AD NUMBER
AD836039
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USAMERDCOM ltr, 9 Sep 1982

AD 836039

AUTHORITY: USAMERDCOM ltr 9 Sep 82

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GENERAL ELECTRIC
RESEARCH AND DEVELOPMENT CENTER
SCHENECTADY, NEW YORK

Special Technical Report
On Joints in Series

HARDIMAN I PROTOTYPE PROJECT

Prepared by

Specialty Materials Handling Products Operation
General Electric Company
Schenectady, New York 12305

10 June 1968

Supported Jointly by

Engineering Psychology Branch (Code 455)
Office of Naval Research
Washington, D.C.
Contract Authorization Identification No. NR196-049

and

Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia
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Contract N00014-66-C0051

S-68-1081

38

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FOREWORD

This study has established a method for stabilizing high performance servos that are in series. The Hardiman servos can be stabilized and made to perform as required using this technical report as a guide.

This report represents the successful completion of the servo analysis work initiated during the Special Interim Study (see Special Interim Study, S-68-1060, 19 April 1968)

ACKNOWLEDGMENT

We wish to thank the following scientific officers and project monitors for their efforts in the guidance and direction of this program during the period covered by this report:

Mr. J.W. Beaudet
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We also appreciate the interest and constructive comments of Mr. Geyer and members of his staff.

Mr. G.J. Geyer
Naval Air Systems Command
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Washington, D.C. 20360

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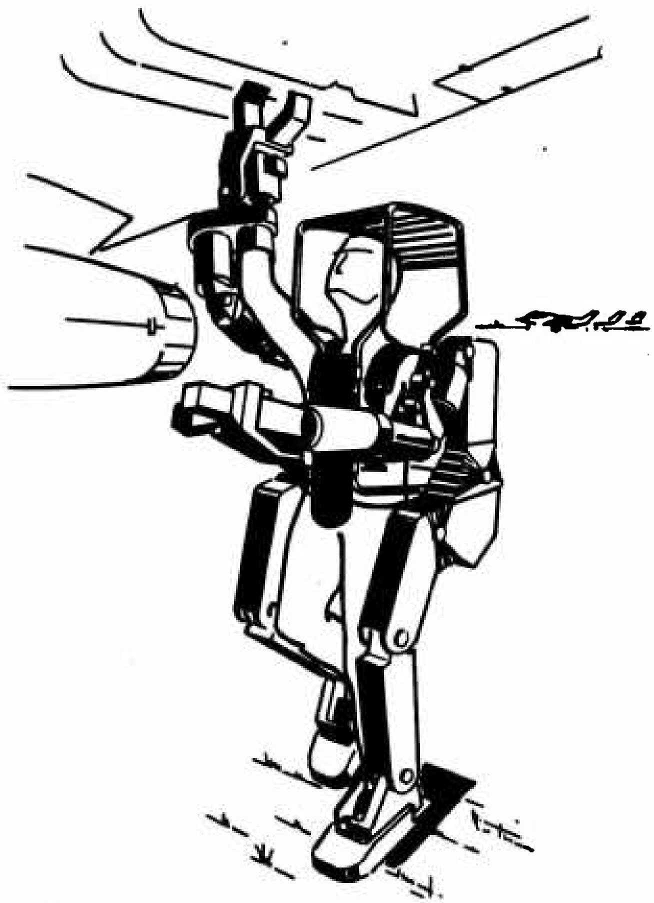

THE POWERED EXOSKELETON PROJECT

The Powered Exoskeleton concept is that of a material handling machine under intimate control of the operator.

"Worn as an outer mechanical garment, the exoskeletal structure will be powered to dramatically amplify the wearer's strength and endurance by a factor of approximately 25 to one, i. e., when the exoskeleton wearer lifts 25 pounds, he will 'feel' as if he is lifting only one pound. The device will provide him with a set of 'mechanical muscles' that enables him to lift and handle loads in excess of 1000 pounds. The human operator will 'feel' the objects and forces he is working with almost as if he were in direct body and muscle contact. This feature, called force feedback, will provide the operator with sensitive control of the structure and will act as a safeguard against the application of excessive force.

"The exoskeleton, called 'Hardiman,' mimics the movements of its wearer, presenting a literal union of man and machine. Thus, the human's flexibility, intellect, and versatility are combined with the machine's strength and endurance."*

---

* Naval Research Reviews, July 1967

Section 1

INTRODUCTION

During the development of Exoskeleton servos, it became apparent that the effect of interactions between servos in the series of joints in the arms or legs must be considered. These interactions have for a long time been a question in the design or manipulators. The past history has been to wonder about them, ignore them in design, and find no obvious ill effects in operation.

The Exoskeleton presented a different situation than previously encountered. The needed servo performance was higher than ever before in manipulators; the force ratio (25:1) was high; the load (1500 lbs) was much greater than previous experience. The first look into joints in series analysis was occasioned by the hope that the intercoupling effects might make the solution to the Exoskeleton servo problem easier. This was not to be, however.

It was found that for the particular Exoskeleton parameters, the intercoupling reduced the stability of the servos rather than helped as had been hoped. With the help of consultants, Dr. H. Chestnut and P. C. Callan, a solution to these problems was found. The change to electrohydraulic from hydromechanical to provide a more feasible method for servo compensation has been previously reported.* There remained the need to show that it is feasible to stabilize the Exoskeleton high performance bilateral servos in series. This report documents a successful engineering solution to this feasibility question. It provides technical guidelines for the stabilization of the general joints in series problem.

The conclusion drawn from this work is that it is possible to stabilize the Exoskeleton arm servos at a level of performance well above that needed for satisfactory operation.

*Special Interim Study S-68-1060, 19 April 1968.

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Section 2

EXOSKELETON STABILITY ANALYSIS

INTRODUCTION TO ANALYSIS

This report is based on studies made of the tickler activated Exoskeleton. The hands, arms, and back are assumed to have provisions for force reflection. The legs and girdle do not have this provision.

Three primary considerations are necessary in examining the stability aspects of such a system. They are:

- The stability of each joint alone: This requires analysis of the parameter variations in the joint model due to load changes on the system.
- The stability of a number of joints connected in series: This requires analysis of parameter variations due to load changes in the model representating the cross coupling terms between individual joints. Also, the stabilization methods used in individual joints must be compatible with inter-joint stability requirements. This is because some terms appear in both places.
- The stability of a number of joints connected in series with force reflection from slave to master: This case is the most difficult, and the wrist joint is the worst case since inertia changes of 250 to 1 are experienced from no load to full load.

SCOPE OF ANALYSIS

This section outlines the analysis performed to obtain data needed to construct the Exoskeleton. A simulation of three joints in series has been achieved on an analog computer. Both the unilateral (leg system) and bilateral (arms) have been studied. A program has also been written for the digital computer using ADA.

The computer models have been used as tools in conjuction with control theory calculations to determine the compensation networks necessary to implement the system and have it stable under all operating conditions.

RESULTS AND CONCLUSIONS FROM ANALYSIS

As a result of the work performed, the following conclusions have been reached:

- Compensation networks in the slave must consist of a proportional network, a rate network, and in some cases a lag network. This results from the fact that a high steady state gain is needed to achieve required compliance.

This high gain causes inter-joint instability which can be eliminated by supplying a rate signal. The rate signal, however, caused the bandwidth of the individual joints to be high, resulting in possible oscillations due to mechanical resonance.

The addition of a lag term, to each joint, reduces this bandwidth and makes it adjustable. When the lag is supplied in parallel with the proportional and rate terms, inter-loop stability is still maintained. If placed in series, inter-loop instabilities result. This is explained in the following subsection, "Analysis Procedure."

- In addition to series rate stabilization velocity feedback must be provided on the master for the bilateral case. The sensor for this feedback will measure the velocity difference between adjacent members, e.g., the actuator at the elbow joint will have a velocity transducer to measure its motion. The actuators at the wrist, shoulder, and back will need the same feature.

ANALYSIS PROCEDURE

The analysis procedure is presented in four parts below. First, consideration is given to a single unilateral joint. Then three unilateral joints in series are considered. Next, a single bilateral joint is examined, and finally three bilateral joints in series are analyzed.

Single Joint - Unilateral

A block diagram of a single unilateral joint for the tickler system is shown in Figure 1. A typical frequency response plot is shown in Figure 2 for the case where G_c is a constant. In general, because of the static compliance limit of ± 1 inch between master and slave, the single joint approaches dynamic instability. In the paragraphs under the topic "Three Joints in Series - Unilateral," it is shown that unstable operation results at all times for three joints in series at the gains required unless additional compensation is provided.

A method of decreasing the crossover phase shift is to make $G_c(s)$ a rate as well as proportional gain. This can be done to produce a lead at the same frequency as the first lag break. The resultant frequency response plot is shown in Figure 3. It is noted that the crossover frequency (and thus the bandwidth) is increased by this method. In any event, the crossover frequency of 100 to 200 radians per second is higher than necessary for dynamic response of the system, and it is possibly higher that the resonant frequency of the mechanical structure.

A means of decreasing bandwidth while maintaining the same unity frequency gain and about the same phase shift is shown in Figure 4. This frequency-gain profile is obtained by putting a lag circuit in parallel with the proportional and rate circuit. With this configuration all of the requirements of steady state and dynamic compliance, stability, and response time can be met for a single loop. The general equation for $G_c(s)$ is:

$$G_c(s) = K_g + K_v s + \frac{K_L}{1 + T_L s} \qquad (1)$$

The two lag breaks due to the hydraulics and geometrical configuration of the system are functions of A, v, λ, ψ, V, Kv, and B; therefore, they will vary from joint to joint. The compensation used in any one joint should be calculated given these lag break values.

A value of K_v of 0.05 cis/psi has been found to be practical in valves, and produces lag breaks of the order shown in Figure 2 for the slave joints examined for this study. The master joints are examined in the latter part of this section.

Three Joints in Series - Unilateral

A signal flow diagram of three joints in series is shown in Figure 5. The large number of inter-loop connections shows the complexity of the system. Analysis of this system was achieved by considering only two joints in series, and then extending to three by simulation on the analog computer.

A block diagram of two joints in series is shown in Figure 6. The transfer functions F_1 (s), F_2 (s), H_{12} (s), and H_{21} (s) are frequency sensitive and are derived by reduction of two joints from the signal flow diagram of Figure 5. The α and β are constants and do not enter into stability calculations.

The loop of interest for examining stability is from F_1 through H_{12}, F_2, and H_{21} back to F_1. This loop has positive feedback which means that the gain must be less than unity for all frequencies for stability to exist. Therefore, the condition for a stable system is given by:

$$F_1 (j\omega)\, H_{12}\, F_2 (j\omega)\, H_{21}(j\omega) < 1 \text{ for all } \omega \qquad (2)$$

Since the product in Equation 2 must be kept less than unity, it is important that lags occur at as low a frequency as possible to keep the gain going down as frequency increases. Of course, if the zero frequency gain is greater than unity, stability cannot exist. In the Exoskeleton joints considered, this zero frequency gain is always less than one.

In the transfer function H_{12} (s) and H_{21} (s), the terms are of the form:

$$H(s) = K_1 \frac{1 + T_1 s}{G_c s}, \tag{3}$$

and F_1 (s) and F_2 (s) are, in simplified form:

$$F(s) = \frac{1}{(1 + T_2 s)(1 + T_3 s)} \tag{4}$$

In general, T_1 is larger than T_2 and T_3, and leads occur at a low frequency tending to increase the gain from Equation 2 as frequency increases. The G_c(s) is the compensation network transfer function from Figure 1.

A typical frequency response plot for a proportional G_c (s) is shown in Figure 7. Since the gain becomes greater than unity (dB), instability is indicated. This was, in fact, observed on the analog computer simulation.

In addition of rate to G_c(s) results in a frequency response plot typically represented by Figure 8. Two additional lags are created because of the lead in each of the G_c(s) terms since G_c(s) appears in the denominator of Equation 3.

The addition of a lag term to reduce single joint bandwidth as indicated in subsection, "Single Joint - Unilateral," does not affect inter-loop stability adversely since another zero is created in G_c(s) as shown by Equation 1. In general, for inter-loop stability there should be one more zero than pole in G_c(s). Hence, there is the necessity for rate feedback in all cases.

It is noted that the introduction of a lag to reduce single joint bandwidth must be in parallel with the proportional and rate terms and not in series with them. Otherwise, the additional lead is not created and inter-loop instability will again result.

This analysis was extended to three joints in series on the analog computer simulation, and the system was found to be stable.

Single Joint - Bilateral

A block diagram of a general bilateral servo is shown in Figure 9. The open loop transfer function of loop 2 with loop 1 held fixed is given by:

$$G_c(s) \; G_2(s) \tag{5}$$

When loop 1 is free to move, the open loop transfer function of loop 2 is given by

$$\frac{G_c(s)\,G_2(s)}{1 + G_c(s)\,G_1(s)} \qquad (6)$$

If $G_1(s) = G_2(s) = G(s)$, then Equation 6 looks like the closed loop transfer function of a loop with forward gain of $G(s)\,G_c(s)$ and unity feedback. Replacing Figure 9 with this representation results in a block diagram as in Figure 10. This servo has an open loop gain equal to twice that of the unilateral servo, a change which can often be tolerated because only a 6 db gain change is present.

With the frequency relationships in mind, the bilateral single joint case can be designed using the concepts described for the unilateral servo as long as the forward transfer function of both the master and slave loops are made to be nearly equal. "Nearly" is a relative term, but it is the approach used, and the computer simulation showed it to work.

A block diagram of a bilateral joint for the Exoskeleton is shown in Figure 11. In the arm system, the value of ψ_{sl} can be as much as 75 times larger than ψ_m. For a given $G_c(s)$, the unity frequency gain of the master loop would be as much as 75 times larger than that of the slave, and the lag breaks in the master loop are quite different from the slave loop.

It is possible to sense velocity on the master and feedback, a strong enough signal in parallel with ψ_m to make the sum of that signal and ψ_m be essentially equal to ψ_{sl}. While this does not make the transfer function of the master equal to that of the slave, it does bring them much closer together, and the bilateral servo transfer function approaches that given by Figure 10.

Simulation of the single bilateral joint on the analog computer showed that this approach works for that case.

<u>Three Joints in Series - Bilateral</u>

A signal flow graph of three joints in series - bilateral is shown in Figure 12. The complexity of the system is evident from the diagram. Because of this complexity, analysis of the entire system uneconomic in time; therefore, an approach is used which extrapolates the findings of the unilateral three joints in series and the single joint bilateral cases.

An extensive analog computer simulation was set up for the bilateral three joints in series to try various approaches. The computer diagram is shown in Figure 13.

Using the approaches outlined above, i. e., compensation networks used for the unilateral case and velocity feedback used in the bilateral single joint case, it was found that the three joints in series - bilateral could indeed be stabilized for the range of changed inertia called for in the design specifications, 0 to 1500 pound load.

Computer runs shown have only proportional and rate components as reflected in Figure 12, showing the signal flow graph. The system worked very well for this case, but it must be kept in mind that mechanical resonance in the actual system will possibly require the parallel lag circuit.

Computer runs showing operation of this simulation are shown in Figure 14. Values of the compensation and feedback parameters to achieve these results are shown on the signal flow graph, Figure 12.

It is noted that the values obtained by this study are not optimized. It is probable that other values could be found which would improve performance. However, the sensitivity of the parameters was found to not be critical when changes were tried on the computer.

Therefore, the feasibility of stabilizing three joints in series - bilateral has been shown and the approach to use in design is spelled out. Provisions should be made for adjusting the proportional, rate, lag, and velocity feedback terms over a large range when building equipment.

RECOMMENDATIONS

It has been shown that there is a method whereby the Exoskeleton arm system can be made stable without being overly sensitive to parameter variations. There are, however, other aspects of operation which should be better understood such as dynamic compliance characteristics and actual frequency response of a joint when connected in series with other joints.

During the actual arm design it is recommended that:

- Optimization runs be made with dynamic compliance constraints to determine the best range of compensation for operation. Now that the dynamic form of the compensation networks is specified, optimization can be performed on the parameters. A suitable digital computer program (ADA) is available for this analysis.
- Frequency response be run on the existing analog computer program to give more information on the system. Work with the computer simulations in conjunction with the planned hardware development will allow design to proceed with insight into operation progressing at the same time.

Appendix I

DERIVATION OF SYSTEM DIAGRAMS

The dynamic behavior of the manipulator linkwork was analyzed to yield terms in a form that lead directly to the construction of servo signal flow diagrams, Figures 6 and 12. The diagram shows three bilateral servos with a number of cross connections between them. Each of the horizontally displayed patterns is in itself the diagram for a single joint; the cross connection, which are displayed more or less vertically, represent the dynamic interaction between joints in series as determined by the analysis.

The analysis was based on the link diagram Figure 15. The following assumptions were made:

- The linkage rest position is a straight line.
- Excursions are small: $\sin\theta \cong \theta$ and $\cos\theta \cong 1$,
- Centrifugal forces are negligible

None of the assumptions are true for the real device. The justification for making them is that they greatly reduce the labor of the derivation and subsequent stability analysis while not invalidating the stability analysis. This is a customary and well established procedure for stability analysis which is the purpose of this work; it is not satisfactory for predicting exact forces, moments, etc. which, of course, was not intended here.

The dynamic analysis (which was done by J.A. Bain of the Engineering Mechanics Unit) proceeded to find force, acceleration equations (Newton's first law equations), for the three links. Since it was convenient to have torque and linear displacement as variables, the general form of these equations is:

$$\tau = \lambda \ddot{y} \qquad (7)$$

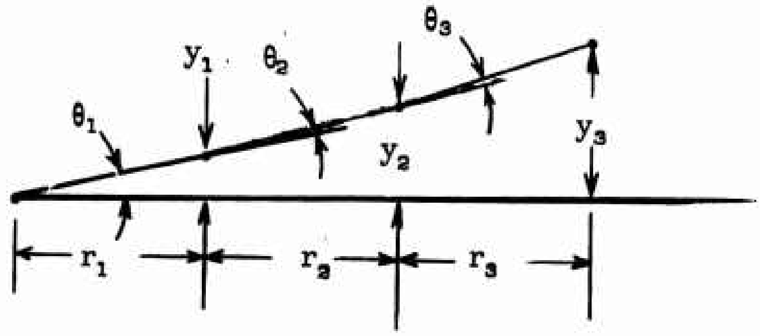
where τ = torque (in lbs).
$\ddot{y}$ = linear acceleration (in/sec^2)

and λ is a mass and link length term of dimensions: lbs. - sec^2.

The results of deriving the various λ terms are shown in Figure 16 and 17. Figure 16A is an extract from the signal flow diagram which identifies the terms, and Figure 16B shows the diagram manipulated by block diagram algebra to the same form as shown on Figure 12. Figure 17 shows a table giving the formula for each λ in terms of mechanical parameters.

The numerical values for these are shown in Figure 12. The distinction between the heavy versus light case implies the load inertia (w_s) is present or absent on the slave. The operator's hand was always assumed present on the master.

These are some other intercouplings as shown on the signal flow diagram. These feed from velocity ($\dot{y}$) to flow. These are necessary to relate the linear velocity to angular velocity at the joints, and thus to flow in the actuators. The derivation follows from the geometry.



For small angles

$$\theta_1 = y_1 / r_1$$
$$\theta_2 = (y_2 - y_1)/r_2 - \theta_1$$
$$\theta_3 = (y_3 - y_2)/r_3 - (\theta_2 + \theta_1)$$

$$\theta_1 = y_1 / r_1$$
$$\theta_2 = y_2 / r_2 - \left(\frac{1}{r_2} + \frac{1}{r_1}\right) y_1$$
$$\theta_3 = y_3 / r_3 - \left(\frac{1}{r_3} + \frac{1}{r_2}\right) y_2 + y_1 / r_2$$

Since actuator flow is related to angular velocity by the area and crank radius of the actuator we have, finally

$$q_1 = (\dot{y}_1 / r_1) A_1 rs_1$$
$$q_2 = \left(\dot{y}_2 / r_2 - \left(\frac{1}{r_2} + \frac{1}{r_1}\right) \dot{y}_1\right) A_2 rs_2$$
$$q_3 = \left(\dot{y}_3 / r_3 - \left(\frac{1}{r_3} + \frac{1}{r_2}\right) \dot{y}_2 + \dot{y}/r_2\right) A_3 rs_3$$

for the three actuator flow terms, which are then converted to paths on the signal flow diagram.

The computer diagram, Figure 13, is made directly from the signal flow diagram, Figure 12, using the customary methods for simulation on an analog computer*. Note that computer time is ten times real time to present a slower moving display.

*See H. Chestnut, Systems Engineering Tools, Chapter 4, Wiley and Sons, NYC.

Appendix II

COMPUTER RESULTS

The purpose of this work was to demonstrate the feasibility of operating three bilateral servos on a series of three adjacent joints of a particular design, namely the Exoskeleton arm. This was done by setting up the analog computer according to the diagram Figure 13 and adjusting the available parameters, loop gain and velocity feedback gain, until stable operation was achieved at sufficiently high performance levels to satisfy the Exoskeleton servo design requirements. Operation should, ideally, be satisfactory at both heavy and light slave mass loading without the requirement to change the gain parameters with load changes.

Satisfactory gain settings were found. The recorder traces Figure 14 and 18 show the system operating stably while responding to a sinsusoidal torque input to the wrist. The following table gives the system properties at these settings:

		Loop Gain	Compliance	Lead Corner Freq.
Wrist	3	65. 0 dB	1. 47%	27. 2 R/S
Elbow	2	56. 5 dB	1. 91%	15. 5 R/S
Shoulder	1	56. 9 dB	1. 32%	16. 1 R/S

The performance represented here is fully satisfactory for the Exoskeleton.

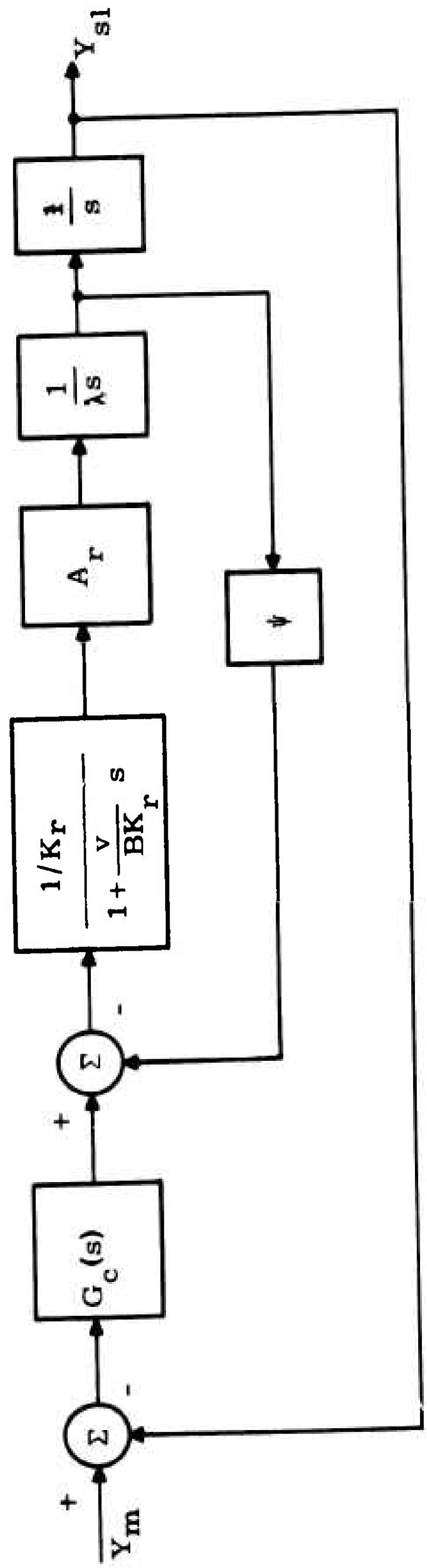


Figure 1. Single Joint Block Diagram

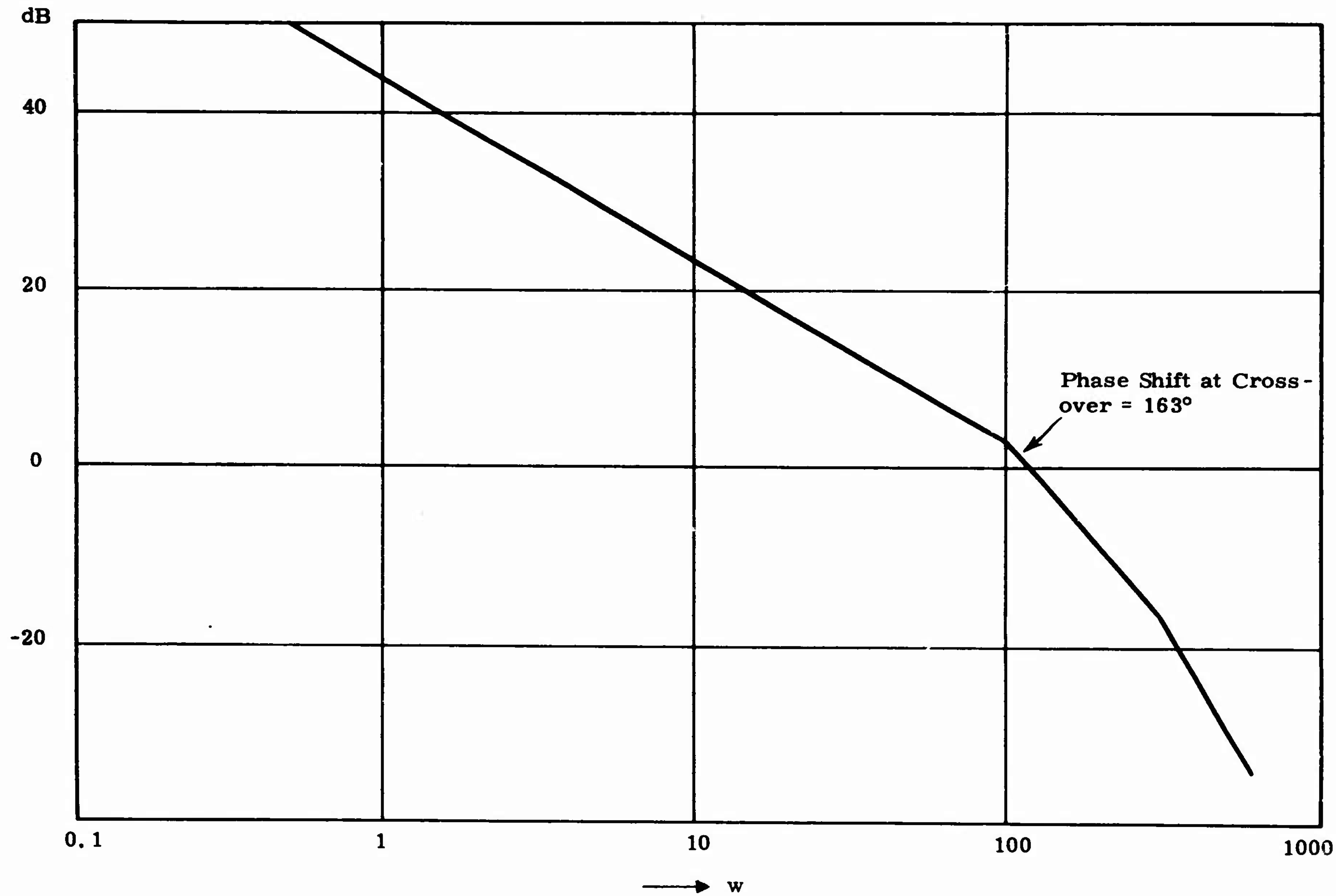


Figure 2. Typical Frequency Response for a Single Joint -- Proportional Gain Only

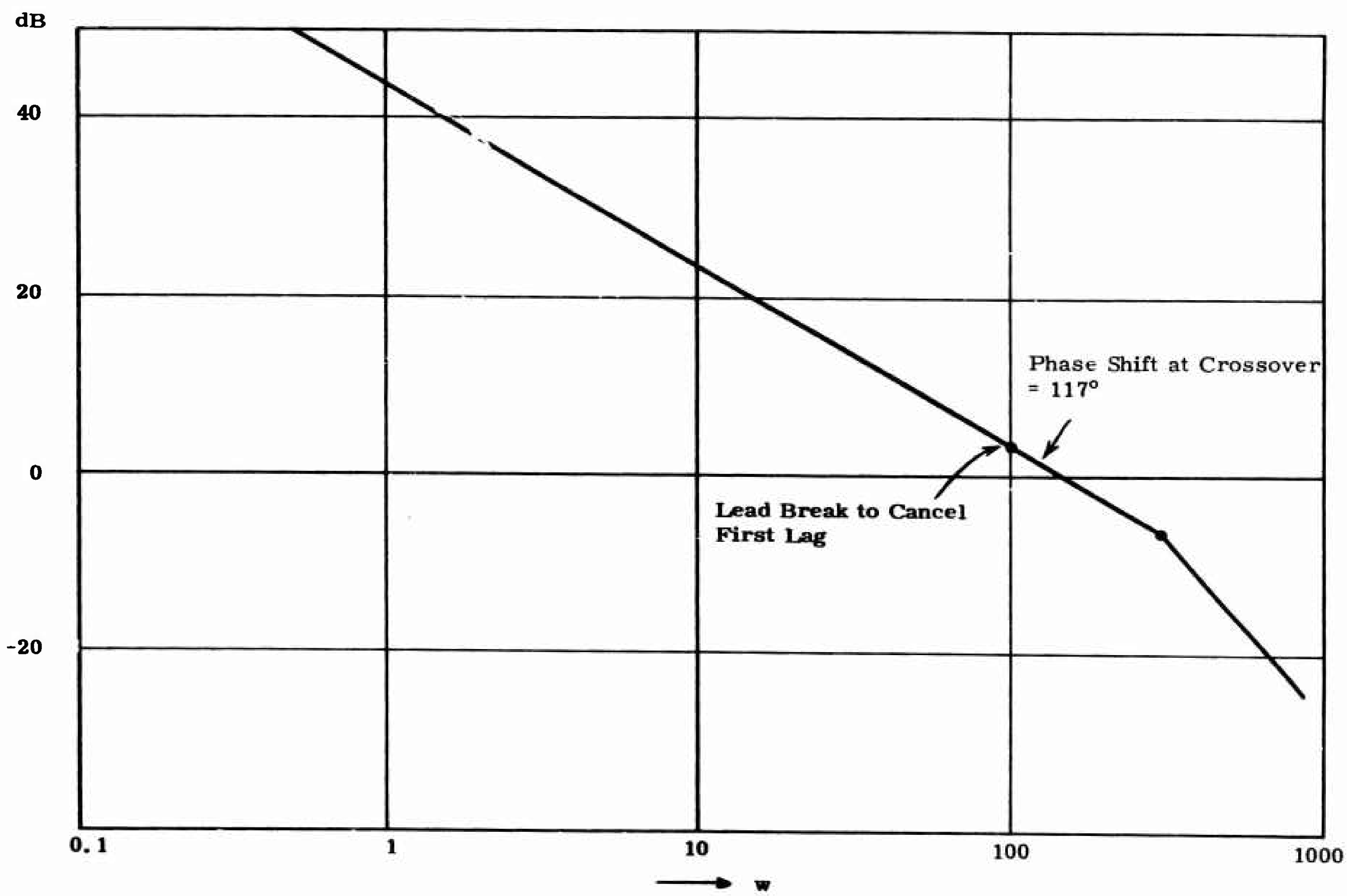


Figure 3. Typical Frequency Response for a Single Joint -- Proportional and Rate Compensation

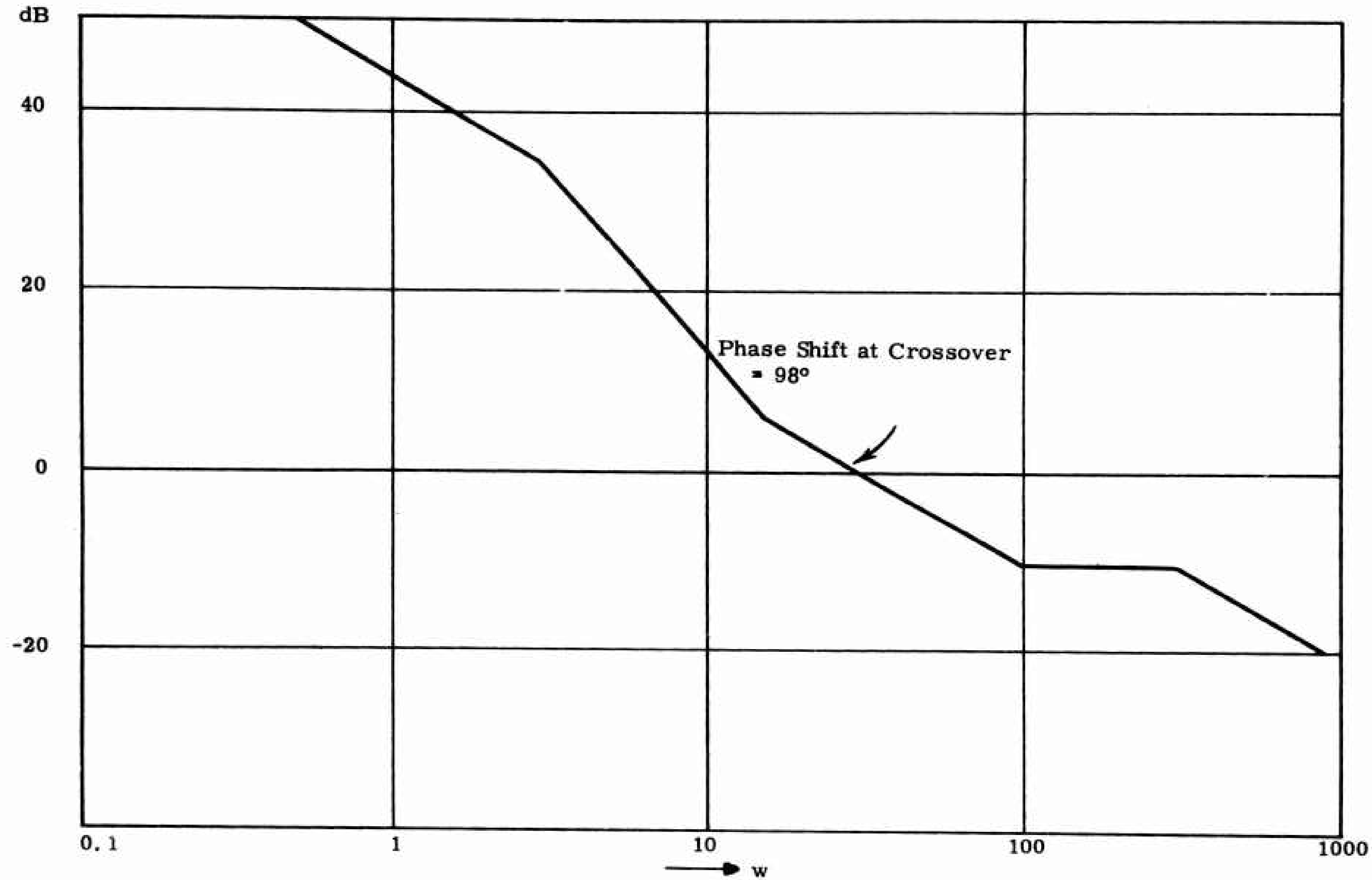


Figure 4. Typical Frequency Response for a Single Joint -- Proportional and Rate and Lag Compensation

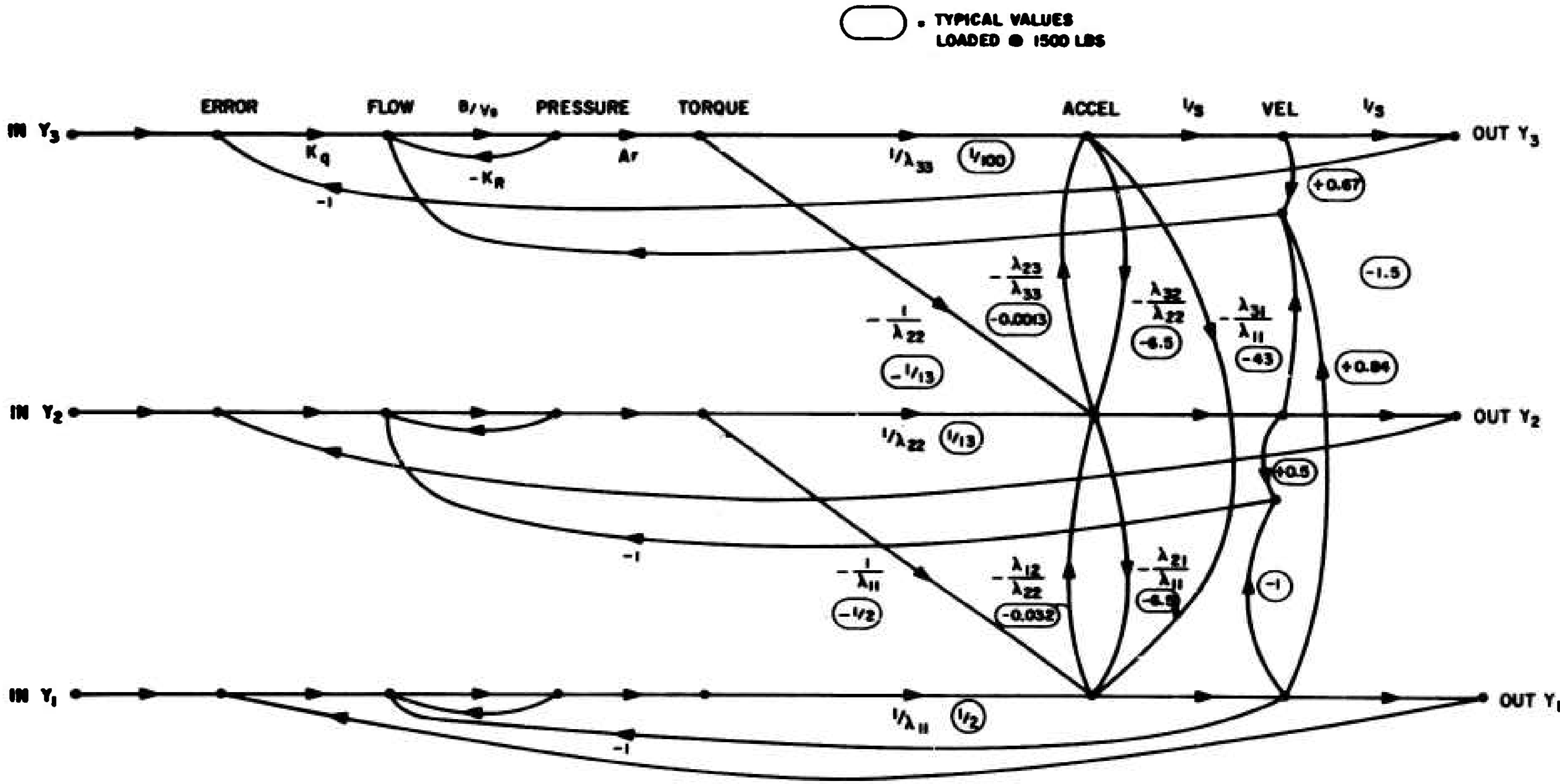


Figure 5. Signal Flow Diagram for Three Joints in Series Tickler Control -- Unilateral

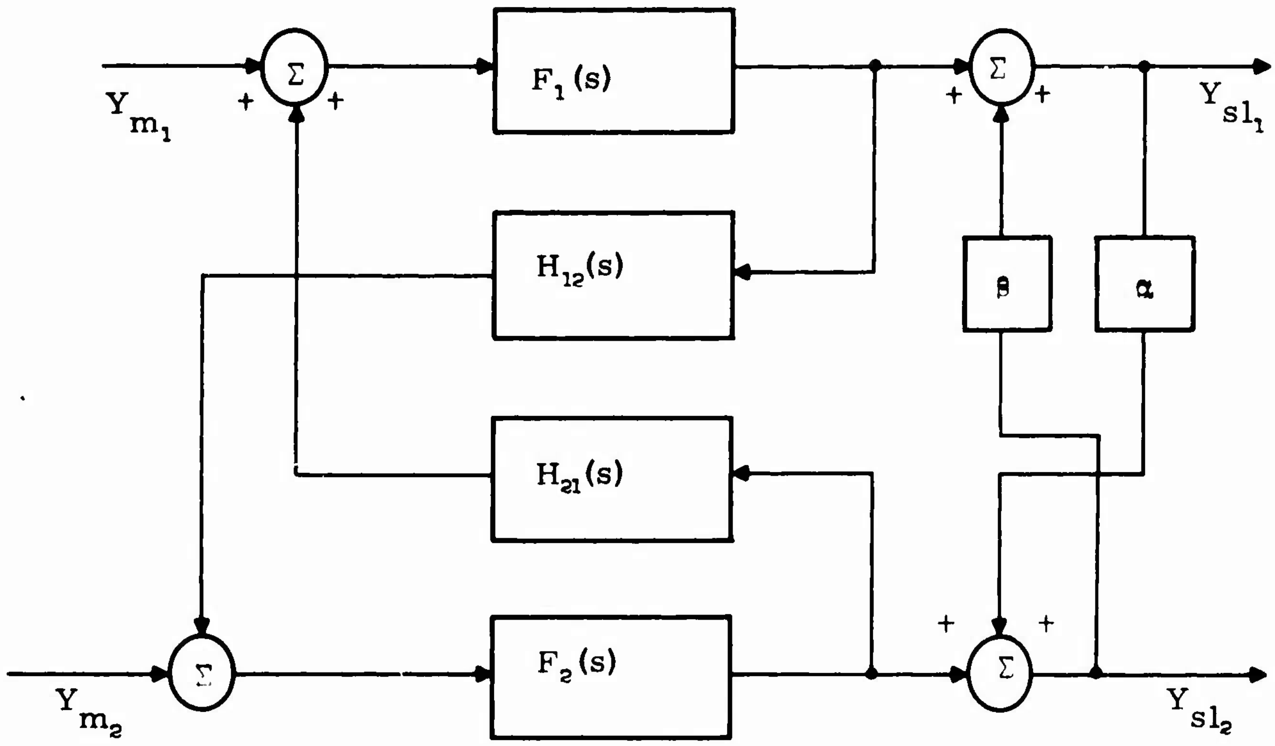


Figure 6. Two Joints in Series Block Diagram -- Unilateral

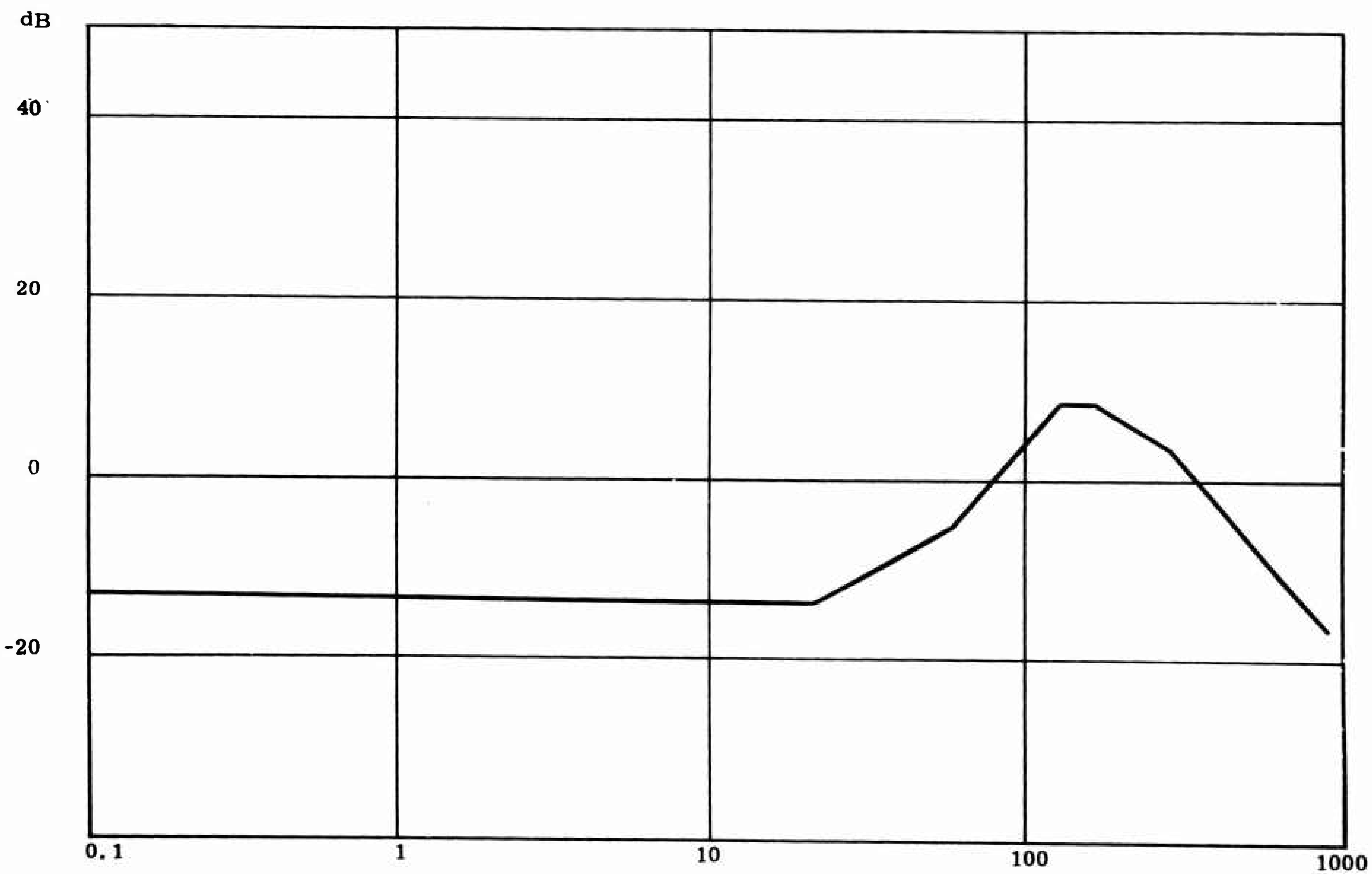


Figure 7. Typical Frequency Response of Two Joints in Series -- Proportional Gain Only

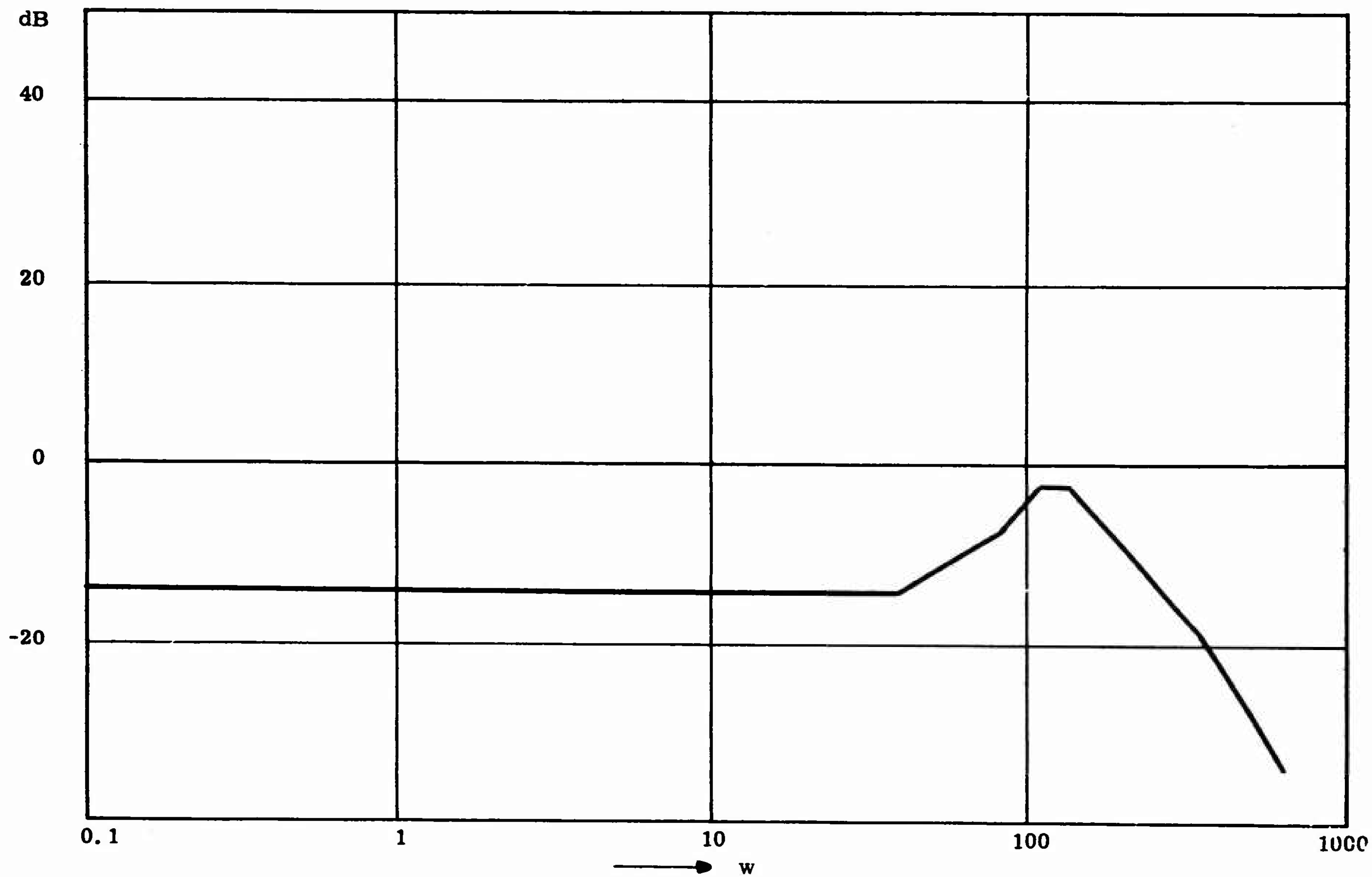


Figure 8. Typical Frequency Response of Two Joints in Series -- Proportional and Rate Compensation

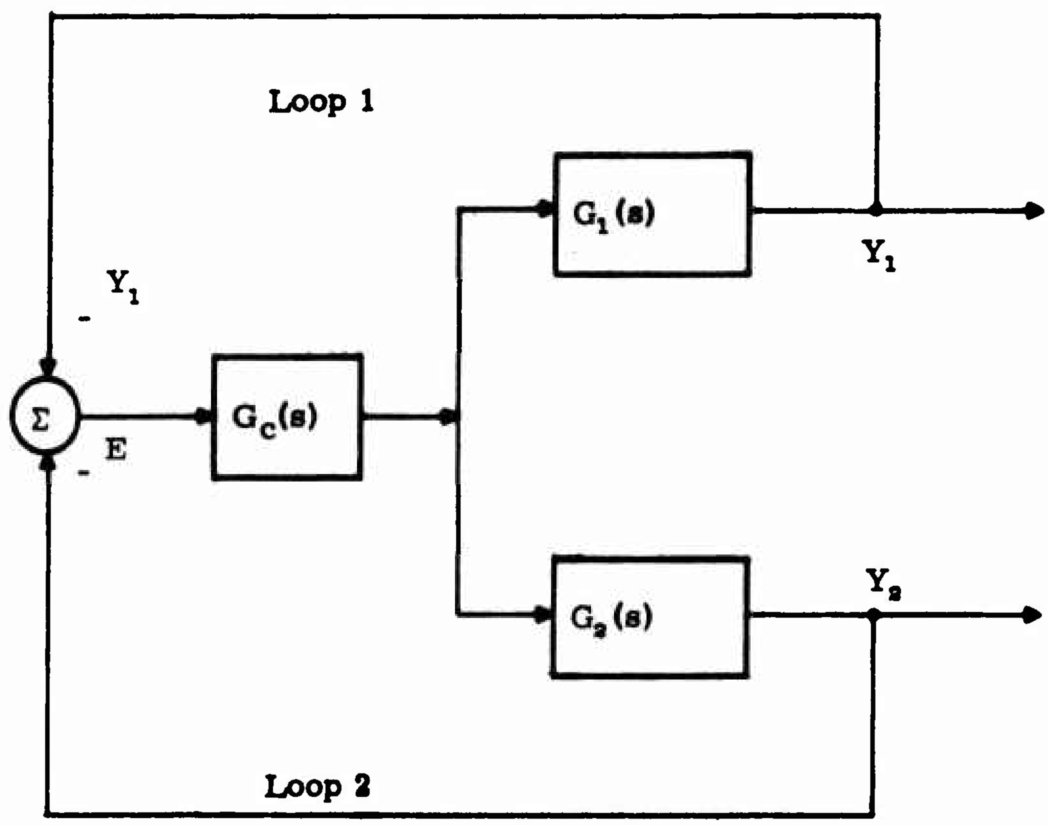


Figure 9. General Bilateral Position Servo

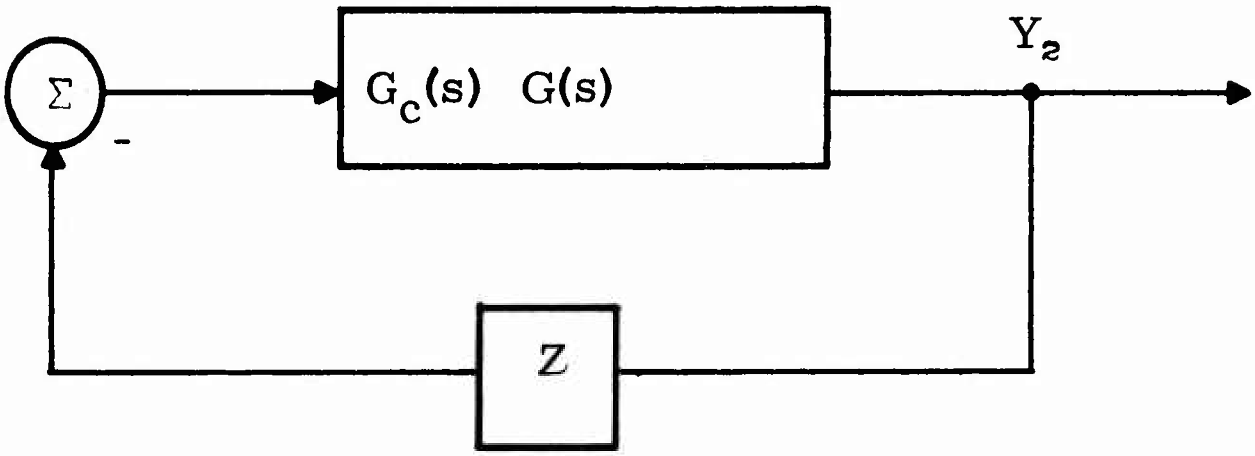


Figure 10. Block Diagram of Bilateral Servo with $G_1(s) = G_2(s) = G(s)$

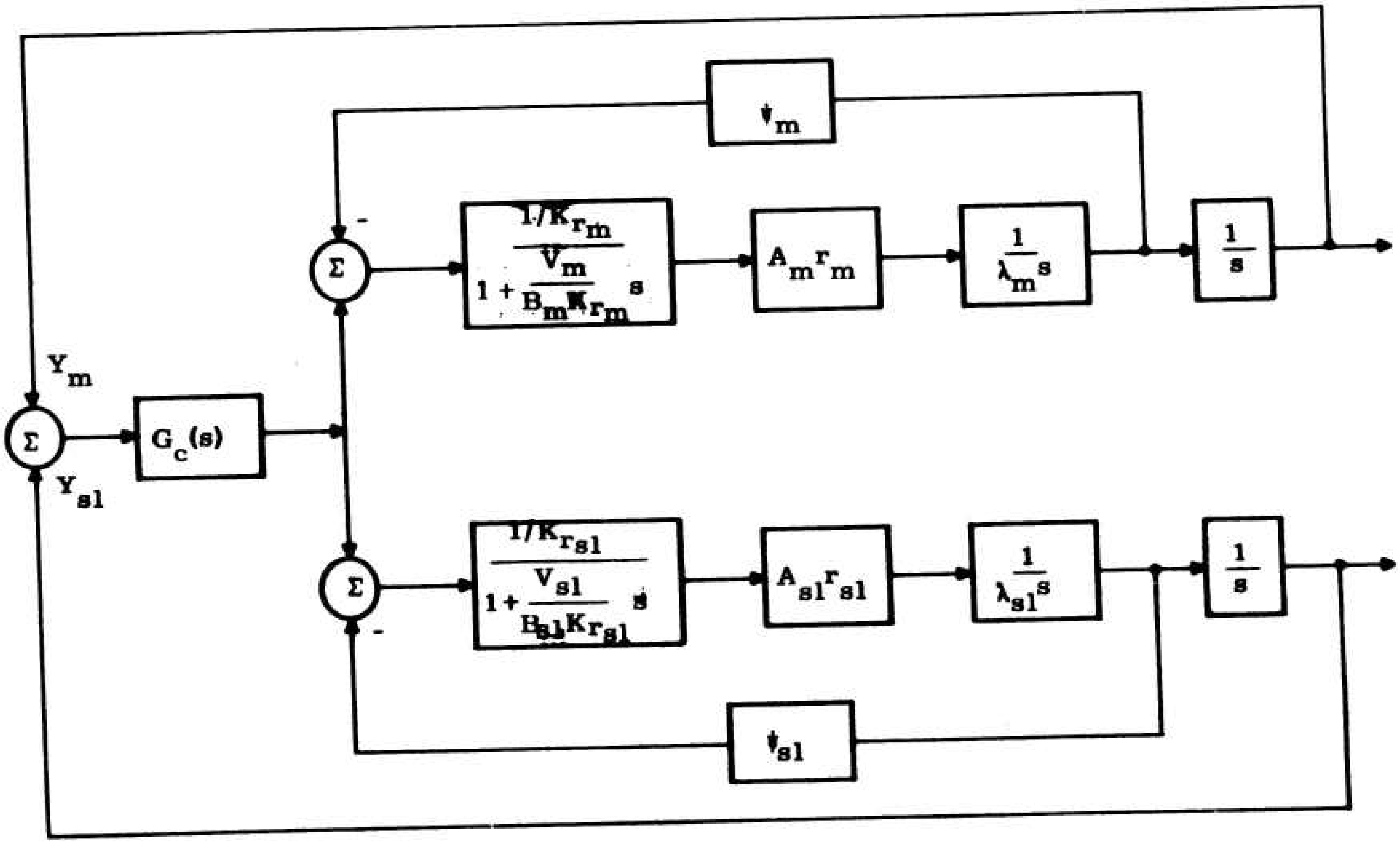


Figure 11. Block Diagram of Single Joint -- Bilateral

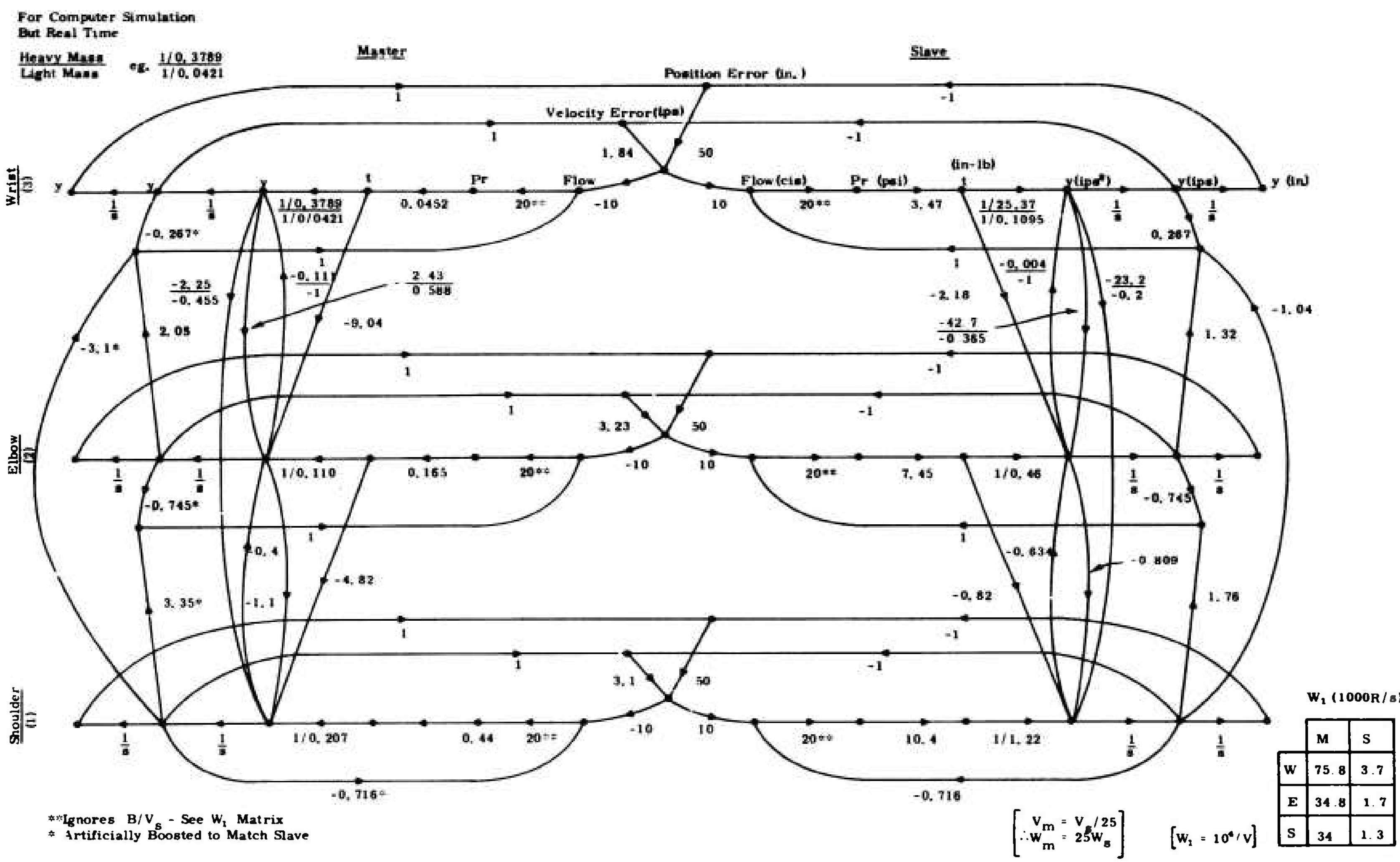


Figure 12. Signal Flow Diagram of Bilateral Servos

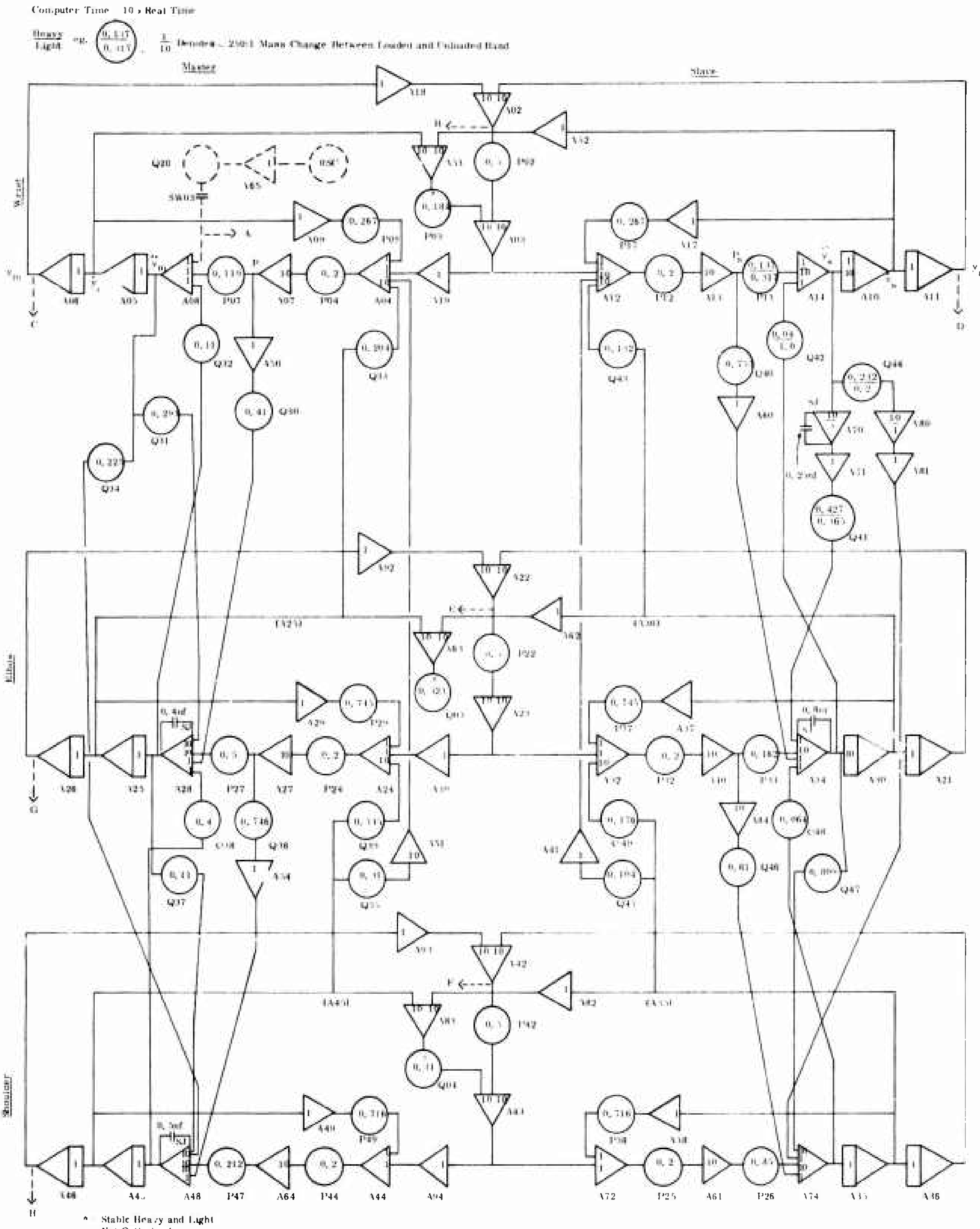


Figure 13. Analog Computer Diagram of Exoskeleton of Three Joints in Series

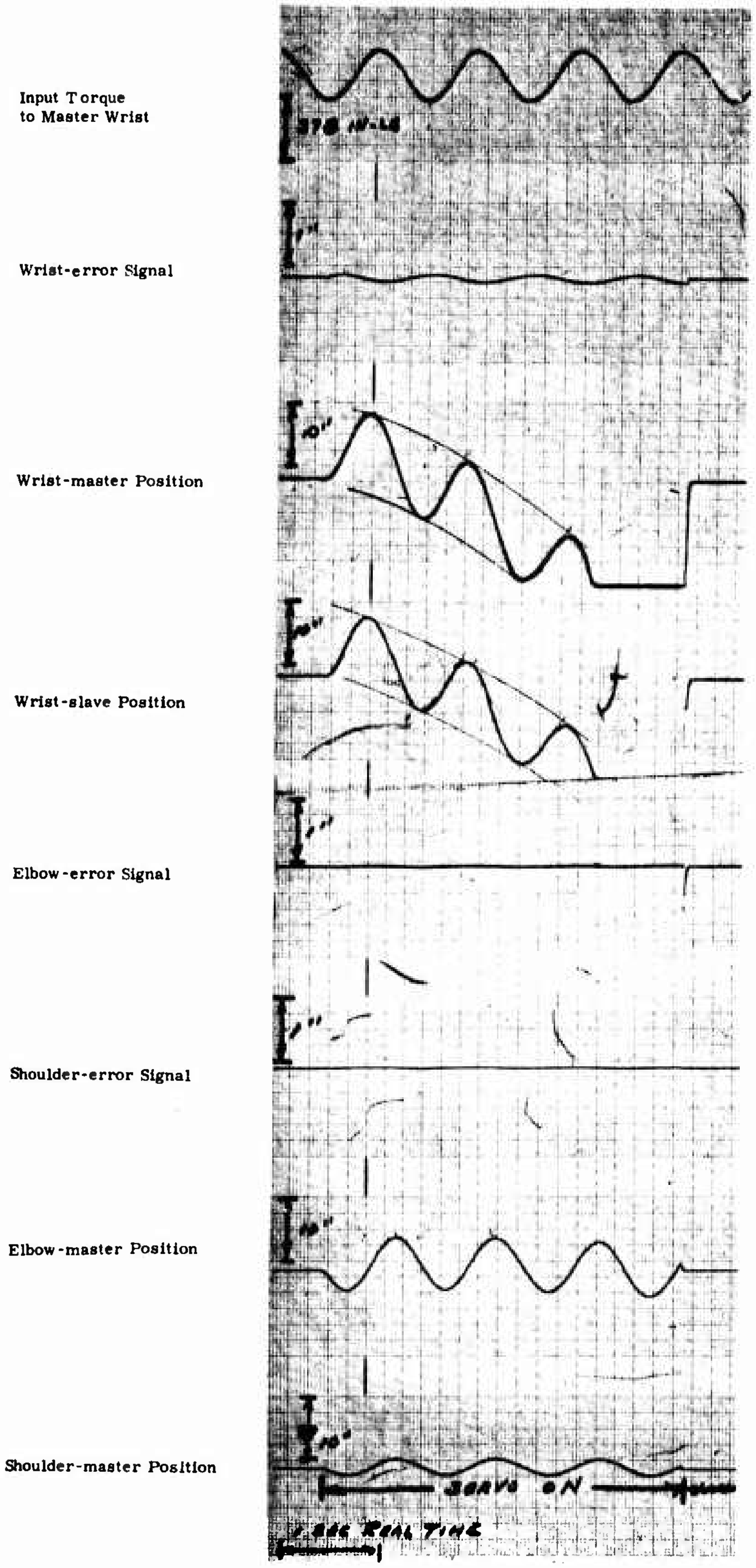
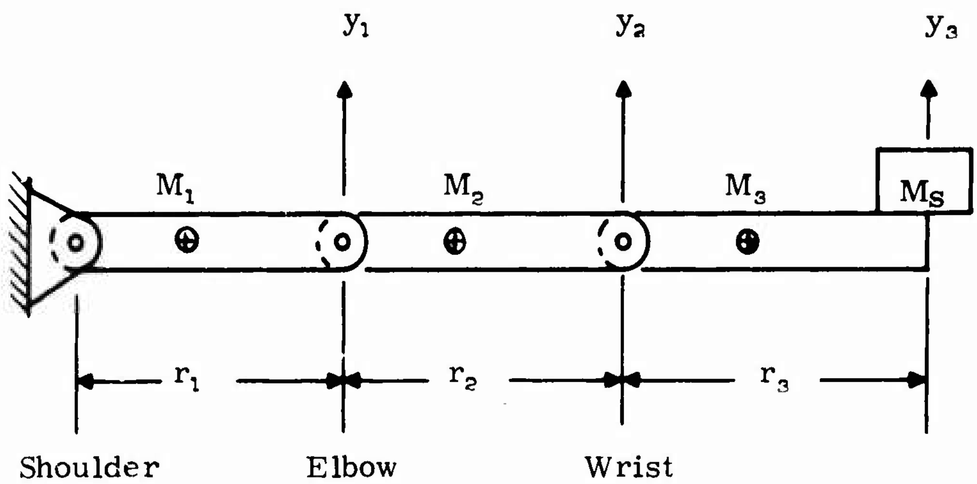
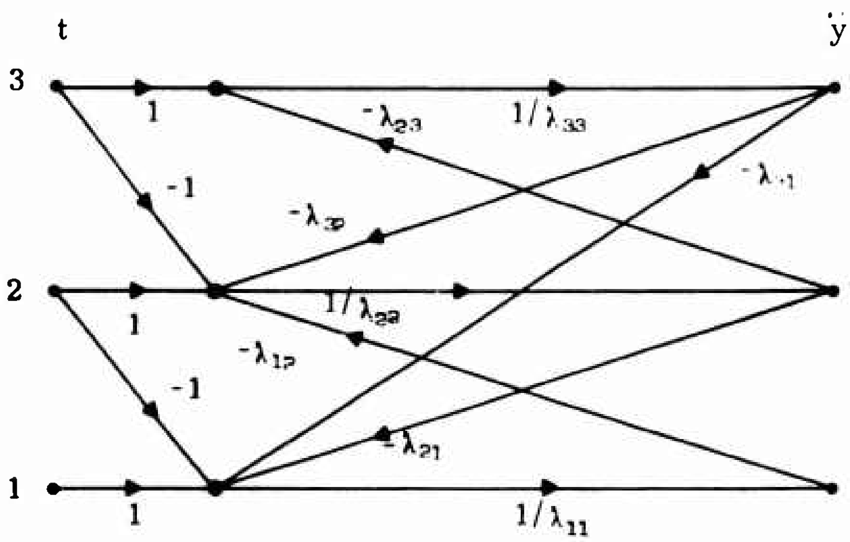


Figure 14. Recorder Trace of Analog Simulation of Exoskeleton Arm - Light Mass



		r (in)	M (lb sec^2/in) Master	Slave
Shoulder	1	19.5	0.0145	0.056
Elbow	2	10.0	0.0202	0.130
Wrist	3	13.0	0.0174	0.037
Load	s	--	0.026	1.94

Figure 15. Mechanical Parameters



t = torque
ÿ = acceleration

Figure 16A. Partial Signal Flow Diagram Based on Derivation of Dynamic Intercoupling Between Links

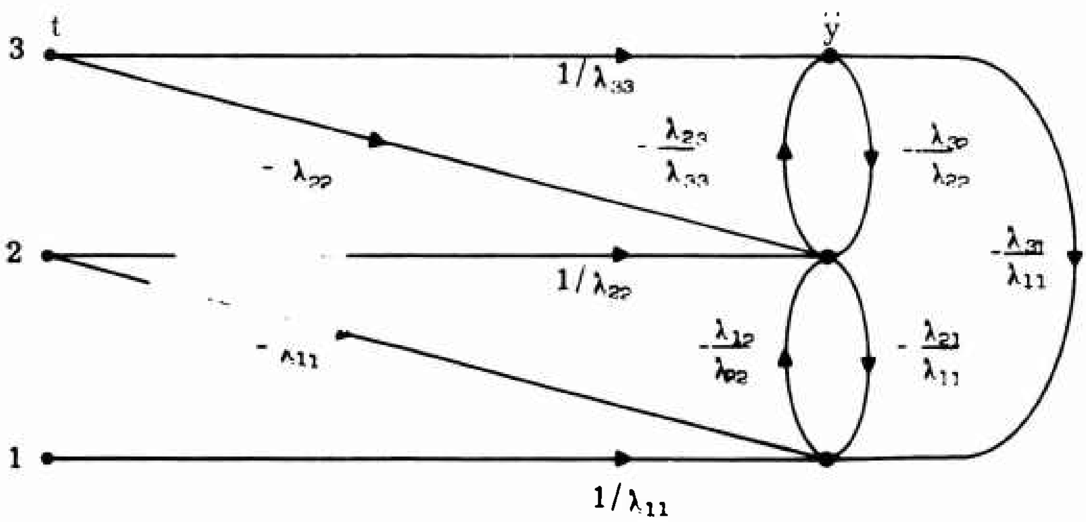


Figure 16B. Same Diagram Rearranged to More Convenient Form. This is the Form Used in the Complete Signal Flow Diagram (Figure 12)

$$\lambda_{jk}$$

j \ k	1	2	3
1	$r_1 \left(\frac{M_1}{3} + \frac{M_2}{2}\right)$	$r_2 \frac{M_2}{6}$	0
2	$r_1 \left(\frac{M_2}{2} + \frac{M_3}{2}\right)$	$r_2 \left(\frac{M_2}{3} + \frac{M_3}{2}\right)$	$r_3 \frac{M_3}{6}$
3	$r_1 \left(\frac{M_3}{2} + M_s\right)$	$r_2 \left(\frac{M_3}{2} + M_s\right)$	$r_3 \left(\frac{M_3}{3} + M_s\right)$

Figure 17. Formula for Each λ

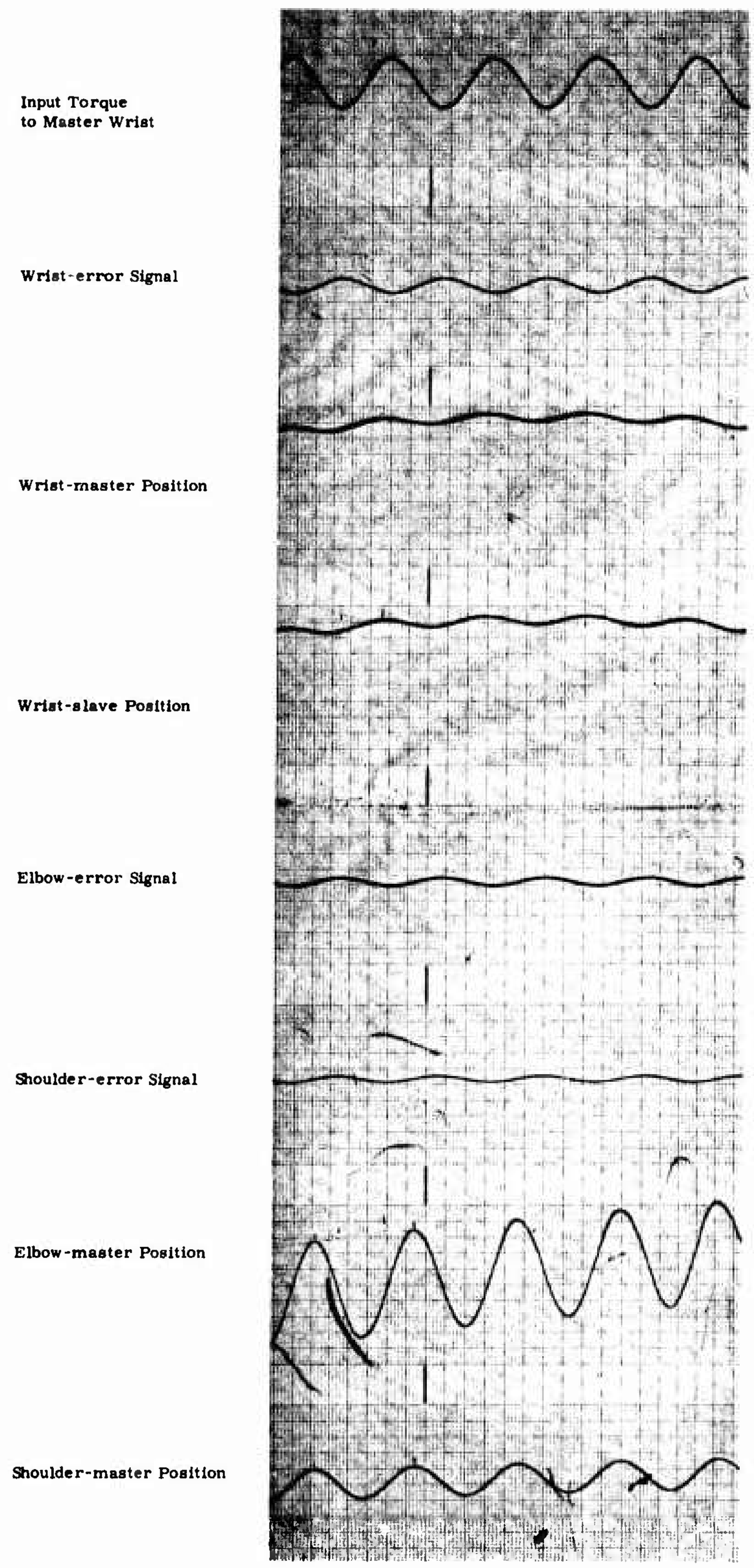


Figure 18. Recorder Trace of Analog Simulation of Exoskeleton Arm - Heavy Mass

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Specialty Materials Handling Products Operation General Electric Company 1 River Road, Schenectady, New York	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP - - - -

3. REPORT TITLE
Hardiman I Prototype Project

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Special Technical Report on Joints in Series

5. AUTHOR(S) (First name, middle initial, last name)
Kendall E. Gilbert
Patrick C. Callan

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
10 June 1968		3

8a. CONTRACT OR GRANT NO. Contract N00014-66-C0051 b. PROJECT NO. Project No. IM62101050702 c. Contract Auth. Ident. No. NR196-049 d.	9a. ORIGINATOR'S REPORT NUMBER(S) S-68-1081 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT Each transmittal of this document outside the agencies of the U.S. Government must have the approval of the Army Mobility Equipment Research and Development Center (Attn: SMEFB-HM), Fort Belvoir, Virginia 22060, or the EngineeringPsychology Branch of the Office of Naval Research (Code 455), Washington, D.C. 20360.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Office of Naval Research and U.S. Army Mobility Equipment Research and Development Center

13. ABSTRACT
Stable operation of unilateral and bilateral servos on a series of manipulator links for Hardiman was analyzed and demonstrated on an analog computer.

DD FORM 1 NOV 65 1473

Unclassified
Security Classification

Unclassified
Security Classification

14 KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Manipulator						
Exoskeleton						
Bilateral Servos						
Joints in Series						
Hardiman I						

Unclassified
Security Classification

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