December 5, 1963

SUBMITTED BY
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Pittsburgh 36, Pa.

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INFORMATION CATEGORY

UNCLASSIFIED

12/17/63
Authorized Classifier Date

TORQUEMOTOR CHARACTERISTICS

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ABSTRACT

The initial investigation into the properties of the torquemotor-servo valve combination (typical of the types proposed for the 1st Generation Actuator) disclosed some unexpected characteristics. The problem centered in the torquemotor where the relationship of driving voltage to the current flow resulted in excessive lag. The ability to make a given torquemotor respond, therefore, depends on the driving means as well as the parameters of the torquemotor. The driving means used in the 1st Generation Amplifier is discussed and found lacking. A transfer function typical of the torquemotor input conditions is described, and any voltage drive must account for this transfer block as part of the overall transfer function of the torquemotor. The proposal is made that considering all known factors a high impedance current source be used with the loop (through the torquemotor coils) closed on current. If the circuit can be made stable, this method should permit a significant increase over the previous level of performance.

Scope: The servovalve used in the 1st Generation Control Drum Actuator consists of a torque-motor made by Servotronics, Incorporated and a two stage valve designed by General Electric Company. Its purpose is to convert an electrical signal supplied to the actuator into a proportional pressure output to the piston which drives the control drums. Because of its importance in the control loop, it is necessary to describe the transfer function for this device under various operating and loading conditions. This report will describe briefly the torque-motor characteristics which formed a part of the initial investigations into the servovalve properties.

Objective: To describe the characteristics of the torque-motor and its relation to the driving source. The results of the tests performed on the entire servovalve will be covered in a later report.

Background: As a means of evaluating the entire servovalve, a test fixture was constructed as shown in Figures 1 through 3 to provide both the environment and the loading conditions expected during actuator operation. The driving source (input to the torque-motor) duplicates the output stage of the 1st Generation Lab Amplifier and is preceded by an operational amplifier which mixes a bias and a sine function signal. Thus the torque-motor can be set at some operating point and then oscillated with varying amplitudes and frequencies. The circuit is shown in Figure 4 with typical values for the various elements.

The particular servovalve used in this report was the single-stage single-sided (SSSS) valve. Checks were also made on the single-stage single-sided with dynamic pressure feedback valve (SSDPF) to verify results, but the data is not included. The following list shows representative values for the SSSS valve torque-motor:

Rated Current	± 40 ma
Resistance at 75°F	1440 ohm
Static Gain	.077 lb/ma at Nozzle Centerline
Net Gradient, No External Springs	+74 lb/in. at Nozzle Centerline
Nozzle Centerline to Armature Center	0.9 in.

FIGURE 1

Test Assembly, Control Equipment, and Recorders Prepared for Room Temperature Run

FIGURE 2

Test Assembly Showing Dewars in Position Prior to a Low Temperature Run

FIGURE 3

Test Fixture with Cover Removed Showing Valve and Torquemotor

Test Results: The inductance was measured with the coils connected in series aiding (as it is used in actual operation) and a value of 6.02 henry at 20 volts and 6.10 henry at 40 volts was obtained. The net capacitive effect was only .001 μ fd at 1 KC. Since the coil is installed in a circuit with a total of 2000 Ω (a desirable load line for a 6L6 cathode-follower, the time constant, current to voltage, was expected to be in the order of:

$$\tau = \frac{6.02}{2000} = .003 \text{ sec.}$$

In a simple first order system this would be a break frequency of about 50 to 60 cycles/sec. And if a torquemotor was a series RL combination (with the inductance acting as a static inductance) this would represent the point at which the current would start attenuating (relative to the driving voltage) with approximately a 45° phase lag, i.e. one might describe the torquemotor as:

$$KG(S) = \frac{K}{\tau S + 1} \text{ where } \tau = \frac{L}{R} \cong .003 \text{ sec.}$$

Reference to Figure 5A shows the results obtained with the armature blocked, thus permitting no movement. The current break is approximately as expected from the simple time constant measurement.

The very first test which permitted the armature to move showed that the torquemotor is far from a simple first order lag, and further that the static inductance is no indication of the dynamic value. Reference to Figure 5B through 5D show the type of results obtained by frequency response plots.

<u>Figure</u>	<u>Flow Medium</u>	<u>Current Level</u>	<u>Sine Wave P-P</u>	<u>Break Frequency I/V</u>
5B	Helium	7.5 ma	4.86 ma	7.0 cps
5C	Helium	7.36 ma	2.70 ma	$\cong$ 7.0 cps
5D	Nitrogen	10.8 ma	5.75 ma	7.8 cps

As a means of checking the above results the SSDPF valve torquemotor was tested by step response. The reason was two fold, one, this torquemotor could be observed for movement while being tested, and two, if it displayed the same properties it would tend to generalize the results already obtained. At this point the SSSS valve torquemotor results could be considered unique and not generally characteristic of our

FIGURE 5D

FIGURE 5C

FIGURE 5B

FIGURE 5A

FIGURE 5

class of torque motors. A typical step response trace is shown in Figure 6. The results shown in Figure 7, while not rigorous, do indicate the type of effects observed. It should be noted that this particular torque motor has somewhat different characteristics than the SSDPF torque motor, however, the tests are consistent with the results already described.

Using Figure 5B as typical of the SSSS valve torque motor at 530°R under normal gas loading pressures, the following transfer function can be written,

$$KG(s) = \frac{K (.00536s + 1)}{(.0339s + 1) (.00426s + 1)} \text{ for } \frac{\text{Current}}{\text{Voltage}}$$

which is accurate to within 1 db of the plotted curves for Figures 5B, 5C, and 5D. While this seems to hold for peak-to-peak sizes of 2.5 to 5 ma, it should be further explored above and below these values. The operating point (10 volt bias contrasted with 30 volt bias) is influential in two ways. First the dynamic value of the inductance is a function of both current and position in the gap. Second, the velocity of the armature (therefore the counter-EMF) will decrease as the armature load is increased. This latter effect can occur when the valve (the torque motor load) is required to go to full pressure, i.e., close the nozzle.

An aid to thinking about the effects of the various electrical and mechanical parameters is shown in the equivalent circuit of Figure 8. This circuit is described by Frazier and Atchley in their reports on the DACL torque motor work at MIT.

This is an all electric equivalent circuit which includes the effect of the mechanical loading on the circuit. Since a torque motor is an electro-magnetic device with moving iron the analogy of force to current must be used and the circuit shows that force (current) is absorbed by the torque motor inertia, viscous resistance, and mechanical spring. By the same analogy the velocity of the armature in the air gap will produce a counter EMF, and tend to oppose the buildup of current in L_{eq} which is a measure of deflection of the armature. Whether this is an exact analogy depends upon the ability of the coupling constants to show the effects seen mechanically, and the amount of mechanical non-linearity present.

Since the mechanical loading of the torque motor is reasonably well known, it becomes easier to evaluate the dynamic performance by frequency response methods and convert the plotted results to transfer functions.

Typical Step Response

FIGURE 6

TORQUEMOTOR TESTS

TIME CONSTANT MEASURED
FROM STEP RESPONSE USED
TO INDICATE BREAK FREQUENCY

1. PURE RESISTANCE LOAD IN
CIRCUIT. CURRENT RISE LIMITED
ONLY BY APPLIED VOLTAGE RISE.
2. TIME CONSTANT BASED ON
L/R MEASUREMENTS. R
VALUE IS APPROXIMATE.
3. TORQUEMOTOR IN CIRCUIT,
ARMATURE IS FIXED, AND
APPLIED VOLTAGE IS IMMEDIATE
4. WITH ARMATURE FREE, AND
VOLTAGE APPLIED THE CURRENT
INITIALLY WOULD YIELD
5. BUT AS SOON AS MOVEMENT
OCCURS THE EFFECTIVE RISE
TIME WOULD YIELD ONLY

FIGURE 7

Comparison of Speed of Response

FIGURE 7

DEFINITIONS

r_p = Tube Dynamic Plate Resistance

μe_i = Source EMF

e_t = Applied Torquemotor Voltage

e_m = Counter-EMF

R = Coil Resistance

L = Operating Point Dynamic Inductance

C_{eq} = Capacitance Equivalent of Motor and Load Inertia

G_{eq} = Conductance Equivalent of Motor and Load Viscous Damping

$\frac{1}{L_{eq}}$ = Inductance Equivalent of Motor and Load Elastance

Equivalent Circuit for Dynamic Operation

Figure 8

Summary: The foregoing results show roughly a 10:1 ratio between the expected value and the measured value of the speed of response. Most of this difference can be reduced only by changing the design parameters of the torquemotor. However, some percentage can be realized by changing the driving means from a voltage source (used in the 1st Generation Lab Amplifier) to a current source. In the same manner, closing the loop on current would tend to force current through the torquemotor coil and thus reduce the counter-EMF effect. While this in fact amounts to a voltage overdrive (up to the maximum capability of the power supply) it will tend to hold the voltage at maximum until the reference current value is reached. Lead networks might be proposed to compensate for the phase lag, however, this is only effective for continuous inputs. Little benefit can be realized for step changes, and therefore, the constant current source with the loop closed on current would seem to be the best approach. A further disadvantage of the voltage source is that the load (torquemotor coil) resistance goes through approximately an 8:1 change over the temperature range from 530°R to 140°R. Changes of this magnitude in a low impedance circuit will affect the stability margin and are, therefore, undesirable. With the high impedance of a constant current source the effect of the load resistance change will be much smaller.

The information described in this report was conveyed to the General Electric design group early in July. Their previous thinking had included a solution of this type, but it was not believed necessary based on their information. In the light of the data now available some modifications to the 2nd Generation circuit design are being made.