Frequency Analysis and Phase Measurement of vibration Data to detect shaft Failure, A case study of Vibration system for Bently Nevada Corporation

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Abstract

The complicated mathematical aspects of vibration measurement system didn't let it to be a common topic of instrumentation. It is necessary to be said that the presented paper would be so useful for many engineering and maintenance application of rotary machines. At the first part of the article the contactless eddy current based vibration sensor introduced. This vibration measurement system is the most important way nowadays at the industrial applications. At the next section the analysis theorem of vibration information discussed. Some arguments about the vibration frequency analysis and keyphasor techniques are presented. The simple examples of this paper described the concepts of keyphasor and frequency analysis. At last, the main part of the paper is a new way to analyze the condition of the rotating machine by the information extracted from the frequency and vibration data at MATLAB software. This important contribution is shown as some important instances presented based on the application use to show the ways to detect and troubleshoot the machine's failures. Most of the information at the presented paper is based on the technical document and application experiences of the south pars refineries of Iran. The data is extracted by condition monitoring devices in application.

Key words: keyphasor analysis, condition monitoring, frequency response, eddy current.

1. Introduction

The body Vibration measurement is one of the most complicated topics among all concepts of the instrument. As you know there are various vibration measurement systems from various companies. These systems use different physical basics like piezoelectric or seismic mass to measure the vibration of a rotating machine. Bently Nevada Company at decade 1930 generated a vibration system which used a different method of vibration measurement. The accuracy and precision is so high that it gained a good spot at the rotating machines industry. The physical measurement basics of these devices were completely different from its conventional measurement systems. The two renowned physic laws: Faraday law and Lenz law was the base of this devices for vibration measurement. The transducers which use this measurement method are known as eddy current transducers. This paper tends to approach the application field of these transducers and discuss its operation principles. At the first section, eddy current concept and its generation methods introduced. At the next section different parts of a vibration sensor based on eddy current is completely introduced. The third section goes for the operation principles of these sensors. In fact, the paper considered its various mechanisms for different applications for measurements of radial, axial vibration and also keyphasor method. Frequency analysis and keyphasor data extraction is the base of the final part of this paper and finally a method for analyzing the vibration data by MATLAB mathematic tools in the form of some real application instance showed to detect and troubleshoot the machine failure.

2. History

The body The first person who observed eddy current was Arago, the 25th Prime Minister of France. In 1824 he observed what has been called rotator magnetism, and the fact that most conductive bodies could be magnetized; these discoveries were completed and explained by Michael Faraday. In 1834, Heinrich Lenz stated Lenz's law, which says that the direction of induced current flow in an object will be such that its magnetic field will oppose the magnetic field that caused the current flow. Eddy currents develop secondary flux that cancels a part of the external flux. French physicist Leon Foucault is credited with having discovered Eddy currents. In 1855 he discovered that the force required for the rotation of a copper disc becomes greater when it is made to rotate with its rim between the poles of a magnet, the disc at the same time becoming heated by the eddy current induced in the metal. The first use of eddy current for Non-destructive testing occurred in 1879 when Hughes used the principles to conduct metallurgical sorting tests when a conductor moves relative to the field generated by a source, electromotive forces (EMFs) can be generated around loops within the conductor. These EMFs acting on the resistivity of the material generate a current around the loop, in accordance with Faraday's law of induction. These currents dissipate energy, and create a magnetic field that tends to oppose changes in the current- they have inductance. Eddy currents are created when a conductor experiences changes in the magnetic field. If either the conductor is moving through a steady magnetic field, or the magnetic field is changing around a stationary conductor, eddy currents will occur in the conductor. Both effects are present when a conductor moves through a varying magnetic field, as is the case at the top and bottom edges of the magnetized region shown in the diagram. Eddy currents will be generated wherever a conducting object experiences a change in the intensity or direction of the magnetic field at any point within it, and not just at the boundaries. The swirling current set up in the conductor is due to electrons experiencing a Lorentz force that is perpendicular to their motion. Hence, they veer to their right, or left, depending on the direction of the applied field and whether the strength of the field is increasing or declining. The resistivity of the conductor acts to damp the amplitude of the eddy currents, as well as straighten their paths. Lenz's law encapsulates the fact that the current swirls in such a way as to create an induced magnetic field that opposes the phenomenon that created it. In the case of a varying applied field, the induced field will always be in the opposite direction to that applied. The same will be true when a varying external field is increasing in strength. However, when a varying field is falling in strength, the induced field will be in the same direction as that originally applied, in order to oppose the decline. An object or part of an object experiences steady field intensity and direction where there is still relative motion of the field and the object (for example in the center of the field in the diagram), or unsteady fields where the currents cannot circulate due to the geometry of the conductor. In these situations charges collect on or within the object and these charges then produce static electric potentials that oppose any further current. Currents may be initially associated with the creation of static potentials, but these may be transitory and small. Eddy currents generate resistive losses that transform some forms of energy, such as kinetic energy, into heat. This Joule heating reduces efficiency of iron-core transformers and electric motors and other devices that use changing magnetic fields. Eddy currents are minimized in these devices by selecting magnetic core materials that have low electrical conductivity (e.g., ferrites) or by using thin sheets of magnetic material, known as laminations. Electrons cannot cross the insulating gap between the laminations and so are unable to circulate on wide arcs. Charges gather at the lamination boundaries, in a process analogous to the Hall Effect, producing electric fields that oppose any further accumulation of charge and hence suppressing the eddy currents. The shorter the distance between adjacent laminations (i.e., the greater the number of laminations per unit area, perpendicular to the applied field), the greater the suppression of eddy currents. The conversion of input energy to heat is not always undesirable, however, as there are some practical applications. One is in the brakes of some trains known as eddy current brakes. During braking, the metal wheels are exposed to a magnetic field from an electromagnet, generating eddy currents in the wheels. The eddy currents meet resistance as charges flow through the metal, thus dissipating energy as heat, and this acts to slow the wheels down. The faster the wheels are spinning, the stronger the effect, meaning that as the train slows the braking force is reduced, producing a smooth stopping motion. Induction heating makes use of eddy currents to provide heating of metal objects.

3. VIBRATION MEASUREMENT OF OF A ROTATING MACHINE BY EDDY CURRENT SENSOR

As mentioned before, the main idea of these sensors is to measure the vibration without contacting to the shaft. As you know measurement devices based on piezoelectric or seismic should have contact to the machine. This may cause some operational problem during machine rotation. So, the Bently Nevada invents this method to generate eddy current at the ferromagnetic part of the machine shaft by magnetic field. Greater magnetic field at a lower distance of the ferromagnetic body would generate bigger eddy current amplitude. Also these circles of current are generated at the various layer of the body. At the deep layer, the amplitude of the current is small. And the amplitude goes maximum at the surface of the body. Figure No.1 shows this effect.

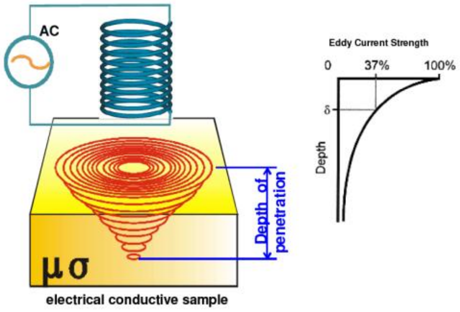

Fig. No.1. Circuit Schematic of shell effect

This effect is renowned as shell effect. A vibration measurement complex comprise of 3 main parts:

- Proximitor, which is a oscillator, modulator and demodulator
- Non contacting probe which is a coil of a good conductive metal like silver.
- Extension Cable to connect the proximitor to the probe.

Figure 2 shows above three parts in a combination with each other.

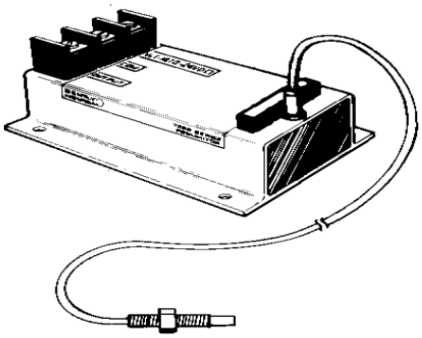

Figure 2, a combination of 3 parts of an instant vibration sensor

Proximitor is an electronic device which has two main duties:

- Generating radio frequency waves by its oscillatory circuits and modulating that.

- Extracting necessary information from the returned RF waves by its own demodulator circuits.

This device is supplied by a power at the range of -17.5 to -26 volts. The proximitor generates the RF waves at a determined range. This frequency depends on the inductance of the probe coil and capacitance of the extension cable. Fig No.3 shows the related parts of a vibration sensor accompanied with its circuit schematic.

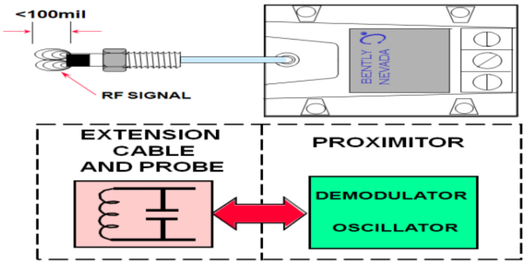

Figure 3. Circuitry schematic of a vibration sensor

The frequency range of the generated signal is between 500 KHz and 2 MHz depending on the type of the probe and extension cable. This electric signal at the probe would generate a variable electromagnetic field around its tip. At an instance of a real eddy current sensor fabricated by Bently Corporation, a variable electromagnetic field can affect to the distance of 0.1 inches from the probe tip. Fig No.4 shows the way of affecting a field to a ferromagnetic shaft to generate many loops of eddy current.

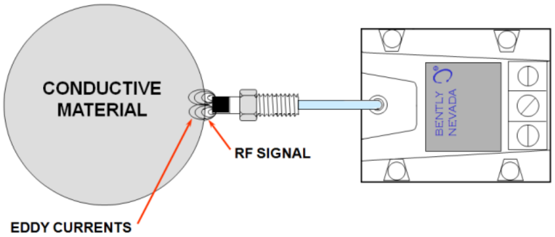

Figure 4. Affecting an electromagnetic field to a ferromagnetic shaft

If the probe approaches to the shaft, the amplitude of electromagnetic field effecting to the shaft will be greater, then the induction of the eddy current would be at bigger amplitude and also the amplitude of the returned RF signal would be lower. In other words, measurement of the returned RF signal can be an evaluation of the distance between the probe tip and the shaft body. The more distance generate less amplitude of eddy current and then more amplitude of returned RF signal. Figure No. 5 shows the returned RF signal at a low distance (A) and high distance (A) between probe and shaft.

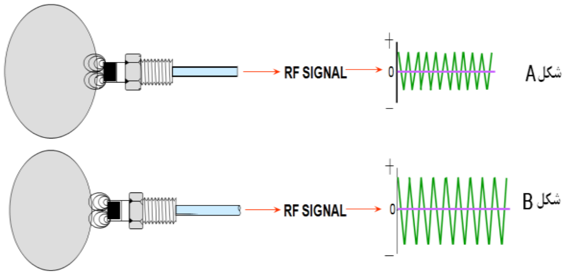

Figure 5. The impact of the distance to the amplitude of returned RFsignal.

In a vibrating shaft, the distance would be low and high periodically and therefore the amplitude of the RF signal would be variable at a frequency of the shaft vibration. Figure no. 6 shows the RF amplitude at a vibrating shaft.

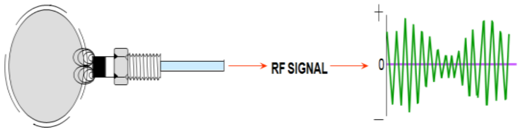

Figure 6. Returned RF signal at vibrating shaft

Now a demodulator is used to extract the below cover of this signal as shown at the fig No.7.

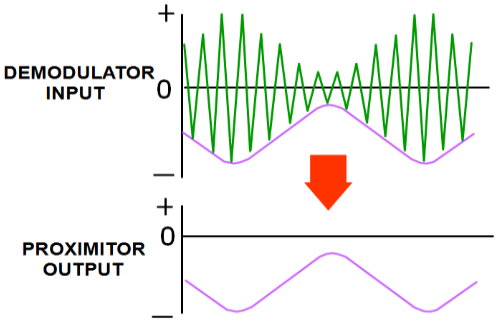

Figure 7. Output of the demodulator in a vibrating shaft

At a fixed distance, the cover of the signal would be a negative constant, but when the shaft oscillates, the output of the demodulator is like fig. No 6. This signal has a DC content which shows the average distance between the probe and the shaft and also an AC content which shows the dynamic movement and frequency of oscillation of the shaft. The output of the demodulator is the output of the proximitor and also the final output of the device. This signal would be analyzed to extract necessary information about the health of the machine operation. The analysis of this information is an aspect of the inspection of the rotating machine. Condition monitoring is the process of monitoring a parameter of condition in machinery, such that a significant change is indicative of a developing failure. It is a major component of predictive maintenance. The use of conditional monitoring allows maintenance to be scheduled, or other actions to be taken to avoid the consequences of failure, before the failure occurs. Nevertheless, a deviation from a reference value (e.g. temperature or vibration behavior) must occur to identify impeding damages. Predictive Maintenance does not predict failure. Machines with defects are more at risk of failure than defect free machines. Once a defect has been identified, the failure process has already commenced and CM systems can only measure the deterioration of the condition. Intervention in the early stages of deterioration is usually much more cost effective than allowing the machinery to fail. Condition monitoring has a unique benefit in that the actual load, and subsequent heat dissipation that represents normal service can be seen and conditions that would shorten normal lifespan can be addressed before repeated failures occur. Serviceable machinery includes rotating equipment and stationary plant such as boilers and heat exchangers [1], [2].

4. ROTATING EQUIPMENT

The most commonly used method for rotating machines is called vibration analysis. Measurements can be taken on machine bearing casings with seismic or piezo-electric transducers to measure the casing vibrations, and on the vast majority of critical machines, with eddy-current transducers that directly observe the rotating shafts to measure the radial (and axial) vibration of the shaft. The level of vibration can be compared with historical baseline values such as former startups and shutdowns, and in some cases established standards such as load changes, to assess the severity. Interpreting the vibration signal obtained is a complex process that requires specialized training and experience. Exceptions are state-of-the-art technologies that provide the vast majority of data analysis automatically and provide information instead of data. One commonly employed technique is to examine the individual frequencies present in the signal. These frequencies correspond to certain mechanical components (for example, the various pieces that make up a rolling-element bearing) or certain malfunctions (such as shaft unbalance or misalignment). By examining these frequencies and their harmonics, the analyst can often identify the location and type of problem, and sometimes the root cause as well. For example, high vibration at the frequency corresponding to the speed of rotation is most often due to residual imbalance and is corrected by balancing the machine. As another example, a degrading rolling-element bearing will usually exhibit increasing vibration signals at specific frequencies as it wears. Special analysis instruments can detect this wear weeks or even months before failure, giving ample warning to schedule replacement before a failure which could cause a much longer down-time. Beside all sensors and data analysis it is important to keep in mind that more than 80% of all complex mechanical equipment fails accidentally and without any relation to their life-cycle period. Most vibration analysis instruments today utilize a Fast Fourier Transform (FFT) which is a special case of the generalized Discrete Fourier Transform and converts the vibration signal from its time domain representation to its equivalent frequency domain representation. However, frequency analysis (sometimes called Spectral Analysis or Vibration Signature Analysis) is only one aspect of interpreting the information contained in a vibration signal. Frequency analysis tends to be most useful on machines that employ rolling element bearings and whose main failure modes tend to be the degradation of those bearings, which typically exhibit an increase in characteristic frequencies associated with the bearing geometries and constructions. In contrast, depending on the type of machine, its typical malfunctions, the bearing types employed, rotational speeds, and other factors, the skilled analyst will often need to utilize additional diagnostic tools, such as examining the time domain signal, the phase relationship between vibration components and a timing mark on the machine shaft (often known as a keyphasor), historical trends of vibration levels, the shape of vibration, and numerous other aspects of the signal along with other information from the process such as load, bearing temperatures, flow rates, valve positions and pressures to provide an accurate diagnosis. This is particularly true of machines that use fluid bearings rather than rolling-element bearings. To enable them to look at this data in a more simplified form vibration analysts or machinery diagnostic engineers have adopted a number of mathematical plots to show machine problems and running characteristics, these plots include the bode plot, the waterfall plot, the polar plot and the orbit time base plot amongst others. Handheld data collectors and analyzers are now commonplace on non-critical or balance of plant machines on which permanent on-line vibration instrumentation cannot be economically justified. The technician can collect data samples from a number of machines, and then download the data into a computer where the analyst (and sometimes artificial intelligence) can examine the data for changes indicative of malfunctions and impending failures. For larger, more critical machines where safety implications, production interruptions (so-called "downtime"), replacement parts, and other costs of failure can be appreciable (determined by the criticality index), a permanent monitoring system is typically employed rather than relying on periodic handheld data collection. However, the diagnostic methods and tools available from either approach are generally the same. Performance monitoring is a less well-known condition monitoring technique. It can be applied to rotating machinery such as pumps and turbines, as well as stationary items such as boilers and heat exchangers. Measurements are required of physical quantities: temperature, pressure, flow, speed, displacement, according to the plant item. Absolute accuracy is rarely necessary, but repeatable data is needed. Calibrated test instruments are usually needed, but some success has been achieved in plant with DCS (Distributed Control Systems). Performance analysis is often closely related to energy efficiency, and therefore has long been applied in steam power generation plants. In some cases, it is possible to calculate the optimum time for overhaul to restore degraded performance.

5. Frequency Analysis of vibration data

Vibration data analysis is a complicated process and needs special experience and proficiency. One of the most famous methods of analyzing vibration data is frequency analysis. Figure No. 8 shows a real instance of an output data of a vibration sensor related to a ball bearing [3]. This data is extracted by a Digital oscilloscope with brand of TEKTRONIX model TDS2022B.

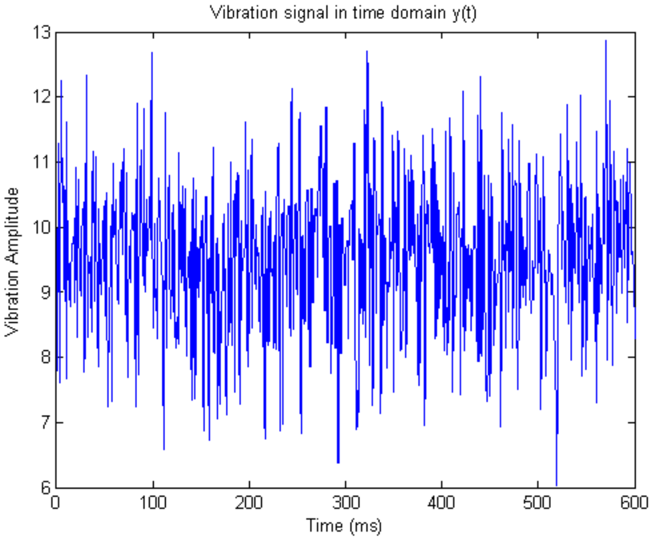

Figure 8. Output signal of a vibration sensor in time domain

More engineering investigation showed that this bearing has some problem in its own operation. It is apparent that the vibration data extracts from the sensor at the time domain. In this domain the data is completely amusing and can be analyzed hardly. So we are going to find a mathematical tool to analyze this data in a comfortable and effective way. This effective method is fast Fourier transform. Figure No. 9 shows the output of the FFT on the above vibration data.

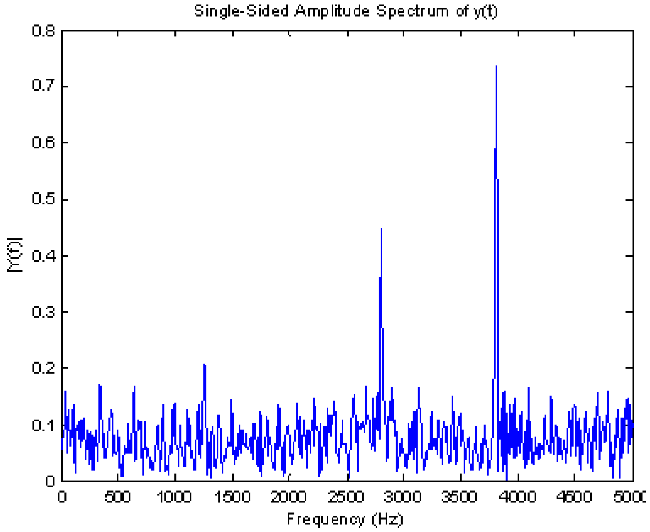

Figure 9. FFT of the above vibration data

Above figure shows power spectrum of the vibration data. Various defects like spall and crack at the surface of the bearing can be detected by power spectrum data. When there is a defect at one point of the bearing, in every rotation and crossing of this point to the vibration sensor, a certain impact can be seen. These effects can generate some resonance mode at the bearing, structures around bearing or at the sensor. In fact, generation of a resonance mode means generation of a vibration at the same frequency. These resonance modes cause impulse signals at the power spectrum.

Power spectral density extracts from the FFT using the equation No.1.

$$PSD = f(\omega) = \frac{1}{2\pi}\left(\left|\int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt\right|\right)^{2} = \frac{1}{2\pi}\hat{x}(\omega)\hat{x}*(\omega)$$

Eq.1

For our case the psd is extracted from discrete statement of its formula as shown in equation no.2.

$$PSD = f(\omega) = \frac{(\Delta t)^2}{2\pi}\left(\left|\sum_{-\infty}^{\infty} x_n e^{-i\omega n}\right|\right)^{2} = \frac{(\Delta t)^2}{2\pi}\hat{x}d(\omega)\hat{x}d*(\omega)$$

Eq.2

The calculation of power spectral density is done using matlab software and its related code is shown at the appendix.

The power spectrum shown at fig. no. 8, an impulse is present at the frequency of 3.8 kHz [5]. This impulse signal is as a result of a defect at the inner circle of the related bearing. Hilbert transform and wavelet based techniques are the other methods of frequency analyzing of vibration data. Figure no.10 shows the output of the wavelet based technique for the vibration data of above ball bearing.

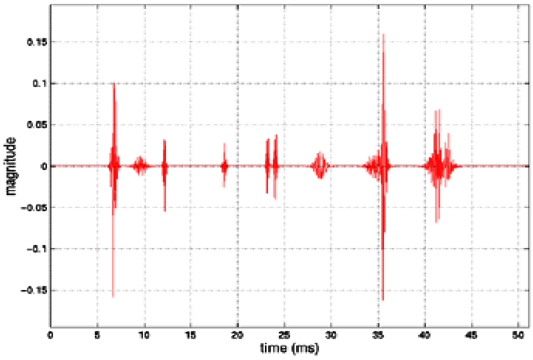

Figure 10, Hilbert transform of the vibration data

This figure shows a defect at the bearing apparently. In a healthy bearing all of the above transform generate smooth figures. So frequency analyzing can extract useful data from the failure of the machine. For instance, high amplitude vibration of the shaft at its rotation frequency is a result of its misalignment and can be rectified by rebalancing of the shaft [4]. As stated before, frequency analyzing is most common method of investigation of the machine condition, but experienced analyzer use another analyzing method, keyphasor, Also. This method is introduced at the rest of the paper.

6. Keyphasor Analysis

A simple example is a pair of pendulums. When they are set so that they swing in Unison, they are said to be "in phase" as shown in Figure 11A, and if they are set to Swing in opposition, they are "out of phase" as shown in Figure 11B.

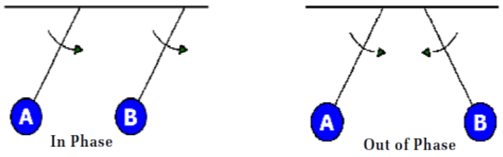

Figure 11. Schematic concept of phase

Of course there are infinite conditions that exist between in phase and out of phase. These conditions are described using angles such as "90 degrees phase difference" for example. If you consider the left side stop position as zero phase point, then the pendulum is at 180 degrees phase when at the extreme right, and continues on to 360 degrees as it proceeds back to the left hand extreme. If the pendulums are swinging at the same frequency, then their phase difference will always be the same. If not, their phase difference will be changing with time. Normally when talking about phase, we confine ourselves to one single frequency and if the motion or vibration is in a steady state, then the phase won't change with time. Now consider a rotating machine. As you know, at a determined frequency, movement phase will change during the time. Also we need a reference point to measure the phase respect to the reference point. The phase of this reference point must vary during the rotation of the machine to be a proper reference for phase measurement [6]. This periodic reference point is generated by keyphasor sensor. The keyphasor sensor in each rotation of the shaft generates a single voltage pulse. It is necessary to be said that, a single keyphasor sensor is not enough for phase measurement and another vibration sensor must be located around the shaft to measure the vibration. Phase measurement is done by comparing the phase of this data by the reference point made by keyphasor sensor. The keyphasor sensor is an eddy current device too. This sensor, locates in a position which a notch is generated at the shaft. As the shaft rotates, in every rotation the sensor passes to the related point and then because of a change in the distance, a pulse will be generated at the sensor output. Two different type of installation of keyphasor sensor is shown in figure No 12.

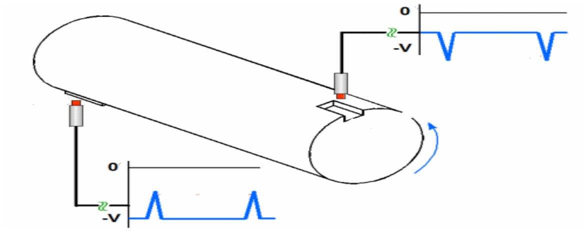

Figure 12. Keyphasor sensor mounted in front of a special point at the shaft body and generates positive or negative voltage pulses.

Keyphasor sensor has 3 important duties: its first application is to count the number of shaft rotation in a determined time (shaft rotation speed, rpm). In the other hand, its generated pulses are the reference for the measurement of the movement phase. Moreover, keyphasor pulses are used by electronic circuits to build a clock pulse to digitize vibration data for analyzing. The calculation method for phase measurement is shown in figure 13.

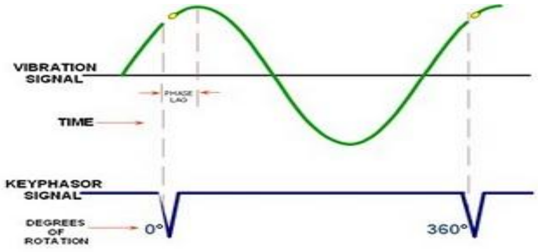

Figure 13. The method of phase measurement.

For the measurement of the phase, the measurement system counts the number of the degrees from the threshold point of the keyphasor pulse to the first positive peak of the vibration wave. This threshold point will be selected from the middle of the pulse to avoid any noise disturbing.

7. REAL WORLD APPLICATION

Jumping from our simple pendulum to the real world, phase differences between two points on a machine reveal useful information. For example, if a machine with an overhung rotor is vibrating excessively at its rotational rate, the vibration could have several different causes, i.e. imbalance, wobble, or misalignment. Observing the phase at two points on opposite sides of the coupling can help differentiate the actual problem. Imbalance and/or wobble will result in "in phase" rotational rate vibration at the two measurement points (Figure 14B) and misalignment will cause out of phase vibration (Figure 14A).

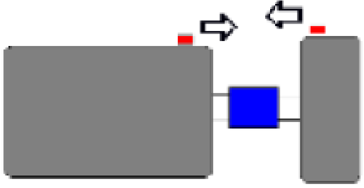

Fig 14A. Angular Misalignment causes out of phase axial movement at the rotational rate.

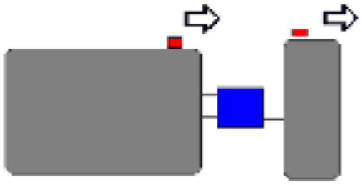

Figure 14B. Imbalance of an overhung rotor causes vertical and lateral movement that is in phase at the rotational rate.

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Using keyphasor data to balance unbalanced shaft

In the technical application about the rotating machine, there is a process which is renowned as dynamic balancing of the shaft. In this case, the shaft rotation is in a condition which a weight must be added in a specific situation to make the shaft balanced. For this goal, vibration data would be extracted from the vibration sensor and also compare to the keyphasor pulse to measure the movement phase. So vibration phase is measured instantly. From this information, a specific computer program, analyze the condition and calculate the difference between the center of the mass and center of the rotation of the shaft and then calculate the needed weight to be added at a certain point from the keyphasor notch on the shaft to balance the rotation.

8. CONCLUSION

In this paper a very important concept in instrument is presented. Vibration sensor based on eddy current is introduced and its operation principles described. Main contribution of this research is a way to analyze real vibration data and discover the failure of a rotating machine by MATLAB software. A mathematic tool presented to analyze the vibration data, frequency and keyphasor analyzing method.

The final part shows the real important vibration data from some real machines which have failure. The results of the analyzing these data based on some experiences presented at the final part. The results of this research give a very good insight from the vibration concept and the ways of using vibration data.

Appendix: Matlab code for calculating power spectral density

```
%X: Osiloscope data

x=[]

plot(x)     % Plot of the vibration at the time domain
title('Vibration signal in time domain y(t)')
xlabel('Time (ms)')
ylabel('Vibration Amplitude')
y=x-9.5;     % Elemination of the DC bias
figure
NFFT = 2^nextpow2(L); % Next power of 2 from length of y
Y = fft(y,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2);
% Plot single-sided amplitude spectrum.
plot(f,2*abs(Y(1:NFFT/2)))
title('Single-Sided Amplitude Spectrum of y(t)')
xlabel('Frequency (Hz)')
ylabel('|Y(f)|')
```

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