DETERMINATION OF VIBRATION ALERT LEVEL IN CONDITION MONITORING OF ROTATING MACHINERY

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ABSTRACT

The setting of alarm levels plays a vital role in a machinery condition monitoring and diagnostic system. Two approaches to set vibration alarm levels using vibration signals produced by shipboard fire pumps are presented for the time and frequency domains. In the time domain, cross peak analysis (CPA) is proposed to extract the dominate peak points. The distribution of these cross peak points is found to have a lognormal distribution and can be normalized to a Normal distribution in the VdB domain. The computed $\mu+2\sigma$ value in the VdB domain is the suggested alarm level. In the frequency domain, 1/1 octave band analysis (OBA) is introduced. An artificial fault simulation was conducted to compare 1/1 OBA with the broadband method. The result shows that 1/1 OBA is more sensitive to changes in VdB level than the broadband method.

1. INTRODUCTION

In recent years, the rising cost of machine maintenance has driven engineers to develop more economical and efficient methods to determine machine health and accordingly plan the required preventive and corrective maintenance. The most popular technique in use today is a predictive maintenance program based on condition monitoring. In naval applications, condition monitoring is commonly achieved utilizing vibration measurement and analysis on-board surface ships and submarines [1-7].

This paper focuses on the use of vibration measurement to monitor machine health and to diagnose system problems which could lead to machine failure. In addition to providing accurate and understandable data on the machine's current condition, a monitoring and diagnostic system must also limit the number of false alarms. Alarm threshold setting is therefore vitally important in machine vibration diagnostics. Alarm thresholds set too high may result in premature machine failure caused by an undetected failure condition. Alarm thresholds set too low may result in frequent false alarms causing unnecessary system interruptions and repairs. False alarms also reduce operator confidence in the monitoring and diagnostic system. Because the optimum setting of alarm thresholds in vibration monitoring and diagnostic systems continues to be problematical, the goal of this paper is to establish alternative ways of setting vibration alarm levels by using time domain and frequency domain data.

2. BACKGROUND

The fire pump on a naval ship provides more than fire fighting water to damage control systems. The seawater provided by fire pumps is also used by vital air conditioning and chill water systems, main drainage systems and decontamination sprinkler systems. At least one fire pump is running whenever a ship is underway or at anchor. In this paper, the vibration velocity signals from twenty fire pumps in a same class of ship were measured by means of transducers strategically placed at pickup locations on the pumps. Schematic layout of a fire pump and pickup locations is depicted in Figure 1. The transducer pickup placement method is uniaxial with one radial pickup at each bearing and one axial pickup at the thrust bearing. The radial pickup locations are motor bearing at free end, MB(FE), motor bearing at coupling end, MB(CE), pump bearing at coupling end, PB(CE) and pump bearing at free end, PB(FE) and PB(FE/A).

Fig. 1: Schematic Layout of Type I Fire Pump
Table 1 summarizes the vibration source components. This table identifies exciting components within each machine and lists the vibration frequencies generated by each component. The vibration frequencies were normalized as multiples of the machine's shaft rotation rate (orders). One (1) order is equivalent to rotational speed of shaft (i.e., operation RPM or Hz). The time waveforms are recorded on magnetic tape by a frequency modulated recorder. Each location on the pumps was recorded for a one minute time series record. The total number of data sets is sixty.

Table 1: Vibration Source Components of Fire Pump

<table>
<thead>
<tr>
<th>Description</th>
<th>Element</th>
<th>Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Shaft (Ref.)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Fan Blading</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>Slots</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Bars</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Holes</td>
<td>MRC 310 &amp; 311</td>
<td></td>
</tr>
<tr>
<td>Bearing</td>
<td>FAG WT</td>
<td></td>
</tr>
</tbody>
</table>

3. ALARM LEVEL REVIEW:

Generally, the vibration of a system can be characterized by a reduced data set in various domains. The criteria to set the alarm level can be considered either in the time domain or the frequency domain as discussed below.

Time Domain Criteria

- **Vibration Severity Criterion Method**: The simplest time domain method is the vibration severity criterion. The root mean square (RMS) value of vibration velocity is usually measured and compared with vibration severity charts [8]. Various companies and national standard organizations published standards for judging vibration severity. For example, International Standards Organization (ISO) standards 2372 and 3945 provide severity guidelines for machinery. This method can be only used for specific types of machinery at a standard operating condition and is insensitive during the early stages of damage [9].

- **Amplitude Probability Criterion Method**: A more sophisticated method was developed by using statistical analysis to examine the distribution of vibration amplitudes. The amplitudes used can be either peak-to-peak, peak or RMS readings of displacement, velocity or acceleration. Both Campel [10] and Murphy [11] use this statistical method to establish alarm levels based on the mean of the reading plus 3 standard deviations. The main drawback of this approach is that it assumes a Normal distribution of the linear readings exists. Vibration readings have a "skewed" rather than "Normal" distribution [12].

Frequency Domain Criteria

- **Broadband Criterion Method**: The broadband criterion method utilizes a vibrometer which can add all the energy dissipated over a wide frequency range (typically 10,000 Hz). The overall energy is normally calculated by applying the RMS summation method to the spectrum. If the overall energy level exceeds a predetermined level, then an alarm is triggered. This is a simple but inadequate method because it is insensitive to small changes associated with bearing defects, electrical defects and gear tooth defects.

- **Octave Band Criterion Method**: The octave band criterion method is often used in acoustics to determine the energy level changes due to noise and vibration. This method utilizes a constant percentage bandwidth to divide the frequency range of interest into several bands which provide more detailed information than the broadband presentation. A commonly used bandwidth is the one-third octave band. Early researchers used this method to check the change in each band level to determine if the amplitudes exceeded normal values [13-14].

- **Narrowband Criterion Method**: Since the broadband and the octave band criteria methods lack detailed vibration information, a narrowband criterion method is gaining popularity. The bandwidth may up to 10% of the center frequency range (typically 10 to 1,000 Hz). The improved resolution is generally up to 400 or 600 lines for the frequency range of interest. With knowledge of the resonant frequencies of rotating components, the narrowband data is very useful for diagnosing specific faults.

4. DATA ACQUISITION AND PROCESSING SYSTEM:

A block diagram of the data acquisition and analysis system used is depicted in Figure 2.

![Fig. 2: Block Diagram of Data Acquisition and Processing System](image)

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The tape recorder plays back the machinery vibration data tapes to generate an analog signal, which is then distributed to the data acquisition system and the oscilloscope simultaneously. The oscilloscope controls the quality of the data by monitoring the signal time waveform. EASYEST LX software, developed by Keithley Asyst, was used as the data acquisition system. All of the data sets were sampled at a sampling frequency of 10 kHz. The sampling duration for each data set was 36.664 seconds. Finally, a 486 PC was used to retrieve these data sequences and perform data processing, with output sent to a laser printer.

5. TIME DOMAIN APPROACH-CROSS PEAK ANALYSIS:

It is obvious that the peak envelope distribution of vibration time domain signals is relevant to the vibration severity of machinery components. For rotational machinery vibration, since we are interested in the peak envelope distribution of the vibration signal, we use the cross peak data points instead of overall peak data points. The CPA can extract the dominant components from a complicated time waveform data set by selecting the maximum peak value between every zero crossing. Figure 3 compares the difference between sampling points and cross peak points. Using measured RMS values to determine the severity of damage to a component without considering the dispersion of the signal is truly a rough guess. It is better to represent the severity of component damage in terms of a percentage acceptance level. The percentage acceptance level gives the percentage of outcomes which will not exceed this level threshold. For a Normal distribution, the acceptance level is closely related to mean (μ) and standard deviation (σ). For example, μ±1.96σ corresponds to a 97.5% acceptance level which means only a 2.5% probability of the signal amplitude exceeding the μ±1.96σ value. At this point, the statistical moment and central moment of a random variable should be discussed [15]. For the discrete random variable x with probability Pr(x), the nth moment E(x^n) is defined as:

\[ E(x^n) = \sum_{k=1}^{\infty} x_k^n \cdot Pr(x_k) \quad (1) \]

The first moment is very useful and is given the name mean value (μ):

\[ \mu_x = E(x) = \sum_{k=1}^{\infty} x_k \cdot Pr(x_k) \quad (2) \]

Of greater significance are the nth central moments which are defined as follows:

\[ E[(x - \mu_x)^n] = \sum_{k=1}^{\infty} (x_k - \mu_x)^n \cdot Pr(x_k) \quad (3) \]

The central moment for n=2 is called the variance of the random variable. The standard deviation, which corresponds to the dispersion of the random variable, can be obtained by taking the square root of the variance. Thus,

\[ E[(x - \mu_x)^2] = \sum_{k=1}^{\infty} (x_k - \mu_x)^2 \cdot Pr(x_k) \quad (4) \]

\[ \sigma = \sqrt{E[(x - \mu_x)^2]} \quad (5) \]

For the higher order central moments (n>2), they are often normalized by dividing the nth power of standard deviation. The third and fourth normalized central moments are mostly used to indicate the shape of the probability density function. They can be obtained by

\[ \text{Skewness} = \frac{E[(x - \mu_x)^3]}{\sigma^3} \quad (6) \]

\[ \text{Kurtosis} = \frac{E[(x - \mu_x)^4]}{\sigma^4} \quad (7) \]

The skewness provides information about the position of the peak density relative to the mean value. The kurtosis indicates the spread in distribution. For a perfect Normal distribution, the skewness is zero and the kurtosis is three.

Figure 4 shows the flow chart for our CPA technique. After importing the sampled data, the DC offset was removed by subtracting the mean value. The cross peak points between every zero crossing was then found by a subroutine. Because the dynamic range of the tape record is 40 dB, we set a 1% threshold to eliminate those distorted points. The data sets for the same type of fire pump and same pickup location were then added together to form a combined data set to perform the statistical analysis. In order to understand the distribution of the cross peak points, probability histograms for each pickup location were plotted with a linear velocity scale. Figure 5 shows an example of a
probability histogram for twelve fire pump measured at Motor Bearing (Free End). Inspection of this figure shows an exponential shape distribution which can be approximated as a lognormal distribution. This was true in all cases [16]. The distributions become normal if the data is transformed by a log algorithm. The method we used to obtain Normal distributions from these lognormal distributions was to convert the linear velocity readings to velocity dB (VdB) readings. The VdB is defined as:

\[ \text{Velocity (VdB)} = 20 \log \frac{V}{V_{\text{ref}}} \]  

where \( V_{\text{ref}} \) is the reference level, normally \( 0 \text{VdB} = 10^{-8} \text{m/sec} \). After we computed the mean, standard deviation, skewness and kurtosis, plots of probability density functions and a statistical analysis report were generated.

![Data Sampling Flow Chart](image)

Table 2 tabulates the results of skewness and kurtosis for the linear velocity and VdB domains. A comparison of alarm thresholds between the broadband alarm level (B.B. Alm. Level) and computed \( \mu+2\sigma \) level is also shown in Table 3. Each pickup position uses twelve data set. It should be mentioned that these two alarm thresholds are based on different methods using data from different domains. The broadband alarm level is obtained by using vibrometer readings in the frequency domain. The computed \( \mu+2\sigma \) level represent the 97.5% acceptance level of the cross peak envelope in the VdB domain. In general, the B.B. Alm. Level and the computed \( \mu+2\sigma \) level in the VdB domain were very close. The relative difference between these two methods for all fire pump were less than 5%. It is also noted from Table 3 and Table 4 that the computed \( \mu+2\sigma \) level for distributions with small skewness is closer to the broadband alarm level than for those with high skewness. This is because the computed \( \mu+2\sigma \) level for the Normal distribution is very sensitive to skewness.

Table 3: Comparison of Computed \( \mu+2\sigma \) in the VdB Domain and Broadband Alarm Level

<table>
<thead>
<tr>
<th>Pickup Position</th>
<th>Linear Domain</th>
<th>VdB Domain</th>
<th>B.B.Alm. Level</th>
<th>Relative Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB(FE)</td>
<td>1.85</td>
<td>6.201</td>
<td>-0.046</td>
<td>2.378</td>
</tr>
<tr>
<td>MB(CE)</td>
<td>2.052</td>
<td>7.195</td>
<td>0.049</td>
<td>2.444</td>
</tr>
<tr>
<td>PB(CE)</td>
<td>1.517</td>
<td>5.638</td>
<td>-0.444</td>
<td>2.476</td>
</tr>
<tr>
<td>PB(FE)</td>
<td>1.253</td>
<td>3.959</td>
<td>-0.335</td>
<td>2.232</td>
</tr>
<tr>
<td>PB(FE/A)</td>
<td>1.086</td>
<td>3.515</td>
<td>-0.519</td>
<td>2.472</td>
</tr>
</tbody>
</table>

6. FREQUENCY DOMAIN-1/1 OCTAVE BAND ANALYSIS:

This method divides the frequency spectrum into constant percentage bands having the same ratio of bandwidth to center frequency [17]. Each band has an upper frequency limit (\( f_2 \)) and lower frequency limit (\( f_1 \)). The center frequency (\( f_c \)) of any such band is defined as

\[ f_c = \sqrt{f_1 f_2} \]  

The ratio of center frequencies of successive proportional bands is the same as \( f_2/f_1 \) for any one band. i.e.

\[ \frac{f_c}{f_1} = \sqrt{\frac{f_2}{f_1}} = 2^{n/2} \]  

where a third of an octave is defined as \( n=1/3 \). The method chosen to examine frequency domain alarm levels in this research was 1/1 octave band (\( n=1 \)). For the frequency range of 10-5,000 Hz of our system, the frequency spectrum can be divided into 9 bands by using the American National Standards Institute (ANSI) preferred...
center frequencies. The center frequencies and pass bands covering the frequency range 10-5,000 Hz in 1/1 octave bands are given in Table 4.

Table 4: ANSI Preferred Center Frequencies and Pass Bands for 1/1 Octave Band

<table>
<thead>
<tr>
<th>Center Frequency (Hz)</th>
<th>Pass Band (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Limit</td>
</tr>
<tr>
<td>16</td>
<td>11.2</td>
</tr>
<tr>
<td>31.5</td>
<td>22.4</td>
</tr>
<tr>
<td>63</td>
<td>45</td>
</tr>
<tr>
<td>125</td>
<td>90</td>
</tr>
<tr>
<td>250</td>
<td>180</td>
</tr>
<tr>
<td>500</td>
<td>355</td>
</tr>
<tr>
<td>1000</td>
<td>710</td>
</tr>
<tr>
<td>2000</td>
<td>1400</td>
</tr>
<tr>
<td>4000</td>
<td>2800</td>
</tr>
<tr>
<td>8000</td>
<td>5600</td>
</tr>
</tbody>
</table>

Figure 6 shows a flow chart for our 1/1 OBA. In order to have better resolution at lower frequencies, it was necessary to use two different sampling frequencies. For time domain data, the lower sampling frequency spanned 2 kHz and the higher sampling frequency spanned 10 kHz. Twenty blocks of data were taken at each sampling frequency, where a block of data was 2046 data points. After the sampling, a FFT was performed for each block with a Hanning window to obtain the smoothed linear velocity spectrum. The averaging VdB spectrum was then produced by transforming the linear spectrum to the VdB domain and averaging the 20 blocks of data. For the frequency domain data, 10 order and 100 order data sets were used as the lower frequency spectrum and higher frequency spectrum, respectively. Then, the 1st through 6th 1/1 octave band levels were computed using the lower sampling spectrum and the 7th through 9th 1/1 octave band levels were obtained using higher sampling spectrum. Finally, the 1/1 OBA was done after combining these into 9 band levels.

1/1 OBA was performed for all types of fire pumps using time domain data. The mean (μ) and standard deviation (σ) for each octave band level for the same type of fire pump with the same pickup location were also computed. Figure 7 shows the results of the 1/1 octave band levels for each pickup location. The thin line represents the mean (μ) band level and the thick line represents the mean plus standard deviation (μ+σ) band level. The broadband level was also computed by adding all the VdB spectrum using a RMS algorithm. Generally speaking, the dominate levels are located at first six bands (10 to 710 Hz). This implies that the energy of vibration is concentrated at lower frequencies. For fire pumps with a 3555 RPM operation speed, these bands are approximated up to 12 orders.

7. SIMULATION OF BEARING FAULT:

In order to assess the 1/1 OBA, an artificial fault simulation was performed. Before we simulated this case, a fault had to be defined. For simplicity, we assumed a fault could be approximated with 5 bars as shown in Figure 6. The bandwidth of the fault is about 4.5 Hz. Based on (Eq. 6), if the amplitude doubles in a linear velocity scale then the VdB level will increase 6VdB at the corresponding frequency. Therefore, we defined a fault with a 6VdB gain at the center bar and use four bars with 3VdB (half the power of the center bar) and 2VdB at the side bands to approximate leakage effect around the corresponding frequency.

For a steady state condition, some periodic signatures exist which relate to corresponding bearing faults, these are called bearing frequencies. In this section, an artificial fault imposed at the Motor Bearing (Free End) of a fire pump has been simulated. The bearing frequencies of this bearing are tabulated in Table 5. Suppose, for example, that there is a wear degradation in the inner raceway. Then the presence of a fundamental frequency spike f_b with harmonics would be expected. Figure 9(a) shows the spectrum for a good bearing. The 6VdB fault is imposed at the 4.95 order and is show in Figure 9(b). The Figure 9(c) shows the resulting 1/1 octave band levels. The 4.95 order is located at the fifth band of the 1/1 octave band. The 10-5,000 Hz broadband levels before and after damage are almost unchanged. However, the fifth octave band level has increased 1.57VdB. This is a good illustration as to why a single broadband level cannot be used to accurately determine the condition of a machine.
Fig. 7: The Summarized 1/1 Octave Band Levels for Each Pickup Location (Ref. 0VdB=10^{-8} m/sec)
8. CONCLUSIONS:

Both time and frequency domain analyses were performed using fire pump vibration data to determine an appropriate alert level. Cross Peak Analysis in time domain and 1/1 Octave Band Analysis in frequency domain were used to set the alert threshold levels. The following conclusions are drawn:

Time Domain - Cross Peak Analysis:
- The measured cross peak envelop data at five different pickup locations follows a Gaussian probability distribution in the VdB domain well.
- The computed $\mu \pm 2\sigma$ value using the cross peak data in the VdB domain gives a broadband peak amplitude with 98% acceptance level. This level is suggested as the alarm level.

Frequency Domain - 1/1 Octave Band Analysis:
- 1/1 octave band analysis uses nine frequency band alert levels which provides more detailed information about machine condition than the simple broadband level measured by a vibrometer. When a significant change in VdB occurs in a particular frequency band or bands, narrow band zoom mode analysis can be performed for the selected frequency band(s) to identify the component(s) which may have faults.
- 1/1 octave band analysis divides the frequency range into 10 bins over 10kHz. The VdB level in each frequency bin is more sensitive to changes in the energy content of the
measured vibration signal than the broadband method.

9. ACKNOWLEDGMENTS:

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References:


