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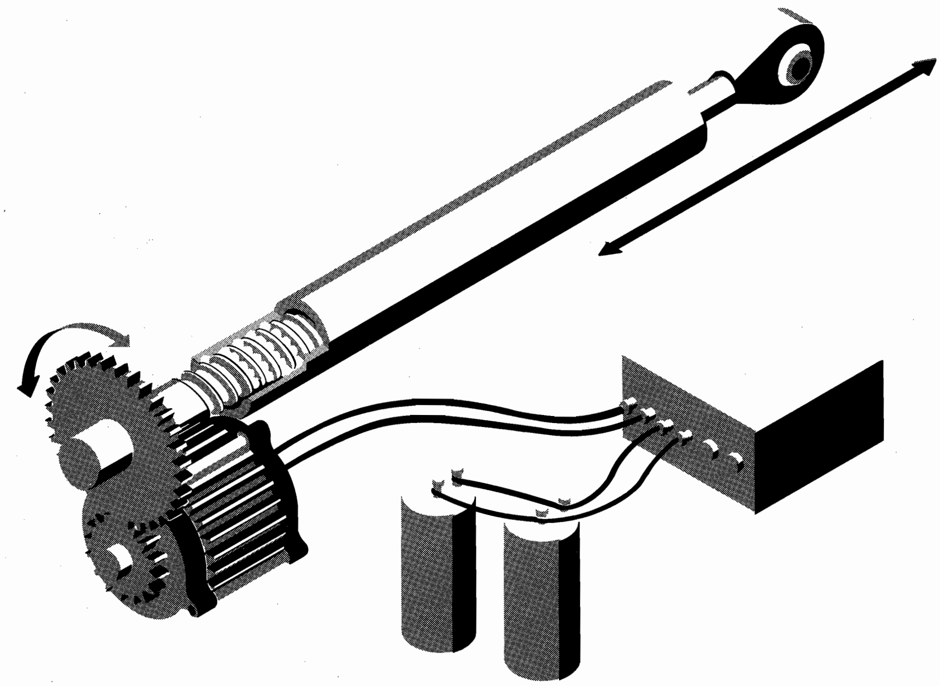

HIGH PERFORMANCE ELECTROMECHANICAL SERVOACTUATION USING BRUSHLESS DC MOTORS

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ABSTRACT

High power density electromechanical actuation, based on advances in magnet materials and power electronics, is a possible alternative to electrohydraulic actuation.

This paper discusses the development of advanced high performance electromechanical actuation systems for applications where weight and size are critical. The general concepts of high performance servoactuation, utilizing brushless DC motors and pulse-width-modulated drives, are reviewed. Two actuation system designs, a fractional and an integral horsepower, are described and experimental data is presented. Each design is a closed-loop servo system employing a rare earth magnet, brushless DC motor and pulse-width-modulated drive electronics.

A mathematical model is presented which includes a detailed nonlinear representation of the pulse-width-modulated drive, the brushless DC motor and the load dynamics. Analytical data from the model is compared to experimental data showing close agreement.

INTRODUCTION

The availability of samarium cobalt permanent magnets has made it possible to reduce the mass of magnet material required in DC motors. Reduced magnet mass results in brushless motors with a low enough rotor inertia to achieve good dynamic response. Brushless motor systems exhibit reliable commutation at a high motor speed. The use of higher motor speed, to provide a required actuator output speed, results in a smaller motor and reduced actuator size. Samarium cobalt magnets also permit higher peak output torque. Advances in power electronics make it possible to build brushless DC motor controllers for higher power applications than was previously possible. Therefore, electromechanical actuation using brushless DC motors is a possible alternative to electrohydraulic actuation for many applications.

High performance actuation systems are characterized by wide bandwidth frequency response, low resolution and high stiffness. Additional requirements may include demanding duty cycles and minimization of size and weight. The application of the concepts of brushless motor technology to high performance servoactuation systems is discussed.

This paper describes recent developments at Moog Inc. in electromechanical actuation and a companion paper, reference 1, does the same for electropneumatic actuation.

SERVOACTUATION SYSTEM USING A BRUSHLESS DC MOTOR

The actuator system is presented in block diagram form in Figure 1.

The electronic controller includes:

- Servoelectronics with appropriate compensation to provide stable and responsive closed loop position control
- Pulse-width-modulation (PWM) to provide efficient proportional control required for good servo performance
- Power switches with flyback diodes to provide a three-phase, full-wave motor drive
- Current limiting to protect the transistors and motor from damage due to excessive heating
- Electronic commutation to provide DC motor characteristics using a brushless motor

The servoactuator includes:

- Three-phase, brushless DC motor
- Precision ball screw to provide linear output motion
- Spur gear reduction from the motor shaft to the ball screw input
- LVDT to provide position feedback
- Rotor position sensors for sequencing the electronic commutation
- Tachometer to provide minor-loop speed feedback for better servo performance

The system depicted by Figure 1 relates directly to the two specific designs presented in this paper. In general the ball-screw spur-gear drive could be replaced by other drive elements to provide the desired coupling ratio and output characteristics.

The brushless DC motor consists of coils in the stator and samarium-cobalt permanent-magnets in the rotor to establish the air gap flux. The motor is made self-synchronous by using rotor position sensors to commutate the stator windings. That is, the controller delivers current to the appropriate stator windings as a function of rotor position to generate motor torque. Brushless motor technology is discussed in references 2 and 3.

A velocity-feedback loop, as shown in Figure 1, aids in providing high performance servoactuation. This inner velocity loop provides a convenient means of establishing a stable position loop having a very high static gain for precise positioning accuracy. The velocity feedback also reduces the effect of amplifier and motor anomalies such as magnetic cogging. It is possible to derive a velocity feedback signal from the motor position information rather than using a tachometer, but this approach has some practical disadvantages. The control loop can be designed to operate without the velocity feedback signal but it is difficult to provide the same level of performance.

SIZING CONSIDERATIONS

The motor and drive train are selected to meet load-velocity, frequency response, and duty cycle requirements, as well as physical package constraints. The coupling ratio (motor speed/output speed) is chosen as high as practical to minimize motor size while retaining good frequency response at a reasonable current limit.

The frequency response of an electromechanical actuator is limited by the voltage and current available at the motor. Figure 2 shows the response limits for the fractional horsepower example presented later. Typically, response is limited in the range of interest by the torque available at maximum motor current. For example, Figure 2 indicates the current limit is dominant at 5% amplitude. Frequency response is usually specified in terms of amplitude ratio and phase lag at a given command amplitude.

The frequency at which the phase lag is 90 degrees will be in the range where the current limit prevails providing the loop gain is high. In certain applications a restriction on maximum amplitude may require lower loop gains so the frequency at 90 degrees phase will be somewhat below the frequency range of the current limit for the amplitude involved.

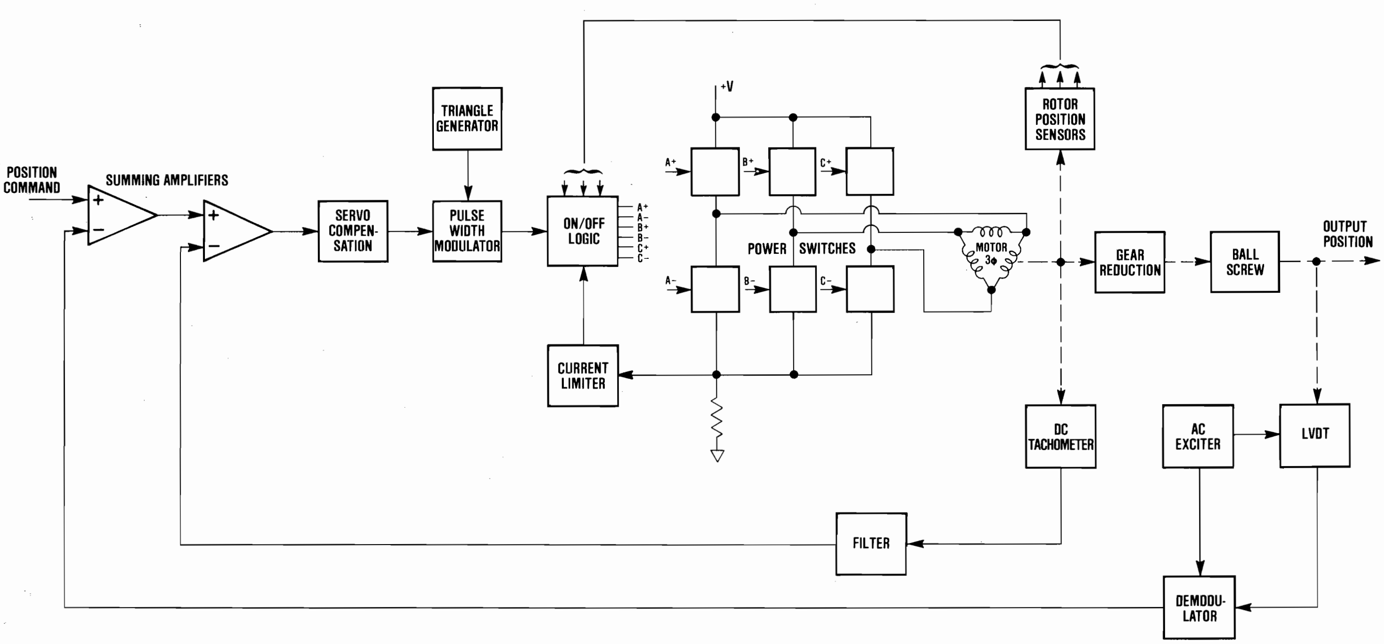


FIGURE 1. ELECTROMECHANICAL SERVOACTUATION SYSTEM

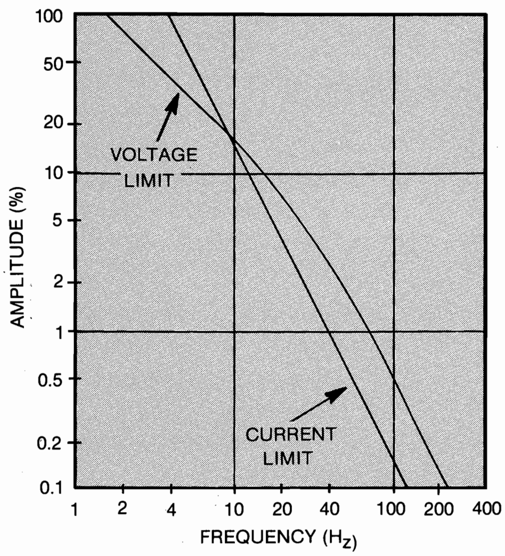


FIGURE 2. RESPONSE LIMITS
(Fractional HP Example)

The current limited response is described by equation 1. Refer to Table 2 for parameter definitions.

$$\theta_L = \frac{K_T I - (T_L/C_R)}{(C_R J_m + J_L/C_R)\, s^2} \qquad (1)$$

Assuming there is no external load ($T_L = 0$), it can be shown from Equation 1 that the maximum acceleration and minimum power dissipation occur when an inertia match exists. This match occurs when the coupling ratio, $C_R = (\theta_m/\theta_L)$, has the value:

$$C_R = \sqrt{\frac{J_L}{J_m}} \qquad (2)$$

Therefore, selection of the coupling ratio, C_R, using Equation 2 may be appropriate in applications having no external load where minimum move time is desired. For example, many robotic applications fit in this category. Selection of coupling ratio for this type of application is discussed in references 4 and 5.

In aerospace applications the objective of the actuation system is to meet the vehicle control requirements while minimizing size, weight, and cost. The actuation system performance requirements are typically specified in terms of load-velocity, frequency response and duty cycle necessary to provide vehicle control stability and performance for the mission. A high external load (aerodynamic spring or friction) usually determines the stall load and loaded velocity requirements. Therefore, since the objective is different and an external load is present, the selection of C_R by Equation 2 is generally not appropriate.

The motor and coupling ratio are sized to meet a load-velocity requirement. This is either the required load-velocity characteristic or a modified characteristic needed to meet the duty cycle requirements with an acceptable motor coil temperature. A higher coupling ratio results in a smaller motor to meet a specific load-velocity slope. Higher coupling ratios can be provided with a much lower weight impact than for the comparable change in motor size. However, the coupling ratio is limited in order to meet the frequency response requirement at a given current (see Equation 1). Therefore, the approach is to maximize C_R within the range of practicality, limited by an acceptable maximum current to meet the frequency response. A brushless motor using samarium cobalt magnets has a relatively low inertia which permits a higher coupling ratio while maintaining a required frequency response at a specific motor current.

The maximum current will influence the controller size and weight. Therefore, it is desirable to set the maximum current at the value which provides the required stall torque. However, in some cases. the size and weight impact of a somewhat higher current may be negligible.

The duty cycle is often dominated by external load torque, rather than acceleration torque. Therefore, there may be little advantage of an inertia match per Equation 2 (i.e. a lower C_R) in minimizing motor heating. In such cases the C_R value has no impact on motor heat dissipation. However, if the acceleration forces and speed are high during the duty cycle, higher values of C_R will result in higher motor current and therefore increased heat dissipation due to both winding and core losses.

The duty cycle may be essentially continuous or it may be very short such as in some missile applications. In applications with short duty cycle, such as 45 seconds, or less, the temperature rise is transient and still rising at the end of the duty cycle. This permits the use of a smaller motor than would be required to maintain the same output torque continuously. Therefore, calculation of the coil temperature through the specific duty cycle is important in arriving at a minimum weight actuator design. In some cases the motor size is determined by duty cycle requirements, while in other cases the load-speed requirement determines motor size. Electronic controller design also requires thermal analysis to establish a minimum weight design which will meet the requirements of the duty cycle while maintaining acceptable electronic component junction temperatures.

In summary, for applications where the external load is large and is dominant during the duty cycle, the coupling ratio can be increased well above the inertia match level of Equation 2, while maintaining required frequency response, thereby minimizing system size and weight.

TABLE 1

COMPARISON OF BRUSH AND BRUSHLESS MOTORS

The actuation system designs presented in this paper use brushless DC motors. However, there are applications for which brush motors are more appropriate. Brush motors can also utilize the advantages of samarium cobalt rare earth magnets to reduce motor size and weight for a given application. The advantages and disadvantages of brush and brushless motors are summarized in the following listings:

BRUSH-TYPE MOTOR

Advantages
- lower system cost
- simpler electronics
- smaller electronic controller

Disadvantages
- commutator switching generates EMI
- brush wear limits life
- brushes limit maximum speed and torque
- poorer dynamic response

BRUSHLESS MOTOR

Advantages
- smaller motor size
- lower motor inertia improves dynamic response
- generally better heat dissipation

Disadvantages
- requires electronic commutation
- requires motor rotor position sensors
- higher system cost

MATHEMATICAL MODEL

In order to provide a valid and realistic analysis of an electromechanical (EM) servosystem, a detailed model of the control loop must include all significant parameters and constraints for each of the components. A model developed for analysis and computer simulation is presented in Figure 3. The DC motor, which is basically a voltage-to-velocity conversion device, is broken down into its essential dynamic elements, (e.g. inertia, back EMF, inductance, resistance, resistance, etc.). The load parameters, (e.g. inertia, friction, backlash and load spring) are included in the load model. The driving amplifier is essentially an on-off switching network which is time modulated at the PWM frequency. Since the non-linear effects of this approach have significant impact on the system performance, it is essential to include these non-linearities. The pulse-width-modulation block includes the appropriate non-linear switching circuitry. For power and heat considerations it is desirable to limit current to the motor and thus current limiting is included. Analytical data from the model has been compared to experimental data from several EM actuator systems showing close agreement. For example, Figure 9 demonstrates the correlation between data from an analog computer simulation using the model of Figure 3, with experimental data. The parameters used in the model are defined in Table 2.

TABLE 2

SERVOACTUATOR PARAMETERS

K_A	amplifier gain (volts/volt)	r	ball screw ratio (in/rad)
K_t	tach feedback gain (volts/rad/sec)	x	actuator position (in)
K_X	position feedback gain (volts/in)	F	actuator force (lbs)
V_s	supply voltage	J_L	load inertia (in-lb-sec^2)
L	inductance (henrys)	K_{ss}	shaft stiffness (in-lb/rad)
R	motor coil resistance (ohms)	B	backlash (in)
I	motor current (amps)	θ_m	motor position (rad)
θ_R	actuator position command	θ_L	load position (rad)
K_T	motor torque constant (in-lb/amp)	θ_A	actuator position (rad)
K_E	voltage constant (volts/rad/sec)	K_I	drive stiffness (lb/in)
S	Laplace transform	K_{LS}	load spring (in-lb/rad)
J_m	actuator-motor inertia (in-lb-sec^2)	L_a	lever length (in)
b	viscous damping factor (in-lb/rad/sec)	K_2	structural stiffness (lb/in)
N	gear ratio	T	actuator torque (in-lb)
T_f	friction torque (in-lb)	T_L	external load torque (in-lb)
G_1, G_2, G_3,	compensator transfer functions	C_R	$= (\theta_m/\theta_L) = (L_aN/r)$

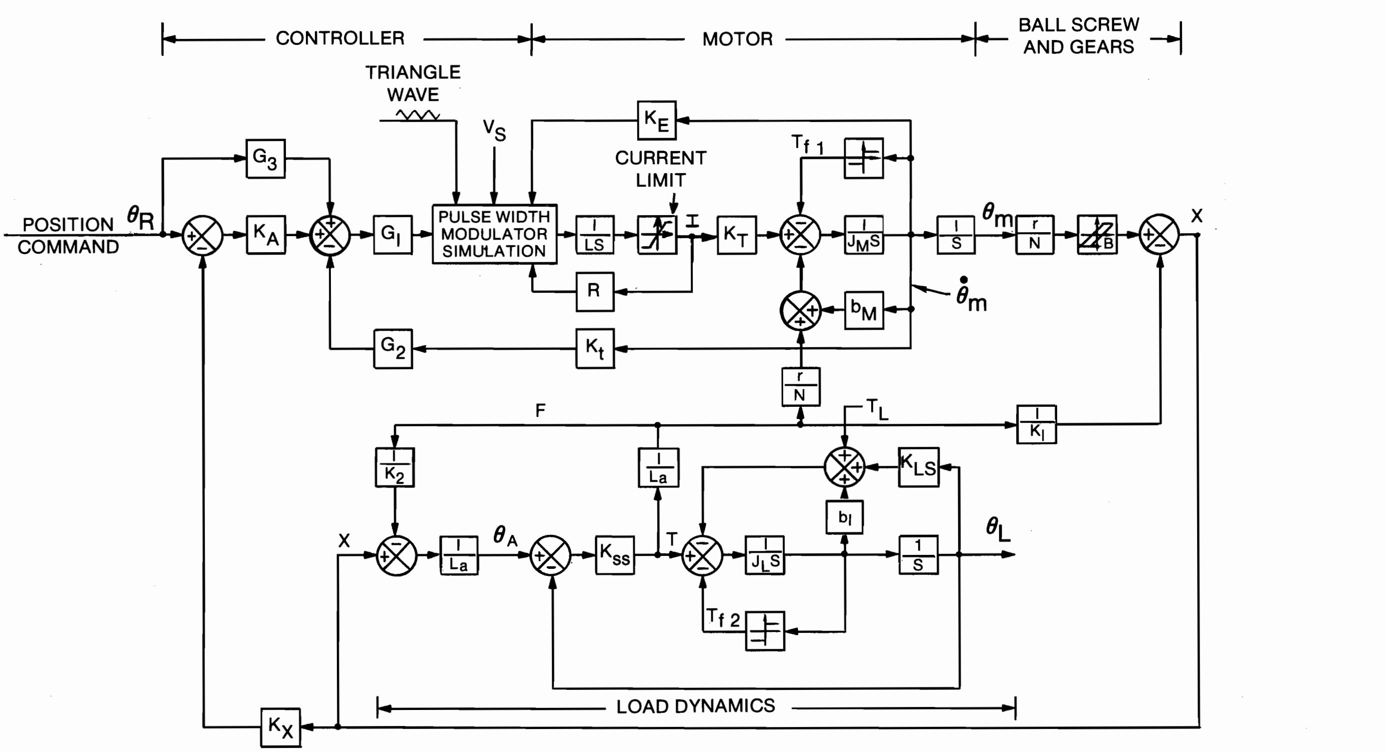


FIGURE 3. ELECTROMECHANICAL SERVOACTUATOR MODEL

FRACTIONAL HORSEPOWER EM ACTUATION SYSTEM

A linear output, one-quarter horsepower electromechanical actuator system (actuator and controller) is presented in detail. This system was designed to meet demanding frequency response and duty cycle requirements at minimum size and weight. The linear output motion is provided by a precision ball screw driven by a samarium cobalt magnet, brushless DC motor through a spur gear ratio. Hall effect rotor position sensors are used for electronic commutation. High performance, closed loop position control is achieved using an LVDT for position feedback and a tachometer to close an inner velocity loop. The servoelectronics operate through pulse-width-modulation of power switches to drive a three-phase, brushless motor. Photos of the actuator and a prototype controller appear in Figures 4 and 5. The system block diagram is shown in Figure 1.

The servoactuator consists of a linear output ball screw driven by the motor through a gear reduction. These basic components are housed in three main members consisting of a tailstock, bearing plate, and front housing. Figure 6 shows a cross-section of the actuator which also includes the spherical mounting bearings, position transducer, velocity transducer, end-of-stroke stops, electrical connector and ball bearings. The tailstock and the adjacent bearing plate, together, form the housing assembly for two, large-angular-contact bearings which support the ball screw and output gear. These bearings also provide the rigidity and positional accuracy needed for the idler gear and the motor pinion and shaft. Position feedback is generated by a linear variable differential transformer (LVDT) mounted co-axially within the ball screw.

The brushless DC motor has a steel-core-wound stator. The rotor has high-energy-product (26×10^6 Gauss Orsted) SmCo magnets to provide high performance with minimum size and weight.

The controller functions are illustrated in Figure 1. The photo shown in Figure 5 is a single-channel prototype housed in a three-channel flight design package. The servoelectronics accept an alalog position command signal and provide closed-loop position control. Appropriate servo compensation is included in the minor velocity feedback loop. These functions are implemented using analog electronic circuitry. The motor current logic circuitry, including pulse-width-modulation, electronic commutation and current limiting, is implemented digitally. Six bipolar transistors, with associ-

TABLE 3

PERFORMANCE OF FRACTIONAL HORSEPOWER ACTUATOR

Maximum Output Force (stall)	400 lbs
Maximum Speed (no load)	8.1 in/sec @ 22 VDC
Maximum Power Point	0.25 hp
(320 lbs @ 5.24 in/sec)	
Stroke	±0.943 in
Resolution	0.0008 in
Stiffness	104,000 lb/in
Frequency Response	
for ±5% command	90° @ 18 Hz
for ±0.8% command	90° @ 38 Hz
Continuous Duty	
output force	186 lbs
output power	0.13 hp
Pin to pin distance (retracted)	6.6 in
Actuator Weight	2.65 lbs
Supply Voltage	28 vdc
Motor Current Limit	23 amps
Controller Weight (3 channel)	9.25 lbs
alternate shape (est.)	7.5 lbs

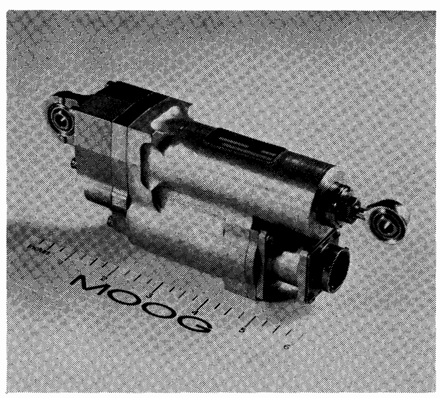


FIGURE 4.
MODEL 17E373 SERVOACTUATOR

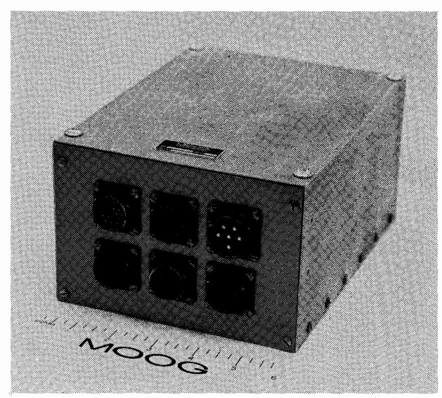


FIGURE 5.
CONTROLLER

TABLE 4

TIME DURATION FOR COIL TEMPERATURE TO REACH 300° F

Force	400 lbs	279 lbs	186 lbs	130 lbs
Time to 300° F				
100° F ambient	95 sec	600 sec	*	**
200° F ambient	40 sec	180 sec	—	*

*Continuous application of the static force results in a steady-state coil temperature of 300° F.
**Coil temperature is lower than 300° F for continuous operation.

ated flyback diodes, provide power switching of the current to the appropriate motor phases depending on rotor position. The power switches are operated by signals from the digital logic circuitry through base drive circuits. Monitor output signals are provided for actuator position and motor current.

Both brush and brushless designs were considered for this design. A brushless motor was chosen to achieve reliable commutation at a higher motor speed thereby permitting use of a smaller motor. The lower inertia of the brushless motor results in good frequency response even at relatively high motor speed.

Experimental test data obtained from the prototype system is presented in Table 3 and Figures 8 through 10. This data compares favorably with the results predicted by the computer model of Figure 3 as discussed previously.

Response characteristics were measured with an inertia plus torsional spring load. The load arrangement is described by Figure 7 where:

$J_L = 0.78$ in-lb-sec^2 load inertia

$K_{LS} =$ 100 in-lb/deg load spring (5729 in-lb/rad)

$L_a = 3.0$ in lever arm

$K_{ss} = 250{,}000$ in-lb/rad shaft spring

The spring load was replaced with a hydraulic loading motor to measure the load-velocity characteristic shown in Figure 8. Response characteristics are presented in Figures 9 and 10. Figure 9 shows the amplitude dependence of the response as discussed previously. The response was also measured with the inertia only (without the torsion spring load) to determine the affect of changes in the load spring rate. At high amplitude the inertia-only response is slightly less damped showing a 1 db peak. This variation in response is acceptably small so that adaptive control of the actuation servoloop parameters is not required.

The servocompensation used in this application includes G_1 (see Figure 3) of:

$$G_1 = \frac{.0033\,S + 1}{S}$$

This integrator network results in extremely low resolution values without limit cycle problems.

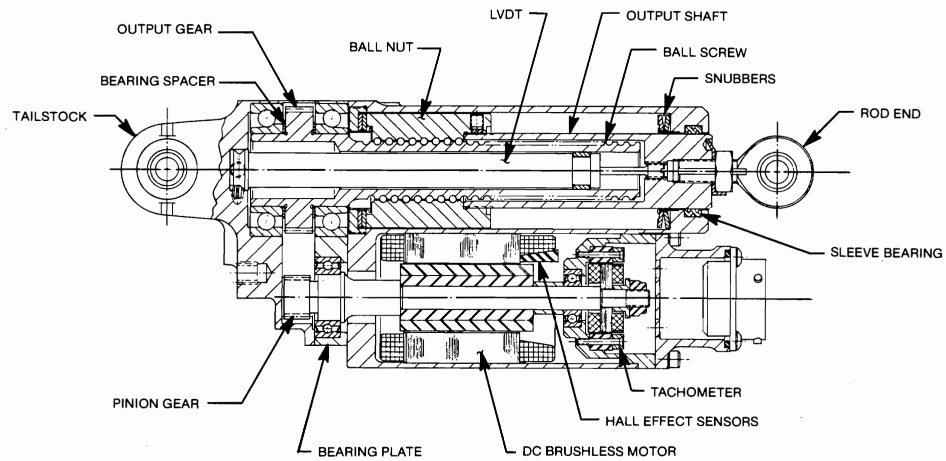


FIGURE 6. MOOG MODEL 17E373 SERVOACTUATOR

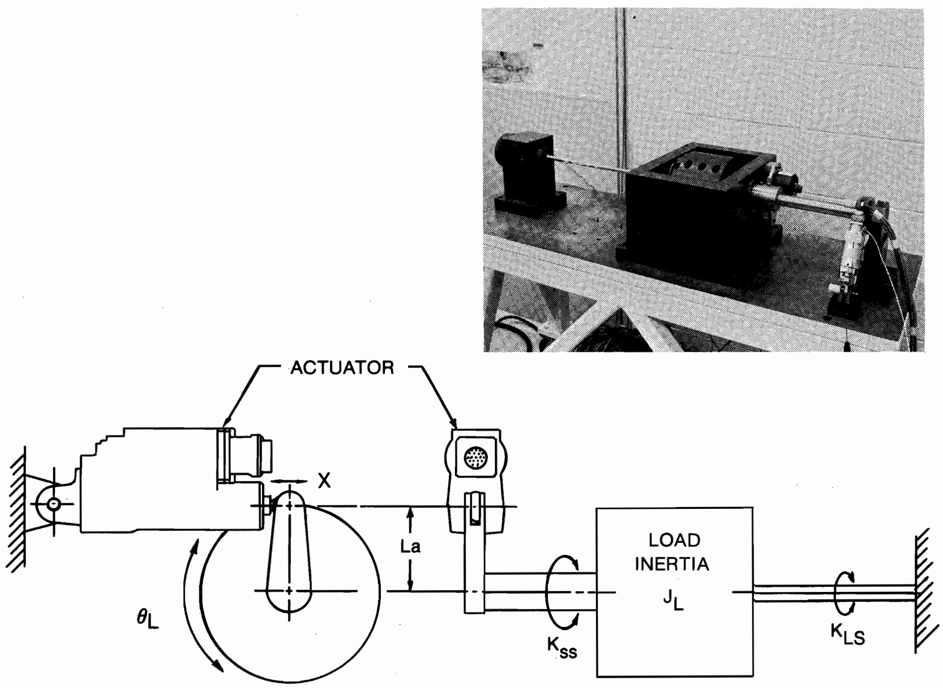


FIGURE 7. LOAD ARRANGEMENT

TABLE 5

PERFORMANCE EFFECT OF VELOCITY FEEDBACK (Fractional Horsepower Actuator)

PARAMETER	WITH TACHOMETER	WITHOUT TACHOMETER
Frequency Response (±5%)		
Phase Lag at 10 Hz	30 deg	38 deg
Frequency at 90° Phase Lag	18 Hz	18 Hz
Stiffness	104,000 lb/in	45,000 lb/in
Resolution	0.0008 in	0.002 in

Since motor resistance varies significantly with coil temperature, the resulting change in response is of some concern. For example, a temperature rise from 77° F to 300° F will cause a 50 percent increase in resistance. Therefore, frequency response was measured at different temperatures to show that the response is independent of coil temperature in the range of interest. One might expect some phase shift due to the change in the mechanical time constant which is directly proportional to resistance. The insensitivity of the response to resistance change results from the design of the velocity servoloop and PWM circuit.

The significant static performance parameters are stiffness, resolution and accuracy. Friction and magnetic cogging are contributors to resolution. The integration in G_1 reduces the resolution and increases the stiffness considerably. The absolute accuracy is dependent on the feedback transducer accuracy and the stiffness. Measured static performance characteristics are summarized in Table 3.

The actuator system was evaluated for both continuous and limited duration duty cycles. The motor operates reliably with a coil temperature to 300° F. The test data in Table 4 shows the time duration that a static force can be maintained within the 300° F coil temperature range.

Actuator system performance was evaluated with and without a tachometer for velocity feedback. A comparison of key performance parameters is presented in Table 5. The position loop gain is slightly higher with the tachometer and therefore the response is slightly better. The use of the tachometer significantly improves the stiffness and resolution.

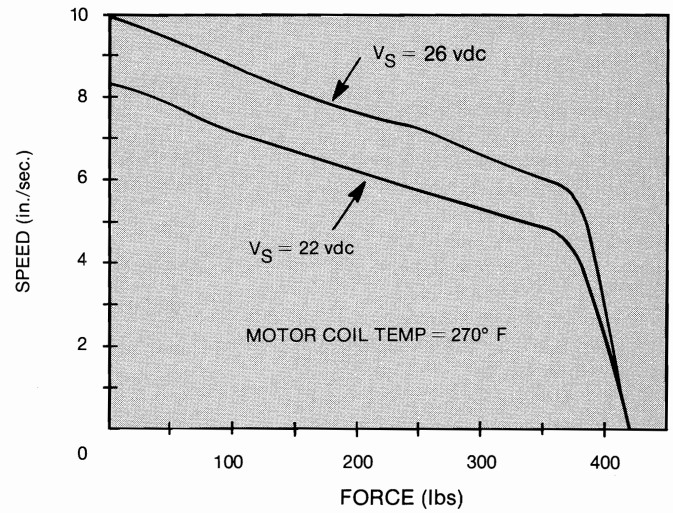


FIGURE 8. LOAD-SPEED CURVES

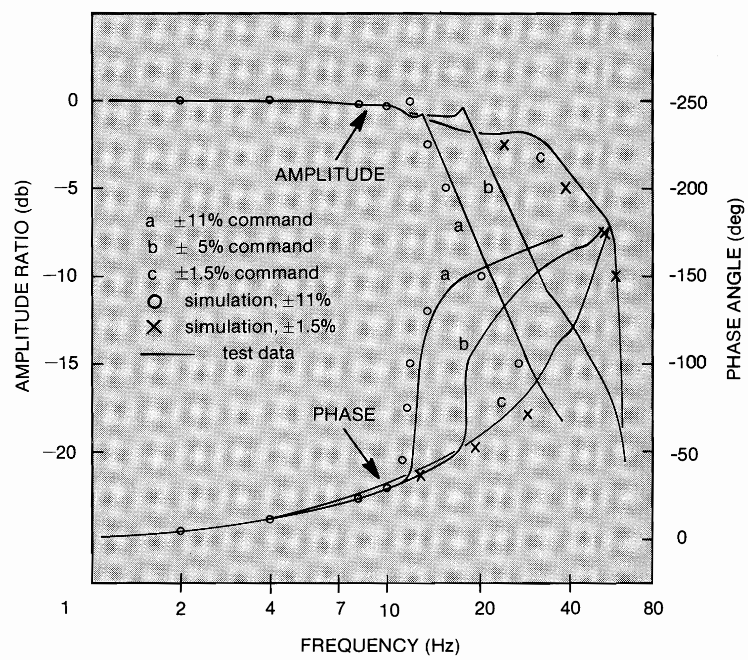
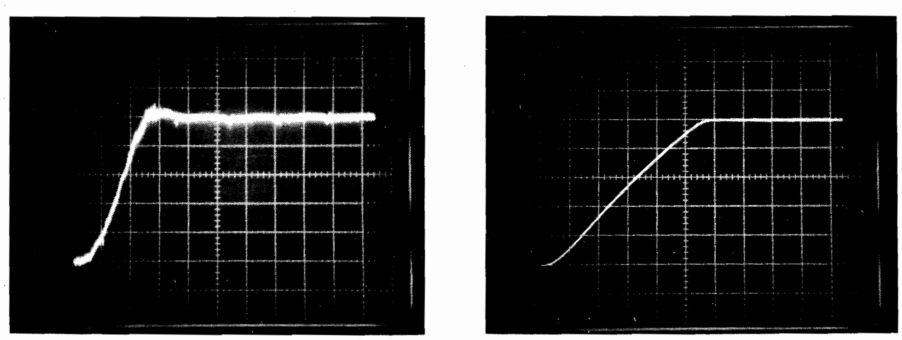


FIGURE 9. POSITION FREQUENCY RESPONSE



a) 5% step, 10 ms/div.

b) 50% step, 20 ms/div.

FIGURE 10. POSITION STEP RESPONSE

INTEGRAL HORSEPOWER ACTUATION SYSTEM

A three-horsepower actuation system is presented as a second example. This design also uses a samarium cobalt magnet, brushless DC motor, a precision ball screw and a PWM drive. Optical rotor position sensors are used for commutation. The system block diagram of Figure 1 applies to this application except that the ballscrew is direct-driven by the motor without a spur gear reduction. Also, the brushless DC motor in this example is an axial air gap design with printed circuit stator coils.

The actuator packaging arrangement is based on a "hollow center" pancake motor. This motor generates sufficient torque to allow direct coupling to the ball screw shaft without use of gear reduction. Two, angular-contact ball bearings provide combined support of the motor shaft and the ball screw reaction forces. Simple concentric splines transmit the motor torque directly to the ball screw centerline. The LVDT position feedback transducer is centrally located within the ball screw shaft.

The controller performs the same functions as in the previous example. However, to provide the higher power required in this application, a supply voltage of 270 vdc was used. The maximum motor current is 32 amps as needed to produce the required stall torque. The selection of power transistors suited for these levels of voltage and current is quite limited. Also, the size of the controller is significantly greater at this power level.

The prototype actuator and controller hardware, shown in Figures 11 and 12 was

TABLE 6

PERFORMANCE OF INTEGRAL HORSEPOWER ACTUATOR

Maximum Output Force (stall)	3000 lbs
Maximum Speed (no load)	20 in/sec
Stroke	±1.68 in
Resolution	0.0005 in
Frequency Response	
(for ±5% command)	−3db @ 10 Hz
(for ±2% command)	−3db @ 16 Hz
Supply Voltage	270 vdc
Supply Current	22 amps max
Required Duty Cycle	5 secs @ stall force
	40 secs @ 50% stall force
Continuous Duty	
output force	698 lbs
output power	1.8 Hp
Prototype Actuator Weight	18.5 lbs
Flightworthy Actuator Weight (est.)	11.9 lbs
Controller Weight (2 channel, est.)	11.0 lbs

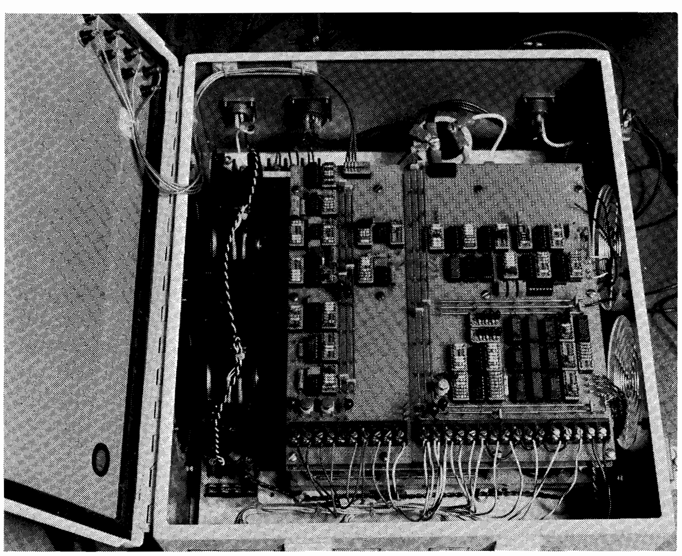


FIGURE 11. PROTOTYPE CONTROLLER

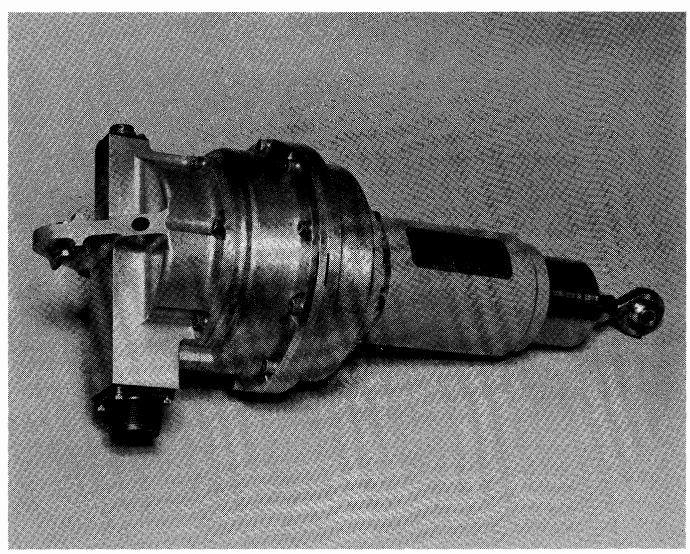


FIGURE 12. MOOG MODEL 17E356 SERVOACTUATOR

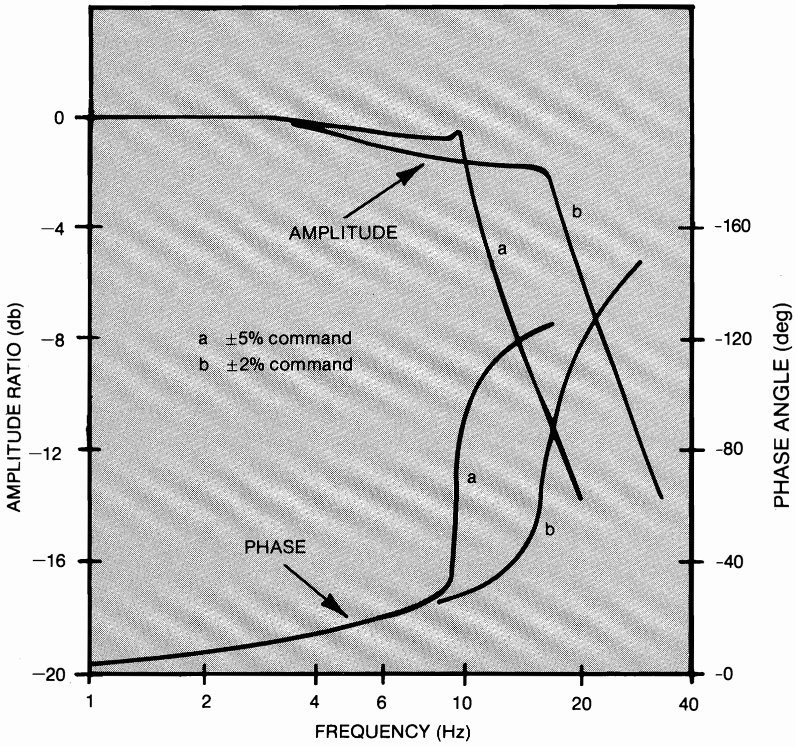


FIGURE 13. POSITION FREQUENCY RESPONSE

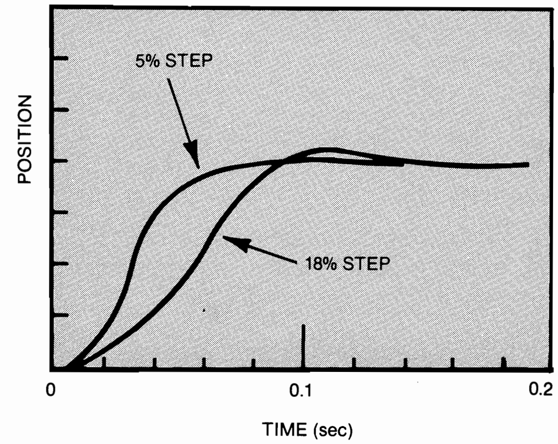


FIGURE 14. POSITION STEP RESPONSE

built and tested as a system. Experimental test data obtained from this prototype system is presented in Table 5 and Figures 13 and 14. The experimental test data compares favorably with results predicted by the computer model of Figure 3.

Feedforward compensation was employed to reduce the phase lag in the 1 Hz to 10 Hz frequency range. In this system an integrating velocity loop resulted in a tendency to limit cycle and therefore was not used. However, without the integration the resolution was very low as shown in Table 5. The difference from the previous example relates primarily to the use of a different motor (i.e., "printed circuit") with its low inductance and lack of magnetic cogging.

This actuation system was designed for a 45 second duty cycle including five seconds at stall force and 40 seconds at 1/2 stall force. Test data shows that the duty cycle requirement is met with a peak coil temperature of 260° F at the end of the duty cycle. The allowable coil temperature is above 300° F. Continuous operation force and power data is included in Table 5. The prototype actuator was driven into both stops at 50% no load speed a number of times with no adverse affect on subsequent performance.

ACTUATION TECHNOLOGY COMPARISON

Both electromechanical (EM) actuators using brushless, SmCo, DC motors and electrohydraulic (EH) actuators can often meet specific requirements for high performance servoactuation. EM actuators using brush motors do not provide as good performance but in some cases performance with a brush motor will be adequate.

EH systems provide high static accuracy when a simple proportional position control loop is used, due to their ability to hold against a stall load with essentially zero servovalve input current. For the same reason, EH systems can hold steady state loads without additional power consumption. Brushless motor EM actuators have certain characteristics, such as the torque/current gain and magnetic cogging, which would result in poorer static performance than obtained with EH actuators if a simple proportional position control loop were used. However, with an inner integrating velocity loop, brushless motor EM actuator static performance can be improved dramatically as demonstrated by the examples given in this paper.

The response of an EM actuator is usually torque limited by the motor inertia and is largely dependent on command amplitude, as shown in Figure 14. The use of samarium cobalt magnets with a high energy product makes possible brushless motor EM actuators having good response. The response of EH actuators is limited by either the servovalve or the load dynamics. In each case the response is not particularly amplitude dependent. EH actuators in the 1/4 to three horsepower range typically have a high load natural frequency and their response is limited by the servovalve dynamics. In such cases, with a command amplitude of one percent or greater, EH actuator response is generally better than a comparable EM actuator response.

When the required performance can be provided by either EM or EH actuators, other factors must be considered in making the selection. A comparison of the advantages and disadvantages of EM and EH actuators is presented in Table 7.

Size and weight comparisons of EM and EH actuation systems is difficult due to the different power source possibilities in specific applications. Generally in applications requiring fractional horsepower, EM actuation is lower weight. In the three horsepower example, EH actuation was slightly lower in weight. A one horsepower missile application with a four-second duty cycle could use an EH actuator with a "blow down" hydraulic supply to give a low weight solution. Another missile application with the same power output requirement, but with a 600 second duty cycle, would require a hydraulic pump for an EH power supply. If an electric motor powered by a thermal battery were used to drive the pump, the EM solution would be significantly lighter weight.

The electronic controller represents a significant portion of an EM actuation system weight and cost while it is a much smaller portion of an EH actuation system. Future development in power switching electronics are expected to strengthen EM actuation capabilities regarding reliability, size, weight and cost.

SUMMARY AND CONCLUSIONS

Application of brushless motor technology to high performance actuation systems was discussed. It was shown by two examples that satisfactory performance can be provided by electromechanical actuation using brushless DC motors. A mathematical model was presented demonstrating that electromechanical actuation performance can be predicted with acceptable accuracy.

- Brushless motors with high-energy-product SmCo magnets make possible lightweight electromechanical actuators having good response and high efficiency.
- Electromechanical actuation is currently an alternative to electrohydraulic actuation for applications requiring up to approximately three or four horsepower. Higher power electromechanical actuation systems are limited at the present time by the lack of reliable, compact, lightweight electronics.
- Electrohydraulic actuation has a proven track record in a variety of aerospace and industrial applications. Development effort is required to demonstrate reliable electromechanical actuation at higher power levels.
- Future improvements in electromechanical actuation could result from further advances in magnet materials, gear drives and electronic components. The latter (particularly, power switching transistors) is a promising area for future size and weight reductions.

TABLE 7

COMPARISON OF EM AND EH ACTUATION SYSTEMS

ELECTROMECHANICAL ACTUATION

Advantages
- lower cost than electrohydraulic
- momentary overdrive capability
- low quiescent power
- low system weight in low HP range
- packaging flexibility
  (conventional or pancake motors)
  (different types of gear reduction)
- easy check-out
- single responsibility for servoelectronics and actuator

Disadvantages
- more complex electronics
  (commutation logic for brushless motors)
  (high power drive with current limiting)
- motor inertia-into-stops problem
- overheating with high static loads
- requires motion reduction/conversion
- generates EMI
- more difficult nuclear hardening
- high power electromechanical actuation not yet proven

ELECTROHYDRAULIC ACTUATION

Advantages
- mature technology
- very high reliability
- highest actuation performance
- smaller and lighter weight in high HP range
- continuous power output capability
- continuous stall torque capability
- wide temperature capability
- high vibration and acceleration capability
- proven long term storability
- nuclear hardenable
- no EMI generation
- simple, low power servoelectronics

Disadvantages
- usually higher cost
- generally requires more complex Power Conversion equipment
- requires clean hydraulic fluid
- quiescent power loss

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