Vibration Monitoring: Envelope Signal Processing

Using Envelope Signal Processing in Vibration Monitoring of Rolling Element Bearings

Summary

This article presents a practical discussion of the techniques used to monitor rolling element bearings. Examples of the processing technique of enveloping, as well as actual analysis data are used to convey the use of this technology.

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Introduction

Why do we want to Monitor Bearings?

In any manufacturing or processing plant where rotating equipment is used, the majority of the maintenance capital expenditure is spent on bearings. Every time an overhaul is performed, salesmen from the major bearing manufacturer make it their business to ensure that the bearings are replaced.

Whatever the reason which caused the machine to break down, the bearings are often replaced, in the vain hope that they might last longer the next time. Bearings are indeed very often blamed for the machine breakdown.

However, the failure of the bearing is a result of a number of different problems: a machine running unbalanced, misaligned, at a critical speed; a bearing fitted incorrectly; the wrong grease being used; or maybe no grease being used at all. A bearing rarely deteriorates from internal causes. Often it is the result of an external force or cause. Very often bearings are replaced without the origin of the failure being addressed. It is well documented that the majority of machinery vibration problems are caused by unbalance or misalignment, often resulting in bearing failure.

Acceleration enveloping is not a new process in the analysis of bearings. It has been around for many years and should be considered when implementing any type of condition monitoring program in conjunction with other complementary techniques. Such techniques are bearing temperature monitoring, oil lubricant analysis, changing running noise and spectral velocity trending; acceleration enveloping is an additional analysis tool.

How is Bearing Damage Exhibited?

Bearing damage exhibits itself by increased noise and vibration, temperature or energy in the higher frequency range. On the wheel bearings of a car, for example, the car is taken to the garage to have the bearings replaced only when the noise becomes unbearable and the driver considers that the wheels are going to fall off of the car.

For representational purposes, Figure 1 depicts a bearing housing, or in this case a pillow block, in which a damaged rolling element bearing with a single defect on the outer race is present. Attached to the bearing housing is an accelerometer. The accelerometer is measuring the vibration transmitted through the bearing and housing. Each time a rolling element goes past the defect shown on the outer race, there is an impact. The impacts are quite small compared to the underlying running vibration. However there are many of them. Depending on the bearing internal geometry and the number of elements, there will be approximately 6 to 10 impacts in a single rotation of the shaft, as the elements hit the defect. For the accelerometer to detect the impacts, they have to travel through the bearing itself and the bearing housing. The impacts cause excitation of structural resonances in the bearing and housing.

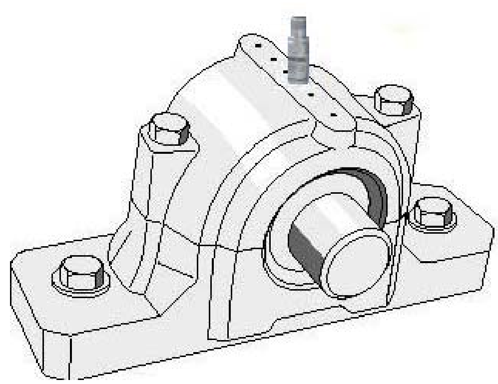


Figure 1. Pillow block with a sensor mounted on the top of the housing collecting data. In this example, there is a defect between the 12 o'clock and 1 o'clock positions, looking at the shaft axially.

Figure 2 shows the time domain signal of the periodic impacts from the rolling element hitting the defect superimposed on the lower frequency rotor related vibration. The Fast Fourier Transform (FFT) of this signal tends to look like Figure 3, where the shaft running speed is clearly visible, possibly with additional harmonics indicating looseness, misalignment, or unbalance, with a 'haystack' effect shown in the higher frequency region (to the right side of the spectrum). This higher frequency energy is caused by a combination of the impacts themselves and the structural resonance excited by the impacts. What is often very misleading is that, if this frequency spectrum was looked at in isolation, the higher frequency energy could be attributed to a wide variety of defects, for example pump cavitation, gearbox noise and structural resonance on their own, steam leaks, etc.

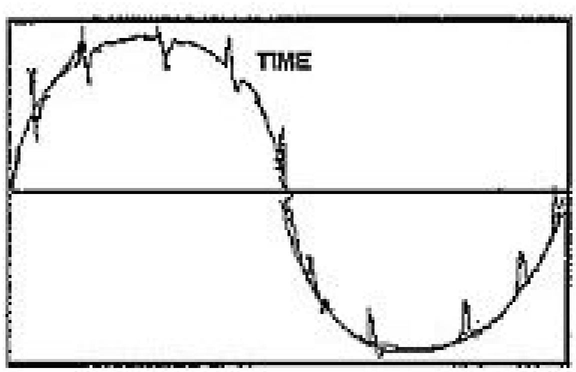


Figure 2. Display of the time waveform of a single signal (sine wave). The peaks, or spikes, in the signal are an indication of a defect on the bearing.

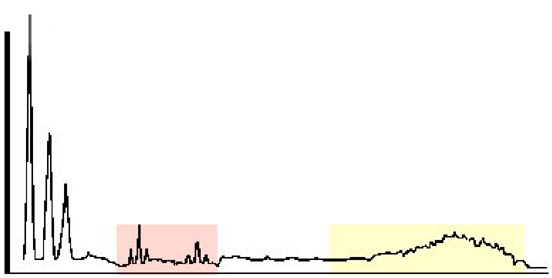


Figure 3. Velocity spectrum of a deteriorating bearing. The first three peaks are machine conditions such as looseness. The hump shape, to the far right, is a deteriorated bearing signal. Also referred to as high-energy noise. The area just to the right of the first three peaks is the bearing defect fundamental frequencies.

Figure 4 shows the different signal processing effects. A single impulse is shown in both the time domain and the frequency domain in Figure 4a. A series of impulses is shown in Figure 4b. The difference between a single impact and a series of impacts is that a great number of harmonics are generated. Figure 4c shows a typical transfer function or frequency response function displaying structural resonances for a bearing housing. Figure 4d shows the time and frequency domain signal from low frequency shaft related vibration on its own. Figure 4e shows the combined effect in the frequency domain of Figure 4b, Figure 4c and Figure 4d. Figure 4e and Figures 2 and 3 can be considered the same, however, to be able to display the harmonics in the haystack or high frequency region, the use of very high resolution FFT with a small bandwidth would be required. In typical vibration spectra, the areas of high frequency energy appear as lumps of energy, rather than a lot of discrete harmonics. As a bearing deteriorates, the impacts get larger, increasing the vibration response and the amplitude of the haystack or higher frequency energy.

Alternative Techniques

There are many different techniques used to monitor bearing deterioration, for example overall acceleration, filtered acceleration, spike energy, crest factor, etc. In essence all of these techniques are trying to put a value on how this high frequency energy or haystack effect increases over time. In general, with the above techniques there will be a single number, which, if trended over time, can increase as a bearing deteriorates further, but the values can also drop. These techniques cannot determine what causes the high frequency energy to increase. Is it caused by a bearing deteriorating, or is it a gearbox meshing problem, could it be a pump cavitating, is there a casing resonance problem? There are a myriad of reasons as to why the haystack is displayed in the spectrum, or the high frequency energy starts to rise. What causes the haystack and why, must be determined.

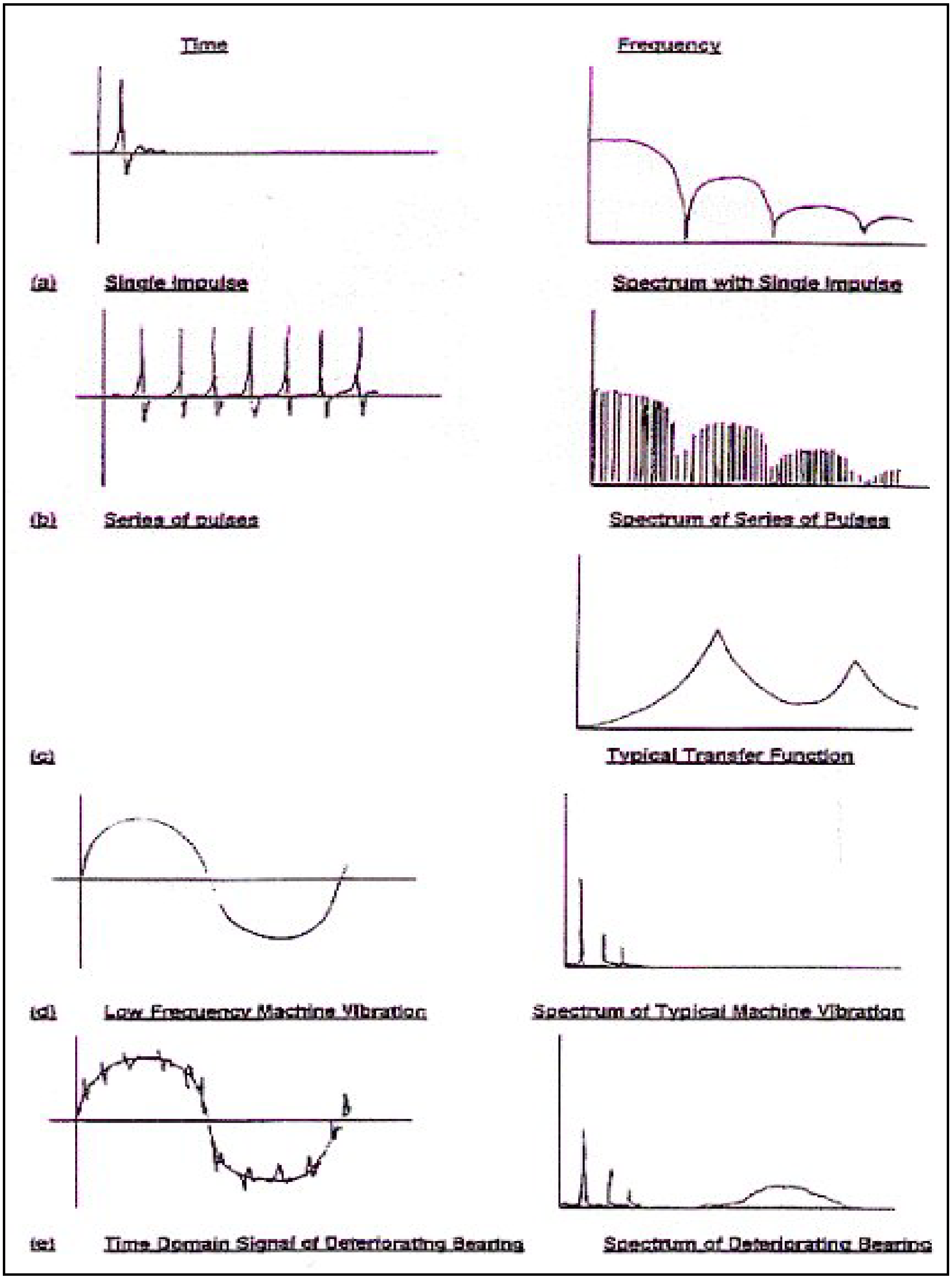


Figure 4. Series of pulses and frequency spectra. A detailed description of each figure is contained in the prior paragraph text.

A Simple Guide to Envelope Signal Processing

Envelope Signal Processing is a two-stage process. The first process involves band-pass filtering of the time domain signal using a band pass filter that centers on the region of high frequency energy. Figure 6b shows the filtered output in the time domain of the original signal shown in Figure 6a. The frequency domain is also shown to aid the understanding of the process. The filtering process results in a series of spiky bursts of energy, which are the impacts from the rolling elements hitting the defect as the bearing rotates.

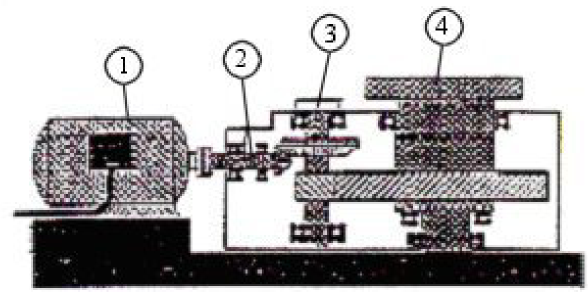
The second stage of the process is to pass this filtered time signal through an enveloper in order to extract the repetition rate of the spiky bursts of energy. The enveloper is an electronic circuit that demodulates or rectifies the signal. The result of passing the signal through the enveloper is shown in Figure 6c. What is extracted is the repetition rate of the impacts. If the FFT spectrum of this enveloped signal is then taken, it displays the bearing characteristics frequency and its harmonics.

Example: Gearbox Shaft Bearing

The following case study shows what a typical enveloped spectrum will look like. The spectra were collected from a power station pulverizing mill drive gearbox. A 350 HP motor drives the gearbox. A schematic is shown in Figure 5. The gearbox comprises of an input shaft, intermediate shaft and an output shaft. Two rolling element bearings, an SKF 232224C and a Timken 97000 series, support the input shaft.

Figure 7 displays the velocity spectrum collected in the vertical direction. The cursor displays the position of the input shaft fundamental and harmonics, however these are not clearly visible in the spectrum. Figure 8 displays the enveloped signal collected at the same position, again in the vertical direction. From this enveloped spectrum, the input fundamental and harmonics are displayed. The inner race defect frequency from the Timken bearing is also displayed, with sidebands of input shaft running speed around the fundamental inner race defect frequency.

As the bearing begins to deteriorate it will develop as a single spall or pitting, on, say, the inner race. The peaks at inner race defect frequency will appear, with possibly some harmonics. The defect may then be transferred onto the ball or rolling element causing defect frequencies to appear at ball passing frequency. A defect may then begin to grow on the outer race causing outer race fundamental and harmonic frequencies to appear. As the bearing deteriorates further the carpet level will begin to rise. The carpet level can be defined as the background noise level in the enveloped spectrum.



1 - AC Induction Motor, 350HP, 965 rpm
2 - Gearbox Input Shaft (n = 985)
3 - Gearbox Intermediate Shaft (n = 222)
4 - Gearbox Output Shaft (n = 37)

Figure 5. Illustration of a pulverizing mill drive gearbox with the various components indicated by the numbering (n = the speed of the shaft in rpm).

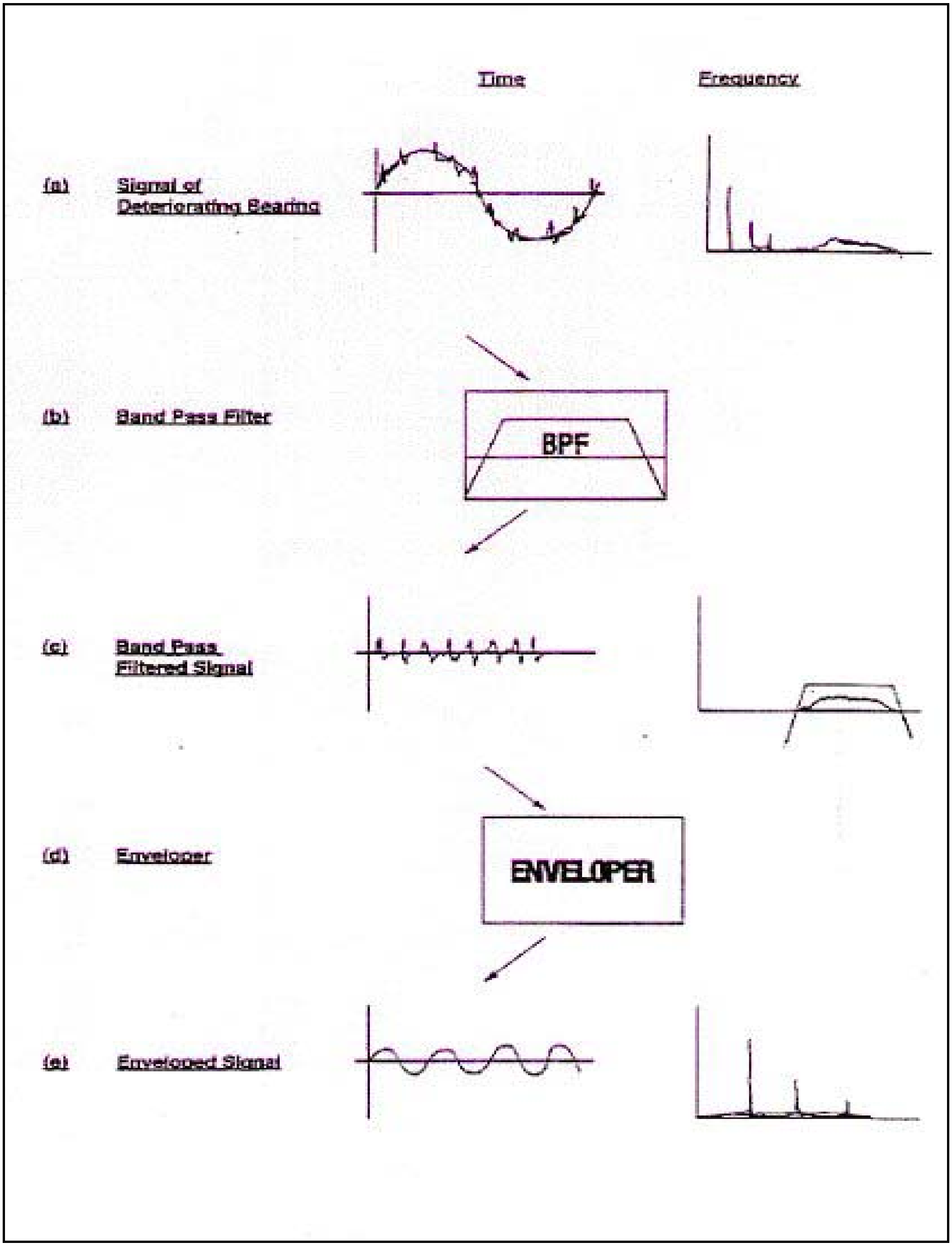


Figure 6. An illustration of the steps taken to envelope a time waveform signal to determine deteriorating components in the system such as bearings or gears.

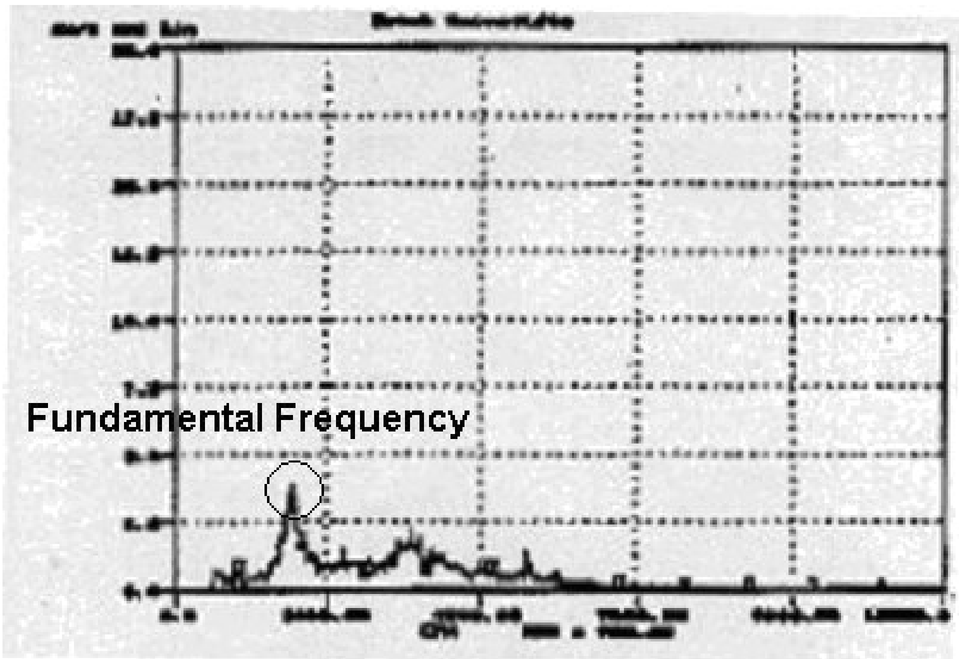


Figure 7. Velocity spectrum of a gearbox taken at the input shaft location (point 2 in Figure 5).

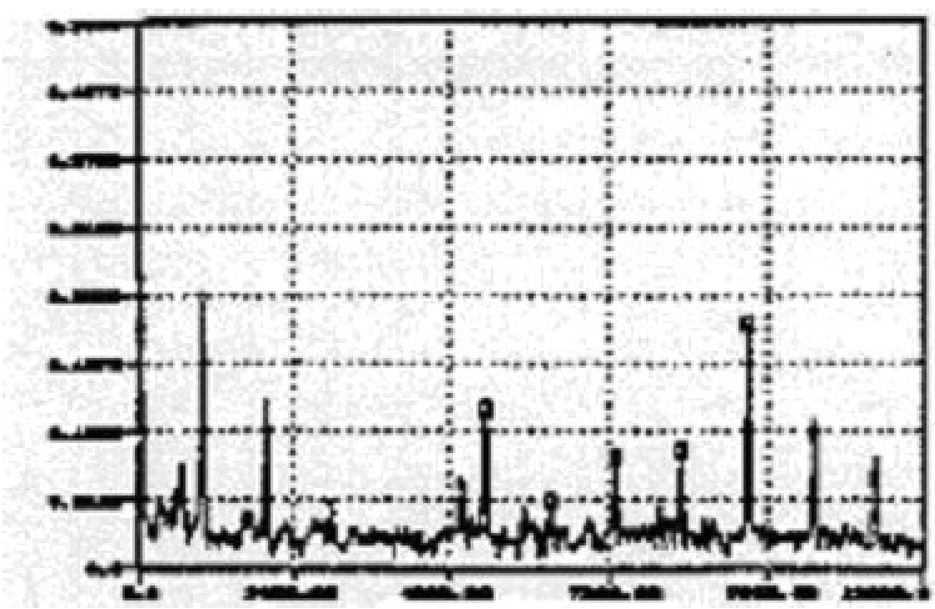


Figure 8. The enveloped spectrum collected at the same point as the velocity spectrum in Figure 7. This spectrum clearly shows the multiple harmonics indicated with the circular markers

Example: Motor Shaft Bearing

Figure 9 displays an enveloped spectrum from a SKF N318 bearing. The bearing was fitted in the drive end of a 115 kW GEC motor driving a Worthington Simpson single stage pump. The enveloped spectrum shows inner race and outer race defects at approximately 20 dB above the carpet level, the carpet level in this enveloped spectrum is approximately 110 dB. Upon dismantling the bearing, defects were found to have been caused by brinelling. Figure 10 shows the enveloped spectrum after the bearing was replaced. This pump is one of five situated on a platform in a nuclear reprocessing plant. The pumps supply cooling water, operating on a four on/one standby basis. The platform where they are situated is built from I-beams and checker plate. The (false) brinelling of the bearing occurred when the pump was removed to allow a new impeller casing to be fitted. The motor shaft was therefore not supported and the vibration generated by the other four pumps was sufficient to cause damage to the inner and outer raceways of the bearing.

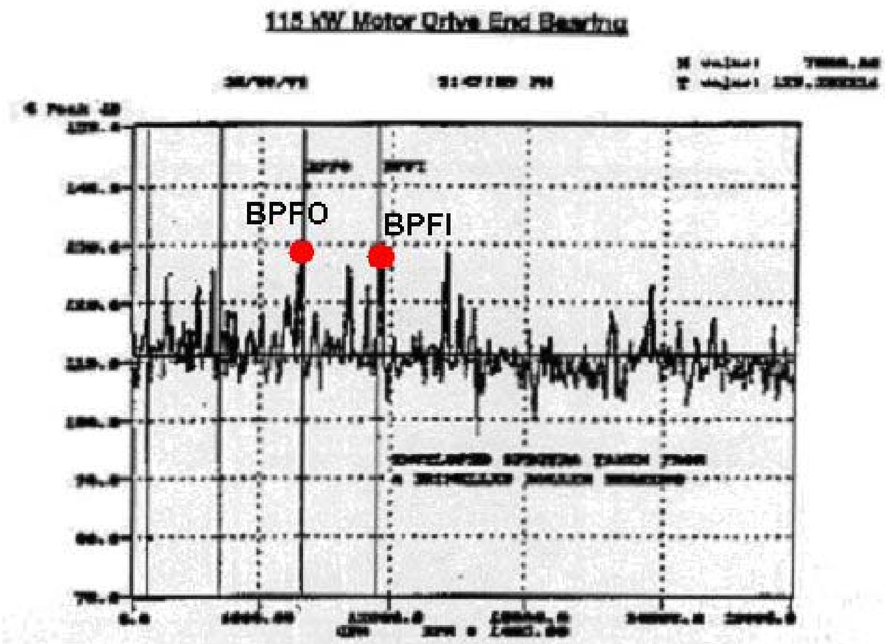


Figure 9. An enveloped spectrum from an SKF N318 bearing. The bearing was fitted in the drive end of a 115 kW GEC motor driving a Worthington Simpson single stage pump. The markers indicate outer race and inner race defect frequencies marked with the red markers.

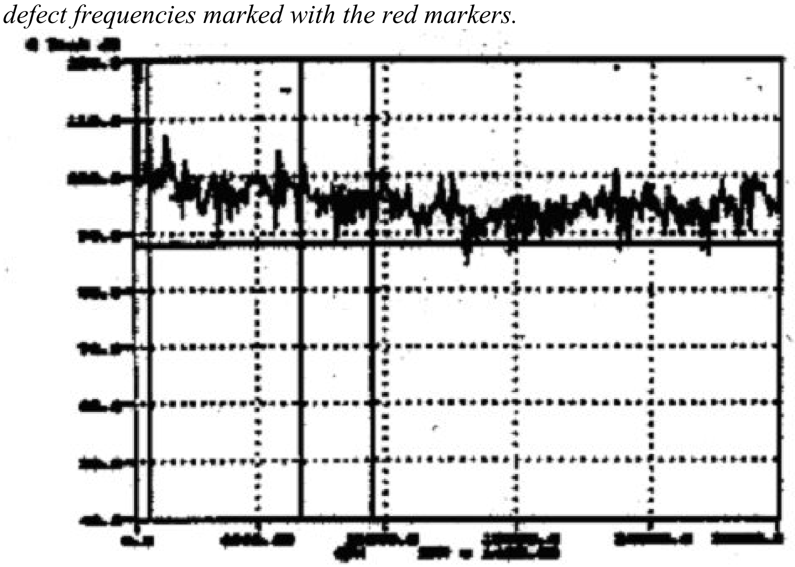


Figure 10. The spectrum of the SKF N318 bearing after the bearing was replaced. As indicated above, there are no major elevated peaks in the spectrum.

How do I Collect the Enveloped Data?

The best technique for collecting the enveloped data is using an accelerometer to measure the raw acceleration signal. The accelerometer should be placed as close to the bearing as possible, preferably in the load zone. For the highest quality of data collection, the accelerometer should be mounted using a stud or bolt fixing directly to the machine or bearing housing. A glued stud or magnetic mount will give reasonable results.

What Type of Data is Required for an Enveloped Analysis?

In Figure 9, the data was taken from an SKF N318 bearing. The frequency range is 30,000 CPM. The motor running speed was 1485 CPM. The bearing monitored has fundamental characteristics frequencies at 11360 CPM inner race, 7930 CPM outer race, 4027 CPM ball spin and 606 CPM cage frequency. The characteristic frequencies of a bearing can be calculated from standard formula if the internal geometry is known. Alternatively, if the number of rolling elements is known, characteristic frequencies can be estimated. The majority of bearing manufacturers make the characteristic frequencies or ratios available in some format. Many condition monitoring programs have them built in. The fundamental defect frequency can be calculated from the bearing defect ratios and the shaft running speed. It is suggested that a certain number of harmonics of the defect frequencies be monitored. This is typically three: the fundamental, second and third harmonic. In general, the inner race defect frequency for bearings is normally the largest, at anywhere between 6 and 10 times shaft running speed. Therefore, the frequency range chosen, should allow the user to view between 18 and 30 orders of shaft running speed. Figure 9 shows up to 20 times shaft running speed.

Which is the Most Useful Envelope Band Pass Filter?

The best method to determine the most suitable band pass filter is to experiment with the bearing to be monitored. An acceleration spectrum between 0 and 20 kHz should be collected, with particular attention being given to haystacks or frequent regions where high-level energy is present. Some users have gone as far as performing structural resonance tests to evaluate which envelope band should be used to obtain optimal results. In practice the most commonly used envelope filter is the 2.5 kHz - 5 kHz filter.

When selecting the number of lines and number of averages to be used, a certain amount of experimentation and experience will again come into play. Typically, 400 lines will be used, however envelope spectra can become very complex with sidebands of running speed or cage frequency appearing around inner or outer frequencies. Often the bearing characteristic frequencies can fall close to integer value multiples of running speed. In both cases, it is often advisable to use 800 or 1600 lines to increase the resolution of the frequency spectrum to make a correct and meaningful diagnosis. In general, four or five process averages are selected when collecting envelope spectra.

Alarm Settings

A condition monitoring program must be able to provide a warning that either the carpet level is rising, the defect frequency peaks are rising, or new peaks are beginning to appear in the spectrum, in order to catch deteriorating bearings early. The simplest method of performing this automatically is by using some of the powerful narrow band alarming techniques available. A narrow band alarm as in Figure 11 will catch rising carpet levels, rising peaks or new peaks from different components of the bearing. Figure 12 shows another example of alarm setting.

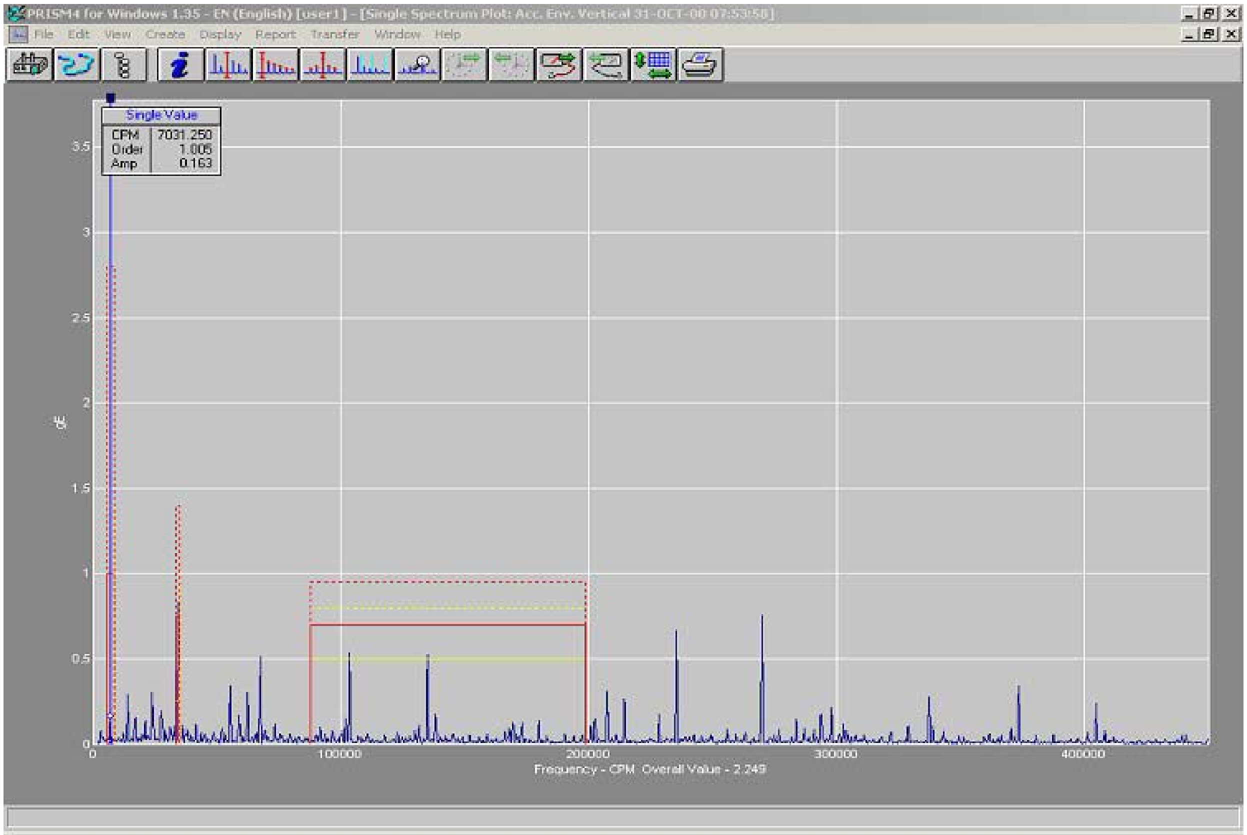


Figure 11. An illustration of a narrow band alarm, shown above, will aid in diagnosing rising levels, rising peaks or new peaks from different components of the bearing. This example shows one area (80,000 – 200,000 CPM) where two peaks have exceeded the recommended level (0.05gE) (yellow alarm limit).

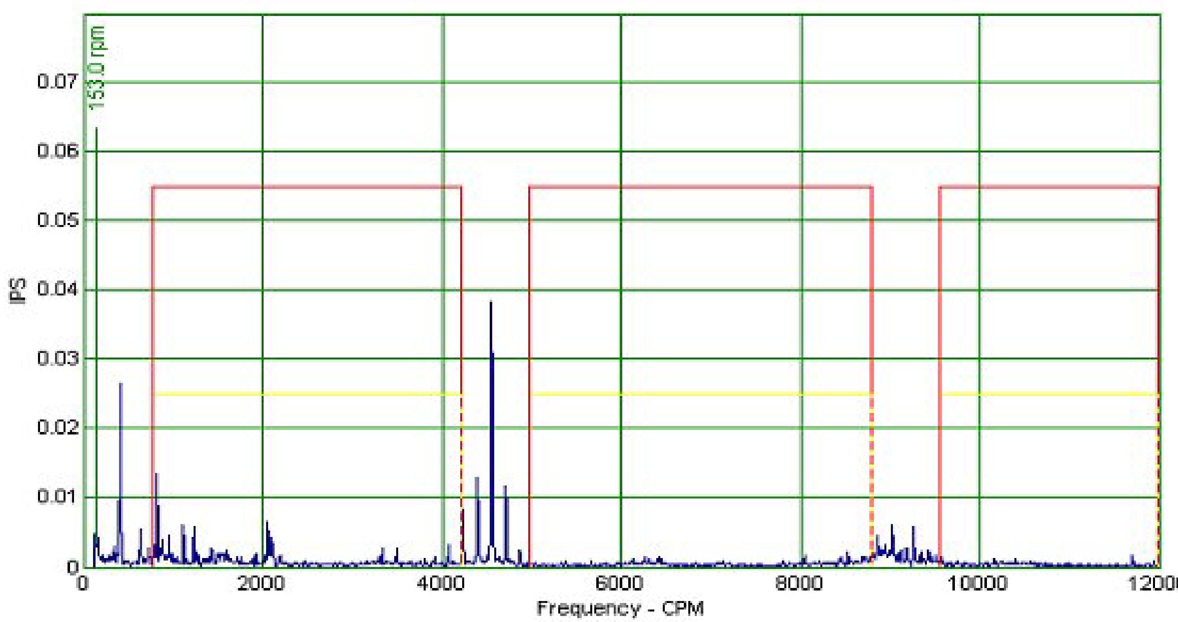


Figure 12. An illustration of a narrow band alarm will aid in diagnosing rising levels, rising peaks or new peaks from different components of the bearing.

Severity Assessment

As nominally 'healthy' rolling element bearings may exhibit at their particular defect frequencies, it is extremely important to be able to accurately measure the presence, and indeed the severity, of bearing deterioration. A general rule can be established for the severity assessment of enveloped spectra. This involves measuring the amplitude of the specific component defect (whether inner race, outer race, ball spin, cage defect frequencies or any combination of each) in dB above the carpet level of spectrum. The envelopes displayed in Figures 13a, 13b and 13c illustrate this point.

The spectrum in Figure 13a shows the amplitude of the bearing defect as approximately 10 dB above the general carpet level of the spectrum. This level is generally indicative of genuine onset of bearing deterioration, however breakdown is not imminent. Greasing may help to reduce the value of the peak.

The spectrum in Figure 13b depicts a bearing defect amplitude of approximately 15 dB (35 dB – 20 dB) above the general carpet level of spectrum. This level is sufficiently high to trigger some form of action, either in terms of increased monitoring or ideally, strip down and repair. The defect amplitude in Figure 13c is approximately 20 dB (40 dB-20 dB) above the carpet level and requires immediate attention.

Example severity assessment

The following case study is from the oil industry and details enveloped analysis on a condenser pump motor. High vibration levels were picked up from the motor and the personnel involved felt the problem was due to a bearing.

Figure 14a shows the enveloped spectrum taken at the non-drive end of the motor on the 4th June. The spectrum has a carpet level of approximately 30 dB, with a ball spin defect approximately 20 dB above the carpet level. The bearing was greased and monitored on a more frequent basis. Figure 14b shows the enveloped spectrum collected on the 27th June, some 3 weeks later. It can be seen that after 3 weeks the bearing defect peaks have only increased by a small amount, but that the carpet level has risen by almost 20 dB to almost the same level as the defect peaks. This is indicative of general bearing deterioration.

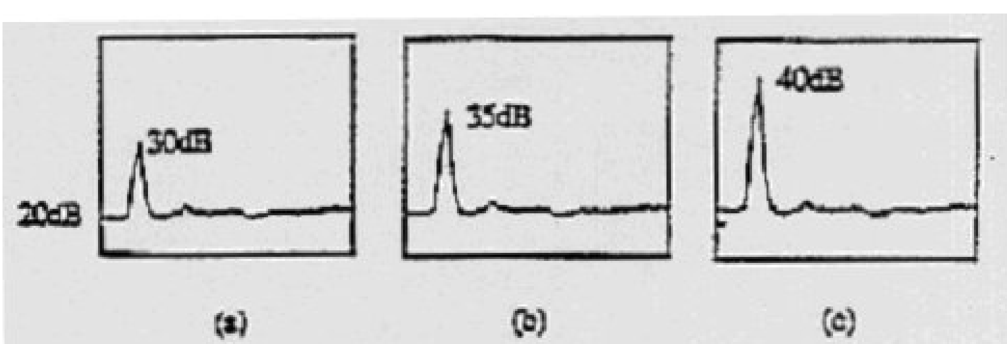
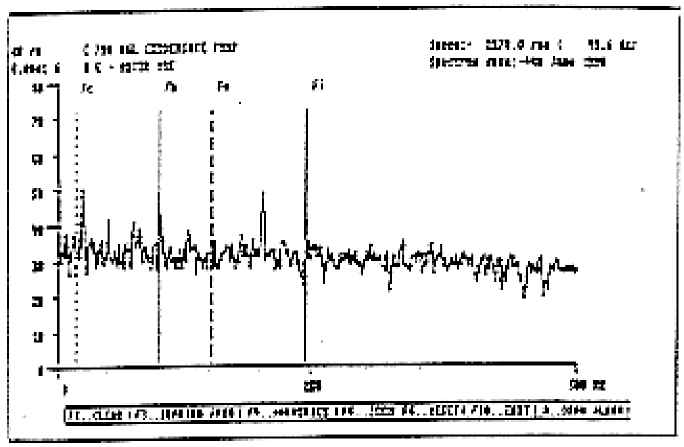
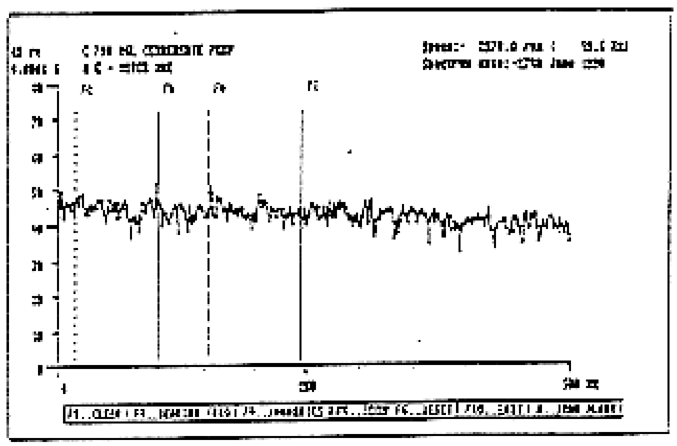


Figure 13.Examples of measurements concerning the amplitudes of specific component defects, such as inner race, outer race, ball spin or cage defect frequencies or any combination, in dB above the carpet level of spectrum.

(a) ESP™ Spectrum 04/06/90
Condensate Pump Motor



(b) ESP™ Spectrum 27/06/90
Condensate Pump Motor



(c) ESP™ Spectrum 02/07/90
Condensate Pump Motor

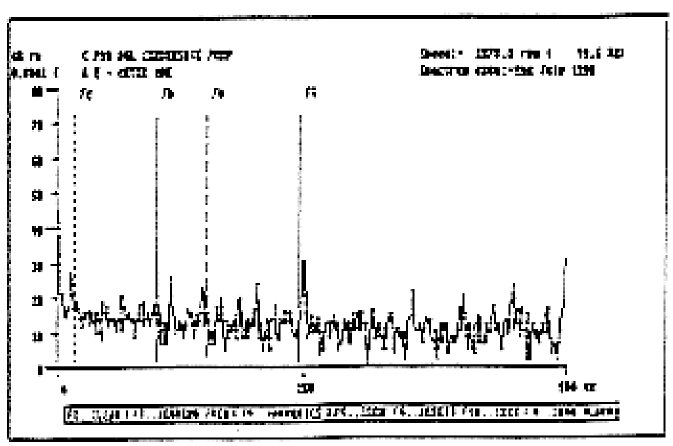


Figure 14. Figure 14a shows the enveloped spectrum taken at the non-drive end of the motor. The spectrum has a carpet level of approximately 30 dB with a ball spin defect approximately 20 dB above the carpet level. The bearing was greased and monitored on a more frequent basis. Figure 14b shows the enveloped spectrum collected 3 weeks later. It can be seen that after 3 weeks the bearing defect peaks have only increased by a small amount, but that the carpet level has risen by almost 20 dB to almost the same level as the defect peaks. This is indicative of general bearing deterioration. The bearing was replaced and Figure 14c shows the enveloped spectrum from the new bearing. The carpet level is approximately 15 dB, with small defect peaks at all four defect frequencies.

The bearing was replaced and Figure 14c shows the enveloped spectrum from the new bearing collected on the 2nd July. The carpet level is approximately 15 dB, with very small defect peaks being seen at all four defect frequencies. Inspection of the replaced bearing indicated the major bearing damage to be fretting of the outer ring. This suggested that there was looseness between the outer ring and the motor bearing housing. This would have caused higher loading and fretting, due to movement between the bearing and housing, contributing to the initial source of high vibration.

A word of warning: Figure 14b, if shown on its own, with no previous historical knowledge or no knowledge of a high vibration level, could have easily indicated that the bearing was in good condition, as the defect peaks were only 5dB above the carpet level, or general level of vibration inherent to the system. It should also be noted that the carpet level can be used as a means of monitoring bearing condition, particularly where detailed knowledge of the bearing is unavailable. As with all condition monitoring techniques, the power of the envelope process is greatly enhanced when *trending techniques are available to allow the user to look for change.*

Finally, the spectrum displayed in Figure 14c really demonstrates the power of the process. This spectrum has been collected from a new bearing recently fitted to the motor. The enveloped spectrum indicates the characteristic frequencies of the four components of the bearing. These can now be monitored from the earliest stage possible, allowing confidence in the condition of the motor and its bearings to be at a high level.

Conclusion

Through this article, a clear understanding of the principles and use of signal enveloping for the analysis of increased rolling element vibration levels have been shown. Several practical cases helped to illustrate the process in which enveloping results were interpreted. The process of enveloping technology is most effectively implemented in conjunction with other types of condition monitoring processes. Through this process of implementation and analysis, a clear understanding of the machine's condition can be realized.

Further Reading

"An Introductory Guide to Vibration Monitoring" @ptitudeXchange, JM02001. http://www.aptitudexchange.com

"Spectrum Analysis" @ptitudeXchange, JM02002. http://www.aptitudexchange.com

"Vibration Principles" @ptitudeXchange, JM02007. http://www.aptitudexchange.com

"Time Domain Analysis of Vibration Data" @ptitudeXchange. JM02012. http://www.aptitudexchange.com

"Vibration Analysis Feature Extraction Techniques", @ptitudeXchange. JM02019. http://www.aptitudexchange.com

About Diagnostic Instruments

Diagnostic Instruments (DI) was formed in 1987 to develop portable instruments. DI brought out the world's first portable dual channel FFT analyzer in 1988. DI's main business over the last years has been through original equipment manufacturing (OEM) arrangements with global companies. Since 2000, DI is part of SKF Reliability Systems.

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