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Superseded by ARP1839

A Guide to Aircraft Turbine Engine Vibration Monitoring Systems

RATIONALE

The Aerospace Information Report (AIR) has been superseded by a completely new document, ARP1839, which provides guidance to aircraft turbine engine vibration monitoring systems. The original AIR1839C information was updated and transformed into ARP1839.

CANCELLATION NOTICE

This document has been declared "CANCELLED" as of January 2017 and has been superseded by ARP1839. By this action, this document will remain listed in the Numerical Section of the Aerospace Standards Index noting that it is superseded by ARP1839. Cancelled Specifications are available from SAE.

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1. SCOPE

This Aerospace Information Report (AIR) is a general overview of typical airborne engine vibration monitoring (EVM) systems applicable to fixed or rotary wing aircraft applications, with an emphasis on system design considerations. It describes EVM systems currently in use and future trends in EVM development. The broader scope of Health and Usage Monitoring Systems, (HUMS) is covered in SAE documents AS5391, AS5392, AS5393, AS5394, AS5395, AIR4174.

1.1 Purpose

The purpose of this AIR is to provide information and guidance for the selection, installation, and use of EVM systems and their elements. This AIR is not intended as a legal document but only as a technical guide.

2. INTRODUCTION

A complete EVM system includes all the equipment, data, and procedures used for monitoring and analyzing aircraft turbine engine vibration and engine driven equipment. A complete comprehensive EVM system is shown in Figure 1 and a simplified system in Figure 2. EVM may be one part of an engine condition monitoring system that monitors a number of engine parameters, or it may be a stand-alone system. A distinction is usually made between that part of the system dedicated to monitoring engine functions on board an aircraft and that part used for ground based analysis and monitoring. The on-board portion is commonly called an airborne engine vibration monitoring (EVM) system, and it is this part of the complete system that is described in this AIR. The ground based portion is described in SAE document AIR4175A.

The primary moving parts of all turbine engines are the rotors, shafts and their bearings. When operating, the engine rotors spin at relatively high speed within the engine case. Elements of these rotors, particularly fan, compressor, and turbine blades, are subject to wear and damage, some types of which may unbalance the affected rotor. Increased rotor unbalance causes increased cyclic stress on the structure and on the associated rotor bearings. In addition, the cyclic forces due to unbalance may induce destructive vibration in other engine parts and accessories. Small amounts of rotor unbalance are always present; large amounts usually cannot be tolerated for extended periods of operation without risk of fatigue by certain engine components. In extreme unbalance events, continued operation may not be safely possible.

Most of the EVM systems now in use were developed to comply with FAR Part 25.1305(d)(3). These systems were intended to provide the flight crew with a relative indication of engine imbalance. In most applications, specific operating instructions were not tied to specific display levels, but rather the display was provided to give the crew some relative indication of imbalance related vibration. With improvements in EVM system reliability and accuracy, increased understanding of diagnostic capability, and the potential for prognostic use, the industry is recognizing the potential for reducing operating costs, and potential safety benefit, from vibration signal analysis as part of engine health monitoring. This benefit is not limited to Part 25 certified transport aircraft as evidenced by the growth in availability of systems for turbine powered rotorcraft and other classes of turbine powered fixed wing aircraft.

EVM systems have also been developed for monitoring the vibration of other powerplant elements including afterburners, reduction gears, bearings, transmissions, accessories and propellers. The recent availability of high speed, digital signal processing integrated circuits has made it practical to provide very sophisticated on-board vibration analysis in today's systems. Similarly, identification and rectification of rotor/propeller unbalance can minimize degradation of the engine and other aircraft systems.

Many specific engine problems are detectable by an EVM system and the technical application is readily applicable to any fixed or rotary wing gas turbine engine installation.

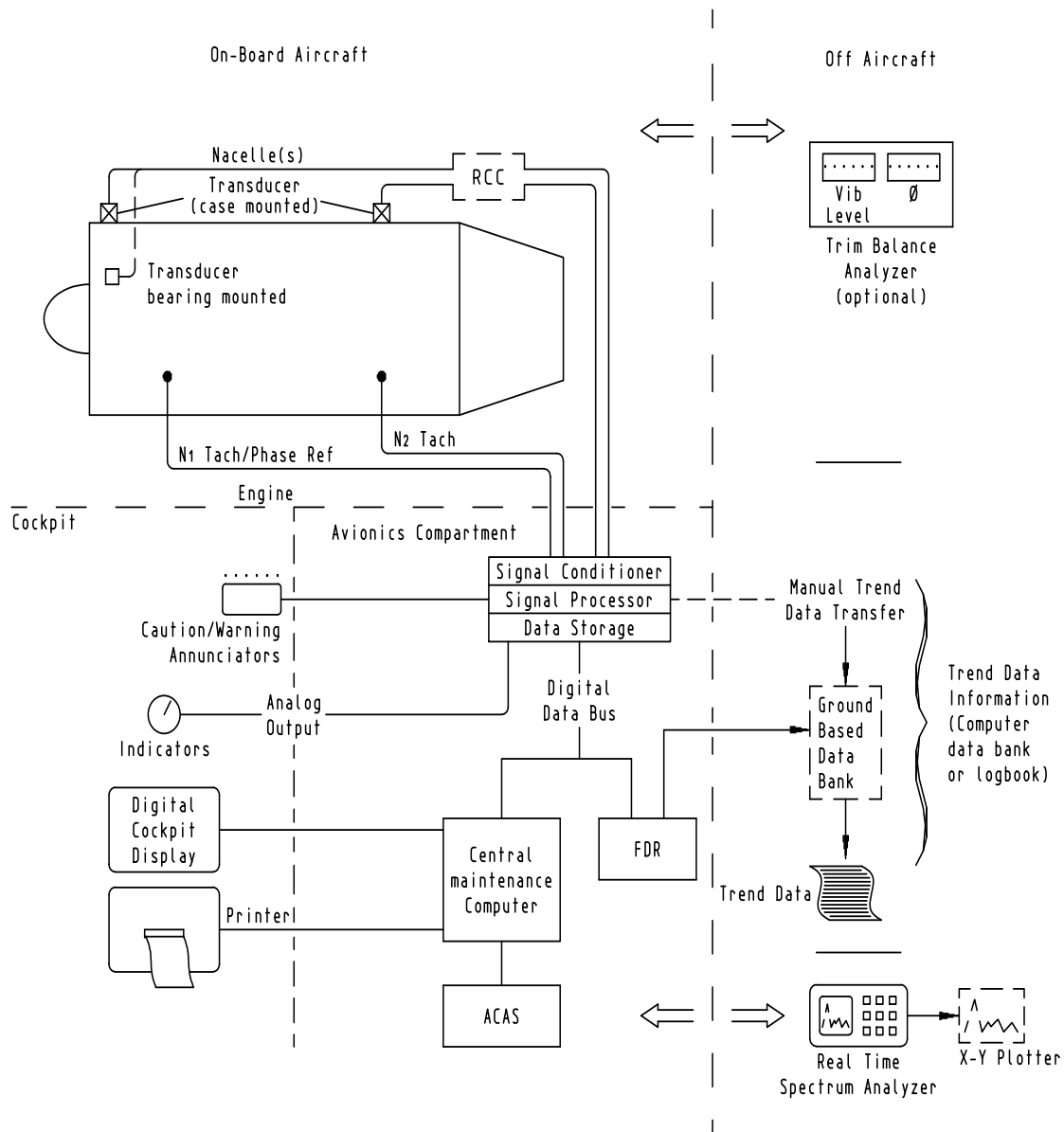
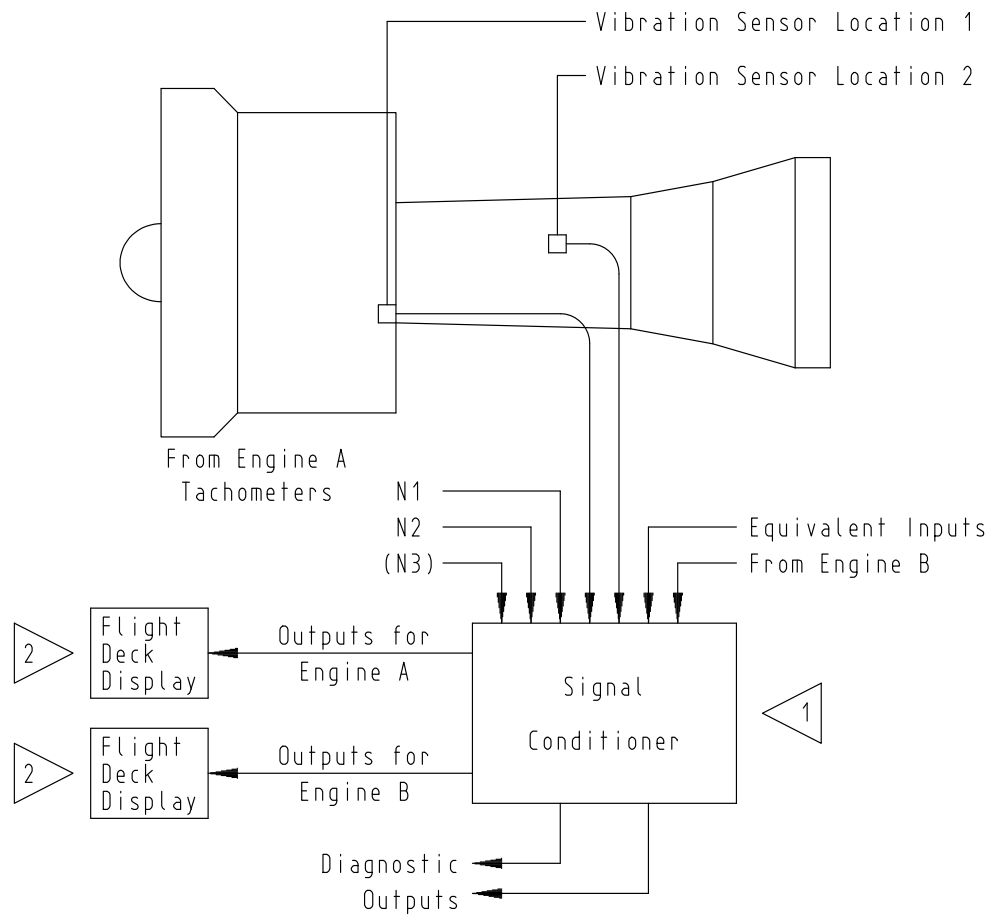


FIGURE 1 - SCHEMATIC OF A COMPLETE ENGINE VIBRATION MONITORING SYSTEM (EVM)



1 Example illustrates a single signal conditioner processing two separate vibration outputs from each of two engines.

2 Dedicated displays shown. Shared multi-function displays may also be used.

FIGURE 2 - TYPICAL EVM SYSTEM COMPONENTS

3. HISTORY

EVM Systems have been available since the late 1940s. Early systems were implemented using analog circuitry and provided a broadband vibration measurement. Vibration sensing was typically done with moving-coil, velocity transducers called velocimeters. These early systems can be characterized as having questionable utility and low reliability.

In 1973 the FAA issued FAR Part 25.1305(d)(3) which mandated the monitoring of engine rotor unbalance in commercial transports. EVM systems began to provide vibration outputs tracked to the engine rotational frequencies using phase-locked loops and demodulation techniques. Piezoelectric accelerometers became the primary means of sensing vibration. These sensing systems have a high impedance output rendering the connecting cables susceptible to noise generation and electrical interference; however good installation and shielding practices have addressed these problems.

In the 1980s digital filtering began to be used to implement tracking filters, providing increased accuracy and reliability over analog methods. The 1990s brought increasing computational power at low cost, stimulating the introduction of other equivalent vibration processing techniques such as Fast Fourier Transform and other Spectral Analysis techniques. In addition, modern systems provide the ability to collect data for implementing rotor trim balancing, soft mount detection, and other phenomena. Increased electronics environmental capability enable signal processing to be engine mounted.

In new generation engines, a new LRU, known as the engine monitoring unit (EMU), that has access to a greater range of high fidelity engine sensor data provides a high degree of functional integration with the FADEC and also permits the system to be tailored to the individual engine OEM's Engine Health Management program. The advent of the airplane high speed data bus has allowed this LRU to be located either on the engine or in the airframe. Typically such systems run complex EHM algorithms which are provided by the engine OEM's and which are readily modified or updated in service to suit the evolving needs of the program. These systems may also be integrated with the overall Aircraft Health Management system (AHM).

The modern EVM system, when installed and maintained correctly, is a reliable system which can produce substantial operating cost savings through early detection of engine damage or abnormal wear, as well as providing rotor trim balancing.

4. EVM SYSTEM FUNCTIONALITY

All present EVM systems detect and monitor engine vibration by means of one or more transducers installed on some part of the engine. The signals from these transducers are received by electronic processing devices of various levels of sophistication. The processed signal is displayed in some form to the flight crew and may also be transmitted to other on-board monitoring equipment. In some instances, it is also recorded for later analysis.

In many jet aircraft, notably those in service with commercial airlines, mechanical vibration is so well isolated from the passengers and crew that engine vibration would have to be present at very high levels before they could be sensed physically through the airframe. Such vibration may lead to severe secondary engine damage if not detected by an EVM system and in turboprop aircraft, airframe damage as well. Even if physical vibration is sensed through the airframe, the crew must be able to unambiguously identify its source and thereby undertake the necessary corrective actions. In some applications vibration-cancellation means are used, making it even more difficult for the crew to detect dangerous levels of engine vibration without an EVM.

As important as it may be to detect the amount of engine vibration, it is equally important to associate the origin of the vibration with a particular source. In the case of an abrupt increase in rotor unbalance it is essential that the EVM system give the flight crew a clear and unambiguous indication as to which engine is the source of the vibration. For this reason, each engine must have its own individual indication of engine vibratory response due to rotor unbalance.

In certain flight conditions high vibration may be an indication of ice accretion and subsequent asymmetrical shedding. In which case the EVM system may be used to assist the pilot in exercising appropriate de-icing procedures.

The severity of engine mechanical damage or degradation and its rate of change are of great interest for safety and cost reasons to both the flight crew and to maintenance personnel. Data obtained from an EVM system can provide critical and unique information to support decisions ranging in scope from potential flight safety enhancement, such as assisting in determination of the damaged engine, to overhaul and service needs, such as rotor trim balancing.

5. SYSTEM DESIGN

The first task of an EVM system design team is to clearly define the purpose and function of the system and its integration to the aircraft. This definition should include considerations of:

- a. Type of data to be acquired and how it will be used
- b. Expected benefits
- c. System costs/cost of ownership
- d. Expected system life
- e. Maintainability/reliability
- f. Previous and current field experience
- g. Provisions for future expansion/improvements

Consideration should be given to defining a system that is no more complex than can be justified by its expected benefits, ref. AIR4176, with due regard to system growth over the life of the program. Only after the system is defined as to scope and purpose should individual hardware and software elements be selected or specified.

A logical place to start the consideration of such a system is at the signal source, since the precision and fidelity of a monitoring system is ultimately limited by the quality of the signals at their source. The second part to consider is then the signal transmission, which is particularly important in an EVM system and, last but not least, the signal processing.

5.1 Signal Source

Signal quality at the source will depend upon three elements: transducer location, transducer mounting and the transducer characteristics.

5.1.1 Transducer Location

The transducer mounting location on the engine or accessory must be one that is mechanically well coupled to the component being monitored, due consideration being given to component natural frequencies and node points. This coupling must be established during engine development.

For the initial selection of the transducer locations, analytical dynamic simulations and sensitivity analysis using whole engine models are useful.

The engine manufacturer normally carries out extensive vibration tests during the course of engine development and the data resulting from these tests provide the basis for initial validation of transducer locations. Final verification of transducer locations should be made through engine ground runs on the aircraft and flight tests.

5.1.2 Transducer Mounting

Transducer mounting provisions may consist of built-in mounting surfaces, special mounting brackets, or simply attachment points for brackets to be added later. In any case, such provisions should always be included in the original engine design and verified during engine development, even if there are no immediate plans for an EVM system. Bonding resistance from transducer to engine should not exceed 2.5 milliohms.

5.1.2.1 Interfaces

Mounting surface/bracket/transducer interfaces should all be flat, clean, metal-to-metal surfaces. Hardened or stainless steel such as 321SS is usually the preferred bracket material. Flatness should be within 0.0005 in/in particularly where frequencies in excess of 5 KHz are to be measured. Attachment screw torque should be specified (typically 80% of yield). For higher frequencies, not only the flatness but also the roughness of the surface is important, this should be as good or better than 0.032 mils.

5.1.2.2 Mounting Point

The best mounting surface is usually one that is part of the engine itself. If this is not possible or practical, a very rigid bracket is the next best choice. For flange mounted transducers, a "T" section bracket is usually best. Care should be exercised to avoid introducing dynamic response problems due to bracket resonances within or near the operational frequency range. Careful consideration of the resonant frequencies of the mount is important. Accepted practice is to design mounts, which together with the accelerometer, have as high a resonant frequency as practical. One must also ensure that the resonant frequencies of the mount and accelerometer together are not the same as a multiple of an engine frequency of interest. Further, forcing frequencies on the engine of a non-integral order must not induce significant resonances into the monitoring system. Cantilevered mounting brackets are usually unsatisfactory.

5.1.3 Transducer Characteristics

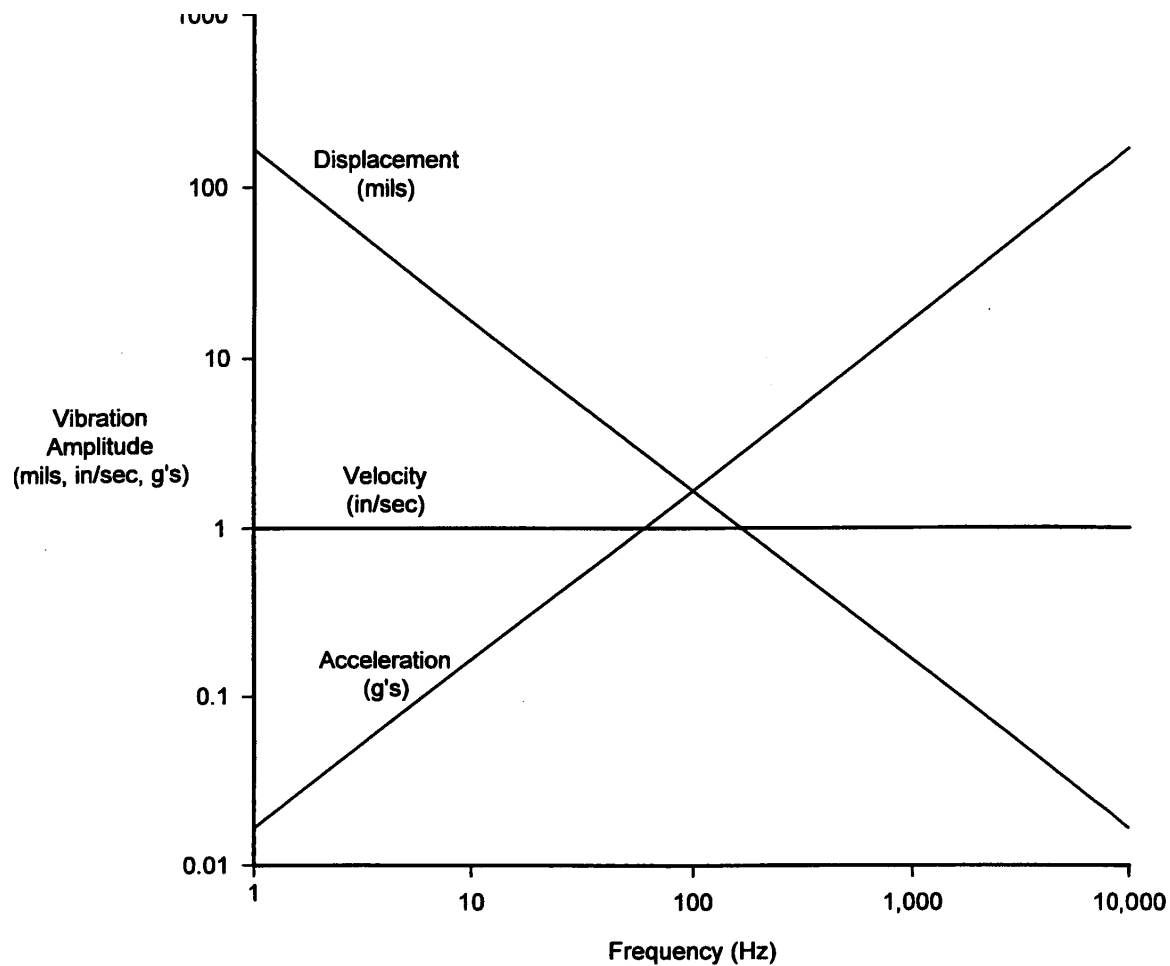
Mechanical vibration amplitude is commonly expressed in units of displacement, velocity, or acceleration, (the relationship is shown in Figure 3), and transducers are available that will sense any of these parameters directly.

5.1.3.1 Displacement Transducers

Displacement sensors are usually used to measure the relative movement of a rotor shaft with respect to the bearing housing on low speed engines with oil-film, journal type bearings. Aircraft turbine engines with ball or roller bearings do not lend themselves readily to this type of measurement.

5.1.3.2 Velocity Transducers

Vibration velocity is quite easily sensed on an aircraft turbine engine by means of a moving-coil velocity transducer. This device generates a voltage proportional to the relative motion of a coil and a magnet as one element moves with respect to the other in response to unit vibration. The moving element is spring-loaded at both ends and the spring rates are selected so that the transducer's operational range will be above its resonant frequency. Besides producing an output directly proportional to vibration velocity, the major advantage of this type of transducer is that it produces a large, low impedance signal, on the order of 100 mV/in/sec. This signal can be easily transmitted over distances of tens of meters using conventional aircraft wiring. The velocity transducer is rarely used in modern EVM systems because wear resulting from friction of the moving parts severely limits its life, however recent technological advances (ceramic bearings) have increased the reliability of such devices. Also, its frequency response is greatly affected by cross axis excitation and mounting orientation.

**Notes:**

1. $1.0 \text{ g} = 9.80665 \text{ m/s}^2 = 32.174 \text{ ft/s}^2$
2. $\text{Velocity (in/sec)} = \text{Acceleration (g's)} \times 61.448 / \text{Frequency (Hz)}$
3. $\text{Displacement (mils)} = \text{Acceleration (g's)} \times 9780 / \text{Frequency}^2 (\text{Hz}^2)$
4. $\text{Displacement (mils)} = \text{Velocity (in/sec)} \times 159.16 / \text{Frequency (Hz)}$
5. $\text{Acceleration (g's)} = \text{Velocity (in/sec)} = 1.0 @ 61.448 \text{ Hz}$
6. $\text{Displacement (mils)} = \text{Velocity (in/sec)} = 1.0 @ 159.16 \text{ Hz}$
7. $\text{Acceleration (g's)} = \text{Displacement (mils)} = 1.609 @ 98.89 \text{ Hz}$

FIGURE 3 - RELATIONSHIP BETWEEN DISPLACEMENT, VELOCITY AND ACCELERATION
AT CONSTANT VELOCITY

5.1.3.3 Accelerometers

Accelerometers are the most widely used type of vibration transducer in EVM systems today. They are usually of the piezoelectric type that produces an electrical charge proportional to the acceleration parallel to the sensitive axis of the transducer. The signal from this type of accelerometer is generated by piezoelectric material, either a polarized ceramic such as lead zirconate titanate or a naturally occurring crystal such as quartz or tourmaline. This material is tightly compressed between a mounting surface (or surfaces) and a seismic mass (or masses). Acceleration of the element causes the mass to apply compression or shear forces on the material in accordance with the familiar relationship of force equals mass times acceleration ($F = Ma$). The force causes electrical charges to appear on the piezoelectric material surfaces that are then conducted outside the accelerometer (see Figure 4). It is convention that a positive going acceleration, i.e. upwards into the accelerometer mounting base causes a positive going signal on the right hand pin looking into the connector with the keyway at the bottom, as illustrated in Figure 4. Piezoelectric accelerometers have no moving parts and are therefore extremely reliable. Typical accelerometer sensitivities range from 10 to 125 pC/g of acceleration, but 50 pC/g has become an industry standard.

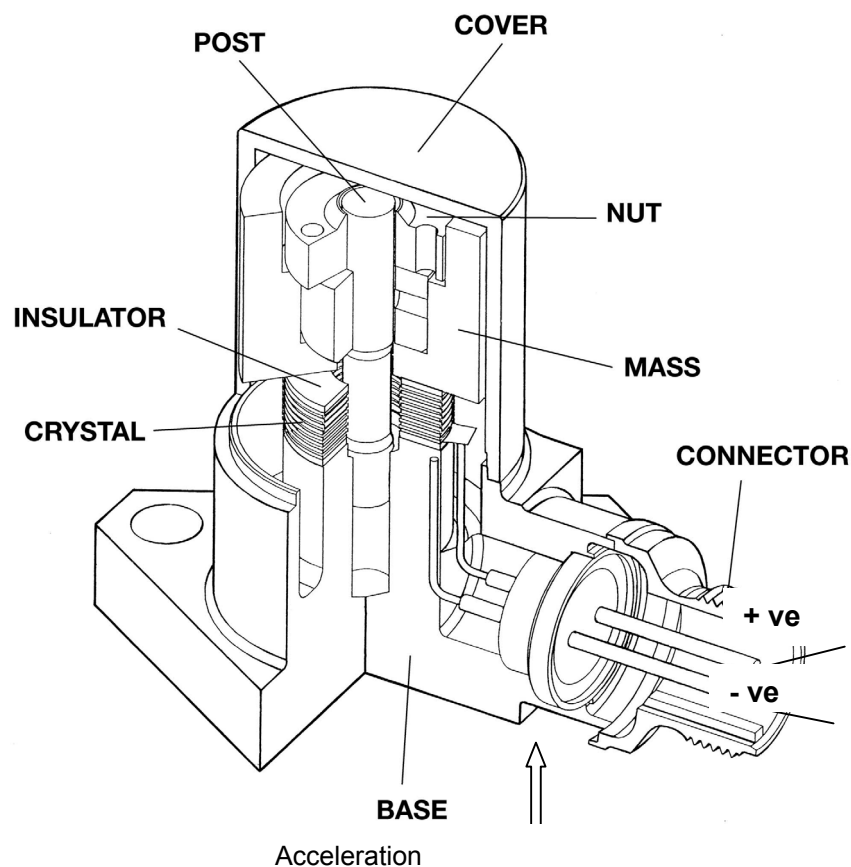


FIGURE 4 - CROSS SECTION OF A TYPICAL EVM COMPRESSION TYPE PIEZOELECTRIC ACCELEROMETER

Accelerometers are used to measure vibration at frequencies well below their resonant frequency. In general, signals at frequencies up to one fifth of the accelerometer resonance frequency will be essentially unaffected by the resonant rise, while those up to one third of the resonance frequency will be amplified less than 10% by the resonant rise. Because of the substantial amount of multiaxis vibration usually present on a turbine engine, the accelerometer selected should be quite insensitive to cross axis motion. A maximum of 5% of the normal axis sensitivity is usually considered to be acceptable, but is unattainable in the region of transverse resonant frequencies of the accelerometer. Temperature changes of an engine and, thus the mounted accelerometer, during various portions of the operational cycle will affect accelerometer sensitivity due to its temperature response. Therefore, accelerometers should be selected for a stable temperature response. Typical temperature response errors are 5 to 10% over the useful temperature range. It is also important that the accelerometer maintain an adequate insulation resistance (typically $> 100 \text{ k}\Omega$) over its operating temperature. Low internal resistance will lead to noise problems with the charge amplifier, particularly at low frequencies.

Some accelerometers, depending on design principles and crystal type used, may have a pyroelectric effect, i.e. they will produce a quasi DC output signal when subjected to a temperature gradient. The preamplifier used in the EVM system should cope for this effect by the use of an appropriate high pass filter. EVM accelerometers should be hermetically sealed (to maintain insulation resistance), of rugged construction, capable of sustained operation in the expected maximum temperature environment, and should have a true differential output balanced according to electrical capacitance.

In addition to the low frequency effects mentioned, the actual output of an accelerometer continues through resonance to very high frequency and amplitude values since most mechanical systems produce high "g" values at high frequencies. This range of output in terms of frequency and amplitude is well beyond the capability of any existing electronics system. It is therefore essential to correctly dimension both the accelerometer sensitivity and the frequency range of interest for the intended purpose. Typically for the primary function of unbalance indication this means optimizing the output for the 1/rev frequencies of the rotor systems. This subject will be further addressed under Signal Conditioning and Filtering.

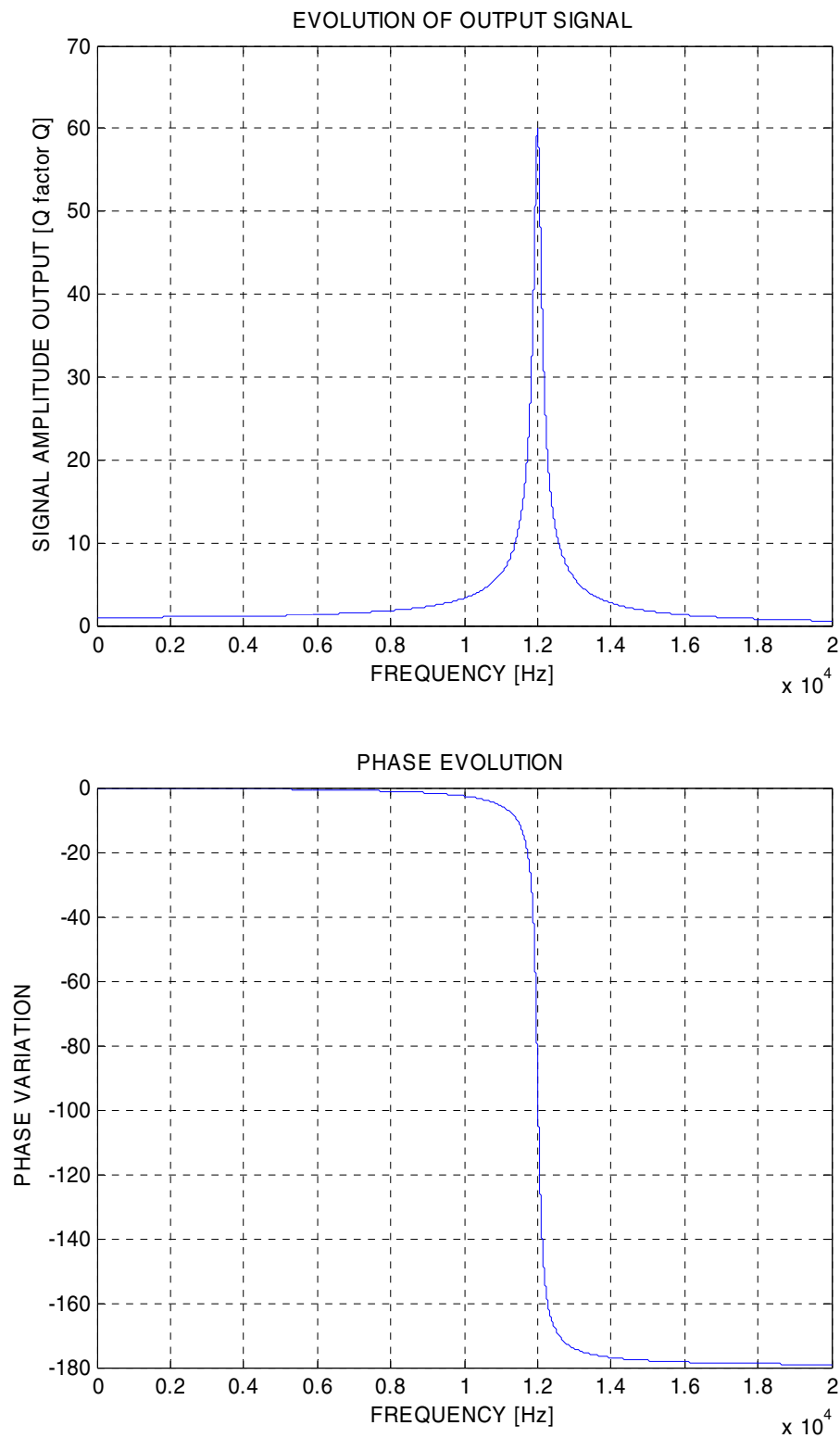


FIGURE 5 - WIDE BAND OUTPUT OF A TYPICAL ACCELEROMETER

5.1.3.4 Surface Mounted Accelerometers with Connectors

Figure 6 shows a typical surface mounted EVM accelerometer with an integral electrical connector. Accelerometers that use a separate cable are quite easy to install but are subject to signal degradation due to connector damage or contamination. A large connector will usually be easier to seal and less susceptible to damage, but its mass may adversely affect the frequency response.



FIGURE 6 - SURFACE MOUNTED ACCELEROMETER WITH CONNECTOR

5.1.3.4.1 Surface Mounted Accelerometers With Integral Cables

To avoid the potential problem of connector damage or contamination, some accelerometers are designed with integral cables. Where the cable will not be exposed to temperatures above 500 °F, a low noise, antimicrophonic, insulated cable (often protected by a metal overbraid and/or conduit) is usually used. At higher ambient temperatures, a steel-jacketed, mineral-insulated "hard-line" cable is usually used. Figure 7 shows a typical accelerometer of this type.

For fan trim balance requirements a most suitable location for a transducer may be inside the engine near the number 1 rotor bearing. An example of this type of transducer is shown in Figure 8. Since these transducers are built into the engine during manufacture, it is important that their reliability be very high as replacement in service may be difficult and expensive.

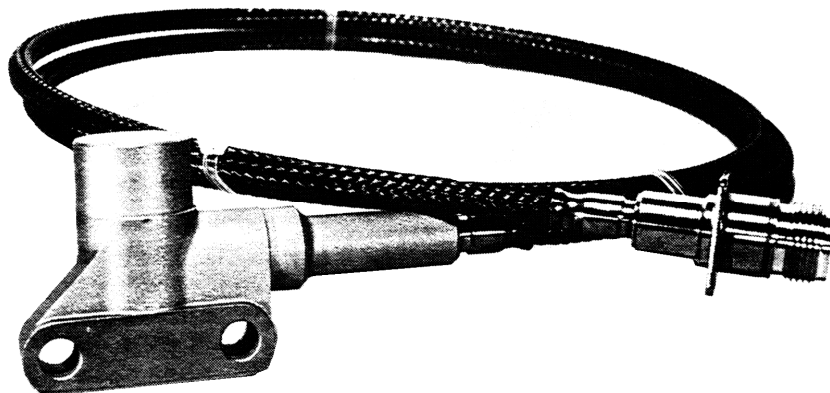


FIGURE 7 - SURFACE MOUNTED ACCELEROMETER WITH INTEGRAL CABLE

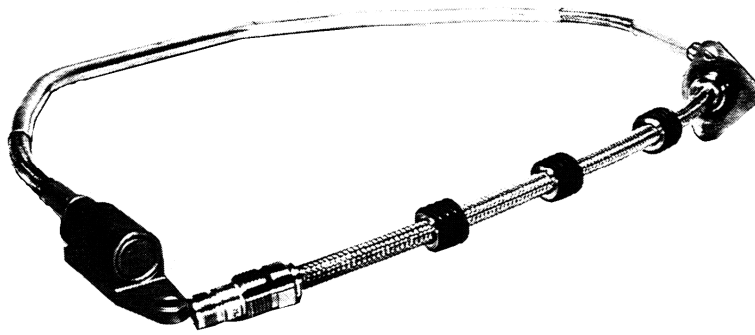


FIGURE 8 - INTERNAL TYPE ACCELEROMETER

5.1.3.4.2 Accelerometers with Built-in Electronics

In some applications, where temperature allows, a small electronics circuit is mounted directly into the accelerometer housing. This circuit converts the high impedance charge signal into a low impedance voltage or current signal which allows the use of normal aircraft cable. The addition of electronics will reduce the mean time between failure (MTBF) of the accelerometer. The high cycle thermal stress and high g vibration level typical on a gas turbine engine are detrimental to integral electronics. Therefore it is recommended to make a careful analysis of overall system reliability.

Accelerometers with built-in charge converters typically exhibit the electrical characteristics of a first order high-pass filter. In such configuration, the influence of the wide accelerometer operating temperature range on the cut-off frequency is to produce variation in the phase of the output signal. This phenomenon has to be considered when the signal is to be used for balancing of the engine.

The processing electronics may be remote from the accelerometer, but integrally connected to it. This configuration is often used when the sensor temperature is higher than that which may be supported by the electronics.

5.1.3.4.3 Co-located/Dual Output Accelerometers

It may be desirable to have two measurements of the vibration at the same location on the engine for purposes of redundancy and system integrity checks. This may be accomplished with either separate co-located accelerometers (sharing the same mounting bracket) or a single dual-output accelerometer. Of these configurations, the two collocated accelerometers have a lower probability of simultaneous failure but the dual-output accelerometer usually provides tighter tolerances between the two outputs as it employs two electrically and mechanically separate sensing elements with a common axis of sensitivity in the same housing. In either case, it is important to be aware of, and protect against, common mode failures. Figure 9 shows a typical accelerometer of this type.