

## CHAPTER 4

# ENGINE VIBRATION

### Introduction

1. All engines experience vibration to some degree. The inherent vibrations may be caused by the dynamic effects of manufacturing tolerances, the rolling and rubbing contact between mating surfaces, or minor out of balance forces of rotating assemblies. Within certain limits some vibration is acceptable. However, when the limits are exceeded, it is usually an indication that a fault is developing within the engine and, depending upon the severity of the vibration, that remedial action may be necessary immediately, or in the near future. Without appropriate instrumentation mild forms of vibration on gas turbine engines are hardly discernible. However, as vibration increases, it rapidly becomes a destructive force that creates premature wear, stress and damage to the engine and its components. If severe vibration is allowed to continue, the engine may be damaged beyond recovery.

2. It could be assumed that because of its operating principles and continuous combustion cycle, to design gas turbine engines which will operate with only the minimum of vibration, would present very little difficulty to engine designers. In some respects however they have proved to be more complex than expected. It is not the engines rotating masses that creates the vibration problems, but matching the airflow characteristics throughout the engine, particularly through the compressors and turbines. Should the airflow over the blades or through the compressor break down at any point within the wide range of operating conditions that the engine encounters, then engine stall or surge will occur which can induce severe vibration. (These problems are fully discussed in Section 2 Chapter 2)

3. When compared to the gas turbine engine, the aircraft piston engine/propeller combination generate high levels of vibration. This can be attributed to the reciprocating motion of the engine, the intermittent nature of combustion and the vibration associated with aircraft propellers. Although recent developments in propeller technology and design have achieved significant reductions in their vibration, it will be some years before the improvements will be in general use.

### VIBRATION PRINCIPLES

#### General

4. Vibration can be described as the physical displacement and return of a body from its equilibrium position, resulting from an external force. The simplest form of a vibratory system is illustrated by fig 7.4.1. A spring that is attached at one end to a beam has a mass suspended from the other. Whilst it remains free from any external force the system is at rest and the mass is in equilibrium at the neutral position (NP).

5. If a force is applied to the mass, moving it upwards until the spring is fully compressed, it will be at the upper limit of its travel (UL). When the force is removed (and ignoring the force of gravity) the energy stored in the spring will cause the mass to travel downwards through the point

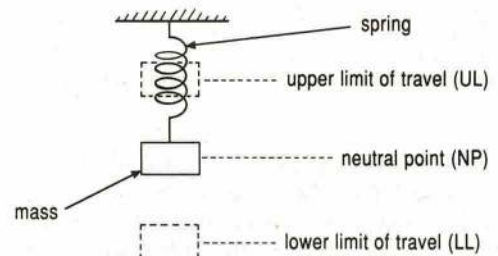


Fig 7.4.1. Basic Vibratory System

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NP to the lower limit of travel (LL), further travel being prevented by the stiffness of the spring. The restorative force in the spring will cause the mass to travel upwards again passing through point NP to an upper limit. This oscillating motion will continue at the systems' natural frequency until the energy in the spring is dissipated by frictional forces acting on the mass and within the spring itself. This is vibration in its simplest form.

6. **The sine wave.** An oscillation of the mass from point NP to the upper limit, back through point NP to the lower limit, and finally back to point NP is classed as one cycle of motion. When this cycle of vibration is plotted against time, it will produce a single sinusoidal wave form, (Fig 7.4.2).

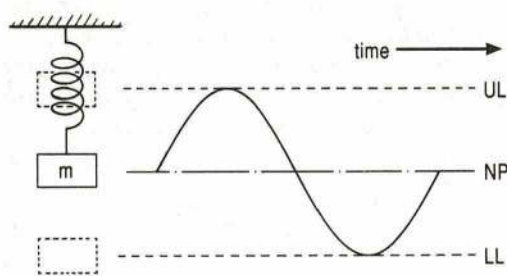


Fig 7.4.2 A Vibration Cycle

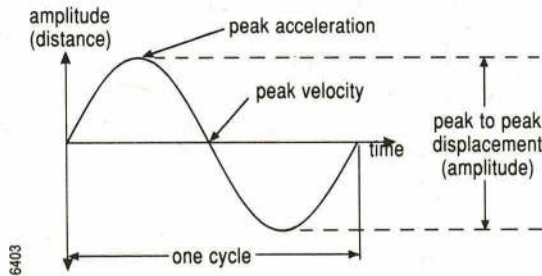


Fig 7.4.3 Vibration Characteristics

7. **Vibration characteristics.** The sine wave form or characteristics reflect all of the parameters that are needed to identify vibration and assess its magnitude (Fig 7.4.3).

8. **Displacement.** The total distance travelled by the mass when vibrating from the upper limit of travel to the lower limit of travel is known as the peak to peak (PP) displacement. It may be expressed in micrometres (mm) where one mm equals one millionth of a metre (0.000 001 m), it may also be expressed in thousandths of an inch (0.001 in).

9. **Velocity.** The speed of vibration of the mass as it travels between the upper limit and the lower limit is constantly changing. At both the upper limit and the lower limit the speed is zero, since the mass must come to a stop before it can travel in the opposite direction. The point at which the speed or velocity is greatest is at the neutral position and it is at this point that the velocity is measured. Vibration velocity is normally expressed in millimetres per second peak (mm/s peak) or inches per second peak (in/s peak).

10. **Acceleration.** Acceleration is the rate of change of velocity. As explained in para 9, the velocity of the mass reduces to zero at each limit of travel. When the mass comes to a stop at a limit of travel, it accelerates rapidly as it starts towards the other limit of travel. As the mass passes through the neutral position, the velocity is constant, and there is no acceleration.

11. **Frequency.** The parameters at para 10 relate to one cycle. The number of complete cycles (c) in one second (s) is the frequency (f) and is measured in Hertz (Hz) where:

$$1 \text{ Hz} = 1 \text{ c/s}$$

12. **Resonant frequency.** Most bodies have their own natural frequency at which they will vibrate when struck by an external force. This is termed the resonant frequency and is determined by the design, material and shape of the body. Not all bodies vibrate at a single frequency. There are those that have a number of resonant frequencies, and are known as complex vibrations, with each resonant frequency producing its own displacement and amplitude signal.

13. **Transient vibrations.** When a body is briefly struck by a disturbing force it vibrates at its resonant frequency. The vibrations are not sustained but will decrease in amplitude, at the same frequency, to zero, when once again the body will be at rest. These are known as transient vibrations (fig 7.4.4). The time taken for the vibration to subside to zero depends upon the material of the body and the frictional forces.

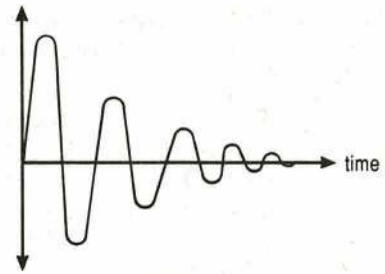
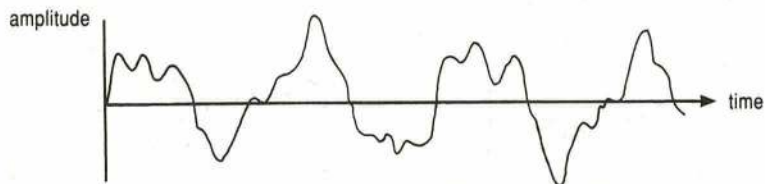


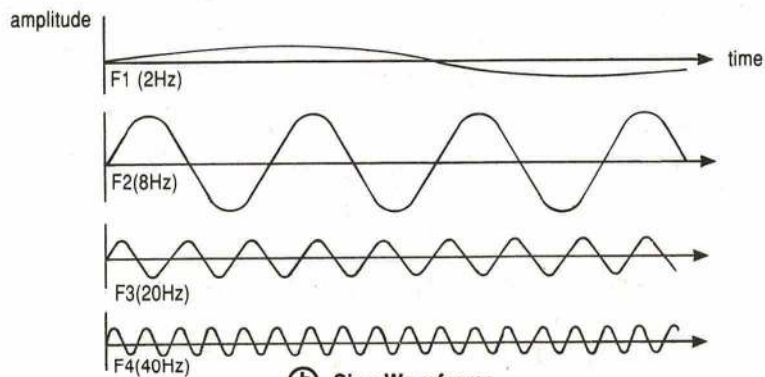
Fig 7.4.4 Transient Vibration

14. **Forced vibration.** If the disturbing force is continuously applied to a body, then the body will continue to vibrate until the force is removed. Such vibrations are known as forced or driven vibrations.

15. **Resonance.** A body subject to a forced vibration will vibrate continuously at the frequency of the driving force, and as long as the forcing frequency differs considerably from the resonant frequency of the system, the amplitudes of the forcing frequency and the resultant vibration remain at their respective levels. As the forced vibration frequency approaches the resonant frequency of the system, the vibration parameters combine to overcome the inherent damping of the system and the amplitude of vibration increases sharply. When the forcing and the resonant frequencies coincide, then a state of resonance exists and the amplitude of vibration suddenly becomes many times that of the forcing vibration, often with destructive results.



(a) Complex Waveform ( $F_1 + F_2 + F_3 + F_4$ )



(b) Sine Waveforms

Fig 7.4.5 Time Domain Waveforms

16. **Time domain.** Up to this point of the chapter, vibration has been considered in terms of amplitude and time, where the vertical axis represents amplitude and the horizontal axis represents time. This form of presentation is known as the Time Domain and is convenient to use where single frequencies are concerned. Where the wave form is more complex it becomes difficult to analyse in the time domain. A fairly simple time domain presentation is shown by Fig 7.4.5a which is the result of four

wave forms of differing frequencies and amplitudes, (Fig 7.4.5b). Some indication of the 8Hz frequency is evident, and the ripple indicates the presence of a high frequency. However the low frequency cannot be detected at all.

17. Machinery vibrations will always be more complex than that shown by a simple sine wave. In a mechanical power transmission system each gear tooth generates a burst of frequencies during its meshing cycle, and each rotating shaft produces its own particular vibration signature. When considered in the time domain, all of the frequencies combine to produce a complex changing wave form from which it is almost impossible to extract useful information.

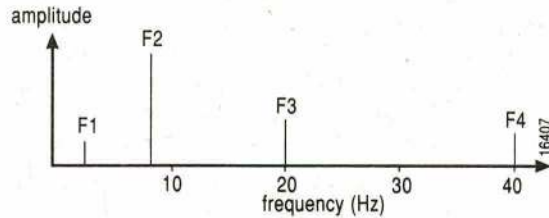


Fig 7.4.6 Frequency Domain Waveform

18. **Frequency domain.** An alternative method of displaying vibration characteristics is to consider amplitude with respect to frequency. This is known as the Frequency Domain (Fig 7.4.6). The vertical axis again indicates amplitude, but the horizontal axis is graduated in frequency. The frequency domain displays the amplitude of each frequency at an instant in time.

19. The relationship between amplitude, time, and frequency, is illustrated by Fig 7.4.7 which shows the view of both Time and Frequency domains.

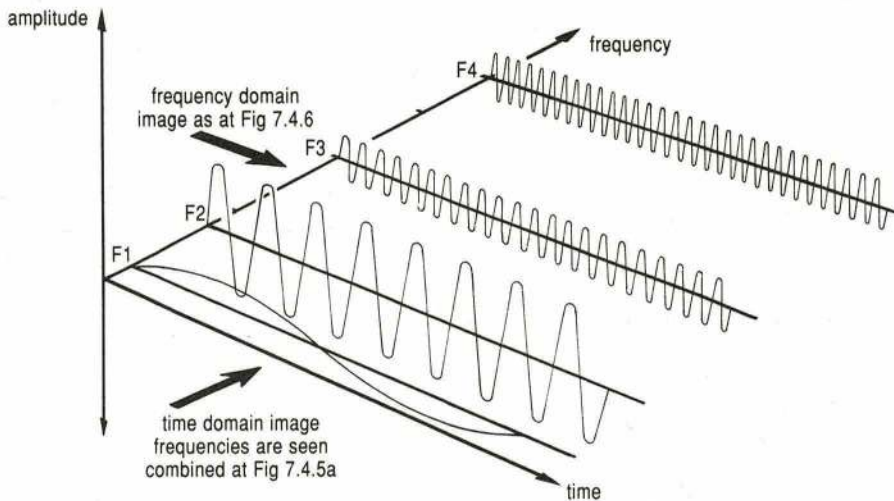


Fig 7.4.7 Time and Frequency Domain Image

20. Measurement of parameters (Fig 7.4.8). When the frequency domain display is plotted with respect to displacement, velocity and acceleration, the following features become apparent.

- Displacement measurement is most sensitive at low frequencies, up to approximately 50Hz.
- Velocity measurement gives measurable values over all of the frequency range, although it is most sensitive between 50Hz and 1kHz.
- Acceleration measurement gives the best indications of vibration levels at higher frequencies above 1kHz.

21. **Harmonics.** Harmonics are sine waves that are the multiples of a basic frequency. They are usually inherent in a machine by virtue of its design. If they reach significant proportions, it may require design changes to eliminate them.

## SIGNAL FILTERING

22. When using test equipment (such as a vibration analyser) to examine a vibration wave form (in the frequency domain) it may be necessary to isolate the wave form by blocking out undesirable frequencies. For example, there may be low frequency resonances in the engine test facility structure, or very high frequencies generated by the engine compressor or turbine blades, which if strong enough may overload the input circuits of the analyser. Manufacturers of vibration analyser equipment, often state the low and high limits within which the equipment must be operated.

23. To remove unwanted effects a filter may be introduced which allows only those frequencies in a specified band to pass through. The following are the types that are used:

- Low pass frequency filter.
- High pass frequency filter.
- Band pass frequency filter.

**Low pass filter.** These filters pass all frequencies below 320Hz and block all frequencies above (Fig 7.4.9a).

**High pass filter.** High pass filters pass all frequencies above a specified value, (approximately 45Hz) and block lower frequencies (Fig 7.4.9b).

**Band pass filters.** This type of filter passes a band of frequencies between certain specified values, blocking all frequencies above and below these values (Fig 7.4.9c).

24. Filters for particular applications may be specified and must be used as directed, otherwise the results of the analysis will be incorrect.

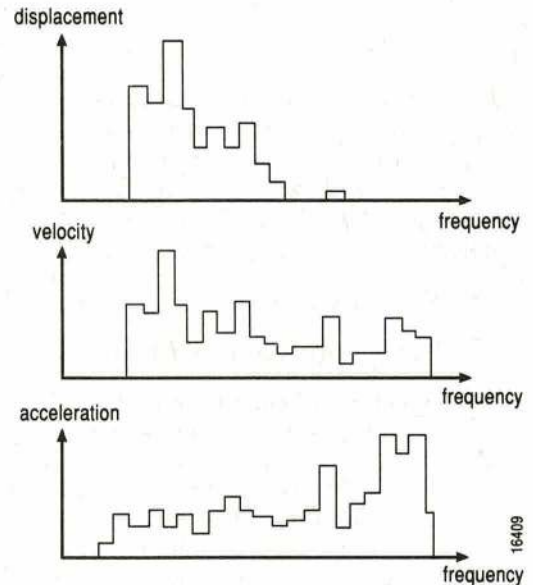


Fig 7.4.8 Features of Displacement, Velocity and Amplitude

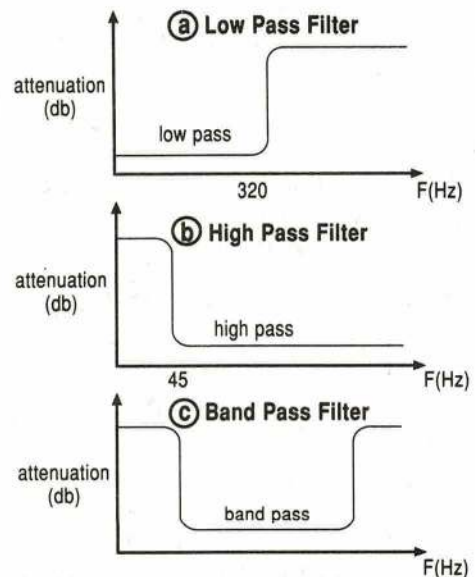


Fig 7.4.9 Filter Frequency Bands

## TRANSDUCERS AND ACCELEROMETERS

### General

25. A transducer is an electrical device that is used to convert an input signal of one form into an output signal of a different form. When used to monitor engine vibration, a transducer converts the mechanical movement of vibration into an electrical signal. The vibratory movement of the engine is so small that the resulting electrical signal has to be amplified in order that it may be analysed, measured and displayed. There are several types of transducer, that are used for a wide variety of applications. Two types of transducer are used to measure engine vibration, these are as follows:

- Velocity transducer.
- Piezoelectric accelerometer transducer.

26. **The velocity transducer.** The velocity transducer (Fig.7.4.10) operates on the principle that when a magnet is moved inside a stationary coil, (or the coil is moved in relation to a stationary magnet), the magnetic field that emanates from the magnet induces a voltage in the coil. The value of the voltage is dependant upon the speed of the vibratory movement between the magnet and the coil and the number of turns in the coil.

27. **Construction.** A bar magnet, which is supported at both ends by springs is surrounded by a wire coil and stands mounted on the transducer base. The whole assembly is housed in a case which is bolted to the engine casing, when the engine is run the vibrations cause the coil to move, with the transducer base. (The magnets springs absorb the vibration therefore the magnet remains stationary). The movement induces an oscillatory voltage in the coil, which is proportional to the vibration velocity. The transducers' output is measured in millivolts per millimetre per second (mV/mm/sec). The ratio of electrical output to mechanical input is a measure of the vibration of the engine.

28. Velocity transducer disadvantages. The velocity transducer has a number of disadvantages, some of which are as follows:

- Moving internal parts are susceptible to wear and damage.
- Frequent recalibration is required.
- It is a relatively large transducer.

Velocity transducers are being superseded by piezoelectric accelerometers to a large extent on aircraft engines.

29. **Piezoelectric accelerometers (transducers).** The Greek word 'piezein' means to squeeze. Piezoelectric accelerometers utilize the characteristics of certain crystalline materials that generate an electric charge when pressure is applied to them (Fig 7.4.11a). This is known as the piezoelectric effect, whereby mechanical energy is converted into electrical energy, when a force is applied to the

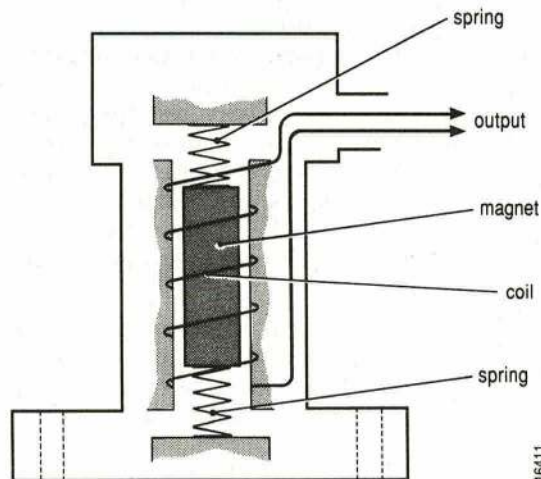


Fig 7.4.10 Velocity Transducer

crystal. The nature of the force may be shear, compression or bending, depending upon the particular application for which the transducer has been designed (Fig 7.4.11b). The resulting electrical charge is proportional to the force acting on the crystal. The crystals are of two basic types, natural crystals and synthetic crystals, the latter being mainly manufactured from ceramic materials. These can be manufactured with a high piezoelectric 'response' and can be made in convenient shapes and sizes for different transducer applications.

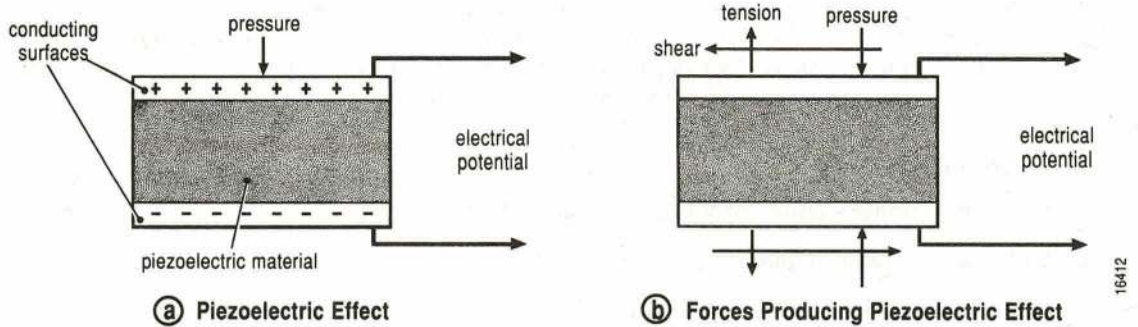


Fig 7.4.11 Piezoelectric Accelerometers

30. Accelerometer transducer construction. The following is a brief description of two types of piezoelectric accelerometers these are:

- Compression type.
- Shear type.

31. **Compression type.** The piezoelectric crystal element of the compression type accelerometer (Fig 7.4.12), consists of a number of discs that are permanently deformed. The discs are subjected to pressure exerted upon them by a pre-loading block, which is under spring pressure. The crystal discs suffer further deformation from the effects of vibrational forces that are transmitted to them by the pre-load block. The electric charge that is generated by the combined pressures is passed to the outlet connector by conducting elements that are situated between the crystal discs. The working parts of the accelerometer are contained in a hermetically sealed case which is mounted on a substantial base. The base may be threaded for a stud or mounting bolt.

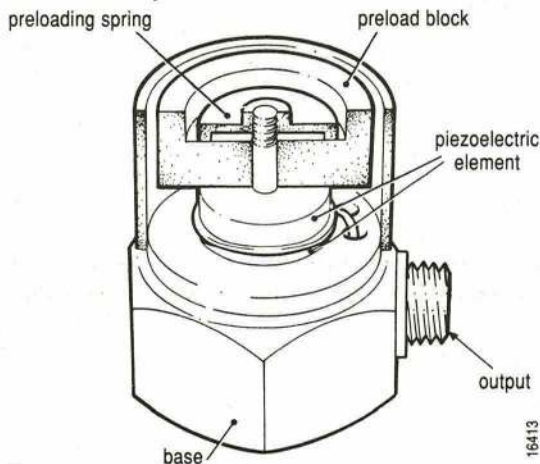


Fig 7.4.12 Compression Type Accelerometer

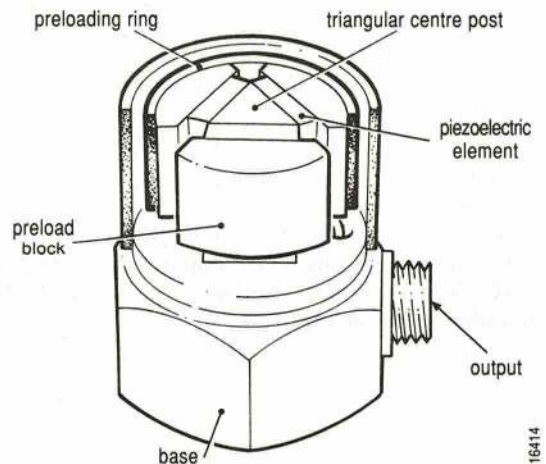


Fig 7.4.13 Shear Type Accelerometer

32. **Shear type accelerometer.** The Shear type accelerometer illustrated by Fig 7.4.13 consists of a triangular centre post which is mounted on a base. Three rectangular piezoelectric crystal elements are clamped to the triangular faces of the centre post by three pre-loaded blocks, which are retained by an encircling pre-loading ring. Engine vibrations are felt in the base and centre post which produces shear forces in the crystal elements. The shearing action generates an electrical charge which is conveyed to the outlet connection by electrical conducting elements.

33. **Mounting.** The location and method of mounting the accelerometer onto the engine is extremely important to producing accurate results. It should be mounted to ensure that the measuring direction coincides with the accelerometers' sensitivity axis. The mating surface should be smooth and clean, and the accelerometer securely bolted or clamped to the engine casing.

### CAUSES OF VIBRATION

34. Some of the common causes of vibration in aircraft engines are;

- Unbalance in rotating parts.
- Damaged compressor and turbine rotor blades.
- Damaged rolling elements of bearings.
- Damaged gears.
- Components and attachments that have not been secured (*i.e.* torque tightened).
- Lack of lubrication.
- Component wear.

35. The monitoring and interpretation of engine vibration levels now play an important part in assessing the overall health and serviceability of an aircraft engine during its operational life. This is largely due to the advances that have been made in recent years in the field of electronics. The advances have led to improvements and new developments in engine vibration and diagnostic equipment, which have increased in both reliability and accuracy

### THE EFFECTS OF SQUEEZE FILM BEARINGS ON VIBRATION

36. If reference is made to Section 2 Chapter 5, it will be seen that many modern gas turbine engines are designed with squeeze film bearings. The film of oil between the bearing outer race and the bearing housing, acts as a damper, absorbing some of the engines inherent vibration, thereby reducing stress, and fatigue to components and parts throughout the engine.

37. The squeeze film principle is very efficient, however the oil film not only dampens much of the engines natural vibrations, but can also absorb and possibly mask the initial vibrations generated by an engine fault that is developing, which would otherwise become apparent on the vibration analysing equipment. The manufacturers compensate for this by reducing the permissible vibration levels allowed, which is a small price to pay for the advantages gained by having squeeze film bearings included in the design.

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