AUGMENTED RIGS

PHASE II REPORT

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

CONTRACT NAS8 28574

TRW
SYSTEMS GROUP
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PHASE II REPORT

AUGMENTED RIGS

NASA George C. Marshall Space Center

Contract NAS8-28574

January 15, 1974

Prepared by:

R. A. Kaminskas
D. McGuire

TRW
SYSTEMS GROUP

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1. INTRODUCTION

This report describes the results of the Phase II Resonant Infrasonic Gauging System (RIGS) development program. The program consisted of design, fabrication, and testing of an "augmented" RIGS concept. The program was conducted under NASA, George C. Marshall Space Flight Center sponsorship, Contract No. NAS8-28574, between 15 July 1973 and 15 January 1974.

The RIGS is a gauging system capable of measuring propellant quantities in zero-g as well as under accelerated conditions. Except for hydrogen, it can be used to gauge virtually any propellant in liquid form, including cryogenics. The gauge consists of a sensor unit which is attached to the propellant tank and an electronic control unit which may be positioned separately from the sensor. The control unit receives signals from the sensor as well as the propellant temperature measurement and the ullage gas pressure, and computes the propellant quantity in the tank.

The principal advantages of the RIGS over more conventional gauging systems such as PVT or capacitance systems are:

- The RIGS can operate under zero-g as well as under accelerated conditions
- It will operate with vented tanks
- It can be used to gauge propellants in tanks using bladders, as well as bladderless tanks
- It can be used to gauge any size or shape tanks, including most tanks incorporating surface tension propellant orientation devices.

During an earlier program, Phase I, two prototype RIGS sensors were designed and fabricated. The sensors were tested first in the laboratory using water as the simulated propellant and later using LN_2. The tests proved that the gauge operates virtually as predicted by theory and yielded a fuel gauging accuracy of 0.75%. However, the system had several shortcomings. As a result, it was recommended that an improved version, called the Augmented RIGS, which promised to overcome all the shortcomings, be developed and tested during Phase II.

The specific tasks that this program (Phase II) set out to accomplish were:

1) Design a new RIGS incorporating an "augmentation" feature
2) Construct a sensor and control system incorporating the augmentation
3) Perform system tests.

Tasks 1 and 2 were accomplished and a complete Augmented RIGS was designed and built. However, system tests showed that a low, damping ratio is required in order to derive the full benefit from the augmentation feature.

2. SUMMARY

Originally, the Resonant Infrasonic Gauge System (RIGS) was designed at TRW for use on the Apollo SPS tanks. The system was thoroughly analyzed and a breadboard model was constructed and tested. Although the test results were very encouraging, it became evident that the system could not be developed and qualified in time for use on the Apollo, and the development was discontinued in 1967. With the advent of the Space Shuttle vehicle, the development of the RIGS was resumed again in April 1972 as a candidate for gauging the shuttle booster LOX tank.

The RIGS system consists of a sensor, which is attached to the tank, and an electronic control unit. Ullage gas pressure and propellant temperature measurement are also required by the control unit for fuel mass computation. The sensor, as shown in Figure 2-1, contains a driver piston (bellows) and a follower piston. The follower piston is free to pivot up and down, and when excited will resonate with the ullage gas volume of the tank (which acts as a spring when compressed). The driver piston is driven up and down by a motor at a frequency such that the two pistons are nearly in phase. At this point the resonating frequency of the follower piston is dependent only on the ullage volume and the mass on the bellows. Thus, the resonating frequency is a measure of the ullage volume in the tank and hence the propellant quantity.

The follower piston uses bellows with a very low spring constant and a mass sized to yield a system resonant frequency of several Hz or less. The original RIGS concept developed during Phase I used an actual weight attached to the bellows. The Augmented RIGS incorporated an electromagnetic subsystem which simulated the weight by electric means.

Use of low frequency serves two purposes:

1) The ullage gas compression occurs in a nearly isothermal mode
2) The pressure wave is transmitted through the propellant without significant attenuation.

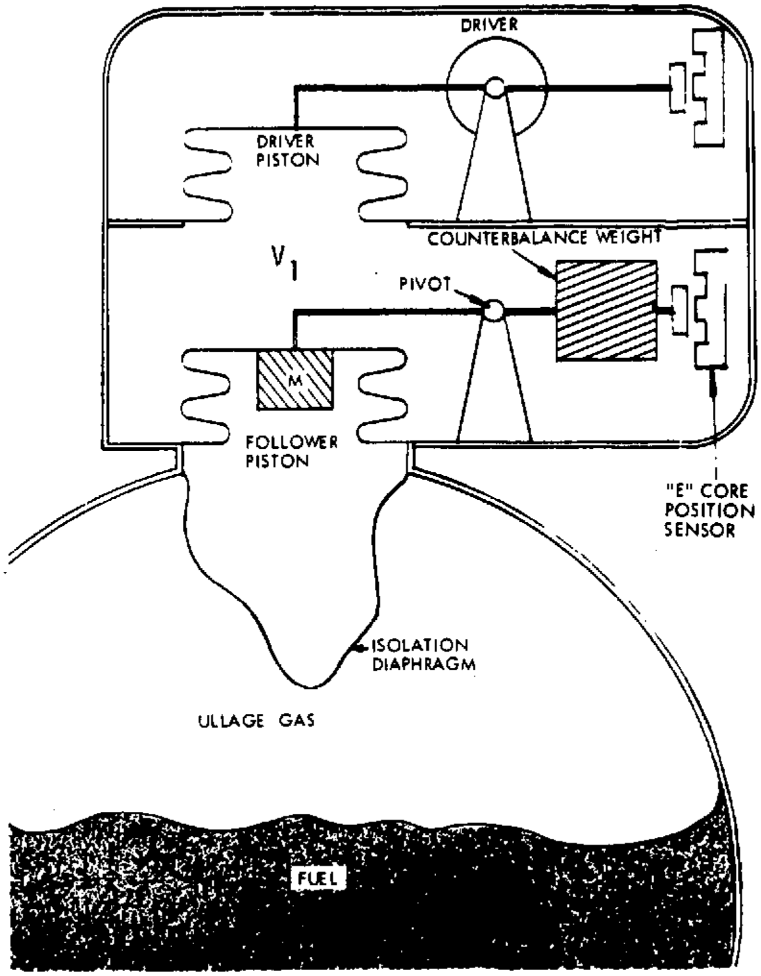


Figure 2-1. RIGS Sensor Schematic Diagram

It is important for the RIGS to operate in essentially the isothermal mode so that the resonating frequency does not change with the constitution of the ullage gas (due to changes in the ratio of the specific heats, γ). This is especially important when gauging a vented LOX tank where the ullage gas is composed of O_2 vapors and helium pressurant in a ratio that can change significantly during the course of a mission.

Figure 2-1 shows an isolation diaphragm between the sensor and the tank. This diaphragm prevents the propellant from entering the sensor but is sufficiently flexible so that it can transmit the pressure waves from the follower piston without attenuation.

The driver piston in the RIGS sensors is actuated by an electric DC motor through a gear reduction and a crankshaft drive. The piston position is measured by an "E" core position transducer as shown in Figure 2-1. The actuating frequency of the driver is varied by the control unit to maintain a given phase relationship between the driver and the follower pistons. Theoretically, the driver should lead the follower by a few degrees when the follower is in resonance with the ullage volume. However, in practice it was found that best experimental results were obtained at considerably larger phase differences (on the order of 25 degrees).

The control unit block diagram is shown in Figure 2-2. It receives the driver and follower piston position signals, computes the phase difference between them and adjusts the driver motor speed to keep the phase at the desired value.

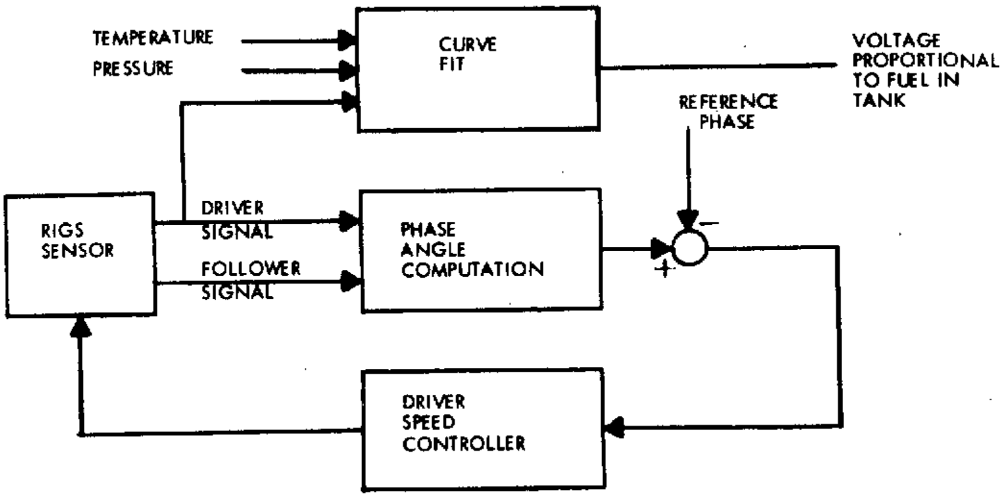


Figure 2-2. RIGS Control System Block Diagram

During Phase I two prototype RIGS sensors were built. They are shown in Figure 2-3 and 2-4. The sensor in Figure 2-3 was made out of plexiglas so that the driver and follower piston motion could be observed and studied. The second sensor, shown in Figure 2-4, was built for tests with cryogenic propellants. The control unit, which was used with both sensors during Phase I and later during Phase II with the augmented sensor, is shown in Figure 2-5.

Some of the test data obtained with the original (not augmented) RIGS are given in Figure 2-6. It can be seen that the sensor performance was very close to the predicted values and the system gave an overall gauging accuracy better than 1.0 percent.

The Augmented RIGS was designed to overcome two principal disadvantages of the Phase I RIGS:

Figure 2-3. RIGS Sensor (First Unit).

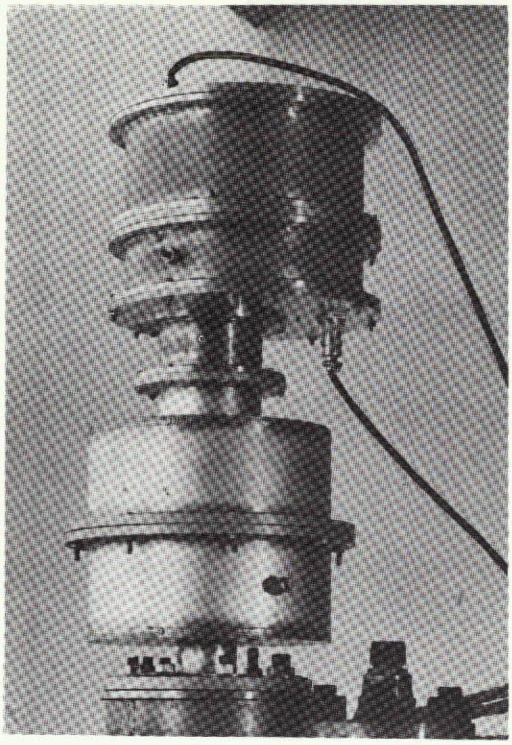


Figure 2-4. RIGS Sensor (Second Unit)

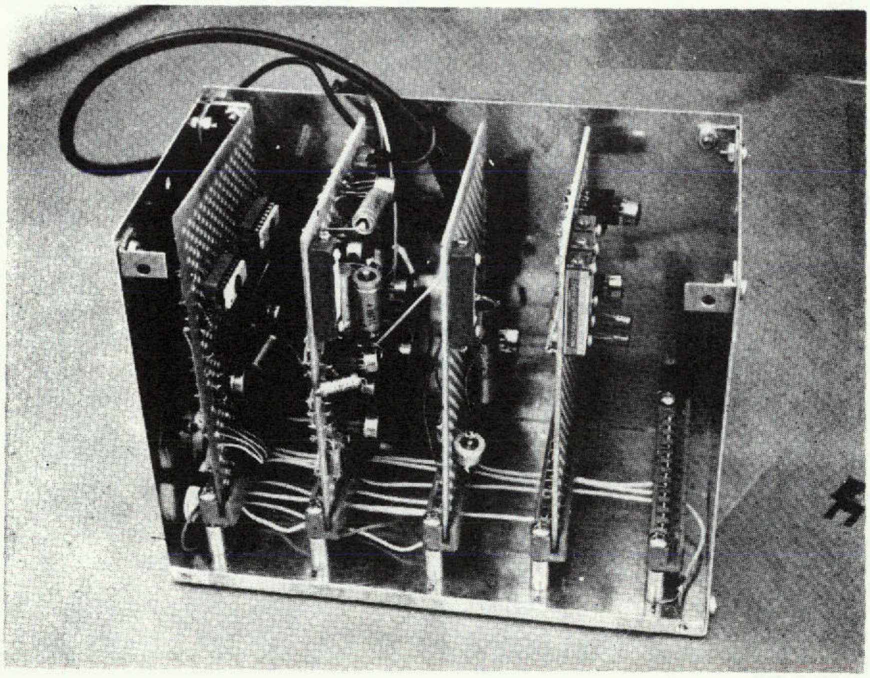


Figure 2-5. RIGS Control Unit Electronics

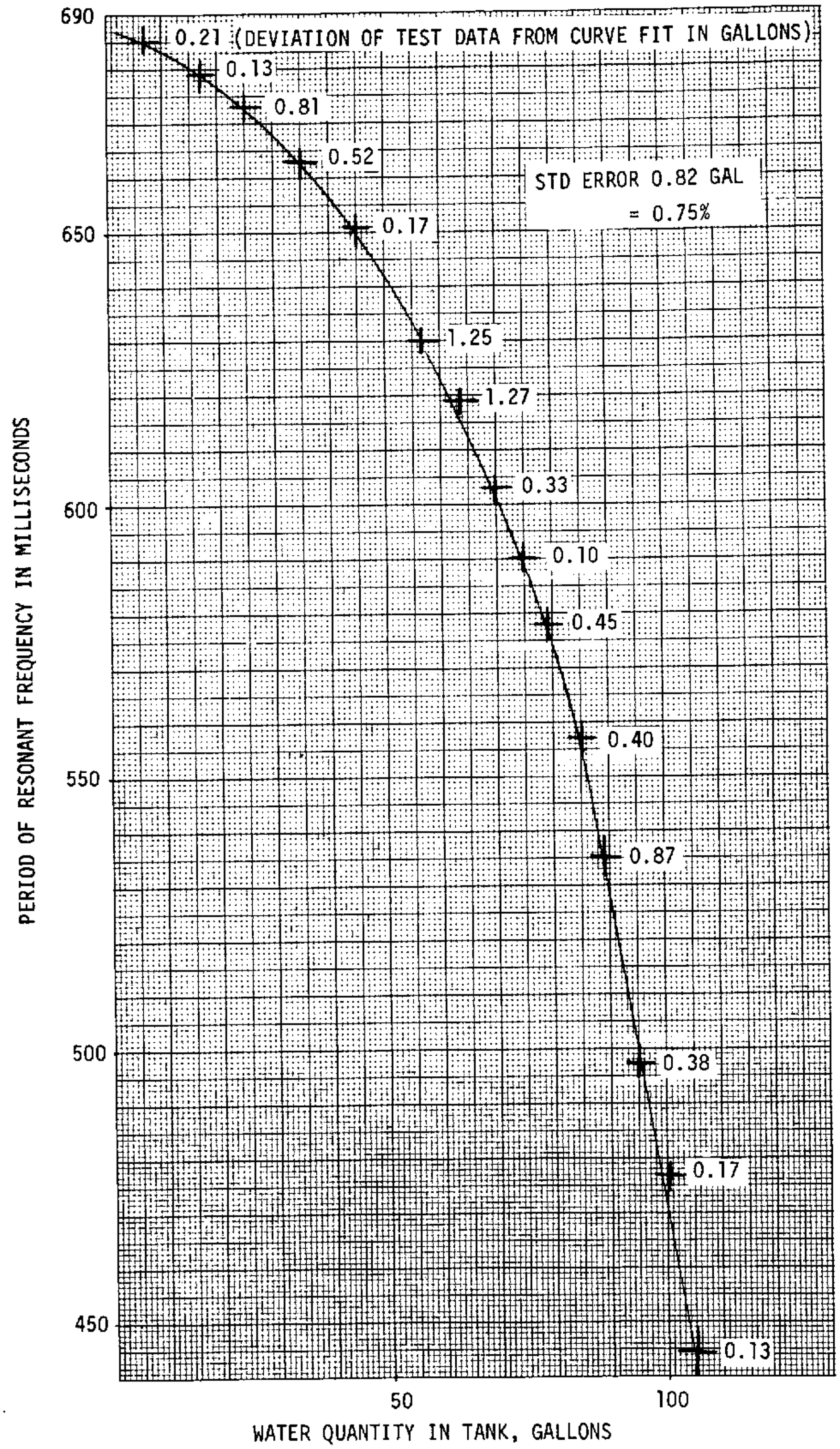


Figure 2-6. RIGS Test Data (Phase I)

1) To make the system resonate at approximately 1 Hz so that pressure waves could be transmitted uniformly to the ullage volume, it was necessary to load the follower bellows with about a one-pound weight and another one-pound weight to counterbalance it. This large weight increment makes the system unattractive for space applications.

2) The required spring constant of the bellows was on the order of 0.1 pound per inch. Thus, thin plastic bellows were employed which were flimsy and difficult to handle.

The augmented version of RIGS developed during Phase II is shown schematically in Figure 2-7. A torque motor attached to the follower piston is used to simulate the mass on the bellows. This is accomplished by taking the follower piston position signal ("E"-core sensor signal shown in Figure 2-7), differentiating it twice so that it represents the follower piston acceleration, and applying it to the torque motor so that the torque produces a force on the bellows to resist the acceleration. In this way a mass on the bellows is simulated by electrical means. Also, the torque motor makes it possible to use bellows with a realtively high spring constant. By applying a torque with the torque motor equal to the force exerted by the spring but in the opposite direction, the spring constant of the bellows could be made to approach zero.

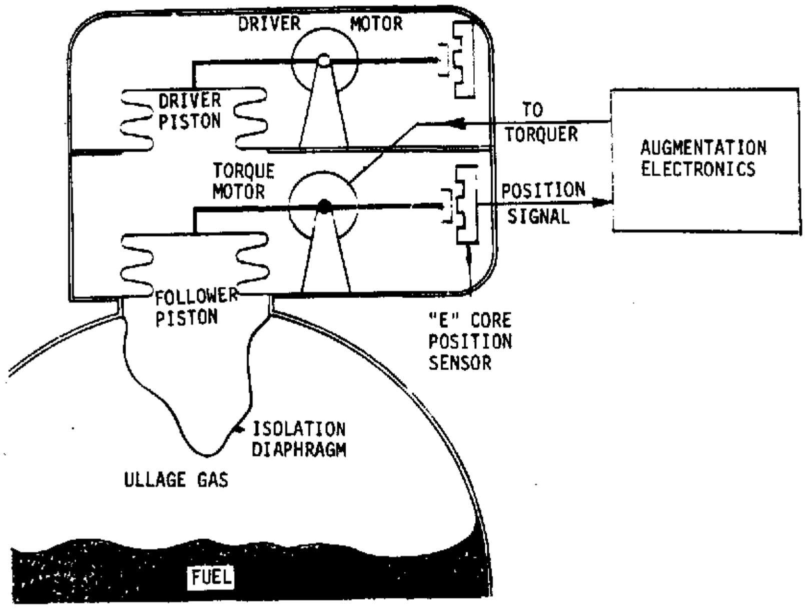


Figure 2-7. Augmented RIGS

The Phase II tests of the Augmented RIGS sensor were mostly devoted to the development of the augmentation system. The follower position signal used to reduce the apparent spring constant of the bellows worked well from the beginning. However, the double differentiation of the follower bellows position signal continued to introduce excessive amounts of noise in the control system and made it impossible to increase the torque gain to the level required to simulate a mass of sufficient size. Filtering of the follower position signal to remove the noise introduced a phase lag, which acted as a damping term and made the follower resonance frequency insensitive to the ullage volume changes.

The experience gained with the augmented RIGS sensor during this phase of the program indicated:

- Use of the torque motor to compensate for the relatively high spring constant of the bellows is quite feasible. Thus, metal bellows with a spring constant on the order of 2 lb/in. could be employed, and this spring constant could be reduced to approximately 0.1 lb/in., or below, by electromagnetic means.
- Simulation of a mass on the bellows using a torquer does not appear to be practical due to excessive noise generated in the double differentiation circuit. Thus, RIGS sensors built in the future will require using a relatively large mass (1 to 2 lb) to yield resonating frequencies in the desired range.

3. OPERATING PRINCIPLES OF AUGMENTED RIGS

The operating components of the RIGS sensor are presented schematically in Figure 2-1. The sensor is comprised of three basic elements, viz.:

1) a driver piston
2) a follower piston
3) a variable frequency driver.

From the arrangement shown, a downward motion of the driver piston will produce a volume displacement in V_1, causing the follower piston to move a corresponding distance; in turn, the follower piston compresses the ullage. If the driver is moved sufficiently slowly such that dynamic effects can be ignored, then the pressure change in the ullage (assuming adiabatic conditions) is given by:

$$\frac{\Delta P}{P} = -\gamma \frac{\Delta V}{(V_u + V_1)} \cong -\gamma \frac{\Delta V}{V_u} \quad \text{with } V_u >> V_1 \tag{3-1}$$

where:

V_1 = volume between pistons
V_u = ullage volume
γ = ratio of specific heats.

On the other hand, if the driver is excited sinusoidally at increasing frequency, equation (3-1) is no longer valid and the dynamic effects must be taken into consideration. This is accomplished directly by noting that the follower piston is simply a mass coupled to the driver and the ullage through two gas "springs" represented respectively by the volume between the two pistons, V_1, and the ullage volume, V_u. Assuming an adiabatic process, the spring rate of the two volumes is:

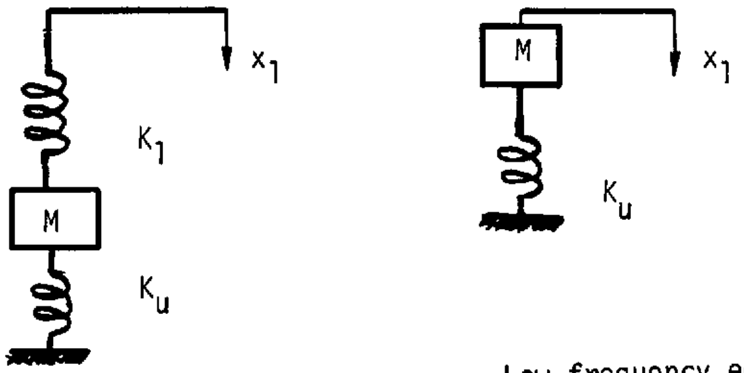
$$K_1 = \gamma \frac{P_1 A^2}{V_1} \qquad K_u = \gamma \frac{P_u A^2}{V_u} \tag{3-2}$$

where:

A = area of follower piston

$P_1 = P_u$ = system static pressure.

The mechanical equivalent of the system is shown in Figure 3-1, where X_1 is driver displacement



High frequency equivalent

Low frequency equivalent

Figure 3-1. System Mechanical Equivalent

Since the ullage gas volume V_u is much larger than V_1, the spring rate K_1 is appreciably greater than K_u, and at low frequencies the upper volume acts essentially as if it were a stiff rod imposing a motion of the mass M (Figure 3-2). The force which must be transmitted by K_1 to produce the motion of the mass is a function of the dynamic impedance of the mass and the ullage gas spring; i.e.,

$$F_{total} = \text{Force to accelerate mass + force to compress } K_u$$

$$= F_M + F_u$$

However, since in practice the pistons are made using bellows, the spring constant of the bellows K_B must also be taken into account. Thus, the equation above is rewritten:

$$F_{total} = F_M + F_B + F_u$$

and

$$F_{total} = M \frac{d^2x}{d\,t^2} + (K_u + K_B)x = M\ddot{x} + (\frac{A^2\gamma\,P_u}{V_u} + K_B)\,x \qquad (3\text{-}3)$$

At some particular frequency, the force required to accelerate the mass will be balanced by the restoring force of the gas spring and the system will be in resonance (i.e., in the absence of friction, the system will continue to oscillate without any additional applied force). At this condition,

$$M\,\ddot{x} + (\frac{A^2\gamma\,P_u}{V_u} + K_B)\,x = 0 \qquad (3\text{-}4)$$

Solving for the resonant frequency yields:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{A^2\,\gamma\,P_u}{M\,V_u} + \frac{K_B}{M}} \qquad (3\text{-}5)$$

Thus, the resonant frequency is related to the spring constant of the bellows and the magnitude of the ullage gas spring rate or the ullage volume. By knowing the mass and area of the follower piston, and the pressure and the effective specific heat ratio of the ullage gas, the ullage volume is uniquely determined by measuring the resonant frequency.

The resonant frequency of the follower piston is determined by demanding that the phase difference between the driver and the follower pistons be of a certain value. As the driver frequency is varied, the phase difference between them varies. At the resonant point, when the follower piston mass is in resonance with the ullage gas cavity, the driver is leading the follower by a few degrees.

In the augmented system a torquer applies an external force to the follower bellows in order to simulate a bellows loaded with a large mass. The force that is required to be exerted on the bellows can be derived from Equation 3-4. Assume that the bellows physically has a small mass (m), and a relatively large mass (M) is added externally by force F(x) through a torquer. Then Equation 3-4 is rewritten as:

$$(m + M)\ddot{x} + \left(\frac{A^2\gamma P_u}{V_u} + K_B\right)x = F(x) \qquad (3\text{-}6)$$

and F(x) required to simulate a large mass (m + M) is $M\ddot{x}$.

By making the torquer force $F(x) = M\ddot{x} - K^1{}_B x$, Equation 3-6 becomes:

$$(M + m)\ddot{x} + \left(\frac{A^2\gamma P_u}{V_u} + K_B - K^1{}_B\right) = F(x) \qquad (3\text{-}7)$$

Now if the force applied by the torquer is equal to and opposite to the spring force of the bellows such that $K_B = K^1{}_B$, no matter what the actual bellows spring constant is (within the torque capabilities of the torquer), it may effectively be made zero or whatever value is desired.

A block diagram of the Augmented RIGS sensor follower piston and associated control system is given in Figure 3-2. In all other respects the RIGS sensor operation remains unchanged from Phase I.

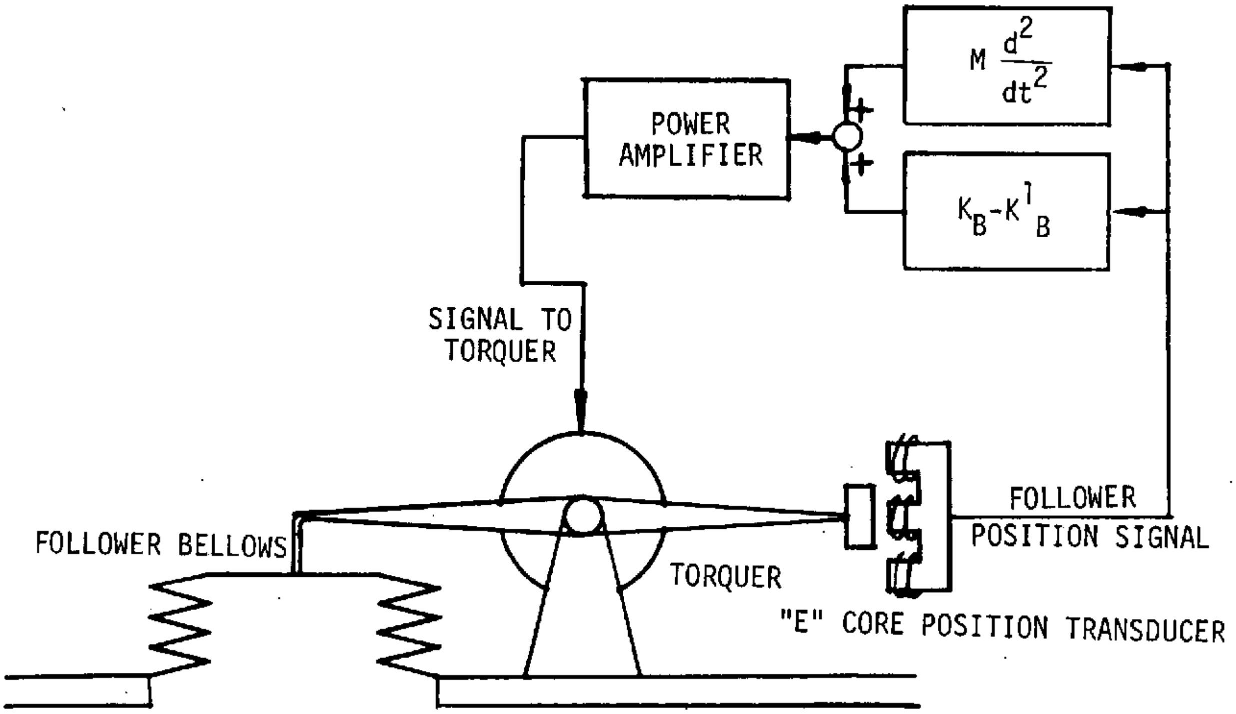


Figure 3-2. Augmented RIGS Follower Piston and Control System Block Diagram

4. AUGMENTED SENSOR DESIGN

4.1 MECHANICAL DESIGN

Photographs of the Augmented RIGS sensor that was constructed during Phase II are shown in Figure 4-1 and 4-2. Figure 4-1 shows the assembled sensor and Figure 4-2 shows the follower bellows assembly and the torque motor. An assembly drawing of the sensor is given in Figure 4-3.

The case of the sensor was built out of aluminum and was 11 inches in diameter by 8.5 inches high. The sensor used Standard Welded Bellows Co. (part number 400-200) metal bellows with 4 inch OD, 2 inch ID, and an effective area of 7.06 square inches. The bellows were specially fabricated from 0.003 inch thick 347 steel and have a spring constant of approximately 2 pounds per inch.

A Clifton Precision DC torque motor (part number D-1938-F-7) was used with the follower system. The torquer is 1.938 inches O.D., 0.625 I.D. and 1.325 inches wide. It has a peak torque of 66 oz-inches at 56.5 volts and draws a maximum of 3.2 amps. Since the torque is required to move only a few degrees in this application, the brush assembly was affixed directly to the commutator (rather than to the stationary part or the magnet of the torquer) to eliminate brush friction.

The follower and the driver counterballance arms were mounted on hardened tool steel shafts and supported by jewel bearings.

The driver arm was actuated by a Clifton Precision DC motor (part number 823007-04H) through a 81.1 to 1 planetary reduction gearhead and an eccentric crank drive.

The follower piston and the driver position signals were picked off by "E" core transducers which were specially made for this project.

The sensor assembly also incorporated various connectors for electrical connections and pressure ports for pressure equalizations. All sensor parts were assembled using "O" rings so that the sensor case was air tight.

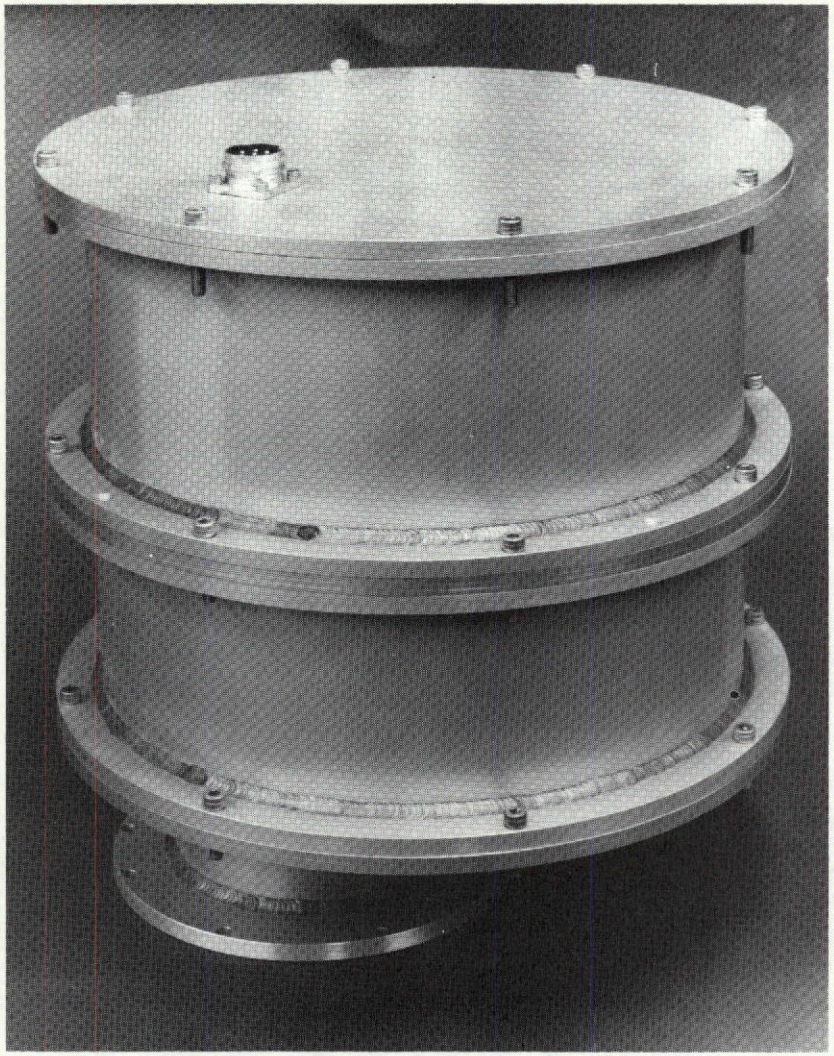


Figure 4-1. Augmented RIGS Sensor Assembly

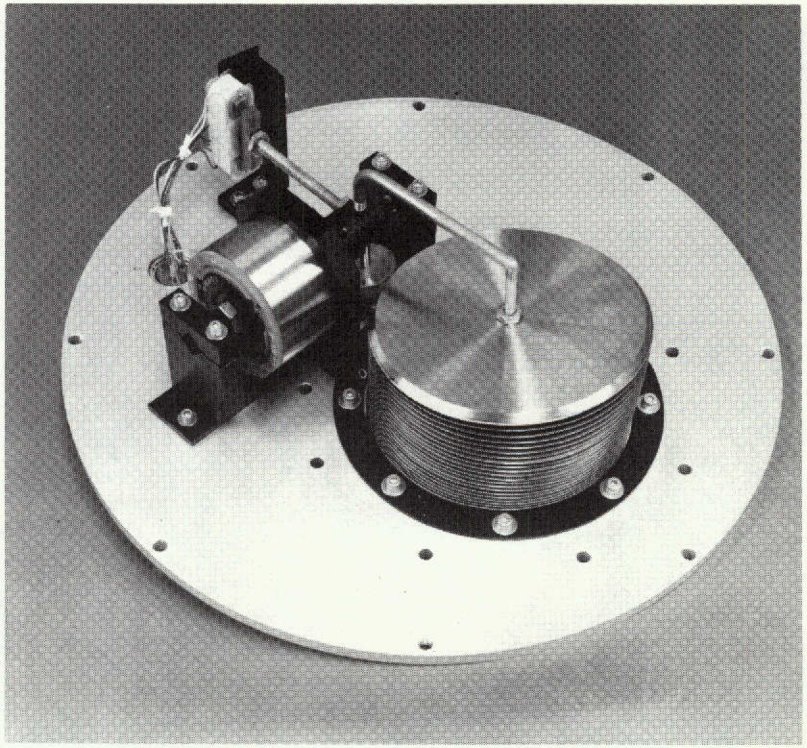


Figure 4-2. RIGS Follower Piston & Torquer

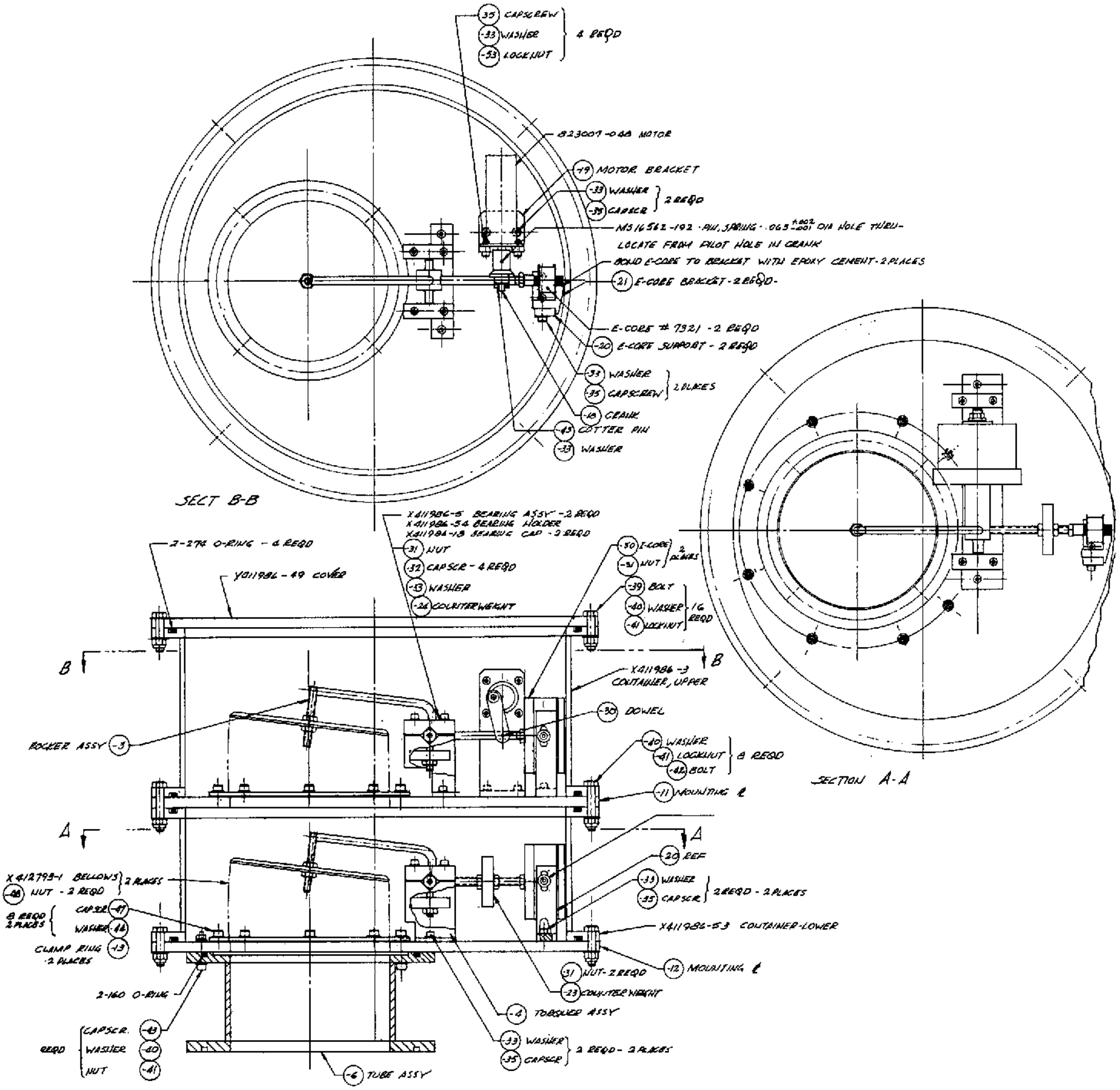


Figure 4-3. Augmented RIGS Sensor Assembly Drawing

4.2 ELECTRONICS

The RIGS electronics consist of two subsystems:

a) Control unit.

b) Augmentation electronics.

The control unit performs the function of adjusting the driver motor speed such that the follower piston is kept in phase with the driver piston and thus in resonance with the ullage volume of the tank. A block diagram of the control system is shown in Figure 4-4. It remained essentially unchanged from Phase I. A brief description of the control unit operation is given below. For detailed schematics the reader is referred to the RIGS Phase I report.*

The driver and the follower E-core transducers are excited from a 400-Hz phase-shift oscillator and sense the position of their respective bellows. The output waveform from the E-cores is a 400-Hz sinusoidal wave with amplitude proportional to the position of the bellows. The demodulators convert this AC voltage to DC. This DC voltage is amplified by high gain amplifiers operating in saturating mode. The resulting square waves are used to trigger a flip-flop which is sensitive to the positive slope of the input signal, so that the driver sets the flip-flop, while the follower resets the flip-flop. The resulting flip-flop output waveform is a square wave whose width is proportional to the phase difference between driver and follower. Figure 4-5 illustrates the method used to compute the phase difference. The flip-flop output is integrated by an operational amplifer with an RC time constant of 10 seconds, which produces a DC voltage proportional to the phase difference. The integrator output is compared to a stable reference voltage that represents the desired phase difference (reference phase). The difference between the reference phase and the actual phase produces a phase error voltage which is integrated by an operational amplifier having an RC time constant of approximately 15 seconds. This integrated phase error voltage is applied to the motor driver amplifier which causes the motor to speed up or slow down in order to reduce the phase error voltage to zero, thus maintaining the desired reference phase.

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*"Development of Isothermal RIGS, Final Report", TRW Systems Contract NAS8-28574, April 9, 1973.

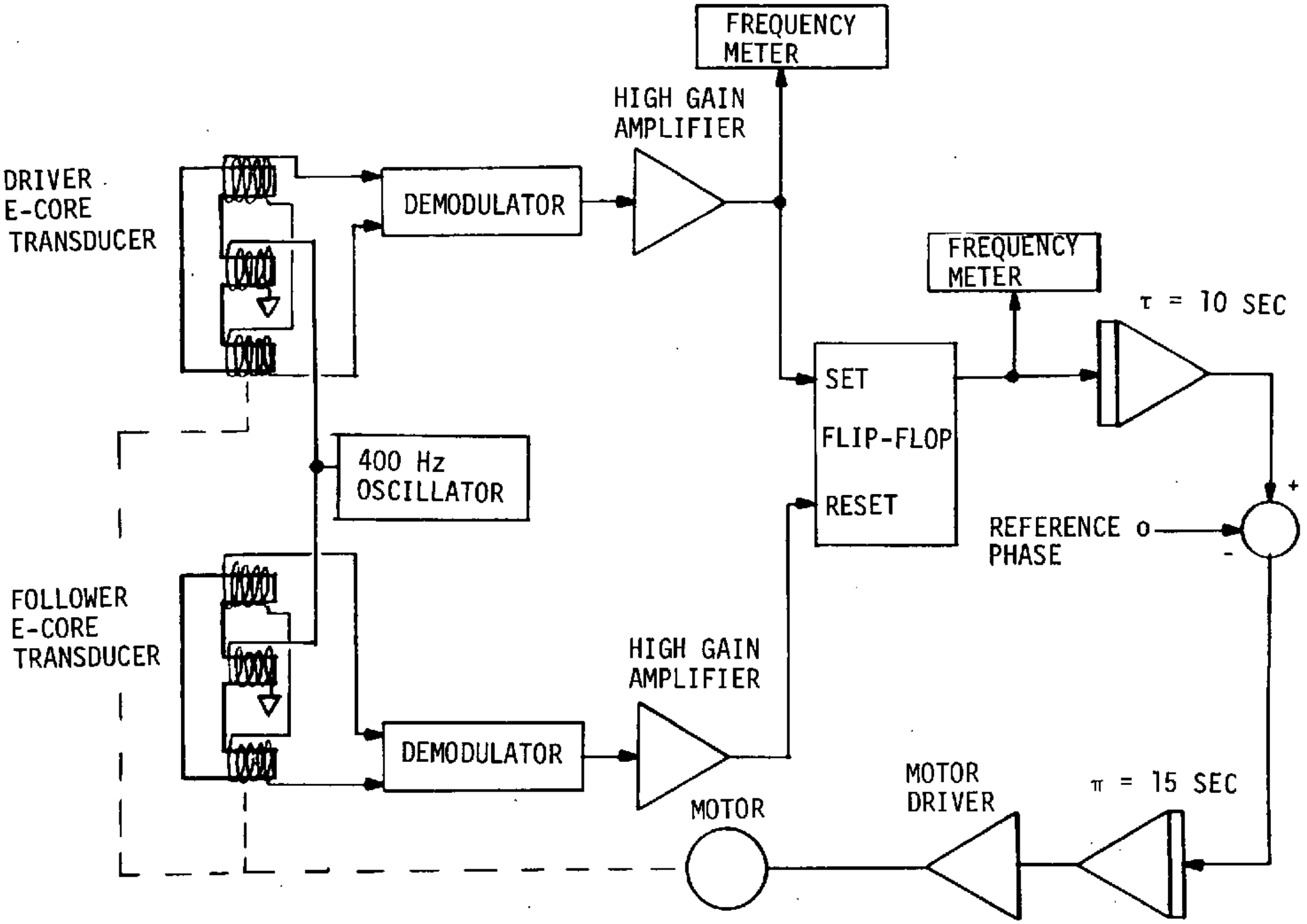


Figure 4-4. RIGS Control System Block Diagram

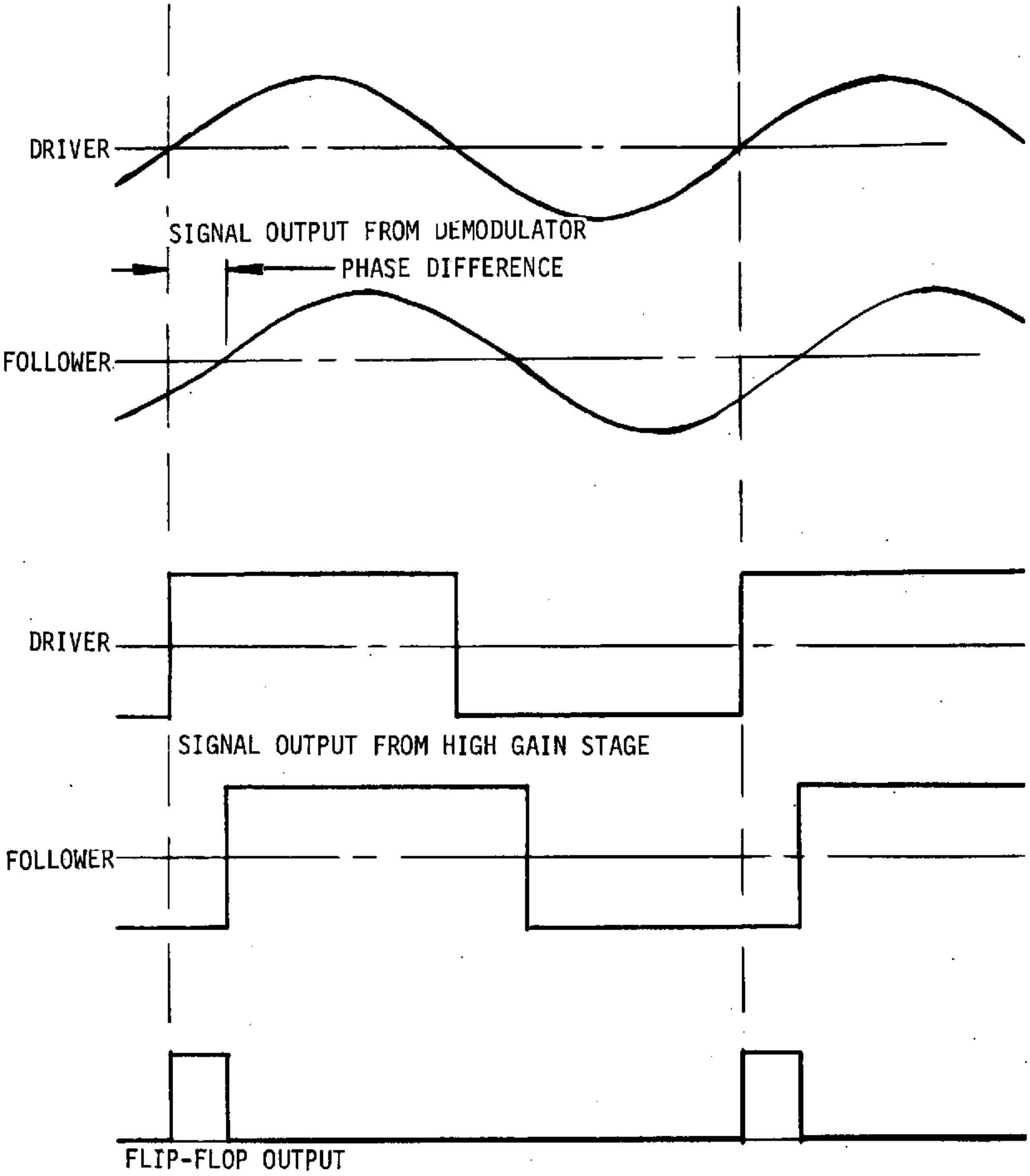


Figure 4-5. Illustration of the Method Used to Compute Phase Difference Between Driver and Follower Bellows

The augmentation subsystem provides power to the torque motor. A block diagram of the subsystem is shown in Figure 4-6. It consists of the following major components:

a) Signal differentiation circuit.

b) Power amplifier.

The follower position signal is picked off from the demodulator in the control unit and is filtered with a low pass filter set at a 300 Hz cutoff frequency to remove the 400 Hz ripple from the demodulator. The filtered signal is then double differentiated by a circuit shown in Figure 4-7. During the course of the program several differentiating schemes were employed. However, the circuit shown in Figure 4-7 appeared to work the best. When tested open loop, it was completely linear in the range of frequencies of interest (0.3 to 3 Hz). The transfer function of the differentiating circuit is:

$$\frac{E_o}{E_i} = \frac{133\ s^2}{(169)^2 + 100s + s^2}$$

where s is the Laplace transform. A Bode diagram of the differentiating circuit is given in Figure 4-8.

A schematic of the power amplifier which is used to drive the torquer motor is shown in Figure 4-9. As can be seen from the schematic the output from the differentiating circuit and the inverted follower piston signal are summed at the power amplifier input. Trim pots are provided so that the gains of the two signals can be adjusted individually. The power amplifier was capable of producing ± 56 volts at 3.2 amps or approximately 175 watts of power.

Figure 4-10 shows the augmentation electronics breadboard. In the foreground is the circuit containing the double differentiation, filters, and part of the power amplifier. Output power transistors are mounted on heat sinks on top of the box.

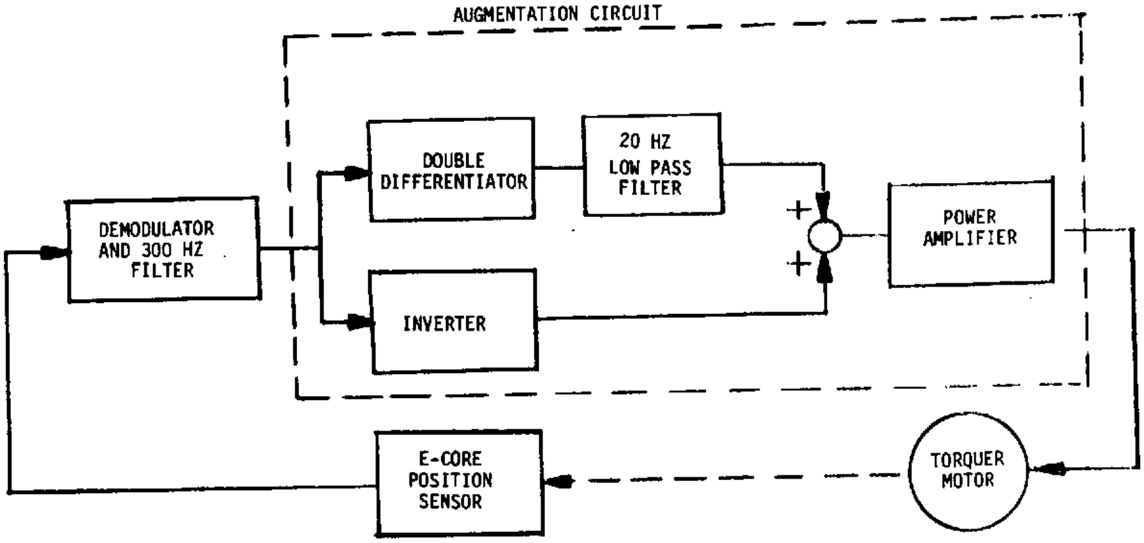


Figure 4-6. RIGS Augmentation System Block Diagram

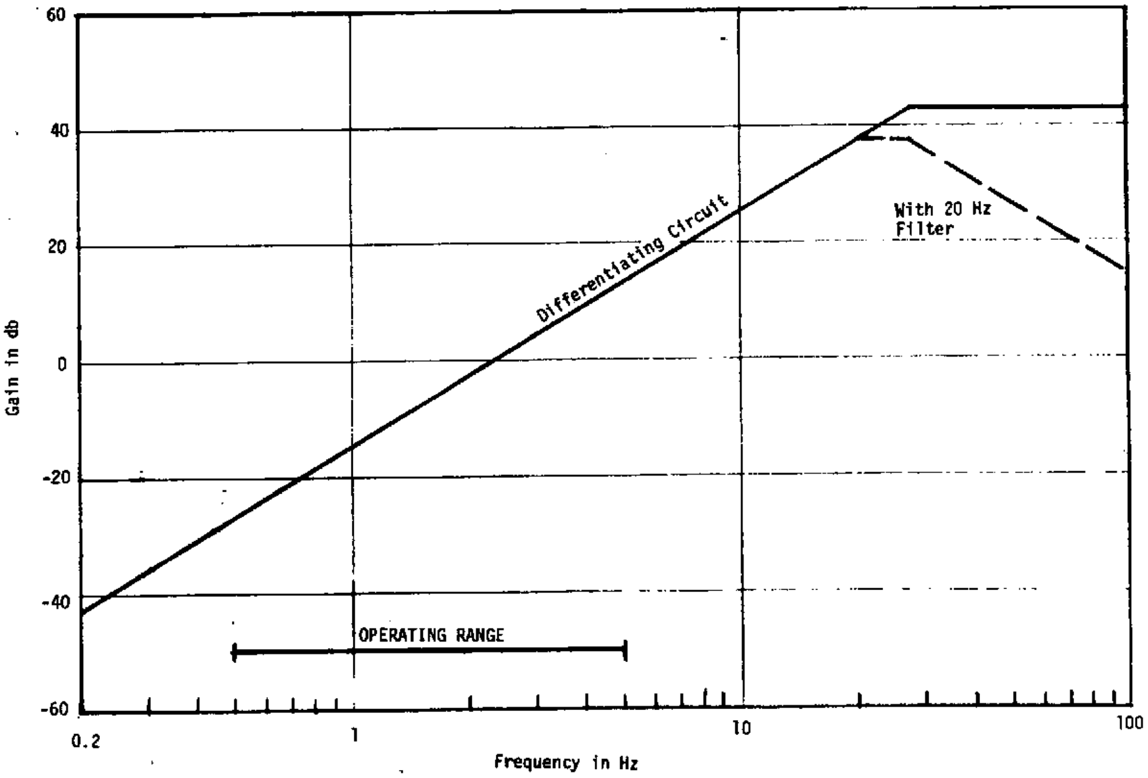
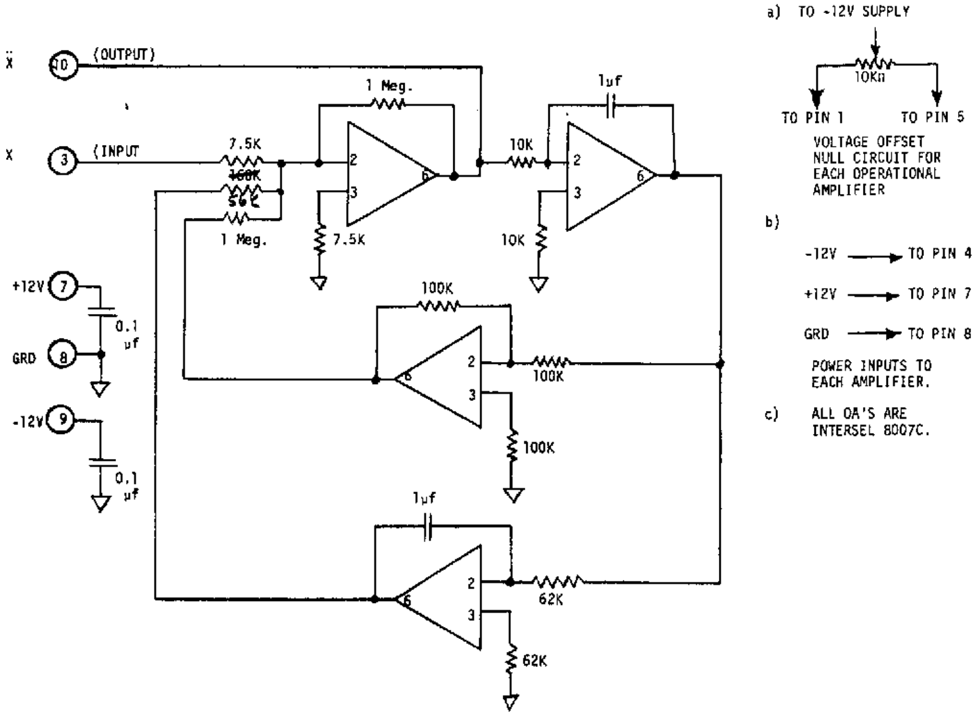


Figure 4-7. Augmented RIGS Double-Differentiating Circuit



a) TO -12V SUPPLY

TO PIN 1 TO PIN 5

VOLTAGE OFFSET NULL CIRCUIT FOR EACH OPERATIONAL AMPLIFIER

b)

-12V → TO PIN 4

+12V → TO PIN 7

GRD → TO PIN 8

POWER INPUTS TO EACH AMPLIFIER.

c) ALL OA'S ARE INTERSEL 8007C.

Figure 4-8. Augmented RIGS Double-Differentiating Circuit

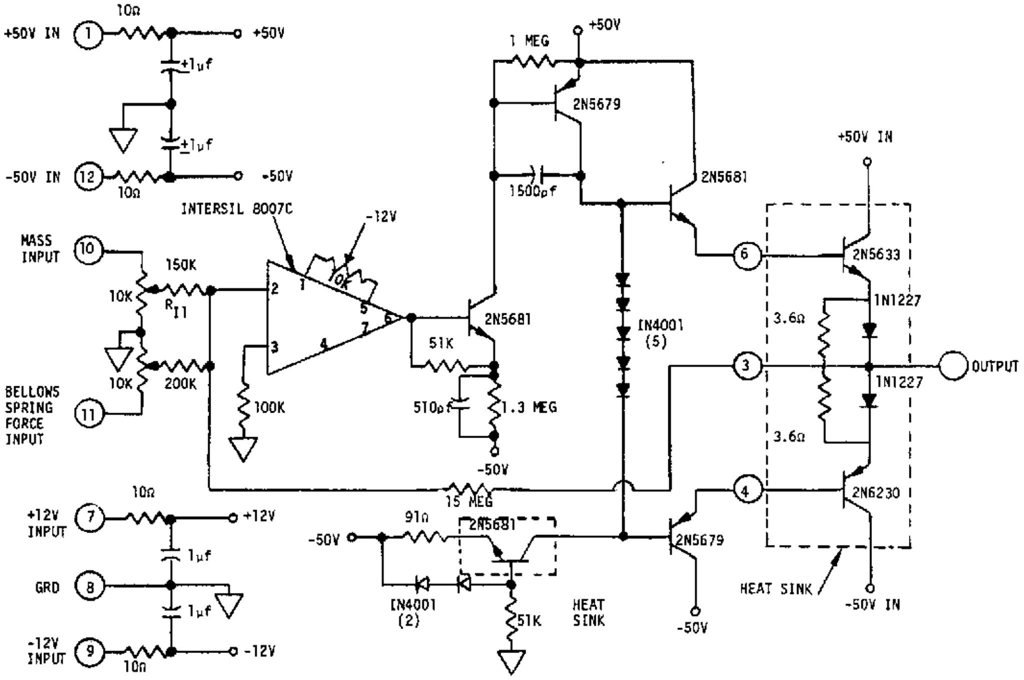


Figure 4-9. Torquer Power Amplifier

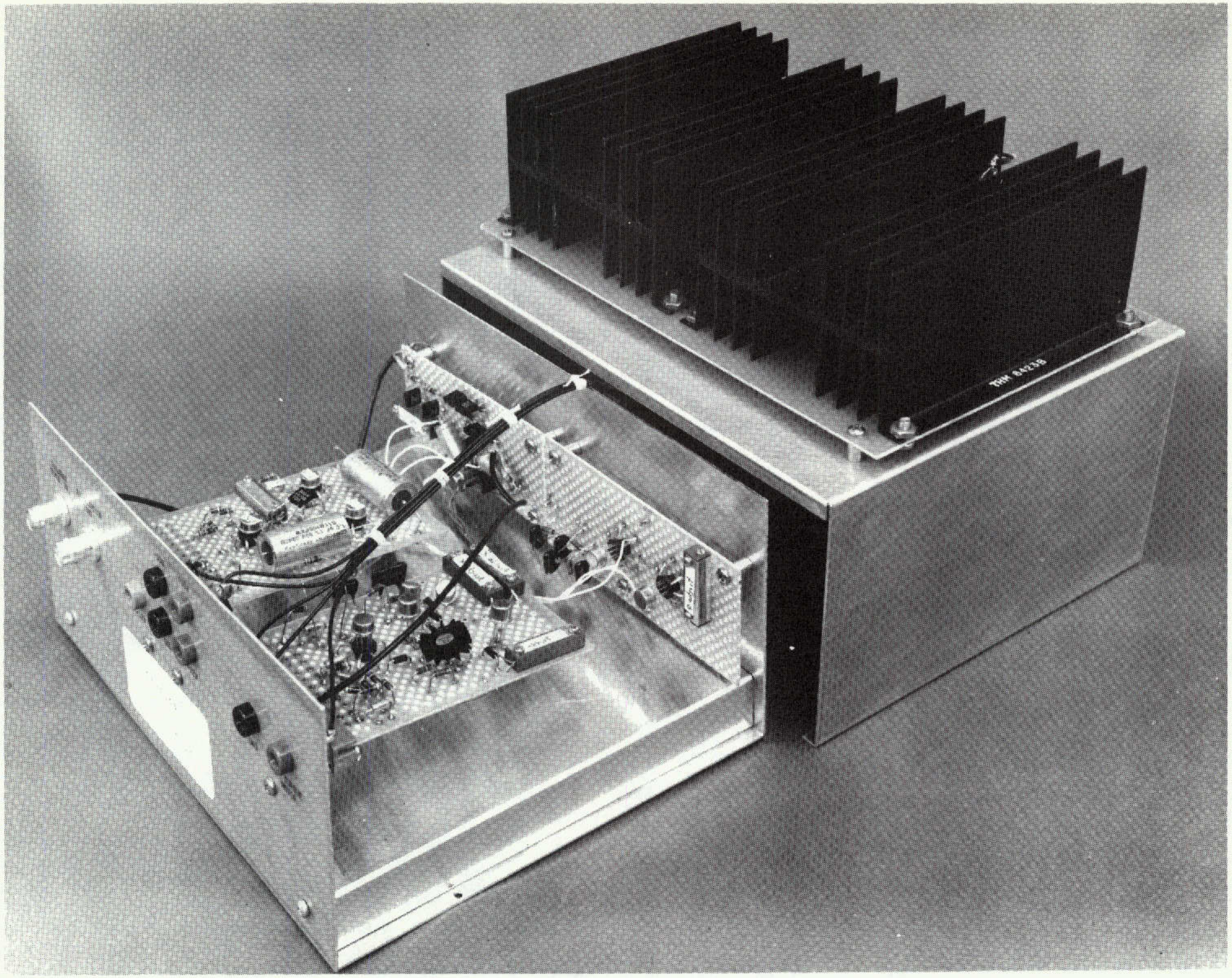


Figure 4-10. RIGS Augmentation Electronics

5. TESTS

After initial system checkout and debugging, a majority of the system tests were performed with a setup as shown in Figure 5-1. Driving signal to the RIGS follower bellows was provided by a sine wave generator. The signal from the generator was summed in with the follower position and acceleration inputs at the torquer motor power amplifier. This setup allowed to drive the follower bellows via the torquer at any desired frequency and amplitude thus making it convenient to perform frequency response measurements.

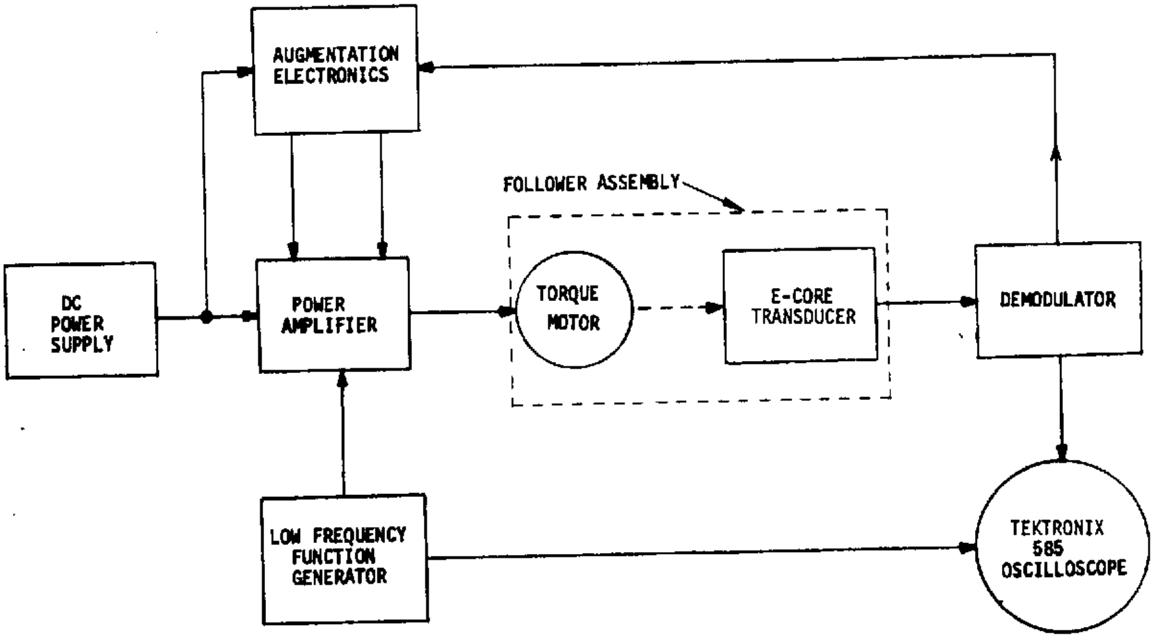


Figure 5-1. Augmented RIGS Test Setup.

The frequency response diagram of the RIGS follower in air (infinite ullage volume) and without augmentation is shown in Figure 5-2. The system had a natural resonating frequency slightly above 5 Hz, and a damping ratio

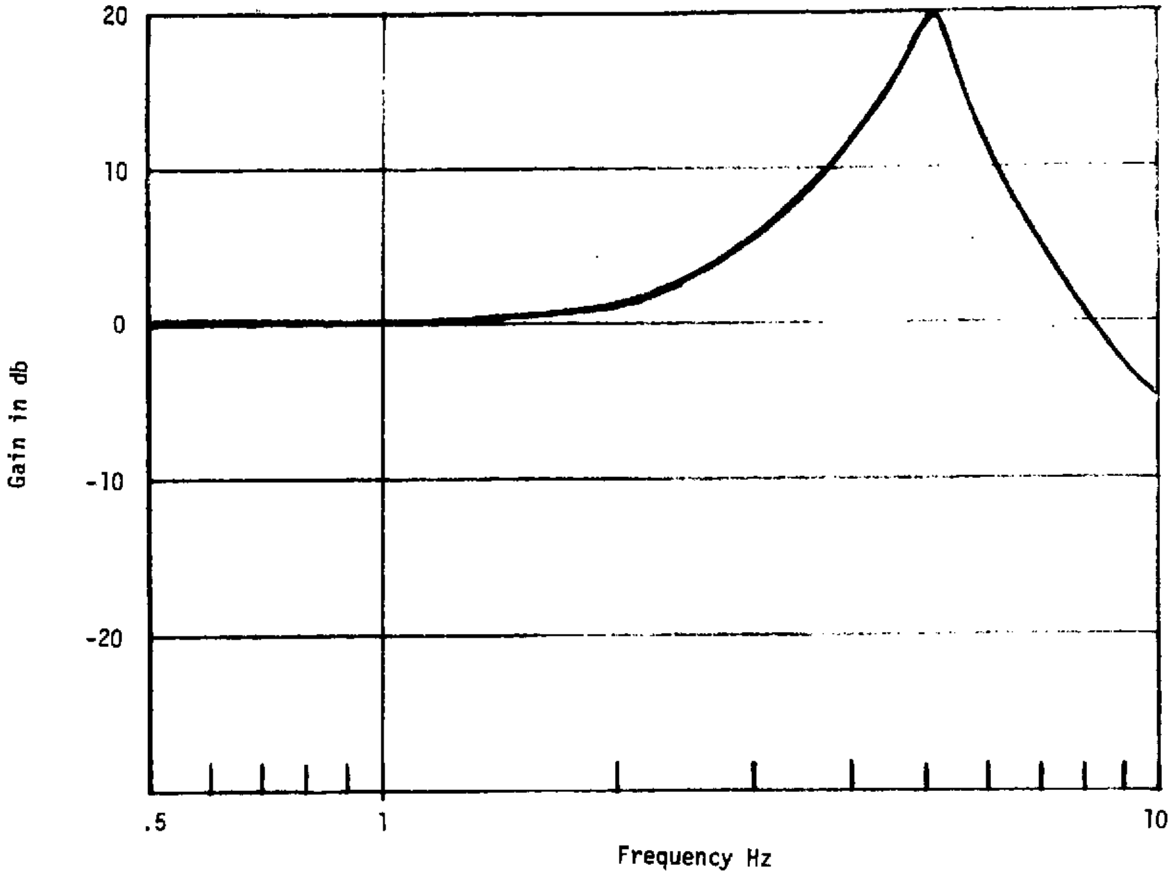


Figure 5-2. RIGS Follower Frequency Response

(z) of 0.1. The effect of addition of the follower acceleration signal is shown in Figure 5-3. The resonant frequency could be reduced to approximately 2 Hz. The reduction of resonant frequency from 5 to 2 Hz represents a simulated increase of the follower mass (M) by a factor of 6.25. For the system to operate properly the natural resonating frequency had to be reduced to approximately 1.2 Hz. However, note that the damping ratio in Figure 5-3 has been increased from the original value of 0.1 to approximately 0.25. This is due to phase shifts introduced in the system which, in spite of all efforts, could not be entirely removed. Additional increase of the acceleration gain required additional signal filtering, which increased the system damping ratio. At the desired resonant frequency of 1.2 Hz the damping ratio was approximately 0.7.

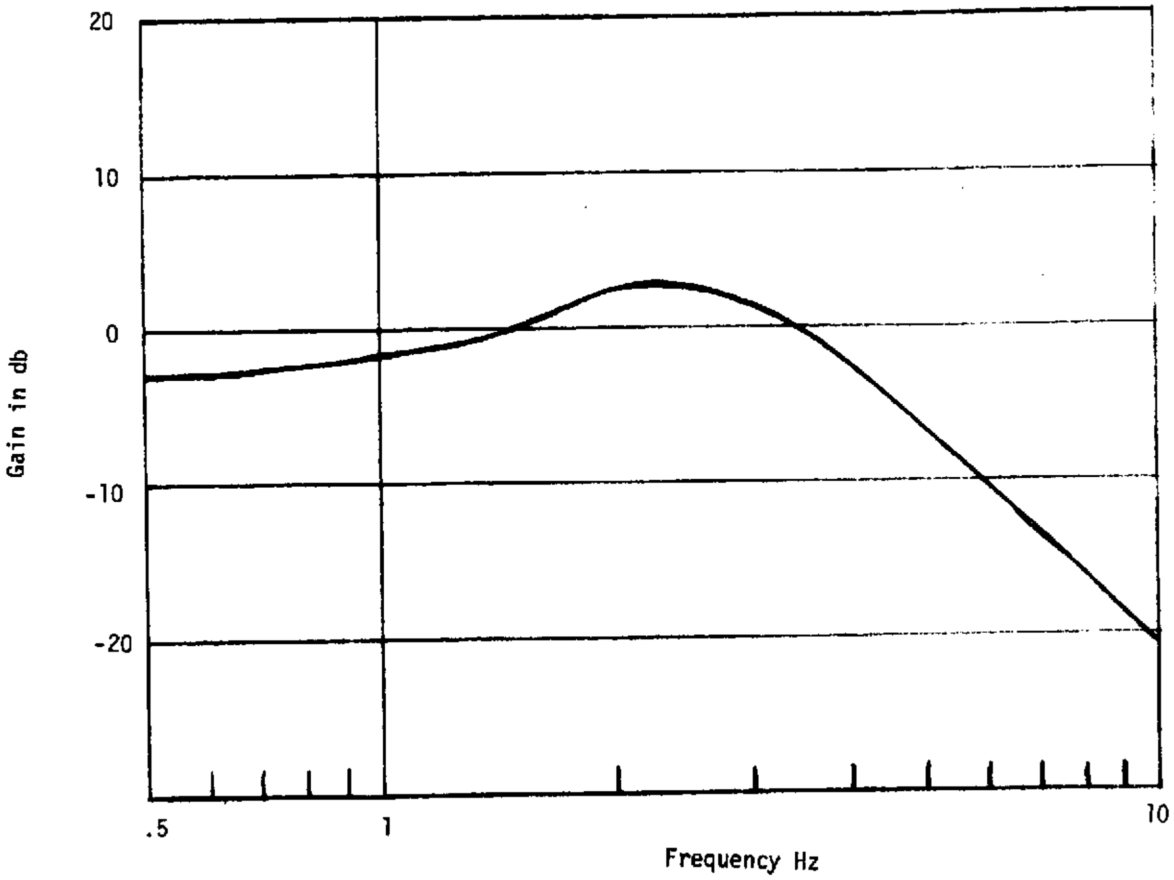


Figure 5-3. RIGS Follower Frequency Response with Augmentation.

For the control unit to operate properly a relatively small damping ratio is required. The control unit compares the phase difference between the driver and the follower pistons and adjusts the driver speed to keep the phase angle between two at a desired value. High values of damping ratio (z), as illustrated in Figure 5-4, produce smaller changes in phase angle with changes in frequency, and as a result the control unit is unable to "lock in" on the proper frequency.

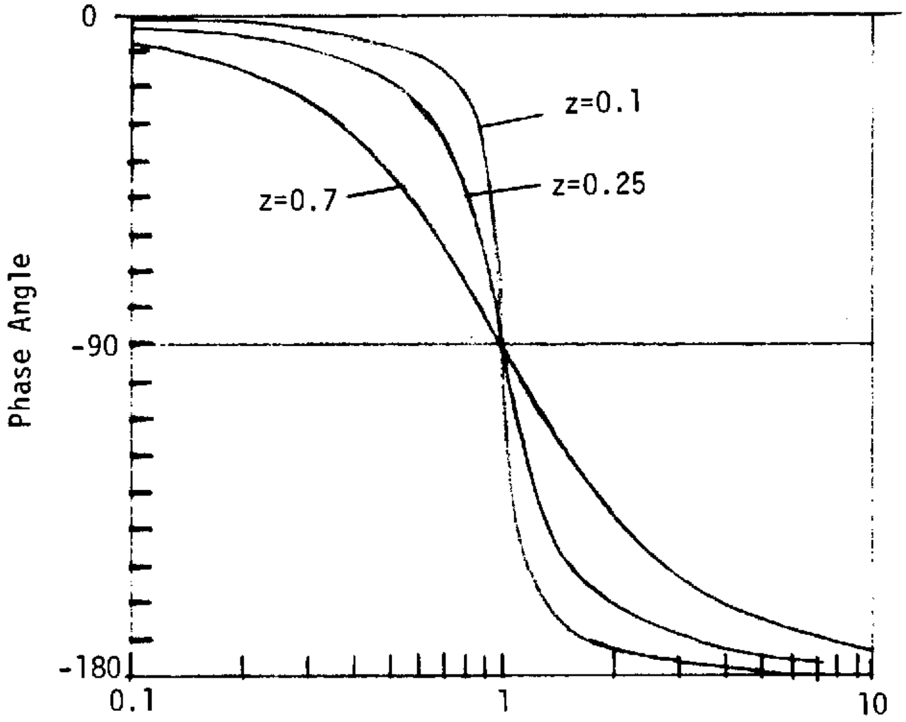


Figure 5-4. Phase Shift as a Function of Damping Ratio (z).

Some of the test data obtained with the follower position signal input alone (the term that compensates for the spring constant) are shown in Figure 5-5. The data were obtained by placing a 35 gram weight on the bellows and recording the follower demodulator output (which is proportional to the follower deflection) as a function of position signal potentiometer gain setting. The scatter in data is due to friction in the system. The data indicate that by increasing the follower position gain the effective spring constant of the bellows is decreased. Thus, for a fixed weight on the bellows (35 grams) a larger deflection is produced.

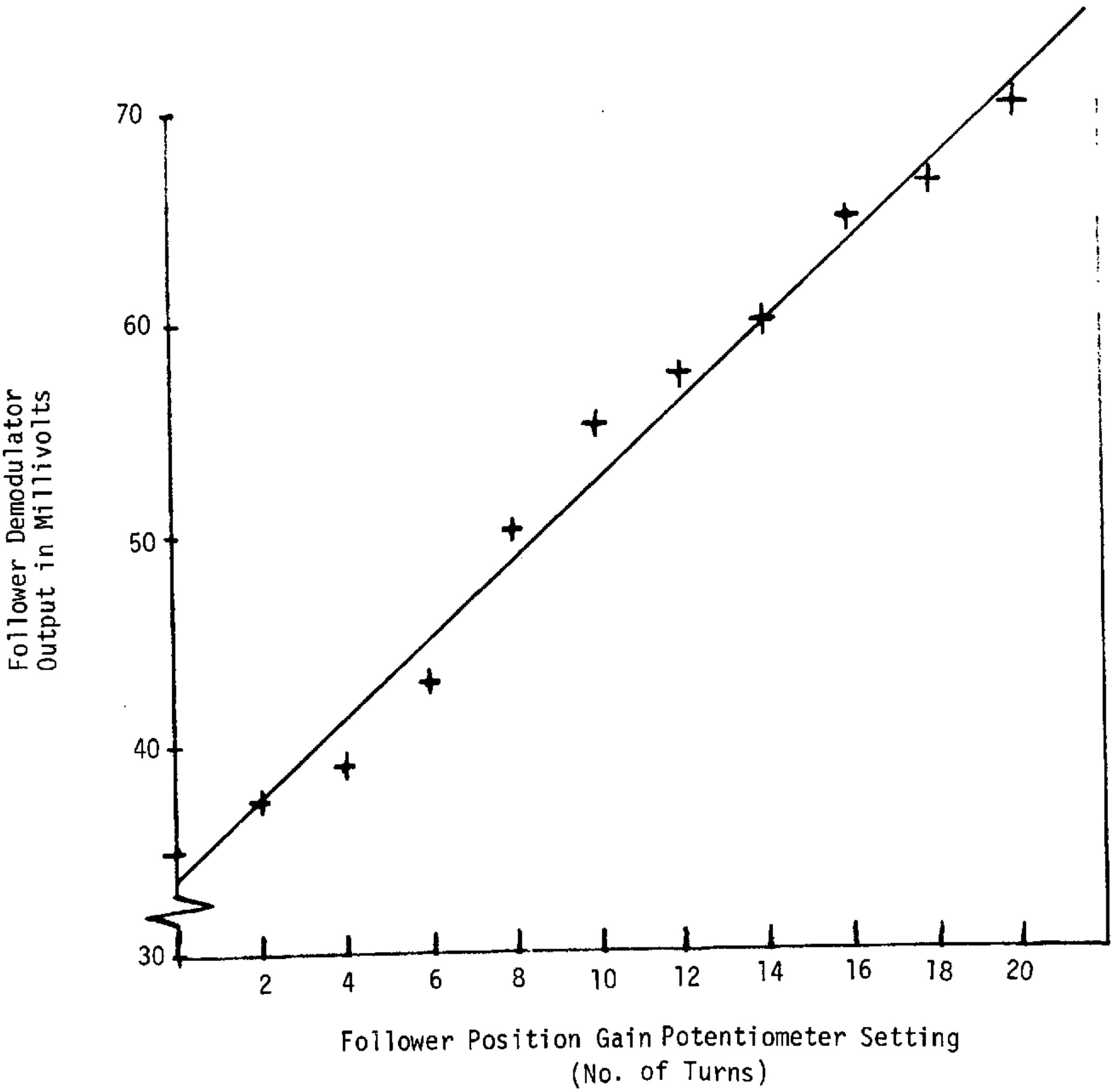


Figure 5-5. Change in Effective Bellows Spring Constant as a Function of Follower Position Signal Gain.