CATERPILLAR®

ENGINE DATA SHEET

EDS 73.1
Date 1-94

Linear Vibration

The purpose of this publication is to:

- Review the basic theory and nomenclature of vibration. A knowledge of the language of this discipline will encourage a fundamental understanding. Such terms as linear, period, displacement, velocity, and acceleration will be defined and compared.
- Identify causes of engine-related vibration. Major contributors to engine vibration are described, as well as procedures to isolate and measure vibrations.
- Provide possible corrective action. Excessive vibratory motion may be encountered in the engine, generator, related components, or any part of the mounting system. If left unresolved, this motion may cause personnel discomfort and/or equipment damage. Balance techniques are discussed, and limits of vibratory forces are defined.

Fundamentals

Any mechanical system which possesses mass and elasticity is capable of relative motion. If this motion repeats itself after a given time period, it is known as vibration. A simple illustration of vibration is to suspend a weight (mass) on the end of a spring (elasticity).

As long as no external force is imposed on the system, the weight remains at rest — there is no vibration. But when the weight is moved or displaced and then released, vibration occurs. The weight will continue to travel up and down through its original position until frictional forces again cause it to rest. This specific illustration is an example of free vibration. If an external force continues to affect the system while it is vibrating, it is termed *forced vibration.*

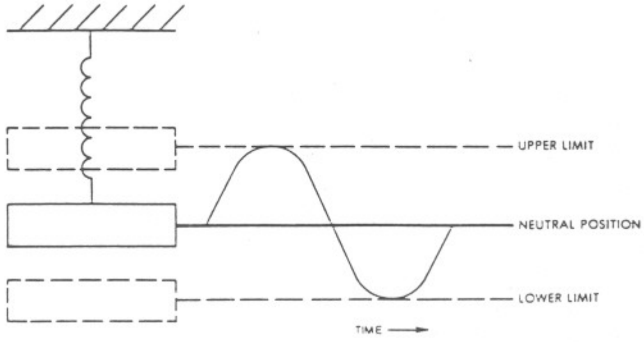

Figure 1

The illustration is also an example of linear vibration. Linear vibration is an *in-line* motion and occurs as an object moves and returns along a repeatable path. Linear vibration must not be confused with the torsional (twisting) vibration motion of the crankshaft and driven rotating shafts. Refer to EDS 202.1 for the subject of torsional vibration.

The time required for the weight to complete one complete cycle is called a period.

If the weight needed one second to complete a full cycle, the vibration frequency of this system would be one cycle per second. A system that completed its full motion 20 times in one minute would have a frequency of 20 cycles per minute, or 20 cpm.

(File in Cat Technical Manual)
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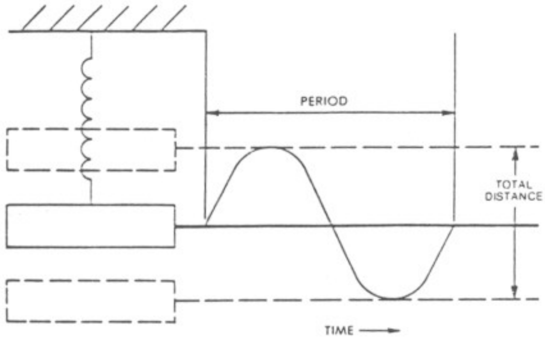


Figure 2

The total distance traveled by the weight, that is, from one peak to the opposite peak, is referred to as the peak-to-peak displacement.

This measurement is usually expressed in mils, where one mil equals one thousandth of an inch (0.001 in.). It can be used as a guide in judging vibration severity.

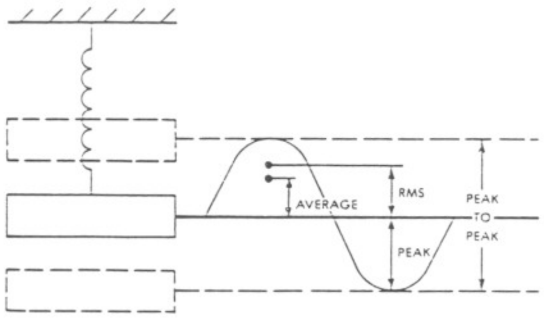


Figure 3

Both average or root-mean-square (rms) are sometimes used to measure vibration, rms = 0.707 times peak of vibration. These readings are meaningful in theoretical discussions but are of limited practical value.

Another popular method used to determine the magnitude of vibration is to measure the vibration velocity. Note that the example is not only moving, but also changing direction. This means that the speed of the weight is also constantly changing. At its limit of motion, the speed of the weight is "0". As it passes through the neutral position, its speed or velocity is greatest.

Velocity is an extremely important characteristic of vibration, but because of its changing nature, a single point has been chosen for measurement. This is the peak velocity and is normally expressed in inches-per-second peak.

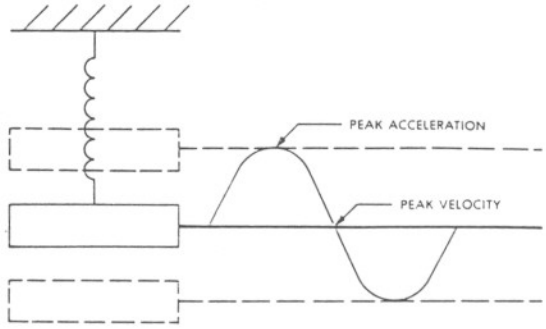


Figure 4

Vibration acceleration is another important characteristic of vibration. It is the rate of velocity change. In the example, note that peak acceleration is at the extreme limit of travel where velocity is "0". As velocity increases, the acceleration decreases until it reaches "0" at the neutral point.

Acceleration is normally referred to in units of "g" (peak) where one "g" equals the force of gravity at the earth's surface.

(980.665 cm/s^2, 386.09 in./s^2, 32.174 ft/s^2.)

Displacement, velocity, and acceleration are all used by vibration experts to diagnose particular problems. Displacement measurements tend to be a better indication of vibration under condition of dynamic stress and are, therefore, most commonly used. Caterpillar has standardized on displacement measurement.

Velocity is a direct measure of vibration and, as such, provides the best overall indicator of machinery condition. It does not, however, reflect the effect of vibration on brittle material.

The relationship between peak velocity and peak-to-peak displacement can be found by the following formula:

$$V_{Peak} = 52.36 \, D \times F \times 10^{-6}.$$

Where V_{Peak} = Vibration velocity in in./s-peak.

D = Peak-to-peak displacement in mils (1 mil = 0.001 in.).

F = Frequency in cycles per minute (cpm).

Acceleration measurements of "g" are commonly used where relatively large forces are applied. At very high frequencies (60,000 cpm) it's perhaps the best indicator of vibration.

The vibration acceleration can be calculated as:

$$g_{Peak} = 1.42\ D \times F^2 \times 10^{-8}.$$

Measurement

The exact nature of linear vibration is difficult to define without instrumentation. The human senses are not adequate to detect relationships between the magnitude of displacement of a vibration and its period of occurrence. For instance, a first order (1 x rpm) vibration of 0.010 in. (0.254 mm) displacement may feel about the same as a third order measurement of 0.001 in. (0.026 mm). However, the severity of vibration does correlate reasonably well with levels of perception and annoyance.

Establishing the vibration frequency is necessary when analyzing this type of problem. It allows identification of the engine component or mass system which is causing the vibration. In discussions of vibration, the frequency of the motion is commonly referred to in terms of *order* of vibration. In an engine, the order of vibration is the number of vibratory cycles exhibited by a component during one revolution of the crankshaft.

$$\text{Order} = \frac{\text{Vibration Frequency (cpm)}}{\text{Engine Speed (rpm)}}$$

Overall vibration motion is the vector sum of the motion of all the orders. In other words, individual order motions will add or subtract to produce the overall. This measurement is not used to identify problems or establish limits, but rather as an indication of the total linear vibration motion. A vibration analyzer is a prerequisite to troubleshooting a problem of this nature. A unit that measures frequencies and amplitude is suggested. Further, the analyzer should be rugged and easily understood. Good results have been obtained with Caterpillar's service tool 4C3030. The tool is offered through Caterpillar's Parts network or can be purchased directly from the manufacturer at:

Computational Systems Inc.
835 Innovation Drive
Knoxville TN 37932
(615) 675-2110

All measurements must be made on the *main rigid structural members of the engine and generator.* The instrument pickup must be *positioned on the crankshaft centerline* at the locations shown on the sample form. Measurements (except torque reaction and some misalignment) can be made at no-load operation. If measurements are taken while the generator is loaded, the magnetic field of the generator leads must be avoided.

If excessive linear vibration motion is present or suspected, an initial measurement should be made to identify the source prior to starting corrective action. A sample form is described in this data sheet for convenient recording of raw data at various engine speeds (generator frequencies). This form can be used for the basic engine, single-bearing generators, and two-bearing generators.

Identification

Experience has shown that in order of decreasing importance, the primary sources of linear vibration motion problems are:

- Misalignment of engine and driven equipment.
- Unbalance of rotating parts.
- Resonance from structural mass (weight) and stiffness (rigidity) combinations.
- Torque reaction.
- Cylinder misfiring.
- Combustion forces.
- Unbalance of reciprocating parts.

As test data is reviewed, if excessive vibration motion exists, it will be due to one of the following causes:

Misalignment or Unbalance

Most linear vibrations of generator sets are caused by misalignment or unbalance of the rotating members. This results in first order vibration which can be corrected in the field.

The vibration motion is relatively constant over the speed range but exceeds accepted limits. For generator set applications, this may be determined by operating between 45 Hz to 65 Hz. Load does not change vibration motion caused by unbalance.

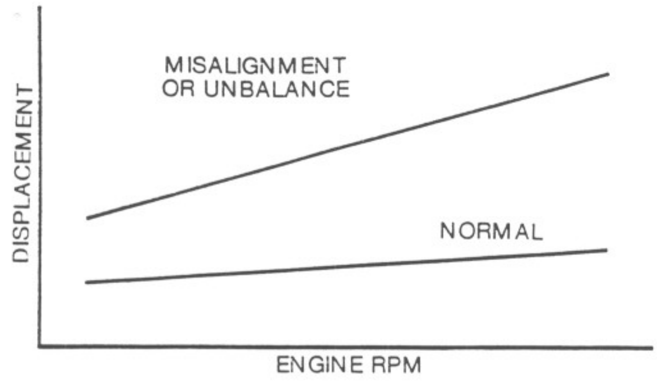


Figure 5

Resonance

Large vibration motion (amplitude) occurs within a narrow speed range. This can occur on the generator set and/or the attached equipment, such as piping, air cleaners, etc. When vibrations peak out in a narrow speed range, the vibrating component is in resonance. Resonance occurs when the disturbing force in the engine has the same frequency as the natural frequency of the part which is vibrating. The force of the vibration is, therefore, added to each cycle of the vibration part causing magnification of the original vibration.

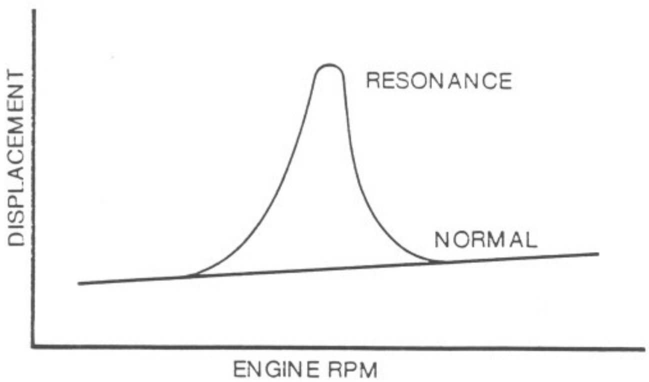


Figure 6

Torque Reaction

The vibration motion increases as load is applied. With a two-bearing generator, it can be caused by insecure mounting of the engine or generator to its base and/or by a base not sufficiently rigid to withstand the associated forces.

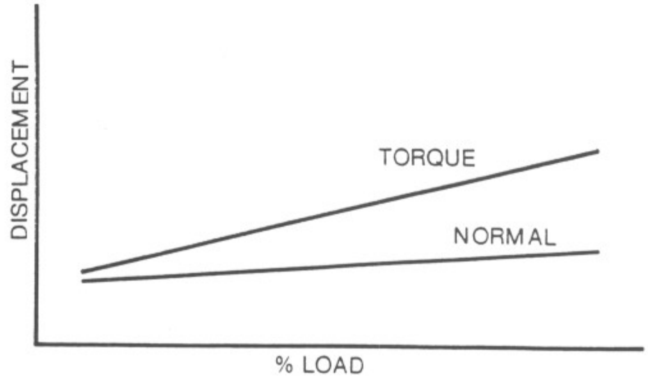


Figure 7

Torque reaction problems are not found with close-coupled two-bearing or single-bearing generators. The rigid joint between the flywheel housing and the generator body is generally adequate to withstand torque.

Assuming that a two-bearing generator is mounted on a weak base, first order motion and orders related to the number of cylinders firing with one crankshaft revolution are due to torque reaction which, in turn, causes misalignment. In this case, the first order motion would be most prevalent. A few engines do not follow the cylinder firing rule. These are the D346 and D379 with second order and D349 and D399 with fourth order, in addition to the first order motion.

Certain specific causes of linear vibration can be further identified:

Vibration Frequency	Correctable Causes
1/2 x engine rpm (one-half order)	Misfiring of one or more more cylinders
1 x engine rpm (first order)	Unbalance, misalignment, out-of-time balance weights (3408), crankcase overfill
2 x engine rpm (second order)	Unbalance, out-of-time balance weights, rotating twice engine speed (3304, D346, D379)
1 1/2, 2 1/2, third higher orders	Normal cylinder and combustion (not correctable)

Corrective Action

General

If a component is the only item with excessive motion, the component mounting will have to be altered until the motion is reduced to an acceptable level at operating rpm.

When the vibration motion measurements show that 1/2 order is causing the problem, the engine fuel and governing system must be serviced to eliminate engine misfiring. No other work should be attempted until engine misfiring is eliminated.

When excessive second order vibration occurs on 4-cylinder and vee 8 engines, the timing of the second order force balancers should be checked.

Other high order vibration levels cannot be corrected with flywheel balance weights or balancer timing. Usually these orders involve the structural characteristics of the generator and base which would have to be altered.

If the vibration motion involves non-engine-mounted structures and the engine vibration motion is acceptable, either the off-engine components must have their mounting altered or proper vibration isolators would have to be installed between the generator set and the structure.

If the engine unit has excessive motion, the following steps are required to remedy the various types of vibration. However, if the vibration motion for first and second orders only still remain excessive after these procedures, the engine should be removed from the set and placed on suitable isolators. If the engine is within limits, a vibration specialist should be consulted. If the bare engine exceeds the limits, engine components rotating at engine speed (first order) or twice engine speed (second order) should be inspected.

Misalignment and Unbalance

- Check alignment of the unit. Refer to Caterpillar Special Instruction for single and two bearing generator installations instructions. These are indexed under Section 4450 in the Caterpillar Service Department Master Index microfiche system. The Special Instructions are also in the microfiche system.
- If vibration is still excessive, refer to *Balance Procedure* on page 6.
- Should this procedure fail, mount the unit on isolators and the *balance procedure* repeated until a satisfactory level of vibration is obtained.

Resonance

With resonant conditions there are two ways of reducing the vibration level. These are:

- Reduction of the exciting force.
- Changing the natural frequency of the unit.

If the following checks show that the structure of the generator set is mounted on is the cause of the problem, a vibration specialist or mounting system specialist should be consulted.

- Check alignment of the unit.
- If vibration is still excessive, refer to Balance Procedure.
- Should this procedure fail, mount the unit on isolators and recheck. If the unit is satisfactory, the problem is an improper mounting system which requires changing. Consult the proper specialist.

  Should the balance procedure fail and the set has excessive linear vibration motion when installed on the proper isolators, repeat the balance procedure until the linear vibration motion level is satisfactory.

Torque Reaction

- This condition is generally encountered when the engine is driving a conventional two-bearing generator which is not close-coupled. Check alignment of the unit.
- If the two-bearing generator set utilizes a structural steel base which is point-mounted, i.e., pads, isolators, etc., torque reaction can deflect the weak base. This deflection can cause severe misalignment and resulting vibration. Assuming the unit continues to exhibit vibration after alignment, the base is not strong enough to hold the torque reaction and needs strengthening. One method of strengthening is to weld plates on top and bottom of the base across the width of the base from 6 in. forward of the rear engine supports to 6 in. behind the generator feet closest to the engine.

Balance Procedure

The following correction procedure applied to first order vibration motion.

- The crankshaft must assume the same position each time a balance adjustment is made. To assure this identical location is assumed, position flywheel to top dead center (TDC) of number 1 cylinder. A chalk mark or scribe across flywheel and coupling plates will provide an easy reference during the balancing operation.
- Remove bolts holding generator coupling plates to flywheel. Rotate generator rotor with plates attached 90° clockwise while flywheel remains at number 1 TDC. Replace coupling plate bolts and retest for vibration.
- If vibration remains, again position flywheel at TDC number 1 cylinder, index generator rotor another 90° clockwise (total 180°), and retest.
- If necessary, repeat the previous step by rotating another 90° clockwise.
- Position coupling assembly relative to flywheel where least amount of vibration occurred. If magnitude of vibration remains unacceptable, add weight of 2 oz (56.70 g) under any single coupling plate to flywheel bolt. Flat washers can be used for this purpose. Bolt must be sufficiently long to maintain at least 1 1/4 times the bolt diameter of thread engagement.
- Observe vibration level and relocate weight 90° quadrant to identify where minimum vibration occurs.
- Add additional weight at point of minimum vibration identified in the previous step until vibration level is no longer diminished. In no case should more than 5 oz (141.75 g) be added under any one bolt.
- If vibration levels are still unacceptable, a local vibration control specialist should be consulted.

Linear Vibration Guidelines

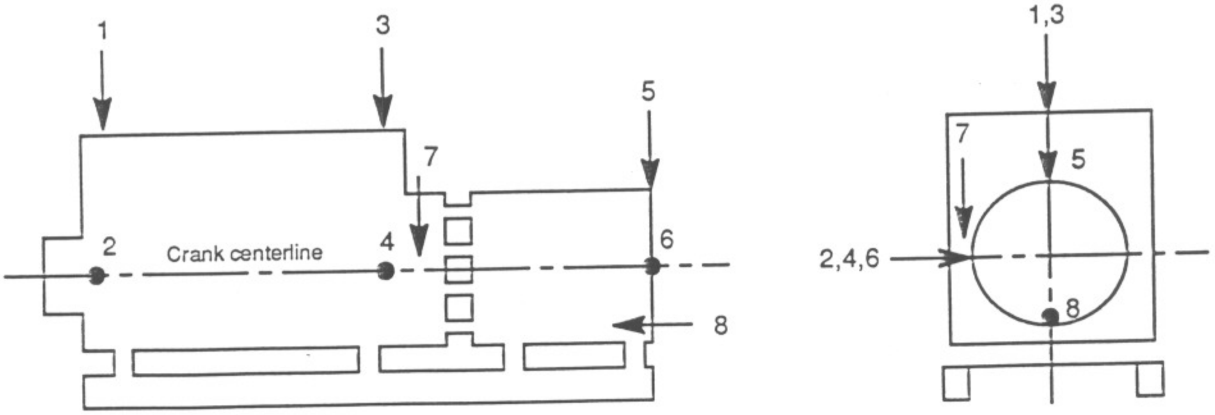
The following table of vibration limits is required for assessing the vibration severity of a generator set. The maximum allowable limits below apply only to measurements made on the basic engine/generator structure and *do not apply to component or attachment vibration.*

1. Peak-to-peak displacement limit at 1/2 order frequency = .13 mm (5.0 mils).
2. Peak-to-peak displacement limit at first order frequency = .13 mm (5.0 mils).
3. Overall displacement = .22 mm (8.5 mils).
4. Overall velocity = 34.3 mm/s (1.35 in./s).

These limits apply to packages installed with or without isolation mounts. If linear vibration is higher than the limits shown above, complaints due to personnel discomfort and premature part failure may arise.

Refer to the following for the vibration measurement locations and their descriptions.

Linear Vibration Measurement Locations



Conditions:

- Full Package Rating
- Rated Speed

Location Number	Location Description
1	EFV: Engine Front Vertical
2	EFH: Engine Front Horizontal
3	ERV: Engine Rear Vertical
4	ERH: Engine Rear Horizontal
5	GRV: Generator Rear Vertical
6	GRH: Generator Rear Horizontal
7*	ERR: Engine Rear Roll, vertical on rear flywheel housing
8	GRA: Generator Rear Axial, on the bearing bracket

**For 3600 Engines, the measurement is made at the rear mounting foot.*

Linear Vibration Test

Date: ____________________

Tested by: ____________________

Engine: rpm ____________________

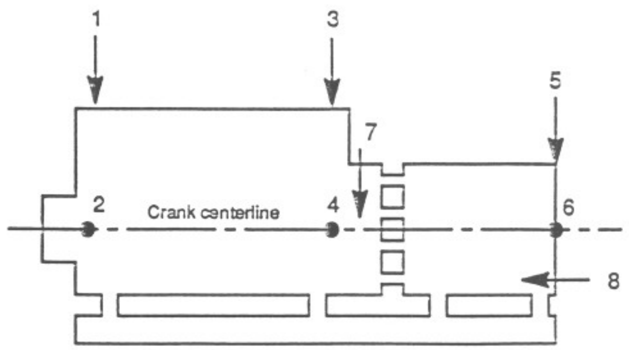
S/N ____________________

Generator:

Manufacturer ____________________

Model ____________________

S/N ____________________



Run No.: ____________________

Description of Correction:

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Test Location	Over All	Order (Vibration Frequency / Engine rpm) 1/2	1	1 1/2	2	2 1/2	3
1							
2							
3							
4							
5							
6							
7							
8							

Run No.: ____________________

Description of Correction:

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Test Location	Over All	Order (Vibration Frequency / Engine rpm) 1/2	1	1 1/2	2	2 1/2	3
1							
2							
3							
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