Technical Paper

Triaxial Vibration Spectral Data: An Important Ingredient for Proper Machine Diagnostics

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Correct diagnosis of rotating machinery mechanical faults depends on having complete information about the vibration spectral data. Since machines in general have three degrees of freedom of lateral motion, good science and logic suggest that data from all three axes will provide more information, if we can analyze it properly. The purpose of this paper is to demonstrate the improved diagnostic capability provided by collecting triaxial data compared to single axis radial data mixed with some axial data.

The three orthogonal axes are designated axial, radial and tangential. As indicated by the term, The axial is the direction in line with, or parallel to, the shaft. Radial and tangential are the two perpendicular axes in the plane of rotation. Generally, radial is vertical for a horizontal machine while tangential is in the transverse direction. For a vertical machine, radial and tangential are both horizontal axes such that radial is toward the center of the shaft and tangential is as the name implies.

Three single-axis accelerometers are incorporated into a small cast bronze cluster block with a threaded pin. Bronze disks, with a threaded hole to accommodate the cluster pin, attached with adhesives to bare metal surfaces at selected transducer locations. These disks remain indefinitely unless a special effort is made to remove them. The selected locations are bearing housings or on stiff portions of structure that are physically close to, and have a direct vibration path to, the bearing housings. Generally we acquire the triaxial spectral data at one or two transducer locations on each major component of a machine. The decision of whether to use one location or two usually is dependent on the size of the machine. The data quality and frequency range are comparable to permanently installed transducers.

Data collection is performed using a portable multi-channel digital data collector with an infrared barcode wand and a short cable at the end of which is the triaxial cluster of accelerometers. Data collection is started by scanning a barcode (used to eliminate operator error) with the infrared wand at the first transducer location. The instrument then collects vibration data for all three axes simultaneously. In approximately 20 seconds, two frequency ranges of data are collected and transformed into 800-line spectra for all three axes. Assuming that it takes 26 seconds to unscrew the cluster from one pad, screw the cluster into the next pad and scan the next barcode, a machine with four readily available transducer locations can be tested within three minutes.

After the data has been collected, the spectra are downloaded to a PC. Data processing includes order normalizing the spectra (changing the frequency scale to reflect multiples of the machine rotating speed), screening the spectra to obtain significant spectral peaks, and performing automatic diagnosis to determine specific machine faults and their severities. Using all three axes of data per location, data from a typical machine can be processed in about 30 seconds, depending on the number of transducer locations. The philosophy of using triaxial data is independent of software and may be used with any method of fault diagnosis.

ROTATIONAL RATE VIBRATION

Although the software can accommodate vibration displacement, velocity or acceleration in any unit of measurement, we generally measure machinery velocity vibration in VdB (velocity decibels), which is a log scale referencing 0 VdB=10-8 meter per second RMS. For the sake of perspective, 0.1 inch per second peak vibration is equal to 125.1 VdB. A 6 VdB differential is linearly a factor of two and 20 VdB is linearly a factor of ten.

The spectral amplitudes of vibration are compared to average baseline data accumulated for a specific machine type. The levels used are average plus one standard deviation values statistically computed for each spectral peak from selected past test data for the machine type. When we refer to the relationship of an amplitude to average, we mean average plus sigma. Fault severities are designated “slight”, “moderate”, “serious” and “extreme”.

The analysis software computes the severity based on the margin by which the various test amplitudes, and exceedances of average plus sigma compare to the threshold values as required for the specific fault diagnosis. This information is provided as a brief explanation of the numbers presented in Table 1, which are vibration amplitudes, in VdB, and exceedances of average plus sigma (also in VdB), at shaft rotational rate frequency.

Rotational rate frequency (1x) vibration is often simple to comprehend and detect in a spectral signature. However, the variety of mechanical fault diagnoses that can be indicated by abnormally high level 1x vibration can make it difficult to determine what the actual problem is. For example, consider a direct drive motor and centrifugal pump with a coupling. Excessive 1x vibration may indicate motor imbalance, pump imbalance, angular misalignment, foundation horizontal flexibility, a radial or thrust bearing clearance problem, or motor cooling fan blade damage. It is our experience that collecting triaxial data at both the motor and pump is essential to diagnose and differentiate among these faults.

The following illustrate a variety of 1x diagnoses and the logic by which the results were obtained, manually and with ExpertALERT diagnostic software. Each example represents survey test data taken from motor-driven centrifugal pumps aboard U.S. Navy aircraft carriers. Although test data included two frequency ranges of continuous spectra and forcing frequencies, the 1x amplitudes and deviations from average plus sigma have been extracted and summarized in Table 1. Examples #1 through #7 are coupled machines with one transducer location each on the motor and pump. Examples #1 through #3 are vertical, and Examples #4 through #7 are horizontal. Examples #8 and #9 are horizontal closecoupled pumps (bearing, motor, bearing, overhung pump impeller) with one transducer location.

EXAMPLE #1

This configuration is a vertical motor-driven pump with one transducer mounting disk on the upper motor bearing and one on the upper pump bearing. One can generalize that, all else being equal, the horizontal 1x vibration levels should be roughly twice as high (6 VdB higher) at the motor than the pump due to the cantilever effect. This relationship should be reflected in the average data. Another physical consideration for a vertical machine is that any rotor imbalance can cause the whole unit to rock. The rocking motion can cause 1x axial vibration to be abnormally high as long as the axial amplitudes and exceedances of average are lower than those for radial and tangential. A third consideration is that vertical pumps usually are structured with one face of the coupling and upper pump bearing exposed, so that the axis of structural support flexibility allows the unit to vibrate in that direction, while the perpendicular axis is much stiffer and only allows more localized vibration.

Given these physical factors, examine the data for example #1 in Table 1. Assume that we have only axial and radial data at both ends. The diagnosis could be angular misalignment, since 1x axial is abnormally high at both motor and pump. It could be motor imbalance or pump imbalance, since 1x radial is abnormally high at either end and radial is higher than axial. The axial vibration could be due to the rocking motion.

Rotational Rate Vibration Levels in VdB

Exceedance is the positive deviation from average plus sigma (also in VdB)
baseline data from past tests of identical machines

		Example#	1	2	3	4	5	6	7	8	9
		Orientation	Vert.	Vert.	Vert.	Horiz.	Horiz.	Horiz.	Horiz.	Horiz.	Horiz.
MOTOR	**Axial**	Amplitude	105	108	111	97	114	103	99	109	101
		Exceedance	7	3	16	-8	17	1	-12	-3	14
	Radial	Amplitude	118	119	128	94	114	120	102	118	91
		Exceedance	10	4	19	-9	26	21	-2	8	4
	Tangl	Amplitude	117	124	100	115	125	120	130	124	112
		Exceedance	10	8	-3	7	22	8	16	6	16
PUMP	**Axial**	Amplitude	104	100	113	102	110	101	108	-	-
		Exceedance	9	3	13	-2	11	4	-1	-	-
	Radial	Amplitude	113	117	123	90	99	95	107	-	-
		Exceedance	9	11	19	-11	4	1	6	-	-
	Tangl	Amplitude	92	120	94	118	108	120	124	-	-
		Exceedance	2	9	-9	7	5	14	12	-	-

Table 1 - Vibration amplitudes, in VdB, and exceedances of average plus sigma (also in VdB), at shaft rotational rate frequency.

Rotational rate frequency (1x) is often simple to comprehend and detect in a spectral signature. However, the variety of mechanical fault diagnoses that can be indicated by abnormally high level 1x vibration can make it difficult to determine what the actual problem is. For example, consider a direct drive motor and centrifugal pump with a coupling. Excessive 1x vibration may indicate motor imbalance, pump imbalance, angular misalignment, foundation horizontal flexibility, a radial or thrust bearing clearance problem, or motor cooling fan blade damage.

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If we have only axial and tangential data at both ends, the evidence points more to motor imbalance, since 1x radial at the pump is quite low. With all three axes, it becomes clear that the 1x radial and tangential levels at the motor are dominant over axial in both absolute amplitude and relative to average…thus motor imbalance is indicated. The 1x levels at the pump can be explained by the horizontal structural stiffness mentioned above. The radial axis in this case is the direction of structural flexibility, so that radially the pump is being "wagged" by the motor imbalance. Conversely, the tangential axis is the direction of high structural stiffness and therefore the vibration due to motor imbalance does not transmit to the pump.

EXAMPLE #2

Using the same logic as in example #1, and considering the same physical factors for a vertical motordriven pump, it is evident that the data indicate either motor imbalance or pump imbalance. The 1x radial and tangential levels are much higher than axial in absolute amplitude and relative to average at the motor and pump. Which component is more likely at fault? The 1x radial and tangential amplitudes are higher at the motor, but remember that this is a vertical machine. Amplitudes at the motor are only 2 and 4 VdB higher than those at the pump, much less than a factor of two. Furthermore, the exceedances of average in the radial and tangential axes are 7 and 1 VdB greater at the pump. The diagnostic software concludes that there is imbalance due to the relatively low axial levels and concludes pump imbalance because the radial and tangential exceedances of average at 1x, taken together, are significantly greater at the pump than at the motor.

EXAMPLE #3

Assume that we have only axial and radial at both ends. One can conclude angular misalignment, motor imbalance or pump imbalance. The latter could be concluded because this is a vertical machine and the rocking motion of the whole unit can cause 1x axial vibration to be abnormally high as long as the axial amplitudes and exceedances of average are lower than those for radial. Assume that we have only axial and tangential at both ends. We see abnormally high axial 1x vibration at both ends, suggesting misalignment although missing the radial amplitude that is 17 VdB (a factor of 7) higher than axial. Having all three axes provides a clear picture.

The diagnostic software notes, as should the human analyst, that the 1x axial vibration levels are abnormally high at both ends of the machine and that the axial amplitude is greater than either the radial or tangential amplitude at both ends. This information alone is sufficient to diagnose angular misalignment.

Motor or pump imbalance diagnoses would require that both radial and tangential 1x amplitudes be greater than axial at either end of the machine. Since this is a vertical pump it is structurally much less stiff in one horizontal direction than the other, and angular misalignment will often cause the machine structure to respond by “wagging” strongly in the less stiff direction. Thus we see the 1x radial vibration levels (radial in this case obviously being the structurally limber direction) are not only abnormally high but dominate the spectra.

The analysis software requires the axial 1x vibration meet the appropriate rules for the angular misalignment diagnosis to pass. It uses the 1x radial or tangential levels as supporting evidence so that These peaks are included in the diagnostic report and more importantly, add to the fault severity computation. In this case, including the radial levels increases the severity from moderate to serious.

EXAMPLE #4

Assume that we have only axial and radial at both ends. There is no indicated mechanical fault. All 1x levels are well below average. Assume that we have only axial and tangential at both ends. One can easily assume that there is a moderate degree of either motor imbalance or pump imbalance. In fact, the data shown in Table 1 indicate foundation transverse flexibility. The diagnostic software examines the differentials in both amplitude and deviation from average between radial and tangential. Although it is often normal for a horizontal machine in amplitude than to have tangential 1x vibration significantly higher in amplitude than radial, this characteristic would be evident in the average data. Thus the fact that 1x tangential levels at both ends of the unit are 21 and 28 VdB higher in amplitude, and 16 and 18 VdB higher relative to average than the radial levels, is direct evidence of the foundation flexibility. The foundation is probably corroded or has a cracked weld or loose bolts.

EXAMPLE #5

For this horizontal machine, it appears that angular misalignment and motor imbalance are indicated simultaneously. The former is indicated because 1x axial is abnormally high at both ends of the unit, the amplitude is greater than both radial and tangential at the pump and equal to radial at the motor. The latter is indicated because 1x radial and tangential at the motor are 26 and 22 VdB (up to a factor of twenty) greater than average plus sigma, tangential is much higher in amplitude than axial while the radial amplitude is at least equal to axial.

It is the equal amplitudes of axial and radial at the motor that form a borderline in the diagnostic software rulebase. In this case, both diagnoses automatically would be produced. In fact, either of these faults independently exist or the motor shaft is bent. A bent shaft would produce indications of motor imbalance and angular misalignment. Obviously, this test could be followed up by measuring the phase angles of the 1x vibration in each axis, measuring the shaft for runout and checking the alignment at the coupling.

EXAMPLE #6

The high 1x radial and tangential levels at the motor, both 120 VdB, are clearly excessive and dominant over axial and indicate motor I balance. The 1x tangential level at the pump also is very high, both in amplitude and exceedance of average, but the radial level is quite low.

Similar to the horizontal machine in Example #4, the pump end shows evidence of pump transverse mounting flexibility. In this case, the vibration caused by the motor imbalance is exciting the flexibility at the pump end, indicating this independent fault. Without triaxial data, these two independent diagnoses could not have been evaluated.

EXAMPLE #7

The case is similar to Example #4, only more serious, since the tangential 1x vibration is dominant. Having both radial and tangential data allow comparison of the radial 1x data at both ends of the unit. This indicates that while the foundation transverse flexibility is clearly the problem, there is an underlying pump rotor imbalance that is forcing the inherent structural weakness to respond more severely. This conclusion could not be drawn without data for all three axes.

EXAMPLE #8

For close-coupled pumps, it can be generally stated that high1x radial and tangential levels and relatively low axial indicate motor imbalance, as the motor rotor is supported at each end by bearings. Imbalance of the overhung pump rotor, on the other hand, is indicated by a significant axial component to the 1x vibration in addition to abnormally high 1x radial and/or tangential. In this case, radial and tangential 1x levels are much higher than axial in absolute terms and relative to average. Therefore, this diagnosis is motor imbalance.

EXAMPLE #9

Refer to Example #8. In this case, axial and tangential 1x levels are much higher than radial in absolute terms and relative to average. Thus, this diagnosis is pump imbalance, as the pump rotor was physically rocking on the shaft. Also, consider that one cannot generalize for all machines of this configuration that the axial and radial axes are of paramount importance and that tangential can be ignored. We have seen many other cases where the fan or pump imbalance is indicated by strong axial and tangential 1x vibration only (or sometimes all three axes).

OTHER DIAGNOSES

Whereas 1x diagnoses make up a significant portion of the universe of mechanical faults indicated by vibration spectral data, there is sufficient justification for collecting triaxial data. Still, other diagnoses such as looseness, ball bearing wear, gear problems, pump internal wear, etc., need to be addressed. It has been our experience that having data for all three axes is not necessary in a great many cases to determine if a fault is present; however, relative fault severity is greatly affected.

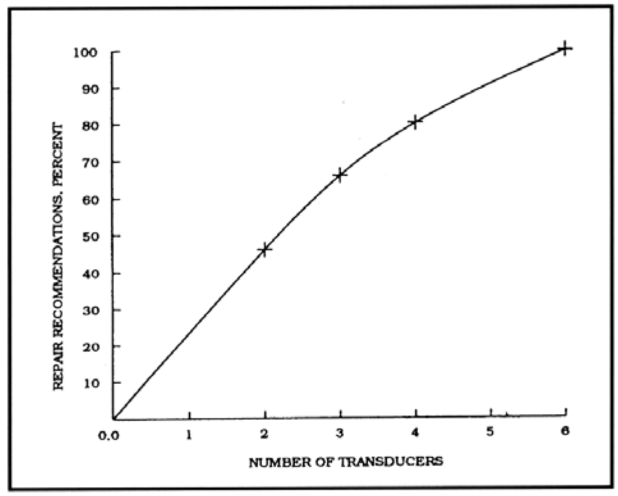
Table 2 (next page) summarizes the rear mesh frequency amplitudes and exceedances of average for a set of four vertical jet fuel transfer pumps found aboard U.S. Navy aircraft carriers. Figure 1 (next page) is an external schematic of these machines showing the transducer locations. The diagnostic result for each machine was “moderate reduction gear mesh problem or wear”. It is also evident that the maximum gear mesh amplitude occurs at different locations and in different axes. Eliminating just one axis would skew the results.

Gear Mesh Frequency Vibration Levels in VdB

Exceedance is the positive deviation from average plus sigma (also in VdB)
baseline data from past tests of identical machines

		1	2	3	4
	Example#	1	2	3	4
	Orientation	Vert.	Vert.	Vert.	Vert.
MOTOR	**Axial** Amplitude	-	104	102	107
	Exceedance	-	9	7	23
	Radial Amplitude	-	103	109	97
	Exceedance	-	4	10	2
	Tangl Amplitude	-	-	117	104
	Exceedance	-	-	18	11
GEARBOX	**Axial** Amplitude	90	95	93	95
	Exceedance	3	8	6	10
	Radial Amplitude	100	108	101	-
	Exceedance	6	14	7	-
	Tangl Amplitude	105	94	99	-
	Exceedance	12	1	6	-

Tables 2a & 2b - A summary of the gear mesh frequency amplitudes and exceedances of average for four vertical jet fuel transfer pumps aboard U.S. Navy aircraft carriers.



Too much information is often better than too little information. The only valid objection is if the time, effort and cost of acquiring, processing and evaluating the additional information is not worth its added value. We have indicated that triaxial vibration data at every transducer location provides a great deal of useful and necessary information. At the same time, triaxial cluster data collection and processing and evaluating the data with an analysis software system, can minimize the added time, effort or cost of this information.

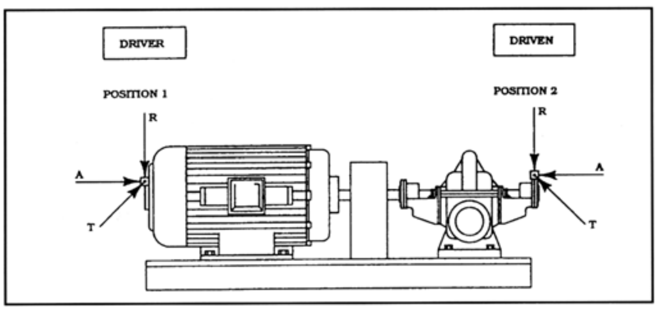


Figure 1 - An external schematic showing the transducer locations.

STATISTICAL INVESTIGATION

Following are the results of a vibration analysis survey conducted in 1987 aboard the USS Constellation in which 379 machines were tested2. Machines with one or three or more transducer locations have been excluded in order to simplify the statistical analysis, leaving 262 machines with two locations. The vibration signatures from machines with two triaxial transducer arrays provided 97 repair recommendations.

To investigate the effect of reducing the number of accelerometer axes, the data we analyzed again for various combinations of axes. The results showing consequent loss in diagnostic accuracy are given in Table 3 (next page). Two important factors should be kept in mind while examining the test results: the vibration excitation is often directional, and the direction of the excitation is problem-dependent and will therefore change from survey to survey; and among the faults that will generate a directional signal are a spall on an outer bearing race, mechanical looseness, misalignment, and a bad gear tooth.

Since it is not possible to predict the direction from which the excitation will be applied, there is no rational way to choose between radial and tangential axes. Our results show no difference between the two, both would give 46 per cent correct diagnoses in the absence of an axial signal. The change of signal direction from survey to survey also was investigated by identifying the transducer axis that provided the highest vibration level for two consecutive surveys. In only 44 percent of the cases was that vibration generated along the same axis.

Analysis of the Vibration Signatures

Transducer Position and Direction	Number of Repair Recommendations	Recommendations Missed	Percent of Recommendations Obtained
1A,1R,1T,2A,2R,2T	97	—	100
1A,1R,2A,2R	78	19	80
1A,1R,2R,	64	33	66
1R,2R	45	52	46
1T,2T	45	52	46

Table 3 - The data was analyzed for various combinations of axes. The consequent loss in diagnostic accuracy is shown.

Single-axis transducer arrangements, either all radial or all tangential, will miss the diagnosis of approximately half of the mechanical faults. Since the direction of the signal is the cause of the problem, it is unlikely that additional transducer locations using the same axis will offer much improvement. Adding one axial accelerometer improves the success rate from 46 to 66 per cent. Adding a second axial accelerometer, to the other transducer array, raises the success rate to 80 percent. The effect of adding transducer axes is plotted in Figure 1 (previous page).

The shape of the curve, fair and close to a straight line, indicates that approximately equal amounts of diagnostic information are obtained from each recorded transducer signal. Any deviation from triaxial measurements thus will be costly in terms of information loss.

Too much information is often better than too little information. The only valid objection is if the time, effort and cost of acquiring, processing and evaluating the additional information is not worth its added value. We have indicated that triaxial vibration data at every transducer location provides a great deal of useful and necessary information. At the same time, triaxial cluster data collection and processing and evaluating the data with an analysis software system, can minimize the added time, effort or cost of this information.

References:
1. *"An Automated Vibration-Based Expert Diagnostic System", Bill Watts and Joe Van Dyke*
2. *"Using Transducers for Machinery Fault Detection", Bert Lundgaard, DLI Engineering*