • An oscillation can be exhibited for which the amplitude under steady-state conditions is determined by system parameters. When compared with a DC control motor, the torque may be comparable at low speed with a motor of similar size and weight. A linear timeinvariant system is described by linear differential equations with constant coefficients. The root loci are generated assuming that Ko is varied from zero to infinity with a maintained at 6.25. 6 are located in the LHP. Such a loop works like this:It's summertime, and a homeowner sets his thermostat to a desired room temperature -- say 78°F.The thermostat measures the air temperature and compares it to the preset value.Over time, the hot air outside the house will elevate the temperature inside the house. If the dominant cluster includes a zero and a pair of poles, the response to a step input will display a somewhat different profile than the second-order response functions as previously presented. This home security panel streams and records video from cameras located around your home while it controls home door locks, window sensors, motion sensors and even connected power outlets. Thus, control functions are described using linear differential equations with constant coefficients (or the corresponding transfer functions). However, when a ramp input was applied to the type-1 system, a nonzero displacement error was observed. To obtain the desired characteristics, it is necessary to control both the frequency and amplitude of the excitation. To plot response functions, the matrices must be specified carefully. In some circumstances, the geometrical configuration of the loci is not complicated, and this procedure can quickly generate a continuous plot (as demonstrated by the introductory example in the following subsection). If you pull on one end of a spring or viscous damper, an equal force is observed at the other end. Double clicking on a sublibrary name will open a new window that displays the content of the group. The systems include an automobile cruise control system, a phase-locked motor speed control system, and a system to control the orbit of a satellite. Figure 12.2 Some phase-plane trajectories showing nonlinear phenomena with a) a stable limit cycle, b) and unstable limit cycle, c) a piecewise linear response, and d) a system with more than one equilibrium state. Since step provides the unit-step response, the display of the response to a step input of magnitude 10 was obtained by specifying a plot of 10*x. Now request a simulation by selecting Start from the Simulation menu. With rapidly changing technologies, it may be risky to attempt to classify control techniques, but some major divisions can be described as generally perceived: 1. 3.1 INTRODUCTION In view of the large variety of analysis and design techniques that use algebraic mod- els, the ability to develop and apply transfer-function models is a fundamental and important skill. If a model is linear, the evaluation of stability and other performance characteristics (percent overshoot, settling time, etc.) is uniquely determined by the model. This phenomenon occurs because the force that acts to provide motion also acts to increase the dry friction. If the transform variable s is set to zero, the transfer function YIR then describes the transfer ratio that is applicable under steady-state conditions 200 Performance Criteria and Some Effects of Feedback Chap. Voltage limiting does not usually cause any physical damage to the circuit, but it does force a temporary departure from linear operation. This situation is typically identified with a plant function with three or more poles that are clustered such that there is neither a dominant pole nor a dominant pair of poles. A specific example occurs in Chapter 8, in which the Routh test is utilized to determine the conditions associated with roots crossing the jw-axis in the s-plane. The phase margin is a measure of the additional phase lag that can be allowed before reaching -180° at the frequency for which the open-loop gain is unity (0 dB). With consideration of the sensitivity of an overall transfer function to the variation of plant parameters, the implementation of a high loop gain (in a limited range of frequencies) produces a low sensitivity. 4.6 Nonlinear Models 103 This configuration is known as the observer canonical form. The modification of transient behavior using pole placement and state estimation is an option that is presented in Chapter 11. Similarly, if y is negative (a point below the horizontal axis), y is decreasing and the direction of the trajectory must show movement to the left. The initial values of the state variables are then the initial conditions as normally defined. However, programs that utilized the repeatability of sets of pretested machine coordinates generally produced smaller position errors than offline programs that depended on calculated coordinate transformations. If minus signs are placed on the integrator gain factors, additional sign changes must be introduced in loops and forward paths as necessary to maintain the original transfer ratio. Maintaining stable closed-loop control required sophisticated controllers that could operate satisfactorily despite significant variations of the response to control actions caused by large changes in altitude and velocity. The level is suitable for junior or senior engineering students. Discrete-event control is presented with emphasis on highly structured techniques that include the use of Petri nets and state-language tables. 5 The simulation programs are, of course, applicable to linear and nonlinear continuous system models as considered throughout this text. If the excitation is changed to a different pole pair, the rotor shifts slightly to minimize the reluctance in the new magnetic circuit. If the simulation technique is formulated such that the independent variable is synchronized with the actual elapsed time, then the simulation is described as occurring in real time. Although some topics of study are initially presented as control system analysis, the study of automatic control gradually evolves to emphasize design-oriented topics. Although field-controlled two-phase induction motors were once widely used, the control was obtained with constant frequency (60 Hz or 400 Hz) supplies. The stretch of the rubber band is a measure of the applied force. The high forward path gain and the negative feedback action of the circuit tend to provide a nearly linear operation within a limited range of signal levels, but there is a level at which the output transistors are forced into cutoff or saturation, and a sharply defined limiting occurs. The powering devices might utilize electromechanical, pneumatic, or hydraulic components, but the control function is most often implemented using electronic circuits. Therefore, application of the Routh test is particularly useful when seeking the limits of parameter variation that can occur without placing roots of the characteristic equation in the RHP. Induction and Synchronous Motors Although alternating current (Ae) motors are not easily controlled over a wide range of speeds, the induction motor is a strong competitor to DC motors in some control applications. Clark, Professor Emeritus. A problem encountered in early experiments with the control of rocketpowered flight was gaining the ability to maintain the required angular position in the initial moments of flight. The summation of forces is a straightforward procedure, and the dependent variables are velocities or displacements. Summing forces at both masses provides two equations in terms of two dependent variables. The method is pursued so that the system error decays automatically to zero, regardless of the reference input. Considering an nth-order system, the state model is composed of n first-order equations with n state variables. The torsional elasticity can introduce a discernible resonance created by an interaction of the torsional spring with the moment of inertia of the load. If the spring produces a load force on Ml' then an equal and opposite force is applied by M1 to the spring. The velocity v will not change instantaneously because dv/dt must be finite. With regard to integral control, the need for an increase in type number depends not only on steady-state performance specifications, but also on the number of inherent integrations that appear in the plant function. With the character of the performance sensitive to excitation level, performance criteria such as percent overshoot and settling time are dependent on the level of the excitation, and a nonlinear system may be stable in one region of operation and unstable in another. The automation of process control systems produced demands for new and improved sensors and powering devices, and the technological advancements introduced the opportunity to improve operations and develop new products. The magnitude and direction of flow of the hydraulic fluid are controlled by a valve that can be designed to be electronically controlled. Therefore, the downward gravitational force (Mg) and the upward Sec. A system of mechanical elements is shown in Figure 2.5, with two masses and a connecting spring and viscous damper. This is a useful phenomenon because a transfer function as obtaine~. Theoretically, there is no upper bound on this process, and no limit on the maximum value of the velocity error constant or minimum limit on the settling time. Lewis Chang Yang Michigan Technological University Lihrary of Congress Cataloging-in-Puhlication Lewis, Paul H. For a mechanical system, the summation of changes in velocity on elements in a loop must be zero, and the summation of forces at a junction of elements must be zero. AA=A-B*K; eig(AA) % Evaluate the revised A matrix % Compute the eigenvalues This calculation will, of course, return the desired closed-loop poles that were originally specified as p (a row vector). The nodes represent variables, and the branches represent transfer relationships. Although RHP and LHP roots are not explicitly evaluated, the Routh test discloses the number of RHP roots, and the test may be extended to precisely locate jw-axis roots. A cancellation will, of course, affect the determination of steady-state error. Englewood Cliffs, N.J.: Prentice Hall, 1970. There are, however, practical limitations that must be considered. When considering systems for which the control requires carefully considered actions, the determination of an accurate 1 2 Control Systems Engineering Chap. The unstable limit cycle (shown as a dotted line) defines an oscillation only if the initial state is exactly on the path and there are no extraneous perturbations. Assuming a knowledge of the relationship between open-loop and closed-loop system functions, the behavior of the closed-loop system can be predicted by investigating characteristics of the openloop system. The ability to combine time-domain simulation with the application of s-plane, z-plane, or frequency-response techniques is a valued skill. Figure 3.25 is a SIMULINK block diagram for the example described in Section 3.8. The block diagram is constructed with the following steps: • Create a working window by selecting New from the File menu of any library window. 5.2 ANALOG SIMULATION AS AN ACADEMIC TOOL Analog simulation is implemented by constructing dynamic electrical circuits that are analogous to the system under study. To obtain this attribute, each element of the system must exhibit linear properties. Sasseen, Disturbance Compensation with Preview Information for an Active Suspension System, M.S. thesis, Michigan Technological University, January 1995. With a type 1 system, no peak is observed in the closed-loop gain function if the phase margin is about 60° or greater. Although nonlinear system behavior is exhibited in myriad variations, certain forms are frequently encountered. Although digital controllers can be designed to imitate the operation of analog controllers, digital techniques offer a greater diversity of potential performance traits. If an acceptable set of performance specifications cannot be achieved by adjusting the open-loop gain, a redesign of the controller function must be considered. D. Plots of root loci are commonly utilized as a design aid. Backlash is observed with many common gear systems, and the magnitude of the backlash angle is dependent on the torque rating and other factors. These approximations are determined with the assumption that the gain margin is greater than 6 dB. The state model is particularly advantageous when applied to simulation, and the linear state model provides the mathematical foundation for an important array of analysis and design techniques. However, if the input is well behaved, with no abrupt changes or discontinuities, the output variable typically changes to a behavior pattern of the forced response, and the error becomes relatively small. The representation of a model is developed in an interactive environment by using graphical representations of all of the simulation elements. The application often involves complex strategies that are utilized for the control of machines, processes, and various manufacturing operations. The actuator is assumed to produce an ideal current-to-force conversion with the generation of an applied force that is proportional to the control current i(t). In either case the goal is to obtain an understanding of the system interactions as part of the process of developing a successful control strategy. The symbol for stiffness, K, is used with both translational and rotational springs, but the units must differ, as described in Tables 2.1b and 2.1c. Diverse Areas of Application In addition to automated factories and aerospace applications, control theory con- cepts developed in many areas. Evaluation of the complete system is considered in Chapter 7. Using microcomputer technology, small control units could store extensive programs, and system designers could quickly revise existing programs or create new programs. Practice is also gained in the design and use of analog circuits. If G(s) is described as a ratio of polynomials with the possibility that one or more of the poles are placed at the origin, then If the type number is greater than zero, there is a potential cancellation of poles and zeros at the origin of the s-plane. However, analog computation is an alternative that provides a realistic and understandable portrayal of system behavior, and the utilization of both digital and analog techniques may be a suitable option in an academic environment. Considering a typical circuit analysis, the initial model is developed as a set of equations, and the use of a matrix solution is a straightforward technique. Assuming that the system model is described with a single dominant pole, the bandwidth is equal to the magnitude of the pole. The study of nonlinear system behavior requires the development of additional insight and understanding in a new realm of study, but the effort is rewarded with the ability to recognize and respond to many realistic analysis and design problems. The control canonical form generates a set of state variables that comprise Xl (t) and derivatives of Xl (t), and the output is a linear combination of the state variables. The step function is implemented by converting the transfer function to an equivalent state model. Systems using discrete actions that depend on discrete events (discrete- event control). If the plant is stable with a single dominant nonzero pole, the utilization of a PI controller to convert from a type 0 to type 1 system is implemented without difficulty. This is a nonlinear phenomenon described as a "limit cycle" oscillation, and the amplitude is determined by parameters of the system model. The control strategy is readily implemented with on/off actuators that employ solid-state switches or relays controlled by analog or digital circuits that determine the switching conditions. Another approach to the evaluation of stability (the Nyquist stability criterion) is presented following the development of frequencyresponse techniques in Chapter 9. The supervised tasks may involve continuous control, thereby providing a combination of discrete-event and continuous control. A transfer relationship as determined for a single frequency designates only the steady-state response to a sinusoidal input. Hassul, Control System Design Using Matlab. Systems were also designed using mobile robots to transfer parts between workstations. Early forms of discrete-action control provided programmable sequences of discrete events; however, the first indications of the full potential for factory automation occurred with the use of electromechanical relays. Kailath, Linear Systems. Depending on the situation, a very accurate model may be required, or an approximate model may be sufficient. Control systems apply an action based on a measurement and almost always have an impact on the value they are measuring. Considering large-signal conditions, electronic amplifiers and other electronic circuits are subject to constraints caused by operationallimitations of the active devices. Both techniques convert differential-equation relationships to algebraic relationships, and differentiation and integration are replaced by multiplication and division, respectively, by the transform variable. The controller introduces a pole and a zero, with the pole located at the origin of the s-plane and the zero located on the negative real axis. These variations, sometimes described as drift, are produced by uncompensated thermal or aging variations of the static operating levels of active devices. The presence of the accompanying zero, however, is generally helpful in maintaining an acceptable transient behavior. Assume that the system model of the example is 4.4 STATE DIAGRAMS A state diagram provides a graphical representation of the algebraic relationships as exhibited by the Laplace transformation of a state model. Inspection of the contour as plotted on a Nichols chart may be helpful in determining the extent of the problem and the correction that is required. Hence, the magnitude of a peak must be evaluated with respect to the low-frequency limit, and the phase margin that corresponds to a O.5-dB closed-loop peak may be somewhat higher than the value required for other systems. In other words, the variations are viewed as a fixed change (rather than studying the evolution of the change as a time-dependent process). Robots and Automated Factories The developments in solid-state technology that allowed the design of automated machine tools also provided the basic technology to design and build industrial robots. Assume that the machine at the left combines various liquids and particulate solids to form a composite continuous sheet that moves to the right. If the actuator power requirement is high, the simplicity of a controlled switch is a conspicuous contrast to the complexity of a power amplifier that must supply a continuously variable signal. 10.9 THE LEAD-LAG CONTROLLER In a fashion that is similar to combining a practical PD controller with PI control to obtain a practical PID control, phase-lead and phase-lag control can be combined to obtain a lead-lag controller. A frequency-response function utilizes phasor algebra to express the steady-state relationship between input and output signals with the application of sinusoidal inputs. This method provides an evaluation of the forced component of error with an extended class of input functions. Hence, if a change in sign appears in the Sec. The system illustrated in Figure 2.14 introduces an actuator that is directly connected between the body and the axle. The results, num = [0 0 40 800] and den = [1 22 180 800], are identical to those in Section 3.8. Another use of the SIMULINK model is to perform the simulation directly with the diagram. The extraordinary value of these computer-aided analysis and design tools is particularly evident when applied to realistic situations with nonlinear models and other sources of computational complexity. However, a clear physical significance can be ascribed to all of the state variables if the transfer function is an all-pole function (no finite zeros). Although several factors may be considered to make this decision, this is a bilevel action that requires a bilevel (yes or no) decision. A common procedure is to sum forces at a junction of two or more elements or to sum the forces acting on a mass. Considering systems that incorporate mechanical motion, bearing surfaces (with either sliding or rolling motion) are subject to the effects of nonlinear components of frictions. If a system is not linear in the region of interest, the development and use of a mathematical model generally becomes more difficult, and the use of digital simulation takes on a particularly important role. Thus, a frequency-response function displays a cross section (A-A') of the surface, and the nature of the contour is sensitive to the relative proximity of poles and zeros located throughout the s-plane. The transform pairs numbered 11 and 12 are presented in a format that is useful when considering inverse transformations. The analysis of nonlinear system stability with certain special cases is considered in Chapter 12. To begin, type simul ink (while in MATLAB)to open the SIMULINK block library. The sensitivity of transfer functions to variations of system parameters is a performance characteristic that is highly dependent on the system configuration. The inverse transform of a constant is an impulse function, and a partial-fraction expansion is applicable to the remainder. With this situation, the phase margin may become less valuable as an indication of the transient performance, and the gain margin may become an important indicator. The value of a node is equal to the sum of all of the incoming signals; thus, a summation is assumed to occur that is derived from summing signals on all of the incoming branches. 12.3 State Space and the Phase Plane 345 Some distinguishing properties of nonlinear systems can be outlined as follows: • Superposition is not observed, and the steady-state response to a sinusoidal input is observed as a nonsinusoidal waveform. 12 variables is greater than three, multiple displays are required that incorporate a reduced number of variables. These systems, described as numerically controlled machine tools (or NC machines), provided the ability to produce automatically a large number of machined parts with virtually identical characteristics. Considering the significance of the models with respect to power and energy requirements, the relationships provide an understanding of basic limitations of motion control. New York: Van Nostrand, 1945. The set of values exhibited by the state variables at any point in time represents the state of the system. 10.4 The Ideal PO Controller 281 With regard to steady-state error, the type number is unchanged by the introduction of the derivative control. It was noted with the description of both phase-lag compensation and lead-lag compensation that shifting the low-frequency pole to the origin converts these functions to PI and modified PID control functions, respectively. Both reviewers injected a mechanical engineering perspective. Consequently, the design of the vehicle and the flight control system required consideration of highly incongruous tasks using a combination of techniques involving both thrusters and aerodynamic surfaces. Because this conversion is designed to simulate a continuous plant in a system with digital control, the c2d numerical model is applied with the assumption that the digital-to-analog conversion between the controller and plant incorporates a zero-order hold. Any two blocks can be connected by drawing a line or several connected line segments from the output port of a block (with ">" pointing out of the block) to the input port of the other block (with ">" pointing toward the block). A practical spring is also constructed with a nonzero size, and the spring will display a distributed mass along 16 Modeling Physical Systems: Differential Equation Models Chap. To obtain coordination throughout a factory, controllers were designed that supervised other controllers, and factory automation required consideration of the communication of multiple control signals with the development of control hierarchies. The gain is represented using decibels, and the gain in decibels is plotted versus frequency with a logarithmic frequency scale (see Figure 7.13a). The intricate relationship between stability and the manner in which feedback is employed is one of the very interesting aspects of control system design. Hazen, "Theory of Servomechanisms," J. Sorgenfrei, "Feedforward Techniques and Motion Control," M.S. thesis, Michigan Technological University, February 1992. The application of SIMULINK is considered in Chapters 4, 5, 12, and 15. If a slender rubber band is fastened to the handle of a heavy coffee mug and a very slowing increasing force is exerted on the rubber band, the motion of the mug will exhibit the characteristics of nonlinear friction. Then the block The ability to perform system simulation studies in the time domain is a valuable resource for a system designer. With a pure time delay, a signal is altered only by a displacement with respect to time. Another type of nonlinear operation that is frequently observed is a system model that exhibits a nearly linear operation that exists only within a specific range of signal levels. If viscous friction is included, the results are modified to increase the positive power requirement and decrease the negative power (power returned to the source) such that there is a net positive consumption of energy. A type 0 system, however, must be considered individually, because the low-frequency limit of the closedloop gain can be somewhat less than 0 dB. The conversion from continuous data to digital data also introduces a small amplitude variation (of predictable level) that is imposed by using a finite word length. Since the value of a set of state variables that exists at a particular point in time is described as the state of the system, the set of initial values is described as the initial state of the system. Transfer-Function Models 60 Chap. With state feedback established in this manner, the eigenvalues of the overall system comprise the roots of det(s I - A + BK = 0) and det(s I - A + GC). Lab. Thus, application of a linear solution technique (such as the Laplace transformation) should be considered with the understanding that the validity of the predicted response is limited by bounds on the values of dependent variables. The application of this methodology is known as the root-locus technique [1], [2], [3]. This type of compensation is particularly effective in situations wherein the plant exhibits a pair of dominant poles. 5.9 Connectionsto Further Study 137 The state model affords an excellent format for the development of simulation models (of any order) using either analog or digital simulation. Note that the phase margin with the higher value of open-loop gain is between 57° and 58°. Systems described as flexible work cells were implemented with a configuration that typically involved the use of several machine tools and a robot under the control of a single supervisory computer. 12 Control Systems Engineering Chap. The center gear contacts the outer gear in the vicinity of the major axis of the ellipse. The insight that can be gained by studying a phase-plane trajectory is dependent on the system model, and a phase-plane portrait becomes particularly insightful when it is used to display the region-dependent behavior patterns that can occur with a nonlinear model. If the system model is entered as a state model, Isim allows the consideration of multiple inputs and a nonzero initial state. Thus, the bandwidth is equal to the inverse of the time constant as observed with a time-domain analysis. of zero and pole n = [00 2*k0J; % Uncompensated system model d = [1/10 1 0J; nc = [00 2*k0/z 2*k0J; % Compensated system model dc = [1/(10*p) (1/10)+(1/p) 10J; [mag,ph,wJ = bode(n,d,w); % Calculate gain and phase [magc,phc,wJ= bode(nc,dc,w); db = 20*log10(mag);dbc = 20*log10(magc); % Convert to dB subplot(211) % Plot in upper half of plot area semilogx(w,db,w,dbc),grid % Plot uncomp. The basic mathematical tool is phasor algebra. 5. Techniques that require a linear model include the Laplace transformation and ph asor algebra. With a lumped element, the variable that passes through (such as the current in a resistor or the force on a spring) is assumed to exhibit the same value at both terminals. Therefore, if the sampling period is small (in comparison to the transient response time of the system), a continuous-signal model will provide a satisfactory prediction of the overall performance. If a system is reduced to a single loop, the open-loop transfer function incorporates the cascaded functions around the loop (excluding the minus sign that is associated with the return of the feedback signal). 8.3 THE RULES OF CONSTRUCTION The following rules provide a set of root-locus properties that are applicable to the representation of a characteristic equation, as described by Equations 8.4 and 8.5. Sec. With regard to the complexity of computation, the transformation techniques provide an interesting interchange of computational traits. An efficient and effective utilization of the root -locus technique requires a clear understanding of the graphical conditions and the various properties. When tasks involve extensive automation, developing efficient and understandable programs is often important. 5.3 DIGITAL SIMULATION WITH LINEAR SYSTEM MODELS The application of a numerical technique (devised to solve differential equations) is a common approach to the simulation of linear and nonlinear control system models. These blocks are organized into groups (or sublibraries) according to their behavior. This provides a hierarchic control system in which the discrete-event controller is supervising the operations of various tasks placed in a lower level of the hierarchy. If there is a wide lateral expanse between clustered groups of poles and zeros in the s-plane, then order reduction is readily implemented. The transformations convert differential-equation models to algebraic models, but they also replace functions of a real variable by functions of a complex variable. The linear performance and the insensitivity to variations of the active elements is dependent on the feedback action that occurs with a very high loop gain. However, the algebraic model can provide an improved comprehension of causeand-effect relationships, and use of the transformed model provides the basis of a number of important analysis and design techniques. However, the total frictional torque (assuming a nonzero velocity) is 7.7 SENSITIVITY Another property of feedback systems is the ability to alter the sensitivity of an overall transfer function to the variation of specific system parameters. If all poles of sEes) are located in the LHP, a limit exists, and the steady-state error is easily determined using the final-value theorem. Since the corresponding time constant is equal to the inverse of the magnitude of the pole, multiplication of the inverse of the smaller magnitude by 3 or 4 provides an approximation of the 5% or 2% settling time, respectively. To pursue this concept, stability is typically evaluated in the vicinity of a potentially static condition known as an equilibrium state. The intent of this presentation is to develop a fundamental understanding of efficient and systematic approaches to the design of discrete-event systems (including the consideration of concurrent and hierarchical control). If the mechanical relationships are considered in terms of force and velocity (or torque and angular velocity), there are obvious analogies that may be useful when comparing models or performance characteristics of electrical and mechanical systems. However, the derivative control introduces the possibility of increasing the loop gain to a higher value than is feasible without the improved stability; and this change, in turn, can increase the magnitude of a steadystate error constant. The discrete-event materia] of Chapter]4 can be inserted at any point in the sequence. • A system can exhibit more than one equilibrium state and more than one mode of oscillation. By introducing a dominant zero into the forward-path function, a PD controller can be utilized to improve the performance of a system that is characterized by a moderate imbalance in the number of dominant poles with respect to zeros. The ability to produce sketches allows a designer to investigate quickly various design options. The surface as displayed in Figure 7.11 represents the magnitude of a transfer function with poles located at -1 ± j2. Considering the stability of nonlinear systems, it is important to understand that similar performance characteristics are observable with both linear and nonlinear systems, but there is a significant underlying difference. If the load applied to an induction motor increases, the velocity of the rotor tends to lag further with respect to the stator field velocity. Thus, most robots were designed to utilize a program/teach mode, in which programs were constructed using manually controlled command signals. The gear ratlO can also be selected to maximize the ratio of load velocity to developed torque under steady-state conditions (zero acceleration), and the result is a gear ratio equal to the square root of the ratio of load friction to rotor friction. A fundamental design concern is the ability to obtain and maintain stable operation. The root loci are generated by varying the proportional gain while maintaining a fixed ratio of integral to proportional gain. Alternate techniques include the utilization of filtering and the attempted cancellation of measured disturbances. The model as presented in Figure 9.21 describes a hypothetical process control operation. Natick, Mass.: The Math Works, Inc. A fundamental tool for the analysis and design of control systems is the ability to describe the plant, powering devices, and controller using a mathematical model. The use of phase-lead compensation is effective if the plant exhibits a moderate excess in the number of dominant poles with respect to dominant zeros. When determining solutions for physical systems, the highest power of s in the denominator polynomial is usually higher than the highest power in the numerator polynomial; thus, one or more zeros is located at infinity. The maximum extent of windup can be limited by setting the saturation level of the integrator such that integration ceases when the output of the integrator reaches a level that can produce saturation of any following device. Application of the Routh test to a specific polynomial provides the number of right-halt-plane roots and evaluation of any jw-axis roots. The ability to alter stability and change the character of the natural response is a commonly observed effect of feedback. Control systems were developed for missiles that were directed toward their targets using beam riding, heat seeking, or Sec. Each point on the contour is shifted directly upward by 4 dB. The transfer function is function. One approach to the selection of state variables is to utilize variables that are directly associated with energy storage. The grooves, however, cannot be in perfect alignment on all pole faces because the spacing of grooves is slightly different in the rotor as compared to the stator. If the desired behavior cannot be obtained using proportional control, there are various alternatives that can be directed toward the fulfillment of a specific set of design objectives. If a control system is designed with a shaft to transmit torque from an actuator to a load, an insufficiently high spring constant can adversely influence the dynamic behavior. If a sinusoidal signal is applied to a linear system, the steady-state output is another sinusoid, and a phasor-algebra transfer function describes the relative magnitude and phase angle. A linear set of differential equations is replaced by a set of linear difference equations, and the state model again assumes a particularly convenient format that is comfortably similar. The input is a controllable voltage source that is transferred to one (or both) coils, and the state variables, Xl and x2' represent the currents. Thus, an unbounded polynomial input may produce a constant or zero steady-state error. If a system is linear, the state model can be expressed using a matrix equation that retains the same format regardless of system order. The conventional analog simulation symbols for the various operations are shown in Figure 5.1. Since the simplest implementation of an analog integrator reverses the polarity of the signal, the only alteration that may be helpful in the conversion is to change signs on the signal-flow graph to correspond to this requirement. With a step input, this modification is viewed as a faster response. One example is a single-frequency sinusoidal input. 1 The system designer can select the strategy employed in the design of the controller and the powering devices, and the basic character of the controller tends to categorize systems. Generalization to other systems is not difficult, but it is beyond the scope of this text. The book is appropriate for engineering courses at both the undergraduate and doctoral levels. Englewood Cliffs, N.J.: Prentice Hall, 1991. Digital controllers were developed that were capable of generating a combination of quasi-continuous and discrete-event control. • Chapter] 5 presents three system design studies that use techniques presented throughout the book. Because the step format that was applied to this example did not include a time vector, the time interval and final time are selected automatically. If practical realizations of these circuits are considered carefully, it becomes apparent the pole is not exactly at the origin in the s-plane. Reviews of the text extended the range of expertise, and the authors are particularly appreciative of the many helpful and insightful suggestions provided by Joey K. To simplify the analysis, the description uses a "quarter-car" model, with the consideration of one wheel (and one half axle) and the suspension of one quarter of the body mass. 2 the path of the deflection. A single semester (or a single quarter) can be organized by comp]eting the first six chapters and then selecting topics as desired from the remaining chapters. However, it is common practice for a digital controller to provide both sampled-data and discrete-event control actions. If a system model includes a spring, a desired simplification in notation is usually obtained by choosing the displacement reference (x = 0) to coincide with the relaxed position of the spring. It is apparent that Example 11.1 produces a third-order characteristic equation with three independently adjustable coefficients. If a system model is linear, the evaluation of stability involves only system parameters. The system acts as a filter, and the shape of the frequency-response function determines the manner in which the spectral content of the input signal is modified. 6. Ogata, Solving Control Engineering Problems with Matlab. The final step is to specify the simulation procedure by selecting Parameters from the Simulation menu of the working window. Problems 79 The representation of systems using block diagrams and signal-flow graphs is common, and they appear frequently in the following chapters. Although either model could be utilized in a simulation using MATLAB, the state-model format allows a simultaneous consideration of both inputs, and use of this format generates output data that include all of the state variables and output variables. With regard to a nonzero component of derivative control, there is again a cost factor. Although particular selections exhibit singular features, other options may exist that provide a valid simulation without exhibiting any special features. MATLABfunctions that are applicable to the study of time-domain behavior with linear continuous system models include impulse, step, and initial. The signals are constructed by specifying the vertices of the signal over one period. The utilization of frequency-response functions is significantly expanded in Chapter 9, and stability criteria are introduced that are directly applicable to design in the frequency domain. However, if the bandwidth is too large, excessive noise power is received in addition to the desired signal. This library contains all the commonly used building blocks for drawing block diagrams (e.g., transfer-function block, gain-factor block, integrator, summing junction, step input, signal generator, graph display). The barrel organ was an early example in which real-time programming was provided by arranging pegs on a cylinder. A non circular driver on the (highspeed) input shaft controls the rate of rotation of the ellipse by controlling the shape of the inner gear. Kuo and D. The material as presented in this section describes the development of linear state models, and analytical solution techniques are presented that demonstrate fundamental properties of the matrix formulation of a linear system solution. These are linear system design techniques that utilize a state model of the plant. The utilization of the graphical conditions is not obsolete, however, because the graphical conditions provide the basis for many parts of a third option. This combination of capabilities allows the inclusion of learning processes, adaptive control, optimal control, expert knowledge, and various other advanced concepts. If a spring responds to translational motion, the spring can be totally compressed or expanded beyond the elastic limit. The total input is An interesting application of this concept is obtained with consideration of a position control system as modeled in Figure 7.29. If one or more of the equations is not linear, superposition is not observed, and the model is characterized as nonlinear. Because analytical- difficulties can increase significantly if a system model is nonlinear, the conclusion that a model can be formulated using a set of linear 13 Sec. If a ph asor-algebra transfer function describes the phasor relationship for all frequencies, the relationship constitutes a frequencyresponse function, and the function contains sufficient information to comprise a linear system model. Lewis, Chang Yang. The tire is modeled as a combination of a spring and viscous damper, and a spring is connected in parallel with the actuator between the axle and body. 207 208 Root-Locus Techniques Chap. A similar grid can also be added to a computer-generated plot using a program, as described in Section 9.7. 9.6 AN APPLICATION: SYSTEMS WITH TRANSPORTATION DELAY Time delays are commonly observed in process control loops, and the application of a frequency-response technique offers the capability to develop a relatively uncomplicated mathematical model. Although a typical response will show a slightly lengthened settling time with the observer in the loop, this particular initial state produces a situation in which the observer configuration introduces a slight reduction in settling time. The starting point for this process is the linear state model with Section 5.5 5.5 SIMULATION Simulation Using MATLAB 127 USING MATLAB The MATLAB2 software package provides a set of computer-generated computational procedures that offer efficient numerical analysis capabilities with computations that typically utilize matrices or arrays. Mason, "Feedback Theory-Further Properties of Signal Flow Graphs," Proc. The programming environment offers basic mathematical operations plus a number of operational procedures (known as functions) that are each invoked using a single MATLAB command. Thus, a nonzero initial statdis freely implemented. 2.3 Modeling with Lumped Linear Elements 15 are assumed to be time invariant, and the linear time-invariant models (LTI models) are composed of linear differential or difference equations with constant coefficients. Simulation 138 Chap. b) The overall function showing negative resistance. And the effector is the air conditioning unit.Automated flight control systems work the same way. The 5.6 A CONTROL SYSTEM APPLICATION Returning to the antenna position control system as considered in Chapter 3 (Section 3.6) and Chapter 4

(Section 4.2), the system is described using a transferfunction model and then using a state model. On the other hand, a well-conceived feedback configuration can create a stable performance when applied to an unstable plant. 1 generally received at the controller as bilevel signals, and the control actions returned to the plant are also bilevel signals. Stated in a slightly different fashion, a steady-state condition can occur only after the integrator seeks and finds a constant output level that produces zero error. For example, a nonlinear system that exhibits stable behavior with a step input applied at a relatively low signal level may become unstable if the input level is increased. 12 designed to convert a continuous-time state model of a linear plant to a discrete-time model. The final two transform pairs (11 and 12) in Table 3.2 can be used to obtain inverse transforms directly when working with quadratic factors that are not expanded. The following set of programs provides computational aids to controller design using frequency-response methods with models that are specifically applicable to Example 10.8. % Example 10.8 - Uncompensated % A check of the uncompensated frequency response (with Ky = 100) k0 = 50; % K0 set to satisfy Ky = 100 n = [00 2*ko]; % Enter the open-loop model d = [1/10 1 0J; bode(n,d) % Calculateand plot Bode plots (gain and phase) [gm,pm,wpc,wgcJ= margin(n,d); % Calculate gain and phase margins pm,wgc % Printthe phasemarginand gain crossoverfreq. Readers without a prior introduction to MATLABare referred to Appendix B, in which information is presented that is helpful in the process of learning basic operational concepts and procedures. Ideally, the resisting force (or torque) varies in direct proportion to the translational (or angular) velocity. The conversion of a state model to an analog simulation diagram is obtained without any uncertainty with regard to the identificatjon of signals that appear at the outputs of integrators. The insertion of the pole adds an integration to the open-loop function, and the presence of the zero is usually helpful with respect to formulating a satisfactory transient performance. 1934. A static backlash characteristic is shown in Figure 2.22. Because the placement of the closed-loop poles governs stability and other characteristics of transient behavior, the totally compliant nature of the placement is a useful property. If the switching conditions are not complex, the control characteristic is typically obtained using electronic comparator circuits. In other words, the use of a full-order observer adds eigenvalues, but the location of the dominant eigenvalues is unchanged with respect to the location, as predicted using actual state variables. This is a proportional plus integral controller (known as a PI controller). A system designer must also be concerned with the robustness of a control system with regard to stability-it is important that the ability to display a stable response is not significantly altered by changes that occur in the value of system parameters. With automated sensing and position control, intricately shaped parts could be machined in large quantities. An exact pole-zero cancellation as described in Example 10.1 is not a practical concept, but the effect of an imperfect cancellation is easily investigated. The FrontPoint Touch Screen Control Panel supports 39 sensors and allows the programming of unique codes for each user according to PC Magazine.Vivint SkyControlSimilar to the ADT Pulse, the Vivint SkyControl offers a seven-inch interactive touch screen along with a one-touch alarm activation control. A variation of the pole-placement technique is to utilize an observer to estimate the state of the plant. 4.2 LINEAR SYSTEM MODELS Although a state model is not limited to describing linear systems, the matrix model that is obtained with the description of a linear system provides a mathematical foundation for numerous valuable and powerful analytical techniques. It is an important concern whether the formulation of the model requires linear or nonlinear differential equations. Thus, the operation with field control requires relatively low-power electronic circuitry to control the field voltage, but additional high-power electronic circuitry is required to control the armature current. However, the linear ratio of variables that is defined for one element can involve an integral or derivative of a variable that is used to define the linear ratio for another element. If a step input is desired, the Inport block is replaced with a specific excitation signal block from the Sources Library that is labeled Step input. This procedure will not normally generate the same ratio as obtained when maximizing acceleration. If the low-frequency pole is shifted from a nonzero value to zero, the compensation function assumes the form of a PI controller or a practical PID controller, respectively. In addition to providing an efficient interaction with digital techniques, utilization of this model allows the simultaneous consideration of multiple inputs, multiple outputs, and nonzero initial conditions. Linear system solutions do not normally introduce any special computational difficulties, and an efficient solution technique (using a matrix exponential algorithm) is Linsim. The number of right-halt-plane roots is determined by inspection of the completed array. The size can be very small because there is no need to produce any significant electrical power. The high-frequency content may be largely composed of noise, and a compromise is required between tracking capability and the attenuation of noise. With relatively large values of zeta 1.4), the placement of the two poles on the negative real axis differs such that the value of the larger pole is greater than the smaller pole by a factor that exceeds 5.6. Hence, an approximation for settling time is obtained by considering only the dominant pole (the pole with the smaller magnitude). The evaluation throughout the s-plane generates a surface. A variation of discrete-event control is provided by a system that incorporates a trilevel control signal with a positive on, a negative on, and an off level. REFERENCES 1. The system tends to maintain the antenna angle at the position described by the input reference function. With this combination of discrete and continuous actions, the digital components will contribute some undesired delays associated with conversion time, data handling, and the use of sequentially structured computation. Use only two state variables. However, the component of pressure introduced by the inertial component will be relatively insignificant unless there is a rapid transient variation in the rate of outflow. The elements are resistance, inductance, and capacitance, with the assumption that R, L, and C are constant. This method allows the development of a pencil and paper sketch that can often be produced very quickly. The assumed mathematical background includes the ability to apply matrix algebra and develop differential equations. If a system displays a quasi-linear operation within a limited range of signal levels, a linear state model can be developed that is valid with specific limitations imposed on the signal level. Sec. The methodology as shown assumes the use of a mathematical model. 1.5 THE DESIGN PROCESS Gaining the ability to plan and skillfully fashion a successful control strategy requires creativity and imagination, but expertise is also dependent on the acquisition of knowledge and experience. For example, criteria such as the settling time or the percent overshoot (with a step input) are not altered by a change in the amplitude of the step. In addition, the response to a constant acceleration of input angle then becomes a bounded function. Considering systems such as machine tools, robots, tracking radars, missile-guidance systems, etc., the behavior that follows the initial transient can be equally important (or critically important) in terms of desired performance. Analog controllers, however, display a tendency to allow at least small components of extraneous phenomena (such as thermal variations, the aging of components, or the presence of various noise sources) to be observed as variations in control information. The lag network is applied in the low-frequency range, and the lead network is applied in the high-frequency range. Gillespie, "Fundamentals of Vehicle Dynamics," Course Pack for ME458, The University of Michigan Transportation Research Institute, 1991. 1 model often provides the basis of developing a successful and robust control strategy. Using the results of a time-domain study in conjunction with other design tools will often provide important insight into the development of a successful design. 4.7 BLOCK DIAGRAMS COMPOSED OF STATE MODELS Block diagrams describe the flow of signals between interacting subsystems, and they can be used with subsystem models that are described using transfer functions, state models, or nonlinear transfer relationships. Double click on the block to open a dialog box. With closed-loop operation the benefits usually included improvements in efficiency and quality control. For example, specifying [0 2 4] for Time values and [0 1 0] for Output values produces a triangle wave that oscillates between 0 and 1 with a period of 4. The growth of the transient is eventually bounded by some form of nonlinear behavior, but the limitation may not occur gracefully. The variation of methodology, however, shifts attention to the z-transform and the position of poles in the z-plane. If the load on a synchronous motor increases, the angular orientation of the rotor field vector tends to lag further with respect to the angle of the rotating stator field vector. Thus, the inverse transformation can be pursued by applying a partial-fraction expansion to a ratio of polynomials. Moreover, the parameters and vectors can assume a symbolic form if they are defined in MATLABbefore a simulation is requested. A feedforward cancellation that is independent of velocity under steadystate conditions requires a linear relationship between the applied voltage to the motor and the steady-state velocity. The implementation of a practical resistor requires a nonzero size, and the resistor will exhibit a small distributed inductance along the current path and a small distributed shunt capacitance to adjacent circuits. A property of the "infinite gain" operation of the operational amplifier circuits is to produce transfer functions that are almost totally dependent on the characteristics of the passive Rand C elements. Various techniques that will improve the control are considered in the following chapters. Phasor algebra, on the other hand, is applicable only with sinusoidal inputs, and phasor algebra provides only the forced or steady-state response. 3.3 TRANSFER FUNCTIONS AND BLOCK DIAGRAMS The mathematical models as described in Chapter 2 comprise differential equations, and the application of the Laplace transformation converts these models to equivalent algebraic relationships. 4.6 NONLINEAR MODELS Considering a physical system, a nonlinear model is obtained if one or more of the system parameters varies as a function of signal level. If a state model is used to describe each of the various operating modes of a piecewise linear system, all of the required information is available. For this example, choose Linsim as the simulation algorithm; enter 0 for Start Time, 2 for Stop Time, 0.0001 for Min Step Size, 0.01 for Max Step Size, 0.001 for Tolerance. The test is particularly useful as a method of determining the range of variation of system parameters with respect to maintaining system stability. The simulation techniques described in Chapter 5 provide response functions with specific inputs, but there is little insight into the corrections that may be required if the behavior is unsatisfactory. This part of a signal is particularly vulnerable to small offsets in level. Within a limited range of slip, the developed torque increases in proportion to the velocity error. Considering the solution to Example 2.3, it is apparent that the velocity profile of Figure 2.17a is not feasible in a practical sense because it requires the application of an infinite force (and infinite power) to start and stop the motion. An achievement of major significance was the development of systems that provided automated control of machine tools. Consider an nth-order polynomial with the subscripts of coefficients numbered consecutively beginning with subscript zero applied to the highest order.2 Then the polynomial is If a row of zeros appears (an entire row is zero before the array is complete), this is an indication that there are jw-axis roots or certain other combinations of roots that are located with equal magnitude and equal angular spacing about the origin. Therefore, the direction of the trajectory must show movement to the right. The state model provides a particularly convenient mathematical format for developing a discrete-time model. The block diagram format is offered with a large selection of operational blocks, including transfer functions, state models, nonlinear relationships, and userdefined functions. To obtain nearly ideal dynamic properties, the capacitors must exhibit a nearly pure capacitance (the dielectric resistance is ideally infinite). The bandwidth must be large enough to ensure a good tracking capability, but if the bandwidth is too large, it can allow the transmission of undesired signals. The relative displacement of the ends of the spring provides a measure of the force on the spring, and the relative velocity of the ends of the viscous damper provides a measure of the force on the damper. 10.11 USING MATLAB The controller design procedures as presented are all aided by digital computation, and a combination of different techniques can be useful. There are obvious analogies between systems of electrical and mechanical elements, and the analogies can provide additional insight regarding the formulation of differential equation models. Some successful applications included welding, painting, measurement, and small parts assembly. If a sinusoidal input is applied to a system, the forced response is observed as another sinusoidal signal of the same frequency. Electronic circuits used to detect difference in phase provide a similar 34 Modeling Physical Systems: Differential Equation Models Chap. A consequence of the physical displacement is the introduction of a time delay in the loop function. Static and coulomb friction are nonlinear phenomena, and one commonly observed effect is a suppression of motion when the force (or torque) is small. Because the transfer function is an all-pole function, the conversion to a control canonical model produces state variables that are proportional to the output and the first derivative of the output (see Section 4.5). A real-time simulation is sometimes realized using parallel 113 114 Simulation Chap. A conversion from a state model to transfer-function model is readily obtained using either a matrix algebra expression or a state diagram. Because the system model is a type 1 system, the lowfrequency limit of the contour exhibits infinite gain and a phase angle of -90°. 2. This process is described as system identification. Since an integrator will retain a nonzero signal as a result of prior operation, establishing a specific initial state will require an Sec. This text is designed for a basic course in control systems engineering with a presentation that is applicable to programs in electrical, mechanical, aerospace, industrial, and chemical engineering. This attribute indicates that system parameters do not vary as a function of signal level. Parker, University of Alabama at Tuscaloosa, and Eric T. As an example, a thermal system and a corresponding electrical analogy are shown in Figure 2.12. Although phasor algebra exhibits no resemblance to Laplace methodology with respect to the representation of signals, there is a conspicuous similarity with respect to operational relationships as applied to the system model. This is one possible configuration that can be used to insert a controlled force into the suspension system. Therefore, this effect is not normally a significant factor in the evaluation of performance, and the use of a lumped-parameter model is a reasonable approximation. Although it would seem to require a differentiator in the feedforward path, it is assumed in this case that both displacement and velocity commands are available as input functions. Thus, linear models should be described with the understanding that there are limits on the magnitude of dependent variables. If the model is not linear, the state model format can be generalized to encompass nonlinear functions with x A transfer-function model is, of course, a linear system technique. Much of the incentive for work that began in the 1920s and 1930s was derived from an interest in the ability to steer ships and aircraft automatically. Generating solutions to the end-of-chapter problems is an excellent method of dispelling any hesitancy in adjusting to discrete-event concepts. Motors as Velocity or Torque Sources It has been shown that voltage control of an armature-controlled DC motor tends to provide the characteristics of an ideal velocity source. Example 10.2 illustrates this conversion with PI control applied to a model of the antenna control system, as modeled in previous chapters. 5 the relationship to the output. Nonlinear system simulation can be pursued using ode23 or ode45 to introduce an applicable integration algorithm. 1 REFERENCES 1. 4. Thus, the output of the integrator will continue to change unless the error signal is driven to zero. Considering the circuits of Figure 5.1, the open-loop gain of the amplifiers is extremely high only in a limited frequency range, thereby limiting the nearly ideal performance to a limited bandwidth. The gain factor 0.4 can be replaced with G1 in the block, and G1 = 0.4 must be entered in MATLAB. T. 4 Conversions between state models and transfer-function models can also be determined using MATLABcommands ss2tf or tf2ss. Considering the model of a linear time-invariant system, the Laplace transformation can be used to provide a transfer ratio that relates the transform of an Using Block Diagrams The transfer-function model is an algebraic model, and a block diagram is a graphical depiction of algebraic relationships. For example, a resistor will exhibit a notable change in resistance (or melt) if the current exceeds a reasonable value; a capacitor will break down if the voltage is too high; a spring will become totally compressed or reach an elastic limit if deflected beyond anticipated limits; and an inductor with a magnetic core will reach saturation if the flux density is sufficiently high. With the system at rest, there is an initial deflection of the spring equal to Mg/K. Although nonzero velocities can exist on both ends of a spring or damper, there is only one velocity associated with an inertial element. If the components are continuous, the desired model is obtained as a set of differential equations. Hence, a circuit can be designed that activates a negative feedback loop around the integrator during periods of large transient error. 8.1 INTRODUCTION Root-locus techniques are utilized to study the changes in performance of linear systems that occur with variations of system parameters. Although power is supplied to the plant in only three discrete levels, the energy supplied in any time period is, of course, dependent on the timing of the switching actions. If a lead screw is designed with a low pitch and without the use of ball bearings, the efficiency is very low, and the lead screw may be observed to transmit power only in the forward direction. Basic relationships of either methodology provide similar operational functions. The interaction of poles, zeros, and gain factors of various subsystems can be evaluated, and performance characteristics of the overall system can be studied with respect to the contribution of the various system components. Thus, a simulation algorithm is readily applied by introducing a system model and then invoking an appropriate MATLAB command. The phasor-algebra transfer function describes the steady-state gain and phase shift as a function of frequency. If a system model exhibits four or five dominant poles or a significant transportation delay (see Section 9.6), the phase lag may increase rather sharply as the frequency increases. A. In a strict sense, this behavior is not possible with a device of nonzero size. 3.3 Using Signal-FlowGraphs 59 denominator, this situation is not typical, and the calculation should be carefully reviewed. Am. Soc. Yang, Ch'ang. and compo gain axis([.l 10000 -40 40]) % Define plot bounds ylabel('Gain (dB)'), xlabel('Freq (r/s)') subplot(212) % Plot in lower half of plot area semilogx(w,ph,w,phc),grid % Plot uncomp. will be inordinately large, and the transient signal levels will likely exceed the bounds of the linear model. Since the procedure does not require an iterative search, the test can be performed simply as a "pencil and paper" task. A sufficient frequency range must be considered to locate dominant poles and zeros. The viscous dampers produce a force or torque that varies with the translational or angular velocity. The use of a numerical technique, however, is a common procedure, and with certain nonlinear models, a numerical simulation may be the only straightforward approach to the study of cause-andeffect relationships. Assuming that Xl = Y and x2 = y, then y is plotted as a function of y. Interesting illustrations of human ingenuity included the design of fanciful clocks with automated chimes Sec. Within a limited range of angular variation, the torque increases in proportion to the increase in angular error. A test for state controllability is described in a subsequent discussion. The minus sign indicates that this circuit introduces a polarity reversal; however, the sign is easily counteracted. A basic understanding of this phenomenon is obtained by considering the static system model, as shown in Figure 7.33. o. However, the preponderance of successful applications of control techniques has occurred with application to systems for which the interactions are completely described by the laws of physical science. Assuming that u is a step input of magnitude 10 and the model is The response is y(t). Thus, the application of state feedback produces a situation in which the three roots (a real root and a complex conjugate pair) can be placed as desired. As the sheet solidifies, measurements of properties such as thickness and density are obtained, and this information is utilized to provide feedback to the controller. Boston, Toronto: Little, Brown and Co., 1978. It is, of course, impossible to maintain an exact cancellation. In situations with a group of dominant poles, the use of a PI controller may allow the designer to satisfy a steady-state error specification without increasing the high-frequency gain, thereby avoiding a potentially significant stability problem. A simple example that illustrates this phenomenon is obtained by considering two coils, as illustrated in Figure 11.5. Assume that the coils (with L = 1.0 Hand R = 1.0 12) are placed such that there is no magnetic coupling. The harmonic gear form uses a circular outer gear (with inner teeth) and a flexible inner gear (with outer teeth). Observability involves the manner in which the state variables of the plant influence the output of the plant, and a test for observability involves the A and C matrices. Assume that a step input is applied. Describing the areas of study that depend on the use of algebraic models is difficult because the list is remarkably extensive. Backlash Backlash is a nonlinear phenomenon that can occur with various linkages, but it is usually associated with the performance of drive systems that employ gears between the motor and load. The implementation of control system simulation is subject to several options, and techniques can be devised that offer varying degrees of realism. The property of controllability involves the manner in which the input to the plant influences all of the state variables. The diagram on p. Saadat, Computational Aids in Control Systems Using Matlab. When several elements are connected to form a system, a linear model is valid only within specific bounds on dependent variables. The Routh criterion (reported by E. Output feedback is realized by using a full-order observer to estimate the state variables. However, if the model is nonlinear, the character of the performance is also sensitive to the magnitude of the excitation, and an additional dimension is added to the study of system behavior. Given the state of the system, the model defines the change to a new state that will occur in a small time period. Only two analogous elements (capacitance and resistance) are associated with the thermal model. Thus, the state variables attain physical significance only in terms of the established relationship to the output. If a system is type 2 or type 3, the open-loop contour extends upward (to infinity) with a phase shift of -180° or -270°. The development of high-performance aircraft placed extraordinary demands on the design of flight control systems. When utilizing s-plane techniques, a combination of computer-generated root loci and time-response calculations can provide extensive performance data and decisive assistance in the design process. The development of a mathematical model for the plant can be pursued by determining a set of differential equations that accurately describe the plant. It is a process that would probably fail without the feedback. The Inport and the Outport blocks are copied from the Connections Library. 3.4 USING SIGNAL-FLOW GRAPHS In mathematical terms, a block diagram provides a graphical representation of a set of simultaneous algebraic equations. The application of SIMULINK provides a graphical approach with the development of a block diagram. Hurwitz in 1895) describes the development of a set of determinants that must all be positive as a necessary and sufficient condition for all LHP roots. With the model as specified, the open-loop phase shift approaches -180° asymptotically as w approaches infinity; hence, the gain margin is infinite. ~ ntrol o Systems Engineering 1.1 INTRODUCTION The essence of control systems engineering is an inquisitive endeavor to continually advance our understanding of methodologies that provide the ability to control systems. Hazen [4] described these systems as servomechanisms using the Latin word servo, meaning "slave" or "servant," and terms such as servomotor and servosystem remain in common usage when describing modern components that provide a similar function: Another source that contributed to the development of control theory was the work of circuit theorists such as H. It is apparent that changes in the open-loop gain alter various performance characteristics in a manner that is interactive and often conflicting. Considering the series RLC circuit of Figure 2.1, application of Kirchhoff's voltage law requires that the voltages sum to zero in the loop. Unless the spectral range of a control signal is temporarily transferred to a higher frequency range (using a modulation technique), the control signal will include a component that is very slowly varying (or constant). A discussion of basic concepts that are relevant to the present discussion can be reviewed in Section 7.3, and some of the introductory comments are briefly reexamined in the following section. Although limited to models of linear (or nearly linear) systems, transfer-function techniques are widely used with application to numerous analysis and design techniques. 3.9 3.9 Modeling Using SIMULINK 75 MODELING USING SIMULINK In addition to the command-line programming environment, MATLABcan be supplemented with a window-based graphical user interface known as SIMULINK, in which a system can be described graphically by drawing block diagrams. Sensors placed in each magnetic field measure the field strength, and the output is the sum of the two measurements. The discrete actions may be acting alone, or they may be providing supervisory control to other control systems in a hierarchical set of systems. 12.5 SIMULATION WITH A DISCRETE-LEVEL CONTROLLER A controller that produces only two or three output levels is conceptually simple, and the operation is uncomplicated and highly efficient. Another approach to the design procedure is to place the zero such that it cancels the open-loop pole. If an element gradually deviates from linear operation as the level of excitation increases or the associated temperature gradually rises, this occurrence can be described as a soft nonlinearity. This particular partitioning of the response separates the component that occurs if the input is zero and the component that occurs if the initial state is zero. His mechanism utilized a paper roll and a cylinder to lift automatically the correct set of threads over the shuttle. The propagation time, however, is usually substantially less than the response time of the system, as determined by the natural dynamics of the system. There are several possible variations of state variable selection that produce unique characteristics when applied to specific linear system design techniques. If the system model is globally linear, the properties of a linear system are observed throughout the entire space. Courtesy of HD Systems, Inc. Since matrices can be created by adding parts, the inputs can be generated by adding portions that occur in different time periods. There is also a specific velocity that must be avoided because a resonance occurs that involves transfer between magnetic and inertial energy storage. Either of the signal-flow graph configurations as described in Chapter 4 (Figures 4.8 and 4.11) will provide a workable graphical representation. Despite the presence of one or two additional poles, the use of an approximate differentiation introduces a controller path that intensifies extraneous signals. Note that when the block diagram is saved as blockmodel, it can be recalled in future sessions simply by entering the name in MATLAB.Redrawing the diagram will not be necessary. Thus, there is a temporary loss of coherence between drive and load motion that occurs each time the torque transmitted through the gears changes in sign. 62 Transfer-Function Models Chap. Another approach is suggested by the perception that the action of a pure integrator is neither necessary nor desirable during periods of large transient error. . If the motor power requirement is low enough that the efficiency of the electronic controller is not a major A disassembled harmonic gear is shown. A study of system stability (Chapter 6) will show that a necessary (but not sufficient) condition for a stable response is the presence of the same sign on all coefficients of the denominator polynomial. The use of FOR loops to generate the input vectors (the reference input and the wind disturbance) versus time is one of several possible alternatives. An alternative format for control system models is the state model, as introduced in Chapter 4. A trajectory is typically determined to begin at t = 0 and end at t = 00. Students are generally aware that the ability to work in this area is a valued skill, and they are eager to participate. Torsional springs are commonly implemented using nothing more than an extended steel shaft, and the symbol for a torsional spring is shown simply as an extended shaft. Note that the zero of the open-loop function also appears in the closed-loop function, Y(s) / R(s). 1.4 1.4 The Classification of Control Techniques 7 THE CLASSIFICATION OF CONTROL TECHNIQUES A basic block diagram of a control system with feedback is shown in Figure 1.1. Although the control can be applied to tasks as diverse as controlling the position of a space vehicle or controlling the position of a read/write head on a digital memory disc, the term plant or process is commonly used to describe the part of the system that is controlled. A Significant Shift to Solid-State Digital Techniques The rapid development of solid-state digital technology in the 1950s and 1960s introduced profound changes in both continuous and discrete control techniques. However, the inability to respond to high-frequency components of the input is not necessarily an undesired characteristic. The model as proposed at the lower left is the state model, and the opposing option is a familiar model because it is often produced with linear system models using transfer-function techniques. To satisfy this requirement, the feedforward function must include a zero at the origin. With this exclusion, a left-half-plane location for all poles is sufficient assurance that all of the terms of the natural response will decay asymptotically to zero (regardless of the point of observation). In contrast, the use of a PI controller increases the type number, but the introduction of an additional integration increases the order and changes the character of the natural response. A home security system helps to ensure you're safe from intruders. The movement and possible placement of roots can then be evaluated in terms of the corresponding transient performance. Music machines were developed that automatically controlled the excitation of resonant pipes, reeds, strings, whistles, chimes, and a variety of percussion devices. The natural response can be described as the part of the response that produces a transition from the initial state to the forced response. The final selection of a gear ratio may be a compromise that considers the relative importance of several factors. For example, the first four aforementioned blocks are contained in the Linear Library. The design process is then normally pursued with the development of a model of the complete system that also includes the controller and powering devices. An example of this type of phenomenon is the limiting that occurs when the output level of an operational amplifier circuit approaches the magnitude of the DC supply voltage. An appreciation of the value of these plots is dependent on a clear understanding of the significance of pole position with respect to system behavior. The corresponding manual operation would require many time-consuming measurements. This procedure is repeated for different frequencies of the sinusoidal input. The method as described is applicable to all-pole systems. The simulation is piecewise linear, and each of the linear models is applicable under carefully defined conditions. The frequency-response topics of Chapter 7 describe the development of performance criteria as observed with closed-loop transfer functions. If the system model is linear, the difference-equation model is composed of constant matrices, and the solution is formed by repeated matrix multiplications. 12.1 INTRODUCTION The linear (or nonlinear) character of a dynamic system model can have considerable impact with respect to the ease of analysis and design. Since digital techniques enable operations that are strictly repeatable, digital controllers display both a short-term and long-term consistency of performance that is highly desired in systems with particularly demanding requirements. Many applications of automatic control require somewhat similar combinations of continuous and discrete actions. If the number of state 346 Nonlinear Modeling and Simulation Chap. Assuming that there are no poles of the open-loop function in the RHP (Case 1), type number is accompanied by an increase in the order of the system and a change in the character of the natural response. Although it may be possible to develop a control strategy by relying on expert knowledge rather than the use of a specific system model, the expert knowledge is derived from the experience of working with various mathematical models. The plant portion generally displays inherent properties that cannot be altered by the designer, and the plant is typically characterized as dynamic and continuous. The design requirements of the shuttle involved consideration of velocity variations from zero to about Mach 25 and altitude variations from ground level to orbit altitudes of 125 miles and higher. With a nonlinear model, the description of the model cannot be entered simply as a set of matrices; thus, a somewhat different technique must be employed. Robots were generally designed to provide at least 5 or 6 degrees of freedom, and often the configurations imitated human arms and wrists with the use of cascaded members connected by rotating joints. The signalflow graph is somewhat easier to sketch because the symbols are simpler. To minimize the energy requirements, the average actuator force is ideally maintained at zero. The error constants provide an evaluation with regard to the magnitude of error in the specific situations that produce a constant nonzero error. The coefficient of viscous friction with translational motion is expressed in terms of force per unit velocity (force in newtons and velocity in meters per second), and the coefficient of viscous friction with rotational motion is expressed in terms of torque per unit of angular velocity (torque in newton-meters and angular velocity in radians per second).2 The other phenomena as shown are relationships for mass (or moment of inertia) and linear springs. The Routh array provides an absolute test of stability. Consider the following polynomials: It is apparent that the roots of the first two polynomIals do not all eXIstIn me L.t1Y, but a conclusion with regard to the third polynomial is not apparent unless additional information is obtained. Englewood Cliffs, N.J.: Prentice Hall, 1994. A mass transmits the same velocity at two connecting points, but the difference between a force applied to the mass and a force exerted by the mass (to another element) will provide a measure of acceleration. The steady-state (polynomial) error, however, may assume the form of a derivative (or a summation of derivatives) of the input. The state of the system at any instant in time is a point in state space, and the natural response generates a unique trajectory through state space. Some devices provide a characteristic that is nearly linear considering a limited range of signal levels, but significantly nonlinear beyond specific levels. Considering the model as described, the capacitance of the tank tends to maintain a uniform pressure and counteract any sudden changes in an outflow. These results are illustrated in Figures 7.20a and 7.20b. The PI controller converts the antenna control system from type 1 to type 2. The state model is 128 Simulation Chap. More than a century later, punched paper tapes were used to program early versions of automated machine tools, and punched cards were used to program early versions of electronic computers. If a system model is linear and time invariant, the evaluation of system stability is relatively straightforward and uncomplicated. The use of transfer functions often provides valuable insight into cause-andeffect relationships, and the parameters are readily related to experimental data. This is a special format that comprises the state model. a> Settling Time with a Dominant Pair of Poles The settling time with an underdamped response is defined as the minimum time in which the step response settles to 2% (or 5%) of the final value and remains within Other Pole-Zero Clusters Various other groups of poles and zeros may predominantly determine the response. Since some of these devices exhibit nonlinear characteristics, the approximations that can be used to obtain a linear model are carefully described. C. The first term of the summation is the response if the system is unforced, and the second term is the response that is obtained if the initial state is zero. This is accomplished by canceling undesirable terms of the plant model and introducing desirable terms that involve multiplying factors that are applied to the input and derivatives of the input. The capacitance is constant if the cross-sectional area of the tank is independent of depth. A subject of mutual interest was the analysis and design of feedback amplifiers. MATLAB functions are utilized as an aid to other areas of study, including the development of root loci, frequency-response plots, discrete-time system simulation, and pole placement techniques. The ability to increase the loop gain may also allow an increase in the value of a finite error constant. The numerical algorithms are set up very quickly and efficiently if the model is introduced in the state model format. However, certain nonlinear systems can exhibit special computational problems. Any corrections or changes to the parameters of a block can be made by double clicking on the block and reentering the parameters. Depending on the location of the immobilized pole (or poles), the consequence of this condition can vary from a slightly troublesome limitation to a catastrophic inability to stabilize the response. Although an exact cancellation is not a practical concept, the approximate cancellation of an LHP pole is usually an acceptable procedure. Motor control circuits must be capable of functioning with power transfer in both directions, and gear systems are used to improve power utilization with the operation of high-speed motors. Considering the state model of Equations 4.50 and 4.51, the following program defines the state model, obtains an equivalent transfer function, and then converts it back to a state model in control canonical form: a = [0 1 0; -4 -24; -10 0J; % Define the A matrix b = [04 1J'; % Define the B matrix c = [1/20 0J; % Define the C matrix d = 0; % Define the D matrix [n,dJ = ss2tf(a,b,c,d) % Convert the state model into a transfer function [aa,bb,cc,ddJ = tf2ss(n,d) % Convert the transfer function back to a state model The state model provides a format that is particularly useful when applied in conjunction with digital computation; it also provides the basis of numerous linear system analysis and design techniques. The steady-state errors are described as an array in the table with the rows and columns identified by a type number and an input function2. A somewhat different approach is introduced in Chapter 9 that utilizes relationships between characteristics of the open-loop function and stability of the closed-loop function. There is a significant difference in available power, however, because the DC motor is capable of operation at a much higher maximum velocity. A limit cycle appears in state space as an isolated closed path, and if more than one of these paths exists, each path represents the potential to engender a periodic variation. In other words, an error signal of opposite sign must be integrated for a sufficient time period to return the output of the integrator to the normal operating range. The input frequency (and phase) varies with time due to the relative motion of the transmitter and receiver. 3 characteristics. Returning to the coffee mug experiment, if a pencil is inserted in the handle and then used to move the mug left and right, backlash is observed. The temperature of a resistor can increase to a point that the resistance changes significantly or the resistor melts. With the implementation of state feedback, closed-loop transfer functions can be obtained using either a matrix transfer equation (Equation 11.5) or the construction of a state diagram. Nyquist, "Regeneration Theory," Bell Systems Tech. • Because nonlinear phenomena are often an important concern with practical contro] systems, nonlinear models are considered intermittently through the text and Chapters] 2 and 13 are specifically devoted to this topic. Mason's gain formula (described in Chapter 3) provides a set of structured rules for the determination of closed-loop transfer functions. The magnitude and angle of the ratio are sometimes described as the gain and phase shift, respectively. With an improved capability to retain and manipulate data, the use of digital technology offers a greater flexibility in the employment of mathematical operations. Digital simulation is commonly implemented as a sequence of computational tasks that are implemented in time intervals that are dependent on the complexity of each sequential task. Although plant variables may be sampled at discrete intervals of time, the plant variables are typically observable as continuous signals. If all of the blocks are described using transfer functions, closed-loop transfer functions can be determined using linear system techniques that are applicable to the solution of a set of simultaneous algebraic equations. With step and impulse, the model can be entered as a state model or a transfer-function model. With digital control, part of the system uses discrete-time signals, and a careful representation of the behavior under all conditions requires a discrete-time model. Models of springs in Tables 2.1band 2.1c are expressed in terms of displacement (x or e) with the assumption that the displacement reference is the position that corresponds to zero force or zero torque. Each of the state variables (as specified in the model) appears as the output of an integrator. Real-time operation allows a "hardware-in-the-loop" simulation with parts of the actual system included, or the system may include a human operator as part of the control loop. 2.3 MODELING WITH LUMPED LINEAR ELEMENTS When describing a single two-terminal element, the magnitude of one dependent variable is determined as a difference in value between the terminals, and a related variable is assumed to pass through the element. When the temperature inside exceeds 78°F, the thermostat sends a signal to the air conditioning unit.The air conditioning unit clicks on and cools the room.When the temperature in the room returns to 78°F, another signal is sent to the air conditioner, which shuts off.It's called a negative feedback loop because the result of a certain action (the air conditioning unit clicking on) inhibits further performance of that action. Because the presence of nonlinear phenomena is a pervasive concern, nonlinear plant models are considered intermittently through much of this text (Chapters 12 and 13 are devoted to this topic). Because the topic area is multidisciplinary, the book's examples are drawn from a variety of engineering disciplines.Mathematical Models of Physical Systems, Control Systems and Components, Concepts of Stability and Algebraic Criteria, Root Locus Technique, Frequency Response Analysis, Liapunov's Stability Analysis, Optimal Control Systems, and Advances in Control Systems are just a few of the topics covered in this book. As applied to the telescope control system, this means that the object is moving in a manner that produces a constant rate of change of angle, and the steadystate angular motion of the telescope assumes the correct rate of change of angle, but there is a constant angular lag. Linear System Simulation If a system model is linear and continuous, MATLAB commands that are applicable include step, impulse, initial, and lsim. The response to a step input exhibits an overshoot of about 1%. 3 Although signal-flow graphs will be used in various situations, Mason's gain formula can be applied directly to a block diagram. 2.1 INTRODUCTION A basic prerequisite to the development of almost all strategies for control is the ability to obtain a mathematical model for the plant (the part of the system to be controlled). A straightforward approach is to place the zero to cancel (or approximately cancel) the dominant pole; the system is changed from a type 0 to type 1 with the closed-loop function again displaying a single dominant pole. Functions of this form are strictly proper, and a partial-fraction expansion is directly applicable. With a zero-order hold, the input to the plant is constant between sampling instants. and time invariant.3 Unfortunately, there is no guarantee that all of these system traits will be applicable in a realistic situation. This type of operation occurs with the presence of phenomena such as static and coulomb friction, or it may be generated by the intentional introduction of a nonlinear characteristic, such as the action of a relay controller. The noncircular shape of the wave generator on the left produces a rotating ellipse that is transmitted through the bearings to control the shape of the center gear. 6 6.2 STABILITY CRITERIA AS APPLIED TO TRANSFER·FUNCTION MODELS Considering a single-input, single-output (SISO) system with an overall transfer model of Y(s) / R(s), the location of the poles of the transfer function determines the character of the natural response as observed at the output. The elements of the row just prior to the row of zeros are utilized to form an equation known as the auxiliary equation, and determination of the roots of this equation provides the equally spaced roots that produced this phenomenon. 170 Performance Criteria and Some Effects of Feedback Chap. If the actuator is a hydraulic cylinder, the force is obtained by applying hydraulic fluid to the cylinder at high pressure as provided by a hydraulic pump. Block diagrams are sometimes used with a mixture of transfer functions and other model formulations. L. Thus, stability is a fascinating and important topic. Tachometers A tachometer can be used to sense the angular velocity of a rotating system. The solution displays a summation of matrices that describes the zero-input response and the zero-state response. However, the consequences of neglecting nonlinear components of friction can be significant, particularly if there is a need to determine accurately the response at low signal levels. The motivation was created by wartime concerns, and much of the early work was performed in the restrictive environment imposed by wartime security. Because this function provides the unit-step response, the factor of 10 was introduced by increasing the numerator coefficient. If, however, a system is characterized by a complex combination of interactions, a study of experimental data may be required to provide system identification. There are also hard nonlinearities that are observed when elements abruptly change at a specific level of excitation. With a larger system bandwidth, the spectral content of the input is passed without alteration over a broader frequency range; hence, the output spectrum is a more faithful representation of the input. 4 Control Systems Engineering Chap. The Elements of a Successful Design Experience It is, of course, satisfying to develop an ingenious solution or a creative design that evolves from personal experience and education. The use of digital simulation is also advantageous if there is a need for high precision or a need to generate input waveforms that are not readily formulated as analog signals. Baumgartner, Jet Propulsion Laboratory. When the design is complete and all parameters are fixed, there may be other parameters of the plant that change or drift away from their nominal values-the values that were determined and used during the initial modeling and design process. The magnitude and angle of the transfer function represent gain and phase shift, and various techniques that utilize this model are described as frequency-response techniques. Furthermore, the active system characteristics are adjustable. Although the methodology is restricted to linear systems (or systems that are quasi-linear within a restricted range of signal levels), the breadth of application is extensive, and a significant insight into cause-and-effect relationships can be gained by studying these techniques. If the contour on the Nichols chart skirts just to the right of grid line that denotes 0.5 dB of closed-loop gain, the response to a step input will produce roughly 10% overshoot. The use of a cascade control function offers the ability to modify an open-loop function in a manner that can significantly improve the performance of the closed-loop system. Black, "Stabilized Feed-Back Amplifiers," Electrical Engineering, 53, Jan. However, the field intensity affects both the developed torque and the back EMF, thereby producing a very nonlinear steady-state speed versus voltage characteristic that is inverted through much of the operating range. Given a specific input function, the calculation of a response function is obviously much simpler if components of static and coulomb friction are neglected. In other words, there is normally more than one set of variables that will engender a valid state model. Composition of the State Model Considering the techniques as presented in Chapter 2, system models are developed with the application of physical laws that govern the dynamic behavior, thereby producing a set of differential equations. 10.3 The PI Controller 277 gain is increased throughout the range that contains the cluster of nonzero poles. Increasing the Type Number A desired improvement in steady-state performance may require an increase in the type number. 10.10 SELECTING A CASCADE CONTROLLER Considering options between PI, PD, and PID control, the use of integral and derivative control should be considered carefully with each application. The dashed line shows the position of the contour with a 4-dB increase in open-loop gain. To produce roots that all exist in the left half Sec. The transformations provide transfer-function models, and there are many analysis and design techniques that employ the algebraic models. K. The minimization of backlash occurs because the curvature is very similar in the region where the elliptical gear contacts the circular gear. Given a specific model and a specific input, the response functions can be calculated using the Laplace transformation and matrix algebra techniques. 3.5 SOME SUBSYSTEM MODELS The following discussion includes the description of devices that are commonly used as actuators or sensors in electromechanical control systems. This technique has been almost entirely replaced by digital simulation in research and development applications, but there are characteristics of analog simulation that are particularly suited to academic studies. The implementation involves the formulation of control actions determined in response to the observed sequential and combinational characteristics of a set of command and sensory conditions: Input and feedback conditions are 10 Control Systems Engineering Chap. From a mathematical viewpoint, the best approach is to describe a nonlinear model as one that is not linear. Hazen [4] presented mathematical analyses for electrically connected control systems. 7 An alternative to the evaluation of time-domain criteria is the evaluation of frequency-domain characteristics. In practice, the DC gain of an operational amplifier is not infinite and the dielectric resistance of the capacitor is not infinite; hence, the poles are displaced slightly to the left of the origin. A phase-lead compensation function is identical to a PD function (with one pole added to the ideal function), and this compensation technique is subject to the same consideration with regard to disturbance signals and the relative position of the zero and pole. On the other hand, difficulties related to word length and speed are rapidly diminishing with improvements in digital technology, and the use of digital data provides a high level of immunity to noise and component variation. When using SIMULINK, the major programming tasks are all performed internally. Several different examples are presented that illustrate surprisingly dissimilar effects with regard to system stability. The required model is formulated as a set of differential equations. Another variation of control strategy is to sense the road profile with the purpose of using this additional information to improve the performance of the suspension system. Sensing devices-such as differential transformers or electronic phase detectors-exhibit a conversion characteristic that is nearly linear when the deviation from a null condition is small. The models for various linear components and subsystems can be described using transfer-function models. The blocks labeled Constant, Step Input, Sine Wave, Pulse Generator, and Signal Generator will produce signals that are commonly used to test dynamic systems. Some systems exhibit an inherent integration that is generated within the physical system that describes the plant and the physical measurement of system variables. In other words, the tracking capability cannot be perfect. Examples based on outdated technologies have been removed, and the same has been updated with more relevant cases. The value of a node is applied to all outgoing branches. 2.3 Modeling with Lumped Linear Elements 17 A set of passive mechanical elements is shown in Tables 2.1b and 2.1c, assuming translational motion (Table 2.1b) and rotational motion (Table 2.1c). A slight deviation from an exact cancellation does not (in most cases) produce a significant change in the system performance, and the behavior with a small deviation is easily simulated and studied. An experimental determination of a phasor-algebra transfer function is obtained by applying a sinusoidal signal of some frequency, w, to the input and measuring the relative magnitude and/or the difference in phase angle of the steady-state output signal with respect to the input signal. The presence of feedback offers the potential to modify system behavior substantially, and the scope of possible variation is often demonstrated with dramatic results. State Models 108 Chap. The connecting lines can represent a single variable or a vector. The characteristics of a linear system solution can be studied by applying a Laplace transform solution to the vector matrix model. E. For example, a resistor in an electrical circuit must exhibit a ratio of current to voltage that is independent of the level of the applied voltage. The key is to choose ~ proper controller transfer function that contains at least as many independently adjustable parameters as the order of the resulting closed-loop system (which is also the number of equations that can be established for pole placement). This model provides a generalized format that is independent of system order, and it is the basis for a number of analysis and design techniques that are sometimes described as modern control theory. Gain and phase margins can be measured using Bode plots, polar plots, or log-magnitude versus phase plots (assuming that the plots display the open-loop transfer function versus frequency). Nonlinear state models are considered with the application of numerical simulation techniques, and the linearization of nonlinear state models is a topic that is considered with the study of nonlinear systems. em. The author and publisher shall not be liable in any event for incidental or consequential damages in connection with, or arising out of, the furnishing performance, or use of these programs. Nicolas Minorsky [1] provided a mathematical model to describe the control of ships, and H. To obtain the transfer function of the system in MA TLAB, type The first command produces a state model (to be discussed in the next chapter) of the block diagram. The state model is a time-domain model with a formulation that is particularly convenient for digital simulation. Englewood Cliffs, N.J.: Prentice Hall, 1975. The force applied to the viscous damper is also transmitted to the second mass as an Models with Thermal and Hydraulic Components Although models using analogous electrical and mechanical elements are considered carefully throughout this text, analogies to electrical resistance and capacitance can also be extended to thermal systems and hydraulic systems. Classical and current approaches to digital control have been thoroughly examined. The root locus plots show the movement of roots of the charac- Problems 201 teristic equation as system parameters are changed. II. The error in settling time that is produced by this approximation is less than 6% or 3%, using the respective (5 % or 2%) definitions of settling time. Newly designed aircraft were often imperiled by aerodynamic control problems associated with continuing demands for higher speed and greater maneuverability. A dynamic characteristic will vary slightly with respect to the static characteristic, because the kinetic energy of the load can produce a change in the output position when there is no contact between the gears. One approach to the selection of state variables is to select variables that provide a measure of stored energy. 3.7 Order Reduction 71 Other control options can be pursued with the use of accelerometers on the body and the axle. For a large rocket in a vertical lift trajectory, aerodynamic control is not effective until a significant velocity is achieved. The second command converts the state model to a transfer function. However, the correct relationship with respect to time is a documented part of the solution, and the correct relationship is observed when variables are plotted. B. For example, assume that the input signal applied to the system of Figure 7.25 contains a constant term plus a sinusoidal component that is generated by inductive pickup from a nearby power circuit. There are, however, some special situations in which the ability to utilize linear modeling concepts can be retained. The use of a graphical technique may be viable, but the application of a graphical technique to a dynamic feedback model is typically a tedious procedure. Assume that a relative stability specification restricts the maximum peak of the closed-loop gain function to 0.5 dB. A practical realization requires at least one additional pole that is carefully positioned with respect to the location of the zeros. A tachometer is usually a DC machine with characteristics that are identical to a small permanent-magnet DC motor. • Various performance criteria (including stability) depend on both the system model and the level of excitation. The authors believe that it is very important to maintain an appropriate balance between pencil-and-paper analyses, laboratory work, and computer simulation; however, MATLABand SIMULINK are used to reduce computational barriers and improve comprehension in many important areas of study. Printed 10 9 Reprinted ISBN in the United States of America 8 7 6 5 4 with corrections 3 May, 200 I. The conversion to automatic control involved the addition of electrically controlled powering devices, electronic controllers, and sensors to provide feedback. The digital execution time produces a delay, and the computation time places a lower limit on the time between samples. If the natural response does not decay, the effect is observed as a loss of the desired control action. Constant errors are described in terms of error constants that are defined as follows: Sec. S. Consider, for example, a nonlinear state model that is described by 104 State Models Chap. This particular set includes a variable and n-l derivatives of the variable. This feature places a significant number of precision teeth in simultaneous contact. The book is applicable to one or two semesters. These systems are sometimes described as discrete-event dynamic systems. The successful control of these systems provided a test that was often used to evaluate or demonstrate the effectiveness of newly developed control techniques for multivariable systems. With three dependent variables, the n-dimensional space can be envisioned using a three-dimensional Cartesian coordinate system. A classic example of a control system is the negative feedback loop that controls the thermostat in your home. This problem is solved by utilizing a function M-file to introduce the system model. If the equations are combined in a manner that eliminates all but one dependent variable, the result is an nth-order differential equation, and the system is described as an nth-order system. A set of linear differential equations can be converted to a set of linear difference equations using several different techniques. The various properties have been collected into a set of rules known as the rules of construction (see Section 8.3). The values of phase margin and the corresponding performance in the time domain are specified for a particular system model, but the results are very similar to other type 1 systems. The characteristics of each block can be determined by double clicking on the box and examining the corresponding dialog boxes. The design of the controller is typically confined to the use of well-known and easily understood techniques, and modifications or adjustments of parameters are usually performed easily and quickly. Suppose that both state variables, Xl (t) and x2(t), are to be observed, and they are to be plotted together with the excitation signal, r(t), in the same figure. The developed torque is, of course, proportional to the armature current. If both the uncompensated and compensated system models are considered, the corresponding frequency-response functions can be calculated and observed as follows: % Example 10.8 - Uncompensatedand Compensated w = logspace(-1,4,200); % Extend the frequency range k0 = 50; z = 20.2; p = 124; % Specify gain factor,freq. The completed SIMULINK diagram is a model of the system of Figure 3.8 with the specified transfer functions. Black, "Inventing the Negative Feedback Amplifier," IEEE Spectrum, Dec. Unlike the output feedback methods described in Chapter 10, this approach Problems 339 has the capability of arbitrary pole placement. If a plot of x is requested, the variables that constitute the state vector (using the control canonical state model) are plotted versus time. It even offers integration with up to 40 devices according to Protect America online.LifeShield KPC 1000A rubber keypad and plenty of shortcut buttons make the LifeShield KPC 1000 both durable and easy to use. The development of discrete-time relationships for digital simulation also includes some concepts that appear in other areas of study. The signal-flow graph substitutes abbreviated symbols to present the same algebraic relationships as described using a block diagram. Thus, if a third coordinate is added to the s-plane, the magnitude (or the angle) can be evaluated and plotted at every point in the s-plane. The ability to determine models experimentally for nonlinear phenomena can be very difficultthere are no encompassing techniques that will convert experimental data to a nonlinear mathematical model. In some situations, the perception of theoretical relationships can be elusive, and the determination of a model may require experimental tests using system identification techniques. If y contains an alternating signal component, then y is an alternating signal, and the effect as viewed in the phase plane is a rotating trajectory with a clockwise rotation. The magnitude of the time delay is determined by the distance between the control point and the sensors divided by the velocity of the motion. Depending on the desired form of output display, the Outport block is replaced with a block from the Sinks Library. The integration can occur as the result of combinations of plant actions, such as controlling velocity and sensing displacement, or controlling rate of flow and sensing volume. Switching conditions occur as the result of observing feedback signals in relation to desired reference levels. A magnified view of the vicinity of the O-dB crossing is shown in Figure 9.19. Since control systems most often exhibit the characteristics of a lowpass filter, the high-frequency components of the input are usually subject to attenuation. at: The MathWorks, Inc., 24 Prime Park Way, Natick, MA 01760. If a shaft is shown without a symbol, it should be assumed that it is rigid. 9.2 PHASOR-ALGEBRA MODELS AND GRAPHICAL VARIATIONS If a sinusoidal input is applied to a linear system, the steady-state response is another sinusoid of the same frequency. Thus, as Ko becomes large, one pole tends to cancel the zero, and the other moves to the left on the real axis. Conventional analog simulation symbols and the corresponding circuits are shown in Figure 5.1. The 116 Simulation Chap. If you continue to turn pages, you are also involved in a discrete process with a logical decision whether or not to turn each page. 5 A hardcopy plot is obtained by typing print. Although there can be specific aspects of a design that lead a system designer through a somewhat tortuous process, with tentative starts and changes in direction, a gradually gained insight often leads to a highly regarded result. Because the addition of an unnecessary integrator may impose unnecessary limitations on transient performance criteria, a decision to utilize integral control should be approached prudently. A translator circuit accepts the control pulses and direction information and then applies the pulses (at a higher power level) sequentially to selected stator windings. The motivation generally involved an emerging desire to create and control machines. This mechanism was later revised by Jacques de Vaucanson, and a refinement in the early 1800s by Joseph Marie Jacquard introduced a chain of punched cards to produce the desired pattern automatically. Assuming that stability is maintained, the result of this change is to produce a zero steady-state error with a constant rate of change of input angle. It is an intrinsic property of linear systems that stability is not dependent on signal level-linear system stability depends only on characteristics of the system model. All negative feedback loops require a receptor, a control center and an effector. If the force component tending to provide motion is relatively small, it is exceeded by the static breakaway level of the associated friction. The root loci display the migration of roots of the characteristic equation as a system parameter is varied from zero to infinity. Although the results are relatively imprecise, the real-time operation provides a realistic simulation, and the effects of changes in parameters can be observed quickly. A related interest involved the use of electrical signals to provide control of remotely located mechanisms. This type of control (Chapter 14) is most often associated with various forms of factory automation. The trapezoidal algorithm is somewhat more complex, but the error is considerably smaller if considering a fixed step size. The book has been updated to include several new subjects, including Neural Network Control, Nonlinear Systems, and Robotics Modeling and Control. This particular phenomenon, however, is not usually a problem with the operation of a control system (or the simulation of a control system). A major part of this chapter is devoted to the consideration of models that are generated as a set of linear differential equations. These are necessary conditions for determining that all of the roots exhibit negative real parts, but they are not sufficient conditions. Returning to the concept of an n-dimensional space, two or more linear models can exist in various regions of the space, and the linear regions (with different linear models) can be immediately adjacent. Blocks labeled Mux and Demux from the Connections Library are used to combine variables (or vectors) into a vector of increased dimension or to split a vector into individual variables. The response to a unit-step input, a unitimpulse input, or a nonzero initial state can be obtained using step, impulse, or initial, respectively. The application of either the Laplace transformation or phasor algebra requires a linear system model, and a characteristic equation is a property of a linear model. Figure 11.15 The response with output feedback and estimated state variables. To complete a discussion of distinguishing properties, an extremely erratic behavior known as chaos [2] can occur in certain systems, with a radical change in response incited by a slight change in the initial state. 3. A block diagram is drawn by copying blocks from the library to a working window and drawing properly directed lines to connect the blocks. Although subject to the same practical limitations as a PD controller, the derivative portion is useful with respect to maintaining or improving transient performance criteria. If the transfer function is an all-pole function, a state model can be developed in which the state variables encompass the output and derivatives of the output. Considered in terms of a frequency-response analysis, the integral control modifies the low-frequency gain as required to satisfy the steady-state performance requirement. The ADT Pulse also streams video from cameras set up on your property while it checks weather, monitors security status and even monitors levels of carbon monoxide in your home according to ADT.com.Protect America's Simon XTA rubber keypad and a text-based LCD screen make the Protect America's Simon XT a little simpler than some of the other home security control panel options, but this system works hard. No part of this book may be reproduced or transmitted in any form or by any means, without permission in writing from the publisher. The digital simulation techniques as presented are all developed using the state-model format. Figure 3.15 presents linearized models that are greatly simplified and conceptually valid only within limited ranges of operation; however, they illustrate the fundamental feedback action. The plant actions are dynamic in the sense that energy storage exists within the plant, and the performance (as observed at an instant in time) is dependent on both past and present excitation. Another approach is the measurement of performance criteria as they are observed in the frequency domain. The root-locus technique is applied to a linear system model, and it is particularly useful as a design aid. Transfer functions are, of course, only applicable to linear models. Thus, Chapter 5 includes an extensive discussion of the use of MATLAB and SIMULINK. The second-highest derivative of the output variable is designated as state variable xn' and the model is completed by sequentially designating each of the lower-order derivatives with a decremented state variable number. If an immovable pole is located in the RHP, the system is not stabilizable. If the completion of sequential operations is sufficiently fast, the timing can be controlled to produce an apparent real-time operation. The lack of a peak in the closed-loop gain function indicates a high degree of relative stability. With the consideration of certain nonlinear phenomena, the operation is characterized by abrupt changes in the model that occur at specific signal levels. However, any variation in offset or closed-loop gain exhibited by an operational amplifier circuit (regardless of the severity) is observed as a corresponding variation in control signal information. As the cylinder rotated, the pegs opened valves to supply air to the various pipes. A digital computer (using skillfully designed programming) offers a computational facility that is perhaps best suited to the complexities of this type of study. Assuming that the maximum velocity of the DC motor is 10 times greater than the stepper motor, then a gear system with a 10 to 1 speed reduction on the DC motor will increase the low-speed torque by a factor of 10. The performance is then described as discreteevent control. A method that is applicable with any transfer function can be realized by carefully constructing a signal-flow graph in one of two distinct configurations. The transfer-function model of an ideal PD controller is an improper function, and the results of a simulation using an idealized model are not realistic in a practical sense. 3The plant is time invariant if the parameters do not vary as a function of time. There are also certain situations in which a PI controller can be utilized to satisfy a steady-state performance specification in a manner that alleviates a potential stability problem. When selecting gears, obtaining the desired gear ratio and an acceptably high torque rating in a physical package that is acceptable in view of size and weight is often difficult. If one gear is fixed, the other is forced into a rate of rotation that is a small fixed fraction of the rate of rotation of the major axis of the ellipse. By introducing continuous feedback control, this simple invention transformed Watt's steam engine into a practical method of energy conversion. Many of the results of the following simulations are displayed using the phase-plane format. The presence of the zero alters performance criteria such as peak time, percent overshoot, and settling time. If the model is specified as a transfer function, the format (with numerator and denominator denoted as "num" and "den") is [y, x, t]=step(num,den). Therefore, a solution can be pursued using a block diagram or signal-flow graph with the application of 4.5 CONVERSIONS BE1WEEN TRANSFER-FUNCTION AND STATE MODELS The solution methods as introduced in this chapter utilize a Laplace transformation of the state model, and the solutions involve the determination of transfer ratios that involve all of the inputs and all of the state variables. Subbaram Naidu, Idaho State University; and Bahram Shafai, Northeastern University. "MATLAS" and "SIMULINK" are registered trademarks of The MathWorks, Inc. This is the result of considering an ideal PD controller and assuming that there are no other poles to the left in the s-plane. A nonlinear system will respond to a specific input signal in a manner that is sensitive to the magnitude of the excitation. Bode, Network Analysis and Feedback Amplifier Design. Note, however, that a transfer-function model is internally converted to an equivalent state model, and the numerical simulation in each case is realized using a matrix exponential solution technique (see Section 5.3). Thus, academic pursuits of various aspects of control theory are an important part of the development of design skills. Converting Transfer-Function Models to Analog Simulation Diagrams Although there are various techniques that will convert transfer-function models to analog computer circuits, a universally applicable technique utilizes a graphical representation of the transfer function. Nonlinear behavior is not necessarily an undesired situation, and a system designer may purposely introduce nonlinear elements into a control strategy. To obtain automated machining using a sequence of different machine tools, transfer machines were developed that automatically shifted large parts from station to station. Therefore, controller circuits with amplifiers, digital-to-analog converters, etc., will impose limitations on the maximum signal level. This phenomenon can be illustrated with the addition of a PI controller to a system that is initially second order and type 1. However, only MATLABwith the Control Systems Toolbox and SIMULINK(see Section 3.9) are employed in conjunction with this text. Assuming that stability is designated by a positive gain margin, placing the open-loop contour outside of the curved 0.5-dB line implies a gain margin that is approximately 6 dB (or higher). Power is also the rate of change of energy; thus, the integral of power provides the energy supplied to an element. The compilation of techniques generated by using transfer-function models is sometimes described as classical control theory. Hence, the need for Cascade Controller Design 304 Chap. For example, the angular input reference can be created as follows: tl=[0:.05:2]'; thetal=.25*tl; t2=[2.05:.05:8]'; theta2=.5+0*t2; t=[tl;t2]; theta=[thetal;theta2]; % The reference input % Time; Reference input completed Because the program creates and manipulates a number of matrices, care must be taken to develop matrices that are not transposed or otherwise inconsistent with dimensions as required for mathematical operations and plotting. With series and parallel connections, the state model can be derived in a similar manner. SIMULINK is an extension of MATLABthat allows the user to simulate dynamic systems using a graphical representation. The angles of vectors from poles and zeros along the real axis to the right, however, must be considered because each vector either adds or subtracts 180°. The feedforward function is selected to produce a partial cancellation in the error function that is equivalent to the change that occurs to an error function when a system is converted from type 1 to type 2. The describing-function technique (Chapter 13) employs an interesting application of a transfer-function technique in conjunction with a spectral approximation. A smooth input signal can be tracked with zero steady-state error provided that system signal levels do not exceed the linear range. Englewood Cliffs, N.J.: Prentice Hall, 1993. If each block can be described using a single input variable and a single output variable, then each block is a single-input, single-output (8180) subsystem. For low-power applications that require precise control of velocity or position, systems using DC motors or stepper motors can provide very similar performance 64 Transfer-Function Models Chap. The changes, in part, reflect the remarkable capabilities of modem computers and programming techniques. An autopilot is an example of a control system. If the friction were viscous, the slightest force would produce motion, and the stretch of the rubber band under steady-state conditions would be proportional to velocity. Shahian and M. A feedforward cancellation technique is also described. For more information about MATLABand SIMULINK, contact The MathWorks, Inc. This is a very useful capability when working with multivariable systems or when combining signals for1~e display of multiple output signals. The translational viscous damper is composed of a cylinder with a movable piston. Systems with continuous control (sometimes described as analog control) 2. With configurations that are relatively complicated, a similar process can be pursued utilizing a digital computation (see Section 8.5). 2.4 AN AUTOMOTIVE APPLICATION An active suspension system for an automobile is described, and a model is developed for the passive parts of the suspension plus an ideal actuator. Due to similarities in the mathematical properties, you can easily interchange transfer functions between several techniques. The corresponding variation of settling time (in response to a step input) is less than ±0.03 s. The hydraulic resistance is a nonlinear function of pressure difference; thus, the linear model as shown is a valid approximation only for small variations of pressure. The techniques that provide analyses of fluid mechanics, heat flow, electrical circuit behavior, or dynamic mechanisms are familiar examples of the application of physical laws to system analysis. With a block diagram model, however, a signal-flow graph model is directly applicable, and the solution using Mason's gain formula is a very effective and fascinating alternative to other solution techniques. A block or line segment can be removed by clicking on it and then pressing the delete key. 4.8 MANAGING STATE MODELS WITH MATLABOR SIMULINK A linear state model as represented by the A, B, C, and D matrices is a common format for entering models into MATLAB commands. This command will accept user-defined inputs, and if the model is entered as a state model, the use of lsim will also allow the consideration of multiple inputs and a nonzero initial state. Note that the input and output signals of the H2(s) block flow from right to left. The limit cycle is an isolated closed path, and this portrait is obviously a different phenomenon from the portrait of marginal stability as shown in Figure 12.1. With marginal stability of a linear system, a succession of small changes in the initial state produces corresponding small change in the closed path, and a continuum of closed paths can be created. If the temperature is assumed to be uniform within the container, then the heat flow entering the container, qi (in joules per second), is divided into a stored component and a heat loss component such that where pet) is the relative pressure at the bottom of the tank with respect to the pressure on the outlet side of the valve. Phillips, Theory of Servomechanisms. An alternative to the application of matrix algebra is the utilization of a state diagram with the solution obtained using a signal-flow graph and the application of Mason's gain formula. In reality, however, no system is perfectly linear in a global sense. Since the elliptical inner gear has slightly fewer teeth than the circular gear, the two gears must rotate at a slightly different relative velocity. Simple Models and Analogies If the linear relationships of Tables 2.1a through 2.1c are compared, similarities are apparent in the electrical and mechanical models. If the order of the polynomial is greater than two, iterative root-finding algorithms are usually employed, and the location of roots is normally accomplished with the aid of digital computation (see Section 6.5). Although the formation of the two diagrams suggests different concepts, the two models are, of course, equivalent representations of the algebraic model. Because the continuous part of a system typically includes energy-storage elements, the model must accurately reflect the static and dynamic performance characteristics of a continuous dynamic system. using one technique is readily converted to use with the other technique by merely replacing the Laplace variable s by the phasor algebra variable jw or vice versa. In practice, all systems are subject to inherent nonlinear behavior at some level of excitation. A linear system simulation can also be realized using the matrix exponential function. 7.3 FREQUENCY·RESPONSE CRITERIA The use of frequency-response techniques provides an alternative to the consideration of time-domain performance criteria as applied to linear time-invariant systems. When considered as a state model, the linear model can be represented using a vector matrix equation, = Ax + Bu, in which the elements of A and B are independent of x and u. A model involving n state variables is generated using a transfer ratio that explicitly involves only one dependent variable. Although limiting can occur with a breach of either the maximum current or maximum voltage level, current limiting is easily avoided if the impedance level of the passive elements is selected in a sufficiently high range. Considering any point above the horizontal axis, y is positive and y is increasing. The PI controller is a variation of a proportional plus integral plus derivative controller (or PID controller), as described in Chapter 10. When using feedback, system variables that represent measures of performance are monitored and returned to the portion of the system that is carrying out the control strategy and generating the control signals. The use of Isim allows the consideration of a user-defined input. This can be achieved by selecting Flip from the Options menu of the working window to reverse the direction of input and output ports (the default direction is from left to right). Assuming that x2 = Y and Xl = y, some phase-plane trajectories for linear systems are shown in Figure 12.1, with arrows showing the direction of increasing time. Although similar time-domain performance characteristics are exhibited by both linear and nonlinear systems, the evaluation of linear system performance criteria is independent of the level of excitation. Since the phase-lead transfer function is identical to the practical PD controller function, the same precaution applies to phase-lead compensation. This is especially convenient for the simulation of dynamic systems (a subject discussed in detail in Chapter 5). The physical configuration of a control system typically includes several devices (power amplifiers, gears, etc.) that readily allow the insertion of a counteracting sign change. However, the change is accomplished without increasing the gain at higher frequencies, thereby avoiding the tendency toward instability that occurs if the loop Sec. In each case the type number is increased by one. A digital simulation of this system reveals that a ±5% error in the pole-zero cancellation introduces a barely perceptible variation of the shape of the transient waveform. Considering a typical situation in which the transformed input signals do not display any poles that are exactly identical to any poles of the system transfer function, the solution can also be subdivided into forced and natural response components. Although vision required the development of complex systems and extensive programming, the addition of vision to a robot provided the ability to correct small system errors and to respond in a limited manner to unpredicted task variations. The simulation of nonlinear phenomena is usually obtained with greater ease and flexibility using a digital simulation. Because power is equal to the product of voltage and current, it is theoretically possible to control the energy supplied to an actuator with no power loss in the controlling device. • Copy a Sum block to the working window by dragging it from the Linear Library to the working window and moving it to a desired location. Dedicated buttons allow you to arm the system when you leave, stay or even disarm completely while emergency panic buttons contact medical help, police or the fire department directly. Unlike the ideal differentiator, the transfer function of an ideal integrator is a proper function, and a quasi-ideal realization is obtained without difficulty. The force applied to the spring is transmitted through the spring to appear as an applied force on M2' and the amplitude of deflection of the spring is proportional to the transmitted force. Mason, "Feedback Theory-Some Properties of Signal Flow Graphs," Proc. A cancellation can occur because a polynomial input introduces poles at the origin, and the transfer function may introduce one or more zeros at the origin. If the manufacturing process involves a continuously formed product (such as the manufacture of a sheet of paper), there is usually a physical displacement between the point at which a control action occurs and the placement of sensors that measure physical properties. However, with carefully selected components, the displacement can be less than 1 X 10-5, and there is no significant consequence to a slight deviation from the origin. For example, if the system is nonlinear and smooth but stiff (i.e., some variables change much faster than others), then Gear's algorithm may be required to obtain a satisfactory result. Although various esoteric approaches can be applied to order reduction, the following discussion describes a technique that is applicable only if there is an obvious permissible simplification. The authors were also aided by the advice of John R. A relay (bang-bang) controller is designed to provide a control signal that exists only at two or three levels. Since parameter adjustments can be introduced at any point in time, there is rapid feedback of cause-and-effect information. A system exhibits asymptotic stability if the natural response approaches zero as time approaches infinity. The applications include the design of analog PID (proportional-integral-derivative) controllers and various compensation functions. Examples Consider again the multiloop feedback system of Section 4.8 and Figure 4.13. The combination then appears as shown in Figure 10.33. 8 8.2 SOME DEVELOPMENTAL CONCEPTS With the variation of a specific parameter, one obvious approach to the determination of root loci is to compute the roots of the characteristic equation using several different values of the parameter. The phase margin is computed accurately, but a numerical calculation of the gain margin is precluded in this situation by the inability to consider an infinite frequency range. Because the dashed line remains slightly below the 0.5-dB curved grid line, the closed-loop peak will be slightly less than 0.5 dB. The blocks offer a wide selection of operational functions that include transfer functions, state models, nonlinear transfer relationships, and user-defined functions. An alternative is provided by the application of error coefficients and an error series solution. Considering either a phase-lag compensation function or a lead-lag compensation function, both poles and zeros are introduced, but a pole is the nearest neighbor to the origin. Since analog controllers inherently operate in a real-time mode with parallel computation, a change in the order of a control function requires a change in the number of computational elements. The character of the natural response is dependent on the system model, and it is reflected in the composition of transition matrix. Other examples pursued at various points in the book include the analysis and design of a position control system for an antenna, the design of an active automobile suspension system, the design of an attitude control system for a satellite, and the design of a discrete-event system to control the tasks of two mobile robots in an automated fabrication system. With the application of a specific algorithm, the differential-equation model is replaced by a difference-equation model. If all of the poles are located in the left half of the s-plane, then the terms that compose the natural response will all decay asymptotically to zero. Kuo, Automatic Control Systems. The conversion to a transfer-function model is obtained by replacing the Laplace transformation by the z-transformation. Frequency-Response Criteria with a Dominant Pole If a phasor-algebra transfer function that describes a system is determined by a single pole (or approximately determined by a single dominant pole), the transfer function is 172 Performance Criteria and Some Effects of Feedback Chap. The reference input to the antenna is assumed to be the function as described in Figure 5.8. The reference angle is composed of a constant rate of change of angle in the period from 0 to 2 s, followed by a constant angle of 0.5 rad. 7.5 STEADY-STATE ERROR Considering the response of an initially relaxed system to a suddenly applied input, a well-designed system will provide a rapid (but smooth) transition from the initial state to the forced response. These systems often became very complex, thereby exhibiting a high level of automation with programming implemented as hardwired logic. For example, an evaluation of transient behavior is often obtained by applying a step input and then observing the percent overshoot and the time required to settle to a specific proximity of the final value. Transfer functions with wide lateral separations in the placement of poles and zeros can be modified to obtain a simpler model. They represent links to external input and output signals. A simple experiment will demonstrate the nonlinear character of sliding friction. If subsystems are described using state models, either MATLABor SIMULINK can be utilized to convert to an overall closed-loop model. The rotational damper is a similar concept except that operation is rotational and the resistance to motion is exhibited as a load torque. When a condition to change models is detected, the information that is required to continue the simulation is a description of the new model and a description of the state of the system. As expected with the use of a state model, the techniques are applicable regardless of the order of the plarll model. Comparing the element equations of Tables 2.1a through 2.1c, it is apparent that the linear mathematical relationships for mechanical and electrical elements are identical. MORE FROM QUESTIONSANSWERED.NET Sorry, but the page you were trying to view does not exist. and compo phase axis([.l 10000 -180 -90J) % Define plot bounds ylabel('Phase (deg)'), xlabel('Freq (r/s)') [gm,pm,wpc,wgc]= margin(mag,ph,w); % Calculate phase and gain margins [gmc,pmc,wpcc,wgcc]= margin(magc,phc,w) pm,wgc,pmc,wgcc % Printphasemarginsand gain crossoverfreqs subplot(lll) % Return single plot format %ngrid('new') % Nichols chart option (remove %) %nichols(nc,dc,w) % Nichols chart option (remove %) If formulated as a script M-file, the preceding set of commands can be adapted to controller design using phase-lead, phase-lag, or lead-lag compensation functions. The response functions can be observed and recorded using an oscilloscope that is interconnected with a printer or plotter. In controller design, the control function is not necessarily linear. The integral portion of the controller increases the type number of the system. With nonlinear models, a Runge-Kutta 3 or Runge-Kutta 5 algorithm is usually sufficient. Experimental results usually show that the overall loop function can be simplified, and the model is sufficiently accurate if G1 (s) and G2(s) are replaced by constant gain factors. 11 Although the potential to place the poles of a controllable system without constraint is a powerful concept, the application must be tempered by the knowledge that the analysis is dependent on the validity of the linear model. When the type-O system of Figure 7.19 was replaced by a type-1 system, the steady-state error with a step input changed from a nonzero value to zero. However, a transfer function is a linear system model. Two- and three-axis autopilots obey the same principles, employing multiple processors that control multiple surfaces. 7 Note that the bandwidth is equal to the inverse of the time constant as determined when viewing time-domain characteristics. Given a specific block diagram, a signal-flow graph can be easily sketched to show an identical graphical structure. 1.2 SYSTEMS, SYSTEM MODELS, AND CONTROL TECHNIQUES What is a system? It is a branch of science and engineering that can also be characterized using rather general terms, such as automation or automatic control, or it may be described in a slightly more restrictive context as the study of feedback control. The control of motion, however, is easily modified to give a smooth transition with a finite power requirement. Process control operations (such as paper mills, steel mills, oil refineries, and ore-processing plants) were often initially designed as open-loop systems. Black [3, 7], Harry Nyquist [2], and Hendrik Bode [5]. The influence of feedback is observed in a significant realm of system behavior that includes steady-state performance, disturbance rejection, and the sensitivity of performance characteristics to variations of system parameters. This decision may be based on the observation that you have completed a page, or it may occur as a result of your evaluation of the desirability of reading another page in comparison with other options. Topics that are considered in subsequent chapters include the concept of pole placement using state feedback and the utilization of a state observer. The block diagram of a control system typically shows the various subsystem models with the signal paths clearly visible. This shift in pole position can be accomplished without altering transient performance criteria, and the value of a finite error constant is changed from a large value to infinity. Hence, the model provides a piecewise linear solution. To obtain an acceptable transient performance, the contour must exhibit sufficient phase lead in the central region of the Nichols chart to curve to the right and bend around the oval grid lines that represent a maximum desired closed-loop gain. Note that a gain factor preceding or following a state model block can be absorbed into the model by multiplying the B matrix or C matrix by the gain factor. Many experimental designs were developed in the 1970s and early 1980s, and there were initial failures as well as successes. The use of a DC motor requires the design of a feedback system that utilizes precise angle information as obtained using an optical encoder or another type of position sensor. The authors typically devote about six class hours to this subject with reinforcement of design concepts as provided by two laboratory experiments. If a velocity profile requires an instantaneous change in energy, the controlling force (and power) must exhibit an infinite amplitude. In some situations the student can observe the performance with manual control and then switch to an automatic control strategy. The Vivint SkyControl works with your smart thermostat and allows the addition of up to 48 codes for users according to PC Magazine. All rights reserved. The Forced Component of Error with Other Inputs The steady-state error can be determined with input signals other than a finite series of polynomial functions. 1977. A set of state variables is selected by choosing variables that are mutually independent. Basic Control Systems Engineering Paul H. Voltage limiting is avoided only by carefully controlling voltage levels in the circuit. The shift may occur with a change in direction, or it may occur during a period of rapid deceleration, with the kinetic energy of the mug producing a force that tends to maintain the motion. In addition to individual effort, the development of teamwork, consultations with experts in various areas, and an extensive literature search can become important elements of the design process. Transportation delays are often observed in manufacturing operations that involve the manufacture of products such as paper, sheet steel, magnetic tape, chemicals, and iron-ore pellets. When summing forces, it is important to note that forces are transmitted through springs and viscous dampers without change. In this case, performance criteria are related to measures that involve the extent and shape of frequency-response functions. Although adaptable to a variety of situations (using a script M-file), the following is a listing of simulation tasks with models as required specifically for Example 10.6 (a PD controller design): % Example 10.6 % Root loci with K0 varied alpha = 6.25; beta = 50; % Specify controller zero and pole n = [00 10/alpha 10J; % Enter pes) d = [l/beta 1+4/beta 4 0J; rlocus(n,d) % Plot loci [k,rootsJ = rlocfind(n,d) % Place crosshair to evaluate a specific point pause % Any key to proceed % Step response k0 = 10; % Speci fy loop gain factor n1 = [00 10*k0/alpha 10*k0J; % Enter closed-loop model d1 = [l/beta 1+4/beta 4+10*k0/alpha 10*k0J; [y,x,tJ = step(n1,d1); % Calculate step response plot(t,y), grid % Plot output versus time ylabel('y(t)'), xlabel ('Time (sec)') [t' yJ % Print time and output in adjacent columns A root-locus plot can be retained for hardcopy by enabling the program with the time-domain plot command temporarily disabled using a % symbol. However, an expression that is valid as frequency is varied from zero to infinity constitutes an encompassing linear model. With the use of solid-state electronic circuitry, control can be obtained using electronically switched signals to generate a variable-frequency polyphase excitation. Variations of this concept provided flexible programming using interchangeable discs or paper tapes with punched holes. Chapter 5 presents various methods of system simulation, including digital simulation using numerical techniques. These systems used feedback techniques to control the position of high-power output mechanisms that tracked the position of hand-operated input controls. The state model corresponding to this diagram is Sec. James, N. Transfer-function-based pole placement offers another output feedback technique. Transfer Functions: Format Conversion A transfer function is usually described using two row vectors, each of which contains the coefficients of the numerator and denominator, respectively. A poorly conceived feedback configuration can create an unstable situation when applied to the control of a stable plant. Because a transfer function is expressed explicitly in terms of only one dependent variable, the state variables do not acquire a physical significance unless there is a meaningful relationship to the output. 1 The extreme freedom of motion that is a characteristic and defining feature of a robot was displayed with the development of a variety of mechanical configurations. Frequency-response concepts are commonly applied to the problem of identifying (or verifying) the composition of a transfer-function model. When selecting state variables, the number of state variables must correspond to the order of the system model, and the selected variables must be mutually independent (one cannot be an algebraic function of the others). The history of control system development is an intriguing web of interactive human accomplishment that has resulted in the control of machines, ships, aircraft, space vehicles, and many other physical systems. If the transfer function is evaluated at specificvalues of s in the complex s-plane, the evaluation at each point provides a complex number that can be described in terms of a magnitude and an angle. On the other hand, an exact cancellation may not be required to obtain the desired reduction in steady-state error, and the improvement in steady-state characteristics is obtained without an increase in the order of the system. Assuming that the closed-loop system is stable, a polynomial input will produce a polynomial error function under steady-state conditions. Thus, the contour initially appears at the top of the plot at about -90°, and it is nearly superimposed with the closed-loop grid line that indicates a gain of 0 dB. 4 A generalized procedure for the linearization of state models is presented in Chapter 13, which is devoted to the analysis and design of nonlinear systems. The steady-state output achieves a rate of change equal to the rate of change of the input, but it shows a displacement error. 2.3 Modeling with Lumped Linear Elements 19 force produced by the corresponding deflection of the spring (Mg) are equal and opposite, and both components are dropped from the equation. It is readily shown that the characteristic equation exhibits a zero coefficient, and the system is unstable for all values of Ki· A slightly modified approach that increases the type number with a somewhat less detrimental effect on stability is to retain the proportional control in a parallel path, as shown in Figure 7.24b. This particular dominant combination (two poles and a zero) occurs rather commonly with the application of some typical controller functions. Hydraulic Actuators Hydraulic actuators are particularly valuable in applications that require an operation with a very high force or torque in conjunction with a low velocity. All of these phenomena as considered are susceptible in a practical sense to some form of physical limitation at finite signal levels that limit the linear region of operation. Connect all of the blocks as shown in Figure 3.25. If a linear physical system is continuous, transfer-function models are obtained using the Laplace transform, the Fourier transform, or the methodology of phasor algebra. Automatic Pilots, Telephone Amplifiers, and Maritime Concerns Although the early developments were intriguing precursors of future events, the twentieth century witnessed the emergence of automatic control as a distinct and important science. Nichols, and R. If the proportional and integral actions are combined in a single analog circuit, the circuit can be modified as shown in Figure 10.9 with the capability to set a zero or nonzero initial state as desired. The first element, as described in both tables, is a viscous damper. A single nth-order transfer ratio must be separated into n first-order relationships with the introduction of n state variables. An increase in the type number is obtained with the replacement of a proportional controller with a PI controller. Since energy is the integral of power, the strength (or 30 Modeling Physical Systems: Differential Equation Models Chap. 94 State Models Chap. To be certain that the asymptotic decay is also exhibited by internal variables of the model, it is necessary to exclude an unusual special case-there must be no pole-zero cancellations 1 that exist on the jw-axis or in the right half of the s-plane. The modeling and simulation of a control system with consideration of the effects of dry friction are presented in Chapter 12. The various partitions are best illustrated with an example. Some intriguing properties of nonlinear systems become apparent when studying response functions. The sudden change that is required at t = 0 excites the "natural" modes of the system. In the example above, the receptor is the thermometer that measures air temperature. 96-53660 629.8-DC21 CIP Acquisitions Editor: Tom Robbins Associate Editor: Alice Dworkin EditoriallProduction Supervision: Rose Kernan Editor-in-Chief: Marcia Horton Managing Editor: Bayani Mendoza DeLeon Copyeditor: Pat Daly Cover Design: Karen Salzbach Director of Production and Manufacturing: Manufacturing Buyer: Donna Sullivan Editorial Assistant: Nancy Garcia David W. A design approach that is recommended is to place the zero (a specific ratio of integral to proportional gain) in a position that is then evaluated and modified as necessary. 12 LINEAR AND NONLINEAR SYSTEM MODELS: DISTINGUISHING PROPERTIES A model is linear if it comprises a set of linear differential equations. Before a simulation is requested, a numerical integration algorithm is selected in the Parameters dialog box. In the process of control system design, the designer often introduces one or more adjustable parameters, and these adjustments are used to shape and tune the behavior of the system. ix x Preface • There is a consistent consideration of practical issues (such as device limitations, windup, noise bandwidth, practical PI and PID control functions, etc.) that are brought to the attention of the reader at appropriate points throughout the text. Since there are remarkable similarities when comparing continuous and discrete techniques, the ability to apply a continuous model to a continuous design technique will be surprisingly helpful when applying a discrete model to a similar technique. Note that the user can select symbolic notation for input data and system variables as desired, but the sequence of symbols as placed in the argument of a MATLABcommand must correspond to a specific format. Thus, analytical expressions for criteria such as percent overshoot and settling time are not easily derived, and the study of time-domain performance criteria will require a computer simulation. Various special-purpose functions are grouped into toolboxes; the Control Systems Toolbox, the Signal Processing Toolbox, and the System Identification Toolbox are the most commonly used in the modeling, analysis, design, and simulation of dynamic systems. Chapter 7 describes transient performance criteria that provide measures of relative stability. If a time vector is defined, the time-vector symbol must be added to the input argument of the step command, and the output data will reflect the change. Thus, a faster response (a smaller time constant) corresponds to a larger bandwidth as determined using a frequencydomain criterion. Although the controller may be implemented as either a continuous-signal or a discrete-signal system (using either analog or digital techniques), the plant is ordinarily a continuous-signal system. 11.5 TRANSFER-FUNCTION-BASED POLE PLACEMENT The combination of state feedback and a state observer is one approach to pole placement when only the output is available for feedback, and this approach is based on the use of state models. 8.3 The Rules of Construction 215 vector is zero. MA TLAB, High-performance Numeric Computation and Visualization Software, user's guide. Wieber, and Richard B. Hence, the roots can be placed to obtain the desired degree of stability and to obtain other desired variations in the character of the natural response. Because all practical systems become nonlinear when the levels of dependent variables are sufficiently high, the systems are not globally linear. If the loop gain is severely limited by the presence of a group of dominant poles, phase-lag compensation offers an appropriate solution. This can be accomplished easily by starting with a low-order controller transfer function and checking whether the number of controller parameters matches or exceeds the order of the closed-loop system. Early examples of discrete-event control were exhibited in several fields of endeavor, with intriguing variations of programmed control. Another method of removal is to select a block or line segment and then select Cut or Clear from the Edit menu. The analogies as presented can provide additional insight when writing equations, and similar analogies can be extended to other phenomena, such as the thermal and hydraulic systems, as illustrated in subsequent discussions. Study of the limit cycle phenomenon yields an illuminating insight into oscillatory behavior that complements the limited view as afforded with the assumption of global linearity. To ensure reliable operation of an automatic control system, it is necessary to anticipate and analyze the effect of parameter changes. A PID controller tends to combine the characteristics of PI and PD control. There are certain characteristics of phase-plane displays that are inherent properties of the phase-plane format. In this case, all of the numerator coefficients are zero except ao' and the state variables are proportional to the output and derivatives of the output. The characteristic is corrected if the armature is supplied using a constant current source, but the implementation of a constant current source requires electronic circuitry with sufficient power capacity to supply the armature. This information can be utilized in the determination of an acceptable compromise between desired tracking characteristics and noise rejection. 5 (concurrent) computation; hence additional complexity is reflected in the use of additional computing elements rather than an increase in calculation time. 11 Note that the plant input was scaled by 1/4 so that it could be placed on the same plot with the other response functions. Integration of the velocity then yields absolute position. Hence, commonly occurring nonlinear phenomena (such as static and coulomb friction) are incorporated into the simulation studies. Franklin Inst., 218, 1934. Designing Discrete-Event Systems If performance requirements involve discrete-event control or a combination of continuous and discrete actions, the designer should consider the development of a state-transition diagram or table. If the velocity at some point in time decreases in magnitude and declines to zero,4 the model will revert to Equation 2.19 with dv/dt instantly forced to zero. The response is then generated using recurrent operations. 7.3 Frequency-ResponseCriteria 171 over input amplitude, and the phase shift is determined by the difference between the angle of the output phasor and the input phasor. The determination of stability with application to discrete-time systems displays some similarities to the methods of this chapter. • The remaining blocks can be created and defined in a similar manner. 2The plant is a lumped-parameter (rather than distributed-parameter) system if it can be described using ordinary (rather than partial) differential equations. 1 Sensors monitored the progression of events, and specific combinations and/or sequences of bilevel input and bilevel feedback signals initiated new control actibns. The additional severity of the stability problem requires parameter adjustments that are usually reflected as an increase in settling time. The performance criteria as considered in this chapter are (in almost all cases) derived with the assumption that the model is linear. The concept, however, introduces some interesting insight into the limitations of feedback compensation. • Chapter 14 presents the analysis and design of discrete-event control systems a topic that is not usually contained in control engineering texts. Thus, the selected variables might include the velocity of a mass, the current through an inductor, the voltage on a capacitor, etc. To obtain an acceptably linear control characteristic with efficient operation, it is necessary to use a high-efficiency rotor operating with low slip. If the highest power of the numerator is equal to the highest power of the denominator, the numerator polynomial can be divided by the denominator polynomial to obtain a constant plus a strictly proper function. The consideration of linear system stability is directly applicable to subsequent evaluations of continuous system performance using both s-domain and frequencyresponse techniques. If the system model is linear, it is feasible in certain circumstances to develop analytical expressions that relate performance criteria to the placement of poles and zeros in the s-plane. A system can be linear (or quasi-linear) in a specified region, but not globally. Discrete-Event Control Discrete-event control is sometimes described as sequential control or programmablelogic control, and because at least part of the system is dynamic, it is also described as discrete-event dynamic control. Automatic control TJ213.L434 1997 references I. If the delay is significant, it is observed as a destabilizing effect, and the development of a successful control strategy must involve consideration of the delay. However, root-locus techniques and frequency-response techniques (see Chapter 9) are quantitative approaches that develop cause-and-effect relationships. For example, the model can be accessed in MATLAB for analysis or simulation. Considering the possibility of a transition between stability and instability (due to a change in a parameter of the system model), the transition condition can be directly evaluated. Both techniques permit the consideration of a nonzero initial state. Two different views of the operation of the RLC circuit of Example 3.4 are depicted using two block diagrams, as shown in Figure 3.5. The first model is suggested using Equation 3.30 (with initial conditions set to zero), and the second model is a representation of Equation 3.31. 7 There is an obvious and useful correlation between transfer-function models that are derived using phasor algebra and models that are derived using Laplace transform techniques. This condition is generally satisfied if the physical size of the system is very small in comparison to the wavelength of the highest frequency of interest. 1.3 A BRIEF HISTORY It is possible to go back over a period of several hundred years and trace some of the separate pieces of scientific development that evolved into this important branch of science and engineering. The marginal stability condition is theoretically obtained with a lossless resonant system or with an invariant linear feedback system that places a pair of poles exactly on the jw-axis. With a linear model, the system parameters are assumed to be independent of the excitation level, and the property of superposition is observed. Includes bibliographical ISBN 0-13-597436-4 I. 157 Sec. Since digital controllers typically control continuous plants, a digital-to-analog conversion is required between the controller and the plant, and some form of analog-to-digital conversion is required in association with sensing of plant variables. In the automotive industry, large banks of relays were disappearing in favor of small solid-state systems described as programmable logic controllers. A signal that is not directly available can be produced by creating the time and signal vector in MATLABand importing the data into SIMULINK using the From Workspace block. However, performance characteristics are best understood with the ability to view the performance in terms of power and energy requirements. An alternative to the configuration of Figure 4.8 is the signal-flow graph as shown in Figure 4.11. The limitation on rate of change of current is observed as a limitation on the ability to transmit high-power pulses to the motor at a high pulse rate. Although not as widely utilized as matrix techniques, the use of a signal-flow graph and Mason's gain formula is applicable to the solution of any problem that requires the solution of a set of simultaneous algebraic equations. With a nonlinear simulation the user can employ MATLAB-defined subroutines that invoke function ode23 (second- and third-order Runge-Kutta algorithms) or function ode45 (fourth- and fifth-order Runge-Kutta-Fehlberg algorithms). 5.7 5.7 SIMULATION Simulation Using SIMULINK 133 USING SIMULINK SIMULINK is a supplement to MATLAB(see Section 3.9) that is used primarily as a tool to simulate dynamic systems. If a system model is second order, the state space becomes a state plane with state variable x2 plotted versus state variable Xl. A special version of the state plane, known as a phase plane, is created if the model is described such that x2 is equal to Xl. The character of the response can be investigated throughout a region in the phase plane by considering several different initial states, and the augmented display reveals a phase-plane portrait. Considering impulse and step, the system description can be entered either as a state model or a transfer-function model, but the solutions are realized using a state-model description. The phase-plane portrait with more than one equilibrium state illustrates a situation in Figure 12.1 Phase-plane trajectories showing linear response characteristics with a) critical damping, b) an underdamped condition, c) marginal stability, and d) an unstable condition. The evaluation is obtained by considering the loci of roots that are engendered with various fixed placements of the zero. The LifeShield KPC 1000 is designed to communicate with cameras and sensors, and it offers a 24-hour backup battery life along with wall mounts or a stand according to Security Baron.FrontPoint Touch Screen Control PanelA seven-inch touch screen control panel and a single touch arm and disarm option make the FrontPoint Touch Screen Control Panel simple to use. For example, an inertial component of pressure difference (proportional to rate of change of flow) will theoretically add to the resistive component of pressure difference in the example of Figure 2.13. The velocity of an inertial element is always specified with respect to the zerovelocity reference. 86 presents the progression of events in the determination of a model with two diametrically opposed outcomes. If a system cannot be described using a state model in the vector matrix format (with all elements of the A and B matrices constant or functions of time), then the model is nonlinear. Although a linear system can theoretically display a transient response that neither increases nor decays, the usual manifestation of instability is a natural response that exhibits an exponentially increasing magnitude or an oscillation with an exponentially increasing magnitude. For hydraulic systems, a third element can be introduced to consider the inertia associated with fluid flow. Early tracking radars that depended entirely on mechanical movement of the antenna were replaced by units with phased-array antennas, which added electronic control to the beam orientation. An elem~t that instigated work in the 1940s was the desire to describe the performance of complex systems, such as tracking radars and gun control systems, using mathematical models. Since the transient behavior of a dynamic system depends on the location of the poles (i.e., the roots of the characteristic equation), a methodical approach to studying the variation in pole locations is a valuable design tool. As the frequency is increased, the contour tends to follow the O-dB grid line and then fall continually farther below. The character of the forced response is dependent on the input. With an analog integrator, the initialization is performed in the same manner as described with application to analog simulation. Therefore, when a system model is presented as a block diagram, the conversion to an equivalent signal-flow graph is not an essential step . E-mail: [email protected] WWW: . The utilization of a PI controller provides an increase in the type number with a corresponding enhancement of the steady-state tracking capability. Another important concern is the elimination of any significant backlash. A gradual infusion of computeraided techniques allows the consideration of important areas of study that are often avoided due to perceived computational difficulties. The rotor is a permanent magnet, and the surfaces of the stator poles and the rotor that face each other across the air gap exhibit a series of small grooves. The expansion provides a summation of reduced-order expressions, and the inverse transformation is completed by identifying the simpler expressions as members of a limited set of transform pairs. In addition, the interpretation of experimental data is readily correlated with the structure of the model. The forward-Euler algorithm is easily implemented as a simple program of repeated matrix computations, but the calculation interval must be relatively small. Therefore, the phase margin requirement is similar to the requirement as described with a type 1 system. A complete history of automatic control would require consideration of power systems, biomedical systems, optical systems, and many other areas of research and development. Similarly, a spring in a mechanical system must exhibit a ratio of deflection to force that is independent of the level of the applied force. If motion is mechanically obstructed, the back EMF drops to zero volts, and a voltage control circuit will respond by producing a very large current, whereas the current control circuit tends to maintain a desired current level regardless of the velocity. Thus, the simulation uses an exponential matrix solution technique developed with the assumption that the plant input is a piecewise constant function. The inputs can be typical test inputs, or they can be specially formulated to imitate realistic operating conditions as anticipated with the completed system. One example is the utilization of a controller that produces only two or three discrete output levels that are selected by comparing the system error with specific thresholds. Hence, the corresponding closed-loop gain function does not exhibit a peak. Utilizing the previous specification of A, B, C, D, K, and g, the simulation was obtained using x0=[-0.Z 0J; t=[0:.00Z:1.6J'; r=1+0*t; [y,xJ=lsim(A-B*K,B*g,C,D,r,t,x0); u=r*g-(K*x')' ; plot(t, [x y 1/4*uJ), grid If a plant is controllable, state feedback can be used to control the placement of all of the roots of the characteristic equation. With all 8180 subsystems, a simple approach is simply to convert the model of each block into a transfer function and then proceed with a transfer-function analysis. Unlike most feedback techniques, a totally successful application is prevented by small parameter variations. and wn' If the input to a system includes wide band noise, an expression describing the noise bandwidth provides information with regard to spectral selectivity. Although the operation is simply conceived, the model is nonlinear; and a study of performance characteristics requires switching between multiple linear models in a manner similar to the consideration of nonlinear friction. With frequency control, however, the situation is further complicated by the necessity of maintaining the field intensity at a reasonable level as the frequency is changed. The text under each block can be edited to reflect the characteristics of the particular problem. Basile Bouchon, the son of an organ maker, designed a loom that eased the task of producing patterns in silk. Considering basic algebraic relationships, the configurations of Figure 3.6 show cascaded blocks and parallel blocks with the easily verified result that the Figure 3.5 a) A block diagram showing positive feedback. 85 The Selection of State Variables The n variables that are utilized to develop the state model are described as state variables. Although commonly viewed in the context of physical systems, a universal consideration of interactive phenomena would include many diverse areas, such as systems with a social component (e.g. economic or ecological systems). 358 Nonlinear Modeling and Simulation Chap. A particularly important and useful characteristic of the state model is the relative ease with which the system description is converted to an equivalent discretetime model, as required for digital computation. The velocity returns with a nonzero dv/dt, and the probability of observing a discrete value of exactly zero is very small. A request for Sec. The gain characteristic of this dominant-pole function is utilized to obtain a high gain at low frequencies while suppressing the gain in the frequency range where the plant function is producing an excessive phase lag. Synchros and resolvers (used to measure angles of rotation) provide examples of this phenomenon. A tachometer can be used to sense angular velocity. 7. Series, Boston Technical Lithographers, 1963. J., XI, 1932. The relationship between type number and steady-state error is presented in Table 7.2. The table shows the form of the steady-state error and the magnitude of constant errors. The ability to write to memory and read from memory provided flexibility that was not available with hardwired logic. Routh in 1897) presents a variation of the Hurwitz technique that is somewhat easier to apply, and the revised technique is sometimes described as the RouthHurwitz criterion. New York: Quantum Publishers, 1991. The developed torque of the motor is shown in Figure 5.10. In some situations, applying control signals continuously is not necessary, and control signals can be revised intermittently in response to the observation of specific signal levels or specific events. Place the block to the right of the Sum block. The mass (or moment of inertia) and the springs store energy as kinetic energy or potential energy, respectively. The observer is designed such that any difference in state between the plant and the observer decays as time becomes large, and rate of decay is dependent on the placement of the poles of the observer. Note that the design procedure is described as a feedback process. The elements are described as passive because they can dissipate or store energy, but they cannot introduce energy into a system. Therefore, different approaches may be desirable depending on specific requirements. IRE., 41,1953. J. In view of ease of control, this might seem to be a desirable option. Some applications (such as machine tools and robots) require relatively high torque drives with very precise specifications, and special gear configurations are employed that provide many desirable features, including the apparent elimination of backlash. If the offsets of operational amplifiers are negligibly small (or carefully nullified), the accuracy of an analog simulation depends primarily on the accuracy of signal generators and recording instruments and the tolerances of passive Rand C elements. Thus, generalized methodologies can be described that are independent of system order. The presence of nonlinear phenomena in the region of interest generally produces undesired complexity with respect to determining models and evaluating performance. If, however, the gain of the open-loop function is increased to improve other characteristics (such as a reduction of steady-state error), the entire contour will be shifted upward, and the relative stability is altered. If the relationship is defined for all frequencies from zero to infinity, the phasor-algebra transfer function constitutes a linear system model. Thus, there is an interesting design option with respect to positioning the pole at a point relatively close to the origin in the s-plane, or positioning the pole to obtain an ideal (or quasi-ideal) integration. A root-locus plot for the system of Example lOA is shown in Figure 10.12. The wind disturbance torque on the antenna is assumed to be a burst of 20 N-m that exists only Figure 5.8 The reference input angle and the wind disturbance torque. Depending on the application and the circuitry, the offset variations may be negligible. The operation of a controller that is designed to provide a linear control function can remain linear only within a limited range of signal amplitude, and saturation will occur if transient signals exceed this level. Since there is no requirement for a commutator or brushes, there are advantages in terms of reliability and cost. The functions assume an impulse input, a step input, and a nonzero initial state, respectively. Thus, the image is continually offset from the center of the field of view. However, the state model is not unique, and the state variables are not necessarily the state variables that were initially identified in the subsystems. H. Thus, stability must be specified as it is observed in the vicinity of a particular operating point. To introduce the subtraction, enter + - in the text box labeled List of signs. The approximation of an ideal function is subject to severe problems with EMI (electromagnetic interference). The direction of the force of a specific thruster is determined by a fixed mount angle, and the magnitude of the force is constant during the time that the thruster is active. If plant models are considered that represent realizable and useful systems, a lack of controllability is a somewhat unusual situation. Before proceeding, the reader is encouraged to review the discussion of nonlinear system models and nonlinear simulation as presented in Sections 2.6, 4.6, 5.4, and 5.5. Nonlinear Modeling and Simulation 344 12.2 Chap. This phenomenon is perhaps best understood if related to a physical system. It is common practice to consider a design problem using more than one technique, thereby involving the consideration of a transfer-function model and a state model. Signal-Flow Graph Algebra The symbols that comprise a signal-flow graph are nodes (shown as small circles) and connecting branches (a line with an arrow). The other attributes are less troublesome, and plant models are generally assumed to be lumped and time invariant. Although the controller characteristic is a nonlinear relationship, the controller design is conceptually uncomplicated and readily implemented. 43 44 Transfer-Function Models Chap. Although tedious in comparison to modern digital techniques, an early development for plotting root loci utilized a simple device known as a spirule [4] to facilitate the graphical search. Kuo, Automatic Control Systems (6th ed). Using a state diagram as described in Chapter 4 (Section 4.4), the signal-flow graph is readily converted to an equivalent analog simulation diagram. If a specific pair of poles is energized, the rotor will move to the position that aligns the grooves to produce minimum reluctance in the magnetic circuit path that is externally excited. The signal is a very specific command telling the servo to make a precise adjustment.Each servo has a small electric motor fitted with a slip clutch that, through a bridle cable, grips the aileron cable. In other words, a nonlinear characteristic may be purposely introduced (as a compensation technique) if the dependent variables must traverse an inordinately nonlinear region of plant operation. Considering the transfer-function model of a linear time-invariant system, asymptotic stability is assured if pole-zero cancellations on the jw-axis or in the RHP are avoided, and all of the roots of the characteristic equation Stability 154 Chap. 12.4 SIMULATION WITH A SATURATION CHARACTERISTIC Although analytic solution techniques are sometimes applicable with nonlinear system models, there are no encompassing analytical methods. The amplifier output signals are proportional to the output and derivatives of the output. Gears and other mechanical couplings can exhibit backlash (a shift in relative displacement) when a reversal of motion occurs. The concept of stability in relationship to pole position is considered with the construction of root loci as presented in Chapter 8. Using frequency-response techniques, the gain and phase margins provide measures of relative stability. Chua and P. Although the root-locus technique (Chapter 8) is designed to evaluate the consequences of changes in a system parameter, the changes are interpreted only as they would affect a new calculation with a modified model. G1(s) and G2(s) are all-pole (no finite zeros) second-order transfer functions that model the position control of the spool in the valve and the relationship between fluid and piston velocity. Therefore, the conversion from a state model to a transfer-function model can be obtained by applying one of these techniques and then selecting and isolating a desired function. The linear response functions of Figure 12.1 illustrate (a) a critically damped response, (b) an underdamped response, (c) a marginally stable response, and (d) an unstable response. The graphical technique produces either the control canonical form or the observer canonical form. Although the magnitude of the impulse functions is infinite, the strength of the impulses can be calculated. 2 The velocity profile of Figure 2.17b is a realizable function, and it is not difficult to determine revised functions for force, energy, and power with the addition of viscous friction. If an electromechanical control system responds to a step input with a response time of about 0.1 s, a major part of the energy of the response is distributed in the frequency range between zero and 10 Hz. Although this is a specific example, bandwidth requirements are typically modest. 10 an improved transient performance should be carefully evaluated, and a technique as described in the following chapter may be preferable. The application of Mason's gain formula is used in numerous tasks, including conversions between transfer-function models and state models. One response to this combination of requirements is the harmonic gear. However, the importance of the technique is related to the development of a solution technique that evolves from the graph. The use of excessively large gain factors will also intensify the level of sensor noise. Expressions for approximate settling time are presented in an ensuing discussion of settling time (considering ~ up to 1.4). 1.3 A Brief History 3 and animated figures. A nonlinear model may exhibit more than one equilibrium state. The conversion from a transfer-function to a state model, however, introduces a totally different situation. Naval Eng., 34,1922. Methods introduced in this chapter utilize measurements of bandwidth and peak gain as exhibited by the closed-loop transfer function. There is a wealth of information in a block diagram that can provide a quickly gained insight into the operational characteristics. Thus, the time delay T is equal to d/v. lThe plant is linear if it can be accurately described using a set of linear differential equations. About This Book : The book covers a wide range of topics in the field of control systems engineering. In this situation the closed-loop transfer ratio is predominately dependent on the feedback function. The abstraction that is inherent in the consideration of a general nonlinear model prevents the application of an encompassing analytical technique, and this is an area of study in which computer-aided analysis can playa critical role. Because a transition from stability to instability can occur with a change in signallevel, a situation can exist in which the conditions for a steady-state oscillation unfold at a specific signal level. Thus, if the active elements are not subject to any significant bandwidth limitations, an increase in computational complexity does not add undesired time delay. There is, in general, no unique set of state variables. Under these circumstances, a solution can follow a trajectory from one linear model to another, with the dependent variables at the juncture providing the initial conditions for the new region. If the torque that a drive gear imparts to a load gear changes sign, the contact between gears is momentarily lost until a small, relative angular motion occurs that shifts the contact to the opposite side of the contacting teeth. The Protect America's Simon XT connects sensors, lights and locks. However, the result can be expressed with all positive signs by equating the voltage rises to the voltage drops such that Sec. Choose this system to arm and disarm your entire home security system with a single button and signal the fire department, police and medical assistance quickly. Converting State Models to Analog Computer Simulation Diagrams The state model is readily converted to an analog simulation diagram without any uncertainty in regard to the configuration or the physical identity of variables. Designing the loop to track the Doppler variation successfully requires a nonzero bandwidth. The observer poles are typically placed at locations that are obtained by multiplying the values of the dominant closed-loop poles by a factor of 3 or 4. The importance of the Routh-Hurwitz criterion is somewhat diminished by the ability to execute root-finding algorithms easily (with numerical computation), but it is also apparent that this classical technique affords an accurate and simple analytic procedure that is valuable in certain circumstances. A somewhat different partitioning of terms separates the response into forced and natural components. Thus, the anticipated operation may span a region that is characterized as quasi-linear, nonlinear, piecewise linear, etc., and the system model must embrace the characterization. If the open-loop contour of the example is shifted upward by about 4 dB, it will contact (without crossing) the part of the curved grid that denotes 0.5 dB of closed-loop gain. 7 Consider the action of a type 1 system with unity feedback and with the integration occurring in the controller. which a slight variation in the initial state can cause the trajectory to end at a different equilibrium state. The presence of a complex pair can also be ignored because the angles of vectors to a point on the real axis are equal and opposite. The power amplifier will establish a maximum signal level that can be supplied to the motor, and a temporarily large error signal will force the power amplifier output into a limit. The process can then be further pursued and refined using digital computation. 48 Transfer-Function Models Chap. If not, one must increase the order of the controller transfer function until pole placement becomes possible. Because the gain in decibels is a logarithmic function, the net effect of this practice is to produce the equivalent of a log-log plot. Nonlinear mathematical models can be expressed as state models, but the display of a vector matrix format is applicable only if the model is linear. 237 In Figure 9.18, a few of the curved lines that represent fixed values of closedloop gain are added to the plot. Tel: (508) 647-7000. W. Considering the control of a linear system, an important component of a successful design is to obtain a natural response that exhibits a rapid and well-behaved asymptotic decay. Complications with system analyses are usually reduced if the plant model is identified as linear,l lumped? The result can be expressed to consider the transfer ratio from a specific input to a selected output variable. 12.3 STATE SPACE AND THE PHASE PLANE With two or more state variables, it is sometimes useful to consider an n-dimensional state space in which each coordinate describes the magnitude of a state variable. The integration of body and axle acceleration yields absolute values of body and axle velocity. Disturbance rejection is potentially afforded by feedback action, but the rejection is dependent on the point at which the disturbance is introduced and the location and magnitude of loop gain factors. The algebraic relationships might be viewed merely as a step in a solution procedure that involves a direct and inverse transformation. When the cable moves, the control surfaces move accordingly.As the ailerons are adjusted based on the input data, the wings move back toward level.The autopilot computer removes the command when the position sensor on the wing detects that the wings are once again level.The servos cease to apply pressure on the aileron cables.This loop, shown above in the block diagram, works continuously, many times a second, much more quickly and smoothly than a human pilot could. 3 The use of a transform technique can be viewed as a mathematical stratagem that you may wish to pursue to obtain a pencil-and-paper solution or a symbolic solution. Hence, both steady-state and transient criteria are improved by applying both lead and lag compensation techniques in the appropriate frequency range. Some of the configurations presented intriguing kinematic studies, and all of the design variations presented challenging control problems. The format of the response, x, is a matrix of two columns that describe the two state variables as a function of time. To consider the step response with a nonzero initial state, Isim was employed as follows: A=[0 1; -2 -3J; B=[0; 3J; % The plant model C=[5 0J; D=0; p=[-5.00 -5.01J; % The state feedback design K=place(A,B,p); p=[-15.00 -15.01J; % The observer design G=place(A',C',p)'; g=l/(C*inv(-A+B*K)*B); % The input gain AA=[A -B*K; G*C A-B*K-G*CJ; % The closed-loop model BB=[B; BJ*g; CC=[C 0 0J; DD=0; xx0=[-0.2 0 00J; % The initial state t=[0: .002:1.6J '; % The time vector r=1+0*t; % The input vector [y xxJ=lsim(AA,BB,CC,DD,r,t,xx0); % Computation of the response x_hat=xx(:,3:4); % The observer response u=r*g-(K*x_hat')'; % The plant input plot(t, [xx y 1/4*uJ), grid, axis ([0 1.6 -1 1J) % The plotted response 338 Controller Design Variations Chap. However, there is no reason for the electrical load to change, and the transfer ratio (in volts per rad/s) is a fixed constant. Although the control of robots was sufficiently accurate for many applications, it was apparent that performance could be improved if sensors provided feedback directly from the point of operation. The analog simulation diagram is composed of symbols that describe integrations, summations, and proportional gain; hence the composition of a simulation diagram is readily structured to imitate the composition of the signalflow graph. 6.4 StabilityTests 149 of the s-plane, the coefficients must all exhibit the same sign, and all of the coefficients must be nonzero. Considering a state model, the characteristic equation is obtained by expressing the model in the vector matrix formulation and equating det(sI - A) to zero. The state model provides a particularly convenient format for the development of analog simulation diagrams and digital simulation algorithms. This is somewhat analogous to balancing a broom on your finger. A block diagram and the equivalent signal-flow graph provide a graphical representation of a set of simultaneous algebraic equations, and the use of block diagrams provides a view of performance as affected by various subsystems. Depending on the application, the unstable behavior may produce a hazardous situation or catastrophic failure. The following discussion provides an introduction to computer-aided operations by considering a few easily applied tasks that involve modeling and the manipulation of transfer functions. The Routh test is useful in numerous circumstances. Families of root loci or step response curves can be generated by inserting parameter changes and applying hold on and hold off commands to retain plots as required. 118 Simulation Chap. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The design procedure incorporates many of the phase-lead and phase-lag design concepts as previously presented. It is apparent, however, that a significant angular error occurs when the antenna is following the ramp motion as described by the input and again when the wind disturbance occurs. Using full-order state estimation, only the output is measured. All of the observer poles can be moved freely if the plant exhibits the property of observability. IRE., 44, 1956. An interesting perspective of the relationship between Laplace and ph asoralgebra transfer functions is viewed by imagining a three-dimensional description of a transfer function as evaluated in the s-plane. 2.2 LINEAR SYSTEM CHARACTERISTICS When observing the response of a linear system, the character of the response is unaffected by changes in the level of excitation. Data I Paul H. If sufficiently large, the delay and the period between samples are factors that can contribute to a deterioration of dynamic stability. 4.1 INTRODUCTION A state model is a differential-equation model that is expressed in a special format that offers an encompassing and unified approach to the study of control systems. An investigation of stability, however, is not necessarily difficult. However, with the consideration of nonlinear behavior, the system models must describe a much larger and diverse set of phenomena. The simulation techniques as described in this chapter involve the development and utilization of computer models that are devised to study the time-domain behavior of continuous-time systems. If a system is linear, the model can be expressed as a vector matrix equation that maintains the same format regardless of the order of the system. These techniques may be applicable to specific situations. Although the symbol B is used to describe both translational and rotational action, the units, of course, must be different. 3 An apparent option to using an armature-controlled DC motor is to use a fieldcontrolled DC motor with an electrical winding to produce the field. As Ko is increased, the cancellation improves, and the system tends to acquire the characteristics of a firstorder system. Thus, the induction motor is relatively uncomplicated, but the electronic control circuitry is complex. An interesting situation is revealed by considering a type 0 or type 1 system that exhibits a very substantial conflict between the opportunity to obtain a desired error constant and the ability to attain simultaneously an acceptable degree of relative stability. Although there is no unique design procedure, the following example describes a procedure in which the phase-lead portion is considered first, and the phase-lag portion is then added to obtain the desired steady-state error performance criterion. 5.1 INTRODUCTION System simulation is one component of a basic set of computer tools that can significantly ease the tasks of a system designer. The discrete-action controller can initiate tasks and sense completion of tasks that are performed by machines with separate controllers. Stepper Motors Stepper motors are designed to move a small precise fraction of one revolution each time that a pulse is applied to the translator circuit. In this situation, integral control can be utilized to reshape the open-loop function in a manner that emphasizes altering the transfer function as s approaches zero. Hence, the inherent stability of a second-order system is preserved. and index. However, with consideration of a second-order model or a third-order model, a definitive trajectory can be displayed in a coordinate system with two or three dimensions. Because a discrete-level controller also produces a piecewise constant function, the c2d command is directly applicable. Hanselman, Matlab Tools for Control System Analysis and Design. Certain systems can display a condition described as "windup." For example, a positioning system with a PI controller can exhibit this phenomenon. Other types of actuators that display various advantages and disadvantages include induction motors, stepper motors, and hydraulic cylinders. The systems were flexible in the sense that programs could be changed to provide variations in the description of the manufactured part. When comparing competitive design techniques or optimizing various aspects of system performance, it is helpful to consider criteria that provide measures of performance. The hydraulic capacitance defines the inverse of the ratio of change in pressure to change in volume (m3 per N/m2), as determined by the density of the liquid and the tank dimensions, and the hydraulic resistance defines the relationship between pressure and flow (N/m2 per m3/s), as produced by the restriction at the outlet. Depending on the plant function, the introduction of an open-loop pole at the origin of the s-plane may introduce undesired complications with regard to attaining desired transient performance criteria. The higher-frequency zero and pole contribute phase lead in the high-frequency range, thereby improving the transient performance. The gain margin is a measure of the ratio (usually converted to decibels) that an open-loop gain factor can be allowed to change before reaching borderline stability. The circuits as utilized for analog simulation are similar to circuits that are considered in subsequent chapters for the design of continuous controllers. The estimated state is then utilized to implement state feedback. Analog simulation is inherently a real-time (or scaled-to-real-time) computation that utilizes parallel computation. However, the same objective can also be achieved by working with transfer functions. The tachometer rotor is coupled to the system to be measured, and a generated voltage is produced in the armature circuit that is proportional to velocity. Application of the root-locus technique is a valuable design aid 9.1 INTRODUCTION Various frequency-response techniques are applicable to the study of linear system behavior, and the methodology affords an alternative to the use of s-plane techniques. Considering the Routh array format (see Table 6.1), the coefficients of the polynomial generate the first two rows of the array, and the remaining rows are sequentially generated using algebraic relationships that utilize elements obtained from the previous two rows. Extraneous signals are not observed as control signal components unless they are large enough to alter the significant difference between interpretation of digital zeros and ones. It is common practice to use either of these laws to write equations, with a decision that is based on inspection of the configuration. The two parts of the solution as expressed in this format are known as the zero-input response and the zero-state response. This is accomplished by selecting a controller transfer function of sufficiently high order and then matching the coefficients of the resulting closed-loop characteristic equation with those of the desired equation. For the purposes of this text, it is seldom necessary to calculate the spectral characteristics of input or output signals, but it is important to understand the significance of a frequency-response function with respect to the potential alteration of signal spectra. Because the need for a distributed-parameter model is an uncommon requirement, the models are typically composed of ordinary differential equations (no partial derivatives), and time is the only independent variable. If the transfer function is an all-pole function, the conversion to a state model can also be implemented by returning to the corresponding nth-order differential equation and then converting derivatives of the output to state variables. With two real poles (and no finite zeros), the response to a step input approaches the final value with no overshoot. The response functions as shown in Figure 5.4 are easily duplicated using the function described as step. Thus, there is a limited degree of commonality, and it is observed in the structure of the system model. Continuous Control Introductory studies of control usually begin with consideration of systems that operate with continuous signals. 8 Control Systems Engineering Chap. Thus, the gain characteristic of the lower pole-zero pair can be utilized to obtain a desired steady-state error characteristic, and the characteristic of the upper pole-zero pair can be utilized to maximize the bandwidth while maintaining an acceptable degree of relative stability. At the instant that the model changes, the final state of the previous model becomes the initial state of the new model. Because the armature is the source of converted power, the field operates at a relatively low power level when compared to the armature. A branch multiplies a signal by the specified transfer characteristic, with transmission occurring only in the direction of the arrow. The content also reflects the special needs of practicing engineers by including topics such as the simulation of commonly observed nonlinear phenomena and the design of discrete-event control systems. 143 144 Stability Chap. A change in the controller configuration produces a nearly ideal torque source. Since the output y is defined in this example to be equal to xl' a plot of y would be redundant. Performance Criteria and Some Effects of Feedback 7.1 INTRODUCTION The employment of feedback in a control system can be an important part-or a vital part-of a successful control strategy. If the screw is rotated, the lead nut will move with a translational motion, but if a translational force is applied to the lead nut, the screw will not rotate. The model for a permanent-magnet DC motor is readily obtained if the components of nonlinear friction are neglected. Depending on the position of left-half-plane roots, the system may produce a natural response that is unacceptably close to an unstable condition. The response functions as displayed as Example 11.1 were obtained with a system description as required with the implementation of a full-order observer. Considering a particular system function, the type number provides information with regard to the nature of the error with different polynomial inputs. If a change from a linear continuous-time model to a linear discretetime model is required, there are some striking similarities. Because Example 11.4 requires an observer design with repeated poles at s= -15, they are specified with a slight alteration: clear, A=[0 1; -2 -3J; C=[5 0J; p=[-15 -15.01J; G=place(A' ,C' ,p)' A matrix of plant C matrix of plant % Desired observer poles % Compute G matrix % A check of controllability and observability can also be obtained. Consideration of similar problems inspired many academic experiments with the automatic balancing of an inverted pendulum, and various experiments were performed with inverted pendulums on movable carts. However, if the motion of a linear spring and mass is vertical, a constant force provided by gravity, Mg, will produce a constant component of displacement of the spring. A highly desirable characteristic of transfer-function models is the ability to identify relationships between experimental data and transfer-function parameters. Thus, feedback existed only as provided by operators who observed sensor outputs, such as temperature gauges and pressure gauges, and then adjusted process control parameters, such as temperature controls and valve settings. Electrical and Mechanical Elements Table 2.1a presents linear differential equation relationships for passive electrical elements that are assumed to be lumped and linear. Li, Applied Nonlinear Control. Although each point on the trajectory corresponds to a specific moment in time, the trajectory displays one dependent variable versus another dependent variable; thus, the independent variable (time) is not necessarily an explicit feature. Consider the Sec. In this section, a method is described for arbitrary pole placement using controllers that are described by transfer functions. N. For example, the use of a learning process is often associated with the implementation of a neural network; and fuzzy-logic control can be applied to systems in which the plant model is not readily described, with linguistic criteria applied to the development of a control strategy. 2 characteristic, and the small-signal amplification of signals using a transistor amplifier is another example. If the plant exhibits only two dominant poles, the potential improvement using a PD controller is substantial. The Rand C materials should also display small thermal coefficients that are ideally equal and opposite in sign. 1.4 The Classification of Control Techniques 9 Digital Control with Sampled Data The use of digital technology in the design of controllers introduces a remarkable flexibility of design capability. 2.6 NONLINEAR MODELS The elements as described in Tables 2.1a through 2.1c are all elements that can be designed to exhibit linear behavior when operated within a limited range of signal levels. Consider a transfer function with 3.8 MODELING USING MATLAB MATLABis a widely used engineering software package that provides a powerful and friendly environment for engineering computation and simulation. With the PI controller, the forward-path function is then 188 Performance Criteria and Some Effects of Feedback Chap. The observed action is substantially different. However, there will be an unnecessary delay in response to the change while the integrator "unwinds" to a value that will restore linear operation. However, a diligent (or computerassisted) search of scientific journals usually provides a number of references that are collectively valuable as information is gradually assimilated. If the discrete output levels are derived from constant voltage sources, an idealized representation of a trilevel controller is as shown in Figure 12.9. Note that an ideal switch exhibits either zero voltage or zero current. For example, the mass and center of gravity of a rocket change as its fuel is consumed; the mass of an automobile varies as the number of occupants changes; and resistive and inductive components of an electrical power system vary as the load changes. The surface representing magnitude exhibits peaks and valleys, with points of zero and infinite amplitude at the location of zeros and poles, respectively. Autopilot and autothrust systems can work together to perform very complex maneuvers. Other Nonlinear Phenomena Another nonlinear phenomenon is the self-locking characteristic exhibited by some lead-screw drives. Stable operation requires, of course, that all of the roots The frequency-response techniques of Chapter 9 and the root-locus techniques of this chapter are applied to a variety of controller design concepts, as presented in the following chapters. If the spectral content of the input extends into a range in which the system function exhibits significant attenuation, the loss of high-frequency content indicates that the control system cannot produce an output that exactly duplicates the reference input. The runaway action of the natural response tends to overshadow the forced response quickly; thus, the normal control action is defeated. Ogata, Modern Control Engineering. SIMULINK, Dynamic System Simulation Software, user's guide. With an unstable limit cycle, it is apparent that an initial state that is not exactly on the path produces a trajectory that diverges from the path of the limit cycle. The analytical techniques provide valuable insight into cause-and-effect relationships. Perhaps the most significant achievement in flight control was the development of a computer-controlled system for the space shuttle. Although the state model as presented is a continuous system model, a discrete version of the state model is applied to the study of digital control with sampled data. A 0.5-dB peak implies a phase margin of about 57°. 3.7 ORDER REDUCTION A circumstance sometimes exists in which the order of a transfer function can be reduced without a significant deterioration of the validity of the model. Various systems were designed in which robots were used for operations requiring the movement and placement of parts. A branch line can be added by initiating the branch near the output of a block or by pressing the control key when starting the branch. Because any shaft will exhibit some degree of torsional elasticity, this property is not always a desired phenomenon. The Laplace transform, the Fourier transform, and phasor algebra are all transformation techniques-they all provide a transformation of variables, and they all convert linear differential-equation models to algebraic models. There are very interesting advantages and disadvantages to the implementation of a feedforward path as shown. The addition of the Control System Toolbox adds numerous special-purpose functions, and many of these functions are fashioned particularly for the study of time-domain behavior. However, the capacity to modify performance extends to various other areas of study. The evaluation of inverse transforms using a partial-fraction expansion to obtain recognizable transform pairs is described with several example problems. The position of the end effector could be described as a set of machine coordinates that described the angles of the various joints, and the machine coordinates could be mathematically related to a set of workspace coordinates (usually Cartesian coordinates). Some experience with the application of LapJace transforms is helpful, but this background is not absolutely necessary. The deliberate simulation of nonlinear phenomena is feasible using analog simulation, but the implementation requires the incorporation of diodes or other nonlinear electrical elements into the operational amplifier circuits in a fashion that will duplicate the desired function. 2.3 Modeling with Lumped Linear Elements 21 but the corresponding force-voltage analogy would require an electrical circuit described in terms of charge, q(t). The velocity of the stepper motor is limited because the inductance of the motor windings tends to oppose rapid variations in current. Thus, the input and output signals can be expressed as phasors, and a phasor-algebra transfer function (output over input) represents a ratio of phasors. The state-transition techniques provide a systematic and carefully structured approach to the development of programs. The control center is the processor inside the thermostat. This concept is presented with respect to the utilization of a PI controller and repeated in a subsequent section with the consideration of a phase-lag controller. The user must construct the diagram, enter the parameters as required, select a simulation algorithm, and then request a simulation. If a block diagram includes state models as subsystems, then the determination of an overall system model must be developed with consideration of multiple variables, as presented with the state model structure. Error Constants and Type Numbers The definition of error constants and system type numbers provides an organized approach to understanding the relationship between a polynomial input and the corresponding steady-state error. If the Fourier transform of a transient signal is squared, the squared function characterizes the distribution of energy versus frequency. The curved grid specifies closed-loop gain values of 6 dB, 1 dB, 0 dB, and -6 dB. James, Nichols, and Phillips [6] give readers a sense of the remarkable quality of this early work. However, a design task may require a level of understanding for which a designer must seek additional resources. A system might be considered as an assemblage of components that provide interrelated actions. An immediate application of many of these concepts occurs in Chapter 8. On the other hand, if the notation is symbolic, it is not known whether the sign will be reversed when the symbols are replaced by numerical values. Some experience with logic design is useful, but not essential. Because the velocity of propagation is finite, a time-varying signal will produce a variation of signal level that occurs as a function of displacement through the device. The conversion of a transfer-function model to a state model is a somewhat different situation. An example is obtained by considering modification of the optical tracking system, as described in Example 7.5. The addition of a cascaded integrator in the forward path will change the system from type 1 to type 2. The output response will be plotted in a figure that is the same as Figure 3.23 (except for possible differences in the scales and the simulation time). The development and manipulation of transfer-function models are considered in Chapter 3, and these techniques are used in many chapters throughout this text. Although the utilization of a cancellation technique lacks robustness (in the sense that it is sensitive to variations of system parameters), a significant improvement in the steady-state performance is gained without introducing stability problems. With a feedforward technique applied to a system such as a digitally controlled machine tool, the cancellation occurs, but it is observed to be sensitive to variations in the steady-state velocity as well as variations in system parameters. The overall closed-loop transfer function may then be converted to a state model (using one of the methods as described in Chapter 3). The table can be extended in either direction, but the ability to obtain a workable system with a type numbers of 3 or higher is subject to significantly increased difficulties with closed-loop stability. At the selected points, data were recorded that described the machine coordinates. Minorsky, "Directional Stability of Automatically Steered Bodies," J. Extending the meaning of plant to include elements of the controller that are determined a priori (such as an integrator), arbitrary pole placement and steadystate accuracy can be simultaneously accomplished. Design tasks are approached with a somewhat different perspective, and the employment of frequency-domain models sometimes introduces a unique or particularly insightful procedure. The measurement of a forced response at each frequency is obtained with the assumption that the natural response has decayed to a relatively insignificant value. If nonlinear phenomena provide abrupt changes that permit a piecewise linear characterization, then a set of linear state models can be utilized with transitions between models. R. The inner flexible gear is forced into an elliptical shape such that it contacts the circular outer gear in the regions of the major axis of the ellipse. These problems provide a review of traditional techniques and consideration of some alternative procedures. The lead-lag compensation function provides a combination of lead and lag compensation. Using Fourier techniques, a repetitive signal can usually be decomposed into a summation of sinusoidal components, and a transient signal of finite energy is usually expressible as a continuous function of frequency. It is a relatively common practice to construct frequency-response plots using a formulation that is described as a Bode plot (Chapter 1, reference 5). With theoretical concepts interwoven with realistic examples, the material is presented to the student in an understandable but rigorous manner. A study of time-domain behavior is pursued by viewing the response of system variables to the application of a specific input (or set of inputs). Note that marginal stability produces a closed path with a magnitude that is changeable and directly dependent on the initial excitation. Many modern control techniques require mathematical variations that exploit the special capabilities of digital technology. If a system model is accurate, the observation of system variables will accurately reveal the behavior of the physical system, and the system performance is then open to a careful study of the effects of changes in system parameters or variations in the input behavior. A modeling technique that is applicable to this situation is to develop multiple linear models as required to describe the various modes of operation. However, if a position sensor is integrated into the cylinder housing, then a system to provide automatic control of piston position can be implemented using a feedback loop, as shown in Figure 3.20. This chapter is focused differently-analysis techniques are developed that utilize the open-loop transfer function. The conversion to a proper function requires the addition of at least one pole, and the ratio of pole to zero position must be considered carefully to minimize the amplification of extraneous signals. The communication of ideas through technical literature may initially seem to be less than optimum-scientific papers do not always present an unassuming narrative of the author's actual experience. With a continuous LTI model, linear system techniques such as phasor algebra and the Laplace transformation are directly applicable, and a state model (Chapter 4) also assumes a particularly convenient mathematical format. This phenomenon is not predicted using a linear model (assuming viscous friction), but it is readily understood if coulomb friction produces a significant contribution to the system model. Although the dynamic action of the spring is not necessarily a desirable feature, the spring is included to support the body weight. Some airplanes even have autothrust computers to control engine thrust. Inspection of the coefficients of the characteristic equation yields stability information in certain circumstances. The user can also perform a conversion with either the ss2tf (state space to transfer function) command or the tf2ss (transfer function to state space) command. The high low-frequency gain contributes to an improved steadystate performance. Either type of actuator can be incorporated in systems that respond to inputs with various digital formats. The result as attained with this linear example is a commonly achieved result of the application of state feedback, and a plant model that offers the ability to place freely all of the poles can be described as exhibiting state controllability. The Routh version involves the development of an array of elements with a prescribed sequence of algebraic manipulations to detect the condition that all of the roots are in the LHP. The advantages of the new solid-state digital technology were also evident in other forms. Considering both continuous and discrete-action control systems, designers often gain satisfactory control by employing feedback. Considering the plant of Example 11.1, A=[0 5 0; 0 -.160; 0 -1.4 -50J; B=[00 10J'; C=[l 00J; Mc=ctrb(A,B); Mo=obsv(A,C); % Compute controllability and observability matrices rank(Mc), rank(Mo) % Compute the rank Because this plant is both controllable and observable, the answer that is returned in each case is rank=3. Drawing a block diagram requires the use of a mouse with clicking, dragging, and drawing operations. Some Early Examples of Automatic Control Ideas ~ An often cited example occurred in the late 1700s, when James Watt developed a steam engine with a flyball governor. An example (Chapter 12) is the on/oft control of thrusters that release a pressurized gas to control the angular orientation of a space vehicle. It is also possible that the control function within these limits may be intentionally distorted to compensate for a nonlinear plant. The terminology as expressed with respect to both of these configurations is associated with a design topic that is introduced in Chapter 11. Lin, Computer-Aided Analysis of Electronic Circuits: Algorithms and Computational Techniques. 5 corresponding operational functions are shown with the assumption that the operation is ideal. The action of the back EMF provides a feedback action that tends to maintain a fixed ratio between input voltage and output velocity under steady-state conditions. Brown for their participation and suggestions. As an alternative, this block can also be defined by copying a Transfer Fcn block and entering [0 0 100] for Numerator, and [1 2 0] for Denominator. Systems of interconnected relays facilitated the employment of both feedback and programming. The MATLABsoftware package with the Control System Toolbox provides a set of computer-generated computational procedures that afford efficient simulation procedures for linear or nonlinear systems. It is assumed that there is no friction associated with the surfaces. Although the academic background of the authors is electrical and aerospace engineering, the contents reflect an intense interest in the interdisciplinary nature of system design, with a fusion of topics that are typically associated with mechanical, electrical, and other engineering disciplines. By automatically controlling the input steam valve as a function of angular velocity, the governor provided a nearly constant velocity despite variations in load or steam pressure. The simulation of a nonlinear state model is readily achieved using the forwardEuler algorithm, but a satisfactory implementation may require the application of a higher-order algorithm. Riccardi The author and publisher of this book have used their best efforts in preparing this book. An ideal representation includes a pole located at the origin in the s-plane and two zeros located in the LHP. The transfer function relating output to input is Thus, if the cancellation is exact, the system exhibits the steady-state performance characteristics of a type 2 system. Boston: MIT Rad. Problems 4.1 Considering the system as described in Figure P4.1, select a set of state variables and determine a state model to describe the system. This is an area of study that is pertinent to factory automation and process control, and it is often an area of special importance to employers and practicing engineers. A number of helpful reviews were also received in various stages of preparation, and the authors are appreciative of the advice of D. 6.4 STABILITY TESTS A direct approach to the determination of linear system stability is to factor the characteristic equation and check the location of the roots. The development and simulation of systems with nonlinear models are considered in Chapters 12 and 13. The introduction of a controlled force allows an increased flexibility in the development of a control strategy. The following discussion introduces some additional SIMULINK blocks, and the simulation procedure is demonstrated with two examples. The operation, however, is reversed to function as a generator rather than a motor. The implications of utilizing a nonlinear model are very significant-there is an apparent inability to apply techniques that utilize either a transfer function model or the vector matrix formulation of a state model. Some SIMULINK Blocks The Sources Library contains a number of blocks for generating various excitation signals. 'Differential-equation models can be transformed using the Laplace transformation or phasor algebra to obtain algebraic functions in terms of complex variables. 0-13-597436-4 PRENTICE-HALL INTERNATIONAL(UK) LIMITED, London PRENTICE-HALL OF AUSTRALIA PTy, LIMITED, Sydney PRENTICE-HALL OF CANADA, INC., Toronto PRENTICE-HALL HISPANOAMERICANA, S.A., Mexico PRENTICE-HALL OF INDIA PRIVATE LIMITED, New Delhi PRENTICE-HALL OF JAPAN, INC., Tokyo PRENTICE-HALL ASIA PTE. One example is the selection of variables described as phase variables. If a system can be described with reasonable accuracy using a linear time-invariant model, the simulation is readily pursued using anyone of several techniques, and design problems can be approached with a substantial set of mathematical tools. Acceptance of these motors declined as advances in magnetic materials and solid-state control circuitry provided improved options. If the output level is not exactly equal to the level of the step input, the error signal is nonzero, and the rate of change of the output of the integrator is proportional to the error. Thus, it is a common procedure to consider analysis and design concepts in terms of the system parameters as they appear in a transfer function. Thus, the operational amplifier circuits provide models that tend to be nearly ideal and insensitive to variations of the active devices. Modern control topics can be avoided in the first term by temporarily skipping Chapter 4 and major parts of Chapter 5 (but then continuing through Chapter 9). Thus, the composite model must consider differential relationships, and the system is described using a set of linear differential equations. The operation as a servomotor depended on the ability to control slip between 0 and 100%, and the resulting operation was very inefficient and somewhat nonlinear. As considered in the following discussion, the forced response is distinguished as the set of terms that display the same form as the input or derivatives of the input, and the natural response is composed of the set of terms that display the same form as terms that appear in the impulse response of the system. If the model is linear (or quasi-linear), numerous techniques are available to study cause-and-effect relationships, and analytical solutions are readily obtained. Since feedback was obtained by sensing the angles of individual joints, forceful and accurate control was limited by the flexing of cascaded structural members and the compounding of errors with cascaded control systems. The methodology is very similar except that the structure is reversed: The common node for all loops is placed at the right end, the forward paths all emanate from the input node, and the state variables are labeled sequentially from left to right. 7.2 Transient Performance Criteria 161 The Overdamped Response with a Dominant Pair of Poles If the damping ratio is greater than one, the poles are both located on the real axis, and the natural response is defined by two real exponential functions. Although the application of matrix algebra (with a matrix inversion) as described in Example 4.3 will generate transfer-function models, the conversion of a state model to an equivalent transfer-function model is also readily accomplished by constructing a state diagram and applying Mason's gain formula. Considering both the induction and synchronous motors, a polyphase set of voltages applied to the stator windings produces a field vector that rotates with a velocity that is proportional to the input frequency. These signals directed movement to selected points along the paths of desired motion. This combination of objectives is a particular problem in robotic applications. One method of visualizing the bounds on linear operation is to consider an n-dimensional space, where each dimension is determined by a dependent variable. The low-frequency pole and zero allow an increase in the low-frequency gain without altering the gain at higher frequencies. Robots were gradually assimilated into manufacturing operations that provided a variety of useful tasks, and they were particularly desired in applications that were dangerous or tedious when performed manually. 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However, a helpful phenomenon occurs when using the transform techniques; it is generally observed that cause-and-effect relationships are easier to comprehend when viewing the transformed system model (rather than viewing the differential-equation model). If the motor is controlled using a nearly ideal variable voltage source, the motor tends to act as an ideal velocity source. This home security panel offers a camera that creates a record of each time the system is disarmed or takes a photo during an alarm event. With the exception of the transform variable, transfer functions as obtained using the Laplace transformation are identical to transfer functions as obtained using phasor algebra. The development of increasingly complex continuous control systems accelerated rapidly in this period, and the results were often remarkable. The velocity may then remain at zero for some time, or the transition to the zero velocity model may precipitate another transition if the magnitude of J(t) exceeds the breakaway in the opposite direction. A large deviation from the null elicits a significantly nonlinear characteristic. Brogan, Modern Control Theory (3rd ed). Designing Continuous or Quasi-Continuous Systems Although a specific design will require specific studies, the general design procedure illustrated in Figure 1.2 is applicable to the development of continuous or quasicontinuous systems. Inputs are introduced as voltage waveforms, and outputs are generated as modified signals that exhibit the behavior of the analogous system variables. While the power amplifier is in a limit, the output magnitude of the integrator will continue to increase (unless the integrator output also reaches a limit) without any effect on the response of the system. The use of digital simulation is a prevalent technique, but analog computation displays some desirable characteristics that can be utilized in an academic environment. Controller design is extensively pursued in subsequent chapters with the application of both time-domain and frequency-domain techniques. The transfer-function-based pole-placement method described in these examples can readily be generalized for application to higher-order systems. The extensive consequences of linear versus nonlinear modeling are addressed throughout this text. The nonlinear simulation of Chapter 12 is heavily dependent on the application of numerical techniques. Nonlinear System Simulation The forward-Euler algorithm (Section 5.4) can be implemented as a set of MATLAB statements, but there are two algorithms of considerably greater sophistication that are applicable to nonlinear system simulation. For example, if this procedure is used to move poles to the left in the s-plane by an inordinately large factor, the required values of k], k2, etc. The steady-state error with a polynomial input can be evaluated in view of system characteristics such as the type number and the values of error constants. An overdamped response is shown in Figure 7.3 with the damping ratio equal to 1.67. The capacity to produce a significantly large windup is sometimes inadvertently introduced by utilizing a digital integrator with an output range that greatly exceeds the linear range of the following analog devices. With a pair of dominant poles, the shape and extent of the frequency-response function is dependent on ? Bounds on Linear Models Returning to the resistor and the spring as examples of electrical and mechanical system elements, the linear system behavior only exists within certain bounds on the magnitude of the dependent variables. With a relatively accurate plant model, the use of derivatives of the input reference signal provides dramatic improvements in system performance that are impossible to achieve using only feedback compensation. Thus, controllers were developed with computer circuits that continually adjusted the controller parameters in accordance with changes in velocity and air pressure. Static and coulomb friction are examples of commonly observed nonlinear phenomena. P~fu~ ~ The authors are indebted to several colleagues including Jeffrey B. Although the implementation involves concepts that depend on further study, some fundamental understanding of system identification will develop with the application of transfer-function techniques. & Control Systems Engineering Chap. Because these are not isolated closed paths, they are not limit cycles. For example, the text "Zero-Pole" can be replaced with "G2(s)," "Inport" can be replaced with "r," and "Outport" can be replaced with "y," etc. Often, an analysis or design technique will require consideration of a transfer function in view Transfer Functions: Interconnected Blocks The transfer function of an interconnected set of blocks can be determined with the application of MATLAB functions series, parallel, feedback and cloop, and this result might be included as part of a more extensive program. The characteristic equation is obtained by equating the denominator polynomial of a closed-loop transfer function to zero. The application of a sensitivity analysis to a feedback system demonstrates the remarkable change that is attributable to the feedback action. The application of digital technology also introduces an ability to incorporate digital logic and to embed knowledge in the control structure. Mason's gain formula provides a solution technique that is directly applicable to the signal-flow graph, and it is an interesting alternative to a solution technique that requires a matrix inversion. Some salient features of the text are noted as follows: • Computer-aided analysis and design are described using MATLAB and SIMULINK at appropriate points throughout the text. The implementation of a simulation procedure requires the description of input variables and dependent variables as a function of the independent variable (time). A phase-locked receiver is an example of a feedback system for which the bandwidth is determined with consideration of both desired and undesired components of the input signal. Title. The Evaluation of Inverse Transforms Transformed functions, as obtained in the solution of problems involving the use of direct transforms and transformed system models, are typically rational functions (the functions can be described as the ratio of two polynomials). The functions are similar in many respects to the mathematical models that are considered with the study of sampled-data systems. However, the relative velocity and displacement of each end of the actuator mechanism are dependent on the interaction 2.5 POWER AND ENERGY CONSIDERATIONS System models are generally described in terms of variables that are only indirectly related to power and energy. The accuracy of analog computation is dependent on several factors, including the tolerances of passive elements and the small offsets that are introduced by operational amplifier circuits. The cylinder is filled with a fluid, and a restricted path allows the fluid to return to the opposite side of the piston. Englewood Cliffs, N.J.: Prentice Hall, 1980. The output circuit of the controller may employ either solid-state switching devices or relays. After a system model is transformed (using either technique), it is observed that differentiation has been replaced by multiplication by the transform variable, and integration has been replaced by division by the transform variable. Assuming that electrical and mechanical elements are linear and lumped, linear differential equations can be readily determined to describe the behavior of systems of interconnected elements. The operation could then be changed to a playback mode, and the desired motions would automatically occur with incorporation of the recorded coordinates and specified velocity and position profiles. This procedure not only produces an absolute (yes or no) stability evaluation, it also provides information regarding the relative degree of stability of a stable system. Let's consider the example of a pilot who has activated a single-axis autopilot -- the so-called wing leveler we mentioned earlier.The pilot sets a control mode to maintain the wings in a level position.However, even in the smoothest air, a wing will eventually dip.Gyroscopes (or other position sensors) on the wing detect this deflection and send a signal to the autopilot computer.The autopilot computer processes the input data and determines that the wings are no longer level.The autopilot computer sends a signal to the servos that control the aircraft's ailerons. The ability to apply both classical and modern techniques is generally advantageous, and the following chapters are structured to consider both concepts as complementary techniques. If a system is described mathematically by a direct application of established laws, the process is described as modeling. This type of endeavor is a fundamental component of many control techniques. When maintaining a workable mechanical linkage as a backup system was not feasible, the electronic flight control systems became known as "fly-bywire" systems. If the application is considered using frequency-response methods, Problems 307 additional insight is often gained with respect to the controller design. For example, constraints are imposed on the maximum magnitude of variables (such as voltage, current, and velocity) by various device limitations. These characteristics are explained by considering the time-derivative relationship between the variables. Click on each block and set the parameters to define characteristics of the input signal and the range of the output graph. If a system is described as shown in Figure 7.21, the type number is determined by the number of poles of G(s) that are located at the origin. Assuming that state feedback is employed without an observer, the description of the closed-loop model is somewhat simpler. Because MATLABhas many features (other than the control systems toolbox), the student works in a generic programming environment that has gained widespread acceptance as an engineering tool. If the purpose of the integration is to reduce an otherwise small steady-state error to zero, the integral control becomes useful only when approaching a steady-state condition with a correspondingly small tracking error. Depending on the excitation, the system can change between unstable and stable modes of behavior or change from one oscillatory mode to another. Express your result using a vector matrix relationship. If the natural response does not decay to zero, the evaluation of the forced response is not meaningful. There are, or course, limitations. Considering systems that are controlled using predetermined motion profile information (such as robots or machine tools), the separate inputs are obtained by programming the controlling computer to provide both velocity and position commands. Some examples of nonlinear phenomena as they are portrayed in the phase plane are shown in Figure 12.2. The phase-plane trajectories illustrate (a) a stable limit cycle, (b) an unstable limit cycle, (c) a response that occurs as the result of a piecewise linear model, and (d) a response with a system model that displays more than one equilibrium state.

B.Tech Projects for ECE and EEE Engineering Projects. Embedded projects are one of the best choices for ECE and EEE engineering students where most of the students prefer to solve embedded systems based IEEE projects.A few of the most innovative embedded system projects for engineering students are given below. So here is the list of most innovative project … 03/05/2022 · May 2022 - access-templates.com, you can download various access databases and templates for microsoft access software. Get MS access template samples for small business company, non profit education organization and student. Arduino Coding Basics. We have already discussed the popular Arduino Boards, Arduino IDEs, and Installation process of the Arduino software. We learned that Arduino IDE (Integrated Development Environment) allows us to draw the sketch and upload it to the various Arduino boards using code. The code is written in a simple programming language similar to C and C++. Geometric dimension and tolerance (GD&T) is a type of tolerance used along with linear tolerance to define nominal and allowable variations in the part geometry or an assembly.. ASME Y14.5-2009 standard has defined different types of GD&T symbols in detail. This series of articles on geometric dimension and control will help you in the following ways. 22/04/2015 · Stay Safe, Stay Informed. Get the big picture on vaccinations, variants, and other vital COVID-19 trends delivered to your email by subscribing to the Johns Hopkins Coronavirus Resource Center’s weekly newsletter.

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