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# FATIGUE STRENGTH TESTING EMPLOYED FOR EVALUATION AND ACCEPTANCE OF JET-ENGINE INSTRUMENTATION PROBES


Everett C. Armentrout
Lewis Research Center
Cleveland, Ohio



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# FATIGUE STRENGTH TESTING EMPLOYED FOR EVALUATION AND ACCEPTANCE OF JET-ENGINE INSTRUMENTATION PROBES

by

Everett C. Armentrout

## ABSTRACT

This report outlines the fatigue type testing performed on instrumentation rakes and probes intended for use in the air flow passages of jet-engines during full-scale engine tests at Lewis Research Center. Included is a discussion of each type of test performed, the results that may be derived and means of inspection. A design and testing sequence outlines the procedures and considerations involved in the generation of suitable instrument probes.

## INTRODUCTION

During the development and testing of jet engines, numerous pressure and temperature measurments are required. These are obtained through the use of instrument probes, or rakes, which are inserted into the air stream and flow passages of the test vehicle. A structural failure of such a probe not only means the loss of test data, but can easily cause catastrophic destruction of the test vehicle itself. To reduce the possibility of this occurring, uniform qualification procedures have been established by the Airbreathing Engines Division at Lewis Research Center to provide the designer and the test engineer with an assurance that the test probe will survive under specified limits and conditions.

Instrument probes are subject to two different classes of forces: (A) mechanical forces induced through the mounting and (B) aerodynamic forces. These forces, singly or combined, cause vibration of the probe which can lead to instability and failure. The test procedure described is one that has evolved after many hours of testing involving many configurations and attempts to simulate both the mechanical and aerodynamic forces.

Instrument probes are expensive even in their simplest form and an extensive program of destructive life testing for each design would be prohibitive in both time and money. The test procedures used and described in this report do not require long test times nor do they consume numerous probes: The procedures not only qualify the probes but also make the user aware of any limitations in the design so that precautionary measures may be incorporated in their use.

A standarized procedure for instrument probe acceptance testing is advantageous and beneficial to all testers of jet engines but no such standarization exists amoung the military or jet engine manufacturers today. The Navy has a Standard Environmental Test Methods manual, NAVORD OD-45491 (1), which defines the types of tests in broad terms

but leaves the specifics to "experienced engineering personnel." NASA SP-5113 (2) entitled "Non-destructive Testing" provides a review of methods used by the government and aerospace industries. The emphasis, however, is on basic principles and applications rather than detailed implementation and procedure.

The instrument probe evaluation procedures described are not intended for universal application. The actual test conditions must be considered on a case-by-case basis but vibration acceptance tests are considered mandatory for every probe that is to be placed in front of rotating components. Because of the inability of the test apparatus to completely duplicate the operating conditions and because of possible differences in the fabrication techniques employed for different probes of the same design, the tests are not an absolute guarantee of infinite life performance. The probability of failure, however, can be made very small.

## ACCEPTANCE POLICY

The ideal instrument probe inserted into the air flow passage of a jet engine would be very thin and small, so as not to create any flow disturbance, and would function for an indefinite period of time under any conditions of temperature and flow. Such usage naturally creates a concern for the continued well-being of the probe, as well as that of the test engine, itself. To relieve this anxiety and the possibility of failure occurrences, appropriate tests must be made to insure that a structural failure of the probe does not occur. Careful consideration during design and thorough checking of materials and workmanship during construction is not sufficient. Ideally, the most direct method, and the one used in spacecraft testing, is to determine and duplicate the operational environment. For jet engine test work, however, this is not feasible. Here the instrument probes must have a long life and operate reliably in a variety of test conditions. The duplication of conditions for testing becomes impractical and so time-consuming that equivalent simulated conditions must be substituted. Tests and procedures have been adopted in response to the general safety requirements of the Airbreathing Engines Division and apply to all instrument probes and appendages that might be installed in front of or within a test engine. The methods employed to arrive at a level of testing to achieve confidence in a probe design are described in the Test Procedure Section of this report and are based on consideration of the following factors:

1. The environmental conditions to be encountered at the test location.
2. The desired life or length of service.
3. The effect a failure might have on the test vehicle or facility.
4. The availability of test equipment to reproduce or simulate the desired conditions.

The procedures adopted accommodate these considerations and in addition, the forms and records used as part of the procedures serve as a checklist and test performance summary. The tests specified, over a period of time, have also tended to become inherently conser-

vative. By intentionally specifying more rigorous test conditions than anticipated in practice, the chances of probe failure in use are greatly reduced. A sample procedure is outlined in Appendix A.

Responsibility for probe integrity does not end with successful completion of the vibration tests. Proper installation and usage are also factors to be considered. Faulty installation can result in the initiation of high stress levels due to improper fit, wrong torque on the mounting bolts, etc. Installation and removal procedures must be available and diligently followed. In addition, schedules must be established to periodically check all instrument probes while in use.

## TEST PROCEDURES

The types of test specified and discussed for qualifying instrument probes to withstand the shocks and vibrations encountered in service consists of:

1. Sine-Sweep
2. Sine-Dwell
3. Random vibration
4. Shock

All of these tests are predominantly oscillatory, producing repeated reversals of stress at various stress levels. Fatigue failure as a result of repeated reversal of stress is the hypothesis adopted as the chief cause of probe failure and the test specifications are based on this assumption. The largest amplitude of stress reversal occurs at probe resonant condition, so the testing is concentrated about this point.

In the fatigue tests conducted on basic materials, the results show a large scatter at each test level due to slight differences or imperfections in the material. Corresponding fatigue tests conducted on fabricated components show even greater scatter due to the increased possibilities of imperfections and manufacturing differences. Instead of constructing and testing a greater number of probes for a better statistical average, however, only one probe of a particular design is subjected to extensive testing and the test results of all others are compared for similarity, not duplication. The probe that is thoroughly tested is called the 'prototype'. In the normal sequence of verifying a design, a prototype is constructed and tested and if found to be satisfactory, flight and back up models are then built. Because of the time interval between construction of the prototype and flight models, there is a strong possibility that different materials may be used as well as different construction techniques. To circumvent this, all the instrument probes of any one design that are required for testing, plus any spares, plus one more, are ordered or constructed at the same time. It is thus more probable that the same material and manufacturing and assembly techniques will be used for all. After completion, one probe out of the group is selected at random as the prototype model and the others become flight or actual test probes.

Two different test levels are employed. For the prototype model, high amplitude levels are used over long time periods and all four

types of testing are employed in each of three mutually perpendicular axes. The flight models are only subjected to a single axis, sine-sweep test at low amplitudes to preserve their useful life.

The cyclic tests conducted on the prototype model to check fracture toughness impose a total of approximately 2 to 4 x $10^6$ cycles under various loads. To estimate the fatigue life under these variable-amplitude stress conditions, the assumption is made that the number of cycles to failure are used up in a linear and cumulative manner. If D is the fraction of life consumed then:

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i} \geq 1 \quad \text{where}$$

$n_i$ = Number of load cycles at stress condition $S_i$, and
$N_i$ = Number of cycles from S-N chart at condition $S_i$.

As D approaches 1, theoretically the probe approaches failure. For our purposes, a conservative value of 0.5 is used. This is due to the fact that the equation does not take into account the sequence in which the stresses are applied, which is a factor in some materials. In addition, the equation does not consider the possibility of radical inequalities in the number of high stress cycles as opposed to the number of low stress cycles (3), nor does it consider the method of construction.

Instrument probes are constructed of several parts and welded or brazed together. During welding, the metal is melted and resolidified and if not done properly, fatigue 'hot-spots' are created. These welds are considered to be the same as cracks and become the critical areas for fatigue initiation. Figure 1 shows the reduction in allowable stress and life for a typical metal that is butt-welded.

The test procedure discussed in this report does not include any form of thermal stress testing. Thermal testing at either high or low temperature levels would involve the use of considerable test equipment but it is not deemed necessary since the effect can be duplicated in other ways.

Aside from the stresses that arise within the probe due to temperature gradients or extreme operating temperatures, the strength characteristics of the material itself are temperature dependant. The peak value of the endurance limit of most steels occurs at 400° - 500° C but decreases rapidly at slightly higher temperatures. The yield point, the tensil strength, the plastic flow stress and the endurance limit all show this common tendency. The effect of temperature on fatigue life, as shown in Figure 1, can be duplicated by adjusting the stress level for room temperature testing. For example, a probe intended for operation in a 500° C environment, and requiring a minimum life of 5x$10^6$ cycles, could withstand a continuous stress of 31 000 N/cm$^2$ (46 400 psi). Testing at room temperature and a stress level of 46 500 N/cm$^2$ (67 400 psi) would simulate the high temperature condition.

## SINE SWEEP

The sine-sweep test is conducted on each probe to determine the flexural and torsional resonant frequencies and the amplitude associated with each. During this test, the probe is subjected to a sinusoidal force of specified amplitude over a stated frequency range at a stipulated sweep rate. The sweep rate can be constant over the entire frequency range or it may be varied for different segments of the frequency span. If the sweep rate is too fast, however, the response will be erroneous in both amplitude and frequency. This phenomenon is illustrated in Figure 2. which shows a 30 Hz increase in resonant frequency with an amplitude approximatly 150 G's lower for a sweep rate change from 0.5 octaves/minute to 20 octaves/minute.

The sine-sweep test provides graphic proof of the resonant frequencies of the probe for comparison with the calculated design values. Dangerous fatigue stresses exist when parts of the probe or the probe itself are at resonance so it is essential that the resonant frequency be known and operation in this region be eliminated or restricted.

Sine-sweep vibration tests are not standardized and are conducted in several control modes by different testers. The probe can be vibrated over the frequency range in a mode of constant displacement amplitude, a constant velocity rate, a constant acceleration or a combination of the three. Some testers prefer to use a constant velocity mode of 3.0 inches/- second for prototype tests and 0.5 inches-per-second for flight level models. Other testers specify different amplitudes and modes as shown in Figure 3., which are based on the location of usage with the highest amplitudes being used for probes mounted within the engine or at the engine inlet. The engine manufacturers specify a maximum allowable engine displacement for start-up and running conditions of approximately 8 and 5 mils (0.005 in.) respectively. The tests conducted by Airbreathing Engines Division at Lewis Research Center utilize a constant displacement - constant acceleration combination.

For the prototype model, a constant displacement test level of 0.76 to 1.27 cm (0.3 to 0.5 in.), double amplitude is used over a frequency band of 7 to 24 Hz, followed by a constant acceleration level of 10 G's to 3000 Hz. The flight models, which are only subjected to the sine-sweep test are limited to a constant displacement amplitude of 0.25 to 0.76 cm (0.1 to 0.3 in.), double amplitude at low frequencies of 5 to 14 Hz and 3 G's, constant acceleration, from 14 Hz to 2000 Hz.

## SINE DWELL

After the resonant frequencies are determined for the probe, it is subjected to sinusoidal vibrations for 500 000 cycles or 30 minutes, whichever is greater, at both the 1st and 2nd flexural resonant frequencies. If the resonant frequency shifts continuously or changes more than 20% during the 30 minute time period, the test time is extended to 60 minutes. This is a severe test. It subjects the probe

to many cycles at a high strain level far in excess of any condition that the probe is expected to encounter. A big percentage of probe life is consumed during the dwell tests and whether or not the probe survives these tests determines its acceptance.

Experiments have shown that an abrupt surface change such as tool marks, surface flaws, welds, or abrupt changes in cross section, raises the stress concentration and reduces fatigue life and static strength of the probe. Fatigue failures start at these stress risers and since fatigue is accumulative in nature, the sine-dwell test will aggravate any abnormal condition to possible failure. The following table shows the effect of surface finish on life as compiled by V. J. Colangelo using SAE 3130 steel with completely reversed bending at 655 MPa (95 000 psi)(4).

HOW SURFACE FINISH AFFECTS FATIGUE LIFE

| Finishing operation | Surface finish | | Fatigue life (cycles) |
|---|---|---|---|
| | μ-cm | μ-in. | |
| Lathe | 267 | 105 | 24 000 |
| Partly hand polished | 15 | 6 | 91 000 |
| Hand polished | 13 | 5 | 137 000 |
| Ground | 18 | 7 | 217 000 |
| Ground and polished | 5 | 2 | 234 000 |

Instrument probe surfaces are usually finished by vapor honing or peen blasting with glass beads. These two methods produce a 'polish' of approximately 40 μ-inches, rms, on type 304 stainless steel.

Almost all failures occur due to crack propagation but according to the research conducted by S. S. Manson (5), detectable cracking does not occur until 70 - 85% of the cyclic life has been used. The sine-dwell test, therefore, is continued after all the other prototype tests are completed until probe failure so that a more accurate approximation of probe life can be realized. Fatigue life, however, is a function of the amplitude of the strain cycle; the lower the strain, the greater the number of cycles to failure (3). A relationship must be developed in order to arrive at a fatigue life expectancy for the flight type rakes based on the results of the Prototype tests.

Palmgren (6), Langer (7), and Miner (8) proposed a linear damage rule which assumed that at any stage in the loading history of the material, the amount of life used up was proportional to the cycle ratio at that loading condition. That is to say, if a stress range is applied for $N_1$ cycles at a condition where $N_F$ cycles would result in failure, then $N_1/N_F$ percent of the life has been consumed.

In the notch tests conducted by Richard H. Kemp (9), on pressure cylinders and test specimens, failure occurred at approximately 80% of the computed yield strength of the material at room temperature. Tests conducted by Hubert B. Probst (10) resulted in failure at 50% of the normal yield strength. These failures were attributed to the presence of small cracks, usually in the area of welds. The construction of instrument probes usually involves varying amounts of brazing and welding so the notch theory for failure analysis seems appropriate. In addition, surface conditions and finishes affect the fatigue behavior of metals due to the interaction of surface compressive stresses with the core or interior residual tensile stresses as previously discussed (4).

The dwell tests are performed in each of the three test axes on the prototype model only.

## RANDOM

Sinusoidal vibration, although the simplest to evaluate, occurs very rarely in actual practice. The vibration of structures, engines or vehicles is almost never concentrated at a single frequency but usually at two or more discrete frequencies. For jet engines and rockets, the vibration exists over a wide, continuous range of frequencies due to the turbulent flow of air, the audio energy and the imperfections or unbalances of the rotating parts. This type of vibration mode can best be simulated with a random vibration test. In this type test all of the resonances that exist in the frequency range are excited simultaneously. If the structure is composed of several parts, each having its own resonant frequency, they will all be excited at once rather than sequentially so that possible interactions will become evident. Instrument probes are nominally single component assemblies, however, with no moving parts, so the interaction and possible malfunction due to simultaneous resonances within the probe body is not a major problem. Each probe, however, in addition to a mounting flange usually has a external bracket or "billboard" attached as a means of conveniently connecting to the sense lines. The resonance of any external part can be different from that of the probe and of such magnitude that its vibrations can force the probe body into oscillation.

To observe this possible interaction, the prototype probe is subjected to a random vibration test for a period of 15 minutes in each of the three test axes. During this test the external mounting bracket, sense lines and connector panel are left free and unclamped. For all other tests the bracket assembly is secured to the shaker head or mounting fixture. If probe-body resonances are observed as being induced by the external bracketry and are of such magnitude as to be considered dangerous, then a redesign must be considered with respect to the mounting, connector bracket, probe body or the entire instrument probe.

The amplitude level of the random vibration test is expressed in PSD (Power Spectral Density) over a frequency range. For comparison to sinusoidal test levels, this can be expressed as

$$G = \left( \int_{f_1}^{f_2} W(f)df \right)^{1/2} \quad \text{where}$$

G = Acceleration, G(rms)
W = Power Spectral Density, $G^2/Hz$
f = frequency, Hz

[Ref. 11]

The simplest form of random vibration is that of a flat or 'white noise' spectrum in which the PSD is independent of frequency. A typical 'white noise' test spectrum is shown in figure 4. For this example

$$G = \sqrt{w\,\Delta f}$$

$$= [0.1\ (1990)]^{1/2}$$

$$= 14.1G$$

The PSD curve indicates a flat response of $0.1G^2/Hz$, but the instantaneous amplitude at any one frequency follows a Gaussian probability distribution curve such that, in the example above, 68.3% of the vibrations will have a maximum rms amplitude of 14.1 G's; 27.1% will be within the band from 14.1 to 28.2 G's and 4.3% will be in the band from 28.2 to 42.3 G's. For the same number of cycles, the damaging effects of random vibrations are less than those of a sine sweep test, but, by increasing the amplitude level of the random vibrations, the effects can be practically equalized. Determination of fatigue life with random vibration testing is both tedious and time consuming. Sinusoidal stress reversals through sine-dwells or sine-sweep type testing are easier to determine as to number and stress level and consequently are used in lieu of random vibration for determination of fatigue life.

## SHOCK

A suddenly applied, nonperiodic force of finite time interval that results in a transient response of a system is called shock. A sonic boom is an example of such a transient time function; the impact of two bodies is another. A single shock application, unless it is extremely severe, will rarely induce failure. A shock induces vibration at the resonant frequency which adds to the overall number of stress reversals and since stress reversal damage is accumulative, the summation leads to eventual fatigue failure.

For shock pulse testing, the amplitude, pulse shape and time duration of the pulse must be specified. There are five basic types of shock motion or pulse shape: (A) impulse, (B) step, (C) half-sine, (D) decaying sinusoid and (E) complex. The last three, along with triangular and sawtooth forms, typify the motions normally used as shock input forms. The first two are limiting cases and nearly impossible to duplicate in practice.

The time duration of the input shock pulse determines the acceleration rate of the force. For systems with high natural frequencies where the natural period is very much less than the shock pulse duration, the response will follow the shock input pulse very closely. For systems where the pulse duration and half the natural period are equal or nearly so, the response is high and for lightly damped probes, a considerable number of high stress reversals are absorbed during the gradual decay or "ringing". Figure 5 shows response curves illustrating these two conditions (12).

Shock pulses can now be applied through computer control of the shaker head with better control of amplitude and pulse shape than formerly acquired with the 'drop-test' machine. In the Airbreathing Engines Division test procedure, three pulses are applied in each of the three test axes. Each pulse is a half-sine wave of 20 G amplitude and has a pulse time that is equivalent to the resonant frequency of the probe.

## TEST APPARATUS

### VIBRATION TESTING MACHINES

The vibration tests at Lewis Research Center are conducted on electrodynamic type vibration machines commonly called exciters or shakers. For this type machine, the force causing the motion of the table is produced electrodynamically by the interaction of current flow in the driver coil with the intense magnetic field of the field coil. Figure 6 illustrates the essential components of this type of shaker. The mounting base is constructed to allow the shaker to be rotated 90 degrees so that horizontal as well as vertical-axis vibration tests may be performed. In the horizontal axis, the shaker head is usually connected to an auxiliary table which is supported by hydraulic bearings or a fluid film.

The maximum test force is limited by the size of the shaker and the total weight of the test package. Figure 7 shows the allowable test ranges of the two shakers used in our vibration testing. The performance characteristics of the machines are summarized in the following table:

| SHAKER | RATED FORCE | TABLE WT. | MAX. DISP. | MAX ACCEL. | TABLE SIZE DIA. |
|---|---|---|---|---|---|
| C-60 | 26,690 N | 18 kg. | 2.5 cm. | 100G | 45 cm. |
| C-210 | 124,500 N | 154 kg. | 2.5 cm. | 75G | 75 cm. |

Both of these shakers are controlled thru a common source which incorporates computer controls for random type vibration and shock tests on the shaker.

## ACCELEROMETERS

The results from the tests described in the preceding sections are obtained through the use of strain gages or accelerometers mounted on the instrument probe and shake fixture. In order for these results to be meaningful and accurate, an understanding is needed of the performance characteristics of accelerometers as well as an understanding of how sensors and fixtures interact with the shaker and each other.

One of the most critical considerations is the weight of the accelerometer that is used to sense probe motion. Some probes are very small and the seismic mass of the sensor, placed at the point of desired measurement, can significantly alter the response. Accelerometer loading error results in an indication of lower resonant frequency and increased damping. Piezoelectric accelerometers come in various sizes, ranging from 100 grams in weight to 0.15 grams so selection of a light weight accelerometer can remove this source of error. For extremely small probes, where physical size restricts or prohibits the attachment of accelerometers, strain gages are used. Figure 8 illustrates typical placement of accelerometers and the sizes normally used.

Of equal importance to the mass, and also usually ignored, is the means employed to mount the accelerometer and the deployment of the lead wires. If the probes have small crosssectional dimensions, the means of accelerometer attachment, as well as its size, can alter the stiffness in that area and thus affect the amplitude of the vibration as well as decrease the resonant frequency. The use of mounting fixtures only compounds the problem.

Accelerometers can be mounted to the probe by cementing directly to the test surface with quick-set type cements. The cements used must be able to withstand the shocks and surface strains imposed by the test and still provide good frequency response. Bond thicknesses are usually of the order of 1mm or less for cyanoacrylate type adhesives.

Threaded engagements are also used to mount accelerometers as in the case of the control accelerometer for the shake fixture. For this type of mounting:

1. the accelerometer manufacturer's mounting torque should always be used and
2. the mounting surface should be flat, smooth and clean.

For frequencies greater than 4000 Hz, a thin film of silicone grease is recommended to improve coupling. Figure 9 shows effects of various mounting methods (7). The natural frequency and inherent damping of the accelerometer has a profound effect on the results obtained. If the instrument probe has a resonance that is close or identical to that of the accelerometer being used, the output will be high and erroneous. As a rule of thumb, the mounted resonant frequency of the accelerometer used should be 2.5 times that of the highest test frequency. If the resonant frequency of the probe or the test frequency is greater than the resonant frequency of the acceler-

ometer, the output will be low and erroneous due to amplitude roll off of approximately 12 dB per octave on the accelerometer.

Another aggravation and common source of error is cable noise. The use of proper cables and dressing of the cables to avoid flapping or "triboelectric charges" can prevent a large percentage of cable noise (13). The use of a built-in amplifier at the accelerometer also helps overcome the noise generated in ordinary or faulty cable constructions.

## STRAIN GAGES

As part of the initial design of the instrument probe, stress calculations are made with respect to the 'load' the probe must withstand. Accordingly, the materials used in the construction of the probe, the thickness of the material, the cross-sectional area, etc., are all based on these calculations. For the prototype testing, strain gages are mounted on the probe body to determine and check the bending and torsional stresses. The interpretation of the strain gage data for stress analysis is beyond the scope and purpose of this report. A thorough and detailed treatment of stress-strain analysis is available in a book by M. Hetenyi (14). It is important, however, that the items listed below be carefully considered in order to obtain data worthy of interpretation:

1. The temperature dependance of strain gages.
2. The effects of bonding the gage to the probe.
3. Moisture effects on the gage and bonding.
4. Hysteresis and zero shift of the strain gage in the first few strain cycles.
5. The circuitry used - dynamic or static strain and the number of active bridge arms.
6. The non-linearity of strain-resistance effect, especially at high elongations of wire type gages.

For adverse or severe test operating conditions or in a region where probe resonance is possible, strain gages are mounted on the flight probes for continuous monitoring during engine testing. By alerting the engine test conductor of a change in stress condition of the probe, the operating conditions can be quickly changed to a safer or more suitable region.

## SHAKE FIXTURES

The mounting fixture used to adapt the instrument probe to the shaker table or face is a critical piece of interface hardware. The fixture is <u>not</u> designed to simulate the vibration characteristics or exact physical geometry of the actual mounting in which the probe will

be used. Rather, the fixture must faithfully transmit the shaker input into the probe without loss or distortion and without the addition of any spurious side-effects.

The reaction of the instrument probe to known vibration forms and amplitudes is the prime concern. Occassionally a ring or special engine section is tested as an assembly with the probes in place. This type test is considered as an additional check and is not construed as a substitute for the normal probe testing.

The following items are offered for consideration in the design of test fixtures:

Stiffness. The shake fixture should be as stiff as possible such that it is not deflected by the weight of the test item and also stiff enough to transfer the shake table motion with high fidelity.

High Natural Frequency. This could be considered part of the stiffness design requirement but simply making the fixture bulky and heavy can create problems such as dynamic imbalance, rocking motion and excessive table weight. When the dynamic forces from the test fixture do not pass through the center of mass of the test specimen, the condition is called "dynamic imbalance" and this misalignment, combined with elasticity, in the mounting, allows rocking of the specimen. The type of shake fixture used (box cube, angle), greatly influences the degree of rocking that may be present.

Specimen Mounting. The bolts used to mount the test specimen to the fixture should be torqued to 80% of their yield strength. To attach the fixture to the shaker, the greater the number of bolts used, the better the results will be, provided there is sufficient stiffness in the fixture to load the bolts.

Fabrication. If the fixture consists of several parts, as in angle or box type fixtures, the pieces should be welded together since bolted joints cannot transfer loads across the joint as well as welded joints. Bolted joints do allow flexibility and multiple use of the fixture, however, and reduces the cost and number of individual fixtures required.

Mounting Surfaces. Flat mounting surfaces between the shaker head and fixture are a must. Any deviation from flatness decreases stiffness and the natural frequency. If not flat, the fixture will rock, or, if the fixture is stiffer than the shaker head, the head may be distorted when the fixture is bolted down and again cause rocking. A flatness tolerance of 0.005 TIR or better is acceptable.

Material. Aluminum is light, does not weigh down the test machine and has sufficient strength to make a very good test fixtures. For bolted construction, the use of threaded steel inserts is recommended to eliminate galling and stripping of the threads.

Accelerometers. The accelerometers are mounted to the test fixture for control and output monitoring by means of tapped holes. To provide a smooth mounting surface and a perpendicular mounting, the mounting holes should be machine-drilled and spot-faced. More than one accelerometer is recommended to monitor the motion of the test fixture, and one of these should be placed in close proximity to the test specimen's mounting point.

## INTERPRETATION AND SUMMATION

Upon completion of the vibration and shock tests, a judgment is required as to the worthiness of the instrument probes. To assist in this evaluation, the following processes and additional tests are conducted:

1. Construction of a Campbell diagram with resonant frequencies, blade-passing frequencies and engine speeds to show critical areas of operation.
2. Comparison of resonant frequencies and response shape of all Flight and Prototype models of each design.
3. Dye-penetrant and microscopic inspection of the test items exterior: X-ray inspection of the internal construction.
4. Interpretation of strain-gage data to determine bending and/or torsional stress.
5. Leak checks, flow checks and electrical checks of the instrument probes when applicable.

### SINE VIBRATION

Figure 10 shows the typical type of data derived from a sine-sweep vibration test on a flight-type instrument probe shaken in the Z-axis. The input curve (a.) indicates a constant displacement motion of 0.76 cm double amplitude (0.3" D.A.) (double amplitude) from 10 to 14 Hz with a cross over to a constant 3G peak level from 14 to 2000 Hz. This is a controlled input as specified for a flight-type test. The response of the two accelerometers mounted at the midpoint and end of the probe is shown in figure 10(b). This probe was hard mounted at the outside flange and clamped at the hub end by means of a retaining pin. The response curves indicate frequencies of excitation with amplitudes that are considered as a measure of importance as a source of trouble or fatigue. Resonant frequency for this probe was 470 Hz with maximum motion at the midpoint. The amplitude at resonance of 42G's is equivalent to a load of 164.5 MPa (24 000 psi). The endurance limit for completely reversed bending stress of type 304 stainless steel is 620-862 MPa (90-125 kpsi). Using a reduction factor of 3, because of the welded construction of the probe, results in a derived life expectancy of $10^5$ cycles at this resonant load condition (fig. 1). When plotted as a Campbell diagram (fig. 11), the resonant frequency of the probe meets the requirement of being greater than 2E or twice the engine speed frequency. This probe would be equally acceptable if its resonance had been less than 63 Hz, or 10% less than engine idle speed, and did not have any harmonics within the engine speed range.

## VISUAL INSPECTION

Most fatigue cracks start at the surface of a metal, which makes visual detection possible. One of the most widely used methods is that of a liquid dye-penetrant inspection. This method has become popular because of its wide range of applications, its low cost, its ease of use, and its minimum training requirement (15). Its fundamental limitation is the inability to detect flaws that are not open to the surface. The liquid-penetrant procedure is described in Mil-I-6866B.

Extensive work is now being conducted on crack-growth as an indication of impending fatigue. Airplanes are flying with cracks and defects in wings, landing gears, engine mounts, etc., since a "stationary" flaw is not considered as hazardous. Such is not the case for instrument probe usage, however. Here, the presence of any size discernable crack is cause for rejection and not license to repair and use.

## CONCLUDING REMARKS

Extensive experience in jet-engine testing has led to development of a comprehensive acceptance program for instrument probes. The procedures have been effective in providing a high level of confidence in identifying deficiencies in design, in promoting quality fabrication and in providing guidelines for continued safe use of the probes during engine testing. This has been accomplished through the life testing of a "Prototype" probe of each design with limited tests on identical "Flight" probes for comparison of response form.

The extensive testing recommended may be considered superfluous and unnecessary by some since proper engineering design practices can provide probes of suitable life and strength. However, the test procedures serve as visible physical checks against omissions or false assumptions made in the design or in fabrication. In addition, the test results serve a useful purpose in determining acceptability of the instrument probe. An obvious shortcoming in the testing process is the inability to completely duplicate the test environment of aerodynamic loading, temperature and run time.

## APPENDIX

An Instrument Probe Design and Record format is shown on the following pages. It is presented as a guide only for use in the development of particular forms to suit your specific test needs. I· this format the design engineer is made responsible for sections 1 through 5 and is also responsible for the scheduling of a review meeting with the personnel listed in section 6. The review personnel are responsible for checking and verifying the calculations, approving the design, conducting the review and for final acceptance of the probe for use in the test engine. The completed approval is filed with the engine project manager since engine operation and safety is his responsibility.

# INSTRUMENT PROBE DESIGN AND RECORD

1. GENERAL
   - a. Project ____
   - b. Facility ____
   - c. Engine ____
   - d. Engine Station ____
   - e. Type ____
   - f. Number Req'd ____
   - g. Drawing No. ____
   - h. Serial No. ____

2. ENVIRONMENT
   - a. Temperature Range ($^{o}F$) ____
   - b. Pressure Range ____
   - c. Medium ____
   - d. Mach No. ____
   - e. Engine Core Speed (RPM): IDLE ____ 100% ____ MAX. ____
     Fan Speed (RPM): IDLE ____ 100% ____ MAX. ____
   - f. Blade Passing Frequency: UPSTREAM: IDLE ____ MAX. ____
     DOWNSTREAM: IDLE ____ MAX. ____
   - g. Material Compatibility ____

3. MOUNTING FORM
   - a. Separate & Removable ____
   - b. Built-in ____
   - c. Free or Fixed End ____
   - d. Flange Restrictions ____
   - e. Section Dwg. ____
   - f. Relative Surface Motion ____
   - g. Seals ____

4. CALCULATIONS
   - a. Blockage ____
   - b. Resonant Frequency
     1st flex. ____
     2nd flex. ____
     Transverse ____
   - c. Bending Stress, Axial ____
   - d. Vortex Shedding Frequency ____
   - e. Flutter Velocity Parameter ____

5. TEST RESULTS
   - a. T.O. No. ____ Date ____ Run No. ____
   - b. Vibration:
     1st flex resonance ____ Hz. Amplr. ____
     2nd flex resonance ____ Hz. Amplr. ____
     1st Torsional resonance ____ Hz.
   - c. Resonant freq. drift at 1st flex dwell ____

d. Campbell Diagram Plot:

2E intercepts ____________

1E intercepts ____________

e. Dye Penetrant Check:

Date ____________ Results ____________

f. Coolant Flow Rate ____________

g. T/C Electrical Check:

Resistance to Ground ____________

h. Flow/Leak Check of Pressure Sense Lines:

| | |
|---|---|
| 1. ____________ | 5. ____________ |
| 2. ____________ | 6. ____________ |
| 3. ____________ | 7. ____________ |
| 4. ____________ | 8. ____________ |

j. Cycles to Failure ____________

6. DESIGN REVIEW & ACCEPTANCE

Approval:

| | NAME | DATE |
|---|---|---|
| 1. Project Engineer | ____________ | ____________ |
| 2. Research Oper. B.C. | ____________ | ____________ |
| 3. Research Oper. S.H. | ____________ | ____________ |
| 4. Research Engineer | ____________ | ____________ |

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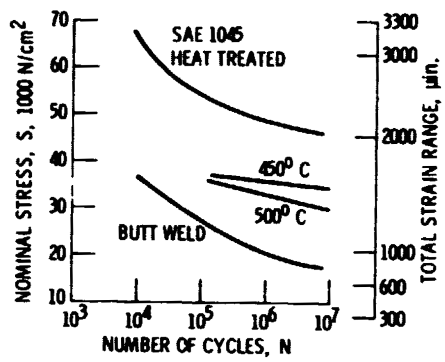


Figure 1. - Typical relation of stress amplitude and cycles to failure for repeated reversal of stress.

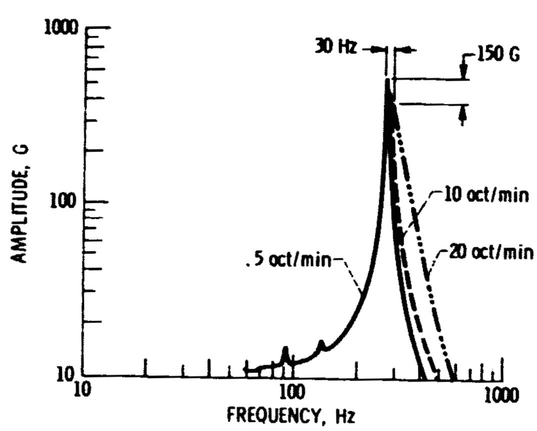


Figure 2. - Response at resonance for various sweep rates.

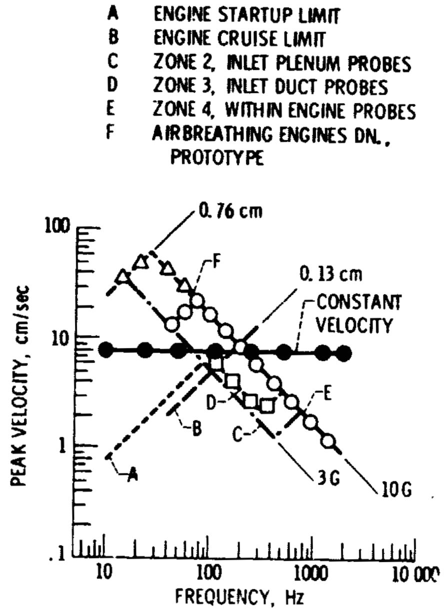


Figure 3. Vibration nomograph.

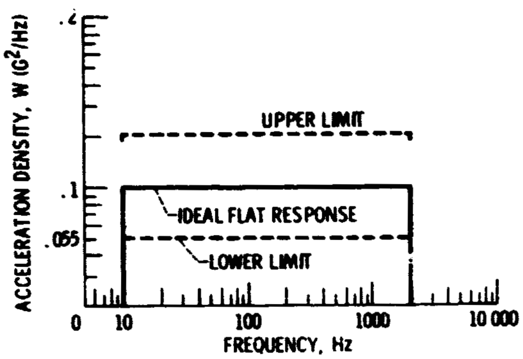


Figure 4. - White noise test envelope with typical ±3 dB tolerance limits.

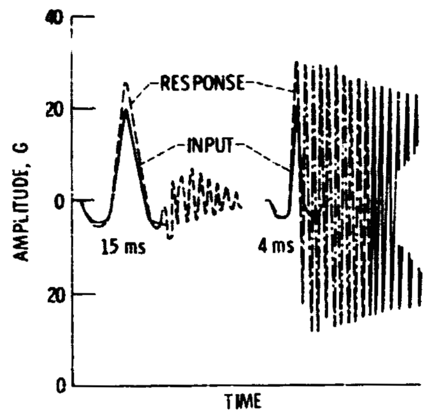


Figure 5. - Acceleration response to a half sine pulse of 15 and 4 ms duration.

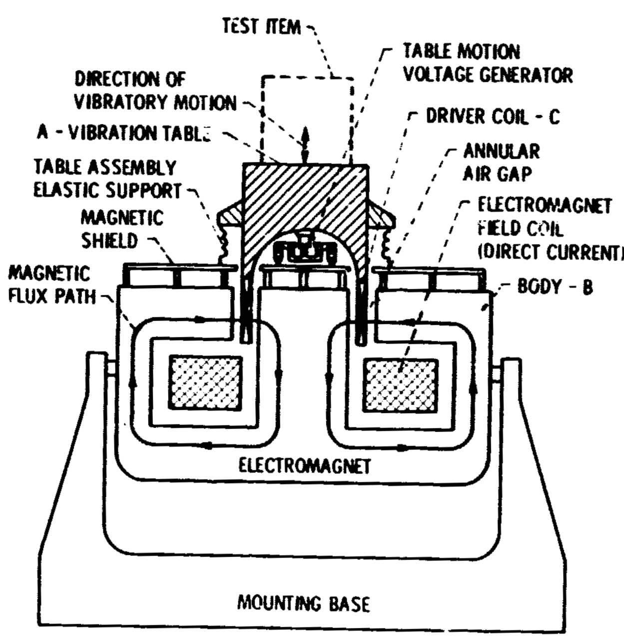


Figure 6. - Electrodynamic vibration machine.

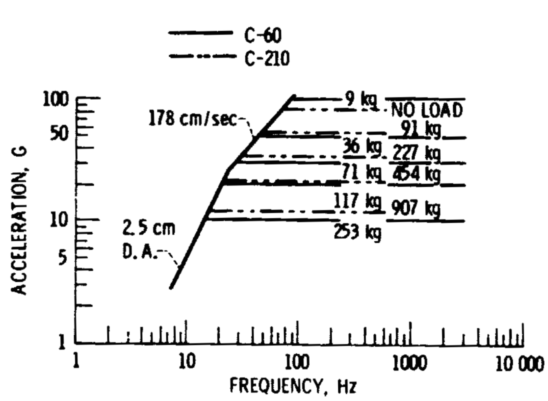


Figure 7. - Vibration test equipment operating limits.

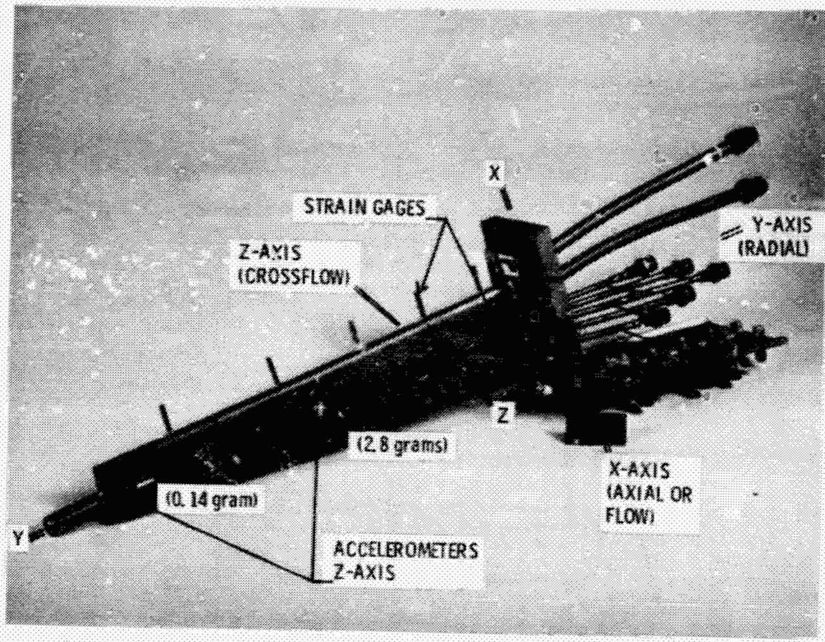


Figure 8. - Instrument probe showing axis orientation and placement of accelerometers for vibration testing.

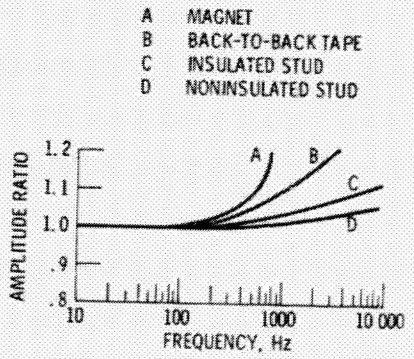


Figure 9. - Effect of mounting on frequency response of a 30 gram accelerometer with mounted resonance of 30 kHz.

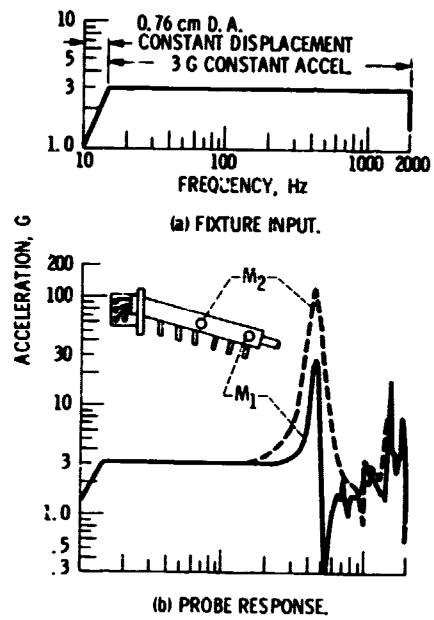


Figure 10. - Sine-sweep vibration flight level test results.

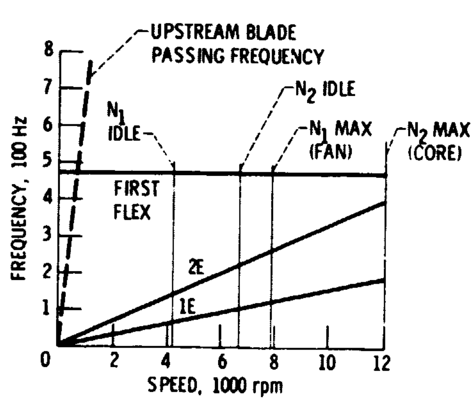


Figure 11. - Campbell diagram of instrument probe.

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16. Abstract

This report outlines the fatigue type testing performed on instrumentation rakes and probes intended for use in the air flow passages of jet-engines during full-scale engine tests at Lewis Research Center. Included is a discussion of each type of test performed, the results that may be derived and means of inspection. A design and testing sequence outlines the procedures and considerations involved in the generation of suitable instrument probes.

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