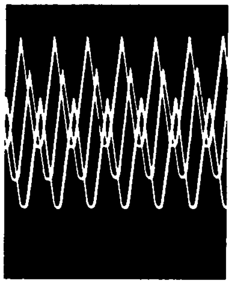
ENDEVCO TECH PAPER



TP 257

Shipboard Vibration Monitoring as a Diagnostic/Maintenance Tool

Charles A. Bowes*

The generally poor correlation between the condition of machinery health and hours of operation is a significant problem for time based maintenance systems. This problem can be overcome with maintenance systems which use knowledge, obtained with instrumentation, regarding the actual condition of machinery health. Knowledge of the vibration characteristic of a machine is particularly useful in determining its condition, and the instrumentation of a machine to obtain this knowledge is relatively easy and inexpensive. The majority of this paper is concerned with the nature of machinery vibration, where it should be measured, how the raw data should be analyzed, and how the results should be interpreted. A brief discussion of the current trends in vibration instrumentation is given at the conclusion.

1. INTRODUCTION

The problem which this paper addresses is that machinery deteriorates with use, and unless it undergoes some form of preventative maintenance, it will eventually fail to perform the function for which it is intended.

Most preventative maintenance systems in use today are based on time of operation; that is, maintenance actions are performed periodically with the length of the period determined by the number of hours of machine operation. The basic problem with these systems is that there is generally poor correlation between the actual condition of machinery health and time of operation. This results in premature or unscheduled failures and, just as important, the performance of expensive maintenance actions on machinery that does not require them.

The performance of maintenance actions on machinery that does not require them is not only expensive, it can also induce problems that would not have occurred if the machinery had been left alone. Even when they are required, maintenance actions are too often performed incorrectly and/or result in failures other than the original problem for which they were intended.

An obvious answer to these problems is a maintenance system that is based on knowledge of the actual condition of machinery health. This knowledge would allow for the efficient scheduling of maintenance actions before catastrophic failure, but only when they are required. It would also allow for the determination of the effectiveness of maintenance actions after they are performed. Generally, obtaining this knowledge requires instrumentation of the machinery to monitor those parameters that are indicative of its health.

---

* Marketing Manager, Industrial and Marine Instrumentation, ENDEVCO, Rancho Viejo Road, San Juan Capistrano, CA 92675, U.S.A. Presented November 1973, at the International Symposium on Marine Engineering, Marine Engineering Society of Japan, Tokyo, Japan.

ENDEVCO

RANCHO VIEJO ROAD · SAN JUAN CAPISTRANO, CA 92675 · TELEPHONE (714) 493-8181

AKRON, OHIO • BOSTON, MASSACHUSETTS • CHICAGO, ILLINOIS • PALO ALTO, CALIFORNIA • DETROIT MICHIGAN • PHILADELPHIA, PENNSYLVANIA • WASHINGTON, D.C. • WEST PALM BEACH, FLORIDA • AUSTRALIA
BELGIUM • BRAZIL • CANADA • DENMARK • ENGLAND • FINLAND • FRANCE • GERMANY • INDIA • ISRAEL • ITALY • JAPAN • NETHERLANDS • NORWAY • S. AFRICA • SPAIN • SWEDEN • SWITZERLAND • USSR
TWX 910-596-1415 TELEX 68-5608
DIVISION OF BECTON DICKINSON AND COMPANY
PRINTED IN U.S.A.

2. CONDITION MONITORING

There are many parameters that are indicative of machinery health, the most obvious of which are those relating to its performance. However, relatively few machines are provided with instrumentation which measures performance parameters, and the addition of this instrumentation is generally difficult and expensive. In addition, there are many problems that can occur in a machine which do not result in degradation of performance until they are at or very near the point of catastrophic failure.

There are other, non-performance parameters that can be useful in monitoring machinery condition such as bearing, oil and coolant temperatures; oil pressure; oil contamination; relative position of parts; etc. All of these parameters should be considered in a complete condition monitoring system, but there is one parameter that by itself is representative of many aspects of machinery health and for which it is relatively easy and inexpensive to instrument. That parameter is machinery vibration.

It has been stated that the failure of a machine is preceded by an increase in its vibration level in more than 90 percent of the cases (1). All machines vibrate regardless of how well they are designed and assembled, and it has been found in industrial practice that good correlation exists between the characteristic vibration signatures of machines and their relative condition (2). The fact that the vibration signature of most industrial and shipboard machinery can be measured with a sensor whose only interface with the equipment is attachment to an external surface makes vibration instrumentation easy and inexpensive in comparison with parameters which require sensors that must interface with the operating mechanisms of the machinery.

3. VIBRATION AS AN INDICATOR OF MACHINERY HEALTH

The vibration at any point on a machine is generally a non-stationary, random phenomena. That is, the time variable signal representative of the vibration at a point on a machine is a complex waveform consisting of many discrete frequencies. It has a randomly varying instantaneous amplitude and statistical properties that vary with time. In addition, the vibration can be measured in several different modes: the amplitude of vibration, or displacement, expressed as centimeters peak to peak; the rate of change of amplitude, or velocity, expressed as centimeters per second peak; and the acceleration of vibration, expressed as centimeters per second per second peak or g's where one g equals 980.6 cm/sec^2. The displacement, velocity, and acceleration of vibration are related to each other as functions of time. Velocity is the time integral of acceleration, and displacement is the time integral of velocity or the double integral of acceleration.

The above discussion indicates that the raw vibration signal, in any mode, from a single point on a machine is not a good indicator of the machine's health, and that is generally true. To determine a machine's condition from its vibration requires that the vibration be measured at several carefully selected points and directions and that the signal be analyzed into the basic components that make up the complex, raw waveform.

The selection of the location for and the direction of measurement is the single most critical factor in machinery vibration monitoring and analysis. If the raw signal does not contain the components that are representative of machinery condition, no amount of analysis will reveal that condition. To borrow a phrase from the computer industry with respect to data input, "garbage in- garbage out".

What are the best locations for measuring machinery vibration? The bearings are. The bearings are where the action is, where the basic dynamic loads and forces of the machine are present, and they in themselves are a critical component with regard to machinery condition. Vibration measurements should be made on the bearing cap of each bearing in a machine. If this is not feasible, the measurements should be made at a point as close as possible to the bearing with the minimum possible mechanical impedance between that point and the bearing. It should be noted here that this is a discussion of vibration as a maintenance tool not as a design or an experimental tool. There are many other locations for vibration measurements besides the bearings which can provide useful information to the machine designer or the person interested in an aspect of the machine other than its condition, such as structure borne noise.

In what directions should the vibration be measured? For a complete vibration signature of a machine, triaxial measurements should be made at each location. However, for rotating machinery, sufficient information can usually be obtained from an axial and a radial measurement at each location.

The different components of a machine vibrate at one or more discrete frequencies and different malfunctions in a given component can cause vibrations at different discrete frequencies. It is the combination of these discrete frequency vibrations that results in the complex vibration waveform at the measurement point. Therefore, a common and useful method of analyzing the measured signal is to reduce it to its discrete frequency components. The results of this type of analysis, usually presented as a plot of amplitude versus frequency, is what is commonly referred to as the vibration signature of a machine.

Knowing which frequencies in a machine's vibration signature are caused by what components and what types of malfunction requires an understanding of the mechanical dynamics of the machine and the effects of the linear and nonlinear combination of discrete frequency signals. However, some generalizations can be made which are useful in a basic interpretation of a vibration signature:

a) Unbalance causes radial vibration at the machine's rotational frequency.
b) Misalignment, bent shafts, and bad coupling cause axial vibration at the machine's rotational frequency with large second and third harmonic components.
c) Oil swirl in journal bearings causes radial vibration at subharmonics of the rotational frequency.

d) Aerodynamic forces in fans or impellers causes radial vibration at a frequency equal to the product of the rotational frequency and the number of blades or vanes.

e) Gears cause vibrations at the shaft rotational frequency and at frequencies equal to the product of the rotational frequency and the number of gear teeth.

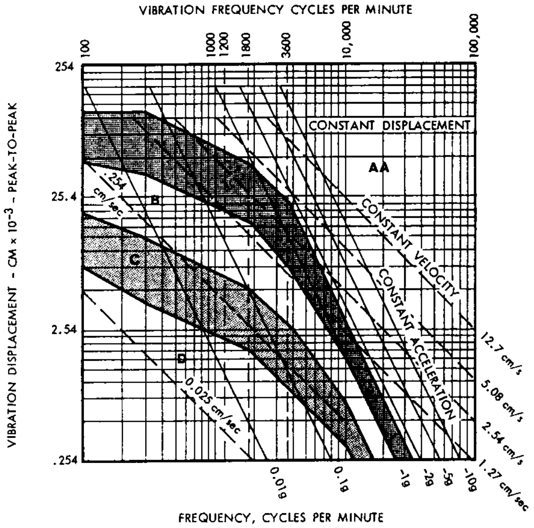
f) Anti-friction bearings cause vibrations at frequencies that are a function of the bearing geometry, the number of rolling elements, and the shaft rotational frequency (4). Bearing vibration is generally indicated by very high frequency radial components measured on the housing.

The actual vibration signature of a machine will contain many frequency components which cannot be readily identified with a specific source of vibration. Some of these frequencies are caused by the mechanical resonance of various components whose resonant frequency is usually known only by their designer. Some of these frequencies are the result of machine vibrations that are periodic but not sinusoidal. The spectrum of these types of signals contains a component at a frequency equivalent to the basic period of vibration and many other components at harmonics of that frequency. Some of these frequencies are the result of the nonlinear combination, in the machine, of signals at different discrete frequencies. This process (modulation) generates frequencies at the sum and difference of the frequencies being combined (sidebands). That every frequency component in a vibration signature cannot be traced to a specific source is no cause for concern. Attention should be paid to those frequencies that can be identified with a source and to changes in the overall signature with time.

What is the best mode for measuring machinery vibration; displacement, velocity, or acceleration? There is general agreement that vibration severity at very low frequencies is proportional to displacement, that vibration severity at the mid-range of frequencies is proportional to velocity, and that vibration severity at very high frequencies is proportional to acceleration. There is less agreement as to the specific frequencies where crossover occurs, but in the range of frequencies of interest for most machinery applications, vibratory velocity is the best indicator of machinery health. This is in accord with the intuitive feeling that the damage potential of vibration is proportional to the dynamic energy being dissipated which in turn is a function of velocity.

What are the levels of vibration that represent a machine in good condition versus one in bad condition? There are no hard and fast rules to answer this question, and there are definitely no rules based on scientific analysis and prediction. However, years of industrial experience in correlating machinery vibration with machinery health on thousands of machines have resulted in some empirically derived vibration standards. Figure 1 is one of the most widely used standards in the United States.

The standards are very general and should only be considered as rules of thumb for judging vibration severity. In actual practice, some machines can operate satisfactorily at vibration levels that would be considered unacceptable for other machines. A better method for judging vibration severity is to establish baseline signatures for a machine known to be in good operating condition (this is not necessarily a new machine as some machines "wear in" to their normal operating levels) and to monitor changes in these signatures with time.



EXPLANATION OF CLASSES

AA	Dangerous.
A	Failure is near.
B	Faulty.
C	Minor faults.
D	No faults.

STANDARD VIBRATION CHART
Figure 1.
(Developed from Reference No. 6)

What magnitude of change in a signature component is considered significant? After years of experience, the Canadian Navy has determined that an increase in vibration level is not significant unless it doubles. As important as the absolute level of change is the rate of change. The Canadian Navy has data which indicates that the mean level of a signature component as a function of time is a straight line with a slight positive slope for 75% of a machine's useful life, at which point it starts an exponential rise to the point of failure (2). Therefore, trend monitoring of vibration signatures is a more useful maintenance tool than a one-time survey of absolute magnitudes.

4. CONCLUSION

The use of vibration monitoring as a maintenance tool requires careful selection of the locations where the vibration is measured and the analysis of the overall measured signals into their discrete frequency components. For most applications the severity of vibration is best indicated by its velocity. Although there are empirically derived general standards against which to judge vibration severity, in practice, the change and the rate of change of vibration from baseline signatures established for individual machines is a better indicator of machinery health.

As important as the selection of measurement locations and the analysis of measured data is the selection of the proper instrumentation. There is a wide variety of commercially available vibration instrumentation. A detailed discussion of this instrumentation is beyond the scope of this paper. Suffice it to say that present trends are toward the use of the versatile, rugged, and reliable piezoelectric accelerometer as the basic sensor coupled with charge sensitive signal conditioning that includes electronic integration. Electronic integration provides signals proportional to velocity and displacement in addition to acceleration so that, depending on the frequency of interest, the most pertinent mode of vibration can be selected for analysis.

Traditionally, most vibration data analysis for machinery maintenance purposes has been relatively broad band using octave and third octave filter sets originally designed for acoustical data analysis (3) (5). Although broadband analysis will continue to be successfully used, the recent availability of field compatible, discrete frequency analyzers should result in a significant increase in the usefulness of vibration analysis as a maintenance tool. In particular, the minicomputer is being increasingly used as a dedicated analysis and control instrument in permanently installed, real time, maintenance monitoring systems.

REFERENCES

(1) Lundgaard, B., "The Relationship Between Machinery Vibration Levels and Machinery Deterioration and Failure", SNAME, Pacific Northwest Section (1971).

(2) Sankar, T.S. and Xistris, G.D., "Failure Prediction Through the Theory of Stochastic Excursions of Extreme Vibration Amplitudes", ASME, Paper 71-VIBR-60 (1971).

(3) Glew, C.A.W. and Watson, D.C., "Vibration Analysis as a Maintenance Tool", Transactions of the Institute of Marine Engineers, Canadian Division, Supplement No. 32 (1968).

(4) Blake, M.P., "Vibration and Acoustic Measurement Handbook", (1972), p. 445, Spartan Books.

(5) American National Standards Institute Specification S1.11 - 1966 for Octave, Half-Octave and Third-Octave Filter Sets.

(6) Blake, M.P., "New Vibration Standards for Maintenance", Hydrocarbon Processing and Petroleum Refiner, Vol. 43, No. 1 (1964).