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(R)

A Guide to Aircraft Turbine Engine Vibration Monitoring Systems

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 functions on board an aircraft and that part used for ground based analysis (ground station) or 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 engine vibration monitoring (EVM) 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 EVM systems now in use were developed to monitor the level of vibration resulting from such unbalance. 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.

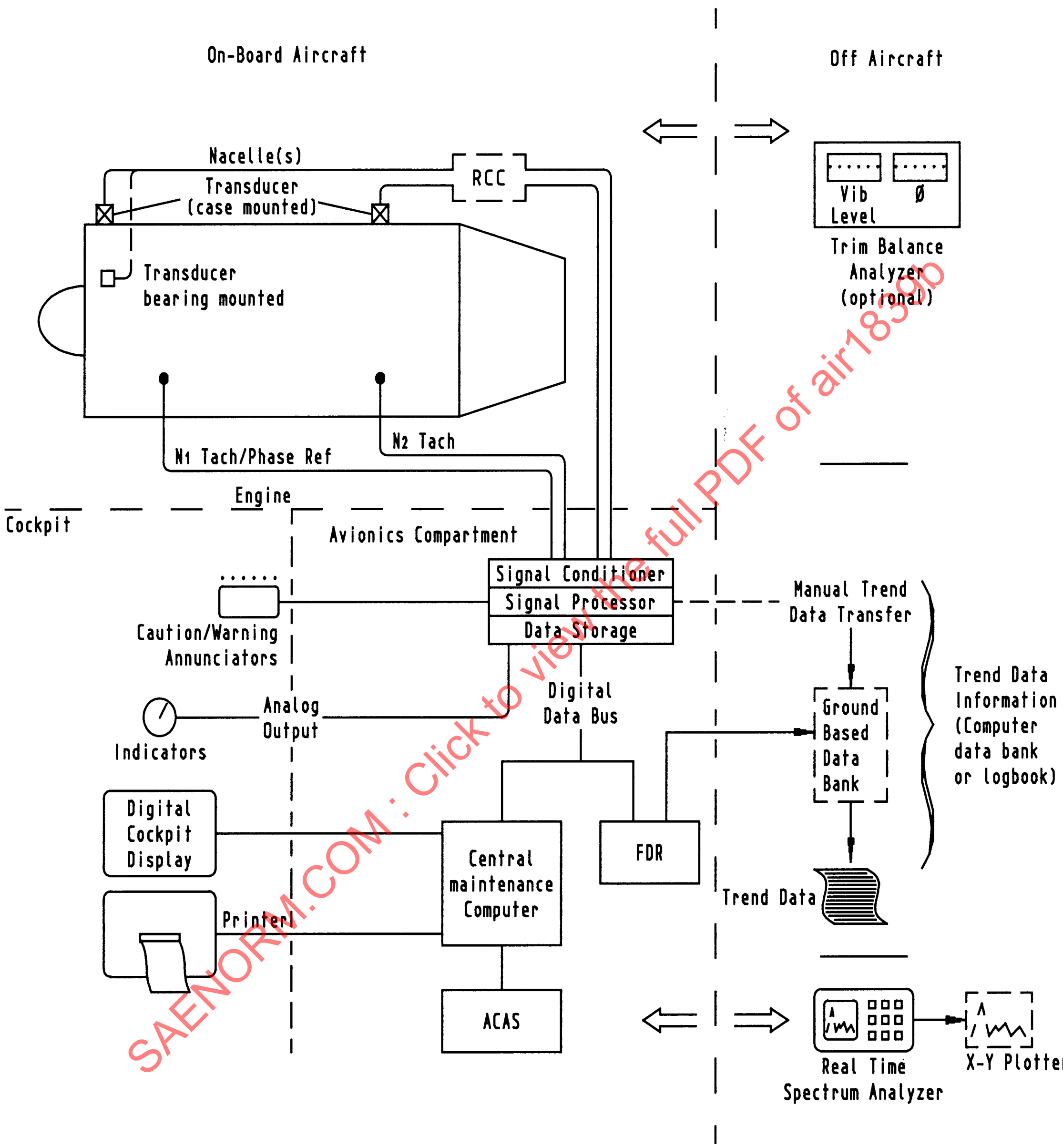
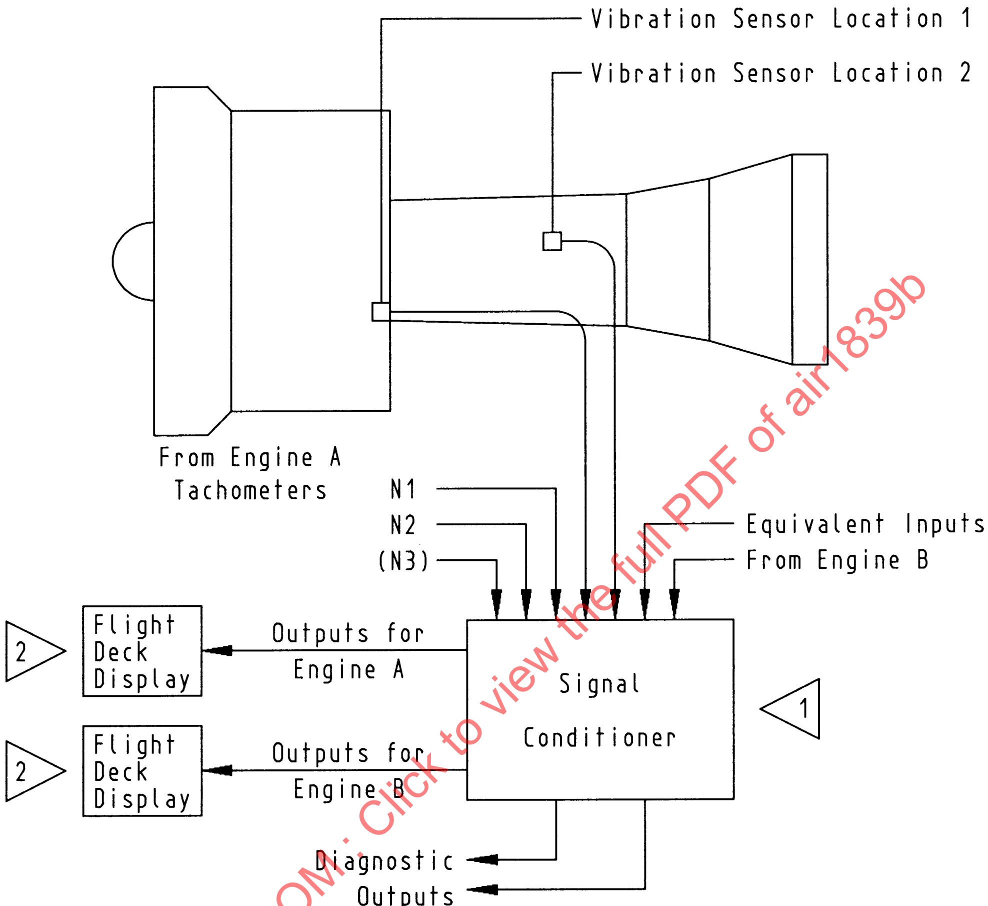


FIGURE 1 - Schematic of a Complete Engine Vibration Monitoring System (EVM)



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

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

1. SCOPE:

This SAE Aerospace Information Report (AIR) is a general overview of typical airborne engine vibration monitoring (EVM) systems with an emphasis on system design considerations. It describes EVM systems currently in use and future trends in EVM development.

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. APPLICABLE DOCUMENTS:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE Handbook on Vibration

ARP1587	Aircraft Gas Turbine Engine Monitoring System Guide
AIR1828	Requirements for Oil System Monitoring in Aircraft Gas Turbine Engines
AIR1871B	Lessons Learned from Developmental and Operational Turbine Engine Monitoring Systems
AIR4061	Integration of Engine Monitoring With On-Board Systems
AIR4174	Guide to Power Train Monitoring Techniques
AIR4176	Cost vs. Benefits of Engine Monitoring Systems
AS8054	Airborne Engine Vibration Monitoring (EVM) System, “Minimum Performance Standard for”

3. TERMINOLOGY AND DEFINITIONS:

ACCELERATION, VIBRATION: The response of a mass to an applied force, usually stated as a ratio, g, of the acceleration with respect to G, the acceleration due to gravity. The first integral of acceleration with respect to time is velocity. Vibration amplitude may be expressed in units of acceleration, velocity, or displacement.

ACCELEROMETER: A device for measuring acceleration. Most accelerometers used for EVM employ piezoelectric sensing elements, which generate an electrical charge signal proportional in amplitude, frequency, and phase to the applied acceleration. Devices with internal signal conditioning are also available. These provide voltage or current outputs proportional to acceleration or velocity.

3. (Continued):

ENGINE VIBRATION MONITORING (EVM) SYSTEM: The on-board aircraft EVM system.

AIRLINE COMMUNICATION AND REPORTING SYSTEM (ACARS)
AIRCRAFT CONDITION MONITORING SYSTEM (ACMS)
AIRCRAFT INTEGRATED MONITORING SYSTEMS (AIMS)
AIRCRAFT INTEGRATED DATA SYSTEM (AIDS): The general terms used to identify a family of systems that acquires, processes, and records data used to determine the functional status and condition of various commercial aircraft systems including engine and engine components.

DATA BUS: A means of transferring information in digital format. Various data bus standards such as ARINC 429 and RS-232 are widely used in monitoring systems.

DISPLACEMENT, VIBRATION: Vibration amplitude may be expressed in units of displacement: inches, millimeters, or mils (0.001 in). Displacement is the second integral of acceleration with respect to time. Both peak and peak-to-peak amplitude units are in use.

FREQUENCY RESPONSE: The amplitude response of a spring-mass system as a function of frequency.

ON-CONDITION MAINTENANCE (OCM): Maintenance only carried out when the condition of the engine (equipment) requires it as opposed to hard-time, the carrying out of maintenance at predetermined intervals of time, either flight hours or elapsed time.

ONCE-PER-REV: A colloquial expression meaning either a signal that is provided once per engine rotor revolution or the rotational speed of a particular engine rotor.

PEAK AND PEAK-TO-PEAK: Vibration amplitude measurement that has a precise meaning only for simple harmonic motion (i.e., single frequency, vibration). Peak is the maximum amplitude of a sinusoidal function with respect to a zero reference; peak-to-peak is the total amplitude measured from maximum to minimum.

PHASE REFERENCE SIGNAL: A signal, usually electrical, provided on some engines, which indicates when a particular point on the low speed rotor passes a reference point on the engine case. The reference signal, which is often superimposed on the tachometer signal, is useful for dynamically balancing the rotor.

RMS: Root mean square. An average of a set of values that is obtained by taking the square root of the arithmetic mean of the squares of the individual values. Vibration amplitude expressed as rms is proportional to the total vibration energy in the frequency band of interest but independent of the frequency distribution within that band.

ROTOR ORDERS: The rotational speed of the lowest speed engine rotor is conventionally identified as N1, the next highest as N2, and the next highest, if present, as N3.

SCREECH: High frequency, acoustic noise generated by engine exhaust gas turbulence.

3. (Continued):

SPECTRUM: An array of the frequency component amplitudes of a signal arranged in order of frequency.

VELOCITY, VIBRATION: Vibration amplitude may be expressed in units of velocity: inches per second or millimeters per second. Velocity is the first integral of acceleration with respect to time.

NATURAL FREQUENCY: The natural frequency of a spring-mass system is proportional to the square root of the ratio of the spring constant to the mass for each degree of freedom.

RESONANCE, MECHANICAL: The condition that occurs when the frequency of an exciting force equals a natural frequency of a spring-mass system.

4. 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.

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.

5. 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.

5. (Continued):

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 rotor unbalance magnitude.

In certain flight conditions high vibration may be an indication of ice accretion and subsequent asymmetrical shedding. In which case the appropriate de-icing procedures should be adopted using the EVM system to indicate a return to a good state of engine balance.

The severity of engine mechanical damage or degradation and its rate of change is 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 safety of flight to overhaul and service needs, such as rotor trim balancing .

6. 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 (Reference 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.

6. (Continued):

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.

6.1 Signal Source:

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

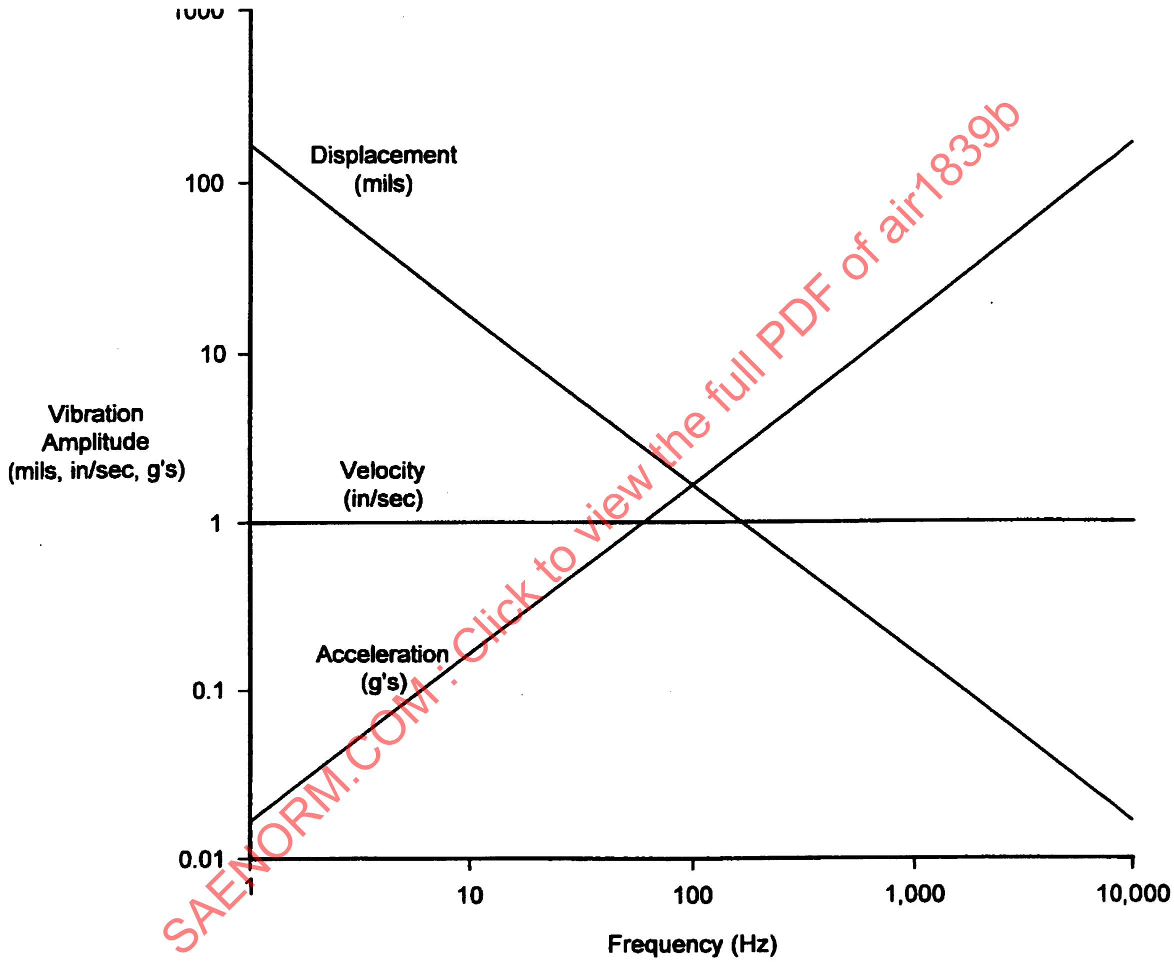
6.1.1 Transducer Location: The transducer mounting location on the engine or accessory must be one that is mechanically well coupled to the component being monitored, due consideration being given to component natural frequencies and node points. This coupling must be established during engine development. 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 dynamic simulation, flight tests and engine ground runs on the aircraft.

6.1.2 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 mΩ.

6.1.2.1 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.

6.1.2.2 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.

6.1.3 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.



Notes:

1. **1.0 g = 9.80665 m/s² = 32.174 ft/s²**
2. **Velocity (in/sec) = Acceleration (g's) x 61.448 / Frequency (Hz)**
3. **Displacement (mils) = Acceleration (g's) x 9780 / Frequency ² (Hz²)**
4. **Displacement (mils) = Velocity (in/sec) x 159.16 / Frequency (Hz)**
5. **Acceleration (g's) = Velocity (in/sec) = 1.0 @ 61.448 Hz**
6. **Displacement (mils) = Velocity (in/sec) = 1.0 @ 159.16 Hz**
7. **Acceleration (g's) = Displacement (mils) = 1.609 @ 98.89 Hz**

FIGURE 3 - Relationship Between Displacement, Velocity and Acceleration at Constant Velocity

6.1.3.1 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.

6.1.3.2 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/s. 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.

6.1.3.3 Accelerometers: Accelerometers are the most widely used type of vibration transducer used 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.

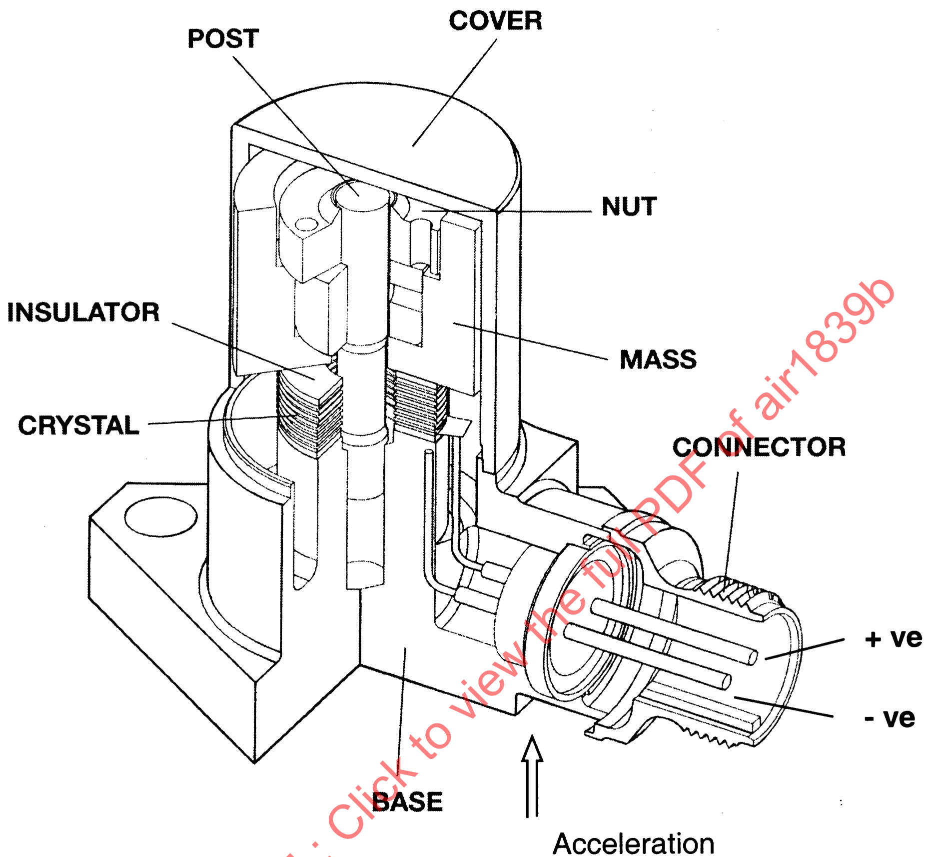


FIGURE 4 - Cross-Section of a Typical EVM Compression Type Piezoelectric Accelerometer

6.1.3.3 (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. 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 kΩ) over its operating temperature. Low internal resistance will lead to noise problems with the charge amplifier, particularly at low frequencies.

6.1.3.3 (Continued):

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.

6.1.3.3.1 Surface Mounted Accelerometers With Connectors: Figure 5 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.

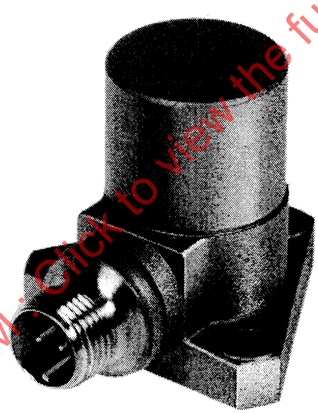


FIGURE 5 - Surface Mounted Accelerometer With Connector

6.1.3.3.2 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 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 6 shows a typical accelerometer of this type.

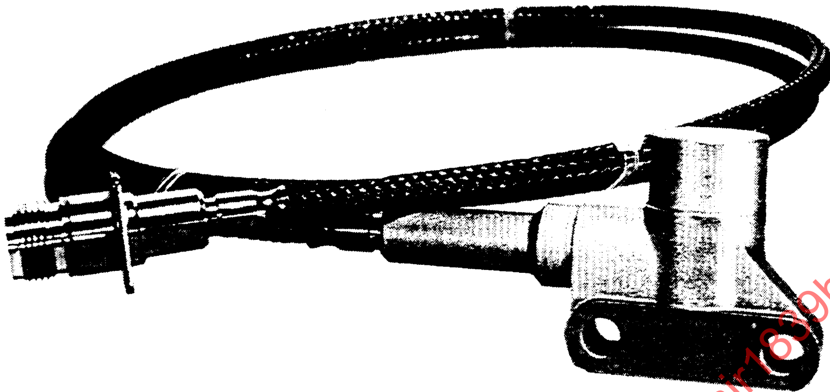


FIGURE 6 - Surface Mounted Accelerometer With Integral Cable

6.1.3.3.2 (Continued):

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 7. 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.

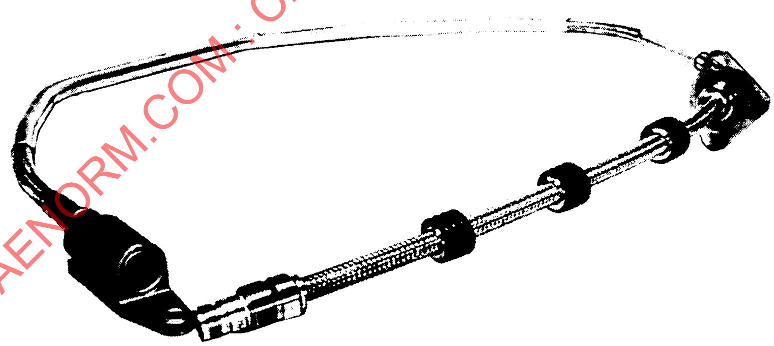


FIGURE 7 - Internal Type Accelerometer

6.1.3.3.3 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.

6.1.3.3.3 (Continued):

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 should 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.

6.1.3.3.4 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 8 shows a typical accelerometer of this type.

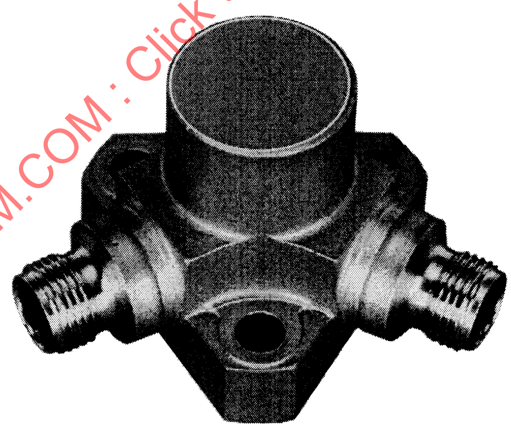


FIGURE 8 - Surface Mounted Dual Element Accelerometer

6.2 Signal Transmission:

Because of the high impedance of the charge signal, there are a number of special considerations for accelerometer signal transmission that are critical to EVM systems such as the system design, the cabling considerations and connector issues.

6.2.1 System Partitioning: A key system design issue for EVM systems is the location of the first stage amplifier for the accelerometer output. Since the accelerometer output is a very high impedance low level charge signal, special care must be taken to transmit this signal to the first stage of electronics, which could be over 100 ft away in the EVM unit. The difficulties of high impedance signal transmission can be avoided by incorporating a preamplifier within the accelerometer body itself, or in a separate unit located near the accelerometer. The preamplifier will convert the accelerometer charge/acceleration output to a voltage/acceleration signal. This provides a more robust signal with improved resistance to electromagnetic interference (EMI) which can be transmitted long distances without the need for special low noise cabling. The power for an accelerometer preamplifier can be provided by the down stream processing electronics on the same wires used for the output from the accelerometer. When a separate unit is used, sometimes called an remote charge converter (RCC), the preamplifiers for more than one accelerometer can be included in one unit, as well as additional electronics to integrate the voltage/acceleration signal to a voltage/velocity signal.

At the present time, however, electronic components for use in such preamplifiers are limited to approximately 350 °F, and many engine locations are considerably hotter than this. This temperature limit poses restrictions on the use of accelerometers with integral preamplifiers, and the location of separate preamplifiers or RCCs. The environment on most gas turbine engines is also severe with regard to vibration and contamination, requiring an RCC with a rugged housing and a vibration resistant design. The RCC may be located in a less severe environment off the engine, but nearby such as in the nacelle or engine pylon. The cost/benefit trade-off is usually very close when comparing properly shielded and secured low noise cable versus less expensive standard cable and a separate RCC. For these reasons, with few exceptions, EVM systems employ charge output accelerometers with low noise cabling, or an RCC located off the engine.

6.2.2 Cabling Considerations: A number of special design features are necessary to preserve the signal from a piezoelectric accelerometer during transmission to the preamplifier. This includes the design of the circuit, shielding which may be single or double, the grounding concept, the cable properties as well as the cable routing and clamping. The normal size of such twin core twisted shielded pair antimicrophonic cable is in the range 4 to 4.5 mm diameter.

6.2.2.1 Shielding: The signal leads should be fully shielded over the entire cable length up to the pre-amplifier which may or may not be incorporated into the processing electronics and the shield should be grounded only at one point, usually the signal conditioner chassis ground.

It is important that the cable is capacitively balanced (i.e., the core to shield capacities of both conductors should be equal within 10%). A capacitively unbalanced cable will reduce the common mode rejection capability.

In recent times, double shielded cables are frequently used. The additional shield acts as a mechanical and electrical protection. When double shield are used, it is recommended to ground the outer shield as often as possible (i.e., normally at every connector via the connector shells). The inner shield however must be fully isolated from the outer shield and at connectors it is carried on via one of the contacts. The inner shield is grounded at only one point, which is usually the signal conditioner chassis ground (similar to the single shield concept).

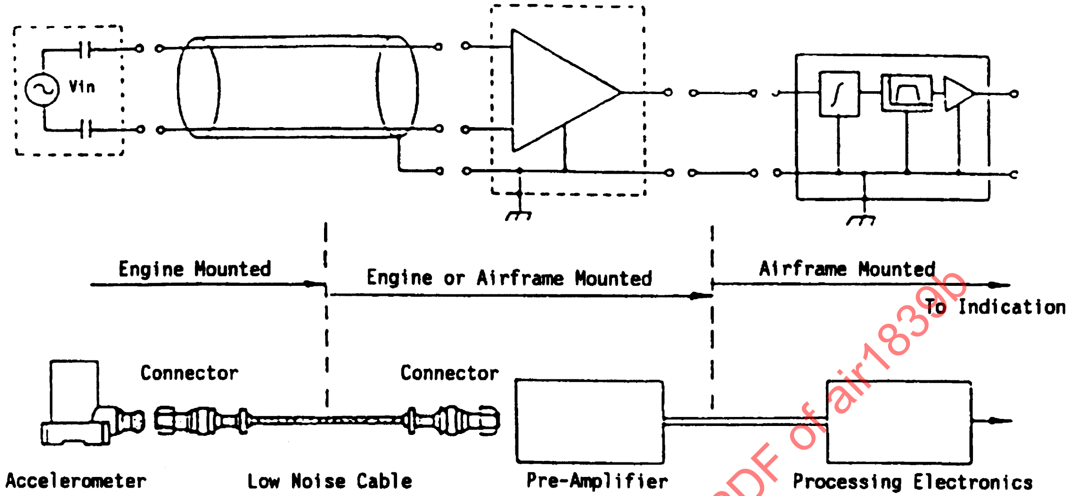


FIGURE 9 - Typical Differential Measurement Chain

6.2.2.2 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 10) in which the internal parts are wrapped in graphite impregnated PTFE tape thereby reducing such charge accumulation. To further protect against triboelectric noise, the cable should be secured to minimize cable motion. Such cables are commonally called antimicrophonic cables.

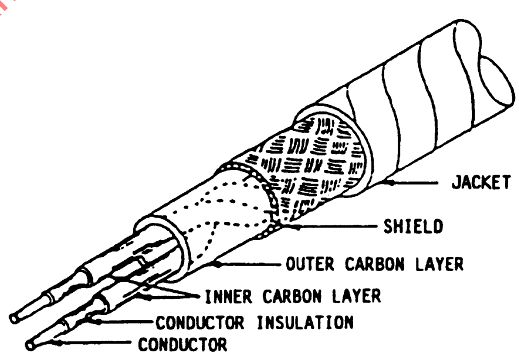


FIGURE 10 - Low Noise Cable

6.2.2.3 Cable Routing: In high vibration areas, such as an engine nacelle, it is usually recommended that the cable be firmly clamped at intervals of approximately 8 in along its length. Attachment points having large displacement with respect to each other should be avoided. Care must be taken when routing the cable that due allowance is made for temperature expansion (engine growth) effects.

6.2.3 Connector Issues: 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. The connector at the transducer itself is critical because, at this point, the highest temperature and vibration environment is usually experienced.

Very often, the vibration and/or temperature specification at the transducer exceeds the capability of standard connectors which are normally certified to 500 °F. In higher temperature cases, the first portion of the cable should be integrally attached to the transducer in order to have the first connector in a more benign environment.

6.2.3.1 Shared Connectors: The connectors associated with the EVM 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.

6.2.3.2 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 always be carried through the connector on one of the connector pins.

The cable shield should be terminated at the connector in such a fashion that 360° shield coverage is maintained in order to minimise EMI.

6.2.3.3 Connector Strain Relief: Connectors should be suitably strain relieved to prevent cable fatigue damage and/or generation of triboelectric noise.

6.2.3.4 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.

6.2.3.5 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.

6.3 Signal Processing:

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

Speed Range: The signal processor shall be capable of handling the complete range of input, internal and output signals which will be encountered over the speed ranges of the engine rotors from below ground idle to above red line limits. The actual limits will be determined for the specific application and shall be sufficiently wide to prevent loss of useful data at, or close to, the upper and lower limits.

Anti-aliasing: Adequate anti-aliasing shall be provided to prevent fold-back of higher frequency vibrations into the analysis frequency range.

6.3.1 Signal Conditioning: With a differential (fully floating ground isolated 2 pin) piezoelectric accelerometer as the signal source, the first stage of the signal conditioner is a 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.

6.3.2 Signal Integration: One integration of the accelerometer signal, with respect to time, yields a signal proportional to vibration velocity. 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 (i.e., 20 to 500 Hz (or higher for small turbines)).

Each stage of integration will emphasize low frequencies and attenuate high frequencies (see Figure 3). This is an important consideration when low frequency noise is present in the signal as is shown in Figure 11.

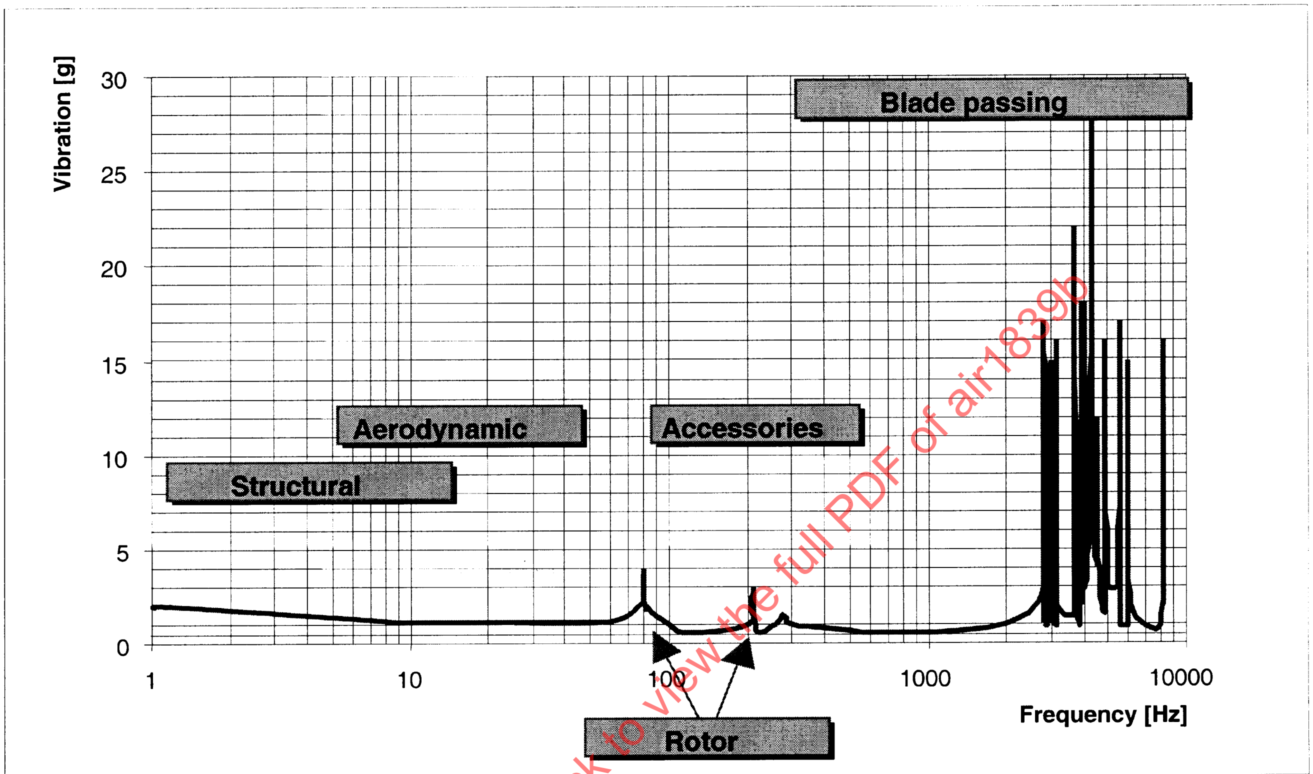


FIGURE 11 - Typical Vibration Spectrum

6.3.3 Signal Filtering: 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 all 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 but may also be caused by low frequency phenomena such as thermal effects and structured movements of large amplitude. These are particularly important when the signal is integrated to displacement terms.

6.3.3.1 Tracking filters shall provide synchronous, narrow bandpass filtering, controlled by the tachometer signals, to measure the vibration levels which are synchronous with the rotational frequency of each engine rotor over the rotor speed ranges. If a rotor system operates at a constant speed, as is the case with some turboprop and/or turboshaft engines, then a fixed bandpass filter can be centered at the rotational frequency and the output will be representative of the rotor's unbalance.

6.3.3.1.1 Tracking Filter Characteristics: The tracking filter center frequency shall be slaved to the engine rotor speed.The filter characteristics shall be determined by the specific application to meet the requirements of this standard and any other requirements specified by the installer. Neither engine acceleration/deceleration (within the limits specified by the installer) nor Tachometer signal noise ("jitter") shall adversely affect tracked data accuracy beyond specified limits.

6.3.3.2 Spectral Analysis: A similar function to a tracking filter may be provided by continuously performing spectral analyses of the vibration signal and isolating the 1/rev (or other) orders as a function of rotor(s) speed. Isolation of the 1/rev unbalance signal can be achieved by performing continuous spectral analyses of the input signal and correlating to rotor speed(s). Spectral analyses also provide a means to reliably monitor non-rotor related and non-integral vibration orders which may be related to engine or component malfunction. Knowledge of the overall spectrum may lead to a higher degree of fault diagnosis.

6.3.3.3 Broad Band: In addition to the required rotor unbalance outputs, a broadband is proposed for the application, the bandpass filter corner frequencies shall be set to cover the speed range of the engine rotors. A broadband filter should, preferably, be specified as true RMS or average. A similar function may be provided by summing the appropriate discrete frequencies from a spectral analysis.

6.3.4 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, ARINC 629, RS-232, or MIL-STD-1553B.

6.3.5 Warning Functions: Warning functions are sometimes provided to alert the flight crew of an event or a change in EVM status. These functions may require lamp drivers, latches, and/or special memory.

6.3.6 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.

The EVM should not respond to non-engine rotor related events, such as fast engine speed changes, passing through resonances etc., which do not need to track exactly in real time. However, such events may be of diagnostic interest with respect to engine health as opposed to a rotor unbalance monitoring system.

7. ROTOR TRIM BALANCING:

The technology that performs tracked vibration monitoring can readily provide data for rotor trim balancing. With the addition of a once-per-revolution phase reference to the EVM, aircraft operators can realize the benefits of in-flight data recording of unbalance data. Additional software can then provide trim balance solutions if a means for the operator to interact with the EVM is available. To furnish operators the advantage of on-wing trim balancing, engine manufacturers are encouraged to incorporate phase reference signals at the time of engine design.

Trim balancing an engine involves placing balance weights at particular locations on an engine. These weights counter-act mass unbalance in the engine, thus reducing vibration. The weights can be placed within one or two circular cross sectional areas of the engine called balance planes. Balance planes are typically located in the Fan area near the front of the engine, and the Low Pressure Turbine (LPT) area near the rear. The Fan and the LPT are connected together and form the low-pressure rotor, which turns at what is called the N1 speed. Fan balance weights are typically bolts arrayed in an evenly spaced circular pattern in the spinner cone. The bolts will have varying weights in order to effect mass corrections. LPT weights are typically clipped onto the LPT blades, mass correction is effected by the absence or presence of a weight.

The EVM determines the vibration unbalance amplitude and phase. Through use of appropriate algorithms this enables one to determine the amount and placement of the balance weights.

7.1 Phase Reference:

In order to measure the phase of a vibration signal, a once-per-revolution phase reference signal is required. This phase reference signal must provide a unique detectable indication, defined as the zero degree reference, which appears once per each revolution of the low pressure rotor. The phase reference signal generator must be coupled to the engine such that the zero degree reference point of the signal occurs each time the engine rotor reaches a fixed position in its revolution. The phase reference is usually incorporated in the N1 tachometer signal (which typically has several pulses per revolution) as a raised or lowered pulse (see Figure 12). The phase reference can also be provided as a separate signal having one pulse per revolution.

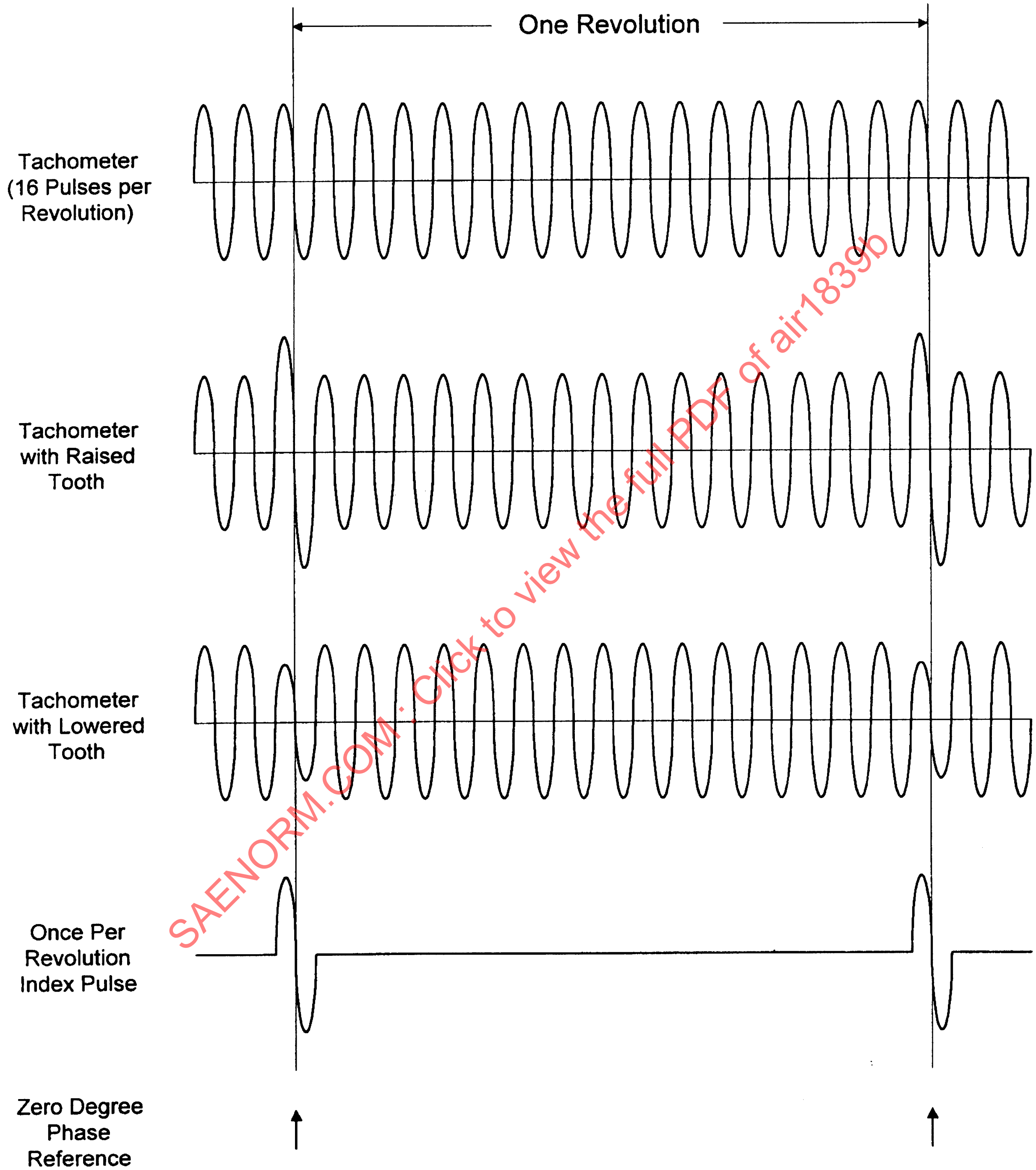


FIGURE 12 - Vibration Phase Reference

7.1 (Continued):

The phase reference signal is usually generated by a magnetic pole-piece on the low pressure rotor in conjunction with a stationary pick-up attached to the engine frame. When the phase reference is incorporated into an N-pulse per revolution tachometer generator, one of the N pole pieces is larger or smaller than the rest, so as to generate a pulse that is larger or smaller than the other pulses. In the case of a single 1/rev pulse, a single pole piece is present on the rotor. It is typical to use the first zero crossing of the unique 1/rev pulse as the zero degree reference.

The same phase reference signal is also used for LPT balancing, since it is on the same shaft as the Fan.

It is essential that the physical angular relationship between the Fan, the LPT and the 1/rev phase reference generator be maintained throughout the life of the engine.

7.2 Phase Measurement Considerations:

A number of terms are used when defining phase measurement most of which are ambiguous. Two major classifications are Lead Phase and Lag Phase. These terms reflect the relationship between the phase reference and some point of the vibration signal. Lead Phase usually means the amount of time (converted to degrees) that a particular point on the vibration signal appears before (leads) the zero degree point of the phase reference signal, when the two signals are displayed simultaneously. Of course, just the opposite could be meant, such as when Lead Phase is defined as the amount of time that the phase reference leads some point on the vibration signal.

Similar definition and ambiguity apply to the definition of Lag Phase, which usually means the amount of time (converted to degrees) that the point on the vibration signal comes after (lags) the phase reference, this however can also mean the converse.

It is clear that, in order for the terms Lead and Lag Phase to have useful meaning it must be defined which signal leads (or lags) the other. Since by definition the phase signal is denoted the reference, it should be the fixed point to which the vibration signal is compared.

Another ambiguity is the nature of the vibration signal being measured. Vibration signals can be measured as acceleration, velocity, or displacement. The phase measure must be defined as relative to one of these three signals. A further definition must also be provided which is the point on the (typically sinusoidal) vibration signal that the Lead or Lag time will be measured. Four choices are possible : the positive or negative peaks, and the Hi to Lo or Lo to Hi zero crossings. Altogether there are 24 possible definitions of phase (12 for Lead and 12 for Lag). There is, however, a fixed phase relationship between the measurement parameters of acceleration, velocity and displacement (Reference Figure 3): acceleration differs from velocity by 90°, and velocity differs from displacement by 90°. For each parameter there are four different possibilities for each of Lead and Lag. The possible phase measures and relationships are summarized hereafter:

TABLE 1

Vibration Signal	**Identical Measurement**	**Identical Measurement**	**Identical Measurement**	**Identical Measurement**
Displacement	Positive Peak	Hi to Lo Zero Crossing	Negative Peak	Lo to Hi Zero Crossing
Velocity	Hi to Lo Zero Crossing	Negative Peak	Lo to Hi Zero Crossing	Positive Peak
Acceleration	Negative Peak	Lo to Hi Zero Crossing	Positive Peak	Hi to Lo Zero Crossing

7.2 (Continued):

The most common choices of phase measurement are:

a. The phase reference signal as the azimuth from which the vibration signal Lead or Lag is determined
b. Both Lead and Lag pulse are common
c. The zero crossings of the vibration signal is generally preferred

The time difference between the zero degree phase reference points and the vibration signal is converted to degrees by comparing it to the time of one revolution. The time difference between two phase reference points represents the time it takes the low pressure rotor to make one revolution, this is equivalent to 360°. The Lead (or Lag) phase measurement is therefore the amount of time that a point on the vibration signal Leads (or Lags) the phase reference, divided by the time between phase reference points then multiplied by 360°.

$$\text{Phase Lead (degrees)} = (\text{Time Lead}/\text{Time one revolution}) * 360 \qquad \text{(Eq. 1)}$$

Lag phase can be converted to Lead phase as follows:

$$\text{Lag phase} = 360 - \text{Lead phase} \qquad \text{(Eq. 2)}$$

and similarly for Lead phase:

$$\text{Lead phase} = 360 - \text{Lag phase} \qquad \text{(Eq. 3)}$$

Balance computation may be carried out in terms of acceleration or velocity or displacement, Displacement data is most commonly used.

The respective angular positions of the 1/rev and vibration sensors must be known and taken into consideration.

7.3 Data Collection:

Rotor unbalance amplitude and phase data can be obtained during flight or ground running of engines.

7.3.1 In Flight Data Collection: In general, flight data is preferred for balancing purposes for three main reasons:

1. It can be obtained over an extended period of time at no extra operating cost.
2. It more accurately reflects the flight operating dynamics of the engine than ground running.
3. Ground running may be difficult for environmental or other reasons and is costly.

The basic instrumentation required is the on-board EVM system which may either simply compute amplitude and phase values, record engine rpm and output them via databus for transmission to ground stations or for recording by other systems, or the EVM itself may also store and process these values into a form than can be used directly by maintenance personnel to balance the engines.

Where the data is transmitted to other systems, the balancing process is defined by any one of a number of specific algorithms.

The on-board computation of balancing solution requires the definition within the EVM of similar data gathering and storage criteria to those used by ground equipment.

Engine speed ranges or bands must be defined which cover the most common operating regimes of the engines and which avoid any known resonances. Additional speed ranges may be specified to cover conditions which cause cabin noise or to suit specific operator's desires.

Stability criteria must be established to ensure that the speed phase and amplitude data is acquired and stored under stable operating conditions within the selected speed ranges. Typical values would be:

Speed = ±1 rpm
Amplitude = ±0.1 mils
Phase = ±10°

All these parameters should be maintained within these limits for 5 s or more.

In addition, it is usual to include provision to update stored data if a later stable dataset is obtained at a condition which is closer to the center of the selected speed band. The selected speed ranges and stability criteria should be readily modifiable by the operator in service, without removal of the EVM from the aircraft.

7.3.1 (Continued):

To cater for varying operating procedures and to permit trend analysis, it is usual to collect and store the selected speed band data over the last “n” flight legs. In some applications it may be desirable to average the data over the number of flights. Even when the EVM contains provisions for on-board balancing, it is usual that it also provides outputs of the phase and magnitude data in appropriate analog and digital formats for use by other systems. A typical example would be the use of ACARS to download the data from flight in real time to the operator’s central maintenance computer system where it forms part of their fleet maintenance database.

7.3.2 Ground Running: The gathering of data on ground requires that the engine(s) be run at stabilised conditions for each of the speeds necessary to obtain a valid dataset for balancing purposes. Often, the high rotor speed cases cannot be obtained under these conditions.

In some cases, where no suitable on-board system exists, the vibration data is gathered by fitting specific speed and vibration sensors connected to ground equipment.

On all modern aircraft it is common to utilise the on-board EVM system in one or more of the following ways:

- To directly calculate the balancing solution in the same way as for data collected in flight operation
- To provide analog vibration and tachometer data to ground based balancing systems
- To provide digital phase and amplitude data to ground based balancing systems or for storage and/or connection directly to the central maintenance computer system

7.4 Balance Coefficients:

Balance coefficients represent the signal received at the accelerometer location due to a known amount of unbalance of a known location. For a given value of physical unbalance in a rotor system, there exists a fixed relationship between its angular position and the position of the 1/rev reference signal from the shaft tachometer, and to the position of the accelerometer used to measure the unbalance. However, in addition to this constant relationship, the actual amplitude and phase of the signal sensed by the accelerometer(s) varies as a function of rotor speed. This is caused by the fact that there are multiple mechanical paths between the accelerometer and the forces created by the unbalance, each with its own transfer function.

In a typical gas turbine EVM system, there are two accelerometers and balancing actions may be calculated for the Fan alone (Single plane) or for the Fan and turbine sections combined (Two Plane).

Since unbalance in either Fan or Turbine sections will normally influence signals on both the accelerometers and the degree of influence will be affected by the above factors, it is necessary to determine a set of “Balance Coefficients” which can be used for each of the selected speeds or speed ranges at which balance data is to be gathered.

7.4 (Continued):

These coefficients are affected by the structure to which the engine is attached and may be different for test stand, ground running or flight operation. The coefficients are initially established by taking baseline vibration measurement, then applying known weights to known locations on the Fan and LPT and taking vibration measurements at each of the operating speeds.

Coefficients are required for both amplitude and phase data.

A typical set of such coefficients would have the following form:

A_{ij}: Response measured at ith sensor due to unit balance moment on jth balance plane - for each rotating speed point.

For an engine with two sensors, located in front and rear, and balance capability on the fan and Low Pressure Turbine (LPT) stages:

i = 1,2 where i =1 is forward sensor (F) and i = 2 is rear sensor (R)
j = 1,2 where j =1 is fan stage (Fan) and j =2 is LPT stage (LPT)

For which these coefficients for each rotating speed can be defined as follows:

$A_{F/Fan}$: Response measured at front sensor due to unit balance moment installed on the Fan.
$A_{F/LPT}$: Response measured at front sensor due to unit balance moment installed on LPT.
$A_{R/Fan}$: Response measure at rear sensor due to unit balance moment installed on Fan.
$A_{R/LPT}$: Response measured at rear sensor due to unit balance moment installed on LPT.

Measured response is usually displacement and the units used for the coefficients are typically mils/oz-in or mils/grm-cm.

For on-board balancing, the appropriate balance coefficients must be stored in the EVM and in any ground based system using the EVM outputs.

In all cases, the coefficients should be clearly identified and stored in an easily modifiable form to permit them to be updated in service. Such updates are typically the result of service experience giving an expanded database which permits the derivation of a more “Typical” set.

Additional sets of coefficients may be needed to balance older engines and the occasional “Atypical” engine.

In cases where engine type and serial number information is available to the EVM, the coefficients may be constantly refined by an iterative process based on the results of the last balancing action taken.

The coefficients are used by the system performing the balance calculation to determine the real physical position of the unbalance prior to computing the required maintenance action(s).

7.5 Balance Calculations:

Balance calculations are possible once the vibration amplitude and vibration phase are available and appropriate balance coefficients have been determined. The primary equation for determining a balance solution is :

$$V_{new} = V_{old} + CW = 0 \quad \text{(Eq. 4)}$$

where:

V_{old} = Originally measured vibration amplitude and angle
V_{new} = Vibration amplitude and angle after balancing (ideally 0)
C = Balance Coefficient magnitude and angle
W = Weight magnitude and angle

Each of these variables are complex number vectors having a magnitude and phase component. The object is to determine a weight vector such that when it is multiplied by the coefficient vector the negative of the measured vibration occurs, thereby allowing the sum to be zero.

7.6 Balance Implementation Example:

As an example, suppose a 1 oz-in weight on a fan at 0° gives a vibration level change at an accelerometer of 0.5 mils single amplitude (msa) at 45°. Then the balance coefficient by definition is:

C = 0.5 msa @ 45°/1.0 oz-in @ 0° = 0.5 msa/oz-in @ 45° (Eq. 5)

Now if the fan had an unbalance resulting in a vibration level of 1.5 msa @ 55°. the balance equation must be solved as follows:

0 = 1.5 msa @ 55° + 0.5 msa/oz-in @ 45° * W
W = -1.5 msa @ 55°/0.5 msa/oz-in @ 45°
W = -3 oz-in @ 10°
W = 3 oz-in @ 190°

Therefore a balance weight of 3 oz-in should be placed at 190° on the fan.

In practice, the balance coefficients vary with engine speed, so vibration measurements due to unbalance need to be taken at various speeds. During the solution process all these measurements and coefficients need combining to generate a single balance solution.

8. RESPONSIBILITIES:

Like any other condition monitoring system design, development and certification of 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.