DESIGN AND ANALYSIS OF A MODULAR SERVOAMPLIFIER FOR FAST-RESPONSE ELECTROHYDRAULIC CONTROL SYSTEMS

by John R. Zeller

Lewis Research Center
Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

A low-cost three-stage servoamplifier has been developed for use in fast-response research servosystems. This device has the capability of improving the low-frequency dynamics of the inductive coils of torque motor devices in electrohydraulic servovalves. In addition, this amplifier provides other servosystem functions such as summing, gain (adjustable), and compensation. A dynamic model of the amplifer-coil combination has been included to assist in analytical evaluation. The flexibility of the modular configuration has been demonstrated in several operational research installations.

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SUMMARY

Fast-response (150 to 200 Hz) electrohydraulic servosystems are used as research tools in experimental dynamics and controls studies. These systems normally include a fast-response electrohydraulic servovalve device that has an electromagnetic torque motor as the initial stage. This input device consists of two mutually coupled coils driven by the output of an electronic servoamplifier device. The response of the torque motor coils, when driven by zero source impedance, is, however, quite low (40 to 50 Hz); consideration must therefore be given to ensuring that the driving amplifier output appears as a very high impedance to substantually improve the dynamics of the torque motor device.

A modular low-cost servoamplifier has been developed to accomplish this improvement in response. The design and analysis of its circuitry is discussed within this report. The three-stage configuration, which has been developed, provides in addition to a high-output impedance, the other servoloop functions of summing, adjustable gain, and compensation.

To aid in analytical studies, a simplified dynamic model of the amplifier-torque motor coil combination has been included.

The modular plug-in packaging arrangement of the amplifier adapts itself easily to various control-room installations. This has been verified in the several single-channel and one six-channel configurations in which this servoamplifier has been employed in the past year.

INTRODUCTION

Research activities in the areas of advanced propulsion systems have dictated a significant need for high-performance fast-response servosystems. This need is

twofold: (1) as disturbance devices for studying the high-frequency dynamics of propulsion systems and their components and (2) as a component of a control loop for these complex systems.

The type of equipment normally selected to provide this fast response (150 to 200 Hz) control capability is the electrohydraulic servovalve and piston-in-cylinder actuator arrangement. Its basic closed-loop configuration is shown in figure 1.
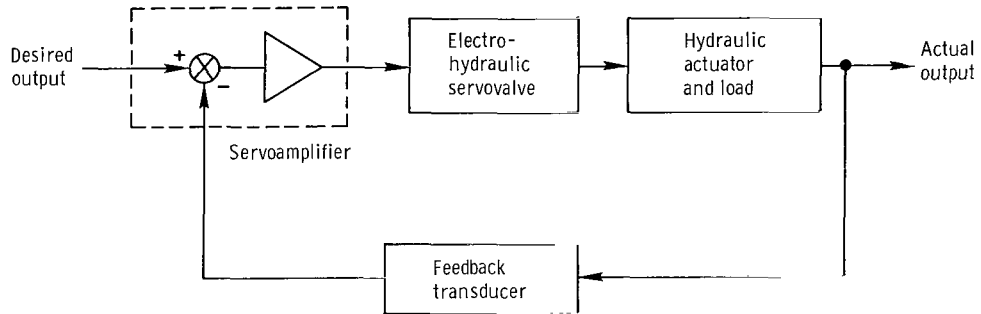

Figure 1. - Block diagram of electrohydraulic servo system.

Most of the parameters to be manipulated at high rates of response involve relatively small dynamic loads. Thus, by hydraulically close-coupling the servovalve and piston actuator, unfavorable resonances due to the hydraulic line and load dynamics are eliminated. Such a system configuration leaves the electrohydraulic servovalve as the predominant element in determining the bandwidth or response capabilities of the closed-loop control system.

These servovalve devices employ some type of electromagnetic torque motor as the low-power control device for a higher power one- or two-stage hydraulic control-valve mechanism. These valves are so designed that the output flow dynamics in response to torque motor output have a bandwidth in the range of 150 to 200 hertz. The electromagnetic torque motor has a torque output that is proportional (dynamically) to the equivalent magneto-motive force of the current in its two mutually coupled inductive coils. These coils can be driven by a voltage source (low output impedance) servoamplifier. They then possess a current-to-voltage response of only 40 to 60 hertz. This limitation in the current or torque response is due to the equivalent inductance-resistance ratio L/R of the coils. Failure to improve the dynamic performance of this torque motor severely limits the ultimate frequency-response capabilities of these electrohydraulic servosystems.

Circuit design techniques by which these current dynamics can be improved to a satisfactory level do exist. A product review of standard servoamplifier devices capa-

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ble of performing this task has, however, revealed serious deficiencies. Much of the equipment available does not provide sufficient flexibility for the diversity of tasks required of research servo hardware. Desirable features are (1) improvement of torque-motor small-signal bandwidth to 750 hertz, (2) provision for multiple feedback loops, (3) provision for active servo compensation techniques, (4) inclusion of an integral adjustable dither oscillator, and (5) packaging flexibility compatible with control-room installation requirements. These features are available in only a limited number of units.

This report discusses the equipment that has evolved in response to research requirements. This program has resulted in a servoamplifier consisting of two basic modules: a summing preamplifier and a power-output stage that will drive the inductive coils at rates of response in excess of 200 hertz. The output module employs a push-pull transistor arrangement with a somewhat unconventional configuration of circuit elements connected in parallel with the inductive collector loads. The preamplifier utilizes state-of-the-art type of components in a more conventional scheme. Thus, the major emphasis in this report will be concerned with a description of operation and performance of the power output module.

POWER OUTPUT MODULE

Description of Operation

The fast-response coil drive circuitry that has been developed is shown schematically in figure 2. This configuration employs a low-power operational amplifier that drives two complementary (NPN-PNP) silicon transistors in a push-pull mode. This particular push-pull stage of amplification separates the two coils from the conventional parallel or series connections normally used with most single-ended servoamplifier schemes. This separation provides the capability for eliminating the mutual inductance factor between the two coupled coils. The equation for the inductance of two identical coupled coils when connected in series is (ref. 1)

$$L_{eq} = L_c + L_c \pm 2M \tag{1a}$$

(All symbols are defined in the appendix.)

The positive sign is required for normal torque motor operation. In addition, the mutual inductance M for most torque motor configurations is about $0.5 L_c$. Thus, the total equivalent inductance of two coils in series is

$$L_{eq} = 2L_c + 2 (0.5)L_c = 3L_c \tag{1b}$$

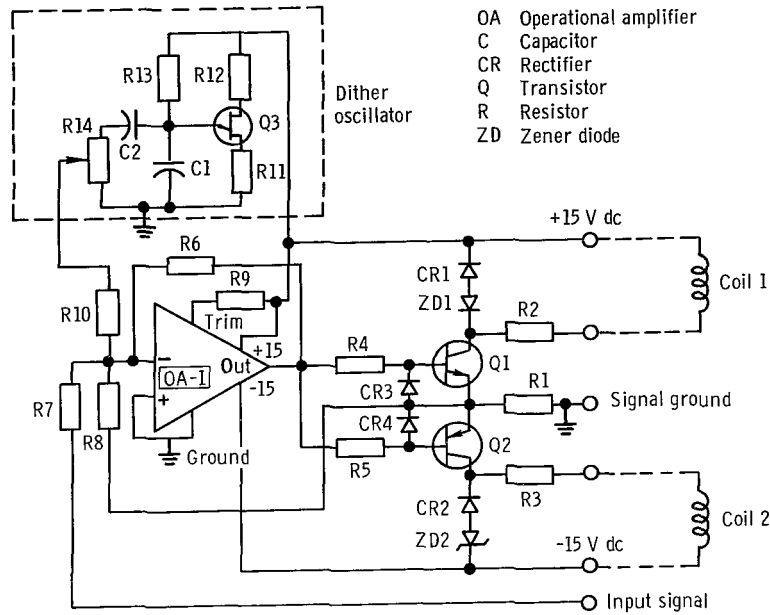| OA | Operational amplifier |
C	Capacitor
CR	Rectifier
Q	Transistor
R	Resistor
ZD	Zener diode

Figure 2. - Power output circuit.

If mutual inductance effects are eliminated, the equivalent L/R time constant can be reduced by a factor of 33.3 percent. This is equivalent to an improvement in response (bandwidth) of 50 percent.

$$\frac{L}{R}_{\text{(conventional)}} = \frac{3L_c}{2R_{\text{coil}}} \tag{2}$$

$$\frac{L}{R}_{\text{(push-pull)}} = \frac{L_c}{R_{\text{coil}}} \tag{3}$$

$$\frac{L}{R}_{\text{(push-pull)}} = 0.667 \frac{L}{R}_{\text{(conventional)}} \tag{4}$$

The mutual inductance is eliminated by preventing any induced current from flowing in the nonexcited coil during rates of change of current in the operating coil. This is accomplished by the circuit techniques described below.

Normally, for inductive transistor collector loads, a free-wheeling diode is placed around the coil (fig. 3(a)). This protects the solid-state device (transistor) from the effects of the stored energy of the coil. A changing current in the excited coil mutually
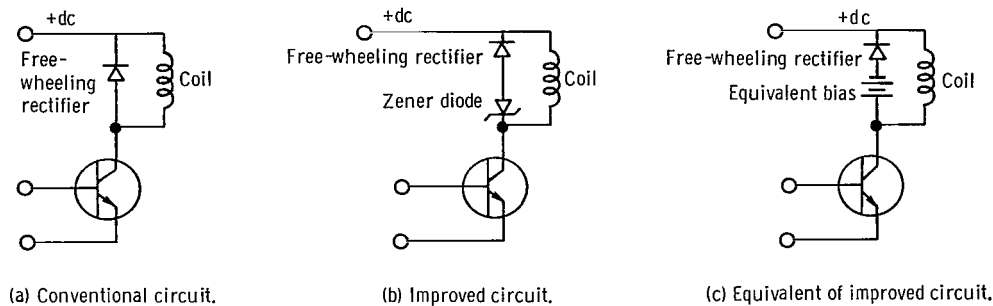
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Figure 3. – Transistor with inductive collector load.

induces a voltage in the nonexcited coil. Currents due to this mutually induced voltage flow easily around the path provided by the protective free-wheeling diode. This mutually induced current will decrease the rate of change of current in the excited coil. A Zener diode in series with the free-wheeling diode (fig. 3(b)) provides a unidirectional bias voltage in this free-wheeling path (fig. 3(c)). The function of this bias voltage is to prohibit any current from flowing in the nonexcited coil until the induced voltage has exceeded the bias level (Zener breakdown voltage). This breakdown voltage is determined by the maximum di/dt (rate of change of current) capabilities desired for the excited coil and the resulting torque motor output. In this way, this power-stage circuit eliminates mutual inductance effects from the coil current dynamics over the desired response range.

The circuit of figure 2 makes use of two additional methods of improving coil current response. First, the common emitter output transistors (Q1 and Q2) are driven by high-valued base resistors (R_4 and R_5) which make this final stage of amplification function as a current source to the individual coils. This effect, although beneficial, only functions over a limited range of the output current because of the saturation effects in the transistor.

A feature that provides response improvement over a much wider range of coil current is the use of negative current feed-back. The coil current signal is provided by a small value of resistance (R1 in fig. 2) inserted between the transistor emitters and signal return. It should be pointed out that this resistance does not provide a pure coil current signal because transistor base current also contributes to the voltage drop appearing across resistor R1. With high-gain output transistors, however, this inaccuracy has negligible effect on current feedback performance.

In addition to improving current response, use of current feedback and a high forward path gain accomplishes other beneficial results. (1) It eliminates the dead-zone nonlinearity caused by the output transistor base-to-emitter junction voltage drop. (2) It com-

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pensates for differences in the push-pull transistor (Q1 and Q2) current gains and stabilizes the overall gain of the output stage over a wide range of input voltages and environmental conditions.

Resistors R_2 and R_3, in series with the transistor collectors and the load coils, have been selected to make the maximum coil current compatible with the voltage power-supply available. Failure to ensure this could result in an unreliable over-current condition in the coils. The addition of this resistance to the coil winding resistance reduces the basic L/R of each individual coil. These resistances are of such a value that winding-resistance changes resulting from temperature variations have a negligible effect on circuit performance.

It should be noted that the power stage module (fig. 2) includes a dither oscillator section. The dither circuit provides an amplitude adjustable high-frequency (300 to 400 Hz) signal to the power stage through summing resistor R10. This signal is then amplified and impressed on the torque motor coils independent of the average output level of the power stage. This type of perturbation signal significantly aids in eliminating the stiction of various moving elements in precision hydraulic control systems.

Dynamic and Steady-State Performance

The circuit shown in figure 2 has been used to drive a standard servovalve torque motor to determine the dynamic and steady-state performance capabilities of such a combination. The valve selected has a resistance per coil of 200 ohms and a rated coil current of 25 milliamperes. Dynamic performance is documented in the curves of figure 4. *Frequency response of coil current amplitude is plotted for various magnitudes*
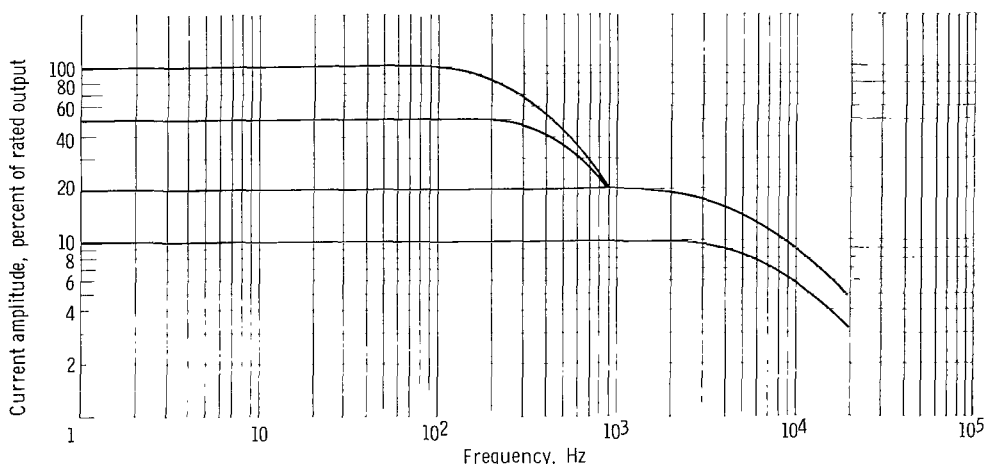

Figure 4. - Experimental frequency response of coil current to input voltage.

of input voltage. The electromagnetic torque motor coils, which have only a 40-hertz bandwidth when driven by a conventional low-output impedance amplifier, exhibit flat response to 5000 hertz for 20 percent rated currents and to 270 hertz for full rated current.

The steady-state capabilities of this circuit are summarized as follows:

Voltage-to-current gain	5 mA/V
Input voltage offset	<10 mV
Minimum coil resistance	200 ohms
Maximum current output	28 mA
Input impedance	10 000 ohms

It is recommended that the circuit be used with a 200-ohm coil requiring 25 milliamperes of rated current. It has, however, been used successfully in a servosystem with a 1000-ohm, 10-milliampere coil torque motor, but with some slight degradation in coil current response.

Component Selection and Packaging Design

In selecting the various components for this power-output circuit, efforts have been made to employ as many standard, state-of-the-art devices as possible. As a result, the operational amplifier used is a miniature plastic encapsulated transistor device. For the accuracy desired in the research hardware, this type of electronic building block was found to be more than adequate from the standpoints of performance, cost, and ease of packaging. The remaining components were selected to achieve the final highly reliable, low-cost configuration. Table I gives a parts list for the schematic diagram of figure 2.

The circuit has been packaged on a standard plug-in circuit board assembly. This permits its use in control room installations. A photo of the final assembled module is shown in figure 5.

TABLE I. - POWER OUTPUT CIRCUIT PARTS LIST

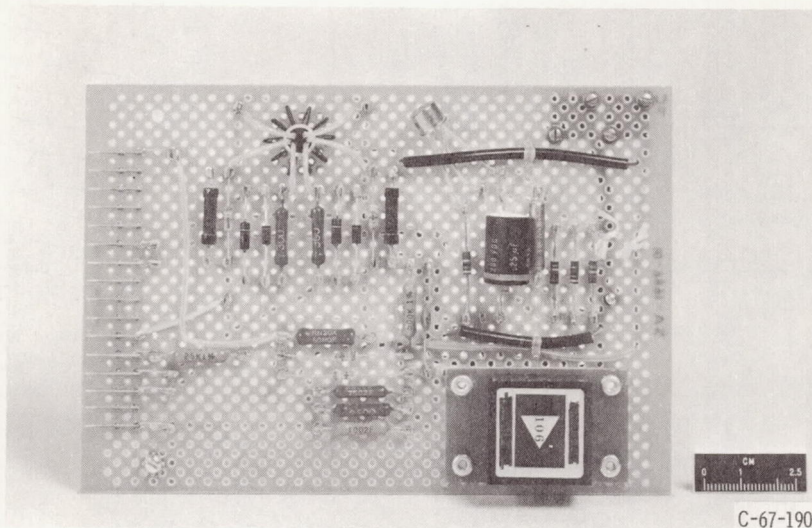| Component designation	Description	Characteristics
OA-1	Operational amplifier	
	Open-loop gain, rated load, min	150 000
	Rated output, minimum	±10 V at 5 ma
	Frequency response, rated load, min	20 kHz
	Overload recovery	1 msec
	Power supply requirements	
	Voltage	±(15 to 16) V, dc
	Current (quiescent)	8 mA
Q1, Q2	Dual NPN-PNP transistor, MD985	---------------
Q3	Unijunction transistor, 2N1671B	---------------
ZD1, 2	Zener diode, IN4744A	---------------
CR1 to 4	Rectifier, silicon, IN645	---------------
C1	Capacitor	0.25 μF
C2	Capacitor	0.01 μF
R1	Resistor, fixed	50 Ω, 1/2 W
R2, R3		300 Ω, 1/2 W
R4, R5		10 kΩ, 1/2 W
R6		500 kΩ, 1/2 W
R7		10 kΩ, 1/2 W
R8		12 kΩ, 1/2 W
R9		27 kΩ, 1/4 W
R10		75 kΩ, 1/2 W
R11		47 Ω, 1/4 W
R12		470 Ω, 1/4 W
R13		10 kΩ, 1/4 W
R14	Resistor, variable	50 kΩ

Figure 5. – Power output module.

# DYNAMIC PERFORMANCE ANALYSIS OF COIL AND DRIVE CIRCUITRY

Detailed Analysis of Circuitry

The experimental frequency response curves of figure 4 show that the dynamic performance of the power output module and servovalve torque motor coil combination is dependent on the desired level of current amplitude. In general, this type of response is the result of a nonlinearity occurring within a feedback loop. The following detailed analysis presents, first, the linear equations and, then, the equivalent block diagram representation of both the linear and nonlinear elements that result in this type of performance.

For analysis purposes, the actual coil drive elements of the complete power-output module of figure 2 are shown schematically in figure 6(a). It is assumed that the combined outputs of the push-pull transistors (Q1 and Q2) have the idealized characteristics shown in figure 6(b). These curves, which are based on the fact that only one transistor is on at a time, assume the following: (1) constant current gain h_{fe} over the complete operating range, (2) negligible collector saturation resistance R_{cs}, and (3) a finite collector resistance R_d in the nonsaturated condition. Using the notation of figures 6(a) and (b), the following equations can be written:

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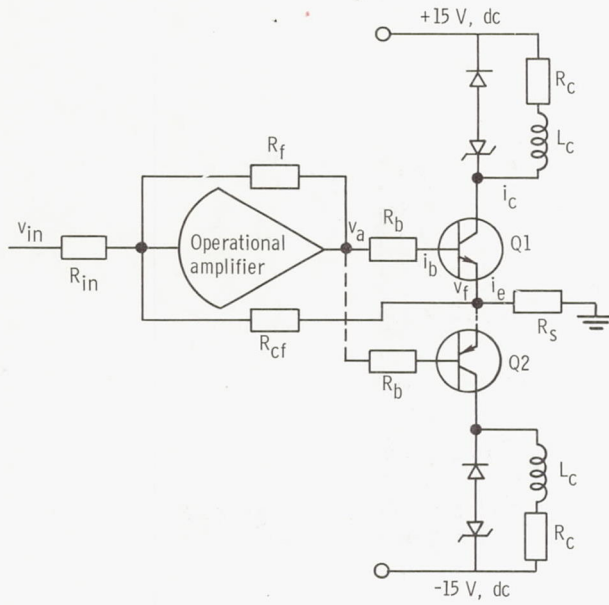
(a) Simplified schematic.
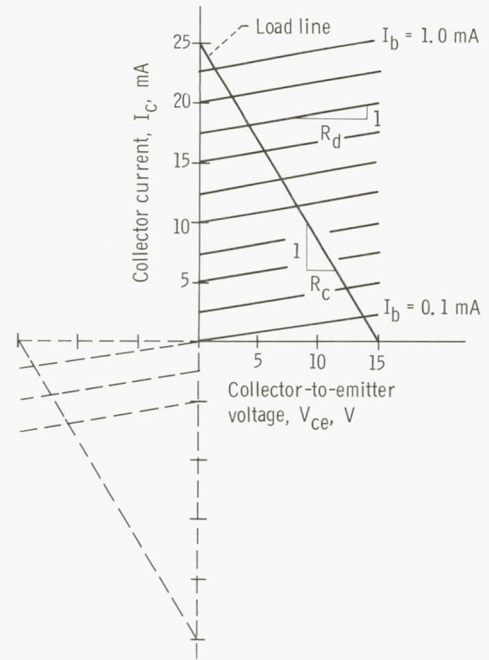
(b) Transistor characteristics.

Figure 6. – Power output circuit and characteristics. Input resistance, R_{in}, 10 kilohms; feedback resistance, R_f, 500 kilohms; current feedback resistance, R_{cf}, 2660 ohms; base resistance, R_b, 10 kilohms; sensing resistance, R_s, 50 ohms; coil resistance, R_c, 600 ohms; coil self-inductance, L_c, 0.57 henry.

$$v_a = -v_{in}\left(\frac{R_f}{R_{in}}\right) - v_f\left(\frac{R_f}{R_{cf}}\right) \tag{5}$$

$$v_f = +R_s\,(i_e) \cong +R_s\,(i_c) \tag{6}$$

$$v_f \quad -v_{in}\left(\frac{R_f}{R_{in}}\right) - \left(\frac{R_f}{R_{cf}}\right)R_s\,(i_c) = v_a \tag{7}$$

$$v_a\left(\frac{1}{R_b}\right) = i_b \tag{8}$$

The preceding equation states that the operational amplifier output voltage v_a results in a proportional transistor base current i_b. In the common emitter configuration of figure 6(a), the output transistors (Q1 and Q2) function as current amplifiers with a small signal-current gain defined as:
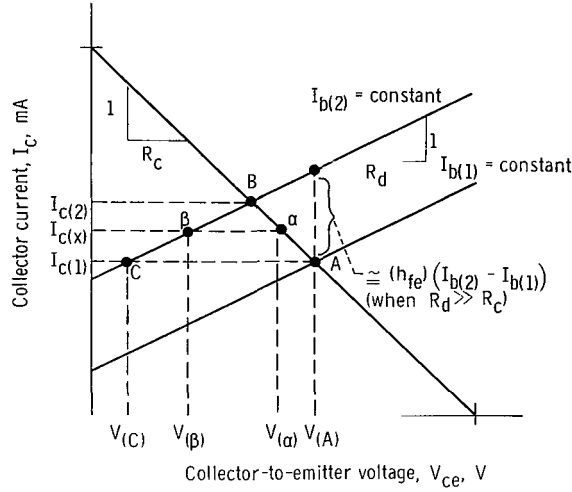
Figure 7. - Output transistor. Graphical representation of dynamic performance.

$$h_{fe} = \frac{i_c}{i_b} \tag{9}$$

When the collector load is purely resistive, a step change in base current i_b results in a step change in collector current i_c. With an inductance in the collector circuit, however, the response of collector current to a step change in base current is not a step. The following discussion and the diagram of figure 7 are presented to describe the response of collector current in the presence of this inductive load. For purposes of clarity, the graphical explanation of the output current i_c transient operation will be limited to a small base-current step change. The size of this change will be such as not to cause saturation of any of the circuit elements.

In figure 7, consider the step change in input base current from $I_{b(1)}$ to $I_{b(2)}$. The intersections of the steady-state load line with the constant base current $I_{b(1)}$ and $I_{b(2)}$ lines define, respectively, the initial and final (steady state) values of collector or coil current $I_{c(1)}$ and $I_{c(2)}$. These intersections are defined as points A and B on figure 7.

Because the current i_c flowing in the inductive load cannot change instantaneously, the small step change in base current will result in an initial (t = 0) excursion (fig. 7) along a constant $I_{c(1)}$ line from point A to point C. This means that the inductive coil will generate an initial induced voltage V(O) equal to $V_{(A)} - V_{(C)}$. This is the coil driving voltage at t = 0. Given a transistor collector resistance, R_d, the initial induced voltage is

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$$V(O) = V_{(A)} - V_{(C)} \cong (h_{fe})\,(R_d)\,(I_{b(2)} - I_{b(1)}) \tag{10}$$

when it is assumed that

$$R_d \gg R_c$$

As time increases, the operating point will remain on the curve $(I_{b(2)} = \text{constant})$ and move from point C toward point B. As this occurs, the coil driving voltage will be reduced by the increase in collector current i_c due to the movements (1) on the steady-state load line ($R_c = \text{constant}$), and (2) on the constant $I_{b(2)}$ characteristic.

The equations for some intermediate transient operating point $(0 < t < \infty)$ between points C and B (fig. 7) are

$$V_{(A)} - V_{(\alpha)} = R_c\,(I_{c(x)} - I_{c(1)}) = R_c\,(i_c - i_c(0)) \tag{11}$$

$$V_{(\beta)} - V_{(C)} = R_d\,(I_{c(x)} - I_{c(1)}) = R_d\,(i_c - i_c(0)) \tag{12}$$

$$V_{(\alpha)} - V_{(\beta)} = (L_c)\,\frac{d}{dt}\,(i_c) \tag{13}$$

Adding equations (11) and (12) yields

$$V_{(A)} - V_{(C)} - (V_{(\alpha)} - V_{(\beta)}) = R_c\,(i_c - i_c(0)) + R_d\,(i_c - i_c(0)) \tag{14}$$

Substituting equations (10) (using conventional step function notation) and (13) into (14) yields

$$(I_{b(2)} - I_{b(1)})\,u(t)\,(h_{fe})\,(R_d) - (L_c)\,\frac{d}{dt}\,(i_c) = R_c\,(i_c - i_c(0)) + R_d\,(i_c - i_c(0)) \tag{15}$$

By rearranging terms

$$(I_{b(2)} - I_{b(1)})\,u(t)\,(h_{fe})\,(R_d) - (R_d)\,(i_c - i_c(0)) = (L_c)\,\frac{d}{dt}\,(i_c) + R_c\,(i_c - i_c(0)) \tag{16}$$

The linear equations (5), (8), and (16) describe analytically the operation of this output circuit and coil combination for small step input changes in base current.

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Under large input changes, however, physical limitations of the circuit of figure 6 are introduced. The maximum allowable power-supply voltage limits the maximum operational amplifier voltage v_a as well as the maximum coil forcing voltage (defined by eq. (10)). In the present circuit these limits are ± 15 volts for both parameters. They are included in the block diagram of figure 8.
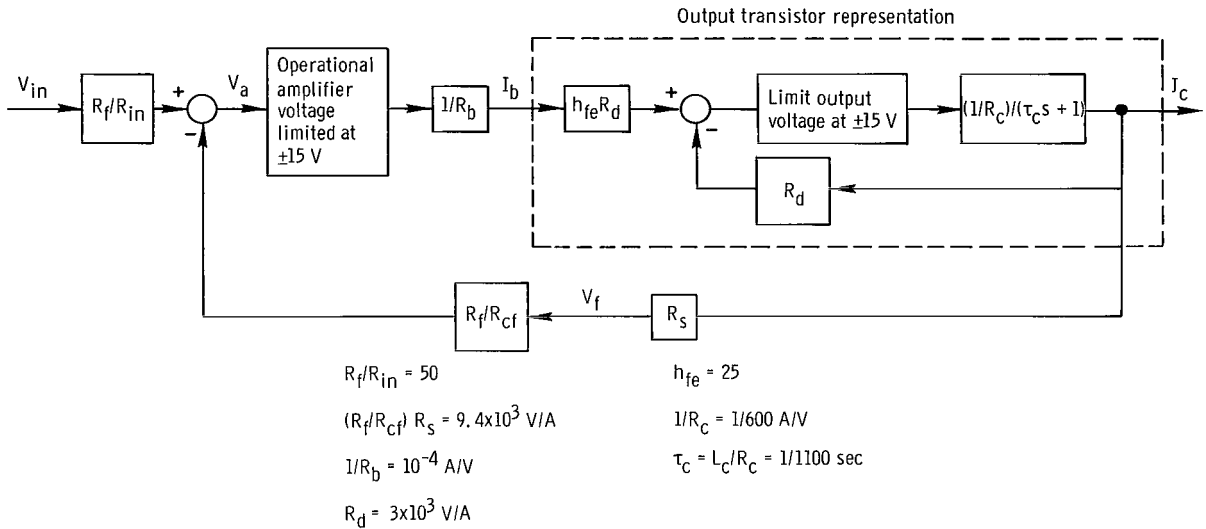

$R_f/R_{in} = 50$

$(R_f/R_{cf}) \, R_s = 9.4 \times 10^3$ V/A

$1/R_b = 10^{-4}$ A/V

$R_d = 3 \times 10^3$ V/A

$h_{fe} = 25$

$1/R_c = 1/600$ A/V

$\tau_c = L_c/R_c = 1/1100$ sec

Figure 8. – Block diagram of coil and drive circuit.

Block-Diagram Representation

By applying transfer function notation to the linear differential equations (5) to (9) and (16) and including the voltage saturation limits described previously, the block diagram of figure 8 may be obtained. The curves of figure 9 show the frequency response of this dynamic model for various levels of desired current amplitude. Comparison of these curves with those of the overlayed experimental curves of figure 4 show good correlation at current amplitudes above 20 percent of rated current. At 20 percent and below, the dynamic model does not respond as well as the actual device. However, the differences between these sets of curves occur at frequencies beyond the range of interest. Thus, for purposes of control-system design, the dynamic model of figure 8 is an adequate representation of the output circuit of figure 6(a).
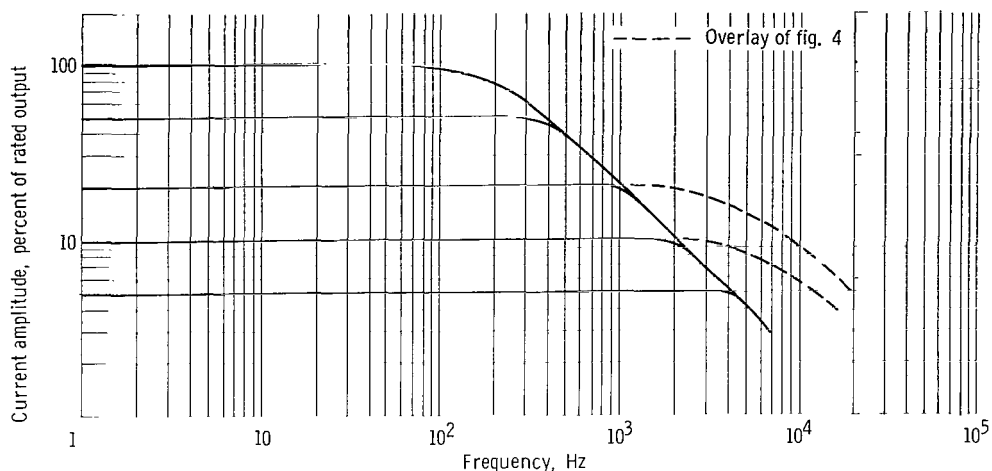
Figure 9. – Complete dynamic model frequency response of coil current to input voltage.

Simplified Block-Diagram Representation

The circuit module described in this report, it should be remembered, has been designed to operate in sophisticated, high-performance, fast-response servosystems. For such systems a complete analog simulation of the particular control system is often undertaken during the early development phases to provide design criteria for component selection and parameter optimization. These simulations, to be completely accurate, will include all component nonlinearities and dynamic elements. The block diagram of figure 8 will serve as a good representation of the power-output stage and torque motor coil combination.

For this circuit, however, a simplified, yet sufficiently accurate, representation has been derived and evaluated. Because of the very high value of parameters h_{fe} and R_d, the output transistors operate in their linear range only for very small base current perturbations. As a result, the output transistor section will operate in saturation for all step changes in input signal V_{in} that would cause a steady-state output change greater than 1 percent of the rated output. By using describing function techniques (ref. 2) to analyze this saturation nonlinearity, the simplified block diagram representation of figure 10 has been obtained. The frequency response of this simplified or less sophisticated dynamic model is shown in figure 11. Comparison of its curves with the overlay of the curves of figure 9 for the detailed model show good correlation for input amplitudes greater than 10 percent of maximum rated current. The bandwidth for reduced amplitudes is beyond the frequency range of interest in both cases. The block diagram of figure 10, therefore, provides a reasonable model for analytical investigations of systems employing this power-output module and torque motor combination.
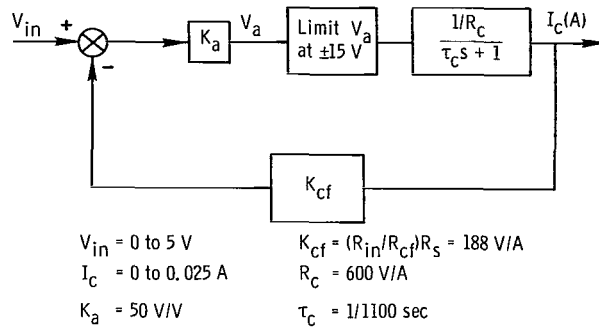
14

V_{in} = 0 to 5 V K_{cf} = $(R_{in}/R_{cf})R_s$ = 188 V/A

I_c = 0 to 0.025 A R_c = 600 V/A

K_a = 50 V/V τ_c = 1/1100 sec

Figure 10. – Coil and drive circuit simplified dynamic representation.
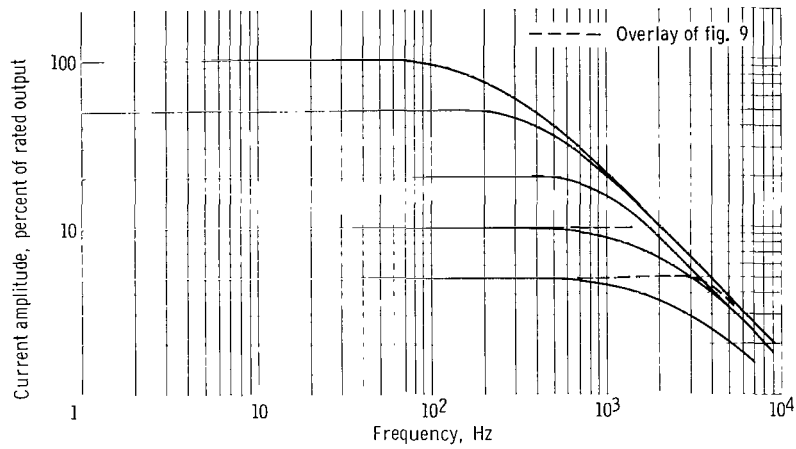

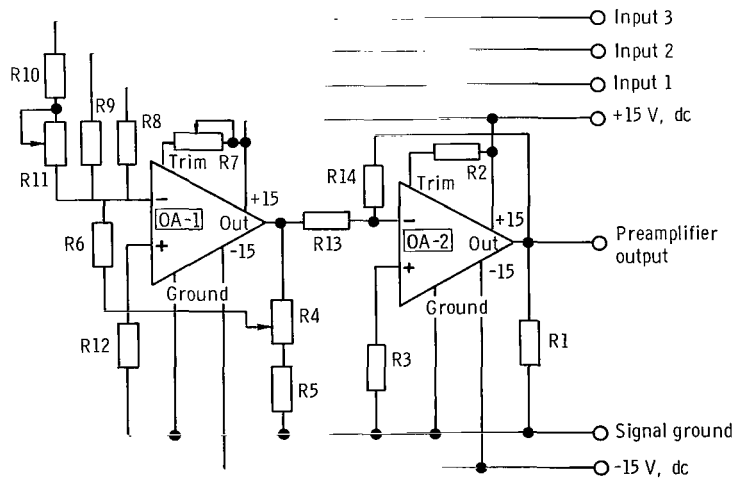Figure 11. – Simplified dynamic model. Frequency response of coil current to input voltage.

Figure 12. – Preamplifier circuit.

TABLE II. - PREAMPLIFIER CIRCUIT PARTS LIST

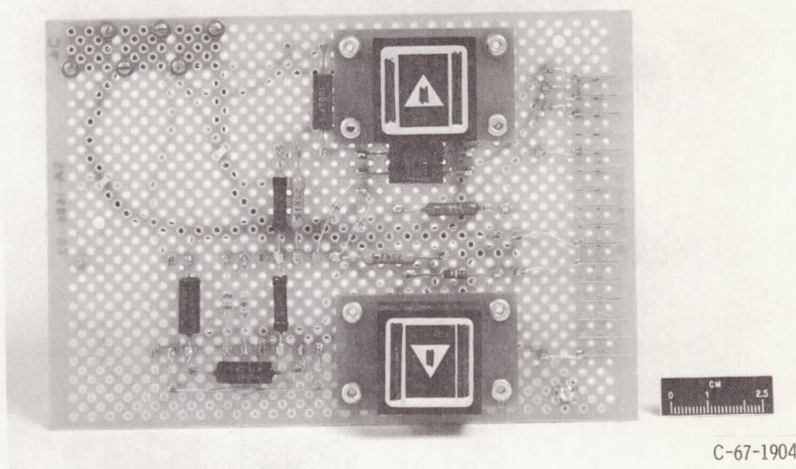| Component designation	Description	Characteristics
OA-1, OA-2	Operational amplifier	
	Open loop gain, rated load, min	50 000
	Rated output, min	±10 V at 2.5 mA
	Frequency response, small signal, min	500 kHz
	Overload recovery	5 msec
	Power supply requirements	
	Voltage	±(15 to 16) V, dc
	Current (quiescent)	6 mA
R1	Resistor, fixed	50 kΩ, 1/2 W
R2	Resistor, fixed	150 kΩ, 1/4 W
R3, R12	Resistor, fixed	25 kΩ, 1/2 W
R4	Resistor, variable	10 kΩ
R5	Resistor, fixed	1 kΩ, 1/2 W
R6, R8, R9	Resistor, fixed	100 kΩ, 1/2 W
R7	Resistor, variable	200 kΩ
R10	Resistor, fixed	75 kΩ, 1/2 W
R11	Resistor, variable	50 kΩ
R13, R14	Resistor, fixed	50 kΩ, 1/2 W

C-67-1904
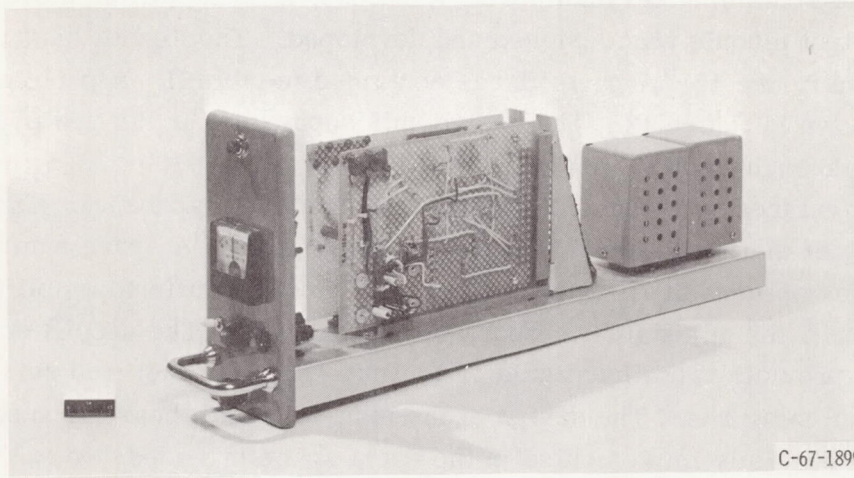
Figure 13. - Preamplifier module.

C-67-1899

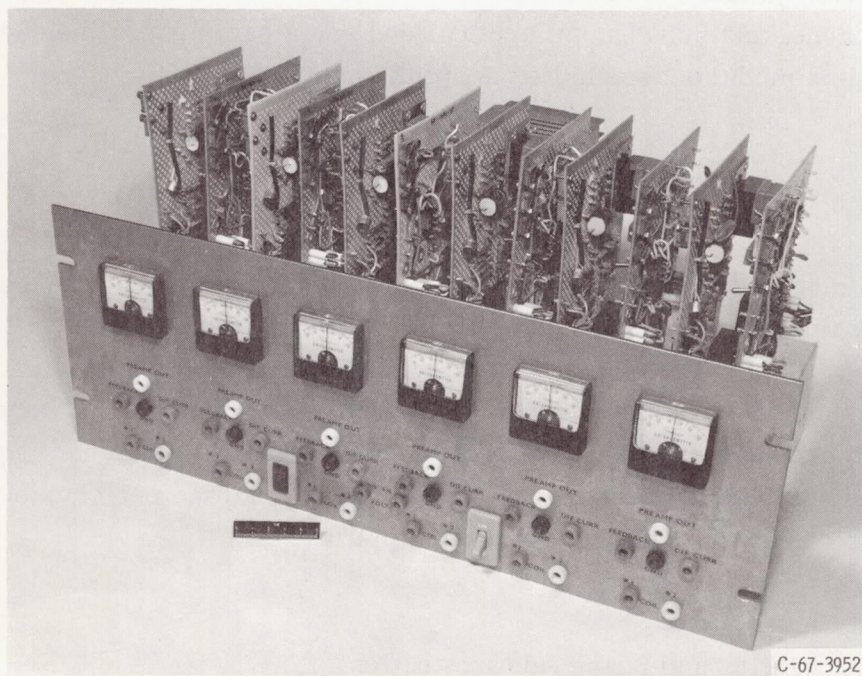Figure 14. - Single-channel servoamplifier installation.

C-67-3952

Figure 15. - Six-channel servoamplifier installation.

PREAMPLIFIER MODULE

To provide the remaining servoamplifier functions, a preamplifier module compatible with the power output module was designed and developed. The circuit diagram for this module is shown in figure 12. A parts list is contained in table II. A photo of the plug-in assembly is shown in figure 13. The design philosophy used in the power amplifier has been carried through into this device.

This module features two stages of operational amplifier capability. The input stage provides summing of the input command and feedback signals. A spare summing channel is also provided for optional inputs. In addition, the first operational amplifier provides variable gain through the adjustable feedback of resistor R4. The second stage is reserved either for providing additional gain or for implementing required servo stabilization (compensation) networks. The design of the plug-in circuit board is such that these modifications can be easily implemented in the extra space provided.

OPERATIONAL INSTALLATIONS

Throughout this report the flexibility of the servoamplifier has been emphasized. To illustrate its adaptability, photos of two different types of installations in which these two-module servoamplifiers have already been employed are shown in figures 14 and 15. These single-channel and six-channel applications are a sampling of the configurations to which these plug-in modular assemblies adapt themselves.

CONCLUDING REMARKS

The circuit modules whose operation and performance has been discussed in the preceding paragraphs are presently being employed in several different high-performance research servosystems. These modules, which have been in continuous use for almost a year, have demonstrated a high degree of reliability and flexibility. More important, these goals have been achieved with a circuit configuration that does not require expensive precision electronic components. Thus, the resulting high performance and low cost of this amplifier render it attractive for many applications.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 2, 1968,
126-15-02-20-22.

APPENDIX - SYMBOLS

CR	rectifier		τ	time constant, sec
d/dt	time derivative		Subscripts:	
h_{fe}	transistor current gain		a	amplifier
I	current (steady state), A		b	base
i	instantaneous current, A		c	coil, collector
K	gain factor		ce	collector-to-emitter
L	self-inductance, H		cf	current feedback
M	mutual inductance, H		cs	collector saturation
Q	transistor		d	dynamic
R	resistance, ohms		e	emitter
t	time, sec		eq	equivalent
V	voltage (steady-state), V		f	feedback
v	instantaneous voltage, V		in	input
ZD	zener diode		s	sensing

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