



Aero Report 1727-FR1

FINAL REPORT

STUDY PROGRAM TO DETERMINE
THE ACCELERATION ENVIRONMENT CAPABILITY
OF THE GG159C GAS-BEARING SPINMOTOR

Jet Propulsion Laboratory
Contract No. 950604

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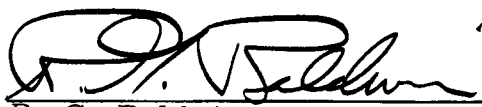
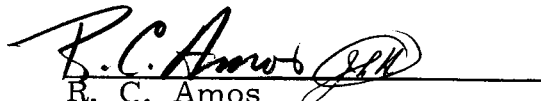
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SECTION I CONTRACT SUMMARY

CONTRACT WORK

The goal of this contract was to determine the g environment under which the GG159C Gas-Bearing Spinmotor (GBSM) could reliably operate. This was fulfilled by building and testing of four GBSM's, a test fixture, and a "dummy" gyro.

The test program was divided into two phases when a gas bearing improvement was required to withstand JPL shock requirement of 200 g. Phase I determined existing g capabilities and performance of the GG159C GBSM and gimbal-case structure. Phase II increased GBSM capability to meet required JPL g environments.

Life tests were run on two GBSM's which were shocked at a high level to obtain bearing contact while rotating at their operating speed of 24,000 rpm. A third (nonoperating) GBSM was exposed to JPL maximum shock levels, and a fourth (nonoperating) GBSM was exposed to random vibration. Both nonoperating GBSM's were then subjected to life testing.

CONTRACT RESULTS

Based on contract test results, these conclusions can be drawn:

- The GG159C Gas-Bearing Spinmotors will withstand JPL shock (200 g's) and random vibration (25 g_{rms}) requirements when using an improved thrust bearing.

- The GG159C gimbal and case structure will withstand the g environment and have 1.1 transmissibility to the GBSM. This 10 percent over unity is believed to be experimental error.

Gas-Bearing Spinmotor g Environmental Testing

Gas-Bearing Spinmotor testing was divided into two phases as shown in Table 1.

Table 1. GG159C GBSM g Capability

Item	Random Vibration grms (20-2000 cps)	Shock g Peak (1.5 millisecond half sine)	
		Phase I Results	Phase II Results
Journal Bearing	>25	190	200 >240 at 37 psi pressure
Thrust Bearing	>25	100	>200
JPL Requirement	25	200	200

Phase II was directed at improving the thrust bearing by testing a new pattern showing theoretical promise.

Gyro Transmissibility Testing

Testing of a "dummy" gyro containing three orthogonally mounted accelerometers instead of a spinmotor inside the gimbal resulted in the g transmissibility of the GG159C gyro structure from the gyro outer flange to the internal gimbal motor mounts. This was obtained for sinusoidal, random vibration, and shock g environments up to and including 200 g shock and 25 g random vibration levels. Transmissibility, found to be about 110 percent (10 percent experimental error), was independent of the environment level.

Gas-Bearing Spinmotor Life Test

Two GBSM's were exposed to a high g environment of 1.5 millisecond shock sufficient to cause bearing contact while the GBSM rotors were turning at 24,000 rpm normal operating speed. One GBSM was severely tested with 13 bearing contacts on journal and thrust bearings and showed hard starting problems for a short time on a 500-hour life test which followed. A second GBSM, exposed to one shock contact on each bearing, started and stopped reliably.

The nonoperating GBSM's, exposed to shock and random vibration, are on life test at the time of this report. A supplement will be written to report the results.

SECTION II

OPERATION OF THE GG159C GAS-BEARING SPINMOTOR IN HIGH g ENVIRONMENTS

DESIGN, BUILDING, AND TESTING OF HOLDING FIXTURE USED TO MEASURE GAS-BEARING DISPLACEMENT UNDER VIBRATION

The function of the holding fixture is to measure displacement between the rotating GBSM rotor and stationary shaft while the assembly is subjected to high g environments. It also provides for spinmotor power and proper gas environment. The maximum gas-bearing displacement (gas-bearing clearance) is less than 100 microinches, and the holding fixture must secure the motor so that its motion is sufficiently less than this gas-bearing clearance so as not to be interpreted as a change in the gas-bearing clearance.

The g environments of random vibration and shock, being transient, can excite resonances at frequencies higher than their basic period. For this reason, the readout system must have resonances above the gas-bearing level to identify the gas-bearing response up to and including its resonance when in a transient g environment.

The holding fixture is shown in Figure 1. The base plate is made of beryllium to obtain the highest fundamental fixture resonant frequency and stiffness within a practical size. The basic resonance of this complete fixture is about 5000 cps; the gas-bearing resonances are between 3000 and 4000 cps.

Holding Fixture Error Determination

Displacement of the gas-bearing rotor relative to the shaft is measured by placing a metal surface within one-thousandth of an inch of the rotor momentum

ring. Figure 1 shows the motor in the holding fixture with the metal surfaces close to the momentum ring. Changes of electrical capacitance caused by the GBSM rotor moving toward or away from this metal surface are transmitted to the dynagage capacitance transducer along a metalized path on ceramic. As motion of this metal surface is indistinguishable from the GBSM rotor motion, the surface requires material such as ceramic, which has a high specific stiffness and modulus and is an electrical insulator. To determine errors introduced within the holding fixture under required g environments, a solid ceramic cylinder matching a spinmotor in weight and having a momentum ring was placed in the fixture and the assembly subjected to environments under which the GBSM's were to be tested.

Sine Wave Errors

Errors under sinusoidal g loading as shown in Figure 2 are less than 10 percent of the GBSM displacements, except for thrust bearing testing in Phase II where they are 20 to 30 percent. Resonance at 1880 cps was eliminated by reducing the size of the plate coupling the vibration machine to the holding fixture and clamping the fixture more firmly to the plate.

Random Vibration Errors

Random vibration errors were measured by observing displacement output over a period of time to obtain maximum indicated displacement at levels up to and including $25 g_{rms}$. Since fixture frequency response and GBSM response are essentially flat (especially motors J-3 and J-4), an error maximum displacement occurs at the same time as a GBSM displacement maximum. Magnitude of this error is 1.0 ± 0.1 microinch/ g_{rms} (20-2000 cps).

Shock Errors

The errors under a shock environment of 1.5 millisecond half sine waveform were obtained using the same solid ceramic "motor". Photographs were taken of the displacement readout during exposure to shocks up to and including 200 g peak. The shock machine was tested for errors introduced by a rate applied during the GBSM testing. This rate was found to be negligible. The displacement error was 0.16 ± 0.02 microinch/g peak for the 1.5 millisecond half sine shock.

Fixture Calibration

The readout during these tests was a voltage which required a calibration ratio of microinch/millivolt dimensions to interpret the results in terms of GBSM rotor displacement. Calibration was accomplished by placing three small pieces of rubber in recesses under the ceramic displacement probes. These rubber pieces raised the ceramic probe off of the beryllium base plate when their holding screws were loosened a half turn. The result was a probe that could be displaced and measured by standard displacement transducers. This displacement, held to less than 100 microinches, was equivalent to a GBSM rotor motion because the same variation in capacitance was obtained. Calibration was repeatable within acceptable limits. Tightening the ceramic probe to compress the rubber pads and bottom the ceramic on the beryllium base plate created desired rigidity for dynamic testing. Calibration was accomplished during GBSM testing by allowing the GBSM rotor to fall the known manufactured limits of the gas bearing when the motor was turned off. Output voltage caused by this known displacement calibrated the specific motor being tested at that time. Calibration was repeated for each test.

Data Reduction Process

The raw data from GBSM testing was processed in the following manner.

Sine Wave -- The GBSM and holding fixture were mounted on an M-B model C-20 vibration machine and vibration was brought up to a selected frequency and g-level. Output of the sine wave data readout equipment (Figure 3) was recorded. The vibration machine was scanned to a new frequency and new readings taken. Each reading was multiplied by the calibration ratio found prior to each test and divided by the g-level. The result is the GBSM rotor displacement relative to the GBSM shaft in terms of microinches per g at the selected frequencies. Included in this rotor displacement are the fixture errors which are subtracted from the rotor displacement data if the errors are greater than 5 percent. This subtraction is involved as it must be done by subtracting vectors. The time phase data indicated as an output in Figure 3 must be used.

Shock -- Figure 4 shows the data reduction process for shock data. The raw data was in the form shown in Figure 5. Figure 5 pictures were taken on a dual-trace oscilloscope where the upper trace is the displacement and the lower trace is the acceleration waveform. A tracing of the pattern formed by the rotating motor with no acceleration imposed on it is shown in Figure 6. This is the TIR of the GBSM rotor momentum ring. When the scope is calibrated by the method described earlier, allowing the rotor to fall through the manufactured clearance, the raw data and the momentum ring TIR can be described in terms of microinches and is shown in Figure 4, A and B. When the holding fixture is tested for errors introduced during shock testing by using the solid ceramic motor mentioned earlier, the errors can be estimated from the shock waveform (Figure 4C) to be Figure 4D. The data reduction process is then the subtraction of B and D from A to determine the gas-bearing displacement, Figure 4E. This drawing out of the waveform is done for explanation. Data shown of the gas-bearing displacement in the next section is done only at the maximum shock and displacement point.

Random Vibration -- The holding fixture and GBSM are mounted to the same vibration machine as in sine wave testing. A random vibration level (20-2000 cps bandwidth) is applied and peak displacement observed. The displacement

is the maximum occurring over a period when this maximum recurs. The level is increased and another data point taken. The readings are multiplied by the calibration ratio previously determined and the fixture errors subtracted out. During testing, the readout is taken from an oscilloscope on which the vertical displacement represents the gas-bearing displacement and motor TIR discussed under shock data. The horizontal axis is the voltage driving the GBSM rather than a linear time axis. The result is a complex Lissajous pattern which allows constant monitoring of the motor synchronism. If bearing contact is made, this pattern "rotates" and gives instant identification of the contact without waiting for data reduction. This monitoring is also observed during shock testing.

BUILDING AND TESTING OF FOUR GG159C GAS-BEARING SPINMOTORS TO DETERMINE THEIR RELIABLE g ENVIRONMENT

General

Four spinmotors were fabricated from standard GG159C materials and processes. Gas-bearing clearances were selectively changed to obtain information relating to the effect of the gas-bearing clearance variations on the displacement under shock and random vibration.

Testing of these motors consisted of exposure to sinusoidal, random vibration and shock g environments up to and including JPL requirements. One motor was tested to a shock level of 240 g's because an indicated transmissibility of 1.1 existed in the gyro structure (discussed on page 15).

The GG159C gas-bearing spinmotors operate with two thrust bearings consisting of two flat discs with a spiral pattern. This spiral geometry can be described by the number of spiral grooves, their angle to a concentric circle, their depth and width ratio. These two patterned discs form the caps on the end of the GBSM shaft. The GBSM rotor rotates around the shaft and between the thrust plates. Axial clearance between the shaft and rotor is the thrust bearing running clearance. The clearance radially is the journal bearing running clearance. The motor stator is in the shaft.

The thrust bearing supports the rotor by means of a viscous pumping action at low frequencies and steady loads. A wedge of pressure builds up in the journal bearing resulting in attitude angle phenomenon. This wedge of pressure supports the rotor at low frequencies and under steady loads. At frequencies higher than about 200 cps for the GG159 GBSM there is another type of gas film support called squeeze film support. This results from squeezing or compressing for a short time, gas which cannot leak out because of gas viscosity. Success of Phase II effort to increase thrust bearing g capability is based on use of the squeeze film theory to create a thrust bearing pattern which would have increased support at high frequencies.

Thrust Bearing Testing

Shock Testing -- Summary of the shock response of the GG159C GBSM's is shown in Figure 7. Data of the first two motors (J-1 and J-2) prompted the Phase II effort which resulted in data of the second two motors (J-3 and J-4). The 37 psi data was taken when a high pressure was used to increase the journal g capability (to be discussed later). Figures 8, 9, 10, and 11 show the individual curves and the data points. The difference between the manufactured and running clearances is believed to be thermal expansion. As the gas bearing is a nonlinear device it is interesting to see the nonlinearity in a form differing from the bending over of the g capability lines of Figure 7. Figure 12 plots the shock wave and the resulting displacement wave, both normalized for easy waveform comparison. At a low g level (50 g) it can be seen the two curves are essentially of the same form, while the displacement wave becomes flat topped at high g levels. Figure 4 shows the shock waveform at 240 g's with no bearing contact, while Figure 12 shows bearing contact.

Sine Wave Testing -- The sine wave data shown in summary form in Figure 13 supports the shock data in that there is increased support from the Phase II thrust plates. Figures 14, 15, 16, and 17 are individual motor data, where J-3 and J-4 are corrected for fixture errors.

Random Vibration Testing -- The random vibration testing summary, Figure 18, does not present as clear an improvement in the Phase I and Phase II data as does the shock and sine wave data. However, it shows the Phase II data to be better in both cases. The individual motor data is shown in Figures 19, 20, 21, and 22. The random vibration requirement of 25 g_{rms} has not been a problem at any time during this contract, except when a 2:1 land/groove ratio thrust bearing was used on motor J-2 (Figure 20).

Static Testing and Land/Groove Ratio Influence on g Capability -- Phase II effort included an investigation of the change in running clearance with a changing steady load or the static compliance. This is the viscous pumping region of the spiral pattern mentioned earlier. Figure 23 shows the compliance can be even lower than the old thrust bearing with this new pattern; therefore, no problem should result from its use. This is the result when the frequency response of a series of spiral patterns shown in Figure 24 is studied. Note that all g capability curves approach the 50 g point at low frequencies. This curve also shows the improvement found by Honeywell in the time between the Phase I and Phase II efforts. Addition of a small sealing ring at the inside diameter of the spiral groove reduces the peak in the compliance curve. This is seen in Figure 13 as lack of a peak in the rotor displacement per g where relation between displacement per g and compliance is just rotor mass. Use of this sealing ring eliminated need for an extensive groove depth optimization, previously thought to be necessary.

Journal Bearing Testing

Sine Wave Testing -- Journal bearing frequency response of the four motors tested is shown in summary form in Figure 25. An improvement in the half speed whirl compensation is the reason for reduction in the peak of deflection at 200 cps. In addition to a reduction in this peak a flattening out of the rest of the frequency response is seen in J-3 compared to J-1 data. Motor dimensions are given on the individual data sheets (Figures 26, 27, 28, and 29). Figure 25 has the shaft compliance subtracted from the data of these figures. Due to attitude angle of the journal bearing at low frequencies, there is a rotor motion at right angles to force. This is shown for two motors in Figures 30 and 31.

Shock Testing -- The shock data summary (Figure 32) shows bearing contact at 200 g's of motors J-1 and J-2. Noncontact of motors J-3 and J-4 is attributed to improvement in whirl compensation already described in Figure 25. Figure 32 has shaft bending error removed from the data of the individual motors shown in Figures 33, 34, 35, and 36. As shaft resonance is well above 2000 cps, the same shaft bending error is used for shock and sine wave data.

Motor J-3 evidently does not bend more than 50 microinches at 200 g's (0.25 microinch/g) because if more than 50 microinches is subtracted at 200 g's rotor displacement becomes less than at 150 g's -- an impossibility since there is no oscillation at peak displacements. When these motors were shocked to obtain bearing contact and taken apart to observe damage, the surfaces were found to be slightly scratched. Photographs taken of these surfaces do not show sufficient contrast for publication. No particles could be found by recalibrating the motors (i. e., allowing the rotor to fall through the manufactured clearance when not turning). Life testing of these motors is discussed later in this report.

The data at 37 psi absolute pressure was taken on motor J-3 to determine the effect of increased ambient pressure. The shock data on the summary sheet figure does not show as much increase in linear capability as would be expected from the sine wave results of Figure 25. Further work is necessary to explain the difference.

The displacement waveform of the journal rotor displacement is shown in Figure 37, as previously shown in Figure 12 for the thrust bearing. The non-linearity again shows itself as a flattening of displacement at high g levels.

Random Vibration Testing -- As in the case of the thrust bearing, the journal bearing does not have any problems in the g capability under random vibration. Figures 38, 39, 40, and 41 show the data taken on these motors. Because the data includes the shaft bending error, and g level at the time of maximum rotor displacement is not known, shaft bending error cannot be estimated. One indication suggests the percentage of deflection, however. This is the straightness of the response, where the percentage of deflection is probably less than 50 percent of maximum, to obtain this linearity. (Note the nonlinearity of the shock response.)

Life Testing of Motors J-1 and J-2

These motors were used in the testing of Phase I and were forced to bearing contact on the shock test, while operating at 24, 000 rpm.

Motor J-1 -- This motor made five bearing contacts during journal shock testing and eight during thrust shock testing. No particles could be found by recalibrating the motor. The motor lost synchronous speed temporarily during bearing contact and then resumed synchronous speed.

The life test on motor J-1 was conducted from 13 December 1963 to 10 January 1964 for a total of 497 hours. Results are summarized below:

- Phase current was essentially constant.
- Power was 6.1 ± 0.2 watts.
- Ambient temperature was 140°F
- The motor was difficult to start during the first few days. When the motor was stopped, no objectionable noise, which would indicate particles or very rough surfaces, could be heard through a sensitive microphone.
- At the end of the life test, the motor started and stopped reliably without cleaning.
- Starting torques were initially less than 11, 000 dyne-cm. After the shock environment life test, the starting torques were irregular and less than 16, 000 dyne-cm.

Motor J-2 -- This motor made bearing contact once each on the journal and thrust bearing. Again no particles could be found by recalibrating the motor. The motor lost synchronous speed only during bearing contact.

The life test on motor J-2 was conducted from 16 January to 11 February 1964 for a total of 647 hours. Results are summarized below:

- Phase current was essentially constant.
- Power was 6.0 ± 0.2 watts.
- Ambient temperature was 140°F
- The motor was not difficult to start at any time. No objectionable noise, which would indicate particles or very rough surfaces, could be heard when the motor was stopped.
- At the end of the life test, the motor started and stopped reliably without cleaning.
- Starting torques were initially less than 9000 dyne-cm and less than 11,000 dyne-cm after shock testing.

Life Test Conclusions -- The 13 bearing contacts of J-1 produced some trouble, as evidenced by hard starting and high start torque.

The more "normal" two-contact performance of J-2 produced no discernible trouble areas.

Nonoperating Testing

Random Vibration -- The last part of Phase II effort consisted of the non-operating test of motors J-2 and J-3 under random vibrations and shock, respectively. (Prior to this test, motor J-4 was found to have a broken

shaft and J-2 was substituted.) Motor J-2 was then exposed to 25 g_{rms} random (20-2000 cps) vibration for 13 minutes. During the journal bearing test on motor J-2 the rotor did not show a maximum displacement. The gravity vector was oriented so the rotor was bottomed on the journal bearing. This caused a rocking motion as the rotor "climbed" out of this position under the random vibration and was oriented at right angles to the gravity vector. Motor J-2 was tested with the 4:1 land/groove thrust plates and showed squared off displacement peaks, indicating a relatively hard contact. Motor J-2 was recalibrated after the test and showed no particles present. Motor J-2 was stopped at four minutes of vibration to check starting, which proved normal. The motor started and dropped out of synchronization at the same voltages after the test as before the test, indicating no particles present and no change in load torque. This motor is presently on a 500-hour life test which began 29 June 1964.

Shock -- The nonoperating shock test was performed on motor J-3 which contained the 14:1 land/groove thrust plates. The shock level was 200 g of 1.5 millisecond half sine waveform. The motor showed the same starting voltage and synchronized dropout voltage after the test as before. No particles could be found. Since the shock machine operates vertically, the bearing made contact on the lower surfaces before the shock stroke of the machine. During the shock stroke the test head was pressure aided rather than just a free fall device, so the bearings tended to separate while the test head was "falling". This separation was about 5 microinches on journal and thrust. At the bottom of the stroke, the bearing impact was on the same surfaces previously in contact. The bearing impact was indicated by one bearing displacing into the solid material of the others by 10 to 15 microinches -- an impossible condition. This means there is a very slight motion of the gas bearing before, during, and after the shock pulse. The journal bearing showed this behavior along with a ringing after the shock at an amplitude of 80 inches peak-to-peak -- the total gas-bearing clearance. The ringing, which was not squared off to indicate a hard bearing contact, lasted for three

- 15 -

cycles at a frequency of 4000 cps, the gas-bearing resonance when the motor is running. This occurs because the gas support at 4000 cps is that of squeeze film support which is independent of rotor speed and exists with the rotor not turning.

Both of these nonoperating test motors are now on 500-hour life test. Their performance will be reported as a supplement to this report.

DESIGN, BUILDING, AND TESTING OF A GG159C GYRO CONTAINING AN ORTHOGONAL MOUNT WITH THREE ACCELEROMETERS IN THE PLACE OF A GAS-BEARING SPINMOTOR TO DETERMINE THE GYRO STRUCTURE TRANSMISSIBILITY

The dummy gyro consisted of:

- A standard ceramic gimbal containing an orthogonal mount for three accelerometers. The gimbal weighed the same as a gimbal with a motor and was balanced.
- Heater-sensor windings to maintain gyro operating temperature.
- Flex-lead array consisting of eight flex leads -- the motor leads became the accelerometer leads.
- Hydrostatic pump to maintain fluid pressure necessary to support the gimbal.
- Moving coil pickoff and permanent magnet torquer.

The departure from conventional hardware is the orthogonal test block containing three accelerometers.

Sine Wave

The first test run on this gyro was a sine wave scan along the three major axes. Transmissibility is shown in Figure 42. This transmissibility is determined by dividing acceleration found at the internal accelerometers by acceleration found from an external accelerometer mounted near the gyro mounting flange. Resonance which occurs above 2000 cps is an internal gyro resonance, also observable in vibration runs of conventional GG159C gyros.

Shock

Shock transmissibility, shown in Figure 43, has an average transmission of 110 percent. In the chance that the 10 percent overage was not instrumentation error, motor J-3 was tested to 240 g shock with an ambient pressure of 37 psi absolute. No bearing contact was observed. A typical waveform of the gyro transmissibility is shown in Figure 44.

Random Vibration

Figure 45 shows the transmission when exposed to 25 g_{rms} random vibration of 20-2000 cps bandwidth. Both the internal and external g levels were read on true rms reading voltmeters.

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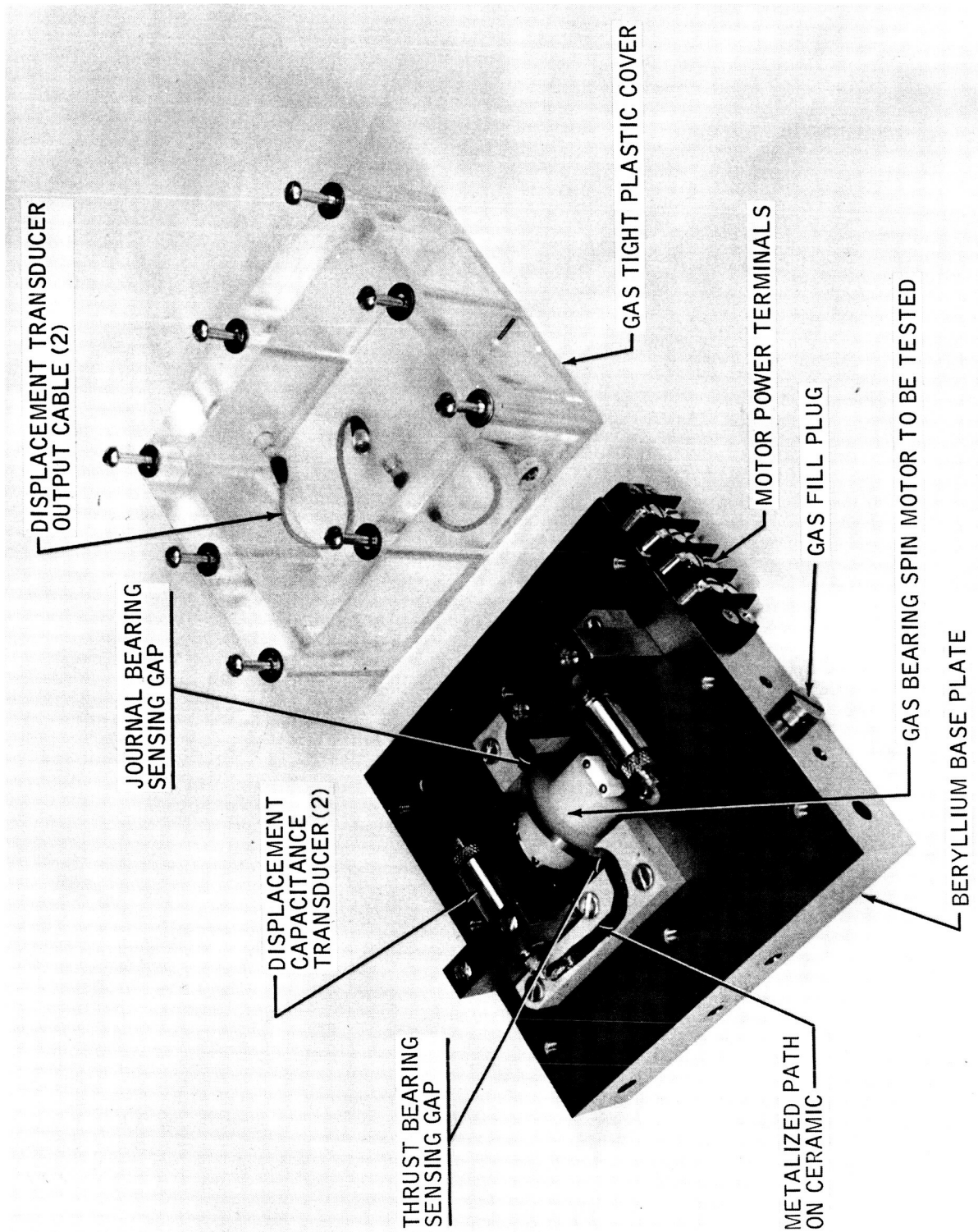


Figure 1. GBSM Holding Fixture

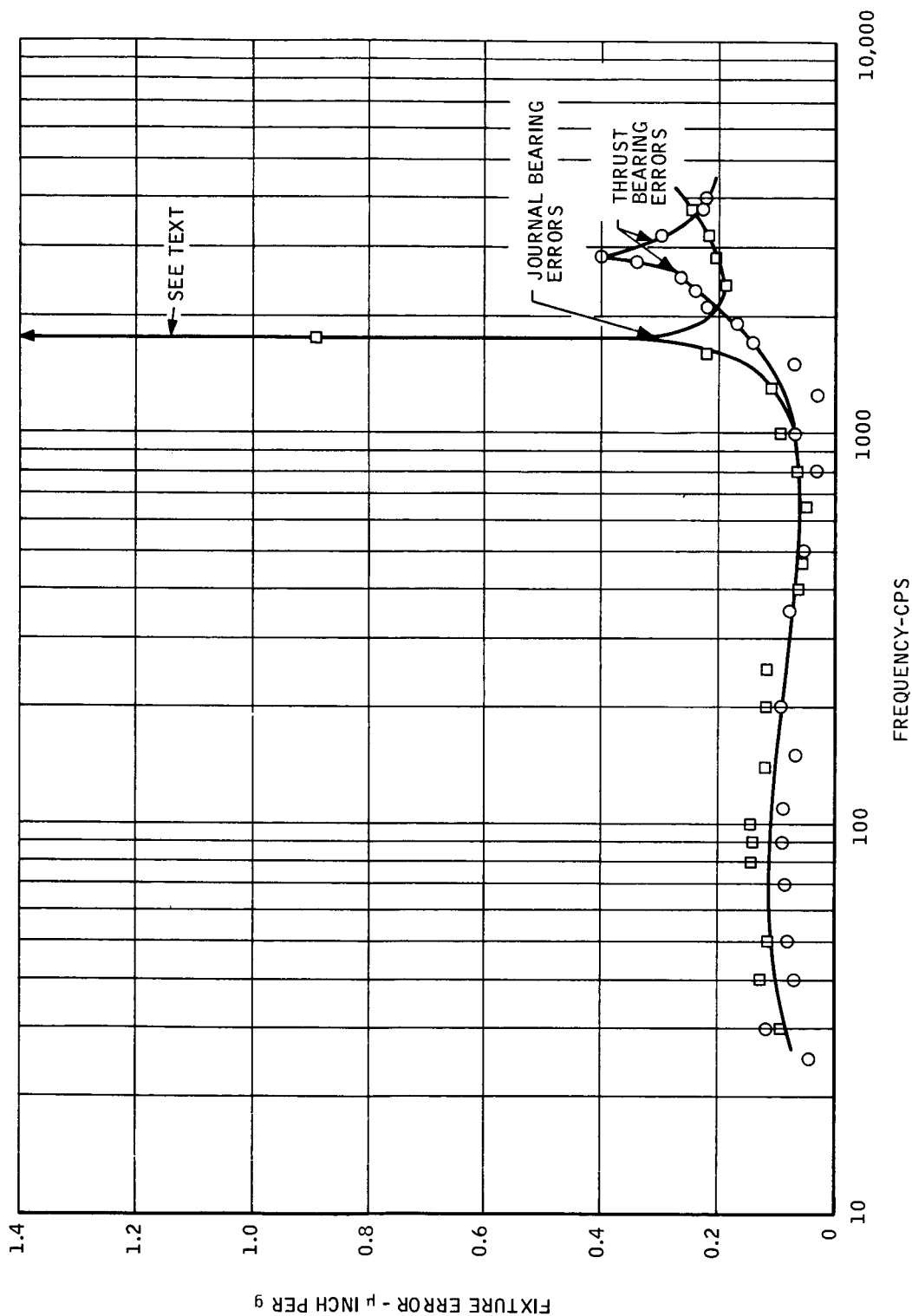


Figure 2. GBSM Holding Fixture Sine Wave Errors

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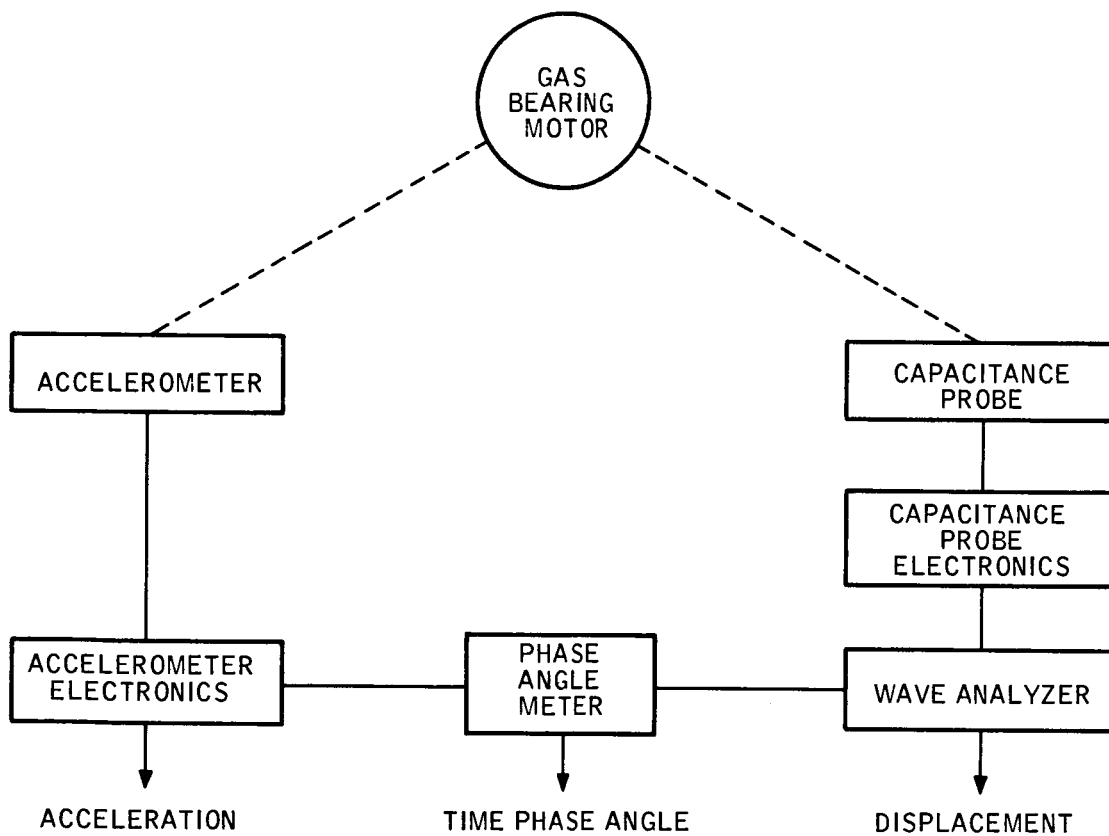


Figure 3. Block Diagram - Dynamic Test Instrumentation

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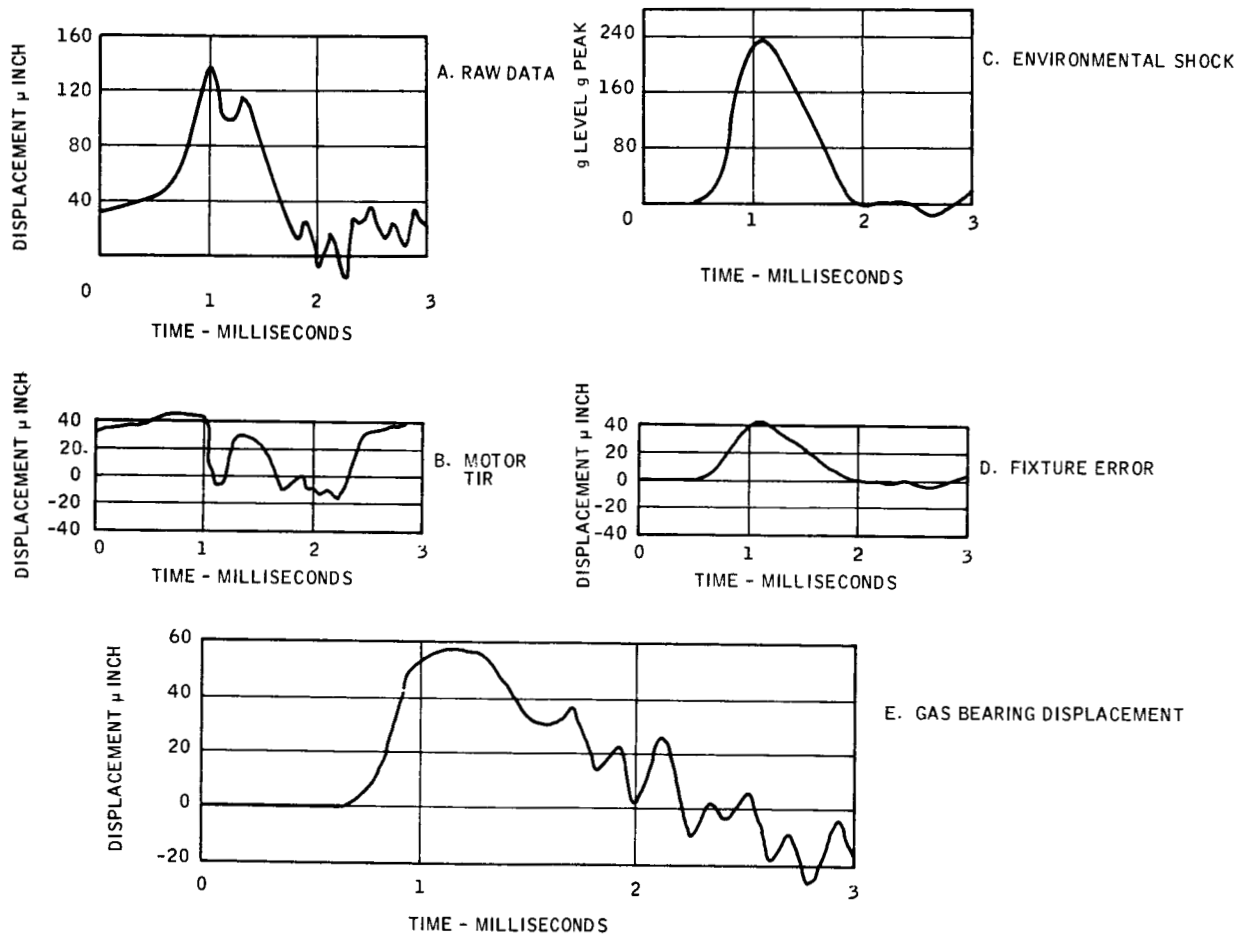


Figure 4. Shock Data Reduction Process

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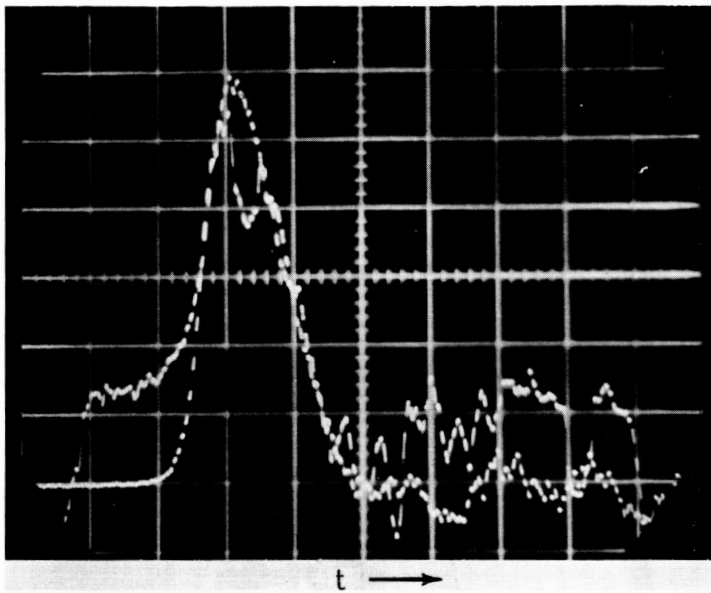


Figure 5. Shock Data Photograph

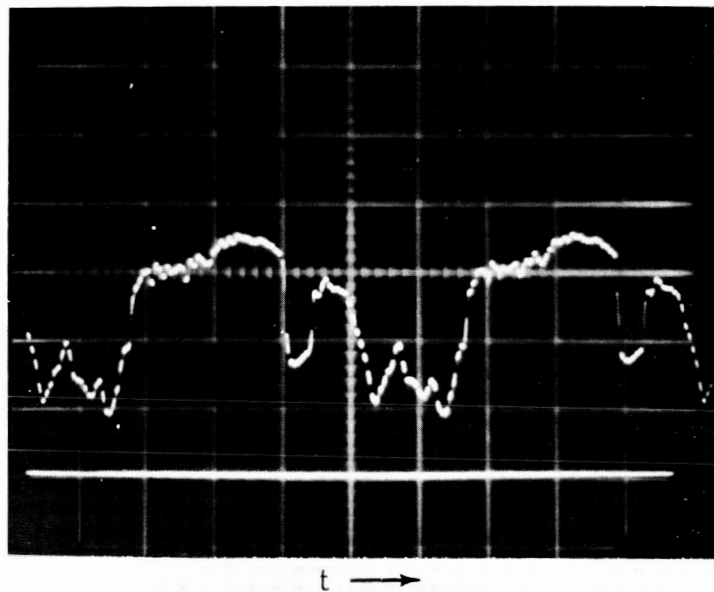


Figure 6. Motor TIR Photograph

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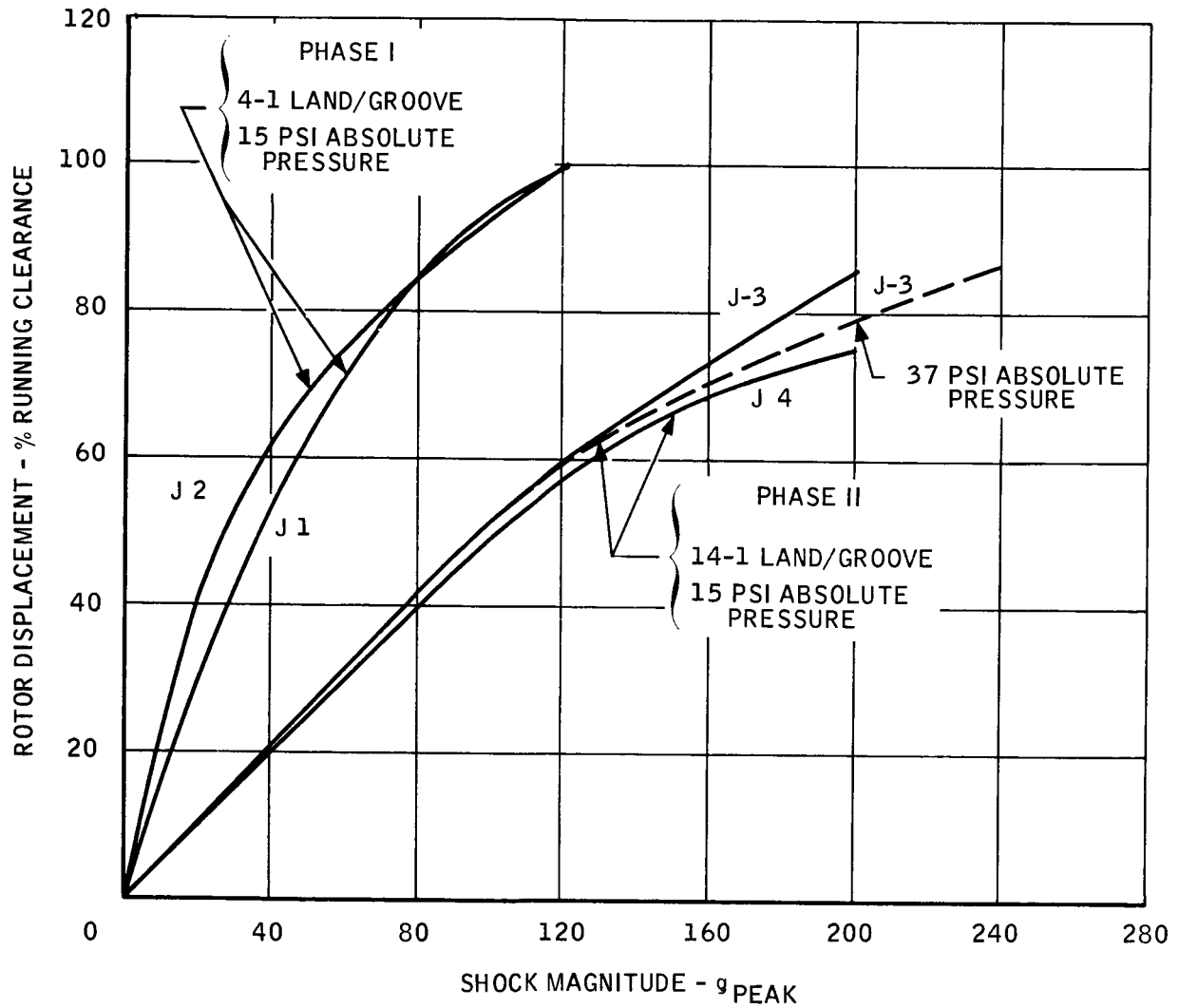


Figure 7. GG159 Thrust Bearing Shock Response Summary

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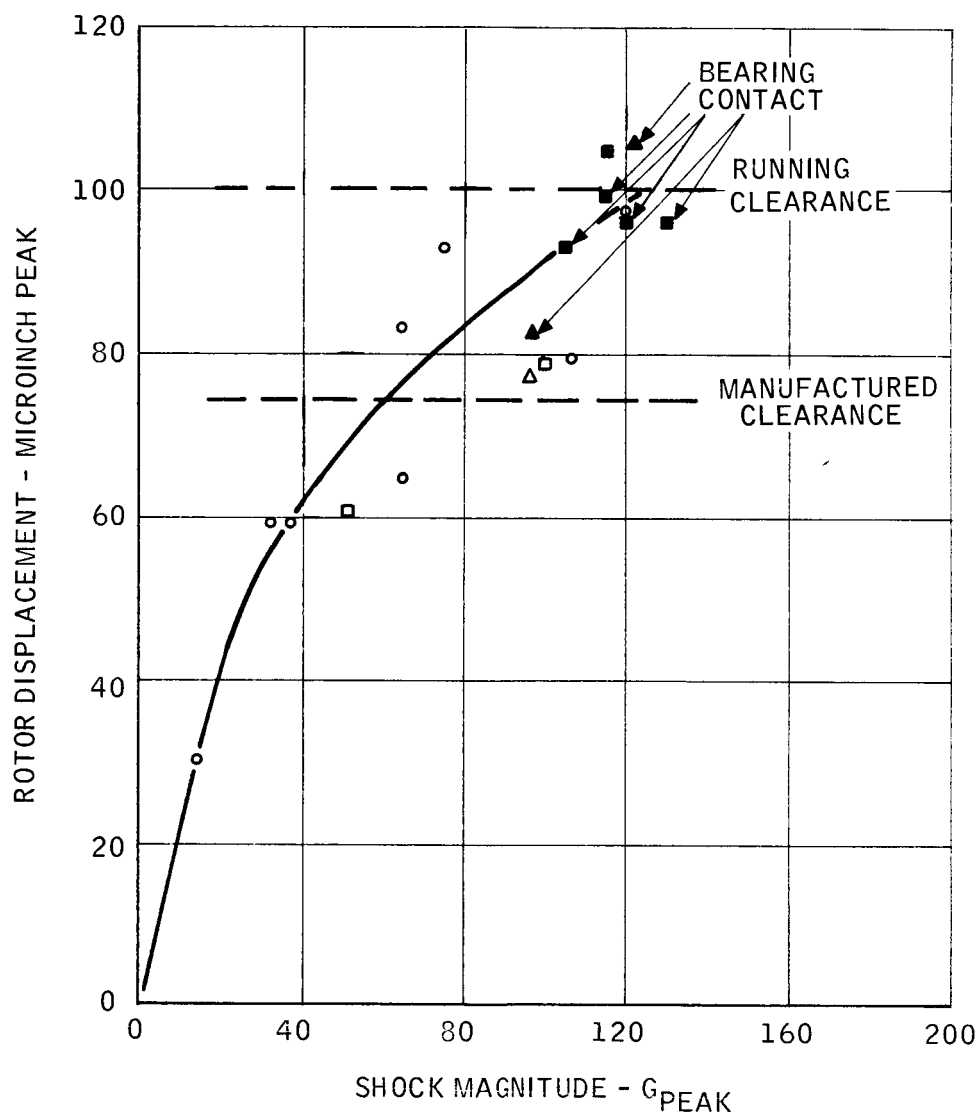


Figure 8. Thrust Bearing Shock Response, Motor J1

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Figure 9. Thrust Bearing Shock Response, Motor J2

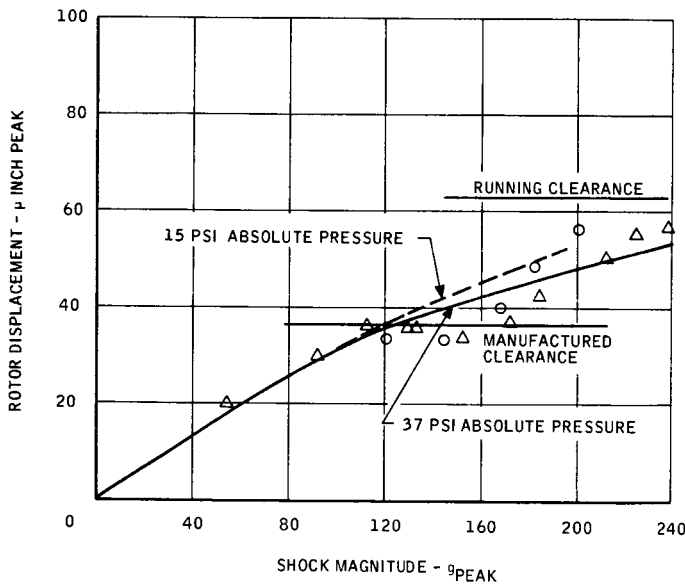
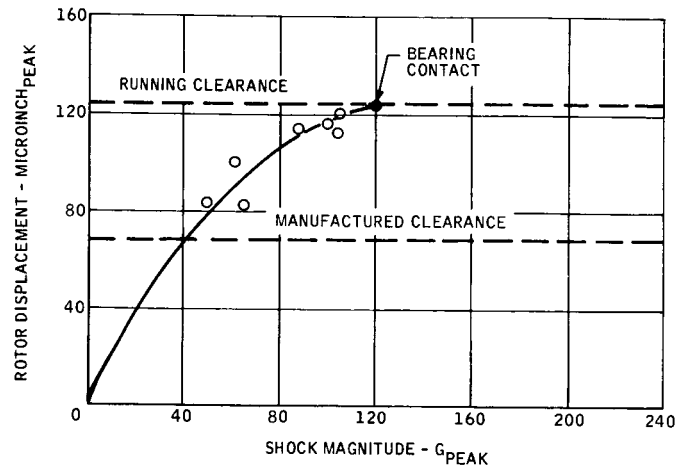
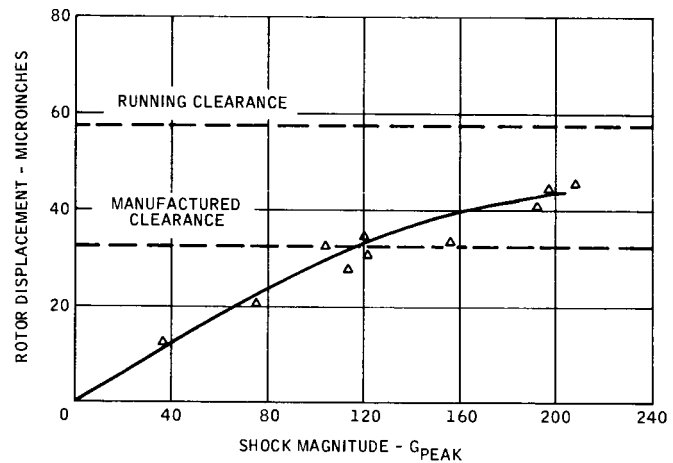


Figure 10. Thrust Bearing Shock Response, Motor J3

Figure 11. Thrust Bearing Shock Response, Motor J4



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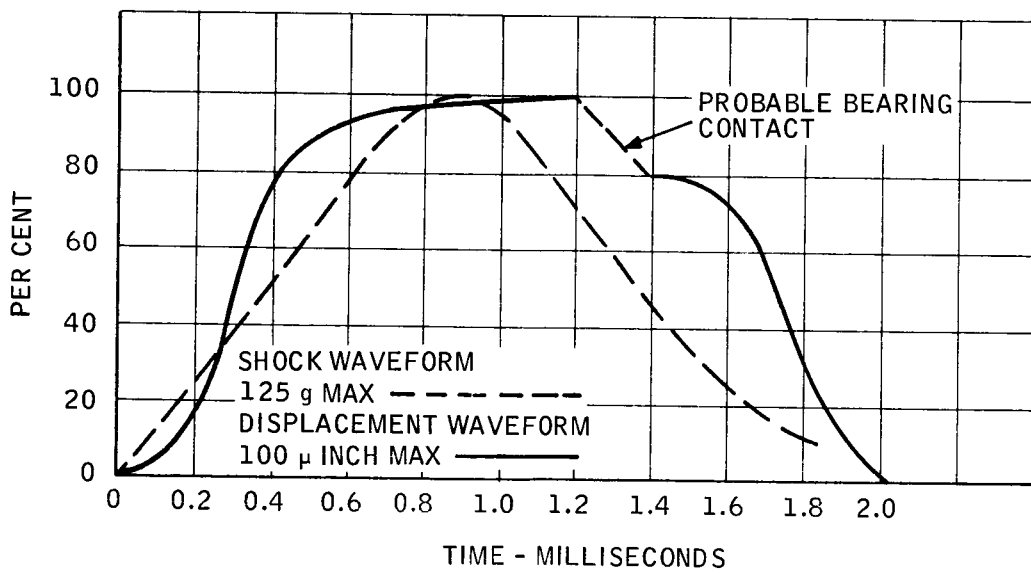
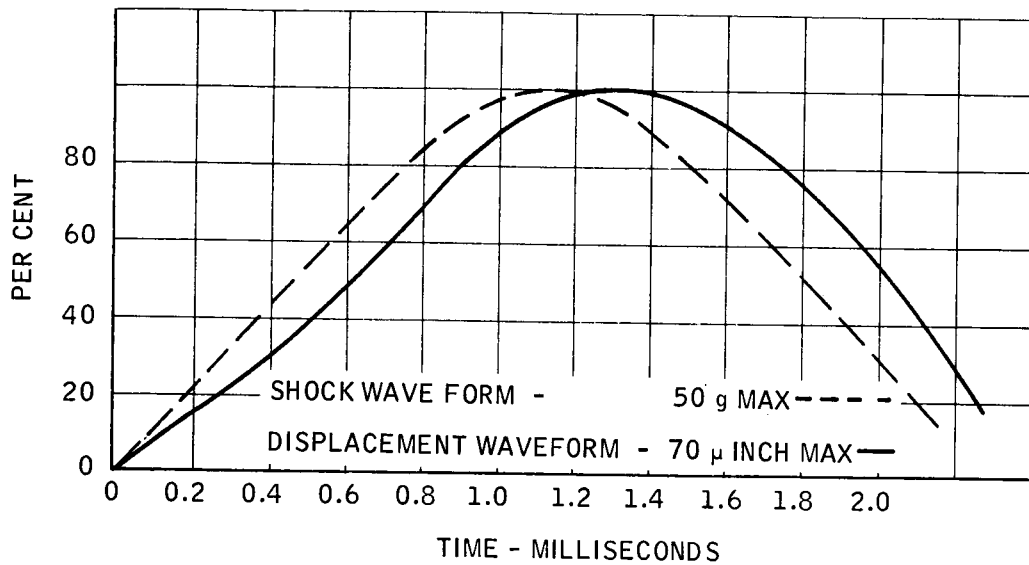


Figure 12. Thrust Waveforms, Motor J1

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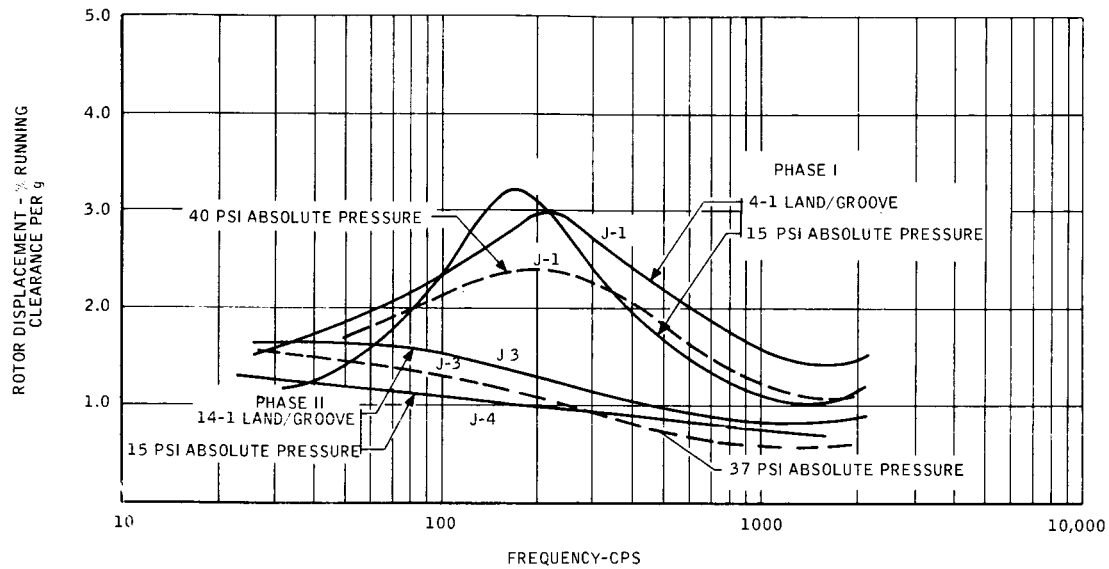


Figure 13. GG159C Thrust Bearing Frequency Response Summary

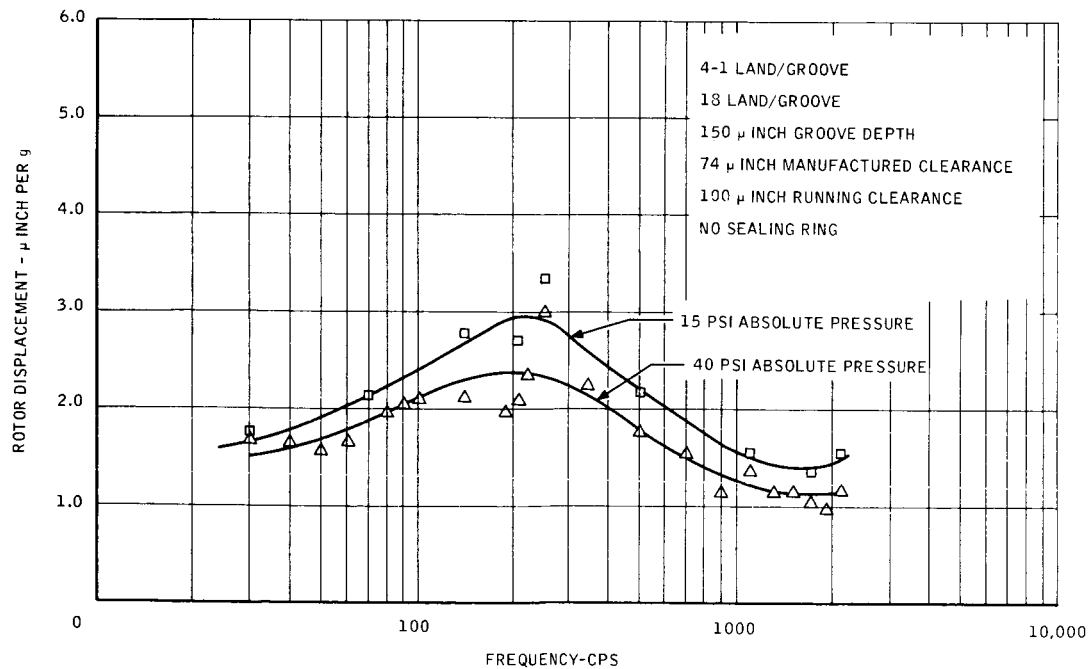


Figure 14. Thrust Bearing Frequency Response, Motor J1

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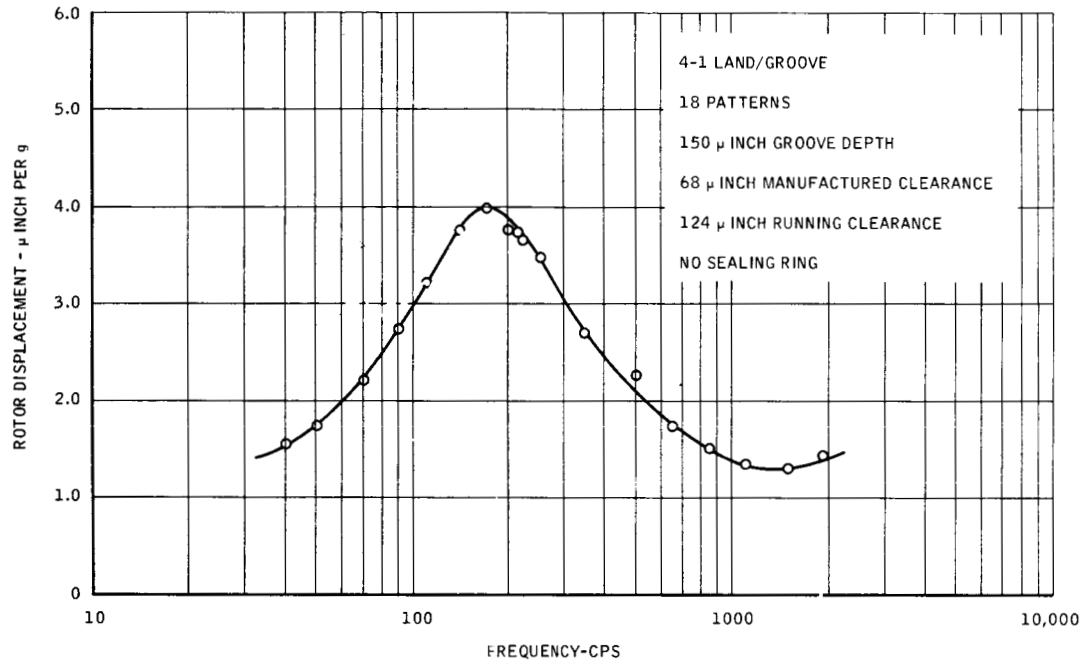


Figure 15. Thrust Bearing Frequency Response, Motor J2

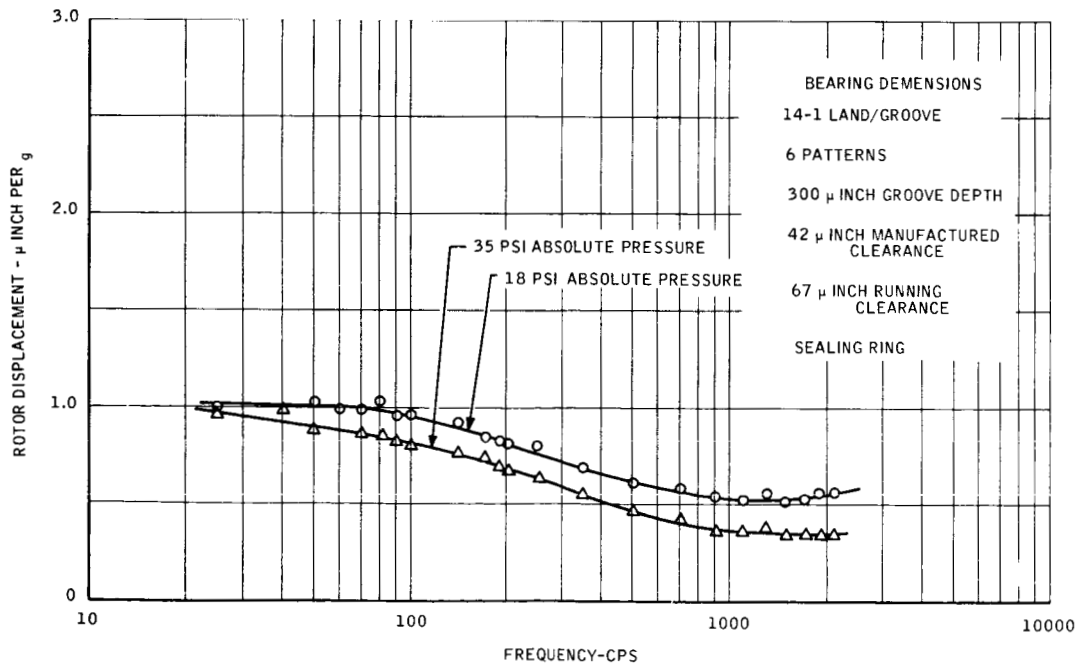


Figure 16. Thrust Bearing Frequency Response, Motor J3

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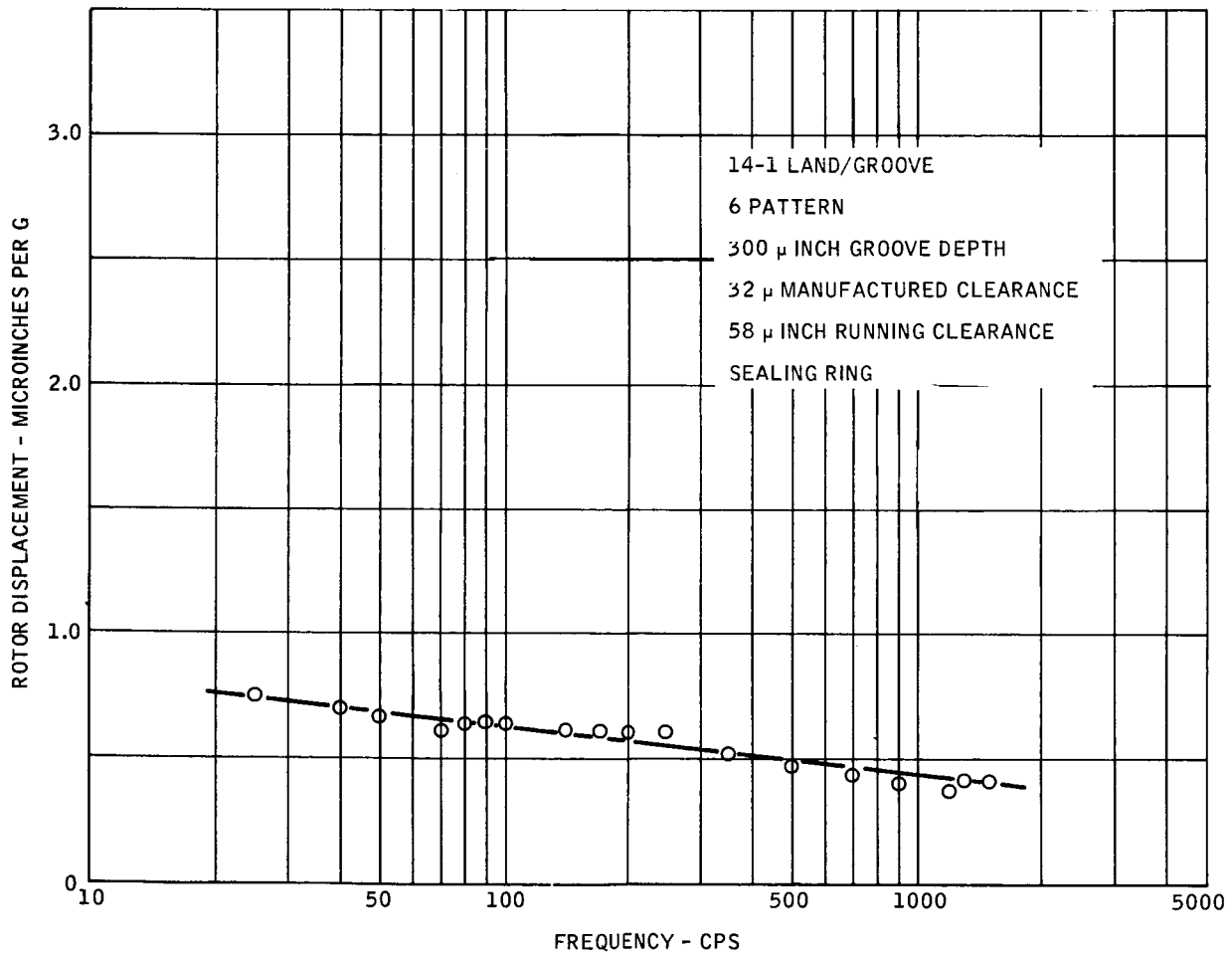


Figure 17. Thrust Bearing Frequency Response, Motor J4

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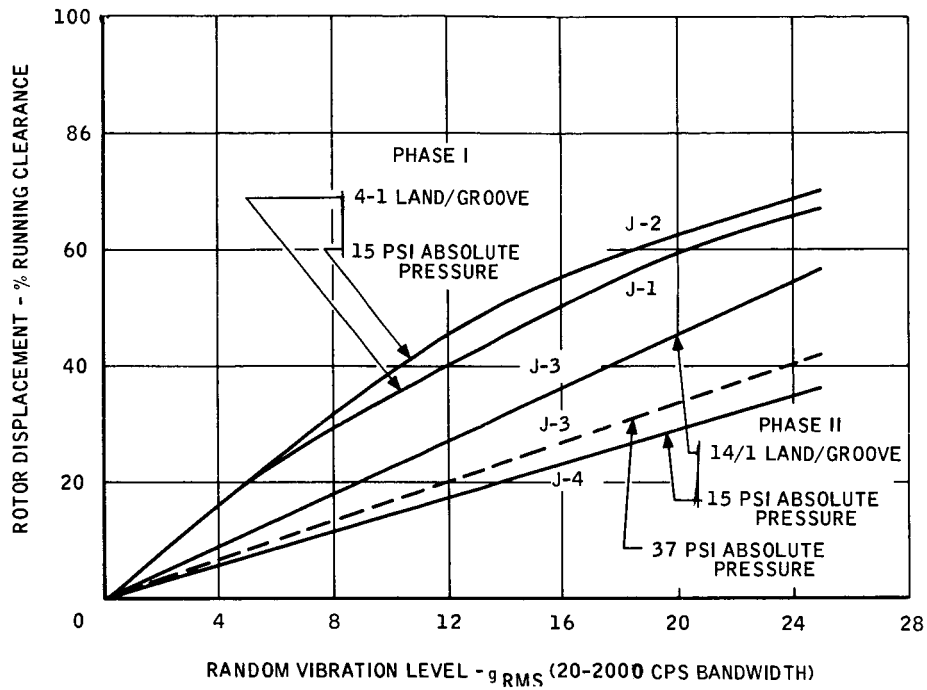


Figure 18. GG159C Thrust Bearing Random Vibration Summary

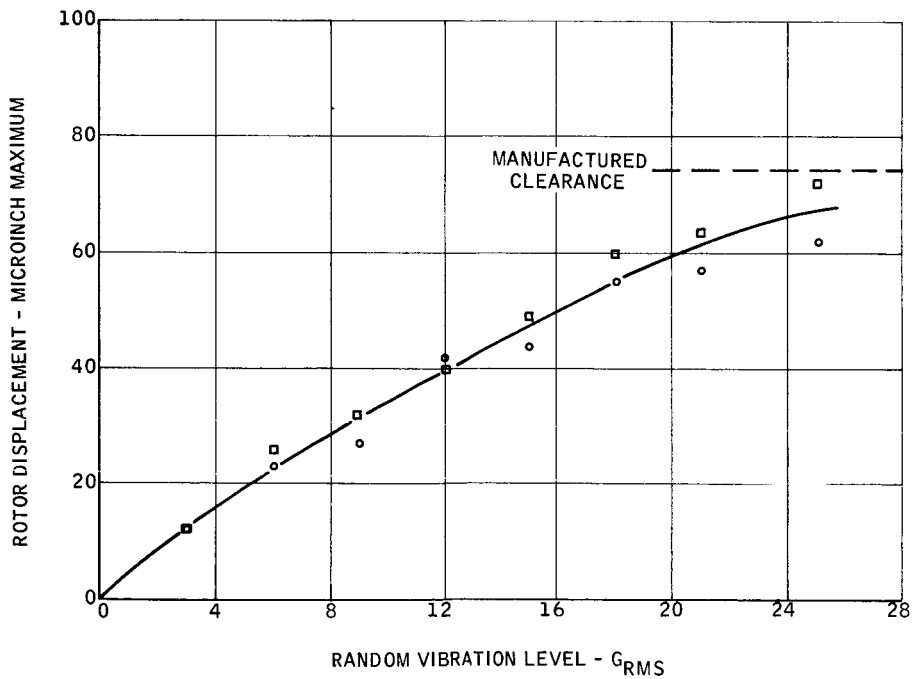


Figure 19. Thrust Displacement versus Random Vibration, Motor J1 (4-1 Thrust Pads)

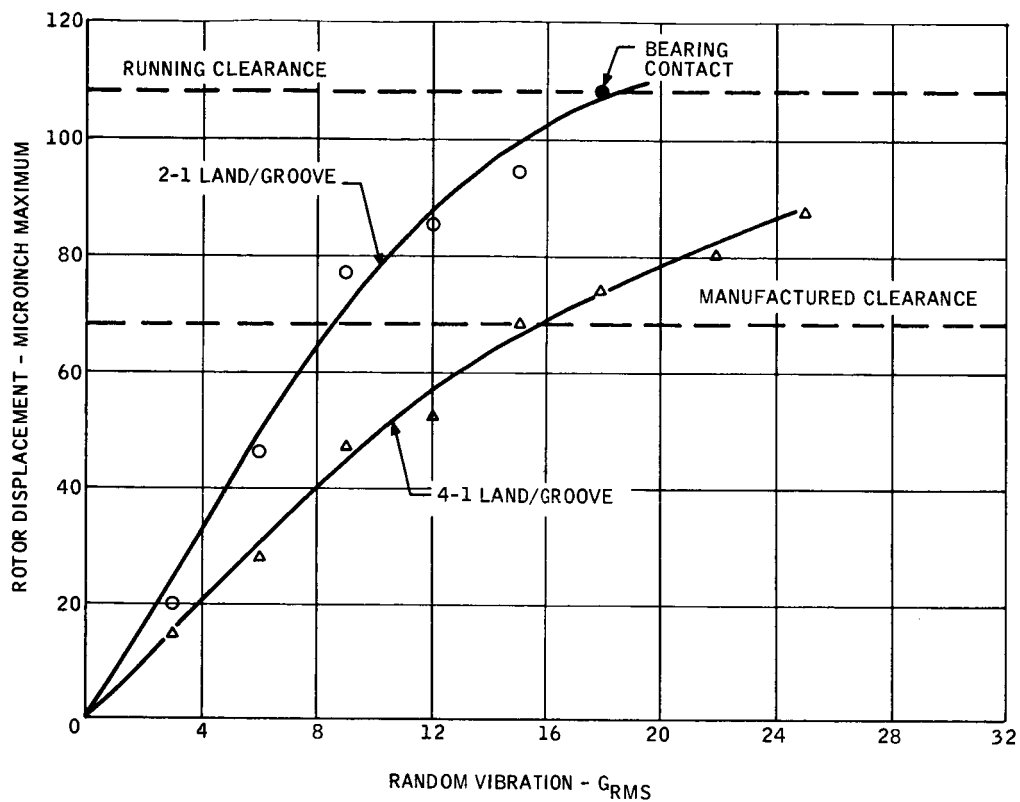


Figure 20. Thrust Displacement versus Random Vibration, Motor J2

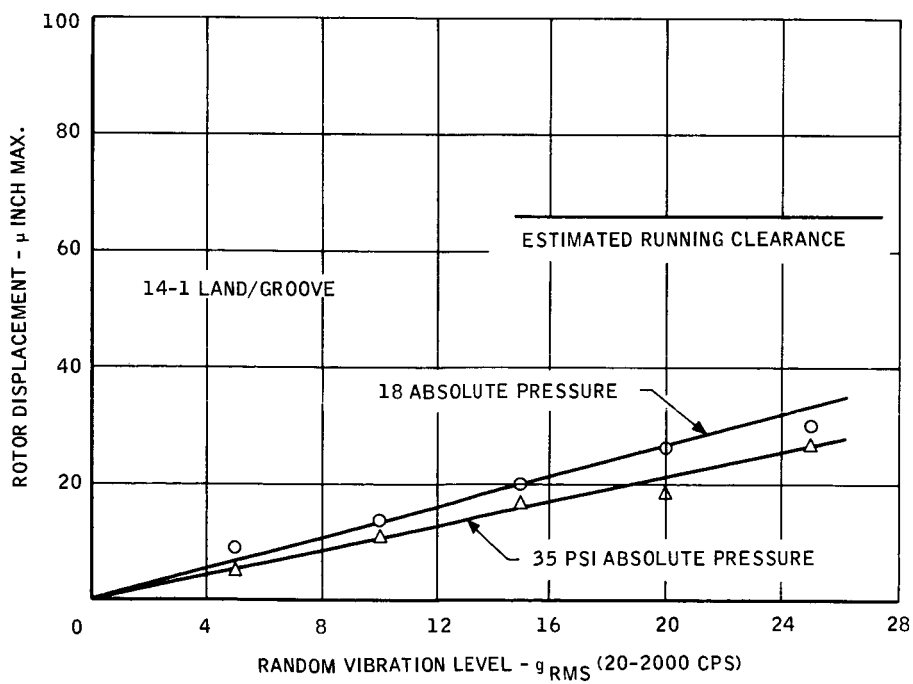


Figure 21. Thrust Displacement versus Random Vibration Level, Motor J3

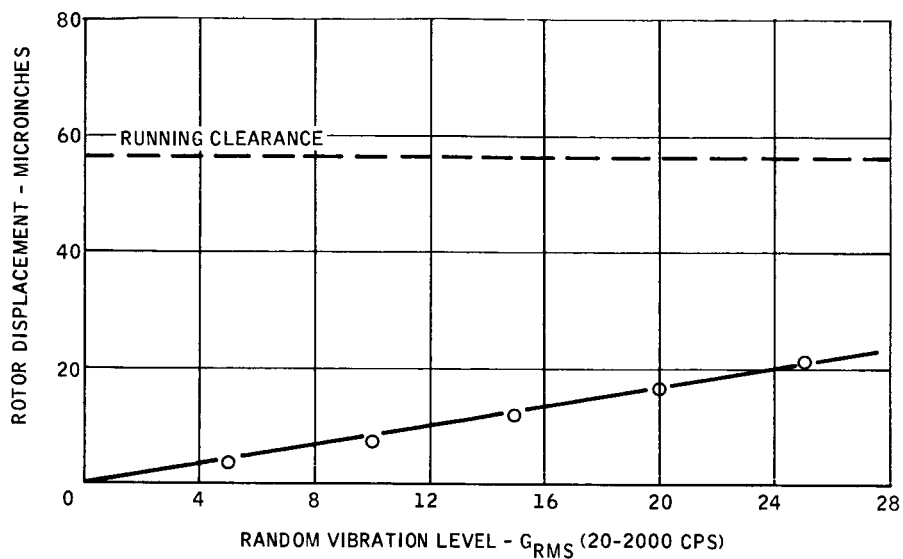


Figure 22. Thrust Displacement versus Random Vibration Level, Motor J4 (14-1 Thrust Pads)

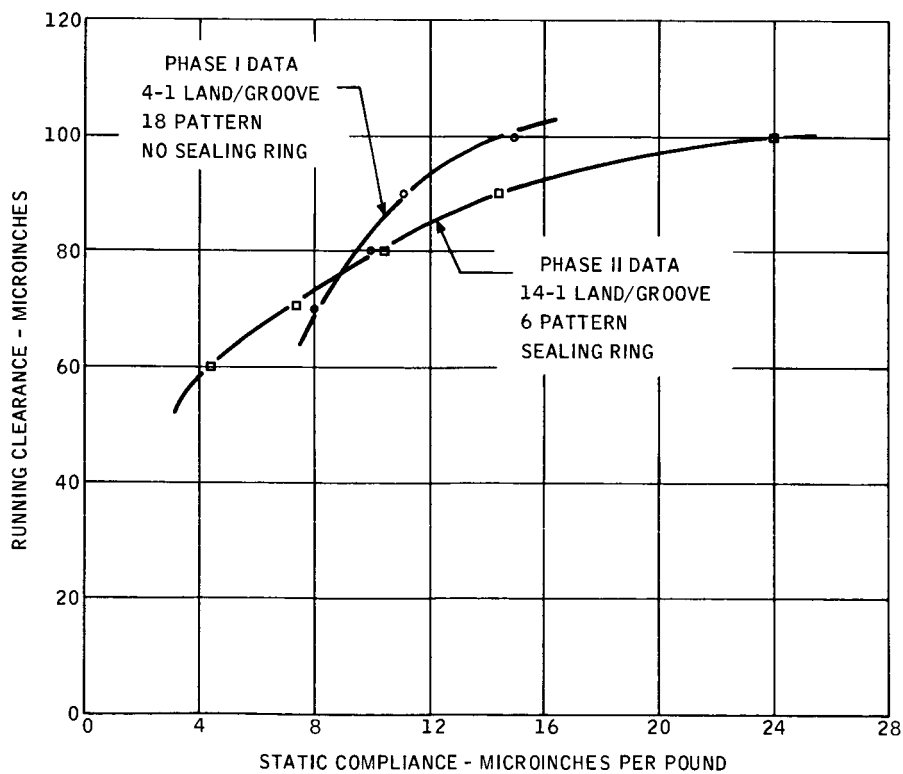


Figure 23. GG159C Thrust Bearing Static Compliance

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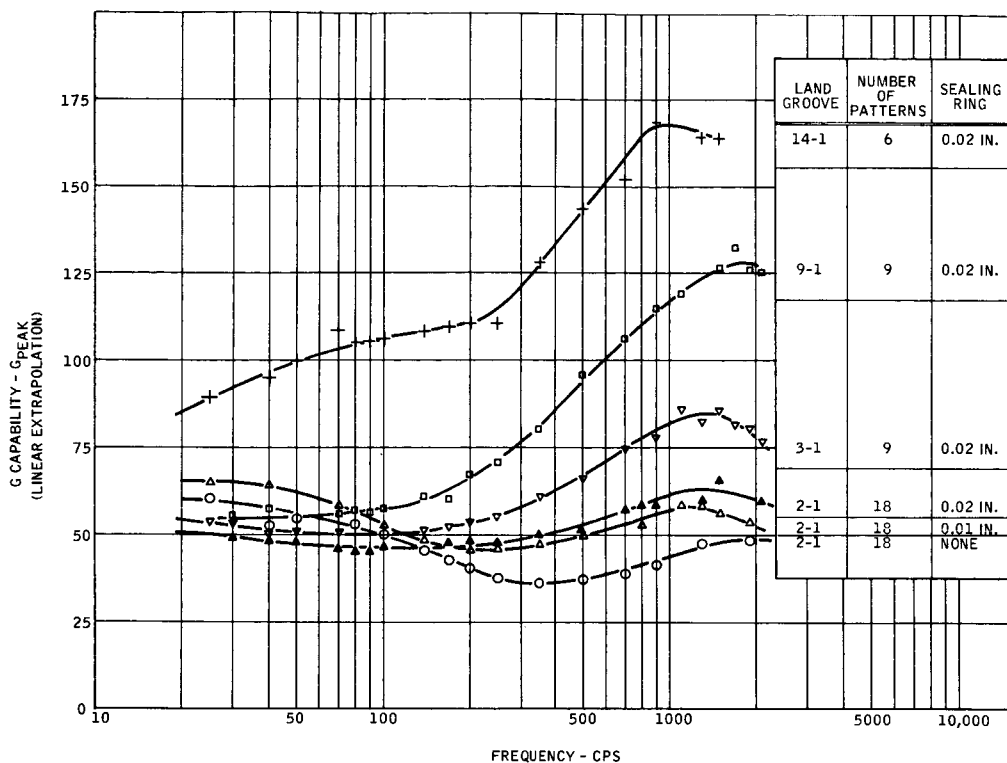


Figure 24. GG159C Thrust g Capability Improvement

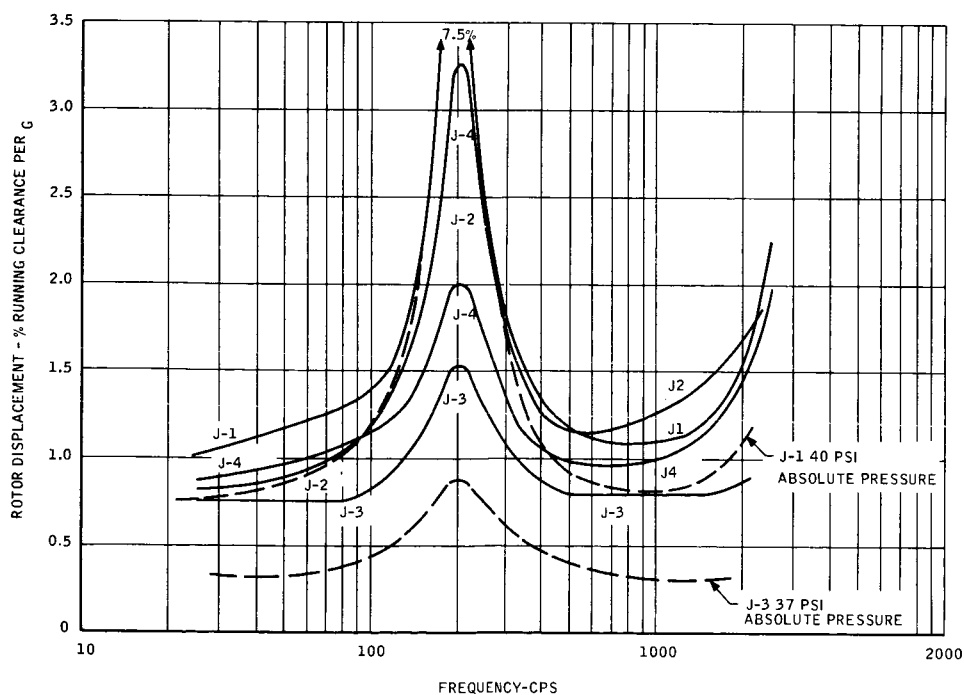


Figure 25. GG159C Journal Bearing Frequency Response Summary

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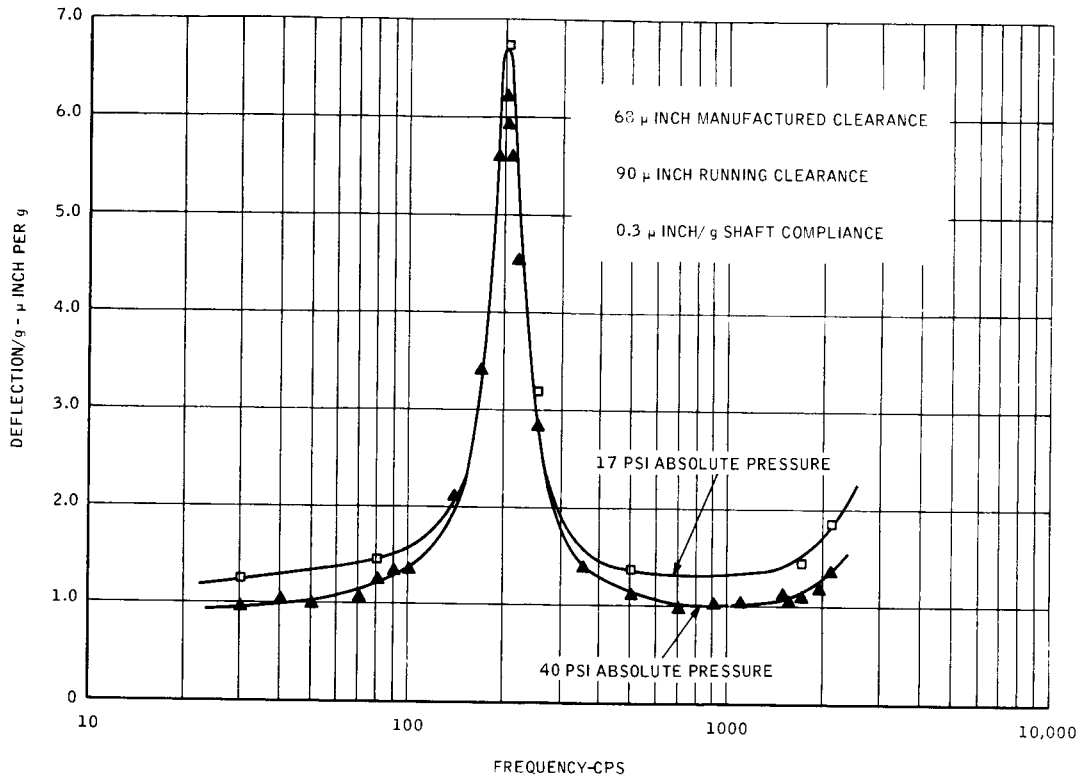


Figure 26. Journal Bearing Frequency Response, Motor J1

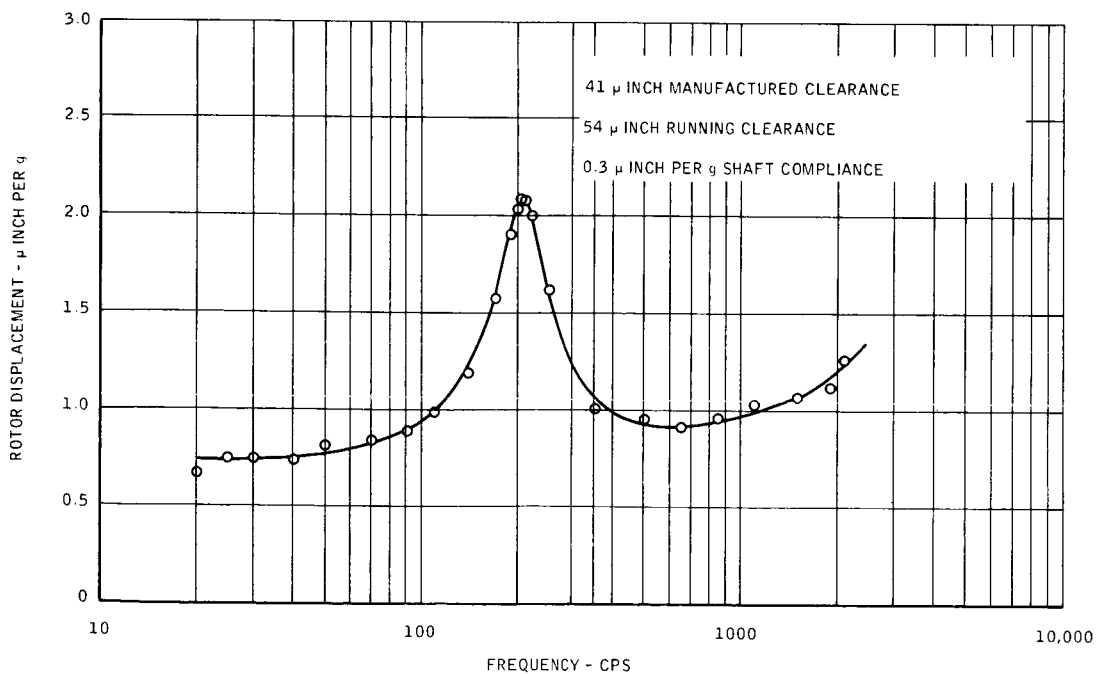


Figure 27. Journal Bearing Frequency Response, Motor J2

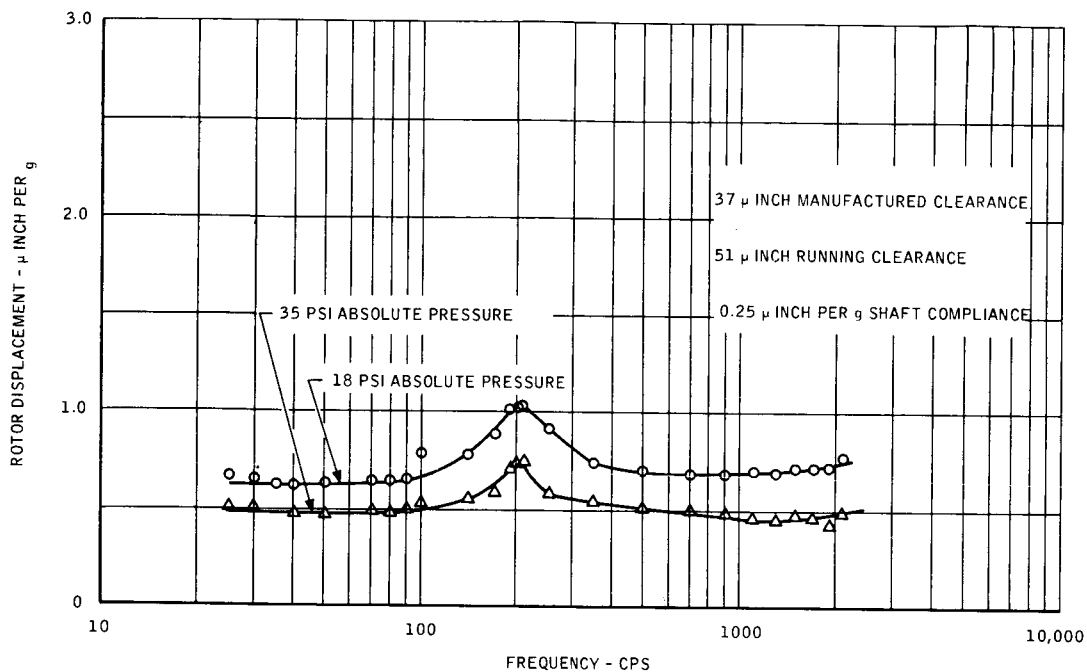


Figure 28. Journal Bearing Frequency Response, Motor J3

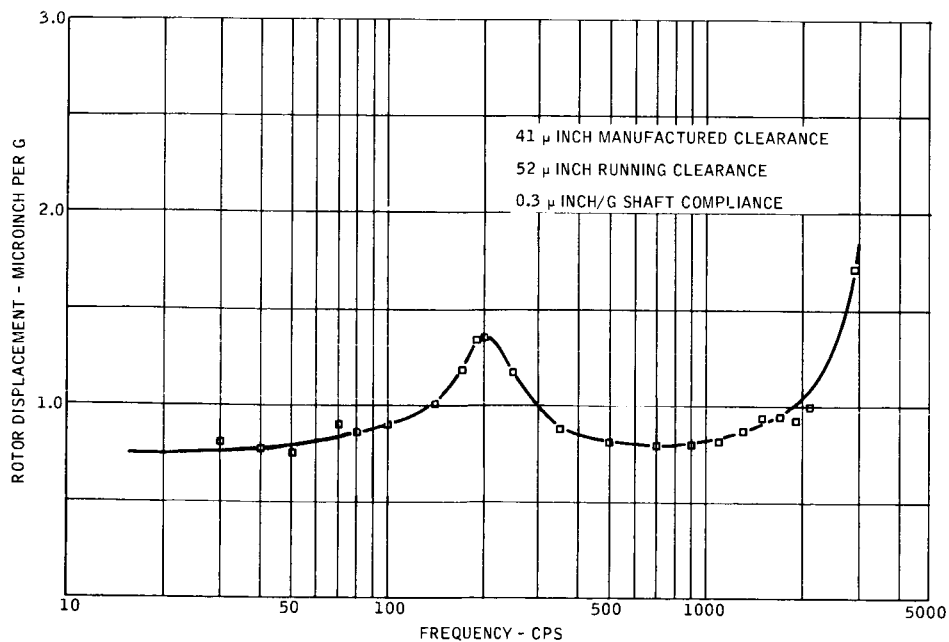


Figure 29. Journal Bearing Frequency Response, Motor J4

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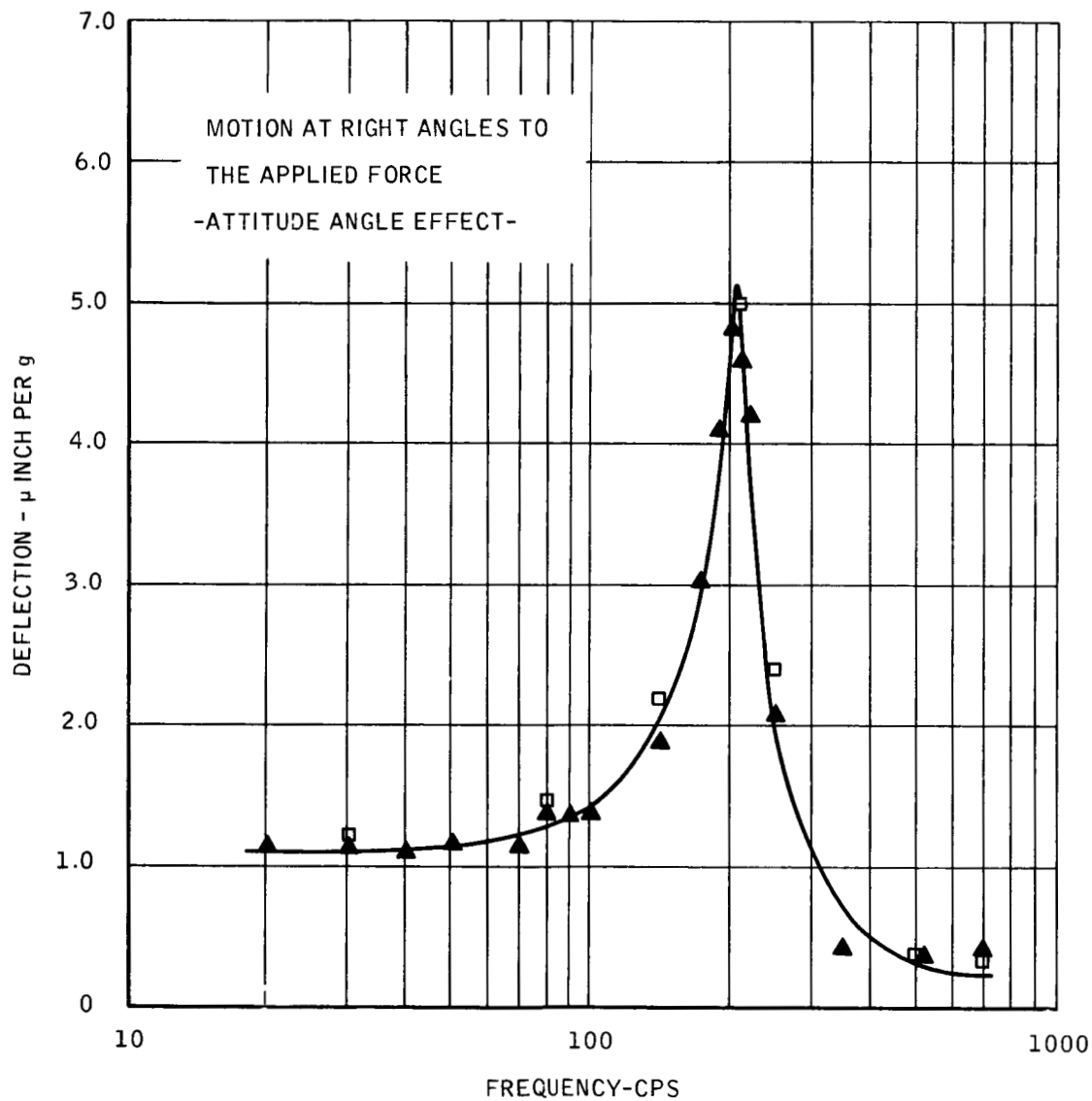


Figure 30. Journal Bearing Frequency Response, Motor J1

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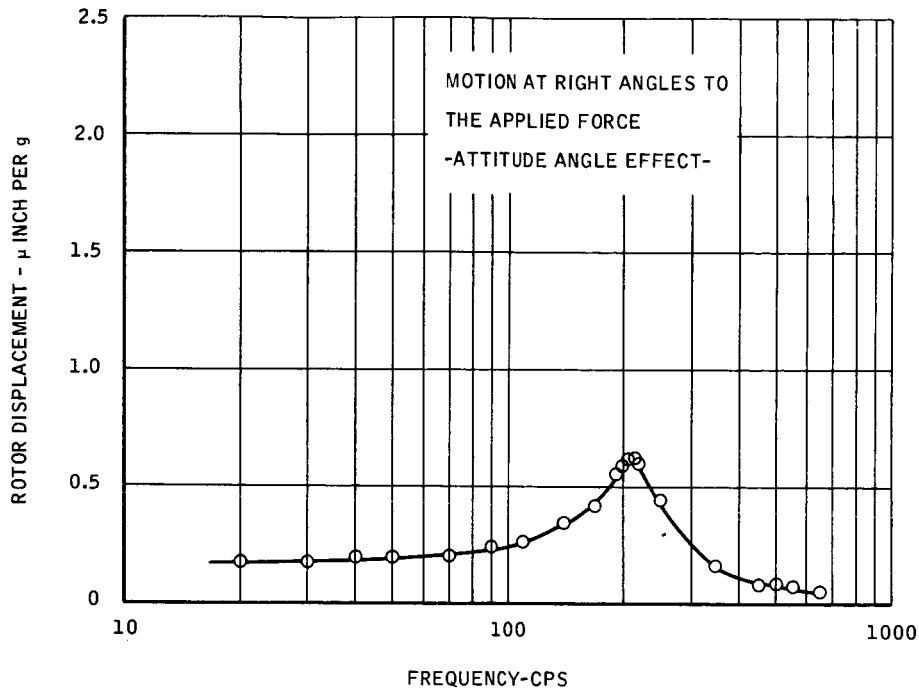


Figure 31. Journal Bearing Frequency Response, Motor J2

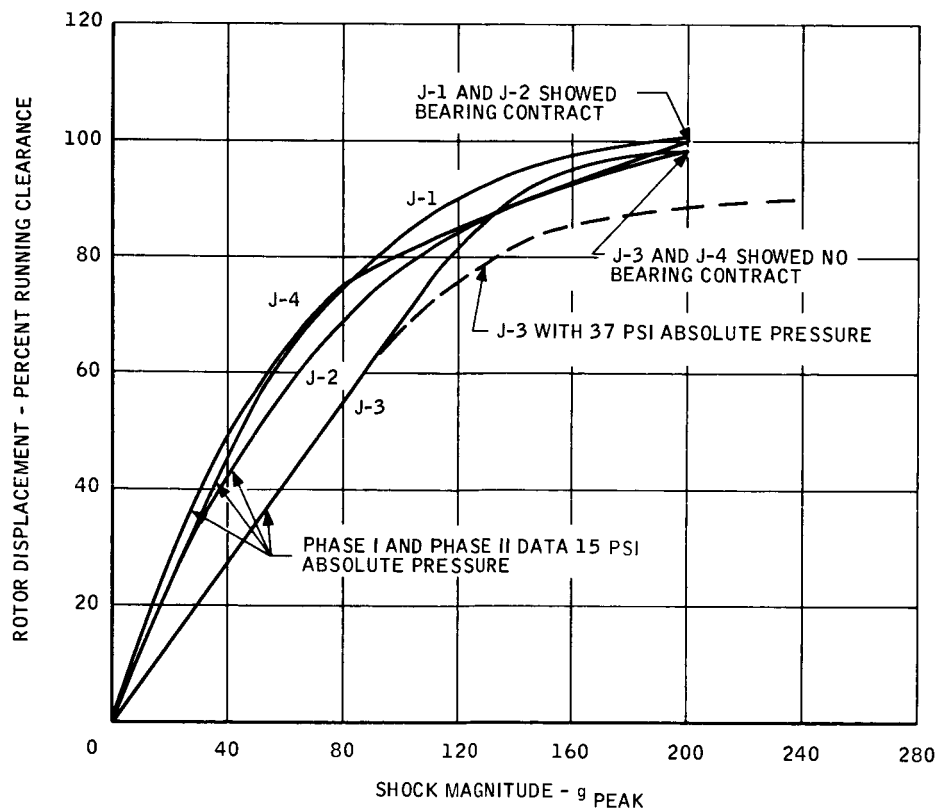
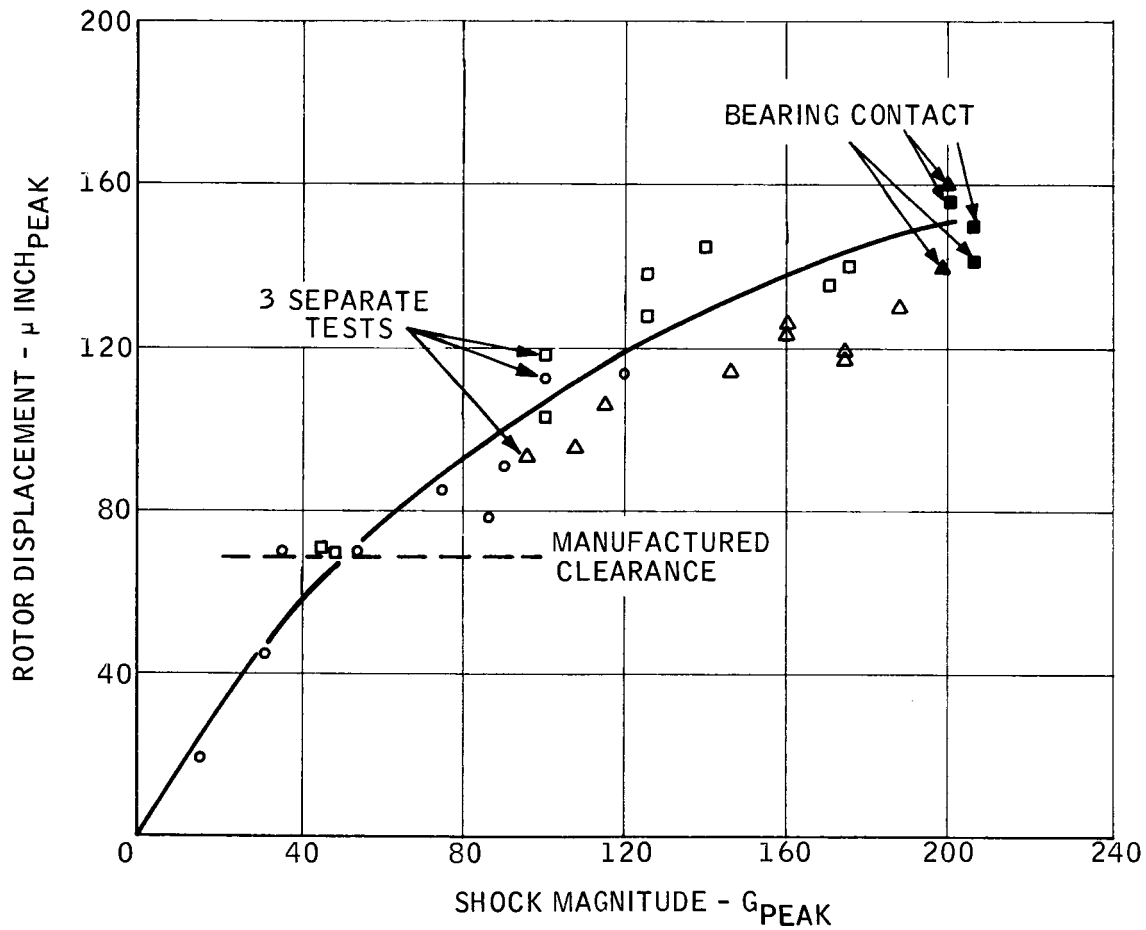


Figure 32. GG159C Journal Bearing Shock Response Summary

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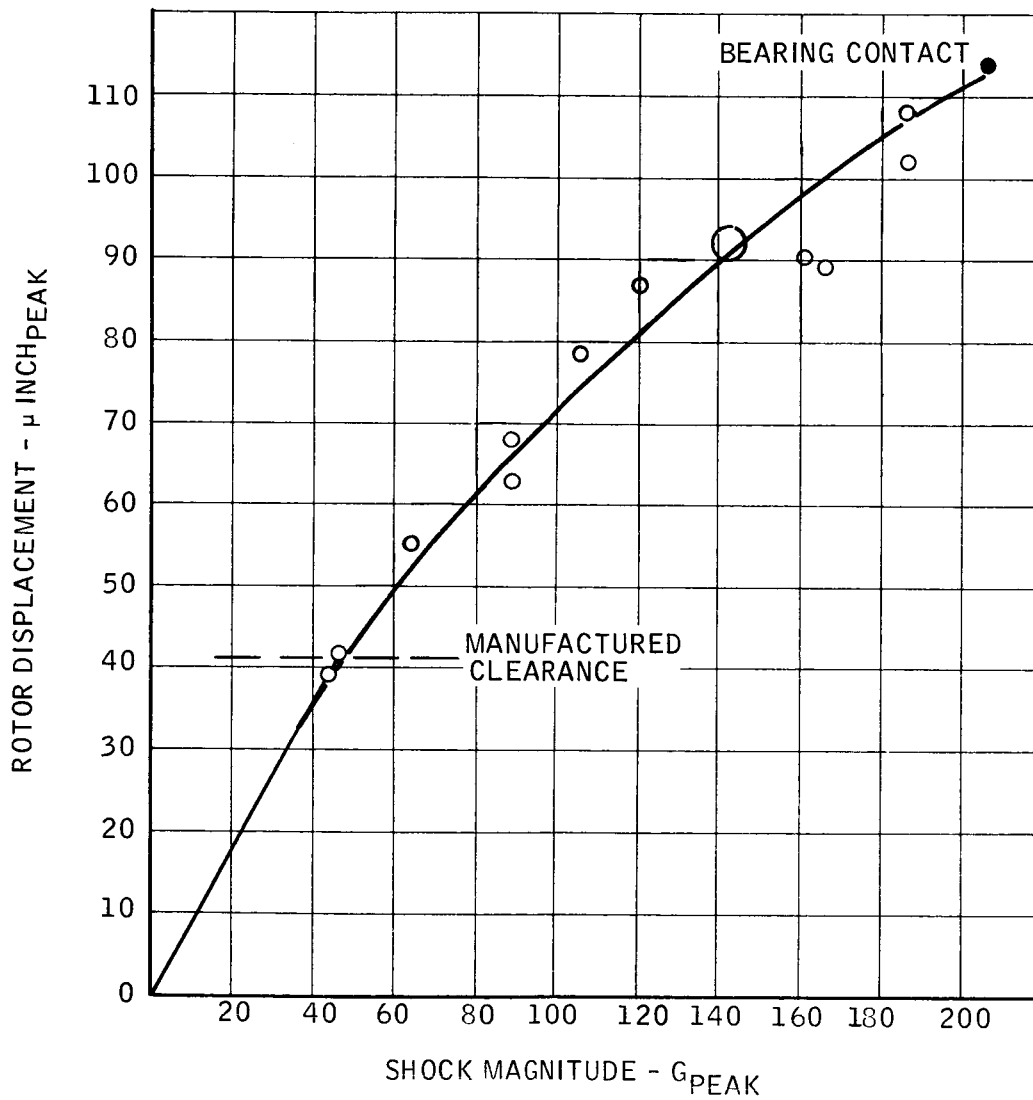


Figure 34. Journal Displacement versus Shock Magnitude, Motor J2

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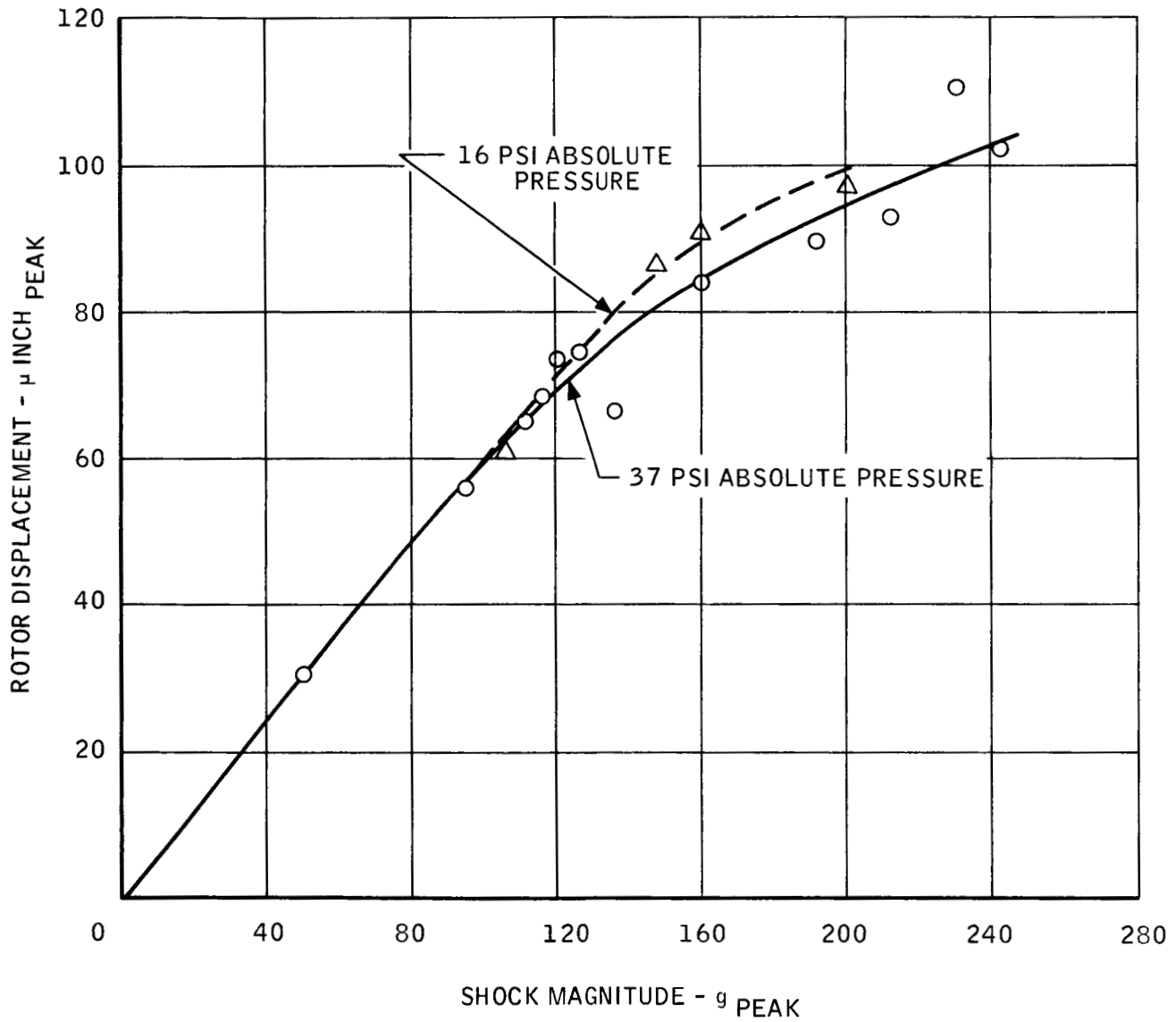


Figure 35. Journal Bearing Shock Response, Motor J3

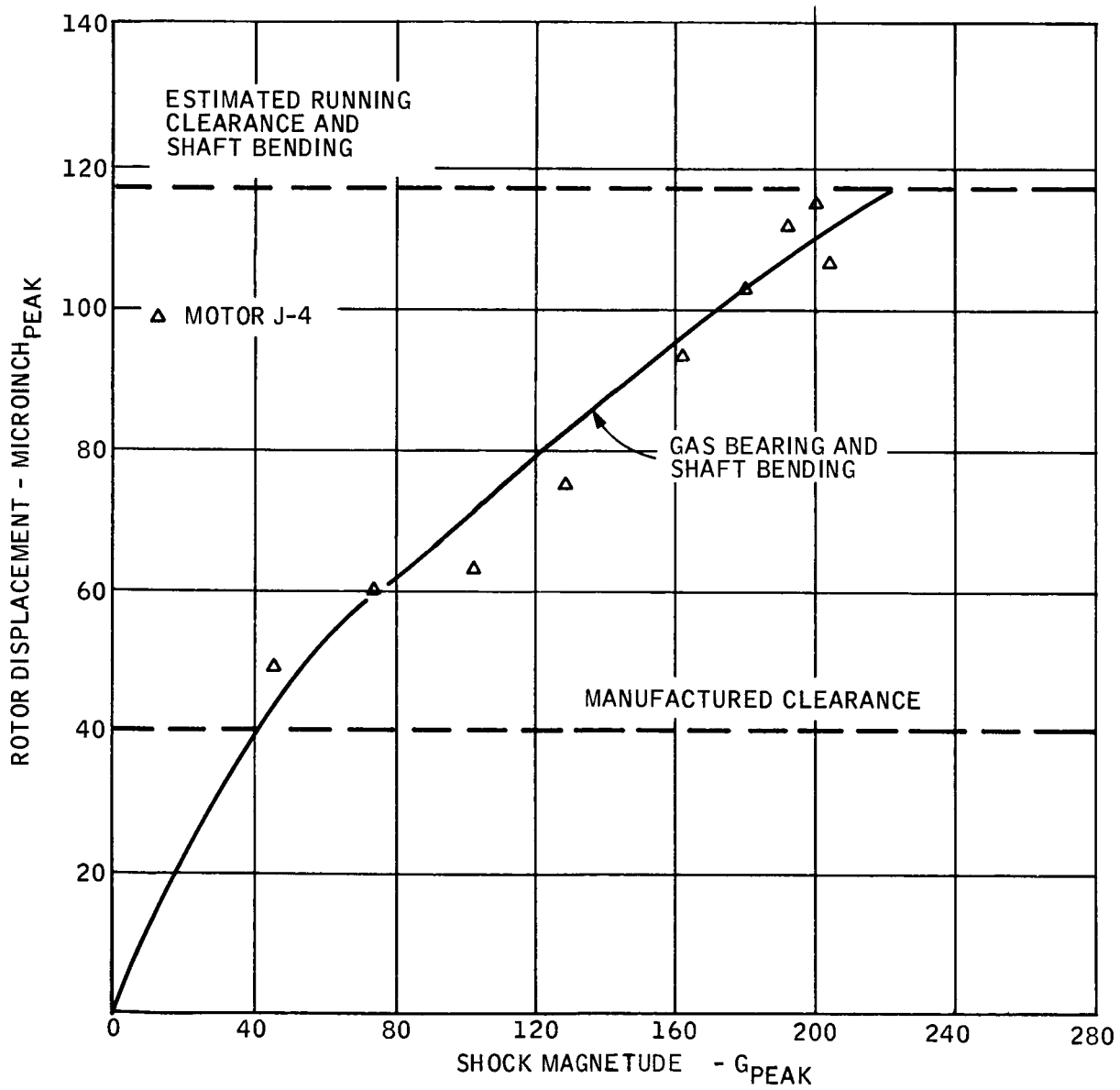


Figure 36. Journal Displacement versus Shock Magnitude, Motor J4

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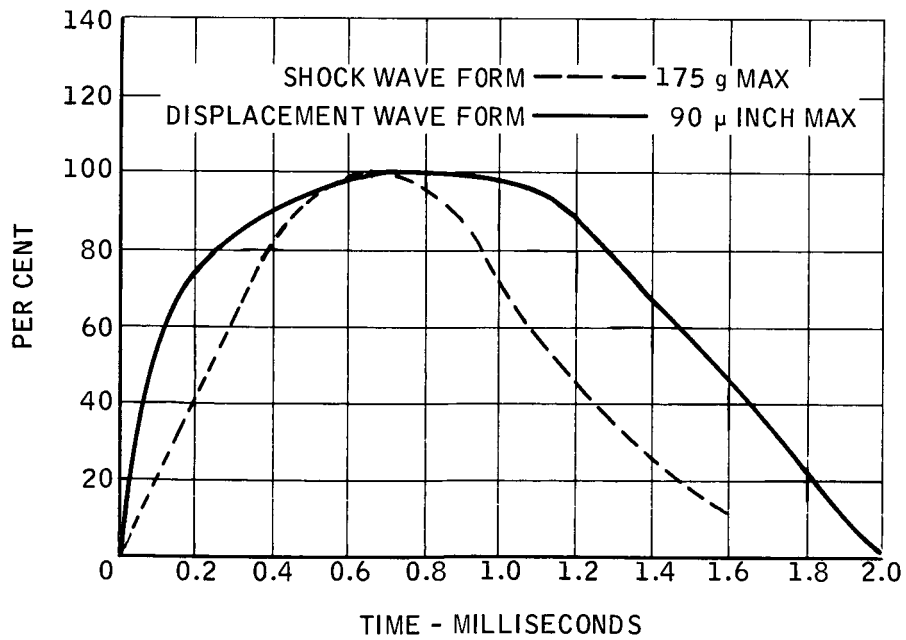
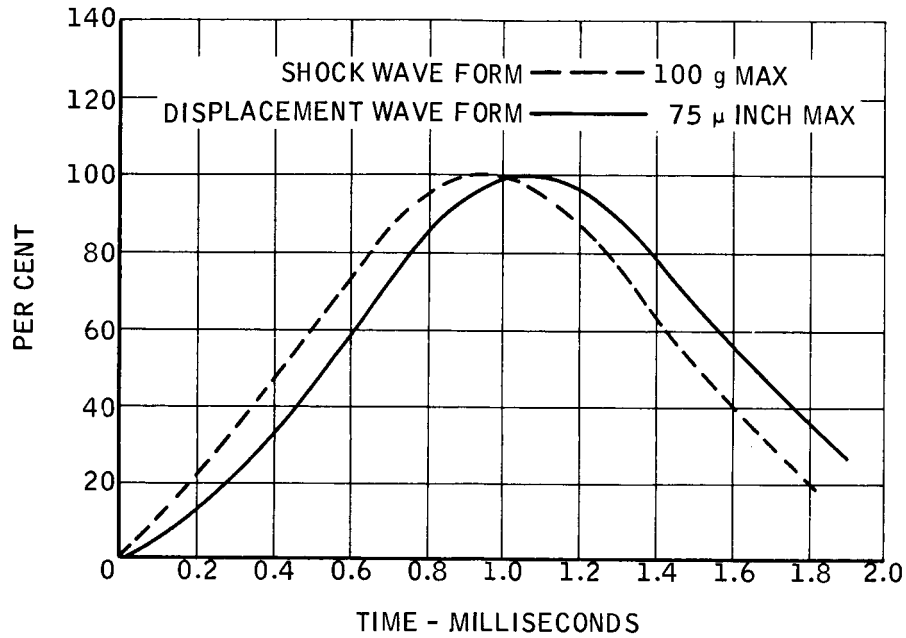


Figure 37. Journal Waveforms, Motor J1

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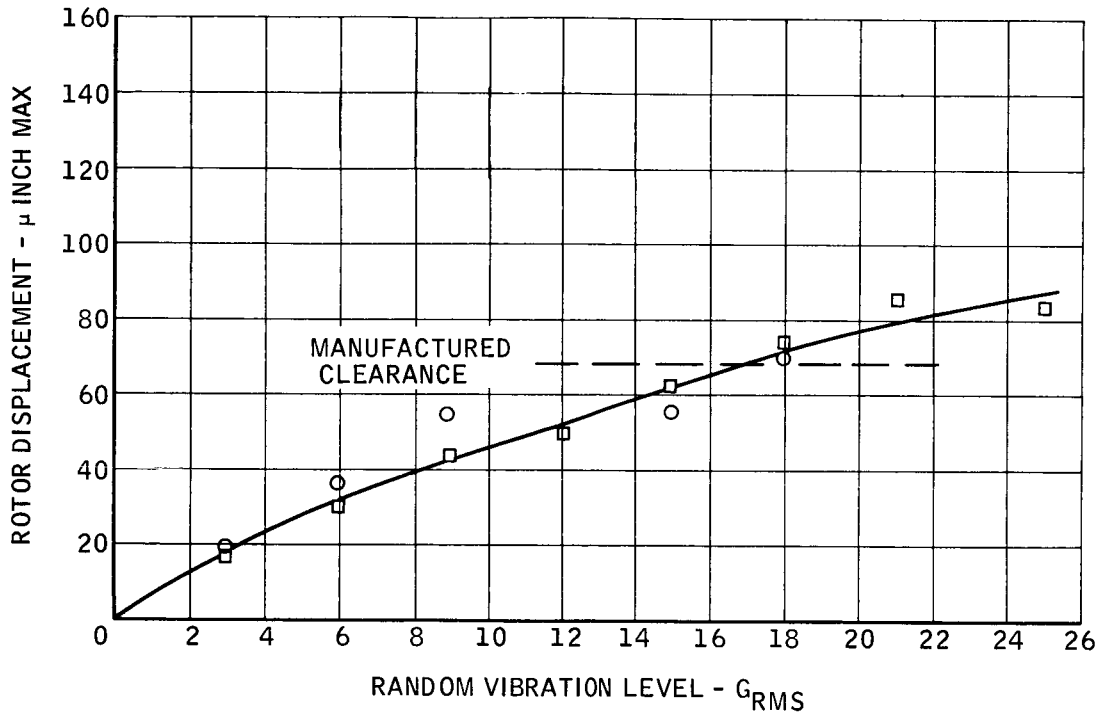


Figure 38. Journal Bearing Random Vibration Response, Motor J1

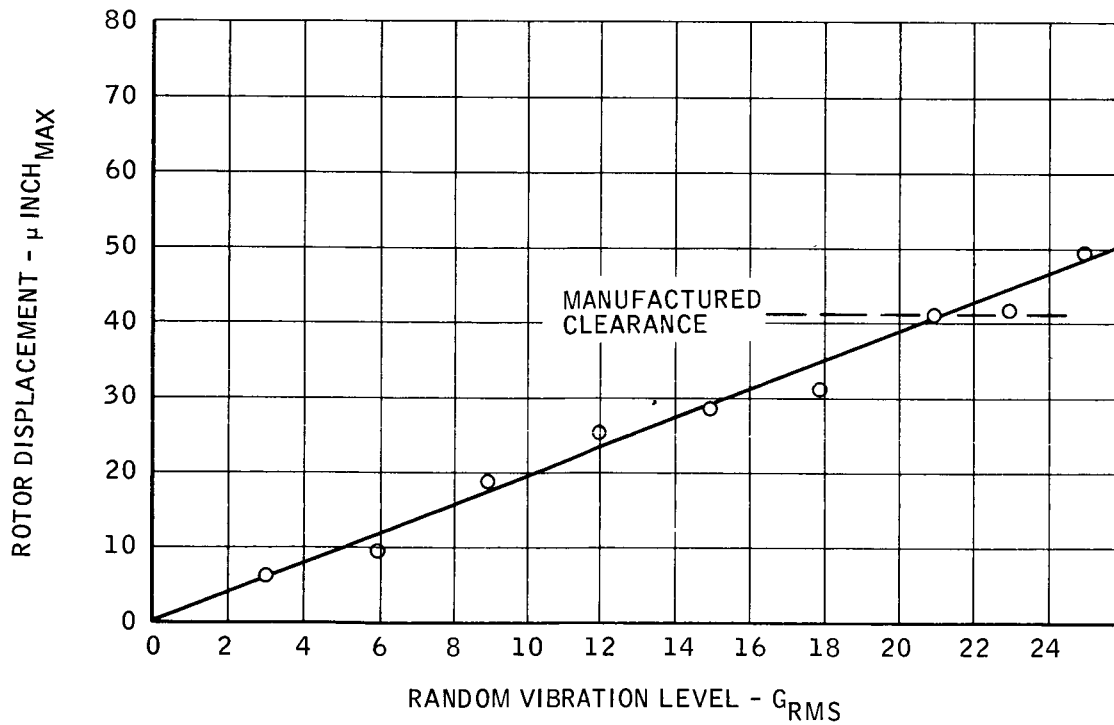


Figure 39. Journal Bearing Random Vibration Response, Motor J2

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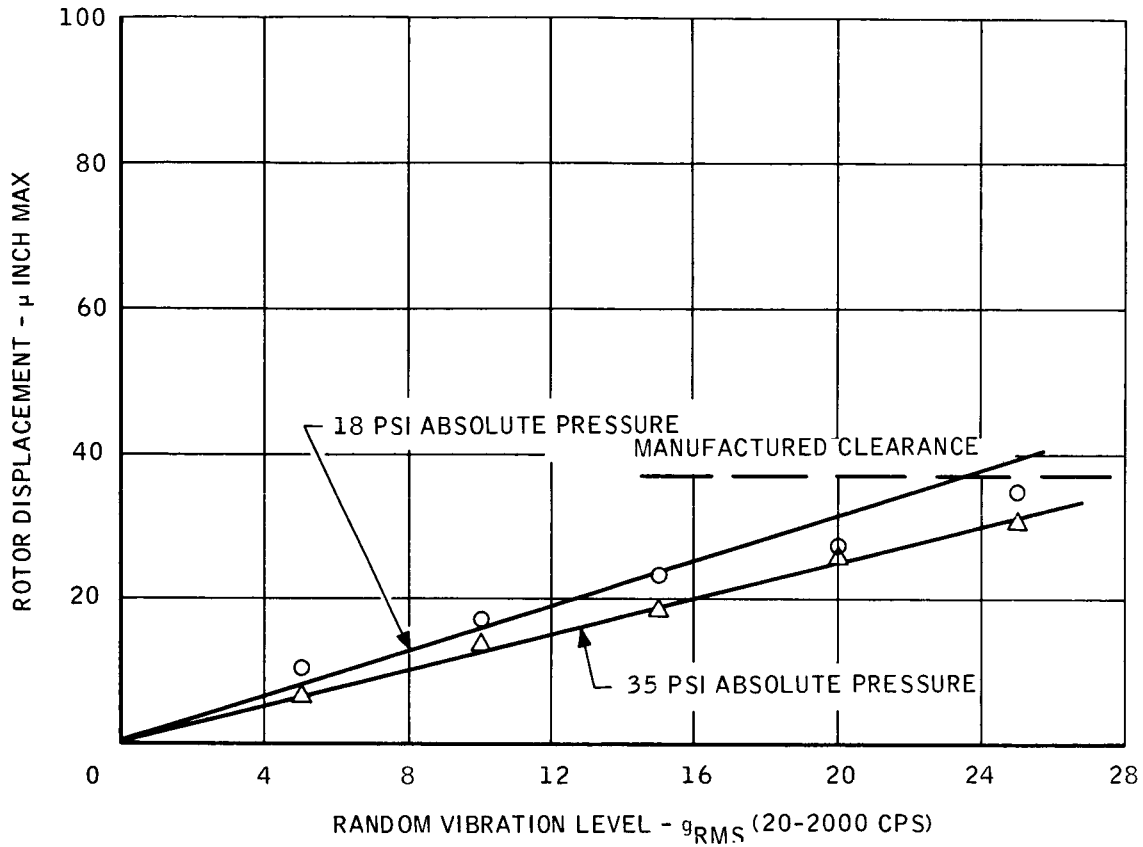


Figure 40. Journal Bearing Random Vibration Response, Motor J3

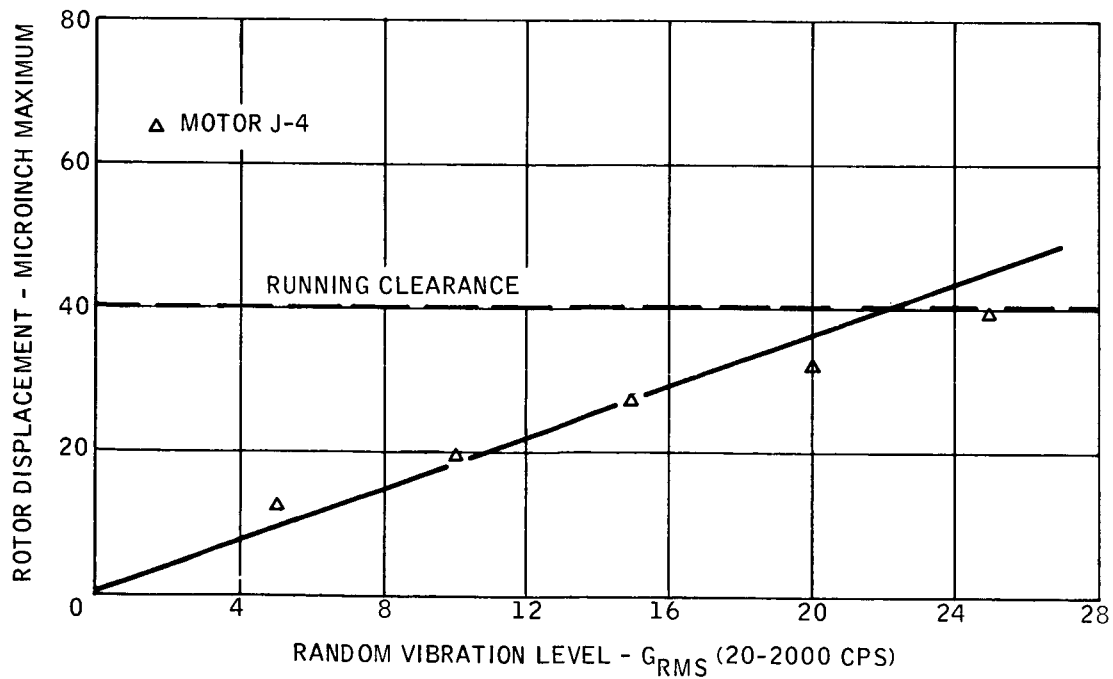


Figure 41. Journal Bearing Random Vibration Response, Motor J4

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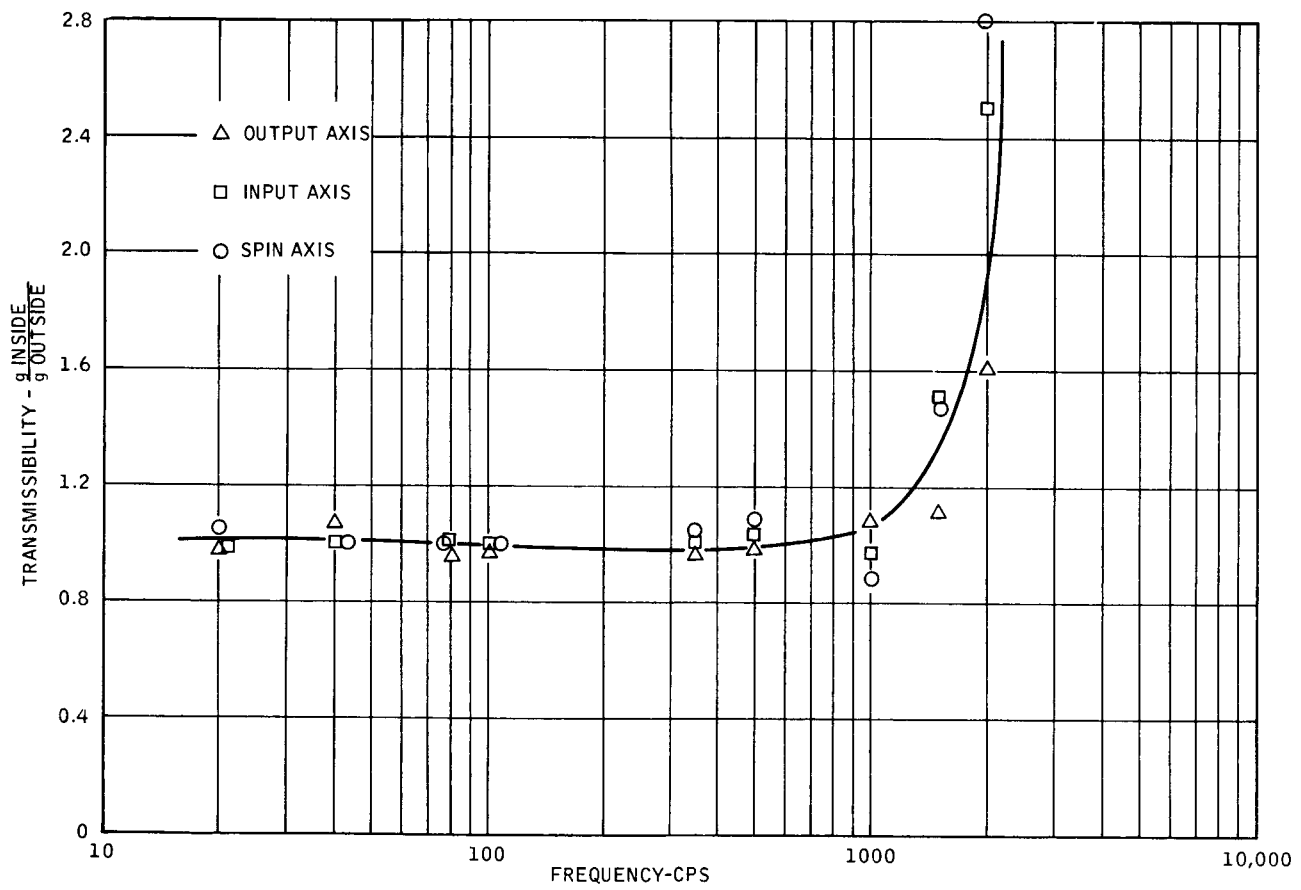


Figure 42. GG159C Gyro Frequency Response

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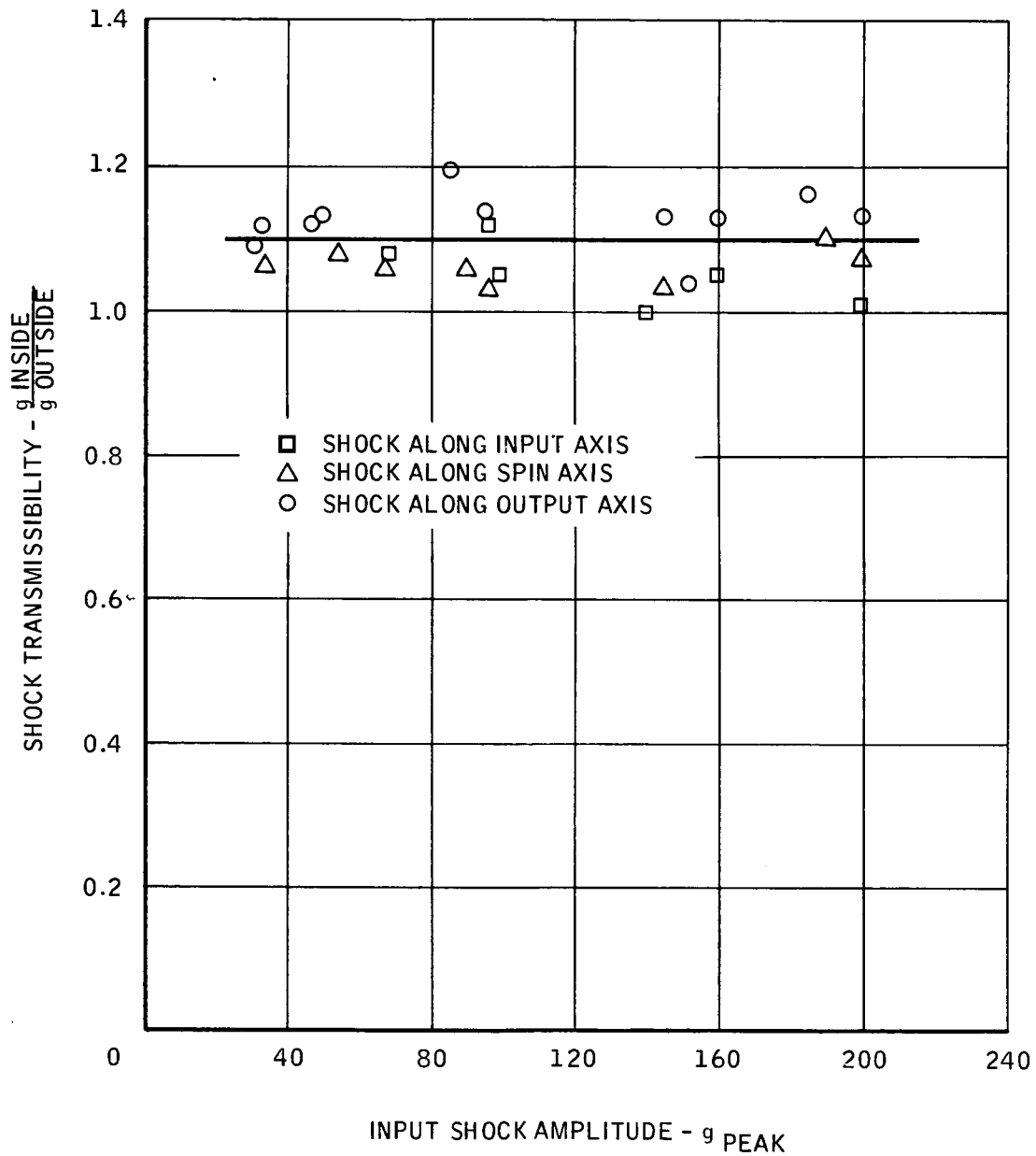


Figure 43. Shock Transmission of a GG159C Gyro,
1.5 MS Half Sine Shock

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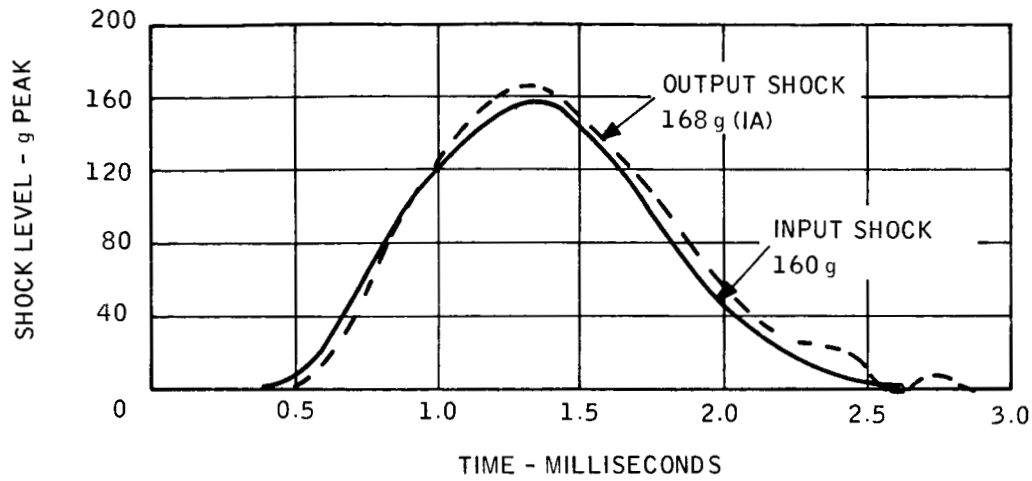


Figure 44. GG159C Shock Transmission Waveform

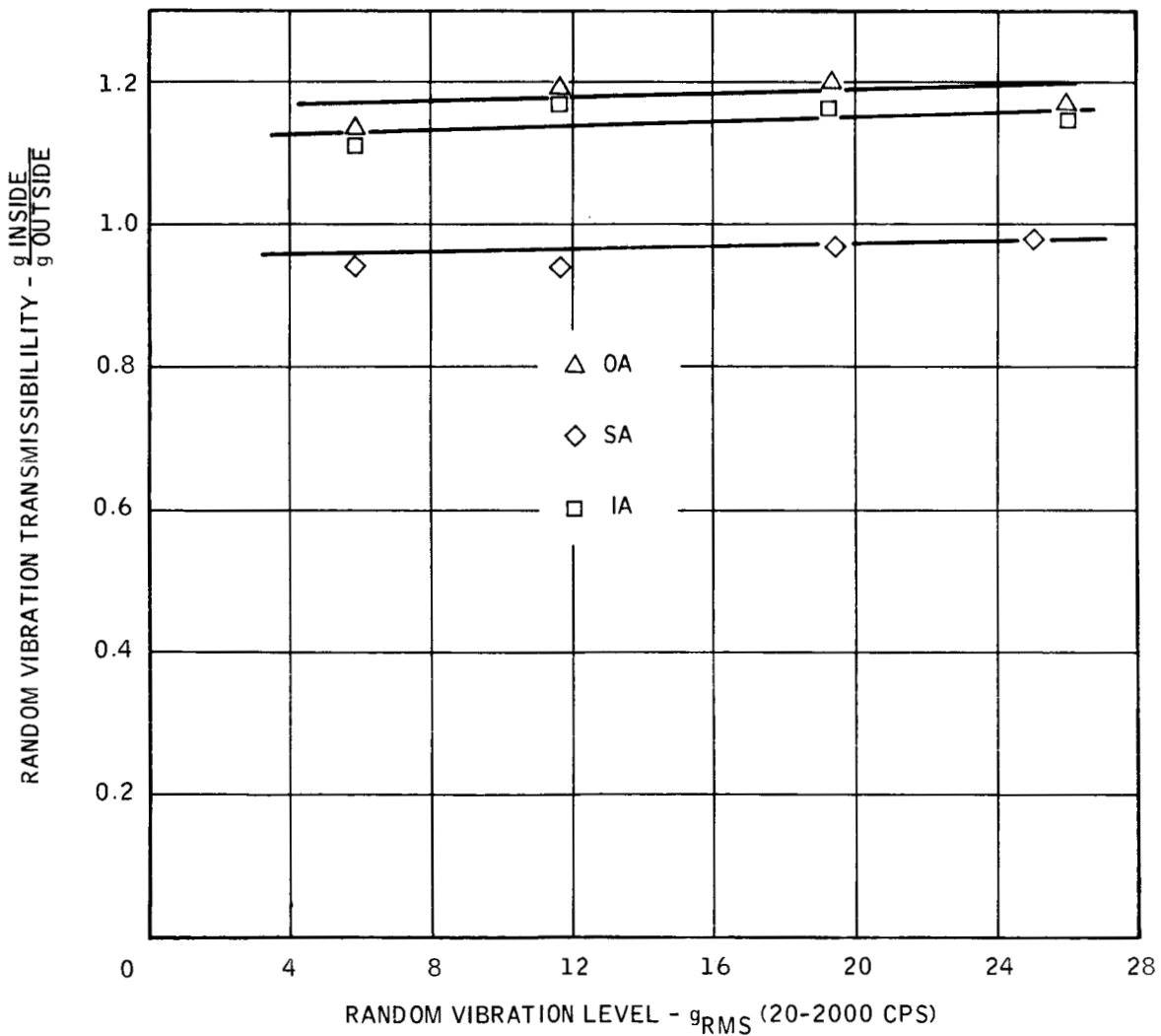


Figure 45. Random Vibration Transmissibility of the GG159C Gyro

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SECTION III ITEMIZED CONTRACT WORK

The work discussed on this contract was performed on the days shown in Figure 46.

A program schedule is shown in Figure 47.

	JULY		AUGUST		SEPTEMBER		OCTOBER		NOVEMBER		DECEMBER		JUNE	
	10	20	10	20	10	20	10	20	10	20	10	20	10	20
GBSM MOUNTING FIXTURE	▼ SHOCK RATE CHECK				▼ PROBE CALIB. ▼ SINE WAVE CHECK ▼ SINE WAVE CHECK ▼ PROBE CALIB.		▼ RANDOM CHECK ▼ SHOCK CHECK ▼ PROBE CALIB.		▼ PROBE CALIB ▼ SHOCK CHECK ▼ RANDOM CHECK					
DUMMY GYRO			▼ ACCEL CHECK				▼ SINE WAVE CHECK		▼ SHOCK TEST ▼ RANDOM TEST					
J-1					▼ SINE WAVE CHECK		SHOCK CHECK ▼		▼ PRESSURE AND RUNDOWN ▼ RANDOM AND SINE TEST ▼ SHOCK TEST ▼ DIMENSION CHECK ▼ TEAR DOWN ▼ REASSEMBLY ▼ SHOCK TEST		▼ JAN 10 LIFE TEST			
J-2									▼ FINAL GRINDING ▼ FINAL ASSEMBLY ▼ RANDOM TEST ▼ TEAR DOWN		▼ REASSEMBLY ▼ RANDOM AND SINE TEST ▼ SHOCK TEST JAN 16→FEB 11 LIFE TEST		NON OPERATING RANDOM TEST ▼ LIFE TEST →500 HR	
J-3									▼ FINAL GRINDING ▼ FINAL ASSEMBLY		▼ 14-1 LAND/GROOVE STATIC TEST		▼ CLEAN AND ASSEMBLY ▼ SINE TEST ▼ RANDOM TEST ▼ SHOCK TEST ▼ NON OPERATING SHOCK TEST LIFE TEST →500 HR	
J-4									▼ FINAL GRIND ▼ FINAL ASSEMBLY		▼ CLEAN AND ASSEMBLY ▼ SINE TEST ▼ RANDOM TEST ▼ SHOCK TEST			

Figure 46. Program Work

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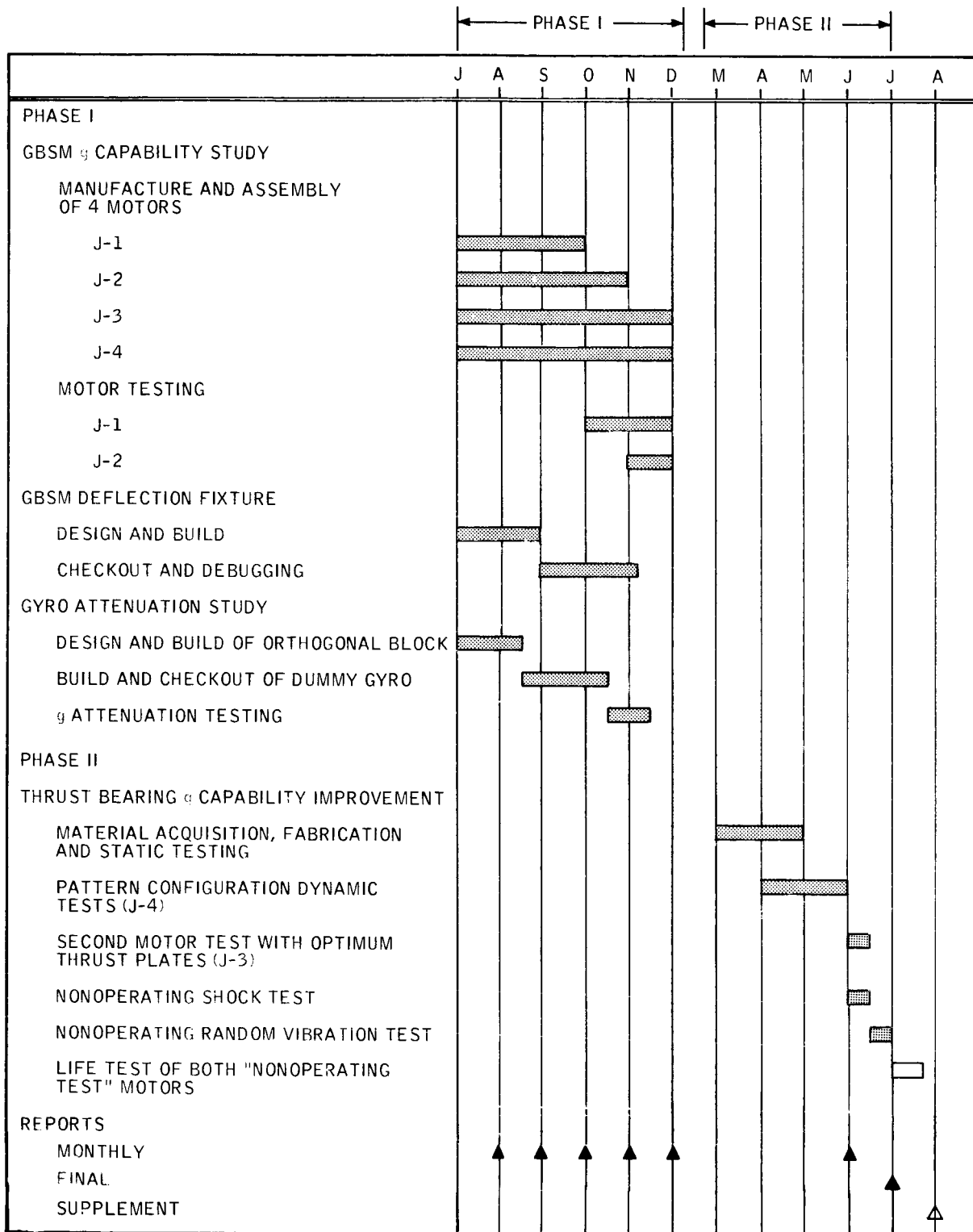


Figure 47. Program Schedule