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# AEROSPACE INFORMATION REPORT

**SAE** AIR1839

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A

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## A GUIDE TO AIRCRAFT TURBINE ENGINE VIBRATION MONITORING SYSTEMS

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## 1. SCOPE:

This Aerospace Information Report (AIR) is a general overview of typical airborne vibration monitoring (AVM) systems with an emphasis on system hardware design considerations. It describes AVM systems currently in use.

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

## 2. INTRODUCTION:

A complete engine vibration monitoring (EVM) system includes all the equipment, data, and procedures used for monitoring and analyzing aircraft turbine engine vibration. A complete EVM system is shown in Figure 1. EVM may be one part of an engine 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 functions on board an aircraft and that part used for ground based monitoring (most commonly with the engine removed from the aircraft and mounted in a test cell). The on-board portion is commonly called an airborne vibration monitoring (AVM) system, and it is this part of the complete system that is described in this AIR.

The primary moving parts of all turbine engines are the rotors and their shafts which, when the engine is producing power, spin at relatively high speed within the engine case. The elements of these rotors, particularly the 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 safely tolerated by the engine. Most of the AVM systems now in use were developed to monitor the level of vibration resulting from such unbalance. AVM systems have also been developed for monitoring the vibration of other powerplant elements including afterburners, reduction gears, bearings, transmissions, and accessories. 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.

Many specific engine problems are detectable by an AVM system (7.6.3.1).

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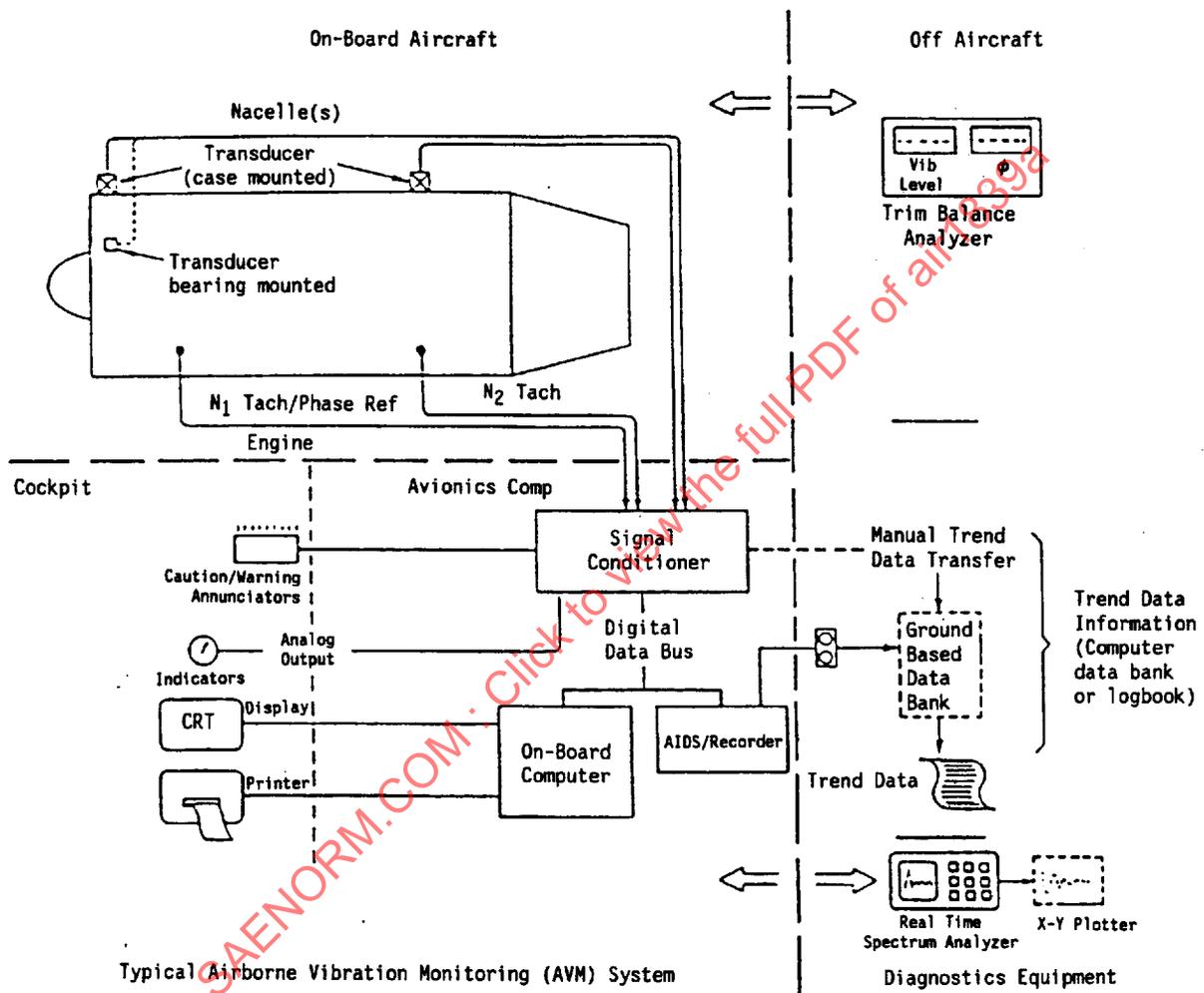


FIGURE 1 - Schematic of a Complete Engine Vibration Monitoring System (EVM)

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## 3. HISTORY:

AVM systems have been available since the late 1940s, yet there is still disagreement within the aviation industry over the need for this type of equipment. The dissenting views arise primarily from concerns over the validity of the data and center on three issues. First, until approximately the mid 1970s, few AVM systems accomplished very much vibration data reduction. A typical turbine engine vibration spectrum is shown in Figure 2. The graphical relationship between time domain and frequency domain, the frequency spectrum, is shown in Figure 3. Separating and amplifying the few frequency components associated with rotor unbalance requires a degree of system sophistication that was not, until recently, either affordable or even practical. Second, the elements of AVM systems often have not been robust enough for long term use in a jet engine environment. Provisions for good vibration sensitivity and frequency response have often been in conflict with the operational requirement for rugged components. Third, AVM systems generally have been quite susceptible to electrical interference, chiefly because the piezoelectric accelerometers normally used as the engine mounted transducer are high impedance devices. When proper design and installation care is taken, AVM systems can produce substantial operating cost savings through the early detection of engine damage or abnormal wear.

## 4. TYPICAL AVM SYSTEM:

All present AVM 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/or 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 vibrations would have to be present at very high levels before they could be sensed physically through the airframe. Such vibrations may lead to severe secondary engine damage if not detected by an AVM system. Even if physical vibration is sensed through the airframe, the crew must be able to identify its source; the absence of a corresponding AVM system indication may lead the crew to look elsewhere for the cause.

As important as it may be to detect the amount of engine vibration, it is equally important to associate the source of the vibration with a particular engine. In a situation where a rotor has experienced substantial and abrupt damage, such as an in-flight bird strike, which can cause the complete loss of a fan blade, it may be difficult to quickly determine which engine was affected without reference to an AVM system.

The severity of engine mechanical damage or degradation and its rate of change is of great interest to both the flight crew and to maintenance personnel. Data obtained from an AVM system can provide critical and unique information to support decisions ranging in scope from safety of flight to overhaul and service needs.

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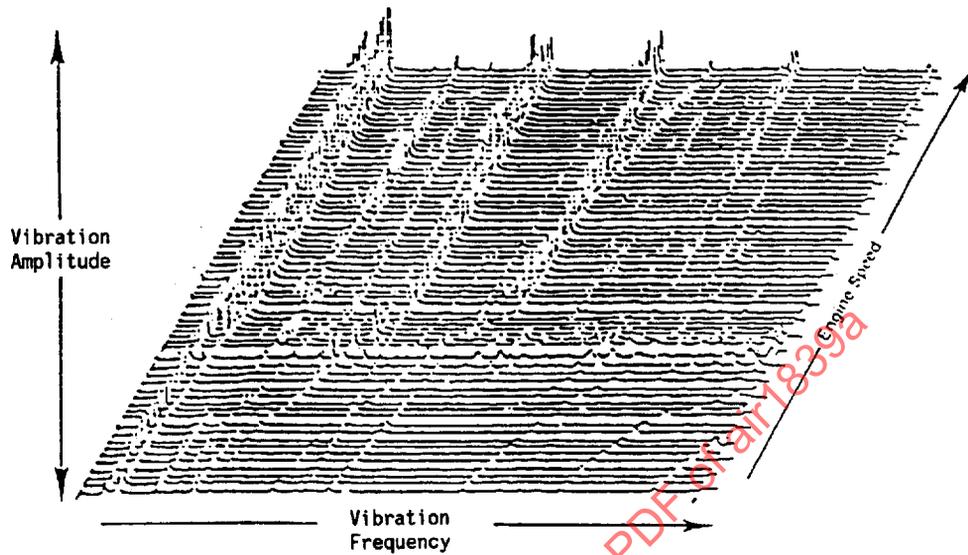


FIGURE 2 - Typical Engine Vibration Spectrum Versus Engine Speed

2 is the summation of these simple waveforms...

1 This complex waveform...

3 ...as revealed by this spectrum plot

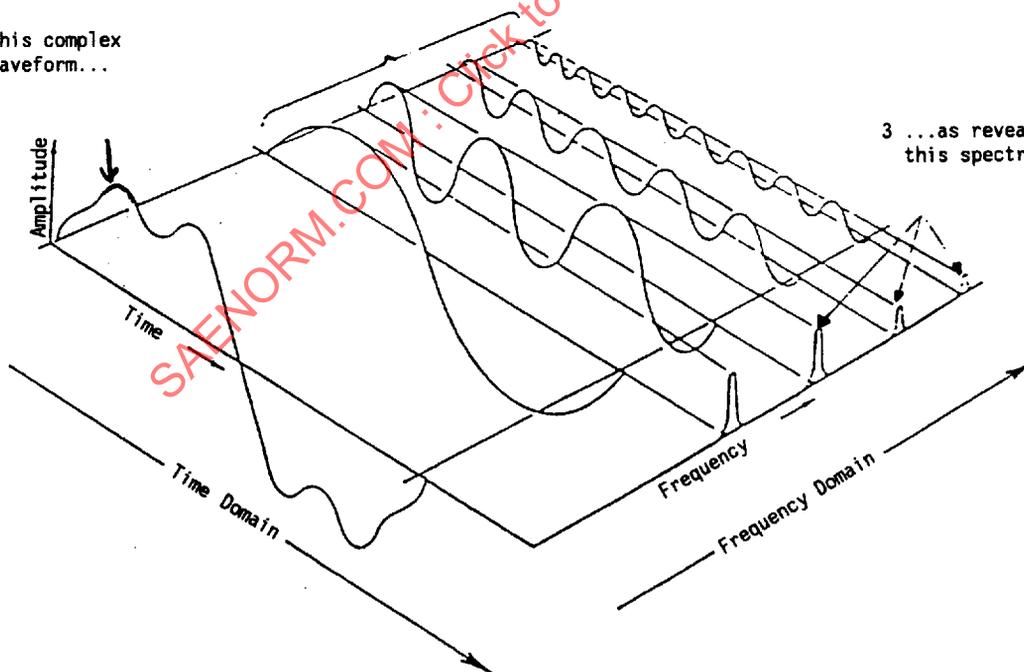


FIGURE 3 - Relationship of Time Versus Frequency Domain

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## 5. SYSTEM DESIGN:

The first task of an AVM system designer or specifier is to clearly define the purpose of the system and its relationship to the complete aircraft. This definition should include considerations of:

- a. Expected benefits
- b. System costs
- c. Type of data to be acquired and how it will be used
- d. Expected system life
- e. Maintainability
- f. Provisions for future expansion

Great care should be devoted to defining a system that is no more complex than can be justified by its expected benefits, 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.

## 5.1 Signal Source:

Signal quality will depend upon three elements: proper transducer location, appropriate transducer mounting provisions, and correct transducer selection.

- 5.1.1 Location: The transducer mounting location on the engine or accessory must be one that is mechanically well coupled to the component being monitored. This coupling must be established during engine development. 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 selection of transducer locations. Final verification of transducer locations should be made through flight tests or engine ground runs on the aircraft.
- 5.1.2 Mounting Surface/Provisions: 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 AVM system.
  - 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 1 KHz are to be measured. Attachment screw torque should be specified (typically 80% of yield).

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- 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 or a very substantial "L" 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. The installed transducer and mounting bracket should have a first resonance at least three times the highest frequency of interest. For this reason, cantilevered mounting brackets are usually unsatisfactory.
- 5.1.3 **Transducer:** Mechanical vibration amplitude is commonly expressed in units of displacement, velocity, or acceleration, (the relationship is shown in Figure 4), 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, sleeve-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 (see Figure 5). 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/s. This signal can be easily transmitted over great distances using conventional aircraft wiring. The velocity transducer is rarely used in modern AVM systems because wear resulting from friction of the moving parts severely limits its life. Also, its frequency response is greatly affected by cross axis excitation and mounting orientation.
- 5.1.3.3 **Accelerometers:** Accelerometers are the most widely used type of vibration transducer used in AVM 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 6). Typical accelerometer sensitivities range from 10 to 125 pC/g of acceleration.

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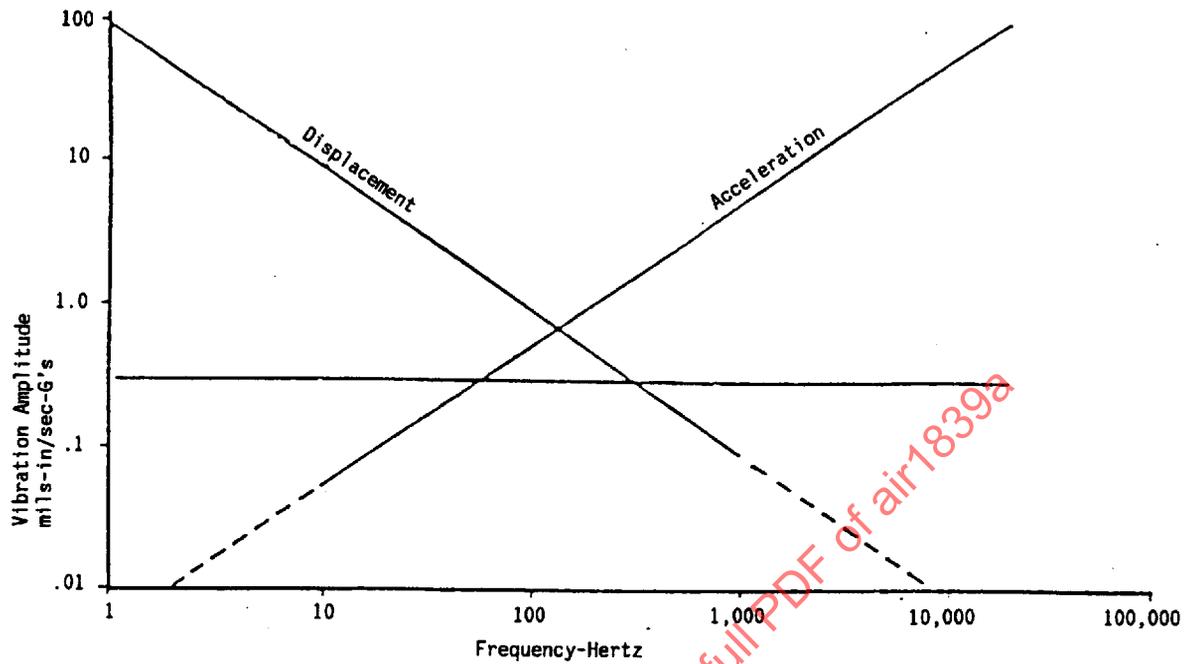


FIGURE 4 - Relationship Between Displacement, Velocity, and Acceleration at Constant Velocity

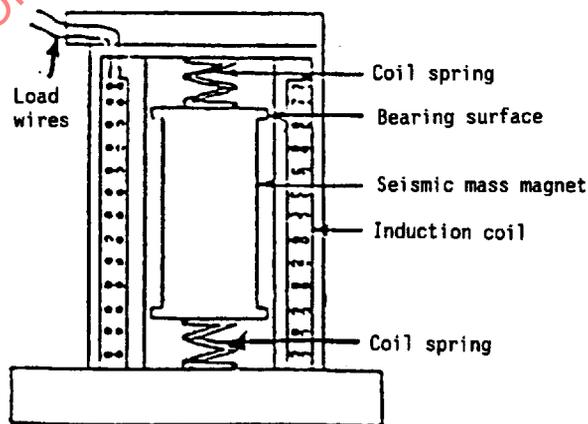


FIGURE 5 - Cross Section Of A Typical Velocity Transducer

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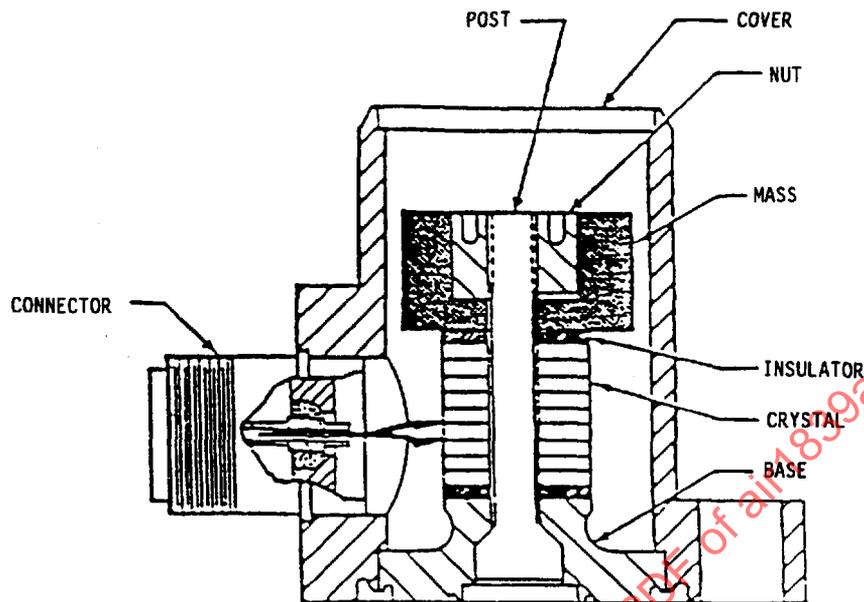


FIGURE 6 - Cross Section of a Typical AVM Compression Type Piezoelectric Accelerometer

#### 5.1.3.3 (Continued):

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. A typical 50 pC/g compression-type accelerometer will have a mounted resonance of about 25 kHz and could be used to monitor vibration in the range of 2 or 3 Hz to about 8000 Hz. Because of the substantial amount of multi-axis 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. Temperature changes of an engine and, thus the mounted accelerometer, during various portions of the operational cycle will affect accelerometer sensitivity. Therefore, accelerometers should either be selected for minimum sensitivity or, they should be provided with compensation for the variation in other parts of the system. AVM accelerometers should be hermetically sealed, 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.

- 5.1.3.3.1 Surface Mounted Accelerometers with Connectors: Figure 7 shows two typical surface mounted AVM accelerometers with integral electrical connectors. 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.

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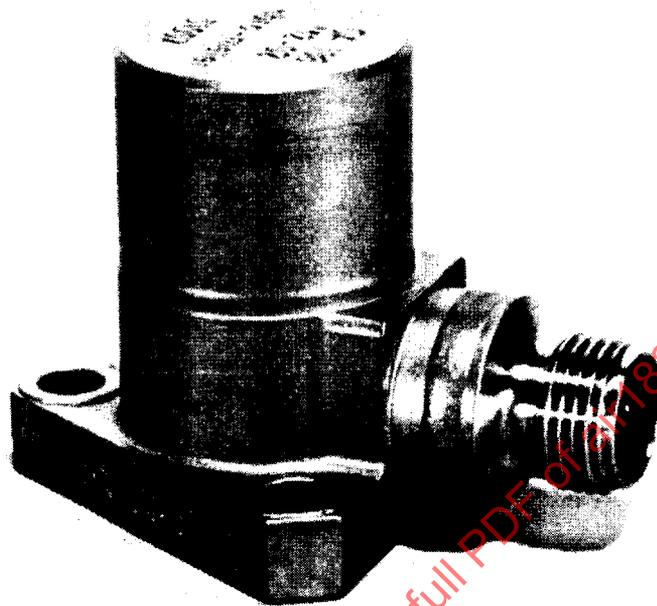


FIGURE 7 - Surface Mounted Accelerometer With Connectors

- 5.1.3.3.2 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 fluorocarbon 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 8 shows a typical accelerometer of this type.
- 5.1.3.3.3 Internal Accelerometers: In some instances, the only suitable location for a transducer may be inside the engine near a main rotor bearing. An example of this type of transducer is shown in Figure 9. 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.

An alternate method of implanting accelerometers in or near a bearing housing consists of using rigid (or semirigid) probe type units that can be fitted or removed from the outside of the engine as shown in Figure 10. Such units overcome the risk of high replacement costs in the event of failure but generally require that their installation be carefully considered at the time of engine design.

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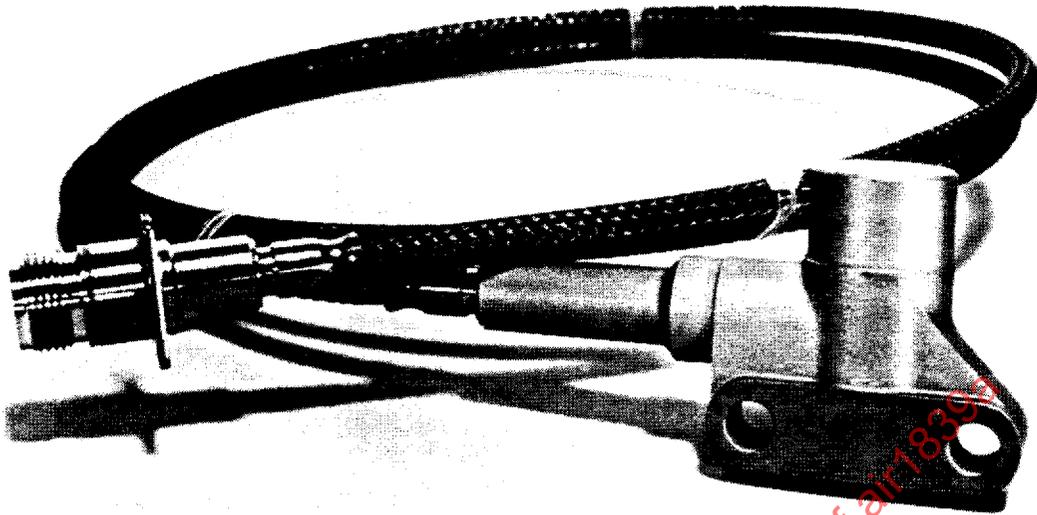


FIGURE 8 - Surface Mounted Accelerometer With Integral Cable

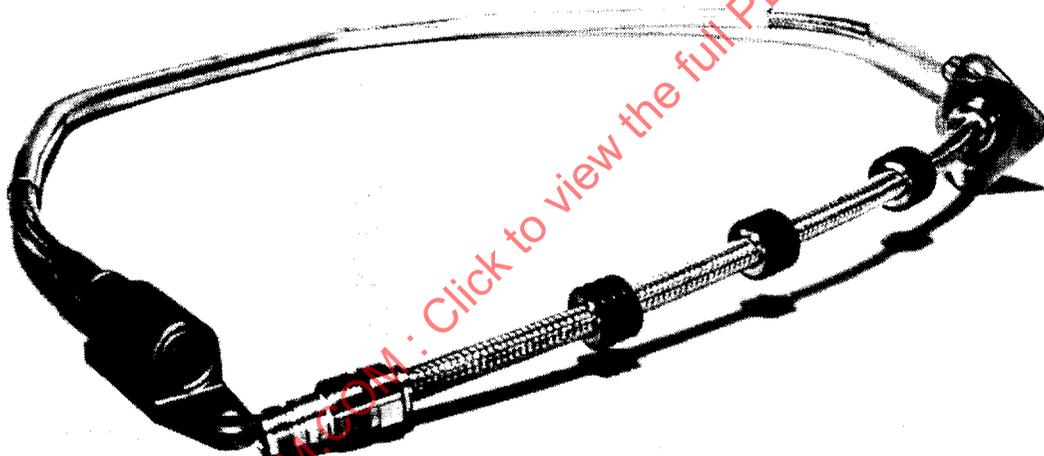


FIGURE 9 - Internal Type Accelerometer

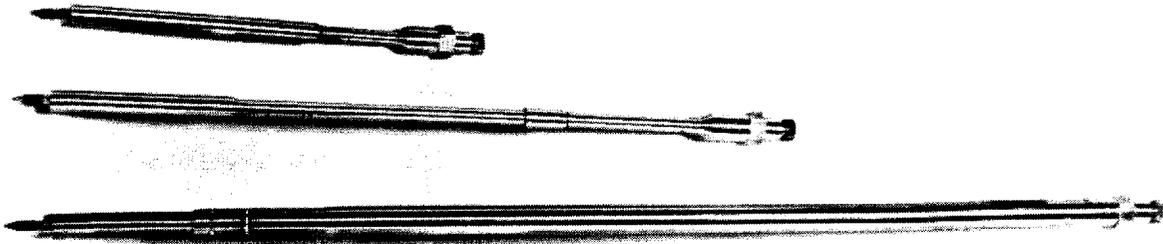


FIGURE 10 - Internal Probe Type Accelerometers

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5.1.3.3.4 Colocated/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 colocated accelerometers (sharing the same mounting bracket) or a single dual output accelerometer. Of these configurations, the two colocated 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.

## 5.2 Signal Transmission:

There are a number of special considerations for signal transmission that are unique to AVM systems.

5.2.1 Separate Preamplifiers: If the preamplifier is located near or even within the accelerometer body itself, then the difficulties of high impedance signal transmission can be avoided. At the present time, electronic components for use in such amplifiers are limited in temperature to approximately 350 °F. Therefore, with few exceptions, internal electronics accelerometers are not used for turbine engine monitoring. This temperature limit also poses a restriction on how close to the engine a separate preamplifier may be located. The potential benefits of improved resistance to electromagnetic interference (EMI) and reduced life cycle costs (LCC) on the aircraft cabling have to be protected against the added costs of high temperature circuit technology and/or the provision of cooling for the electronics. Because the cost difference between conventional wiring and special low noise wiring is usually small, compared to the cost and system complexity of separate electronic elements, most AVM systems have not employed separate preamplifiers and use low noise cable systems.

5.2.2 Cable, Shielding, and Grounding: A number of special design features are necessary to preserve the signal from a piezoelectric accelerometer during transmission to the preamplifier.

5.2.2.1 Circuit Type: The accelerometer, cable, and charge amplifier subsystem should comprise a true differential circuit (see Figure 11). With this design, any interference applied to both signal leads, "common mode" interference, will be rejected because only the difference between signals will be amplified.

5.2.2.2 Isolation: The accelerometer sensing element should be well isolated electrically from its case, typically 20 M $\Omega$  at the maximum operational temperature, so that voltage differences between the accelerometer mounting point and other points in the system will not appear as signals.

5.2.2.3 Shielding: The signal leads should be fully shielded over the entire cable length, and the shield should be grounded at one point, usually the signal conditioner chassis ground.

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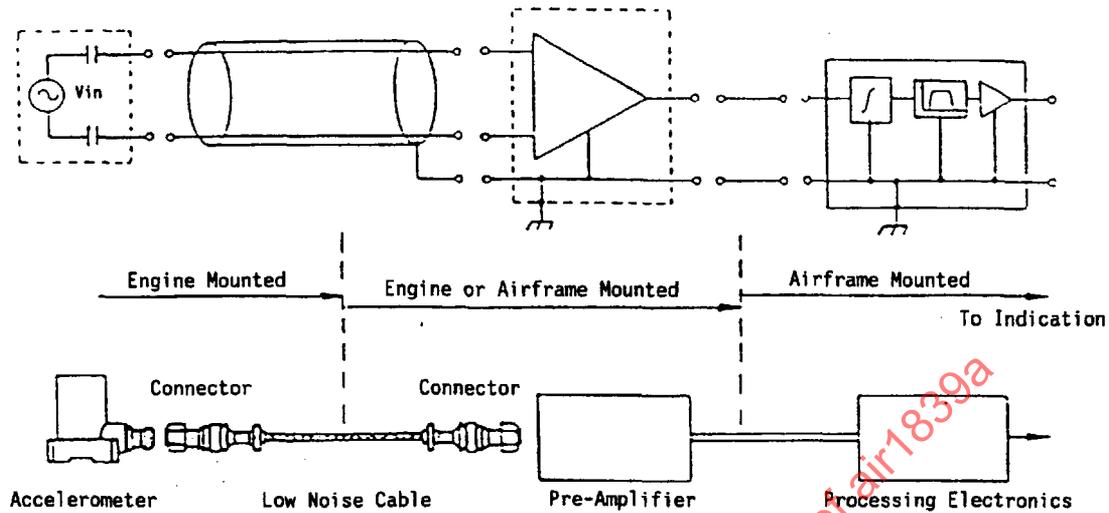


FIGURE 11 - Typical Differential Measurement Chain

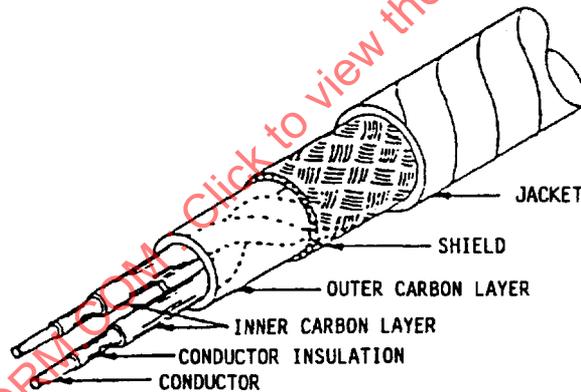


FIGURE 12 - Low Noise Cable

- 5.2.2.4 Low Noise Treatment of Cable: When shielded cables are flexed, the relative movement of the cables' constituent parts may cause static electric charges to be generated internally. In a freely moving cable, the charges will vary with respect to time and, thus, appear to the amplifier as spurious signals. This potential problem, called triboelectric noise, is dealt with by using special low noise cable (see Figure 12) in which the internal parts are wrapped in graphite impregnated tape (PTFE usually) thereby preventing such charge accumulation. To further protect against triboelectric noise, the cable should be secured to minimize cable motion. In high vibration areas, such as an engine nacelle, it is usually recommended that the cable be firmly clamped at intervals of not greater than 8 in along its length.

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- 5.2.3 Connectors: In general, there should be as few connectors between the transducer and the first signal conditioning stage as practical. Where connectors must be used, they should be steel shell, circular threaded type with self-locking engagement or provisions for safety wire. Bayonet type couplings should be avoided because they can permit movement between pin and socket that will appear as noise.
- 5.2.3.1 Shared Connectors: The connectors associated with the AVM system and located between the transducer and the first stage of signal conditioning should, where possible, not be shared with wiring from other aircraft systems. Where shared connectors cannot be avoided, the companion systems selected should be those with essentially DC signals such as thermocouples, or they should be systems that are used infrequently during flight.
- 5.2.3.2 Connector Shielding: In a shared connector, any spare contacts should be grounded and arranged to surround the two signal contacts to provide some degree of shielding. Alternatively, shielded pin type connectors may be used. The cable shield should, with one exception, always be carried through the connector on one of the connector pins. The exception is when the shield is grounded at each end, it must then be open somewhere in between to avoid "ground loops."
- 5.2.3.3 Connector Strain Relief: Connectors should be suitably strain relieved to prevent cable fatigue damage and/or generation of triboelectric noise.
- 5.2.3.4 Connector Sealing: Connectors should be sealed to prevent intrusion of moisture and contaminants such as oil and hydraulic fluid by means of back shell and interfacial seals.
- 5.2.3.5 Connector Contacts: Special high mating force connector contacts should be used in critical areas on or near the engine to provide positive contact engagement and hence good signal continuity. In addition, contacts that are gold plated will reduce susceptibility to corrosion and fretting, thus insuring maintenance of a low impedance connection. Pin size should be Number 20 or larger.

### 5.3 Signal Processing:

The signal conditioner element of the system may be in the form of an individual avionics enclosure, or it may be one circuit element of a more comprehensive system that includes a number of diverse monitoring functions.

- 5.3.1 Conditioning: With a differential piezoelectric accelerometer as the signal source, the first stage of the signal conditioner is the differential charge amplifier. This converts the high impedance charge signal to a low impedance voltage signal. It is a recommended design practice to make a buffered, wide frequency bandwidth output of the charge amplifier available for external maintenance/analysis where off-line signal processing may be desired. It is also good design practice, in order not to sacrifice the common mode noise rejection characteristics of the amplifier, to avoid any switching before the charge amplifier, either between various accelerometers or alternately between test and accelerometer signals. Where high energy, high frequency signals, such as those due to blade passage, are present, it may be necessary to provide input low pass filtering to avoid saturation of the charge amplifier.

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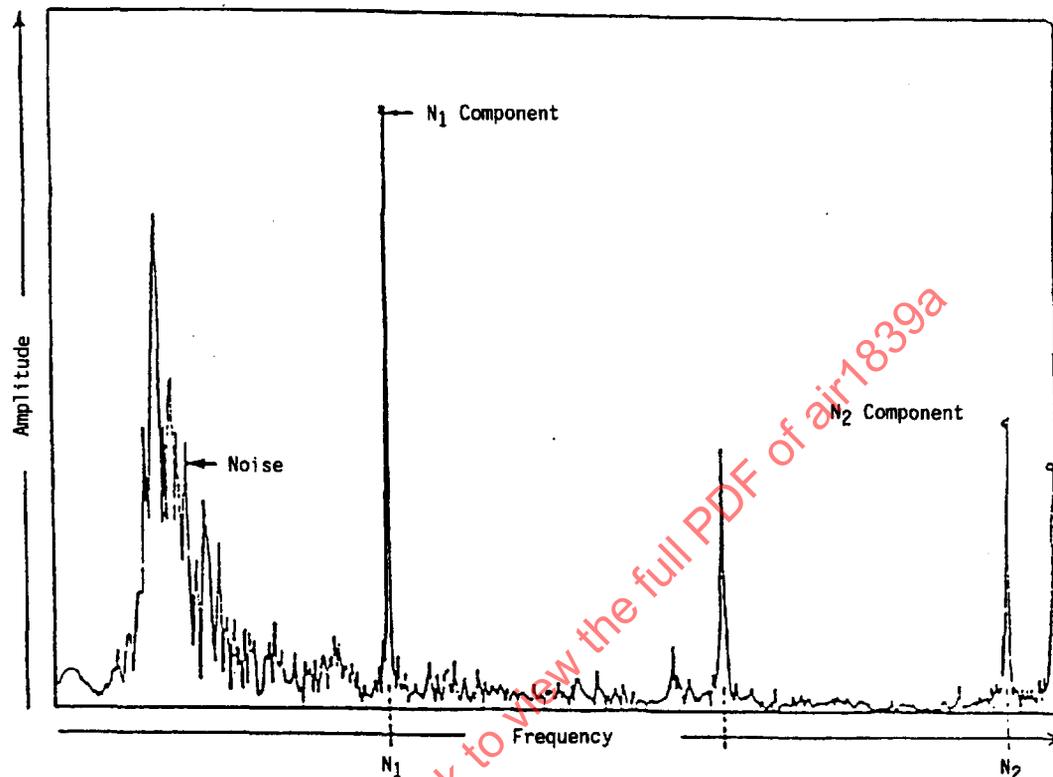


FIGURE 13 - Vibration Spectrum With High Noise Level Present

- 5.3.2 Integration: One integration of the accelerometer signal, with respect to time, yields a signal proportional to vibration velocity and a second such integration yields a signal proportional to displacement. In general, the parameter most commonly associated with vibration measurements at low frequencies is displacement, at mid frequencies is velocity, and at high frequencies is acceleration. Typical turbine engine rotor speeds are in the frequency range usually associated with the parameter of velocity. Since an integration is functionally a 6 dB per octave low pass filter, each stage of integration will emphasize low frequencies and attenuate high frequencies. This is an important consideration when considerable noise is present in the signal as is shown in Figure 13.
- 5.3.3 Filtering: If a rotor system operates at a constant speed, as is the case with some turboprop and/or turboshaft engines, then a fixed band pass filter can be centered at the rotational frequency and the output will be representative of the rotor's unbalance. If, as is usually the case, an engine operates over a range of speeds, then either the filter bands must be wide enough to accommodate the entire rotor speed ranges or narrow band pass filters must be caused to track the signals corresponding to each rotor as a function of speed.

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- 5.3.3.1 Careful selection of the filter characteristics is very important to total system performance. The raw signal from the transducer may contain many elements in its spectrum other than the frequencies of interest, and some of these elements may be very high in amplitude. If not filtered out, they may be confused with the desired signals and/or result in saturation of the input section of the signal conditioner. Most filtering is done after the charge amplifier, but in some cases, it is necessary to incorporate filters before the charge amplifier (input filters) to avoid saturation (overload). Saturation is most commonly caused by high frequency, high amplitude signals such as those resulting from blade passage, gear mesh, and higher rotor orders.
- 5.3.4 Output Formats: The output of the signal conditioner must match system requirements for display, recording, or further processing of the signals. This may involve gain or impedance matching for AC or DC analog outputs and special transmitters for digital outputs in accordance with standards such as ARINC 429, RS-232, or MIL-STD-1553B.
- 5.3.5 Warning Functions: Warning functions are sometimes provided to alert the flight crew of an event or a change in AVM status. These functions may require lamp drivers, latches, and/or special memory.
- 5.3.6 BITE/Self Test: Built-in test equipment (BITE) and self test should be considered in any new system design. BITE should be a means of detecting and recording faults at the time of their occurrence. Self test is usually a means of actively checking the operational condition of an item of equipment.

## 6. TRACKING FILTER BASED SYSTEMS:

In a tracking filter system, one or more band pass filters are caused to be constantly centered at the engine rotor frequencies (or multiples thereof) by reference to the engine tachometer signals. The earliest of these systems employed all analog filtering, while the latest designs employ primarily digital signal processing.

## 6.1 Tracking Filters:

Since the function of a tracking filter is to monitor discrete frequencies while maximizing noise rejection, its bandwidth should be as narrow as possible, consistent with the required engine rotor tracking rate. In general, the tracking rate (or settling time) of any band pass filter is inversely proportional to its Q, which is the ratio of the bandwidth (usually measured at the -3 dB points) to the center frequency. Noise rejection is a function not only of the bandwidth but of the filter shape or roll-off. The ideal narrow band tracking filter response would, therefore, look something like Figure 14. This filter response can be closely approached with a digital FIR (finite impulse response) filter (for which there is no analog equivalent). Typical FIR and analog band pass filter responses are shown in Figure 15. A convenient way of describing such filters is to use a shape factor, usually taken as the ratio of the bandwidth at -40 dB to that at -3 dB. A current digital tracking filter based AVM signal conditioner is shown in Figure 16.

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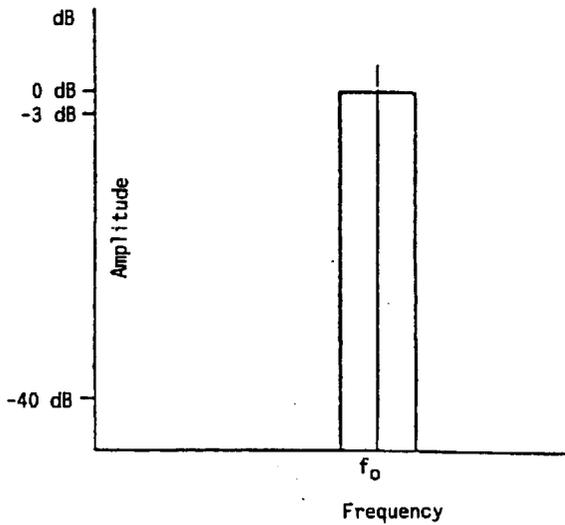


FIGURE 14 - Ideal Band Pass Filter

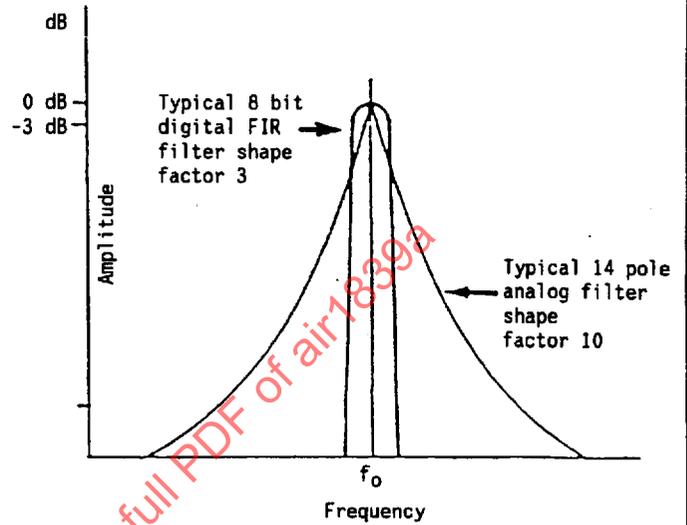


FIGURE 15 - Digital and Analog Band Pass Filters

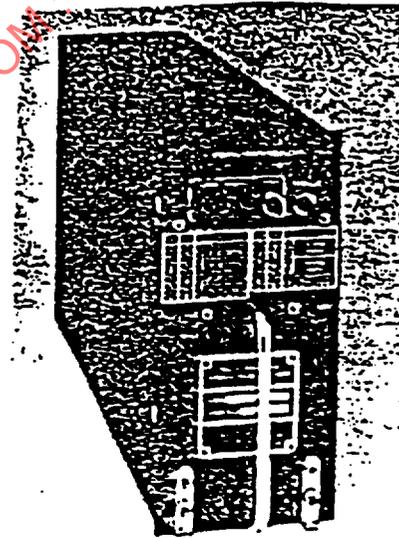


FIGURE 16 - Current Digital Tracking Filter Based AVM Signal Conditioner

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## 6.2 Tachometer Reference:

Because a tracking filter based system relies on engine tachometer signals for filter center frequency reference, close coordination is required between the equipment supplier and the engine manufacturer to accurately characterize the ratios and the output over the entire engine operational speed range. Similar coordination is required with the airframe manufacturer to ensure that the tachometer signals are adequately buffered at the signal conditioner so that the tracking filter does not interfere with other aircraft systems.

## 6.3 Rotor Trim Balance:

If phase reference signals are provided either by means of a dedicated tachometer or superimposed on the engine tachometer signals, then it is possible to use a tracking filter based AVM system for engine fan trim balance with no other support equipment required. Because of the convenience of on-wing trim balance without additional ground running, engine manufacturers are encouraged to incorporate phase reference signals at the time of the engine design.

## 7. RESPONSIBILITIES AND CONSIDERATIONS:

Since vibration on a gas turbine is a monitoring and not a control parameter, the question of the need to fit a vibration monitoring system arises. The answer varies depending upon the engine and its usage and is further influenced by a number of other considerations. Like any other condition monitoring system, a vibration system requires a significant amount of coordination and cooperation between various parties if it is to be successful. The parties responsible for the system development and integration usually include the end user, airframe manufacturer, engine manufacturer, and the equipment supplier. A single point of responsibility should be defined at the outset of a program.

### 7.1 Participants:

7.1.1 The End User: The end user has overall responsibility for establishing system requirements. He should, with the assistance of the engine manufacturer, outline what is to be monitored, how the data is to be presented, how the data is to be used, and what benefits are to be expected from the resulting system. Performance, reliability, LCC, and maintainability objectives should also be stated.

7.1.2 The Airframe Manufacturer: The airframe manufacturer has responsibility for the system integration, the definition with the end user, the mode of display and/or storage of the vibration data, and, finally, with the engine manufacturer, the determination of the engine response characteristics (vibration amplitude versus engine speed) and any alert/alarm levels that may need to be set. Assisted by the equipment manufacturer, the airframe manufacturer should specify the functions, interfaces, and environmental requirements for the on-board signal processor.

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7.1.3 The Engine (and/or Engine Accessory) Manufacturer: The engine manufacturer has the responsibility for defining the engine vibration characteristics, limits, parameters to be monitored, diagnostic strategy, and the environment for the engine mounted components. Assisted by the equipment manufacturer, the engine manufacturer should specify the requirements for the transducer(s) and associated wiring, determine its (their) location(s) on the engine, and define the signal processing (filtering) characteristics required. This should also include suitable rotor phase reference signal sources to satisfy the requirements for in-flight fan trim balance data acquisition.

7.1.4 The Equipment Supplier: The equipment supplier has responsibility for clearly conveying equipment capabilities to the engine and airframe manufacturers. This responsibility includes not only technical choices (current and projected), but also those concerning original fitment cost, LCC, maintainability, reliability, and product support.

7.1.5 Considerations for AVM: Figure 17 should be consulted and followed to ensure that all factors have been taken into account in the application of an AVM. Some factors, not necessarily in order of importance, are discussed in the following.

## 7.2 Regulatory Requirements:

7.2.1 Civil: U.S. Airworthiness Standards for Transport Category Airplanes, FAR Part 25.1305 (d) (3) requires, as of October 31st, 1974, "an indicator to indicate rotor system unbalance", for turbojet engine powered airplanes. This requirement has also been interpreted to apply to turbofan engines and may also be extended to cover new unducted fan and prop fan engines although it does not specifically apply to "turbo-propeller powered airplanes".

7.2.2 Similar requirements apply worldwide (Joint Airworthiness Standards for Transport Category Airplanes, JAR 25.1305 (d) (3)).

7.2.3 Military: There are no overall U.S. military policies or specifications on this subject within the services. The matter is addressed by each branch of the armed forces via their individual procurement specifications. AV-E-8593D, for example, provides engine vibration levels and test equipment requirements for engine design and test.

## 7.3 Human and Technological Factors:

The FAA, as well as the military, in many of their specifications not only require the detection of rotor unbalance, but that it must be isolated from other benign sources and attributed to the correct engine. This is essential to avoid the possibility, which has occurred on several occasions, of the wrong engine being shut down by the flight crew.

In the past, the pilot or crew was often able to isolate the vibration source through secondary indications such as by feel on the throttles of an engine with a cable controlled hydromechanical fuel control. With the introduction of electronic fuel controls, this mechanical link or secondary indicator has disappeared.

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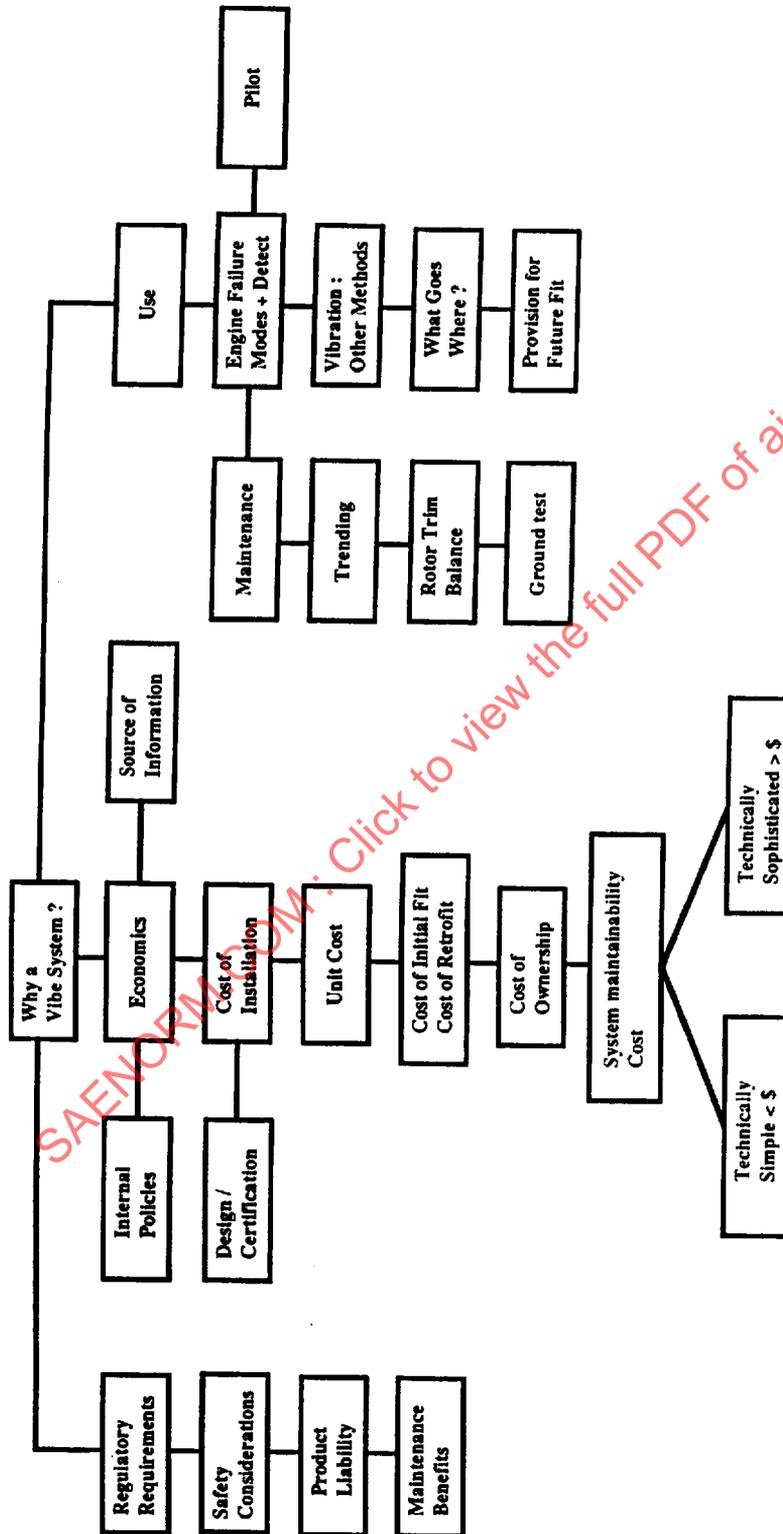


FIGURE 17 - Considerations for AVM

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## 7.3 (Continued):

In addition, significant technological advances in damping, isolating, and absorbing structurally borne vibrations through computer aided design, materials, modal analysis, finite element analysis, and many other methods have been made. These advances have resulted in optimized airframe structures, which are resistant to transmission of any vibration, thereby precluding or mitigating the use of the crew's perceived vibration level to sense rotor unbalance.

Under these conditions, a vibration monitoring system is necessary to give the crew a primary indicator for the detection and isolation of rotor unbalance.

## 7.4 Maintenance Benefits:

In order to realize maintenance benefits from a vibration monitoring system, it is essential that the appropriate information be made available to maintenance personnel and that its use be integrated into the end user's maintenance infrastructure and practices.

The type of information that must be provided is essentially different to the information required on the flight deck. The information for maintenance personnel must contain far more detail and permit a higher level of diagnosis of the nature of any fault. The information given to flight crew must be an unambiguous indication of the need to take action in accordance with predetermined instructions. (See also 7.6)

Because such detailed information is required, and the tendency of both military and civil end users to regard such information as proprietary, direct maintenance benefits are difficult to quantify in an objective manner.

For an example of what can be achieved given the necessary infrastructure and commitment by the end user, refer to the published literature from Lufthansa referenced at the end of this document. This gives a clear example of an end user achieving significant direct and indirect benefits from the use of the in-flight fan trim balance feature of a modern vibration system by total integration into their maintenance practices. This results in their ability to continuously operate at vibration levels considerably below those accepted as engine acceptance limits by the engine manufacturer.

## 7.5 The Economics of a Vibration Monitoring System:

If it is necessary to justify the economics of incorporating a vibration system, the complete LCC associated with the system should be taken into account. These will include:

- a. The direct acquisition costs (including development and certification where appropriate).
- b. The cost of maintaining the system over the expected lifetime of the airplane.
- c. The lost income from the money used to purchase and maintain the system.

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## 7.5 (Continued):

These costs must be offset by:

- a. Projected savings due to number of flight delays or schedule interruptions that will be avoided.
- b. Projected savings from the number of engine shutdowns due to failure where secondary damage would be avoided.
- c. Projected savings due to on-condition maintenance (OCM) rather than "by necessity".
- d. Projected savings in engine ground running for on-wing fan trim balance (where the system includes this feature).

These lists do not constitute a complete LCC model but it does highlight some major elements to be considered.

- 7.5.1 Costs of Initial Installation Versus Retrofit: For a new aircraft design, the question is where to include a vibration system. Should partial installation be provided, or should a provision for later installation be made. Cost of retrofit can be reduced by a partial installation such as aircraft wiring.

Inclusion in the initial design and development phases does incur expenditure of time, money, and human resources when all are in great demand. However, it is almost universally recognized that doing so will result in long-term savings and a superior system.

Additional advantages are that the system is available during the aircraft development should there be any unexpected problems, and if it is later decided to only deliver provision for a system, then these provisions will have been tested.

If an AVM system has not been qualified, then the later addition of a vibration monitoring system is subject to additional costs and risk association with specifying, fitting, testing, and qualification.

The addition of a system to an existing aircraft with no, or minimal, provisions may result in economic and/or technical constraints that will diminish the system performance.

## 7.6 System Usage:

The key questions to be asked are:

- a. What is the system going to be used for.
- b. By whom.

- 7.6.1 What For: The intended use of an AVM is for the detection and location of failures or degradation that give rise to changes in the vibratory response of the engine.

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## 7.6.1 (Continued):

It is not possible during the design and development phase of the engine to accurately determine and predict all of the possible failure modes that may occur during its service life. Those modes that are found are generally designed out before the engine enters service. However, normal usage, wear, unexpected failures, and damage will always occur in-service.

The primary objective of an AVM is to provide timely indication of abnormal vibration.

Since an AVM detects vibration, this ability is primarily concerned with the rotating assemblies, although in some cases, detection of vibration caused by other sources, e.g., aerodynamics, combustion instability, etc., may be included.

Most cases of mechanical damage to the high speed rotating assemblies of the engine are immediately recognizable by changes in the vibration levels associated with those parts. Other engine parameters such as oil pressure and temperature may also change, but the AVM response is generally faster, which allows more time for corrective action and avoidance of possible secondary damage.

- 7.6.2 How: In order to achieve this, the vibration transducers have to be closely coupled mechanically to the rotating assemblies. The most common configuration comprises two transducers per engine, one forward, the other aft. The front transducer is often mounted on the first bearing housing (on large fan engines) to monitor fan/compressor and the rear transducer is used to monitor the various turbine modules.

The signal processing hardware may be mounted in the airframe or on the engine. Some installations split the installation with some signal preconditioning being done on the engine and the remainder being done in an airframe mounted processor. Since transducer (usually accelerometer) signals require special precautions in wiring and connectors, there is a tendency to perform some signal transformation into a less sensitive form directly in the transducer or on the engine. Where requirements exist for a digital interface with the engine, such processing is a necessity.

- 7.6.3 Who: Vibration systems generally provide two categories of output data. One category is intended for use by the flight crew and the other by maintenance personnel.

- 7.6.3.1 Flight Crew: The information presented to a flight crew must be of the highest credibility and reliability. It must be unambiguous and directly related to providing early warning of an impending or developing problem and/or the direct indication and location of the occurrence of an unbalance related incident requiring crew action in accordance with documented procedures.

The forms of presentation range from discrete warning flags on exceedance to automatic presentation of signal magnitudes either "on exceedance" or "on demand". Signal magnitudes may be presented in a normalized form, which permits flight crew to compare the signals from different vibration sources as a function of their individual characteristics and/or requirements.