



AEROSPACE RECOMMENDED PRACTICE

ARP1839™

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A Guide to Aircraft Turbine Engine Vibration Monitoring Systems

RATIONALE

This edition updates content, includes appropriate content from AS8054 and raises AIR1839 to an ARP in accordance with E-32 committee decision.

ARP1839 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This Aerospace Recommended Practice (ARP) is a general overview of typical airborne engine vibration monitoring (EVM) systems applicable to fixed or rotary wing aircraft applications, with an emphasis on system design considerations. It describes EVM systems currently in use and future trends in EVM development. The broader scope of Health and Usage Monitoring Systems, (HUMS) is covered in SAE documents AS5391, AS5392, AS5393, AS5394, AS5395, AIR4174. This ARP also contains the essential elements of AS8054 which remain relevant and which have not been incorporated into Original Equipment Manufacturers (OEM) specifications.

1.1 Purpose

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

2. REFERENCES

2.1 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.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP1587	Aircraft Gas Turbine Engine Health Management System Guide
AIR1828	Guide to Engine Lubrication System Monitoring
AIR1871	Lessons Learned from Developing, Implementing, and Operating a Health Management System for Propulsion and Drive Train Systems
AIR4061	Guidelines for Integrating Typical Engine Health Management Functions within Aircraft Systems
AIR4174	A Guide to Aircraft Power Train Monitoring
AIR4175	A Guide to the Development of a Ground Station for Engine Condition Monitoring
ARP4176	Determination of Costs and Benefits from Implementing an Engine Health Management System
AS5391	Health and Usage Monitoring System Accelerometer Interface Specification
AS8054	Airborne Engine Vibration Monitoring (EVM) System, Guidelines for Performance Standard For (This document has been cancelled. Remaining valid content has been included in this ARP, OEM specifications and industry standards)

2.1.2 FAR Publications

Available from www.acquisition.gov/far.

FAR 14 CFR 25.1305 (d) (3) Airworthiness Standards: Transport Category Airplanes - Powerplant Instruments

2.2 Other Documents

AISI321, Stainless Steel

ANSI S2.41-1985, Mechanical Vibration of Large Rotating Machines with Speed Range from 10 - 200 RPS

ASME PTC 19.1-2005, Test Uncertainty

AV-E-8593H, Engine Performance Specification

Hewlett Packard Application Note 243, The Fundamentals of Signal Analysis

ISO 7919: Evaluation of Machine Vibration on Rotating Parts

ISO 10816-1; Mechanical vibration - Evaluation of Machine Vibration by Measurements on non-rotating Parts

RTCA DO-160 (latest revision), Environmental Conditions and Test Procedures for Airborne Equipment

RTCA DO-178 (latest revision), Software Consideration in Airborne Systems and Equipment Certification

RTCA DO-254 (latest revision), Design Assurance Guidance for Airborne Electronic Hardware

2.3 Terminology and Abbreviations

ACARS: Aircraft Communications Addressing and Reporting Systems

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 and the second integral yields displacement. 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.

DAL: Design Assurance Level

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. If the EVM is engine mounted then many other bus standards may be used both for transfer of data to the EEC and to the airframe system. AFDX, and CAN are two examples.

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

EEC: Electronic Engine Control: An avionics unit used to control the engine (see also FADEC)

EHM: Engine Health Monitoring (Management)

EMI: Electro-Magnetic Interference

EVM: Engine Vibration Monitoring

EVMS: Engine Vibration Monitoring System

FADEC: Full Authority Digital Engine Control: An avionics unit used to control the engine (see also EEC).

FAR: Federal Aviation Requirement

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

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 a single degree of freedom system.

OCM: On-Condition Maintenance: Maintenance only carried out when the condition of the engine (equipment) requires it as opposed to hard-time where maintenance is carried out at predetermined intervals. The intervals are typically in terms of time (e.g., flight hours, elapsed calendar time) or flight cycles.

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.

PHASE REFERENCE SIGNAL: A signal, usually electrical, provided on some engines, which indicates when a particular point on the 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.

RCC: Remote Charge Converter

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

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.

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

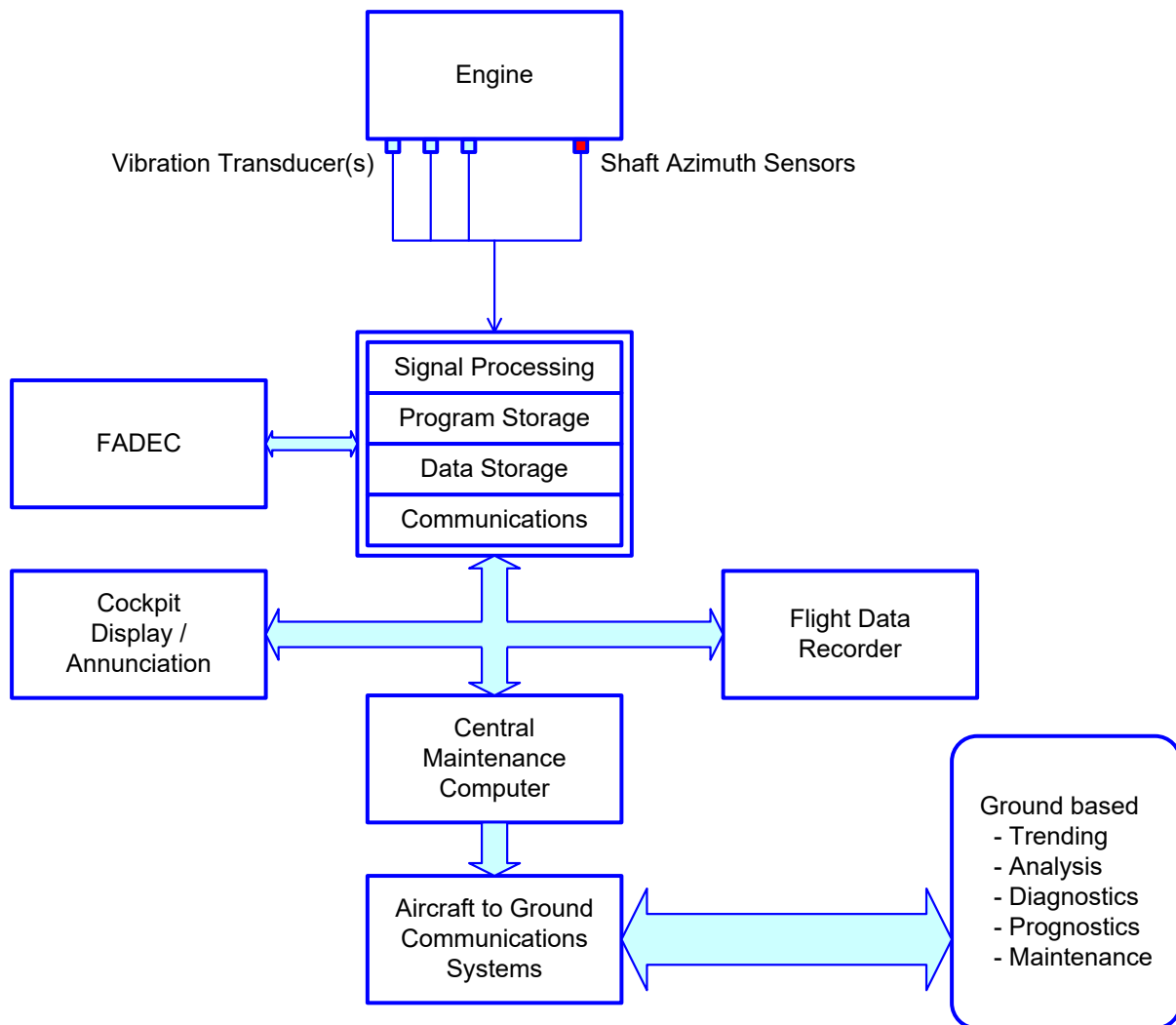
VELOCITY, VIBRATION: Vibration amplitude may be expressed in units of velocity; inches per second or millimeters per second. Velocity is the first integral of acceleration with respect to time.

ZERO-TO-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.

3. INTRODUCTION

A complete Engine Vibration Monitoring (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 its component parts in Figure 2. EVM may be one part of an engine condition monitoring system that monitors a number of engine parameters, or it may be a stand-alone system. A distinction is usually made between that part of the system dedicated to monitoring engine functions on board an aircraft and that part used for ground based analysis and monitoring. The on-board portion is commonly called an airborne engine vibration monitoring (EVM) system, and it is this part of the complete system that is described in this Aerospace Recommended Practice (ARP). The ground based portion is described in SAE document AIR4175.

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



NOTE: A complete system includes human interaction in the loop and therefore human factors must be considered in system design.

Figure 1 - A typical schematic of an engine vibration monitoring system (EVM)

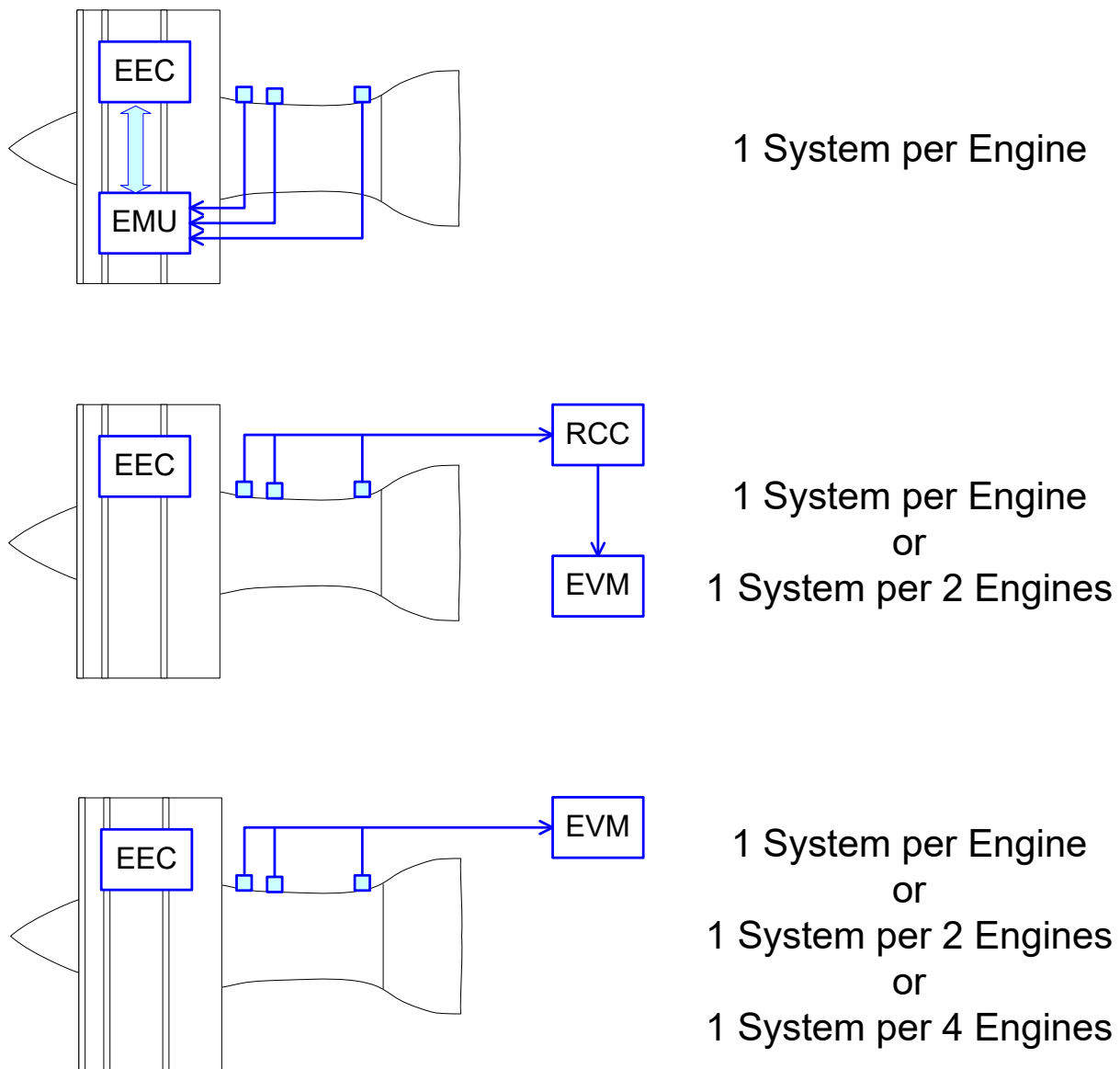


Figure 2 - Typical EVM system components

Most of the EVM systems now in use were developed to comply with Federal Aviation Requirements (FAR) Part 25.1305(d) Turbojet Engine Powered Airplanes (3) an indicator to indicate rotor system unbalance.

These systems were intended to provide the flight crew with a relative indication of engine unbalance. In most applications, specific operating instructions were not tied to specific display levels, but rather the display was provided to give the crew some relative indication of unbalance related vibration. With improvements in EVM system reliability and accuracy, increased understanding of diagnostic capability, and the potential for prognostic use, the industry has recognized the potential for reducing operating costs, and potential enhancement to safety margin, from vibration signal analysis as part of engine health monitoring. This benefit is not limited to Part 25 certified transport aircraft as evidenced by the growth in availability of systems for turbine powered rotorcraft and other classes of turbine powered fixed wing aircraft. Engine Health Monitoring (EHM) is a fundamental element of Integrated Vehicle Health Monitoring (IVHM) which is being covered by publications from the SAE HM-1 Committee and numerous other sources.

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

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

Advanced analysis, diagnostic and prognostic techniques are capable of isolating damage/degradation to specific parts of the propulsion system.

An EVM system, to comply with the FAR, will acquire a vibration signal from engine mounted transducers. This signal is processed electronically to give an indicator of rotor unbalance, for each rotor. The processing electronics is typically aircraft installed. The output signal is scaled to indicate in cockpit units, typically in green, amber, red; an indication to the pilot. In modern systems, the EVM will interface with other engine and aircraft systems as indicated in Figure 1.

Figure 2 shows that systems may range from stand-alone, to somewhat distributed, for example by separating the charge converter out of the EVM into a Remote Charge Converter (RCC). In most recent architectures the EVM is incorporated into an engine-mounted avionics unit that interfaces either with the Electronic Engine Control (EEC) or Full Authority Digital Engine Control (FADEC) or directly to the aircraft systems.

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 will address these problems.

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

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

Integration of the EVM into the overall IVHM system often performs functions beyond the FAR prescriptive unbalance display. These include both on-board signal processing and analysis as well as capture, storage, and transmission of vibration data files for ground-based data analysis. These capabilities enable functions such as rotor trim balance (see section 8) and trending of rotating component wear.

5. EVM SYSTEM FUNCTIONALITY

Currently, all 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 or made available for transfer to ground based systems by various means.

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

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

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

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

6. SYSTEM DESIGN

The first task of an EVM system design team is to clearly define the purpose, function and constraints of the system and its integration to the aircraft. This definition should include considerations depicted in Figure 3.

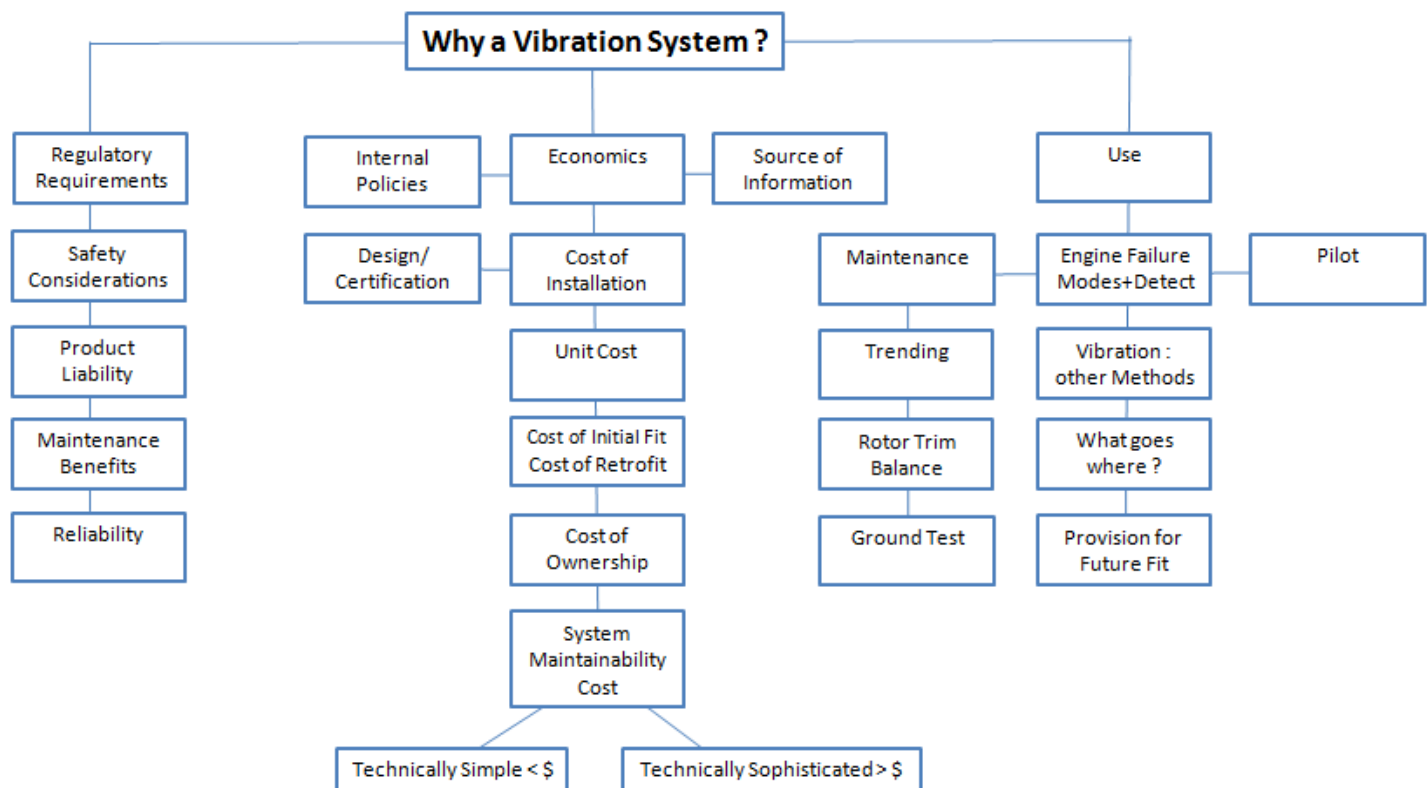


Figure 3 - Considerations for EVM

Consideration should be given to defining a system that is no more complex than can be justified by its expected benefits, reference ARP4176, 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 by evaluation of the potential issues that are desired to be monitored and determination of the most effective method(s) of so doing. These methods should be used to determine the most effective signal source(s). 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 and its location. Questions of measurement uncertainty (see 9.1.5.1) should be addressed at this time.

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 Locations

The transducer mounting locations on the engine or accessory must be ones that are 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 loading of the structure represented by the transducer mass may affect the signal, particularly the frequency response.

For the initial selection of the transducer locations, analytical dynamic simulations and sensitivity analysis using whole engine models are useful. Ultimately transducer location will be affected by environmental, installation and maintenance considerations.

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

Due to inevitable time and people limitations during the system design phase and the inherent nature of a monitoring system which is by definition, looking for relatively rare and/or long term degradation or damage, it is inevitable that there is a high probability for system changes and improvement following entry into service and the rapid accumulation of flight hours that ensues. As far as possible, the system design must accommodate this without need for extensive re-certification and testing.

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. Wherever practical, such provisions should always be included in the original engine design and verified during engine development.

6.1.2.1 Interfaces

Mounting surface/bracket/transducer interfaces should all be flat, clean, metal-to-metal surfaces. Stainless steel such as AISI321 is usually the preferred bracket material. Flatness should be within 0.0005 inch and roughness should be better than $R_a = 0.032$ mils. For higher frequencies in excess of 5 KHz the roughness of the surface is very important, this should be as good as $R_a = 0.008$ to 0.004 mils. Attachment screw torque should be specified with 80% of yield strength being a recommended norm.

6.1.2.2 Electrical Bonding

Because of the inherent nature and sensitivity of piezo-electric signals, correct electrical grounding is essential and the bonding resistance from the transducer mounting surface to the engine should not exceed 2.5 milliohms. The bonding resistance shall be measured just across individual interfaces.

For transducers with an integrally attached cable this requirement does not apply for the resistance between the connector and the transducer mounting flange because it would include the line resistance of the cable shield. However the bonding resistance from the connector mount (connector flange) to the engine shall not exceed 2.5 milliohms

6.1.2.3 Mounting Point

The best mounting surface is usually one that is integrated on a part of the engine itself. If this is not possible or practical, a very rigid but at the same time low mass 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.

The frequency response of the transducer/bracket/engine assembly should be tested on a shaker table or when this is not feasible it should be calculated. Axial resonances of the assembly shall be well above the highest frequency of interest and there should be no transverse resonances within the frequency band. Due attention must be given to the fact that the sensor and mounting resonances in the measurement axis and the cross axis will not be the same and both can adversely affect performance.

6.1.3 Transducer Characteristics

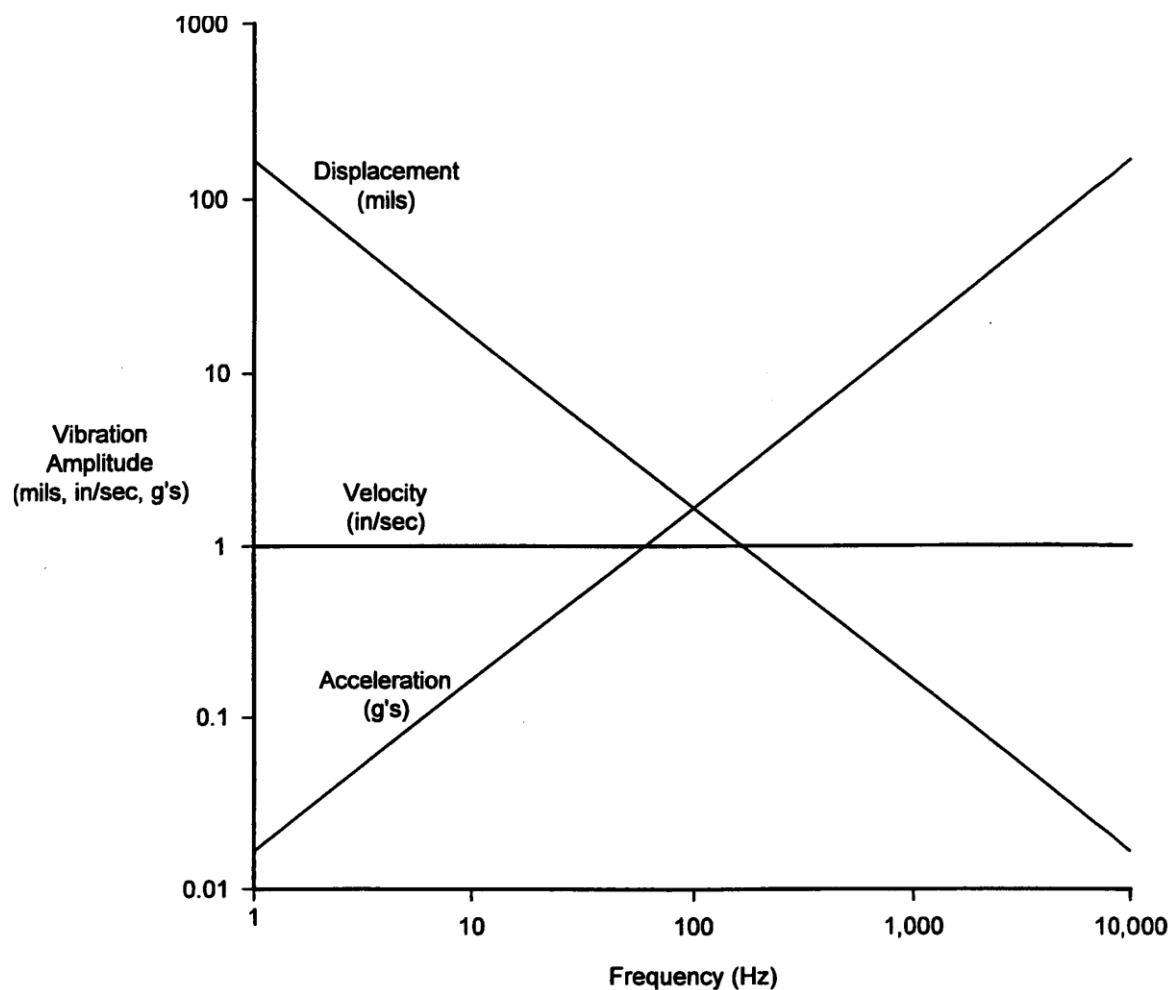
Mechanical vibration magnitude is commonly expressed in units of displacement, velocity, or acceleration, (the relationship is shown in Figure 4), and transducers are available that will sense any of these parameters directly.

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 typically 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 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. However the velocity transducer is rarely used in modern EVM systems because wear resulting from friction of the moving parts severely limits its operational life. Recent technological advances have increased the reliability of such devices but the overall frequency response remains greatly affected by cross axis excitation and mounting orientation.

**Notes:**

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

Figure 4 - Relationship between displacement, velocity and acceleration at constant velocity of 1 inch/second

6.1.3.3 Accelerometers

Accelerometers are the most widely used type of vibration transducer in EVM systems today. They are usually of the piezoelectric type that produces an electrical charge proportional to the acceleration parallel to the sensitive axis of the transducer. The signal from this type of accelerometer is generated by piezoelectric material, either a polarized ceramic such as lead zirconate titanate or a naturally occurring crystal such as quartz or tourmaline. This material is tightly compressed between a mounting surface (or surfaces) and a seismic mass (or masses). Acceleration of the element causes the mass to apply compression or shear forces on the material in accordance with the familiar relationship of force equals mass times acceleration ($F = Ma$). The force causes electrical charges to appear on the piezoelectric material surfaces that are then conducted outside the accelerometer (see Figure 5). It is a common 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 5. 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, pC/g being picocoulombs/g of acceleration.

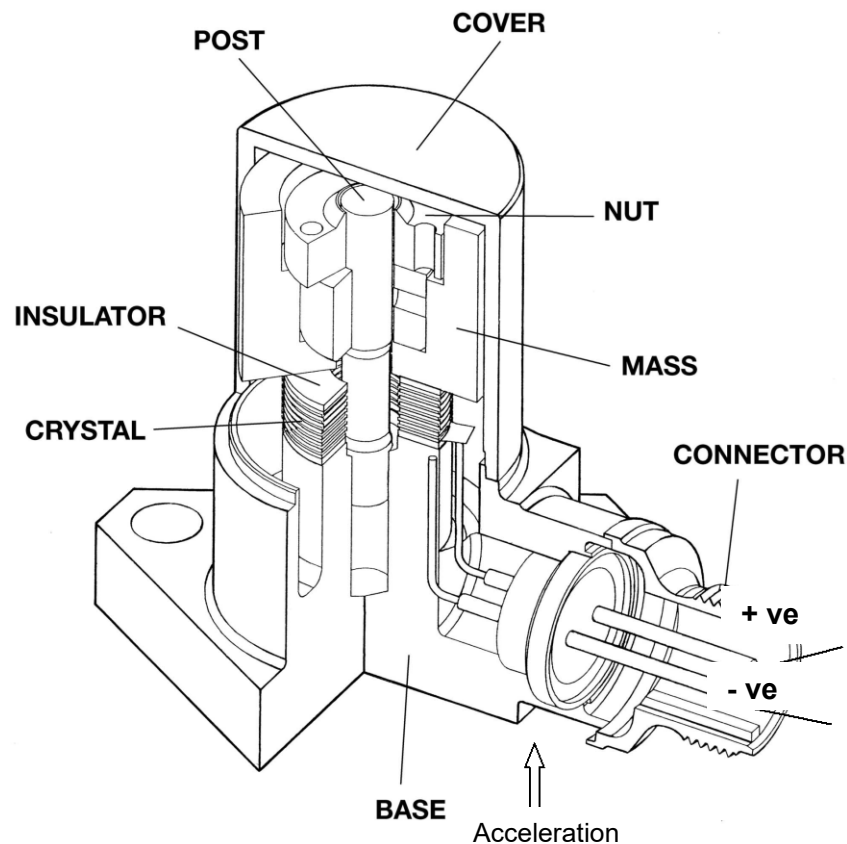


Figure 5 - Cross section of a typical EVM compression type piezoelectric accelerometer