CLARKE®

Date: September 28, 2018

Notice: Engineering Technical Bulletin – ETB 013

Vibration Characteristics of Diesel Engine Driven Emergency Fire Pump Systems

Introduction

It has become commonplace to use internal combustion engines to drive emergency fire pumps due to reliability and other concerns. Diesel engines have become a popular choice.

An engine drive is significantly different than the typical electric motor drive that many are accustomed to seeing in a water pump application. This paper will illustrate the differences between engines and motors; we will discuss how the engine produces power and outline some typical vibration signatures for various engine configurations. Tips on making vibration measurements will be discussed as well as interpreting the data and determination of severity based on existing standards.

Electric motor vs diesel engine drivers

Electric motors are commonplace in industrial and plant settings driving pumps, compressors, and a whole host of various process machinery. People familiar with motors are comfortable with their operation and maintenance. For motors, vibration is often used as an indicator of machinery health. Many in plant maintenance who are in charge of machine reliability are familiar with the vibration severity chart as shown in Figure 1. Historically, this has been a useful guide to determine acceptability of a new installation or long term health of a machine.

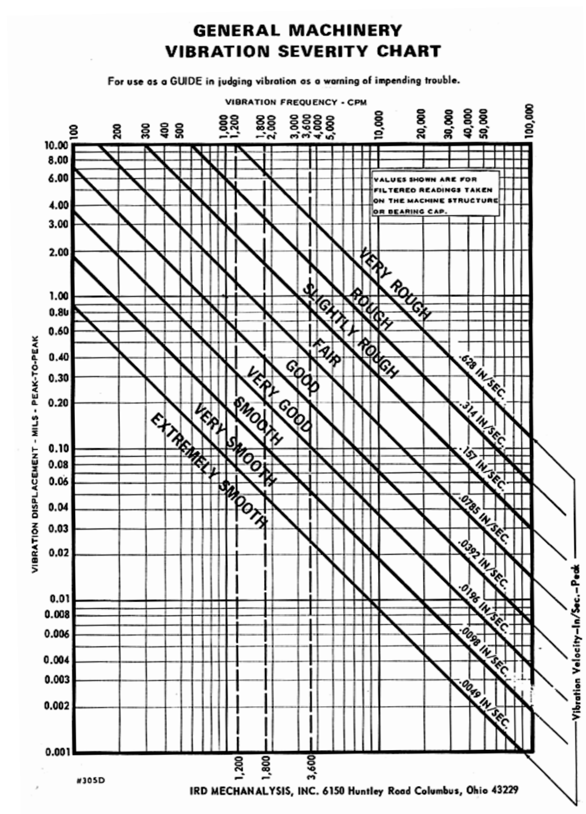

Figure 1. Vibration Severity Chart [1]

Unfortunately, what has been used successfully in the past for a wide variety of motor driven machines is not applicable to a diesel engine drive. An electric motor produces a very smooth torque to the load, and does so without

[1] courtesy of IRD Mechanalysis, inc.

any reciprocating parts or unbalanced rotating components. Typically, the rotor is balanced to a tight tolerance to minimize vibration caused by 1x unbalance forces. There may be some slight torque ripple at harmonics of line frequency, but these are typically a few percent of mean torque or less. If the vibration of an electric motor driven pump shows rough running or worse according to the chart, likely something is wrong.

A diesel engine generates torque in a fundamentally different way than an electric motor. Fuel is burned in a cylinder; the expanding gas generates torque on a crankshaft through a slider crank mechanism containing a piston and connecting rod as seen in Figure 2. The torque is not smooth; a single cylinder four stroke cycle engine produces a torque pulse as seen in Figure 3 (Nestorides, 1958). This process inherently generates vibration in a number of ways:

1. The torque delivered to the load must be reacted against by the engine mounts. Because the torque is pulsating, there will be vibration forces generated at the mount locations.
2. The piston and connecting rod are a significant reciprocating mass which are accelerating and "decelerating", generating vibration forces and moment couples depending on cylinder layout.
3. The crankshaft is fitted with counterweights, not only to balance the offset crank pins and rotating connecting rods, but to also cancel out the shaking forces and moments generated by the reciprocating masses. However, complete cancellation is not always possible.

Examples:

- An inline 4-cylinder engine will naturally produce a secondary shaking force in the vertical direction (Taylor, 1985). This can be minimized through the use of counter rotating balance shafts rotating at twice crankshaft speed at the expense of cost and efficiency.
- An inline 6-cylinder engine is inherently balanced with no shaking forces in any direction generated by the reciprocating or rotating parts (Taylor, 1985). However, the pulsating torque is reacted by the engine mounts. These vibration forces are proportional to load on the engine and cannot be minimized or eliminated using clever counterweight or balance shaft design.

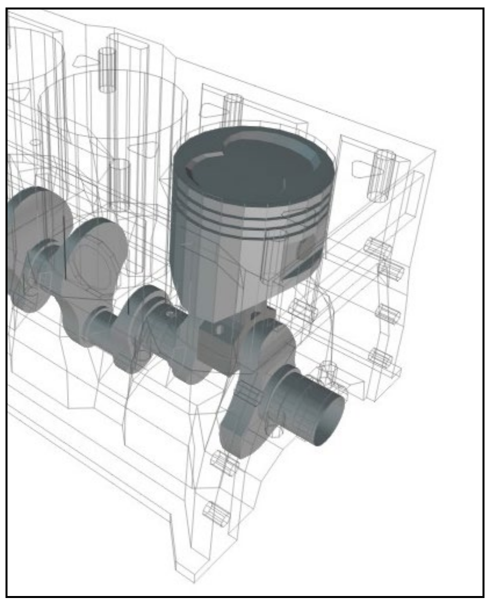

Figure 2. Slider Crank Assembly

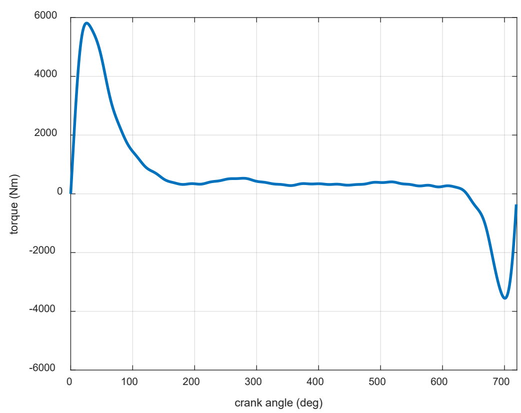

Figure 3. Torque Pulse

These vibration forces described herein are inherent to how the engine produces power and are completely normal. It is how the engine is applied and installed in the facility that will determine the severity of the vibration. The ubiquitous vibration severity chart (Figure 1) does not adequately take these factors into account and will often show that a normal healthy engine driven system has a significant vibration problem.

Measuring vibration on an engine [2]

A typical horizontal split case (HSC) pump installation is shown in Figure 4. The points to be measured and logged are shown and listed in Table 1. A similar set of points would be acquired on an end suction (ES) pump set and vertical turbine (VT) pump set; with the difference being that on a VT, the points normally taken on the pump would be taken on the right angle (RA) gear instead.

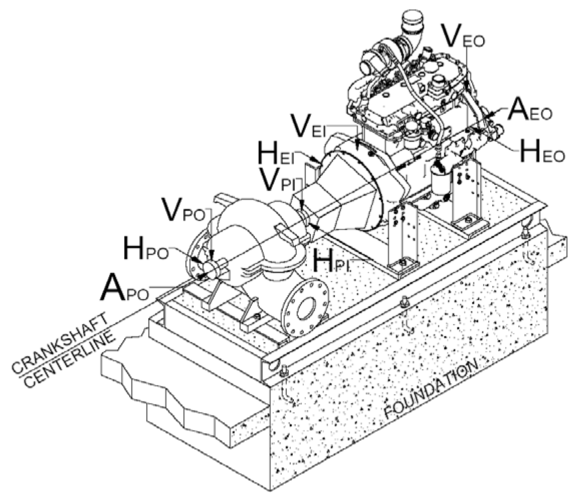

Figure 4. Typical Measurement Locations – HSC

Table 1. Measurement Point Definition

NAME	location	direction
AEO	engine outboard	axial
HEO		horizontal
VEO		vertical
AEI	engine inboard	axial
HEI		horizontal
VEI		vertical
API	pump (gear) inboard	axial
HPI		horizontal
VPI		vertical
APO	pump (gear) outboard	axial
HPO		horizontal
VPO		vertical

Although an accelerometer is typically used to measure the data, the analyzer will often have a setting which will integrate the signal back to velocity or displacement. The difference being that acceleration tends to weight the higher frequencies in the data and displacement tends

[2] ISO standard 10816-1 is an excellent guide on the measurements to be acquired and the measurement hardware to be used

to weight the lower frequencies. Velocity is the customary unit of measure for vibration as is more balanced across the frequency range. Many severity charts tend to use velocity units.

When it comes to mounting the accelerometer to the machine, several different methods are common as shown in Figure 5.

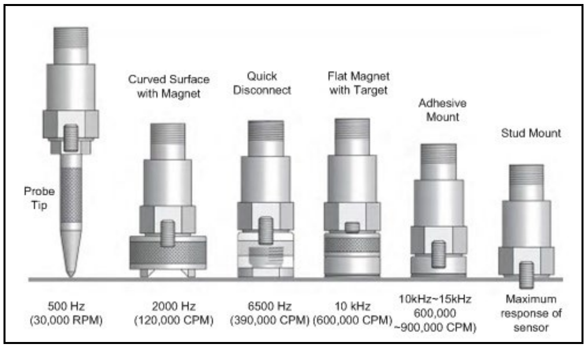

Figure 5. Accelerometer Mounting and Maximum Frequency Response[3]

The easiest approach, the probe tip, is also the most problematic having the lowest frequency response and the ability to measure only along the direction of the probe. Dual rail magnets and flat magnets tend to be popular and effective. These provide a good compromise between ease of use and reasonable frequency range. A triaxial sensor can be mounted with a magnet and all three directions can be measured simultaneously. Just be careful when using magnets that the surfaces are clean and free of debris and the magnet sits tight and secure on the surface without "rocking". A bit of care when setting up the test will save you a lot of time and headache later when trying to make sense out of inconsistent data.

Data presentation

Depending on the analyzer available and/ or the purpose of collecting the data, the results can be presented as either an "overall" level or as a spectrum. An example of some raw data collected on an inline 6-cylinder engine is shown in Figure 6.

The overall RMS vibration level is a single number showing the power contained within a signal; it is the simplest to present, but contains the least information. For example, the overall level would be useful when commissioning a machine and reporting vibration data back to a governing agency or customer. The overall level is also used when trending the vibration behavior over time in a predictive maintenance program; monitoring for any changes which would indicate wear or imminent failure of components.

A vibration spectrum, on the other hand, shows the discreet frequency content of the signal as seen in Figure 7. This has historically been referred to as *filtered* vibration because the individual frequency lines in the spectrum can be thought of as the output of a narrow band pass filter. Using this type of analysis will give the engineer much more detail about the nature of the vibration and the specific harmonics (frequencies) that are present in the data. In this example it can be seen that the majority of the energy is contained at the 88 Hz harmonic. This is the kind of information necessary to diagnose and mitigate problems.

[3] image courtesy of Crystal Instruments

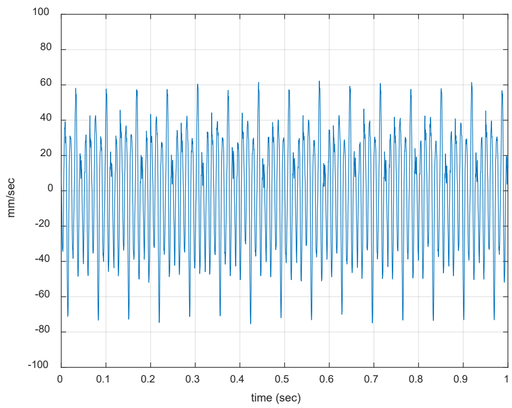

Figure 6. Vibration Measured on an Engine Installation

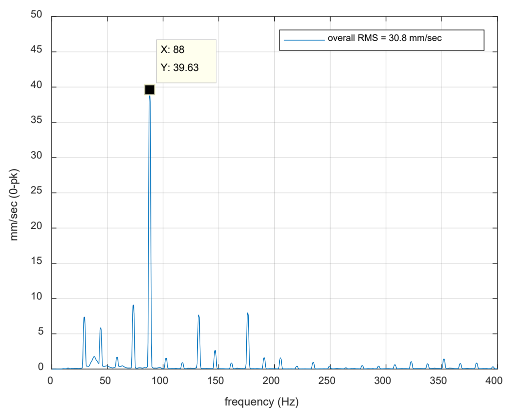

Figure 7. Analysis Results

Data interpretation

There is an ISO standard referring to the vibration of reciprocating machines which should be referenced when evaluating an engine driven fire pump system[4]. This section of the standard provides specific guidelines for interpreting vibration levels on reciprocating machines above 100 kW. There is a severity chart with additional machine classifications as shown in Figure 8. **Classifications 5 and 6 apply to stationary diesel driven fire pump sets.**

For example, an engine driven fire pump system having an overall level measured on the engine at **28 mm/sec** would be considered unacceptable for any machine in classifications 1-4. However, this level is acceptable under a class 5 or class 6 machine.

	Machine vibration classification number						
mm/sec ≤	1	2	3	4	5	6	7
	Evaluation zones						
1.12	A/B	A/B	A/B	A/B	A/B	A/B	A/B
1.78	A/B	A/B	A/B	A/B	A/B	A/B	A/B
2.82	A/B	A/B	A/B	A/B	A/B	A/B	A/B
4.46	A/B	A/B	A/B	A/B	A/B	A/B	A/B
7.07	C	A/B	A/B	A/B	A/B	A/B	A/B
11.20	D	C	A/B	A/B	A/B	A/B	A/B
17.80	D	D	C	A/B	A/B	A/B	A/B
28.20	D	D	D	C	A/B	A/B	A/B
44.60	D	D	D	D	C	A/B	A/B
70.70	D	D	D	D	D	C	A/B
112.00	D	D	D	D	D	D	C

Figure 8. Vibration Severity (10816-6)[3]

Classification number 1 - Small (up to 15kW) machines and subassemblies of larger machines

Classification number 2 - Medium size (15kW to 75kW) machines without special foundations or machines up to 300kW rigidly mounted on special foundations.

Classification number 3 - Large rotating machines rigidly mounted on foundations which are stiff in the direction of vibration measurement.

Classification number 4 - Large rotating machines mounted on foundations which

---

[4] ISO 10816-6 Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts – Part 6: Reciprocating machines with power ratings above 100 kW

are flexible in the direction of vibration measurement.

Classification number 5 - Machines and mechanical drive systems with un-balanceable inertia effects (due to reciprocating parts), mounted on foundations, which are relatively stiff in the direction of vibration measurement.

Classification number 6 - Machines and mechanical drive systems with un-balanceable inertia effects (due to reciprocating parts), mounted on foundations which are relatively soft in the direction of vibration measurement.

Evaluation Zone descriptions:

- A The vibration of newly commissioned machines would normally fall within this zone.
- B Machines with vibration within this zone are normally considered acceptable for long-term operation.
- C Machines with vibration within this zone are normally considered unsatisfactory for long-term continuous operation. Generally, the machine may be operated for a limited period in this condition until a suitable opportunity arises for remedial action.
- D Vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine.

Of course, these are guidelines only, not firm fixed rules; every machine is unique in its tolerance of vibration and fatigue.

Machinery mounting

In a typical HSC or ES fire pump application, the driver and pump are both mounted to a baseplate to maintain alignment. The baseplate as a unit is then shimmed and fastened to a foundation (sometimes referred to as a housekeeping pad) before being filled with grout.

In a VT fire pump application the engine is typically mounted to a baseplate separate from the right angle gear. Irrespective of this difference, the mounting of the base plate to a foundation is typically the same as described above for HSC and ES systems.

From a vibration standpoint, rigid mounting of the engine is acceptable when the foundation is of sufficient mass to attenuate the vibration produced by the system. The rigid mounting arrangement must be designed to avoid a resonant condition being excited when operating at running speed. If properly executed, engine vibration is minimized, although vibration transmitted to the facility may pose a problem if the foundation is not of sufficient mass or isolated from adjacent structures.

Compliant mounting involves supporting the engine on soft isolators between the engine and the base plate. This is done to minimize the transmitted vibration to the base plate and the facility.

Bibliography

Nestorides, E. (1958). *A Handbook on Torsional Vibration.* Cambridge, Great Britan: Cambridge At the University Press.

Taylor, C. F. (1985). *The Internal Combustion Engine in Theory and Practice* (Vol. 2). Cambridge, MA, USA: The MIT Press.

About the Author

Matthew Witter
Principal Engineer

Structural Dynalysis, Ltd.
www.strucdynltd.com

Structural Dynalysis was founded in 2002 and specializes in structural dynamics, vibration testing & analysis, signal processing and driveline dynamics. In addition to the testing services provided, Structural Dynalysis provides thorough torsional vibration analysis (TVA) with comprehensive reporting tailored to the needs of the customer.