

Capstan Speed Control in the Optical Fiber Drawing Process: A Case Study for Mechatronics

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Abstract – Industrial case studies of successful implementations of combined mechanical and closed-loop control design provide students with meaningful examples of classroom theory. Such a case study on the development of a capstan drive with feedback control for use in optical fiber production is presented in this paper. Optical fiber is manufactured by the draw process, heating and pulling high purity glass cylinders to diameters smaller than human hair. Many process and product parameters are controlled during drawing of the fiber. Of critical concern is producing a constant diameter for the glass fiber and its light-guide core. Uniformity of fiber glass diameter within the necessary tolerances creates a product capable of high bandwidth optical data transmission as well as cost-effective production. The optical fiber draw capstan design has direct impact on the resulting fiber quality.

A systems approach to the design of mechanical and control aspects is demonstrated through mechanical/electrical parametric evaluations and modeling as well as in the simulation of the capstan drive. Disturbances in the draw process arise from several sources including the starting glass diameter variation and the draw tension control which affects the glass temperature and viscosity. Simulations reveal the achievable fiber diameter tolerance, with the completed design and control scheme in the presence of disturbances.

The fiber drawing process description, process model, and capstan design are presented as a case study suitable for undergraduate or graduate courses in system dynamics, control or mechatronics. The problem discussed is of a multi-disciplinary nature, typical of many manufacturing processes problems. The case study highlights the use of mechanical and electrical modeling, system identification, and control tools as means of product/process improvement.

Keywords: Design, Control, Manufacturing

INTRODUCTION

The system models, mechanical design, motor selection, and closed-loop control design for the optical fiber draw capstan detailed in this case study are suitable for undergraduate or graduate courses in system dynamics, control or mechatronics. Educational goals and intent of this case study are multifaceted. This illustrative example highlights how machine and performance are linked and improved through an integrated, systems-level understanding predicated on engineering fundamentals and tools from multiple technical disciplines. In industry and in academia, the boundaries and barriers between engineering disciplines can be significant. A case study such as this should broaden the perspective, and help remove boundaries – artificial or real – by encouraging a blended problem-solving approach that draws upon many areas of technical knowledge and competence. Use of mechanical, electrical, and control backgrounds are combined in a single design problem. Note that this design problem is not unique, similar types of designs are numerous in industry applications, and are considered mechatronic designs. Other real-life examples include auto-focus cameras, CD players, smart toasters, and high-tech toys. In general, machines and processes that rely on sensors, actuators, mechanisms, instrumentation, controllers and micro-processors of various types, sizes, and attributes can be called mechatronic systems. It could be said that large-scale

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systems, such as industrial plants or vehicles, with many control loops and inter-connections under computer control are at one end of the mechatronics spectrum and relatively simpler devices such as magnetic bearings and machine axes are at the other extreme. [1, 2, 3]

DRAW PROCESS BACKGROUND

Moving light inside a glass fiber core relies upon the principle of total internal reflection, where the inside glass core has a higher refractive index than the cladding glass around the core, Figure 1. Thus, the optical fiber is a light guide providing the highest bandwidth transfer rates for data traffic. Optical fiber is the primary means of high-speed data transmission, at the terabit (10^{12}) per second level. [4]

The draw process is the only cost-effective means of creating optical fiber from ultra-high purity glass cylinders with the required refractive index profile. [4, 5, 6] An important manufacturing quality concern is maintaining a constant core diameter for efficient light transmission. Core geometry variation leads to dispersion of light and loss of signal strength.

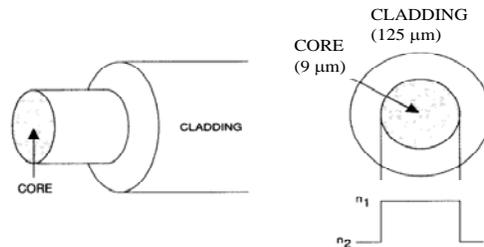


Figure 1. Typical glass components of optical fiber

The optical fiber draw manufacturing process is depicted in Figure 2. A high purity glass cylinder with a prescribed optical index profile, known as a ‘preform’ is heated in a specially designed furnace to the point where the glass flows under low pulling tension. The draw capstan pulls the fiber from the bottom of the glass preform in the furnace, while the glass preform feed drive above the furnace maintains material flow equilibrium through the furnace. The glass fiber is cooled, coated in protective polymers, cured under ultraviolet lights, and wound onto spools.

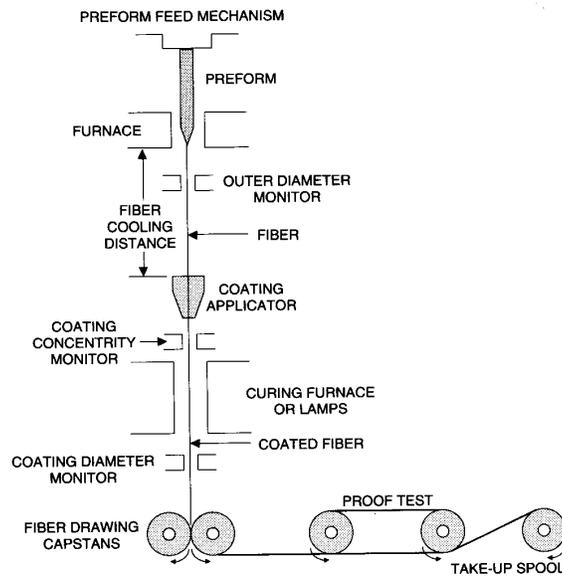


Figure 2. Optical fiber manufacturing processes

The primary control device of fiber diameter is the draw capstan. Measurement of the glass diameter occurs just below the furnace. (Cooling occurs rapidly in the thin glass fiber, so thermal expansion of the fiber relative to room temperature is inconsequential.) The capstan uses draw speed to control the diameter. Using diameter error about a set point as feedback, the capstan's speed is increased when the fiber is too thick, and its speed is decreased when the diameter is too thin. (Note: The draw furnace temperature is used to set fiber tension caused by the capstan pulling the fiber. While the draw tension is important in the fiber draw process, it is not further discussed in this paper.)

The basic design of the fiber draw capstan is a flexible belt partially wound over a flat pulley that moves/pulls a continuous optical fiber all the way from the heated preform, Fig. 3. Tests have validated a relationship between fiber diameter and line speed about an operating point. The basis of the relationship is constant volumetric flow rate of glass.

Variations in fiber diameter arise quite often from process disturbances such as non-uniformity of the preform diameter, mismatch of preform feed volumetric flow that of the preform draw, or the furnace/glass temperature. Thus, in addition to the mechanical design and motor selection, a speed controller must be incorporated in the capstan design for controlling fiber diameter variation from such process disturbances.



Figure 3. Optical fiber draw capstan

DESIGN SPECIFICATIONS AND PARAMETERS

The outside diameter target of the optical fiber glass is 125 μm , while the inside core is 9 μm in diameter. Product specifications call for outside diameter tolerances of $\pm 1 \mu\text{m}$. To achieve this diameter specification the design allowable diameter error must be targeted to a lower dimension. Typically the allowable diameter design deviation is $\pm 0.1 \mu\text{m}$ ($\sim 0.1\%$). The capstan mechanical, electrical, and control designs must be synergistically developed to accomplish this fiber diameter tolerance.

Having established the allowable product deviations, it is important to understand how the critical capstan design parameters interact and affect the resulting product. While many decisions must be made in any design, there are usually a limited number of critical parameters that have significant influence on operational performance. The potential critical design parameters used in this case study are listed in Table 1.

Table 1. Critical Draw Capstan Design Parameters

- Diameter of capstan pulley & tolerances
- Inertia limits, belts contact length, bearings
- Motor torques and speeds
- Control gains
- Amplifier maximum current & power limits

This is a mechatronic system. Both the mechanical design aspects as well as the control design will affect the overall system performance. The primary mechanical design decision is the diameter of the capstan pulley. The required line speed and machining tolerances are the basis of the design. These determine the maximum achievable diameter variations under the condition of no disturbances.

The typical capstan drive is shown in Fig. 4. Belt tension damping and bearing loads are present. Note: Tension in the belt is significantly higher than the small amount of fiber draw tension (typically 50 to 100 grams fiber tension). Dynamic effects of the capstan belt and bearings can be treated as viscous damping and additional inertia.

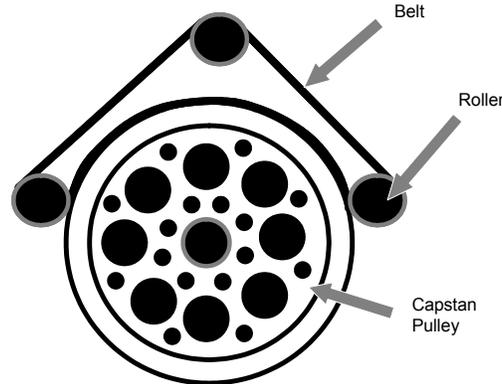


Figure 4. Typical capstan pulley with belt with three rollers

Smaller capstan pulley diameters are desirable because they have less material and lower machining costs, in addition to a lower mass moment of inertia and faster dynamic response with less control effort. The diameter of the capstan pulley is limited on the lower end by the mechanical strength of the fiber under tension and bending. Experiments have shown that smallest allowable diameter is 3 inches in this instance. This must be balanced against achievable machining tolerances and maximum motor speeds. Half of the design error (0.05%) is budgeted to the mechanical tolerances, while the other half is allocated to the control design. Achievable machining tolerances of ± 0.002 inches on diameter indicate that a diameter of 4-inches or large must be used to meet the maximum design error, as seen in Figure 5. Mass moment of inertia of the capstan pulley has a parabolic with diameter, as seen in Figure 6. Lower pulley inertia requires less control effort and power. Clearly smaller diameters pulleys are more desirable from control and inertia effects.

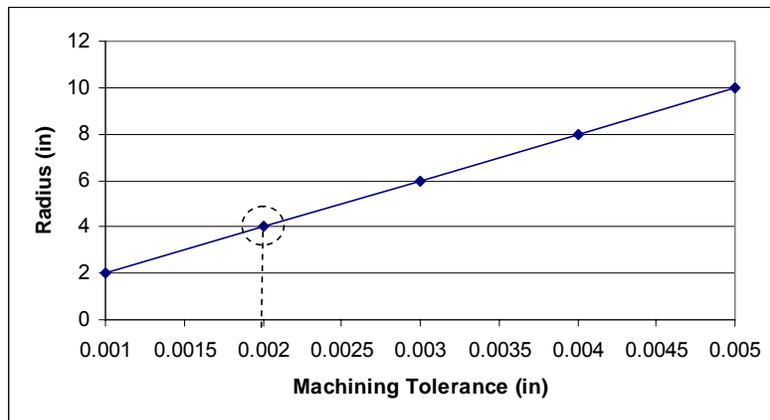


Figure 5. Pulley radius vs. machining tolerance for 0.05% radius variation

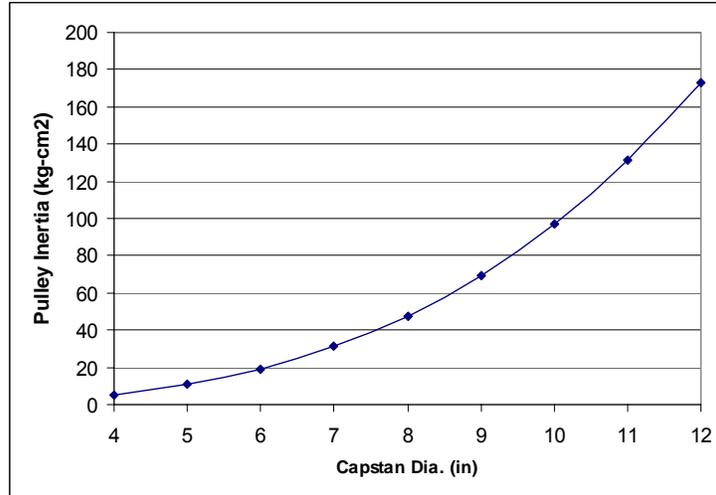


Figure 6. Capstan pulley inertia vs. diameter

The motor maximum speed is another primary consideration in the capstan design. In order to allow for diameter control at a normal draw line speed of 50m/s, the maximum line speed must be higher. Figure 7 depicts the relationship between required motor RPM vs. pulley diameter for an operational draw line speed of 60m/s. Two potential sizes for diameter emerge based on speed requirements. For a motor with a limit of 4000 RPM a diameter of approximately 12 inches is required. An 8-inch diameter is necessary for a 6000 RPM limit. With previous established preferences for smaller diameter pulleys, the 8-inch diameter pulley appears the logical choice, if a motor with a maximum speed of 6000 RPM or greater is available to use.

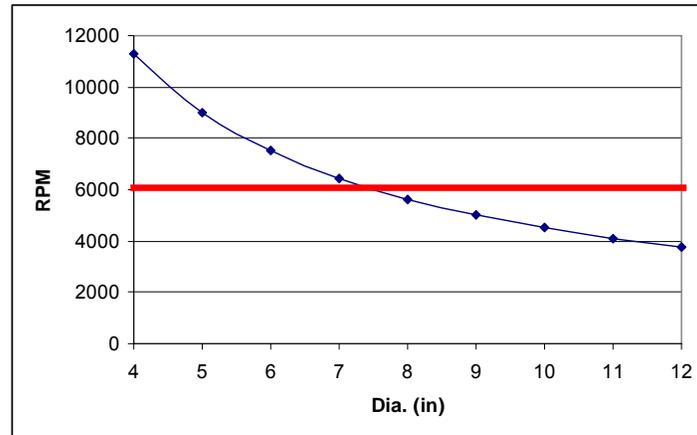


Figure 7. Motor RPM for 60m/s line speed vs. draw capstan pulley diameter

Motor Selection

For each of the two potential diameters (8-inch and 12-inch) for the capstan pulley a motor can be selected. The motor selection depends on several factors including maximum speed, torque, inertia, current and power limitations. Clearly the motor should be sized so that it will handle the controller amplifier hardware limits of 800W per axis continuous and 1600W peak. The rated motor current must be greater than the maximum amplifier current of 10A, to prevent overheating. Specifications for motors compatible with the controller and amplifier are presented in Table 2. The motor maximum speed and torque constants are the most distinguishing parameters for the motors listed. Current and power limits are mostly affected by initial accelerations of line speed. Most of the motors will not approach their current and power limitations during operation at line speed, given the amplifier limits.

As can be seen from Table 2, motors 3, 5, or 7 will meet the speed (600 RPM), power, and current requirements for an 8-inch diameter pulley. Motor 3 is selected because of its relatively lower rotor inertia and roughly equivalent

torque constant. For the 12-inch diameter pulley design, a motor rated at 4,000 RPM or higher is required. Motors 4 or 10 would be acceptable. While motor 4 is slightly below maximum current limit specification (9.6 A), it has a 20% higher torque constant over motor 10. Thus, there are two potential candidate capstan designs: an 8-inch diameter pulley with motor 3 or a 12-inch diameter pulley with motor 4. The preference for capstan design is the smaller pulley.

Table 2. Available Motor Specifications [7]

Motor	Rated Power (kW)	Rated Torque (N-m)	Rated Speed (RPM)	Torque Constant (N-m/A)	Rated Current (Amps)	Rotor Inertia (kg cm ²)
1	1.75	2.2	4,000	0.5	5	5.7
2	2.555	2.2	6,000	0.3	7.3	5.7
3	4.97	4.4	6,000	0.31	14.2	9.9
4	3.36	4.4	4,000	0.46	9.6	9.9
5	7.7	6.6	6,000	0.3	22	12.9
6	3.85	6.6	3,000	0.6	11	12.9
7	11.2	9.2	6,000	0.292	32	22
8	6.23	9.2	3,000	0.52	17.8	22
9	5.25	9.2	3,000	0.62	15	22
10	8.155	9.2	4,000	0.39	23.3	22

DERIVATION OF DYNAMIC EQUATIONS OF MOTION

The potential performance of the two designs for the capstan is based on the simulated dynamic response of the capstan system. Nomenclature for variables used in the capstan dynamic model is provided in Table 3. The equation of motion for the capstan speed is derived beginning with Newton's Second Law as applied to moments in eq. 1. An idealized capstan system is depicted in Fig. 8.

Table3. Nomenclature

b = viscous damping [N - s/m]
B = Rotational damping [N - m/s]
$J \equiv 2nd$ polar moment of mass = $\int r^2 dm$ [kg - m ²] = [N - m - s ² /rad]
$K_t \equiv$ Torque constant of motor
r \equiv outside radius of capstan pulley [m]
t = thickness of capstan pulley rim
h = thickness of capstan pulley center flange
v \equiv belt speed = $\omega * r$ [m/sec]
$\omega \equiv$ motor rotational speed [rad/sec]
$\dot{\omega} \equiv$ motor rotational acceleration [rad/sec ²]
$\Omega(s) \equiv$ Laplace transform of $\omega(t)$

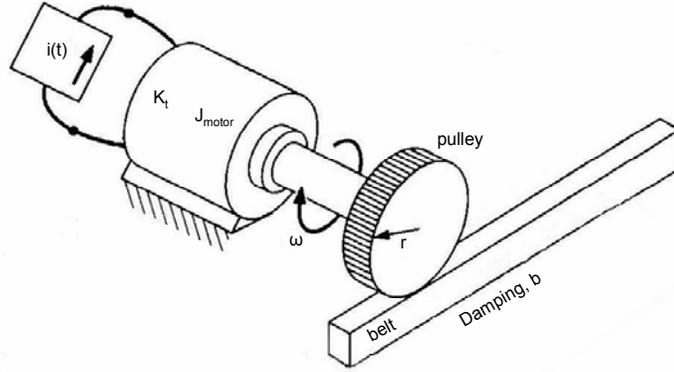


Figure 8. Idealized optical fiber draw capstan pulley

The sum of the applied torques about the pulley center of rotation is summed.

$$\sum T(t) = J_{total} \frac{d\omega}{dt} \quad (1)$$

or

$$J_{total} \dot{\omega} = -B_{tot} \omega + T_{motor} \quad (2)$$

The motor torque is a function of the applied current.

$$T_{motor} = K_t i(t) \quad (3)$$

Substituting into eq. 1 yields

$$J_{total} \dot{\omega} = -B_{tot} \omega + K_t i(t) \quad (4)$$

The effective mass moment of inertia about the capstan rotation center is the sum of the inertia of the motor rotor, pulley, belt and rollers.

$$J_{total} = J_{motor} + J_{pulley} + J_{belt} + J_{rollers} \quad (5)$$

The capstan pulley can be modeled as a rim and a flange.

$$J_{pulley} = M_{rim} r^2 + \frac{1}{2} M_{flange} (r - 2t)^2 \quad (6)$$

The mass moment of inertia for the belt and three rollers is expressed in eq. 7.

$$J_{belt} + J_{rollers} = M_{belt} r^2 + 3 \left(\frac{1}{2} M_{roller} r_{roller}^2 \right) \quad (7)$$

The effective system damping for the system is sum of all the bearings and belt damping. Damping is difficult to calculate but can be estimated by input-output relationships.

$$B_{total} = B_{belt} + B_{bearings} \quad (8)$$

Reformulating eq. 4

$$\dot{\omega} + \frac{B_{total}}{J_{total}} \omega = \frac{K_t}{J_{total}} i \quad (10)$$

Taking the Laplace transform of eq. 10 with no initial conditions

$$s\Omega(s) + \frac{B_{total}}{J_{total}}\Omega(s) = \frac{K_t}{J_{total}}I(s) \quad (11)$$

Using eq. 11, we may derive the transfer function between speed and current.

$$G_M(s) = \frac{\Omega(s)}{I(s)} = \frac{\frac{K_t}{J_{total}}}{s + \frac{B_{total}}{J_{total}}} \quad (12)$$

Using eq. 12 damping (eq. 8) may be readily estimated from current step input and velocity data with system identification tools [8]. The root of the first order system of the eq. 12 is real and negative. As damping values are typically small, the response of the motor may be relatively slow. Control will be necessary for effective disturbance rejection.

CONTROL DESIGN AND PARAMETERS

Figure 9 represents the scheme for the diameter and speed control of the draw capstan. The approach taken here is a cascaded controller of an outer fiber diameter control loop with an inner capstan speed control loop. Diameter error is used to change the capstan speed set point, based on constant volumetric flow. Thus, the volume error must be the square of the fiber diameter error. A positive diameter error would require a positive speed increase. The motor speed change from the diameter variation would be relatively small. The speed change is added to the original speed set point. Thus, the fiber diameter control is fine tuning or trim.

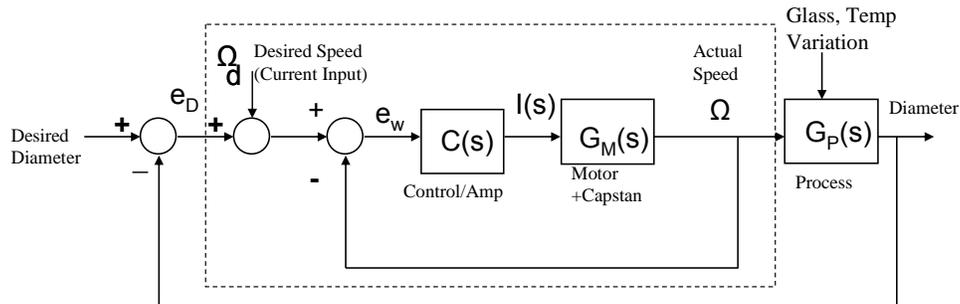


Figure 9. Capstan speed is controlled within a cascaded control loop for fiber diameter.

The open-loop capstan speed transfer function, $G_M(s)$, is a first order system and yields an exponential function of time for a step change in current, eq. 13.

$$\omega(t) = \Delta I \left(\frac{K_t}{J_{total}} \right) \cdot \left[1 - e^{-\left(\frac{B_{total}}{J_{total}} \right) t} \right] \quad (13)$$

Proportional control alone with a high gain will reduce error. However, the steady-state error can be eliminated by using a compensator with proportional plus integral (PI) control (eq. 14).

$$C(s) = K_p \left(s + \frac{K_i}{K_p} \right) \quad (14)$$

Glass preform diameter variations are typically on the order of 2% over 10mm of preform length. Squaring the error yields a 4% volumetric continuous variation over 10mm of preform length. This 4% volume error will be accommodated in the control design, via changing the draw speed set point. A linear ramp is the shape assumed for the preform diameter deviation. The ratio of preform diameter to fiber diameter is approximately 700:1 squaring leads to a volumetric ratio of 490,000:1. Thus the time for drawing 1mm of preform would be approximately 100

seconds. This would require a speed change ramp of 0.04% per second to keep fiber diameter constant. This leaves 1.25 seconds for an uncontrolled fiber diameter to deviate to half of the tolerance budget (0.05% deviation). It is thus desirable to keep the settling time under 1 second for the inner speed loop, to reduce the dynamic effects on the outer control loop.

Controller Electrical Parameters

An integral component of the capstan design and achievable performance is the controller electrical specifications. Amplifier power is limited to 800W per axis continuous and 1600W peak. Current is limited to 10A per axis. The controller update rate is 20 kHz. With these performance specifications (summarized in Table 4) in mind the capstan and controller design can be simulated. The selected 8-inch capstan pulley design with motor 3 can then be assessed.

Table 4. Summary of Controller/Amplifier Specifications for Capstan axis.

Maximum Power	1600W peak.800W cont.
Maximum Current	10A
Settling time	0.25 s
Sample rate	20kHz

The open loop system for the capstan pulley, motor, and speed controller is presented in eq. 15. The speed controller, $C(s)$ was designed with PI feedback control.

$$C(s)G_M(s) = \frac{\Omega}{\Omega_d} = \frac{K_p (K_m/J_{total})(s + K_i/K_p)}{s^2 + (B_{tot}/J_{total})s} \quad (15)$$

The integral and proportional gains, K_i and K_p , were determined using root loci and simulation techniques. An under-damped oscillatory speed response that can cause significant speed error must be avoided, so all roots for eq. 15 were designed to be on the negative real axis. From a frequency domain perspective it was desirable to have a high ratio of integral to proportional gain, placing the transmission zero farther along the negative real axis, away from the origin. Values of 5 and 10 for the K_i/K_p ratio were determined effective through design root loci. This was verified through simulation. Stable values of K_p were found from 0.3 to 30. Figure 10 depicts typical continuous and discrete root loci for $K_i/K_p=5$.

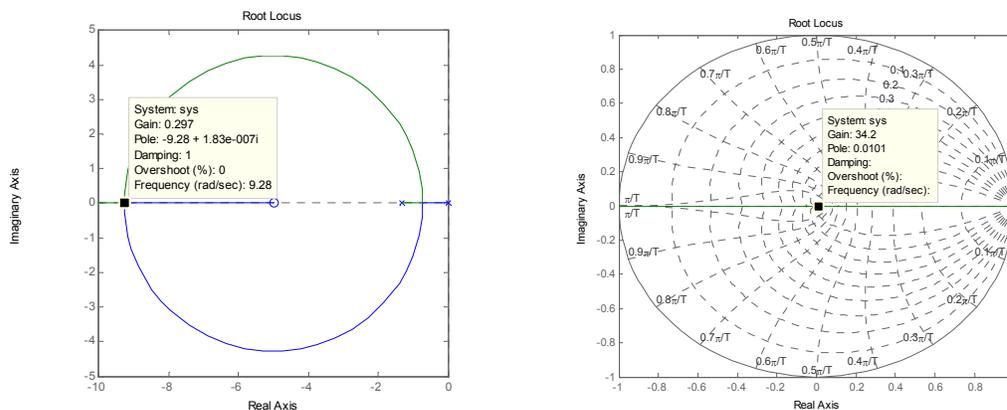


Figure 10. Continuous and discrete root loci

RESULTS

Simulations were performed with a Simulink model of the capstan system shown in Figure 11. A 4% ramp increase in the line speed set point over 100 seconds was modeled and simulated. Line speed error and motor current were examined for various gains for the 8-inch capstan pulley and motor 3.

Figure 12 depicts the results of four simulations for (a) $K_p=30$, $K_i/K_p=5$, (b) $K_p=3$, $K_i/K_p=5$, (c) $K_p=0.3$, $K_i/K_p=5$, (d) $K_p=3$, $K_i/K_p=10$. From these results the design with an 8-inch capstan pulley and motor 3 using $K_p=3$, $K_i/K_p=10$ meets the performance specifications in design criteria. The settling time for speed was under 1 second and power and current limits were not exceeded. These gains ($K_p=3$, $K_i/K_p=10$) were selected as the final design on this basis.

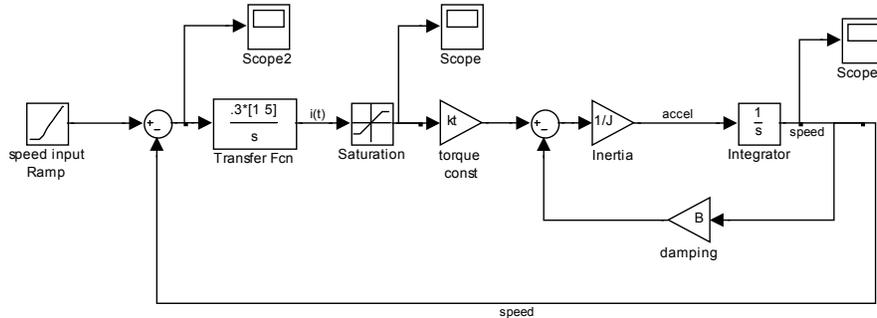
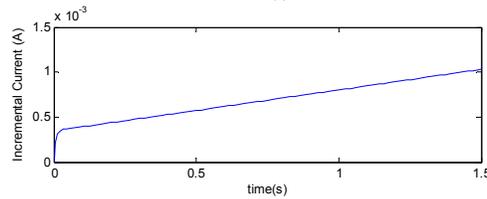
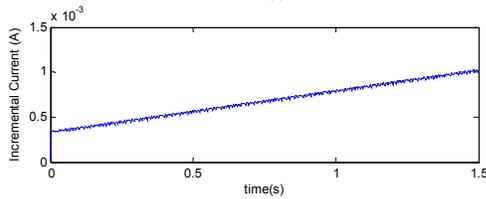
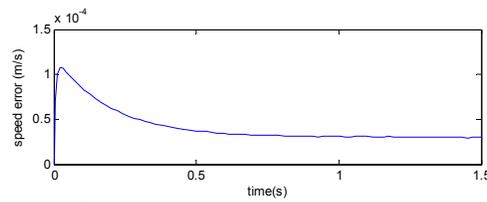
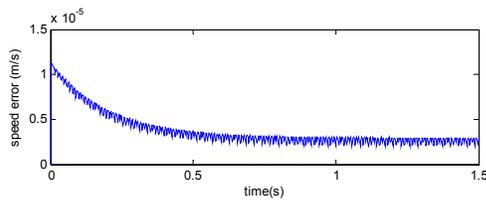
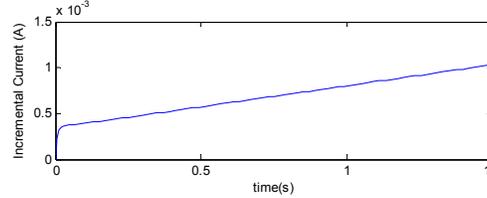
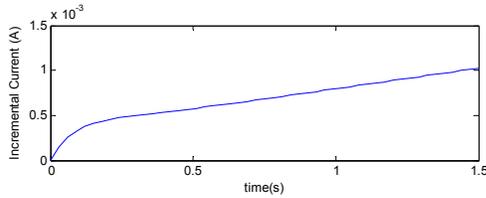
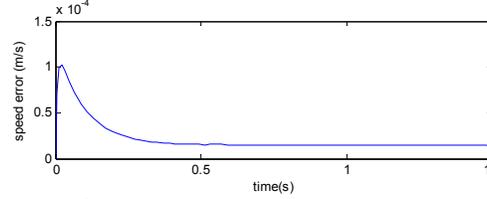
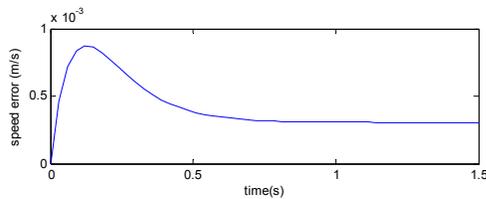


Figure 11 Simulink model of speed control loop



(a) $K_p=30$, $K_i/K_p=5$

(b) $K_p=3$, $K_i/K_p=5$



(c) $K_p=0.3$, $K_i/K_p=5$

(d) $K_p=3$, $K_i/K_p=10$

Figure 12. Simulation results: Line speed error and motor current for varying gains

SUMMARY

The design of an optical fiber draw capstan pulley including the motor selection and control design has been successfully demonstrated for improved optical fiber diameter control. A stable, under-damped response of the capstan speed was achieved without current saturation. Once the design and process relationships were established, an effective draw capstan system was synthesized and controlled. Students can gain a fundamental understanding of how to apply classroom theory to solve a real world problem through this example.

There were several key steps in the design and development of the capstan system presented in this paper that are worthy of classroom study. The modeling of the process and selection of design parameters using multidisciplinary criteria was used to develop a machine that performed better than had the design been serially completed by each engineering discipline.

Although specific hardware and software are prone to change, the fundamental engineering science underlying the successful design, modeling, analysis, and control of a device, machine, or process has remained relatively constant. From this case study students should observe an effective approach to design and process control and have a better appreciation of (1) problem definition, (2) determination of parameters that affect control, (3) system model techniques, (4) physical limitations (5) frequency domain control design, and (6) discrete control design and power limitations. This case study of a real-life process has a broad application to engineering (e.g., control, electrical, and mechanical) due to the multi-disciplinary nature of this design and manufacturing problem.

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