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ELECTRIC-STEPPING-MOTOR TESTS FOR A CONTROL-DRUM ACTUATOR OF A NUCLEAR REACTOR

by Arthur W. Kieffer

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

Experimental tests were conducted on two stepping motors for application as reactor control-drum actuators. Various control-drum loads with frictional resistances ranging from approximately zero to 40 N-m and inertias ranging from zero to 0.424 kg-m^2 were tested.

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ELECTRIC-STEPPING-MOTOR TESTS FOR A CONTROL-DRUM ACTUATOR OF A NUCLEAR REACTOR

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SUMMARY

Experimental tests were conducted to explore the use of a stepping motor for a reactor control-drum actuator. The tests were conducted with two off-the-shelf stepping motors using various control-drum loads. One of the motors tested was a variable-reluctance stepping motor. This motor operated successfully with control-drum frictional torques in the range zero to 20 newton-meters. The other motor, a permanent-magnet motor, operated satisfactorily with frictional torques from zero to above 40 newton-meters. Variation in the control-drum inertia from zero to 0.424 kilogram-square meters had no effect on the performance of the motor because a large 120:1 speed reduction was chosen for the motor transmission. Control-drum rotation in excess of 1° per second was possible for these loads. A rotation of 1° per second is expected to meet reactor control requirements.

INTRODUCTION

A nuclear-reactor heat source for generating 500 kilowatts of electric power in space is currently being investigated at the Lewis Research Center. The reactor is considered to be compatible with either a Brayton or a Rankine cycle. The reactor is of the fast-spectrum type and is designed for 50 000 hours of operation at a power level of 2.17 megawatts. The reactor core consists of cylindrical fuel pins which are cooled by liquid lithium. Six control drums are located at the periphery of the core as shown in figure 1. The drums are partially loaded with nuclear fuel and are rotated for the purpose of changing the fuel geometry (reactivity) in the core. In this manner the reactor power is regulated.

The regulating actuator for each control drum will probably be in a severe temperature and nuclear-radiation environment. If the actuator is located inside the core, it must also tolerate a lithium environment. A location outside the core can avoid this problem, but this requires a lithium seal for linking the actuator with the control drum inside the core.

In addition to meeting these requirements, the actuator must also meet reactor control requirements. This task must be performed with a control-drum load of high inertia (0.318 $kg\text{-}m^2$ equivalent to a weight of 159 kg for the reference design) and of large frictional resistance (maximum expected value is near 40 N-m). A drum positioning capability within 0.5° (1 cent of reactivity) is desired. The rotational speed should be limited to less than 8 cents per second of positive reactivity insertion (representing a drum rotation of 4°/sec).

After several actuator concepts were evaluated, these were some of the main results: The location of each actuator was chosen outside the pressure vessel; a crank and bellows was chosen for transmitting torque through the pressure vessel; a preloaded spring was selected for fast drum rotation during reactor scram; and a motor was selected to perform any necessary slow drum rotation during normal operation.

The primary candidate for the actuator motor is an electric stepping motor. The stepping motor is operated by step commands which electronically switch the stator currents and cause the motor to rotate in discrete increments. This feature is desirable for a control-drum actuator because it allows slow rotation, and the drum position can be determined from the number of step commands. The inherent reliability of the stepping motor is perhaps its principal advantage. The motor requires less insulation and has fewer moving parts than other electric motors. Tests performed for the SNAP program (ref. 1) demonstrated a stepping-motor actuator which operated continuously for 10 000 hours in a high-temperature nuclear-radiation environment. The reactors in SNAP, Phoebus (ref. 2), and NERVA (ref. 3) also use a stepping motor as part of their reactor control actuator. However, these and other stepping-motor applications have previously been limited to small loads.

An analysis performed on the analog computer showed that a stepping motor could be used for rotating the large control drum of this reactor (ref. 4). However, the study found some potential problem areas for this application. The study found that the motor may fail by losing synchronism during stepping. This may happen either because the rotating load lags the stepping rate or because the load is underdamped and its response oscillates. A step command during this oscillation may catch the rotor out of position so that it receives less than the necessary torque to complete the next step. Transmission backlash or excessive motor torque can cause the rotor response to be underdamped.

Friction from the load helps to dampen the response. An ample amount of friction exists in the control drum of this reactor to give a damped response in a 1-g gravitational environment. However, most of this friction is expected to disappear in a zero-gravity environment. To ensure that the response is damped under all conditions, mechanical damping and one of several electronic damping methods given in references 5 and 6 were initially considered.

In order to find a satisfactory damping method and to confirm the analytic predictions, experimental tests were performed on a variable-reluctance stepping motor and a permanent-magnet stepping motor. A hardware simulated control drum represented the motor load. A transmission coupled the motor to the control drum with 120:1 speed reduction. This speed reduction was used to increase the motor torque and to give the desired resolution in drum positioning. The tests were conducted for several friction and inertia loads to encompass a variety of drum designs and gravitational conditions.

For this initial investigation off-the-shelf stepping motors were used.

DESCRIPTION OF ACTUATOR SYSTEM

A block diagram of the test components and instrumentation is shown in figure 2. The actuator system was mounted in a vertical position compatible with the eventual reactor mounting. Figure 3 shows a photograph of the stepping motor (variable-reluctance type), the transmission, and the simulated control drum. A portable analog computer was available for programming the motor step commands and for signal conditioning. The variable-reluctance motor was air cooled to prevent overheating. To reduce electric switching transients, external resistances were added to the phases of both motors. The voltage drop across each external resistor was recorded for an indication of the current through each phase. A description of the major test components follows.

Stepping Motor

The electric stepping motor rotates in discrete increments called steps. But it can be made to rotate continuously by increasing the stepping rate. Stepping is performed by changing the stator polarities. This forces the rotor to change position. When classified according to rotor type, a stepping motor may be a variable-reluctance (VR) or a a permanent-magnet (PM) motor. Both operate according to similar principles. The rotor of the VR motor tends to rotate toward a position of least reluctance, whereas in the PM motor the rotor magnet tends to aline with the stator poles. Both types of motors were tested. They both rotate in 15° increments. The VR stepping motor (made by Bulova Watch Company, model VR 2490-15) had a holding torque (static stall torque) of 0.685 newton-meter (97 oz-in.) at 8 amperes of motor current. The PM motor (made by Sigma Instruments, Inc., model 19-3441) had a holding torque of 2.37 newton-meters at 4 amperes.

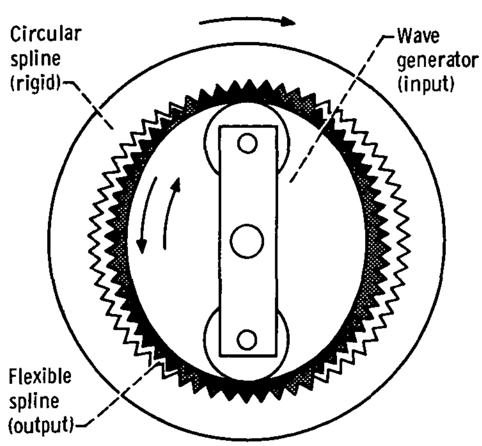
Logic Driver and Step Command Generator

An electronic circuit called a logic driver is used to automatically change the stator polarities of the motor in the proper sequence for stepping. Basically this device consists of power transistors which switch the stator currents and logic circuitry which fires the transistors in the proper sequence.

Square-wave voltages were used to activate the logic driver. One cycle represented one step command. The square waves were produced on the analog computer by a relay switch. A sinusoidal signal from the analog computer fired the relay. A reset-set flip-flop was used to eliminate relay noise.

Transmission

A harmonic drive transmission was used to couple the stepping motor to the drum load. A 120:1 speed reduction was chosen to give a mechanical advantage to the motor and to match the motor step size and stepping rate with the control-drum requirements. This particular type of transmission was selected because it provides a high gear reduction with a small amount of backlash. The harmonic drive transmission consists of an input element, called the wave generator, an output element, which is a flexible spline, and a stationary element, the circular spline, as shown in sketch (a). The wave



(a)

generator deflects the flexible spline into an elliptic shape which causes the teeth of the flexible spline and the circular spline to mesh at the eccentricities of the ellipse. The circular spline has more teeth than the flexible spline. This difference causes the flexible spline to rotate N_c-N_f tooth increments for each wave generator revolution, where N_c and N_f represent the number of teeth on the circular spline and the flexible spline, respectively, The speed reduction, therefore, is $N_f/(N_f-N_c)$.

Load Simulation

Five disks 23 centimeters in diameter and varying in length from 2.5 to 15.2 centimeters were available individually or stacked to simulate the inertia load of the control drum. The various disk combinations allowed changes of inertia in increments of 0.106 kilogram - square meter. A magnetic particle brake was used to simulate the coulomb friction of the control drum. A variation in coulomb friction from approximately zero to 54.3 newton-meters was possible. Some static type friction was unintentionally included with the coulomb friction. Torsional deflection in the magnetic brake shaft also added a springlike effect to the load.

Instrumentation

Instrumentation was used for measuring and recording the pertinent variables. The variables recorded with time were the magnetic brake current, the step commands, the rotor position, the load position, and the motor coil currents. The position measurements of the rotor and the load were made with potentiometers. To avoid loading effects from the recorder, each potentiometer output was first passed through an operational amplifier with 100 K input resistance. The motor coil currents and the magnetic brake current were measured by placing external resistances in series with each coil and recording the voltage across each resistance.

RESULTS AND DISCUSSION

A variable-reluctance stepping motor and a permanent-magnet stepping motor were tested with a load representative of the control drum. A friction load near zero is expected for zero-gravity operation. For 1-g operation the frictional load is expected to be approximately 27.1 newton-meters (20 lb-ft) but may be as high as 40.7 newton-meters (30 lb-ft). Tests were therefore conducted for frictional drum loads ranging from near zero to 40.7 newton-meters. The inertia load was also varied during the tests in order to accommodate future changes in drum design. The tests covered an inertia range of 0.106 to 0.424 kilogram - square meter and included the most recent control-drum design value of 0.318 kilogram - square meter. Various motor currents and stepping rates were used during the tests. The approximate design value for the motor current and the expected value of inertia and friction at 1-g operation will henceforth be designated as the reference value of these parameters. These reference values are shown in table I.

The damping methods originally planned for these tests were not needed because the transmission added some unexpected high friction to the actuator. This friction is independent of gravitation and is expected to give the necessary damping under zero-gravity conditions, where the control-drum friction becomes very small.

Test results are presented for the VR stepping motor. They include results which show the motor driving the transmission only. These results are followed by results for the PM stepping motor. Unless stated otherwise, both motors were operated at the reference current. The maximum stepping rates of each motor pertain to continuous as well as start and stop operation. Stepping rates are given in terms of control-drum rotation, which is 1/120 that of the motor.

Variable-Reluctance-Stepping-Motor Response

Operation without control-drum load. - For the first test case, the motor was operated while driving the transmission only. The motor response for four step commands is shown in figure 4, which is a plot of rotor position against time. The time of each step command is indicated by a triangle. The motor response shows some overshoot but no oscillations. Without damping from the transmission, oscillations would be present which could cause stepping failures. However, the response in figure 4 does not present a problem to the motor. This type of response is even less of a problem to the reactor because the overshoot represents an insignificant amount of reactivity. (According to the latest drum design a step increment represents less than 0.3 cent of reactivity.)

Effect of friction. - Tests were made to determine the motor performance at various control-drum frictions for the reference inertia given in table I. The response for a control drum with near zero friction is shown in figure 5. Figure 5(a) represents the rotor response. This response is quite similar to the no-load case shown in figure 4. The corresponding control-drum response is shown in figure 5(b). A stiff coupling between the motor and control drum would make the response of figures 5(a) and (b) qualitatively identical. However, flexing in the magnetic brake shaft is largely responsible for the difference. The combination of a nonrigid coupling and static friction is responsible for the hesitation (jerkiness) in the drum response near the end of each step in figure 5(b). A maximum control-drum stepping rate of approximately 6° per second was possible for this case.

The motor and drum response with the control-drum friction at 50 percent of reference is shown in figure 6. The response is not significantly different from the previous case of near zero friction. A maximum stepping rate of 1.7° per second was possible for the 50-percent case.

The response for a control drum with the reference friction is shown in figure 7. The rotor response in figure 7(a) shows that the increase in friction to 100 percent eliminates the overshoot of the previous two cases with less friction. The drum response in figure 7(b) shows considerable variation in the size of its steps. This variation is characteristic of a large frictional load because the range of possible rest positions increases with friction. For this reference friction case the motor would stall occasionally.

An analog computer model was made of the actuator tests. The results from the computer model are shown in figure 8 for the reference friction case. These results show a hesitation similar to the corresponding experimental results of figure 7. The analog computer model confirmed that this hesitation was due to a load with a flexible coupling and static friction, because the hesitation disappeared when this type of loading was removed.

Effect of motor current. - A more damped response was obtained as the motor current was reduced. This is evident in the response of figures 9 and 10, which are for respective motor currents of 100 and 50 percent of reference.

Effect of inertia. - The effect of a control-drum inertia change was anticipated to be small because of the 120:1 transmission ratio. Test results shown in figure 11 confirmed this expectation. These results are for a 33 percent of reference control-drum inertia; the friction was at 25 percent of reference. The results are identical to the case for 100 percent inertia shown in figure 9.

Permanent-Magnet-Stepping-Motor Response

A large change in the control-drum inertia showed no effect on the operation of the VR motor. This can also be assumed for the PM motor. Consequently, tests for this motor were conducted with the control-drum inertia at reference only. For these tests the frictional load was varied over a range from near zero to 150 percent of reference. The test results differed in two respects from comparable tests of the VR motor. Essentially no overshoot occurred for any of these tests, and because the PM motor was more powerful, it could operate with higher frictional loads. Figures 12 to 15 show the rotor and the drum response for friction ranging from near zero to 150 percent of reference for the reference motor current. The motor performed satisfactorily at stepping rates up to 1.5° per second.

A slower response was evident when the motor current was reduced. Figure 16 shows results for the motor current at 50 percent of reference with the frictional load near zero. A maximum stepping rate of 0.6° per second was possible for this case.

Stepping-Motor Operation

The previous results showed the effect of friction, inertia, and motor current on the actuator response for a few specific operating conditions. This discussion will enlarge on these results and attempt to define an entire region where the motor can operate satisfactorily. The variable which define this operating region are the stepping rate, the motor current, and the load friction. The VR motor will be discussed first.

Variable-reluctance stepping motor. - Figure 17 shows the motor operating region with the motor current and friction as variables. The upper limit in this region is set by the reference (design) current. The lower boundary is motor stall. The maximum stepping rate for operating the motor in this region depends on the motor current and friction. The maximum stepping rates at various points of the operating region are shown in figure 17.

The stepping rate of the VR motor was limited either because the response was underdamped or because the load could not rotate at the desired rate. Single-step operation where the actuator is allowed to come to rest before the next step command avoids this limit. The maximum stepping rate possible for this type of operation is shown in figure 18. Although this plot was obtained with the motor operating at the reference current, similar stepping rates are possible at less than the reference current, provided the motor does not stall. A previous study (ref. 7) showed that relatively slow stepping rates are adequate for reactor control. Calculations based on the results of the study show that rotating all six reactor control drums at a rate of 1° per second will change the reactor power from 50 to 100 percent of design in less than 7 seconds.

Permanent-magnet motor. - The operating region for the PM motor is shown in figure 19. The maximum stepping rates at specific points of the operating region are as shown. At the reference current the stepping rate ranges from 1.5° to 2.0° per second. Unlike the stepping-rate limit for the VR motor, the stepping rate limit for the PM motor was not governed by the load response. But instead, the limit for the PM motor was caused by the transients of the motor current. These transients were caused by switching the current during stepping; they were larger than those of the variable-reluctance motor and influenced the motor efficiency. To reduce these transients, more external resistance should be added in series with the motor coils (0.6 ohm was used in this test).

CONCLUDING REMARKS

Both a variable-reluctance stepping motor and a permanent-magnet stepping motor were tested for use as a control-drum drive of a nuclear reactor. A hardware simulation of the control drum was used as the motor load. The tests were conducted with several control-drum inertias and various frictional loads to make them applicable to a variety of control-drum designs and different gravity environments. For zero-gravity conditions the friction in the control drum is expected to be relatively small, while under 1-g conditions a large friction is expected. To operate with the large friction a powerful stepping motor is needed. However, for zero-gravity conditions a powerful stepping motor causes the response to be underdamped. The underdamped response can cause unsatisfactory motor operation. Consequently, some damping is desired for zero-gravity operation.

Finding the proper damping was a smaller problem than expected because a transmission was used which had a sufficient amount of friction to dampen the actuator response. This friction is expected to be independent of gravity.

The unexpectedly large amount of friction from the transmission made the VR stepping motor somewhat undersized for the higher range of control-drum friction. However, the motor operated satisfactorily for control-drum friction between zero and approximately 20 newton-meters (15 lb-ft). The motor could be adapted to operate with higher frictional loads by increasing the present 120:1 transmission ratio, but at the expense of a slight decrease in its stepping-rate capability.

The PM motor operated successfully for control-drum friction ranging from zero to above 40 newton-meters (30 lb-ft). A stepping rate of 1° per second appears to be sufficiently fast to meet reactor control requirements. At the reference current, both motors operated satisfactorily at this stepping rate. Consequently, an operating rate of 1° per second seems a good choice for both motors when operating at the reference current.

The control-drum inertia had little effect on the stepping-motor operation because of the large transmission ratio.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 26, 1972,
112-27.

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TABLE I. - REFERENCE VALUES

Control-drum friction, N-m	27.1
Control-drum inertia, $kg\text{-}m^2$	0.318
VR stepping-motor current, A	8.0
PM stepping-motor current, A	4.0

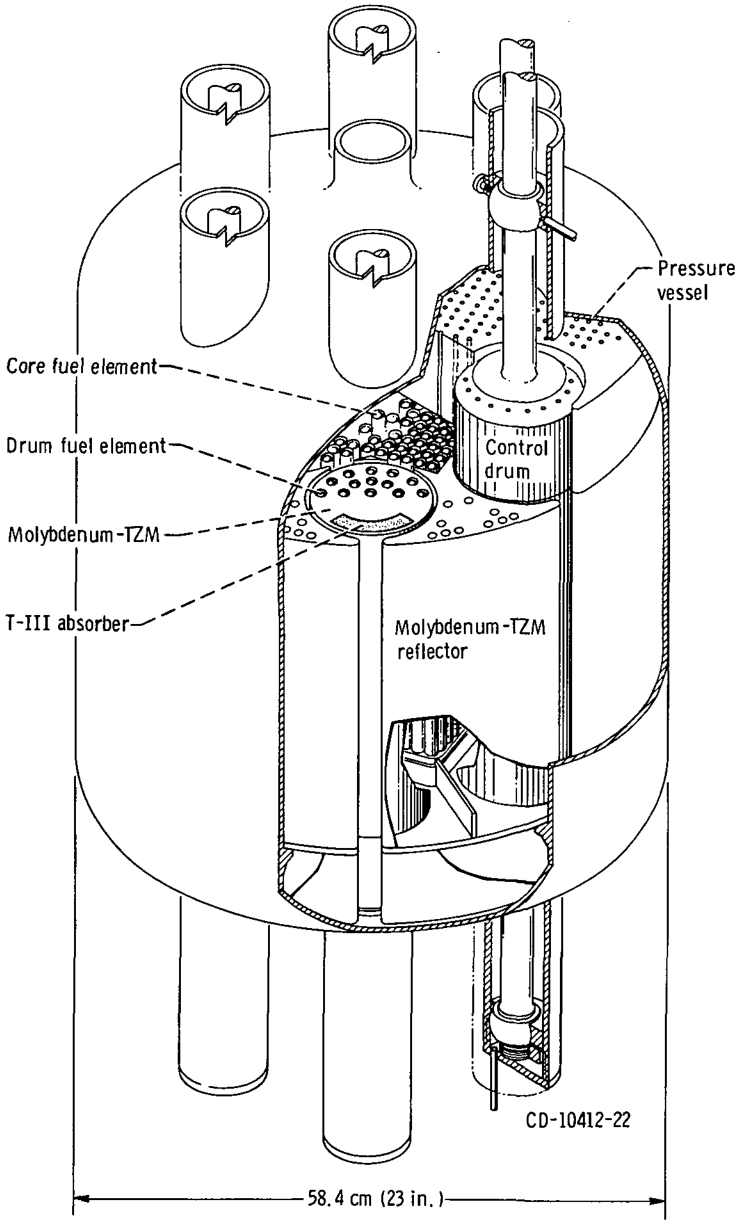
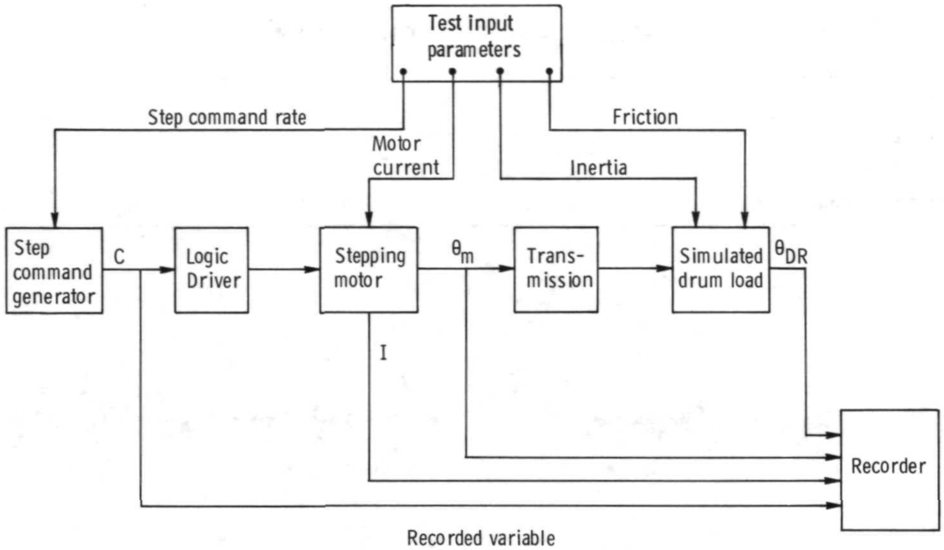


Figure 1. - Nuclear powerplant reactor.



Recorded variable

C	Step command
θ_m	Motor position
θ_{DR}	Drum position
I	Motor phase current

Figure 2. - Block diagram showing major components of stepping-motor test setup.

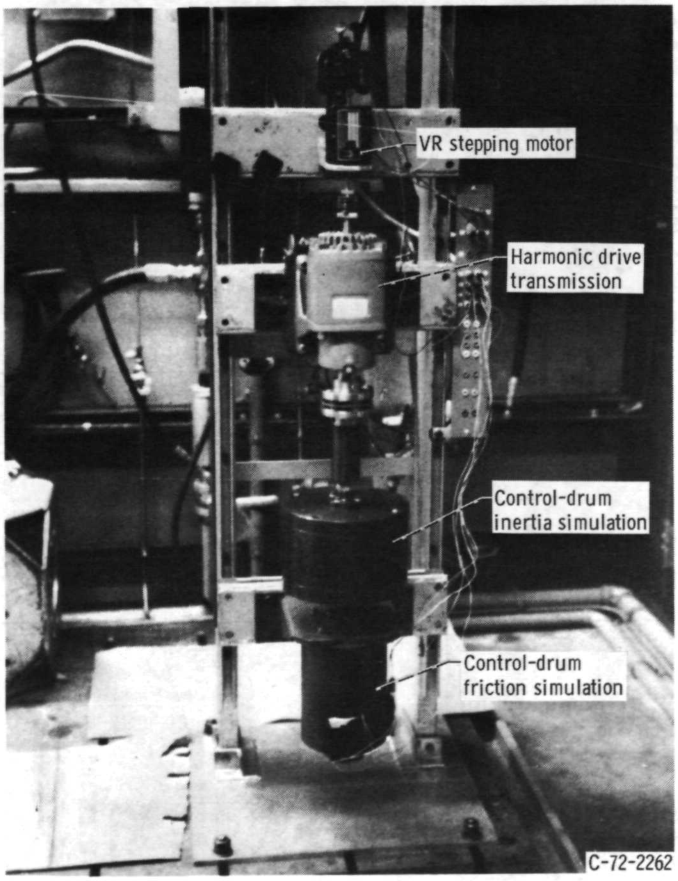


Figure 3. - Partial view of stepping-motor test setup.

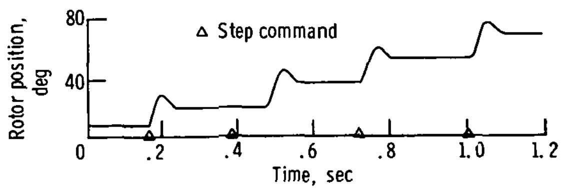
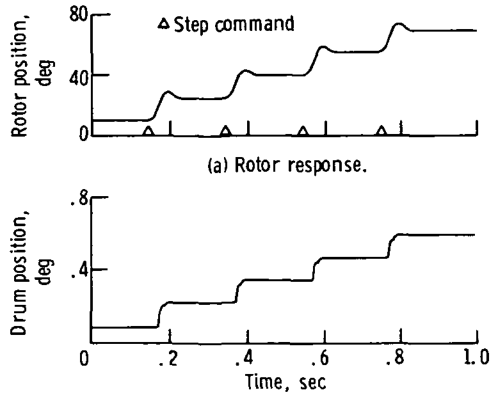
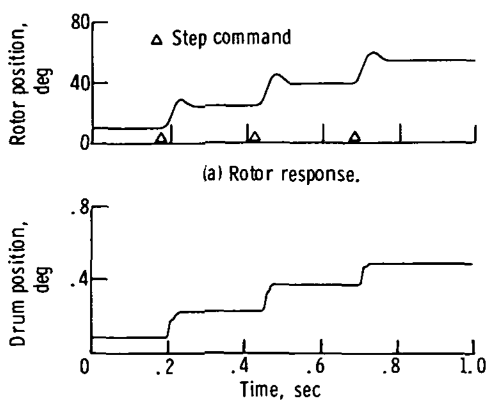


Figure 4. - Rotor time response with VR stepping motor operating at reference current and driving transmission only.



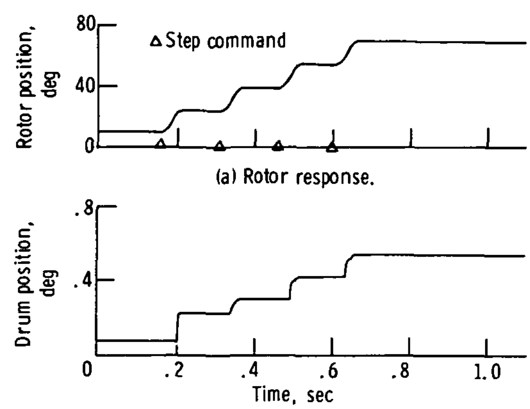
(b) Control-drum response.

Figure 5. - Time response with VR stepping motor operating at reference current and inertia and with control-drum friction near zero.



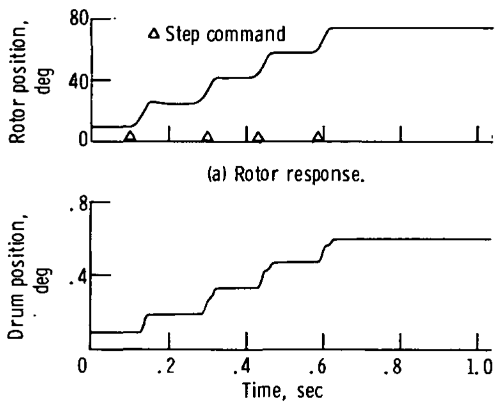
(b) Control-drum response.

Figure 6. - Time response with VR stepping motor operating at reference current and inertia and with control-drum friction at 50 percent of reference.



(b) Control-drum response.

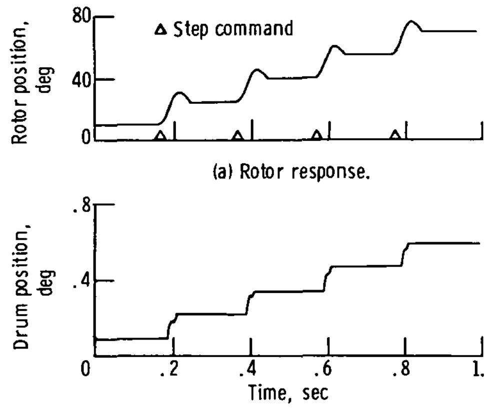
Figure 7. - Time response with VR stepping motor operating at reference motor current and reference load.



(a) Rotor response.

(b) Control-drum response.

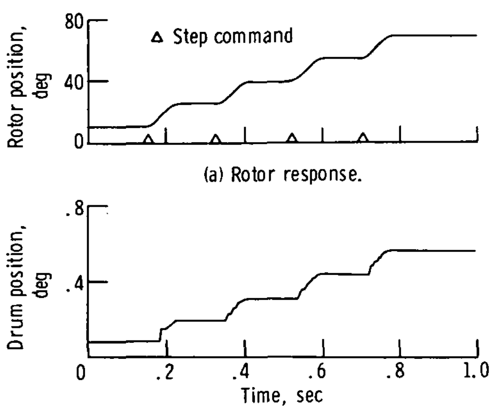
Figure 8. - Time response of analog model showing VR stepping motor operating at reference current and reference load.



(a) Rotor response.

(b) Drum response.

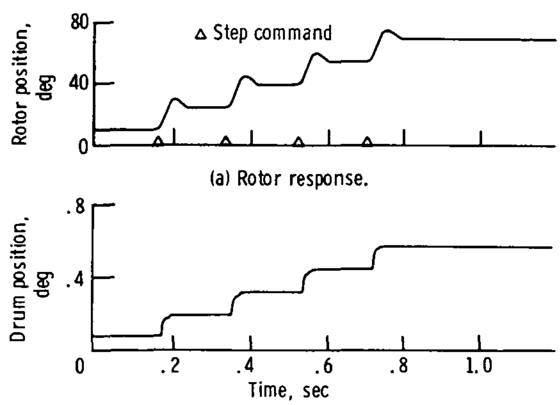
Figure 9. - Time response with VR stepping motor operating at reference current and inertia and with control-drum friction at 25 percent of reference.



(a) Rotor response.

(b) Drum response.

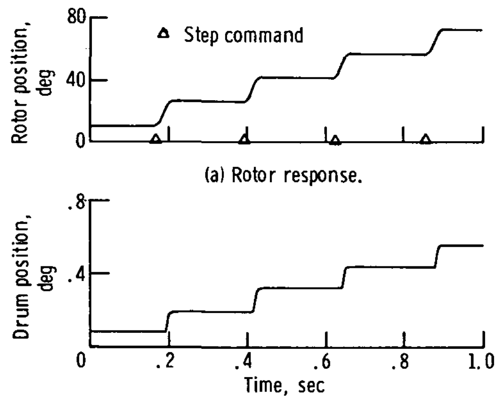
Figure 10. - Time response with VR stepping motor operating at reference inertia and 25 percent of reference friction and with motor current at 50 percent of reference.



(a) Rotor response.

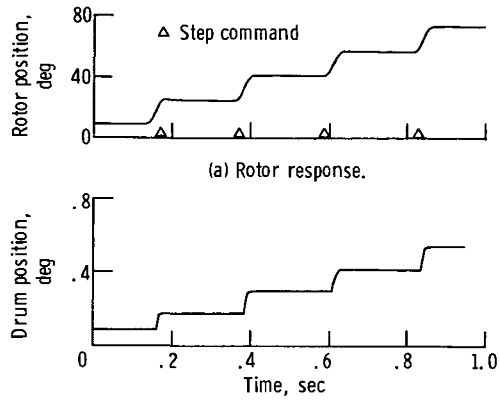
(b) Drum response.

Figure 11. - Time response with VR stepping motor operating at reference current and 25 percent of reference friction and with control-drum inertia at 33 percent of reference.



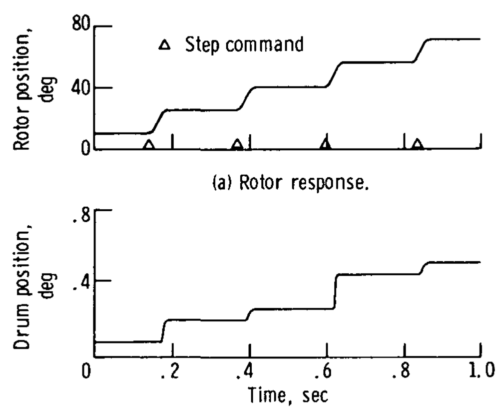
(b) Control-drum response.

Figure 12. - Time response with PM stepping motor operating at reference current and inertia and with control-drum friction near zero.



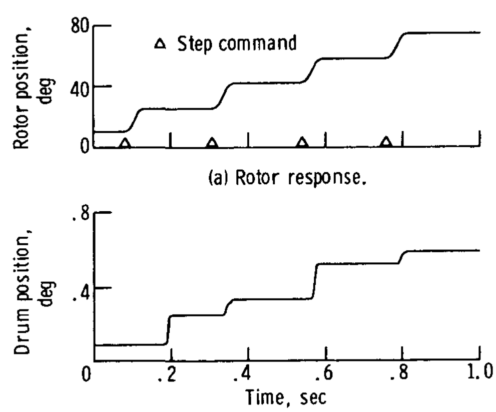
(b) Control-drum response.

Figure 13. - Time response with PM stepping motor operating at reference current and reference inertia and with control-drum friction at 50 percent of reference.



(b) Control-drum response.

Figure 14. - Time response with PM stepping motor operating at reference current and inertia and with control-drum friction at reference.



(b) Control-drum response.

Figure 15. - Time response with PM stepping motor operating at reference current and reference inertia and with control-drum friction at 150 percent of reference.

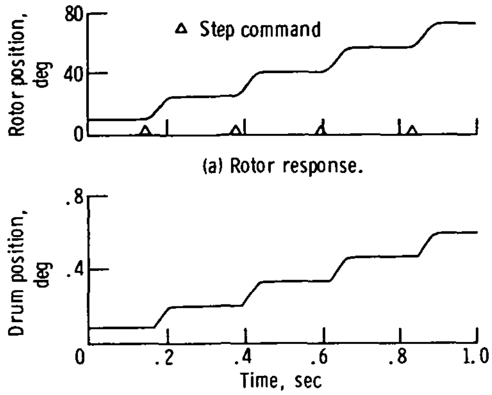


Figure 16. - Time response with PM stepping motor operating at reference inertia and near zero friction and with motor current at 50 percent of reference.

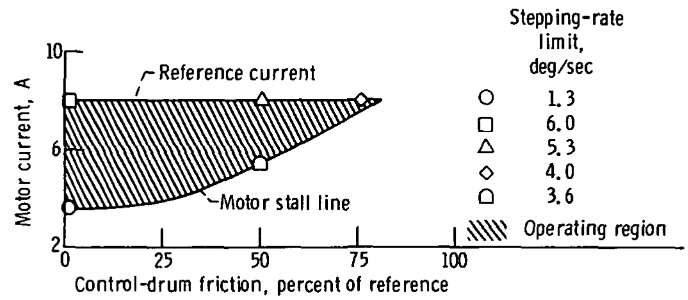


Figure 17. - Operating region for VR stepping motor.

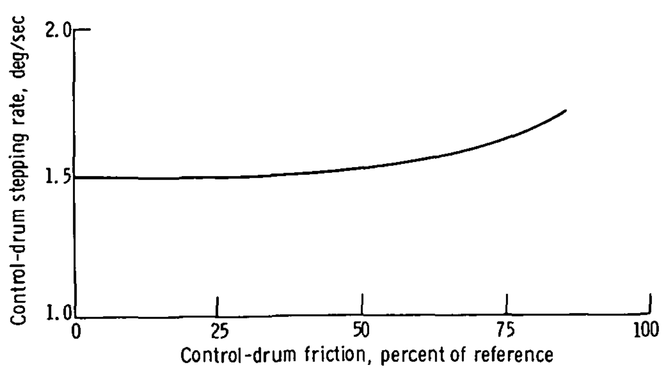


Figure 18. - Maximum stepping rate of VR stepping motor for single-step operation at reference current.

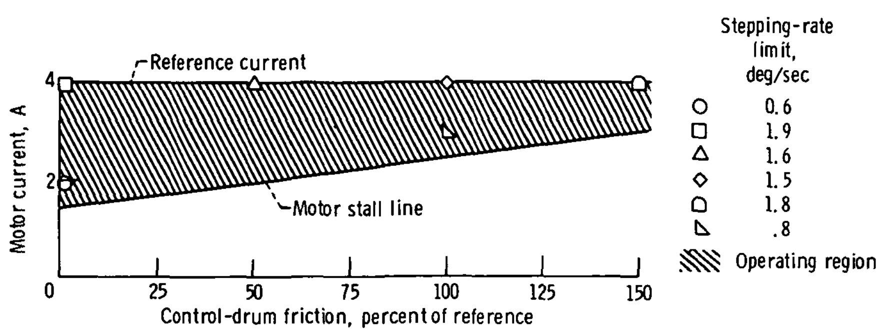


Figure 19. - Operating region for PM stepping motor.

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