An Introduction

to the

SPM HD Method

by

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1 Introduction

The original “Shock Pulse Method”, patented by Eivind Sohoel in 1969, has been used in various applications with success for more than 40 years. It is appreciated for its ease of use and its good capability to detect bearing deterioration and lubrication condition.

The new SPM HD method is based on the same fundamental physics used in the original Shock Pulse Method, namely the fact that in all rolling element bearings, shock pulses are produced in the contact interfaces between the raceways and the rolling elements.

The purpose with this description is to give an understanding of what shock pulses are, how they are measured and quantified and finally how to interpret them. A comparison with vibration enveloping techniques is made as well.

2 The Shock Pulse Method

2.1 Shock pulses

Shock pulses are elastic waves propagating in “rigid” materials. They are created as a result of collisions between “rigid” objects (like steel). As a result of a collision, the molecules at the impact point experience an acceleration, transferred by the molecules close to the impact point to nearby molecules until a “wave front” is created. If the material at the collision point is rigid enough and the collision takes place during a very short time period, a very sharp elastic wave is created. This wave propagates in the material with the speed of sound.

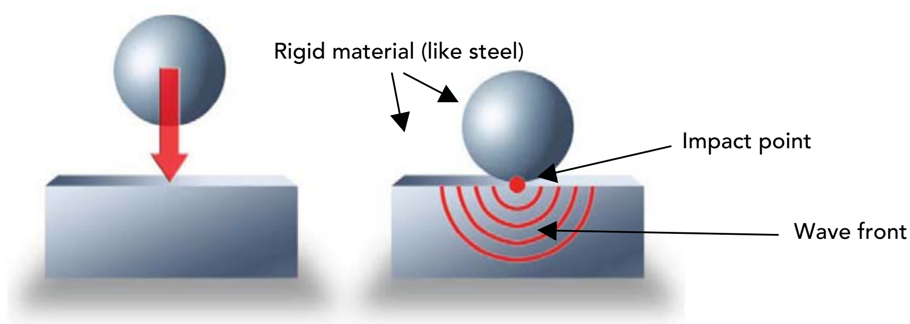


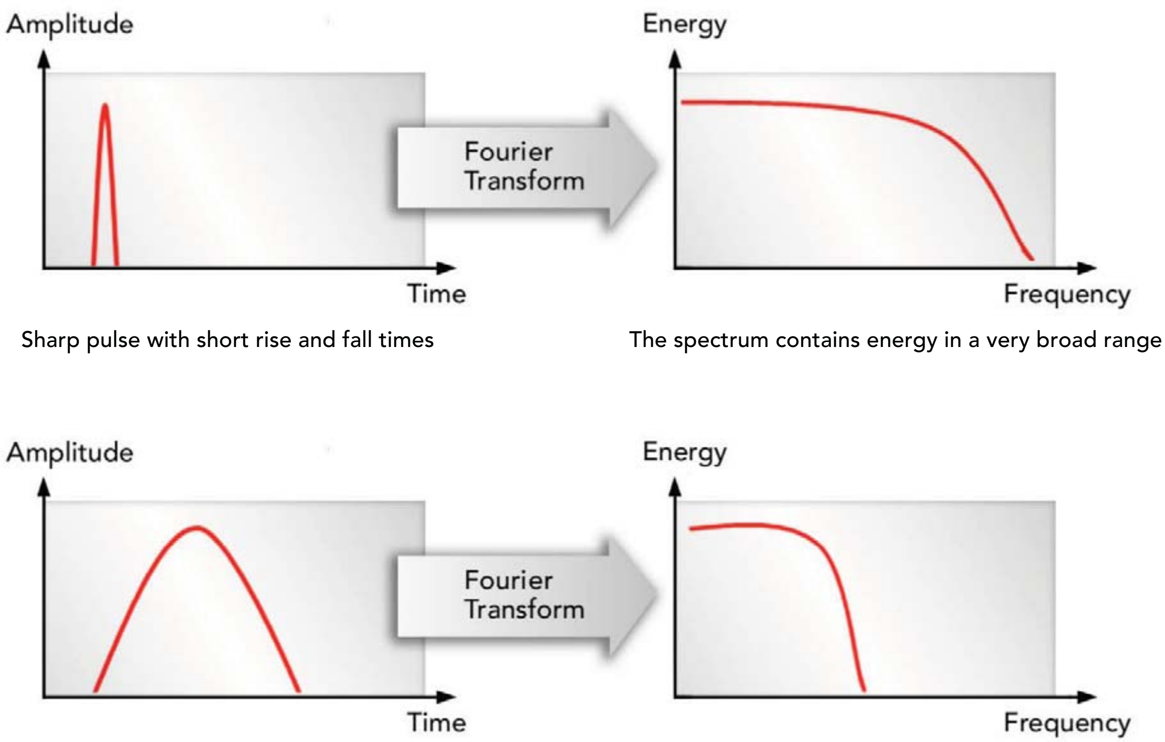
Fig. 1 *An elastic wave front is created as a result of a point to point collision.*

Typical values for the speed of the wave front in steel is 5000 m/s and a typical rise time for an elastic wave is a couple of microseconds up to several decades of microseconds.

An analogy to something familiar is the “wine glass demonstration”. Imagine tapping an empty wine glass with your fingernail. The impact is very short, the wine glass is rigid, the fingernail is relatively rigid and at the point of collision the molecules in the glass are experiencing a huge acceleration affecting the nearby molecules which in turn affects more molecules. This process creates an elastic wave in the glass, originating from the point of impact and spreading out to the whole glass.

This wave front will meet other boundaries (air) and the wave will be reflected back hence creating a very characteristic tone. On the other hand, if you hit the glass with the palm of your hand the impact is "softer" with no resulting elastic waves, it is more of a material movement and not an elastic wave.

Studying an elastic wave in the frequency domain, a sharp pulse in the time domain with very short rise and fall times contains a broad spectrum of frequencies while on the other hand a more "soft" pulse contains limited high frequency energy. Studying the interfaces in a rolling element bearing, the elastic waves typically produced in the surface interaction between the race ways and the rolling elements contains energy well above 40 KHz. This property of a typical elastic wave in rigid material is very important for the understanding of the shock pulse transducer described in a later chapter.



Sharp pulse with short rise and fall times

The spectrum contains energy in a very broad range

Soft pulse with long rise and fall times

The spectrum is more frequency limited

Fig. 2 *Example of a "sharp" pulse in the time domain and the resulting frequency spectrum compared with a more "soft" pulse in the time and frequency domain.*

Studying the interaction of the rolling elements and the raceways in detail reveals that hundreds of shock pulses are produced every second also in perfectly healthy bearings. These shock pulses originate from the small collisions occurring on a microscopic level in all rolling element bearings.

In a healthy, well lubricated bearing only the highest surface asperities will make contact (penetrating the oil film), hence creating shock pulses with a relatively low amplitude, while in a poorly lubricated bearing the repetition rate and amplitude will be higher. In a bearing with damages in the raceways or in the rolling elements very high amplitude shock pulses will be generated with a repetition rate depending on the bearing geometry and shaft RPM.

The strength of the shock pulses generated from impacts is related to the relative speed of the colliding objects. In a rolling element bearing for example, the amplitude of the shock pulses generated are proportional to the speed of the rolling elements.

2.1.1 Summary

Shock pulses are elastic waves in rigid materials (typically steel) with a very sharp rise and fall time. They propagate in the bulk material with the speed of sound (typically 5000m/s). Shock pulses originate from the point of contact between two objects that collide, for example a roller hitting the sharp edge from a spall in a raceway. The frequency content in a shock pulse is very broad and contains a lot of high frequency energy. A more "soft" wave originating for example from unbalance is not a shock pulse and does not contain high frequency energy. The amplitude of the shock pulses is proportional to the relative speed at the moment of impact.

2.2 The shock pulse transducer

As mentioned in the previous section describing shock pulses, a "sharp" pulse with short rise and fall times contains energy high up in the frequency range. In experiments performed at SPM, it has been concluded that in a typical "steel ball hitting a steel bar" test, frequency components well above 40 KHz are easily detected.

The SPM transducer is designed to work at its resonance peak of 32 KHz. This means that if the transducer is exposed to a mechanical signal containing energy at 32 KHz, it will respond with a distinct ringing behavior at 32 KHz.

Studying typical shock pulses with short rise and fall times, they contain a lot of different frequencies and specifically they contain 32 KHz frequency components. This means that if a shock pulse transducer is exposed to a shock pulse, it will be very "receptive" to the 32 KHz frequency and respond with a distinct "ringing" behavior. This "ringing behavior" is transferred to a Piezo ceramic dish that makes it possible to measure the "ringing" within the transducer.

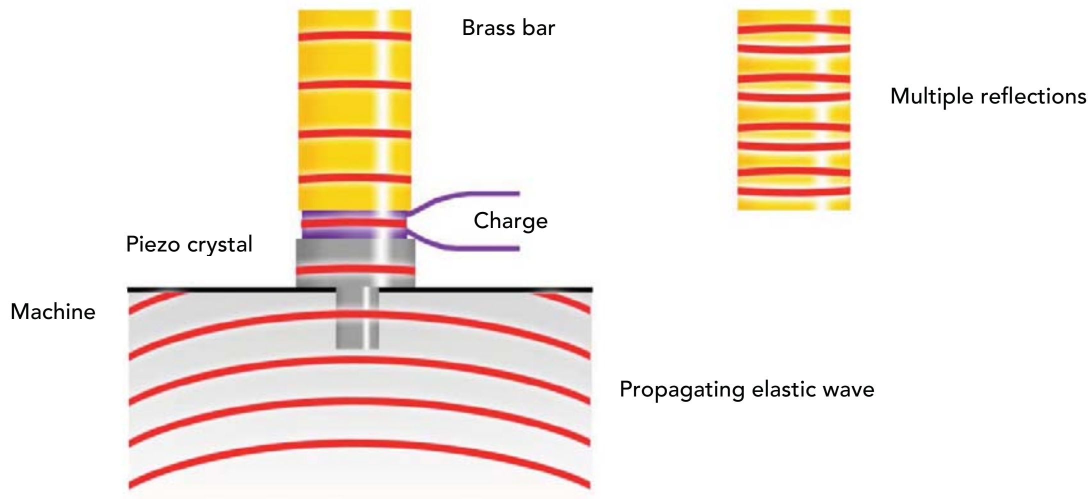


Fig. 3 *Principal drawing and behavior of the shock pulse transducer.*

A shock pulse wave front hits the shock pulse transducer. The wave front reaches the inside of the transducer and passes the Piezo crystal, then travels along a brass bar. When the wave front reaches the end of the brass bar, it is reflected back. The reflected wave is reflected again at the bottom of the brass bar, this continues until the wave decays after a relatively short time. These reflections create a standing wave inside the brass bar with a frequency of 32 KHz.

One important property of the shock pulse transducer is the decay time for the “ringing” behavior. When the transducer is hit by a propagating shock pulse, it starts to resonate at 32 KHz. The first oscillations start with a high amplitude and the following with a gradually decreasing amplitude. If the transducer is hit with another shock pulse before the first oscillation has “died” out, the next pulse will be superimposed on the first one creating false amplitudes. It is therefore essential that the ringing dies out as fast as possible. This can be a problem with vibration enveloping techniques where the ringing time for an accelerometer normally is longer. The shock pulse transducer is carefully designed with this important fact in mind.

Fig. 4 *Typical shock pulse transducer response when hit by a shock pulse. The decay time is short.*

Returning to the wine glass analogy again: tapping the wine glass with your fingernail will produce a very distinct ringing sound. The frequency depends of the shape of the wine glass, the material and whether it is filled with liquid. The wine glass resonance frequency is normally much lower than 32 KHz (typically below 1 KHz), but it is the same principle as the shock pulse transducer. Hitting the wine glass with the palm of your hand will not create any ringing sound; it is not a shock pulse.

The brass bar inside the shock pulse transducer has its own mass, pressing against the piezo crystal that creates signals when exposed to low frequency vibrations. Measuring directly on the crystal will show a combination of the "ringing behavior" with low frequency signals from unbalance etc. To eliminate the low frequency influence, a band pass filter needs to be used in combination with the shock pulse transducer. The so called TMU (Transducer Matching Unit) in combination with the interface in the instrument forms a band pass filter that effectively eliminates unwanted low frequency signals. This is also the reason why it is not possible to use a shock pulse transducer in combination with a vibration interface – together, the shock pulse transducer and the shock pulse interface in the instrument form a unit.

The structural resonance of the brass bar in combination with the band pass filter can be summarized in one sentence: t*he shock pulse transducer is mechanically and electrically tuned to detect elastic waves*.

All shock pulse transducers are calibrated to behave exactly the same way when exposed to shock pulses. This means that the amplitude and the decay time are well specified and almost identical from transducer to transducer.

Compared with vibration enveloping techniques where a standard vibration transducer is used, the behavior when exposed to shock pulses is not clearly defined because the technique is dependent on a structural resonance in the machine itself. This structural resonance will vary from application to application. This will be described in more detail in the section about vibration enveloping.

The selection of 32 KHz as the resonance frequency is an optimal compromise. It is above the interfering low frequency signals created from unbalance, misalignment and gear mesh and well below the ultrasonic frequencies where distance and material transitions severely affects the signal.

2.2.1 Summary

The shock pulse transducer is designed to respond in a clearly defined manner when exposed to shock pulses. Because shock pulses contain a broad range of frequencies, they will also contain 32 KHz components that will trigger the transducer to oscillate. The behavior when exposed to a shock pulse is well defined. All shock pulse transducers are calibrated to behave in exactly the same way. A "softer" signal created for example from an unbalance situation does not contain high frequency components and will therefore not be picked up by the shock pulse transducer. One important property of the shock pulse transducer is its ability to dampen the oscillation quickly before the next shock pulse hits the transducer. This behavior is a clear advantage when compared to vibration enveloping techniques.

2.3 Normalization of shock pulse amplitude

As mentioned in the section describing shock pulses, the amplitude of a shock pulse is proportional to the relative speed of the colliding objects. In the case of a rolling element bearing, the speed of the rolling elements, relative to the raceways, is defined by the diameter and the rotational speed of the shaft. The relation between the shock pulse amplitude and the relative speed of the objects at the moment of impact creates problems when establishing alarm levels. A change in the shaft rotational speed of a bearing will for example affect the shock pulse amplitudes significantly making it hard or even impossible to use a fixed alarm level. One way to solve this is to measure the shaft rotational speed in parallel with the shock pulse measurements and adapt the alarm levels to the RPM, hence allowing higher shock pulse levels at higher RPMs. Another way to solve this problem is to introduce a normalization factor, effectively normalizing the shock pulse amplitude regardless of the rolling element speed relative to the raceways. The result is that the shock pulse reading is presented on a normalized scale.

By defining the diameter of the bearing and by measuring RPM (or by manually entering RPM) the system can calculate a normalization factor called dBi for different diameters and RPMs (or HDi in the SPM HD method) that is subtracted from the measured “raw” value. The algorithm used to calculate the normalization factor dBi (or HDi) was established by empirical methods and is based on a significant number of trials performed during long time.

For example, a measured high value of the shock pulse amplitude in a healthy bearing can be perfectly normal if the diameter is big and RPM is high. In this case the rolling elements hit small surface asperities and because the speed is high, the resulting shock pulses will be strong. The resulting normalization factor will be high and when this factor is subtracted from the measured high value, the difference will be a low value indicating a healthy bearing.

The normalization factor is a significant advantage compared to vibration enveloping techniques; the enveloped vibration value will be affected by varying RPM while the shock pulse value, regardless of RPM variations, will present stable values thanks to the normalization process.

2.3.1 Summary

In order to have an absolute and easy to interpret scale for shock pulse strength, a normalization factor, dBi (or Hdi), is used. The use of a normalized scale enables an absolute interpretation of the shock pulse strength in the terms of green, yellow and red used for direct evaluation of the operating condition. The normalized scale is a clear advantage compared to vibration enveloping techniques for example, where the values are significantly affected by varying RPMs.

2.4 Quantification of the shock pulse amplitude

The nomenclature used in the following sections will be aimed towards the new SPM HD method, meaning that HDi is used instead of dBi, HDm will be used instead of dBm etc.

A number of important facts about the operating condition of a bearing can be established when studying the shock pulses from different perspectives:

- The strength of the highest shock pulse found during the measurement time indicates a possible bearing defect. This value is called HDm (m=max value).
- The threshold level, where 200 shocks per second higher than the threshold level can be found. This level is called HDc (c=carpet). The HDc value indicates lubricant condition.
- The repetition rate of the highest shock values can reveal the source of the shock pulses. Studying a shock pulse spectrum or a shock pulse time signal accurately pinpoints whether the shock source is located at the inner or outer raceways, at the rolling elements or from the cage. Also other shock sources can be identified like gear mesh, commutation frequency from hydraulic motors etc.

As mentioned earlier, the HDm and HDc values will be affected by the RPM and diameter of the bearing so they are both normalized, while the shock pulse time signal and shock pulse spectrums are not. Due to the extremely high dynamics, both the HDm and HDc values are expressed on a decibel scale. The amplitude of the shock pulses generated from a bearing running in good condition can be several orders (more than 1000 times) lower than that from a bearing running in bad condition.

Increase on a decibel scale	**Equivalent increase on a linear scale**
20 dB	10 times
40 dB	100 times
60 dB	1000 times
80 dB	10 000 times

As can be seen from the table above, it is more convenient to handle a scale expressed in decibels. A more detailed description on how to extract the HDm and HDc values will be covered in a separate section.

dBsv	This is the unit for the non-normalized "raw" shock pulse value (the "raw" amplitude value will be significantly affected by RPM and diameter of the bearing).
HDi	This is the normalization factor used to normalize the shock amplitude. The HDi value will increase with increasing RPM and decrease with decreasing RPM (or shaft diameter)
dBn	This is the unit used after normalization. Imagine an observer sitting at the HDi line studying the measured shock pulses. The HDi line will move up and down when the RPM is varying and so will the observer. The amplitude relative to the observer will not vary due to varying RPM because the normalization. The scale has become an absolute normalized scale called dBn (n=normalized). The level is expressed in green, yellow and red and can be used for direct evaluation of the operating condition.
HDm	This is the highest shock pulse found during the measurement time expressed in the normalized scale, normally the value for the mechanical condition of the bearing.
HDc	This is the threshold level where there exits 200 shock per second expressed in the normalized scale, normally the value for the lubrication condition of the bearing.

Fig. 5 *An overview of the shock pulse value abbreviations.*

In the example below, the highest shock pulse value measured without normalization is 45 dB, while the HDi value is calculated to 20 dB (using RPM=860 and diameter 100 mm). The result after the normalization is HDm=25 (45 dB – 20 dB = 25 dB).

The same logic applies for the HDc value in the picture. The raw 200 shock pulse per second tresh-hold level is 32 dB, while the HDi is 20 dB resulting in a HDc value of 12 dB (32 dB – 20 dB = 12 dB).

In this example, the normalized HDm value is 25 dB, indicating that something is affecting the operating condition of the bearing.

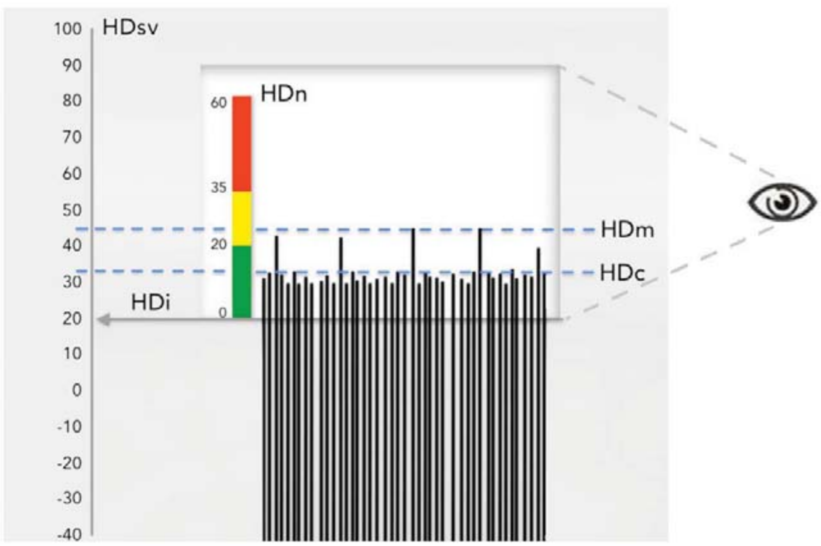


Fig. 6 *Description of dBsv, HDi, dBn, HDm and HDc.*

2.4.1 Summary

To quantify the strength of the strongest shock pulse found during the measurement time, indicating possible bearing damages, the value HDm is used. The HDm value is normalized, enabling an interpretation on an absolute scale indicated with the colors green, yellow and red. The HDc value is used to quantify lubrication condition. Due to the extremely high dynamics of the HDm and HDc values, a logarithmic scale is used expressed in decibels.

3 SPM HD

3.1 Comparison with the traditional SPM method

The SPM HD (Shock Pulse Method High Definition) is based on the same fundamental physics as the traditional Shock Pulse Method: shock pulses are elastic waves propagating in bulk material, generated for example in the contact interfaces between the rolling elements and the raceways in bearings. A tuned shock pulse transducer is used to detect these elastic waves.

The SPM HD method uses the same type of transducer as the traditional Shock Pulse Method but in order to extract more information from the sometimes very weak shock pulses, the electrical interface as well as the data acquisition process has been radically improved. The result is more clear results with much improved dynamics. Especially on low RPM applications, where the shock pulses are weak and close to the electrical noise floor, a dramatic improvement compared with the traditional shock pulse method as well as vibration enveloping techniques can be observed.

3.2 "Black box description" – inputs and outputs

The picture below shows what inputs are needed and what output are delivered from the SPM HD system once the system is up and running. In order to initially set up the system, the user needs to define a number of parameters like number of lines in spectrum, frequency range etc. However, if the default settings are used, this process is very simple and straightforward.

Fig. 7 *Inputs and outputs.*

3.2.1 Inputs

The transducer

The SPM HD utilizes the same type of transducer as the traditional SPM method: a tuned transducer sensitive to shock pulses.

RPM

In order to calculate a proper initial value (HDi) and as an input to the frequency analysis algorithms, an accurate rotational speed input (RPM – revolutions per minute) is important. If RPM is constant a manually specified RPM is sufficient, but when there are variations of the RPM, a good quality RPM sensor is required. For the calculation of the HDi value, only a rough estimation is needed but for the frequency analysis algorithms it is essential to have a very precise and accurate RPM signal. The SPM HD algorithms constantly read the RPM signal and adapt the sampling frequency to the RPM input. If the RPM signal for some reason is of poor quality (e.g. delayed, unevenly spaced pulses if several pulses per revolution are used, or noise), the resulting SPM HD spectrums and time signals can be severely distorted.

If there are several pulses during one revolution, for example bolts on a shaft, equal distance between each bolt is very important otherwise the order tracking algorithms will malfunction, resulting in "smeared" spectrums. For example, if 800 lines is used in the SPM HD spectrum and there are four bolts on the shaft (90 degrees apart), the bolts need to be evenly spaced to a degree better than 90/800=0.11 degrees in order to produce crisp spectrums. If the precision is not that good, the spectrum can be smeared because the order tracking algorithms will interpret a changing RPM.

If there is uncertainty about the precision in the distribution of bolts or holes, it is advisable to use one pulse per revolution. The drawback of having only one pulse per revolution is that if RPM is very low and there are RPM variations between the single pulses, this will not be detected and the result is smeared spectrums.

For example, in a typical wind turbine application the brake disc mounted on the main shaft with holes (for example 24) around the circumference is good enough to produce crisp spectrums.

Note that it is only the SPM HD spectrum and time signal that will be affected by different spacing between the bolts/holes. The scalar values HDm and HDc will not be affected.

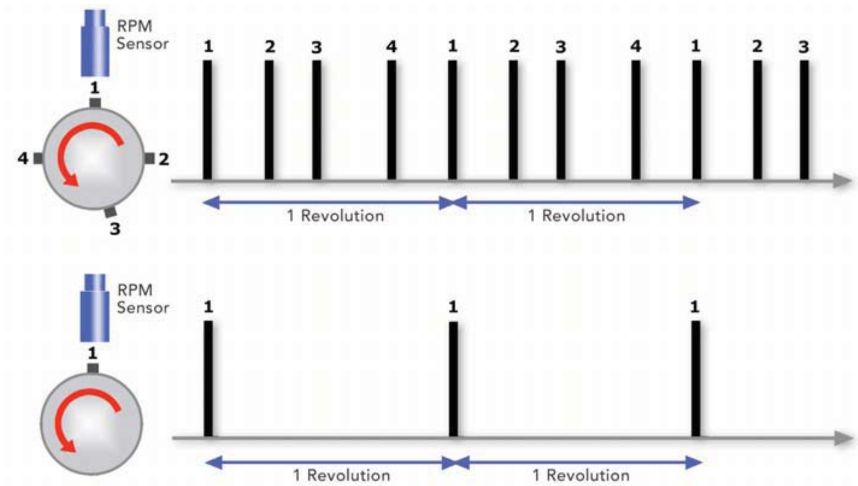


Fig. 8 *Example with four pulses per revolution with non-equal spacing compared with one single pulse per revolution. The distance between bolts 2 and 3 is shorter than that between 1 and 2. Consequently, the time between bolts 3 and 4 is longer. The SPM HD algorithms interpret this as a changing RPM between bolts 2 and 3 and between 3 and 4 even though RPM is constant. The resulting SPM HD spectrum will be "smeared". If only one pulse per revolution is used the spacing is guaranteed to be equal.*

Bearing Data

To calculate a proper normalization value (HDi), the shaft diameter needs to be specified. It is also very useful to have bearing data available for the Time signal/Spectrum signal interpretations.

3.2.2 Outputs

HDm

The HDm value is a scalar value expressed in decibels. It represents the strongest shock pulse amplitude found during the data acquisition time. The HDm value shows the operating condition of the bearing and is typically used to evaluate possible mechanical faults in a bearing. HDm is the primary parameter for alarm settings and trend evaluations.

The data acquisition time is based on a number of revolutions input by the user. The default vale is 50 revolutions. Testing has shown that in order to have a representative reading revealing the condition of the bearing, the data acquisition time should last at least ten revolutions in order to obtain a stable value. Assuming inner race damage, the signal pattern will be different from revolution to revolution because of the geometry of the bearing, so a measuring time spanning over one revolution only will be unstable. In the course of ten revolutions, there should be at least one impact related to the bearing. If the data acquisition time spans over 50 revolutions, the HDm value will be even more stable and should be a good indicator of possible bearing damage severity. In the course of these 50 revolutions, there should be at least five stronger impacts originating from the bearing. If however there are one or two strong shocks in the course of these 50 revolutions, they are most likely disturbances. This logic is the base in the "noise rejection" algorithms.

This means that with the default data acquisition time setting of 50 revolutions, the algorithms can handle up to five strong impacts during this time without affecting the final HDm value.
Above a certain RPM (approximately 100-150 RPM depending on diameter) the HDm value (and HDc) will converge to the traditional dBm and dBc, but especially HDm will have a more stable behavior.

It is also important to point out that during the HDm measurements (and HDc), the maximum sampling rate available is used to cover high frequency activities. This in contrast to the SPM HD spectrum and time signal where the sampling rate (and anti-alias filters) are adjusted to the selected upper frequency range.

HDc

The scalar value HDc represents lubrication condition. As mentioned before, there is a constant multitude of shock pulses emitted from the interface between the rolling elements and the bearing raceways. The high number of low amplitude shock pulses is significantly affected by lubrication.
In a fully lubricated bearing where the rolling elements and the raceways are kept separated by the oil film, the number of low amplitude shock pulses are low, and the HDc value will then also be low. In dry operating condition, the number of higher shock pulses will increase thus resulting in a high HDc value.

In older SPM instrumentation were analogue techniques where used, a threshold level could be selected with a potentiometer. The shock pulses detected by the instrument where fed to earphones, and the level where a continuous tone (=200 pulses/sec) could be heard would constitute the dBc value (c=carpet). The HDc value used in the SPM HD method is defined in the same way; it equals the threshold level where 200 shocks per second are found.

The total measuring time is divided into 5 ms time slots. In each time slot, the strongest shock pulse is identified and temporarily stored. When the measuring time is up, the weakest among these stored values is selected as the HDc value (there are 200 5 ms slots in one second). This gives an approximation of the level where more than 200 shocks per second are found.

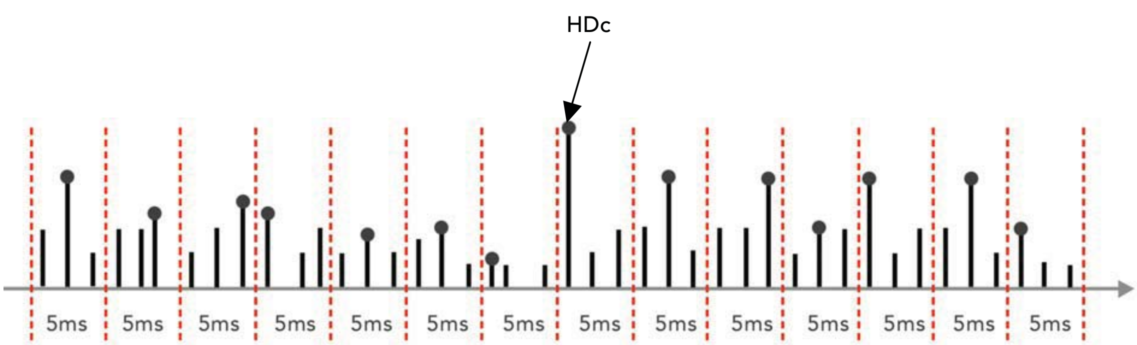


Fig. 9 *Measuring time is divided into 5 ms time slots. The vertical lines represent individual shocks and the dots represent the strongest shock found within the time window of 5 ms. The lowest among the strongest is the HDc value.*

The difference between the HDm values and HDc values (the delta) can be used for a number of conclusions (see more in SPM handbooks).

The HDm and HDc values are measured simultaneously both are expressed in decibels and are normalized with the HDi value.

SPM Time Signal HD

The third output from the SPM HD algorithms is the extremely useful Time Signal HD. The primary purpose of this time signal is to pinpoint the source of the shock pulses. The time signal gives an intuitive understanding of where the source is located.
Before the SPM HD time signal is presented as an output, it has passed a number of advanced digital algorithms (described below), producing clear and crisp results. During the SPM HD field test period, the SPM HD Time signal was in many cases more useful than the SPM HD Spectrum because of its easy to understand results (see examples later).

The SPM HD Time signal is presented on a linear scale. Due to the high dynamics in the SPM signal, values can range from below 1 to over 1 000 000 in some cases. The reason for not using a logarithmic scale is that the clarity is then lost to some extent. Remember that the primary use of the SPM HD time signal is to identify the source of the shocks, not using the value as such.

SPM Spectrum HD

If a Fast Fourier Transform (FFT) is applied on the SPM Time Signal HD, an SPM Spectrum HD is created. To those used to interpreting spectrums, the SPM Spectrum HD is very useful.
The SPM Spectrum HD is also presented on a linear scale.

3.3 Measuring times for HDm/HDc and SPM Spectrum/Time signal

Described in the HDm section the measuring time for HDm/HDc is based on a number of revolutions. The default setting is 50 revolutions and the measuring time therefore is dependent on the current RPM.

The measuring time for HDm/HDc can be calculated as:

Data acquisition time (for 50 revolutions) = 50 * 60/RPM

This may seem as a long data acquisition time for low RPMs, but in order to obtain a representative reading for a particular bearing, the time MUST be adjusted to the RPM. A one second measuring time at 10 RPM for example does not make sense. During that second, the shaft has only moved 60 degrees and the result will vary depending on when the measurements start.

In addition to this measuring time, there is also a very short data handling time. If the measuring time for some reason is too long, the number of revolutions can be adjusted but we do not recommend less than ten revolutions. A lower than ten revolutions setting can affect the stability of the HDm values.

For SPM Spectrum/Time signal HD, the measuring time is dependent on more parameters than HDm/HDc: number of lines in the spectrum, order range, symptom enhancement factor and RPM.

If the symptom enhancer is engaged, the measuring time for SPM Spectrum/Time signal HD can be calculated as:

Measuring time= (Number of Lines/Order range) X (Symptom enhancer factor + 2) X (60/RPM)

If the symptom enhancer is turned off, the measuring time can be calculated as:

Measuring time = (Number of Lines/Order range) X (60/RPM)

Please note that the measuring time for HDm/HDc and SPM Spectrum/Time signal are different. The measurements start simultaneously but their individual duration will normally differ. There is a setting in Condmaster Nova making it possible to force equal measuring times for HDm/HDc and SPM Spectrum/Time HD.

Using default settings, the measuring time for SPM Spectrum/Time signal HD is longer than that for HDm/HDc measurement.

Typical measuring times for HDm/HDc and SPM Spectrum/Times signal (using number of lines=800, Order range=100 and symptom enhancement factor=5:

RPM	Measuring time, HDm/HDc	Measuring time Spectrum/Time signal HD
1800	1.7 sec	1.9 sec
1500	2 sec	2.2 sec
1000	3 sec	3.4 sec
500	6 sec	6.7 sec
100	30 sec	33.6 Sec
10	300 sec	336 sec

3.4 Effects of anti-aliasing filters and modulation on SPM Time Signal HD and SPM Spectrum HD

In order to avoid alias problems (ghost signals), it is very important to apply a so called anti-aliasing filter before sampling. Aliasing may result in spectrums that are very hard to interpret because the real signals are mixed up with non-existent ghost signals. The anti-aliasing filter removes high frequency signals in the transducer signal to ensure that the sampling rate is adequate for the specific settings. For example, if the user selects an upper frequency range of 100 Hz, the anti-aliasing filter will have a cut off frequency above 100 Hz, if an upper frequency range of 1000 Hz is selected the cut off frequency will be 1000 Hz and so on.

The important consequence of this is that if there are signal sources with higher frequency content than the cut off frequency, they will be filtered out. For example: assume that we have a roller bearing turning with a fixed outer race and the turning shaft connected to the inner race. Assume also that there exists a constant load in one specified direction and that the bearing is in good condition. A shock pulse transducer is mounted in the load zone close to the outer race. As described before, we expect many shock pulses with low amplitude produced from the interface between the rollers and the raceways. Especially the interface between the rollers and the outer raceway will produce shocks that will be picked up by the transducer, because the transducer is located close to the outer raceway. Also in the interface between the inner race and the rollers, shocks will be produced but they are weaker due to the distance to the transducer.

In this example we expect many weak shocks detected by the transducer each time a roller enters the load zone. The number of times a roller enters the load zone can easily be calculated by using bearing data, in this case the Ball Pass Frequency Outer race (BPFO).

Fig. 10 *In a healthy bearing, rollers pass close to the transducer and a high number of low amplitude shocks are emitted from the interface between the roller and the outer race. Each time a roller passes the transducer, the amplitude of the weak shocks increases.*

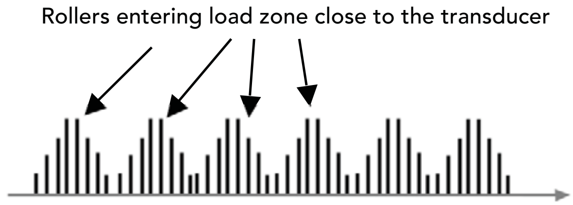


Fig. 11 *The signal pattern from the transducer in fig. 9. The amplitude is low and is modulated with the passing frequency of the rolling elements.*

When doing frequency analysis on the signal above, a frequency range suitable to study bearing frequencies is normally selected (BPFO, BPFI, etc.). The high frequency repetition rate of the shocks in the picture above is well above the cut off frequency of the anti-aliasing filter so the resulting signal will look like this:

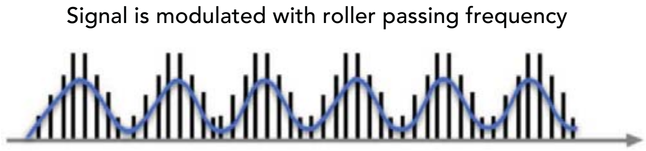


Fig. 12 *Signal after anti alias filtering.*

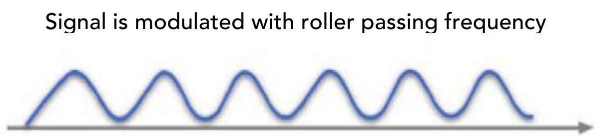


Fig. 13 *The resulting signal.*

Due to the nature of the anti-aliasing filter (low-pass filter), the amplitude is affected. The filter is too slow to follow the sharp shock, so the resulting signal has a lower amplitude than the original signal.

The measurement of HDm and HDc do NOT suffer from this behavior because the anti alias filter is always set to a very high frequency.

The important conclusion from this example is that when studying SPM Time signal/Spectrum HD, the absolute amplitude must be used with care. What is seen in the spectrum/Time signal can be the result of a modulation of a high frequency shock rate. Also, single shock pulses are affected by the filters resulting in lower amplitude. The Spectrum/Time signal should be used only for signal source identification and trending. The HDm and HDc values however, are accurate measurements of the shock amplitude and the absolute values can be used directly.

Sometimes, like in hydraulic motor applications or in gearboxes where a strong natural shock source (commutation frequency and gear mesh) exists, and the HDm is totally dominated by that, Spectrum HD can be used for trending purposes (by applying band values).

Other techniques like vibration enveloping is also affected by anti alias filter and the amplitude of the enveloped signal is unreliable. PeakVue®[1] takes a different approach, the amplitude is preserved but the spectrum can suffer from alias problems.

Summary: The SPM HD method produces four basic results:

HDm is a scalar value expressed in decibels. It is the primary value to use to determine the severity of a bearing damage. It represents the highest shock pulses found during the measuring cycle. This value is also used for triggering alarms.

HDc is a scalar value expressed in decibels. This value represents the level where 200 shocks/second are present. It is useful to determine lubrication condition.

Time signal HD is *extremely* useful to locate where in the bearing a possible damage is located. Furthermore, in many cases it is possible to determine the nature of the damage (cracked inner race with spalling all around or a single crack etc.).

SPM Spectrum HD is the result of applying FFT algorithms on the SPM Time Signal HD. The SPM HD spectrum is useful to determine where a possible bearing damage is located. It is also useful for trending purposes (applying band values).

The RPM signal needs to be accurate and of good quality to obtain crisp and clear results. If several pulses are used for one revolution, they need to be evenly spaced.

The anti-aliasing filters used for the SPM Spectrum/Time signals affect the amplitude of the shock signals. Care has to be taken when analyzing amplitude. SPM Spectrum/Time signal HD are very useful for shock signal source identification. We strongly recommend using the HDm value for amplitude evaluation.

1) PeakVue® is trademark of CSI Technology, Inc.

3.5 SPM HD Algorithm overview

Following the signal paths from the Shock Pulse Transducer to the four main results (HDm, HD, SPM Spectrum HD and SPM Time signal HD) the signal will pass a number of sophisticated algorithms. The normal user does not have to care about the settings four these algorithms, the default values will produce good results. Sometimes, for example when extra sharp spectrums are needed or time is limited, the user needs to change some of these setting to adapt the system for a particular application.

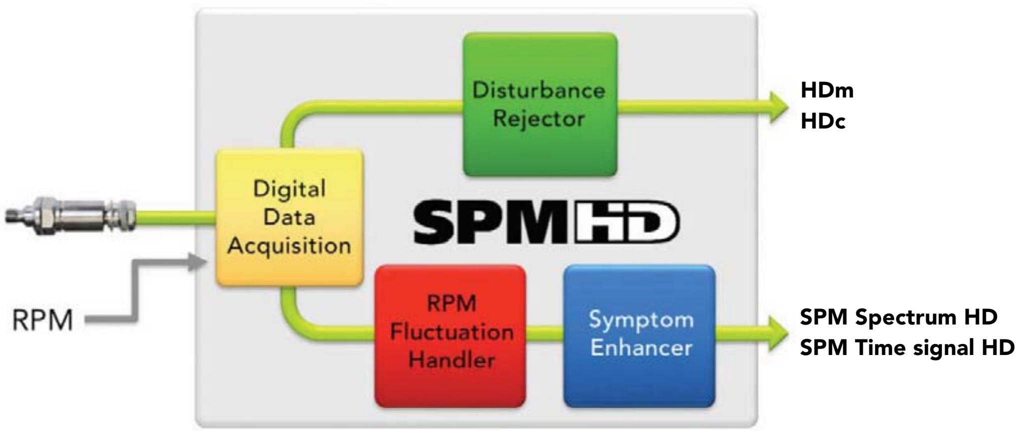


Fig. 14 *Overview of the SPM HD algorithms.*

3.6 Digital data acquisition

Every time the SPM sensor is exposed to an elastic wave (shock pulse), the piezo element in the transducer produces an electrical charge proportional to the strength of the shock pulse. Studying this raw signal more closely reveals that a typical shock pulse looks like a damped oscillation. To do a meaningful analysis, this raw signal is converted to an enveloped signal. This process involves rectification of the signal and finding the shape of the ringing signal (the envelope). By using high performance A/D converters in combination with sharp digital filters, the signal to noise ratio is significantly improved compared to the traditional SPM method. This improvement is essential for low RPM applications where the useful "mechanical" signal is very close to the electrical noise floor. By using digital technique, extremely weak signals can now be detected also.

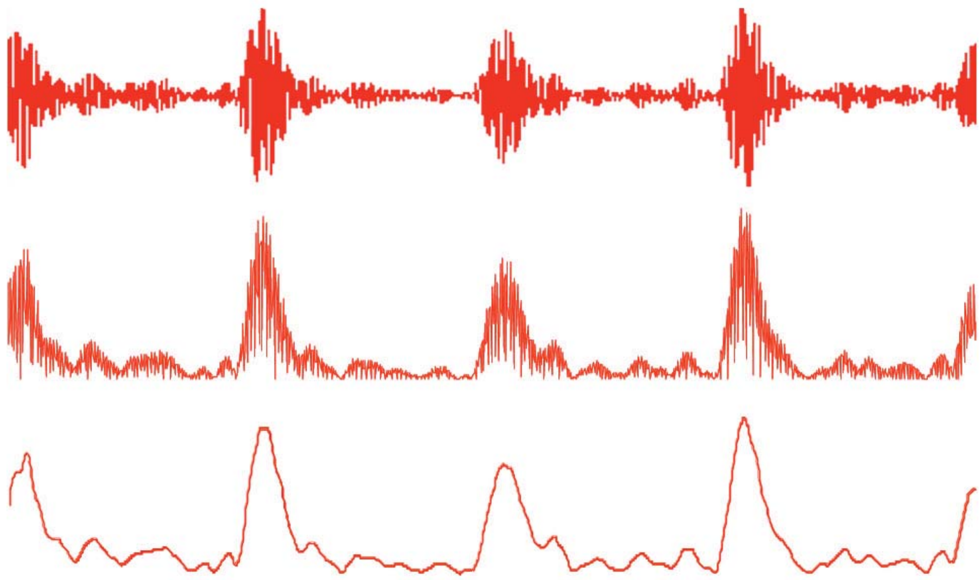


Fig. 15 *The "raw" SPM transducer signal, rectified signal and demodulated signal. By using advanced digital techniques the signal to noise ratio is optimized.*

3.7 RPM fluctuation handler

As mentioned earlier, the SPM HD algorithms uses order tracking algorithms to produce normalized spectrums regardless of RPM variations. The RPM signal is continuously updated in parallel with the SPM HD readings and the sampling rate is adjusted according to the RPM. If there are several pulses per revolution, care has to be taken to ensure that the pulses are evenly spaced. Failing to do this will result in smeared spectrums. In most cases, it is better to have only one pulse per revolution to ensure a proper signal.

It is possible to specify the maximum RPM fluctuation allowed during data acquisition. The default value is +/- 20% and the maximum fluctuation is +/-50%. If the maximum RPM fluctuation limit is exceeded, the measurement will be aborted and a new attempt to measure will be made.

There are clear advantages using order tracking and displaying the SPM HD Spectrums in orders instead of in Hz or CPM, especially when RPM is changing, because the results are much easier to interpret. In wind turbine applications for example, it is very convenient for gear mesh identification.

Note that the order tracking algorithms are only used in conjunction with the SPM Spectrum/Time HD signals and not together with HDm/HDc.

3.8 Symptom Enhancer

The symptom enhancer is an algorithm that enhances repetitive shock pulses and suppresses random shocks. The symptom enhancer can produce excellent clear and crisp results that can be very helpful in the signal source identification.

A common technique used in vibration analysis is to use time synchronous averaging to enhance weak signals. Typically, a trigger pulse is used to start the measurements at exactly the same position every revolution. A number of measurements are made and averaged. Because all measurements start at the same position, all vibrations synchronous with the shaft will be enhanced and other more random signals will be suppressed. This is an excellent technique to increase the signal to noise ratio. It is however not suitable for bearing frequencies because those frequencies are normally not synchronous with RPM. Applying time synchronous averaging to detect bearing frequencies will therefore fail. Another way is to use "normal" FFT averaging. This method is more applicable to bearing frequencies, but will not produce an averaged time signal; only the spectrum is averaged. The symptom enhancer algorithm however, looks for repetitive shock pulses in the time domain without needing a trigger pulse. The result is SPM Time signal HD, where random signals are suppressed and repetitive signals are enhanced. A spectrum based on this time signal is also produced.

To be able to vary the "strength" of the symptom enhancer algorithms, it is possible to change the "symptom enhancement factor" (SEF). A higher factor will improve the signal to noise ratio but the measuring time will increase; a low factor will result in less clear spectrums but the measuring time will be decreased. The default value is 5 and in most cases this is a good tradeoff between clarity in the spectrum and the measuring time. The improvement in signal to noise ratio is not linearly related to the factor, it is more a square root relation. The improvement is significant when changing the symptom enhancer factor from Off to 1, good improvement is achieved when changing from 1 to 5 but the improvement from 5 to 10 is limited. The measuring time however will be much longer when the factor is changed from 5 to 10.

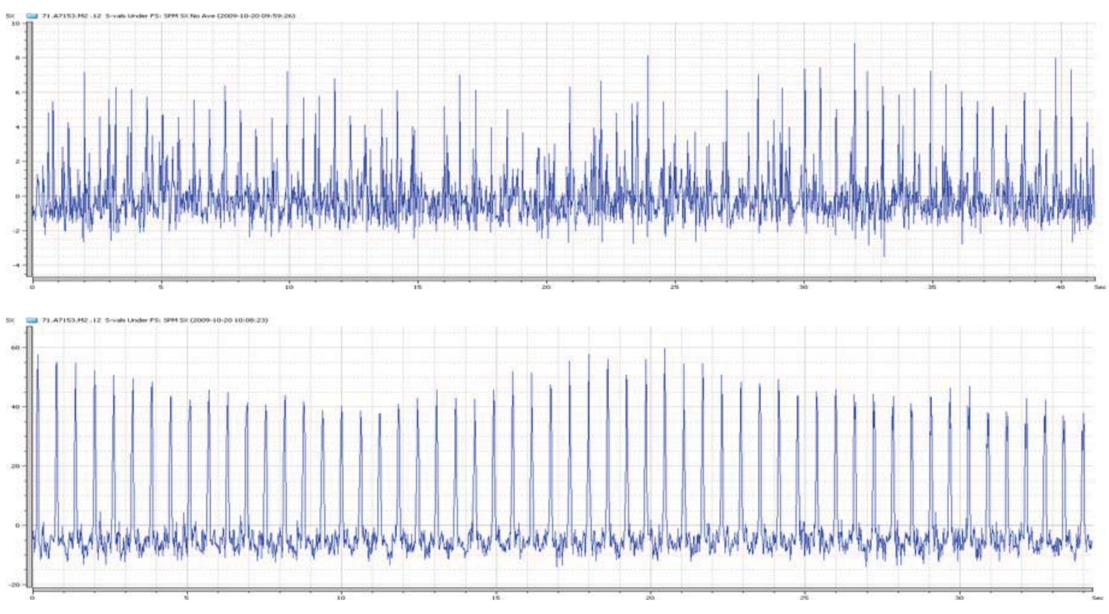


Fig. 16 *Example of a SPM HD Time signal before and after applying the symptom enhancer algorithm. The shocks originate from an outer race damage in a roller bearing at 10 RPM.*

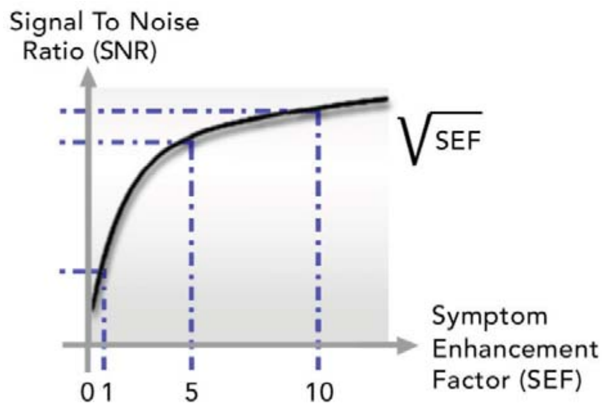


Fig. 17 *The relation between signal to noise ratio and the symptom enhancement factor. The improvement is significantly higher when the factor is changed from 1 to 5 compared with changing from 5 to 10.*

Theoretically, a SEF change from 1 to 2 improves the SNR by 3 dB, a change from 2 to 5 improves the SNR by 4 dB and SEF from 5 to 10 improves SNR by 3 dB. The measuring time increases dramatically with high SEF number changes (see formula in chapter 3.3, *'Measuring times for HDm/HDc and SPM Spectrum/Time signal'*).

Please note again that the symptom enhancer algorithms are used for the SPM Spectrum/Time signal HD and are not affecting the HDm/HDc values directly. If however the measuring time for HDm/HDc is forced to be equal to SPM Spectrum/Time signal HD, the measuring time for HDm/HDc is affected by the SEF.

3.9 Disturbance rejection

The symptom enhancer algorithm is an effective way to take care of random disturbances for SPM Spectrum/Time signal HD, but it does not help the HDm/HDc readings. Randomly occurring high shock pulses are instead, to a certain degree, taken care of by another algorithm: the disturbance rejector. The idea is that if the measuring time covers a sufficient number of revolutions (our recommendation is 50 revolutions), it is not likely that one single high amplitude or even two or three strong shocks will originate from the bearing. They are probably connected to a source other than a bearing. If however we catch five or more strong shocks they probably originate from the bearing. Our investigations shows that there is at least one strong impact for every 10th revolution, during 50 revolutions there are probably five times more. The result of this logic is that the disturbance rejector can handle a couple of strong impacts but not too many. If the default measuring time of 50 revolutions is used, the algorithms handles approximately five strong impacts before the HDm value is affected. If the 50 revolution settings is decreased to ten revolutions for example, the algorithm can handle one strong impact without affecting HDm.

Another way to describe the disturbance rejector is to use the histogram concept. If all shocks measured during the measuring time are stored with amplitude and then plotted in a diagram with number of shocks on the Y axis and the shock pulse strength plotted on the X axis, a histogram is created.

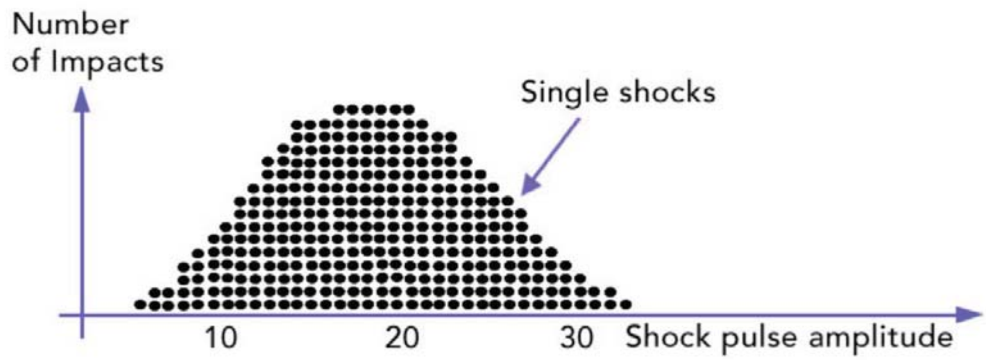


Fig. 18 *A typical histogram for a healthy bearing. The shock pulse strength for an individual shock is plotted on the X axis, while the number of shocks for a certain strength is plotted on the Y axis. Typically the histogram has a Gaussian distribution ("bell shaped"). In this example, most shocks are in the region 16 to 21 dB and the highest are around 33 dB.*

The number of shocks during one measurement can be several thousand and the bulk of shocks are typically very stable even in tuff industrial environments. Strong impacts will show up to the right in the histogram above. If there are a couple of very strong shocks among thousands of smaller shock and the measuring time spans 50 revolutions the likelihood for them to originate from the bearing is small.

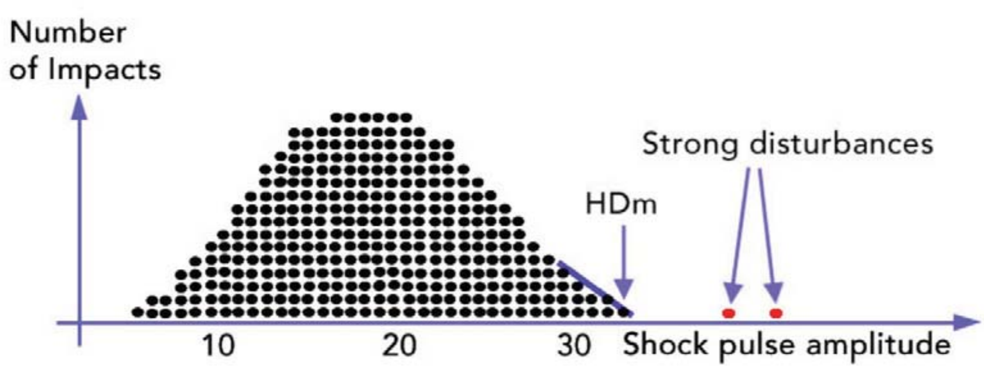


Fig. 19 *A couple of strong impacts shown in red color. They do not affect the HDm value. The slope of the histogram is used to extrapolate the HDm value.*

3.10 Amplitude scales

3.10.1 HDm and HDc

The two scalar values HDm and HDc are shown on a logarithmic scale expressed in decibels (dB). 0 (zero) dB equals a voltage level of 1 mV, -10dB equals 0.3 mV and 60 dB equals 1 V measured on a 40 000 transducer. The reason for using a logarithmic scale is the high dynamics of the shock pulse signal; using a linear scale is hard to understand, especially when the values cover several orders of amplitude. If the bearing diameter and RPM are known, the system calculates an initial value (HDi) which is used to normalize the "raw" shock pulse values. The result is two values, HDm and HDc, shown on an absolute normalized scale. This makes it possible to judge the severity of a possible bearing damage with only one single measurement. The default level for alert is 21 dB and for alarm 35 dB on the normalized scale. In slow RPM applications, bearings can often survive considerable time even with relatively severe damages, so in our field tests with low RPMs, we have used somewhat higher alert and alarm levels (typically 35 and 45 dB).

3.10.2 In the time domain

The Y scale in the SPM Time signal HD and SPM Spectrum HD is expressed on a linear scale. Looking at the SPM Time signal HD, the amplitude scales are different depending on whether the symptom enhancer is activated or not. The reason for this is that the symptom enhancer enhances repetitive patterns, hence affecting the peaks in the time signal so the result of the enhancement is not the real signal measured from the transducer. On the other hand, if the symptom enhancer is turned off, the resulting time signal is the real signal measured from the transducer. The time signal is squared as a result of the symptom enhancer algorithm, and if the symptom enhancer is turned on, the resulting Y scale is called HD^2esv (High Definition squared Enhanced Shock Value) and consequently it is called HDsv if the enhancer is turned off (note that the scale unit is not squared because the symptom enhancer is not involved in this case).

Using an STG02 (a calibration instrument used for calibration of SPM and vibration equipment) with the symptom enhancer turned off, the following results will be produced in time domain:

Amplitude HDsv in time domain	*STG-02 in dB*
1	0 dB
10	20 dB
100	40 dB
1000	60 dB
10000	80 dB

The same exercise but with the symptom enhancer turned on. In this case, the amplitude is dependent of the repetition rate of the shocks. An increase of the repetition rate from STG02 will increase the amplitude in the time domain (this is a result of the energy contents in pulses). In this case the repetition frequency of STG02 is set to order 1:

Amplitude HD^2esv in time domain	*STG-02 in dB*
1	0 dB
100	20 dB
10 000	40 dB
1 000 000	60 dB
100 000 000	80 dB

3.10.3 In the spectrum domain

In the spectrum domain, the scale is the same regardless of whether the symptom enhancer is turned on or off, but the scale unit on the Y axis are called HDesv respectively HDsv. The amplitude is dependent of the repetition rate of the pulses. Using an STG02 with repetition rate set to order 1 gives the following results:

Amplitude HDesv or HDsv	*STG-02 in dB*
1	0 dB
10	20 dB
100	40 dB
1000	60 dB
10000	80 dB

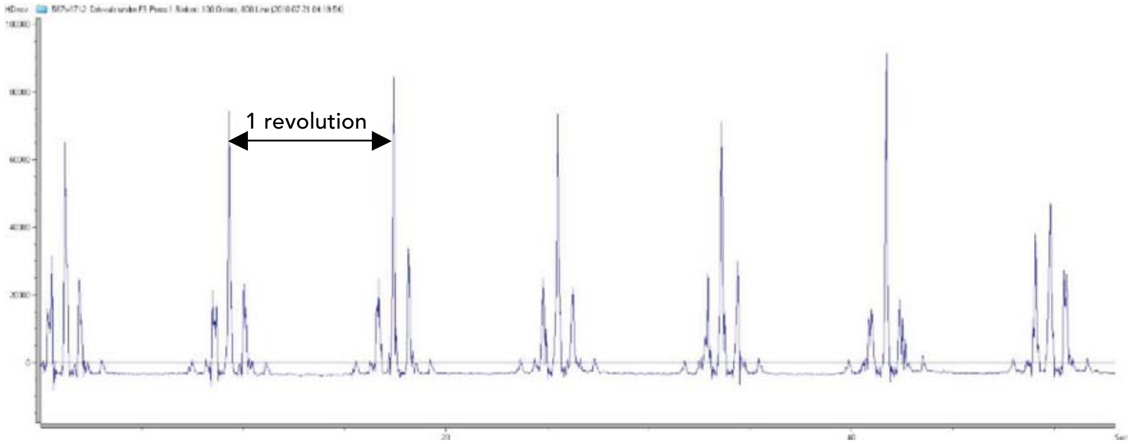
The different scale units can be somewhat complicated to understand, but please remember that the purpose of the SPM Spectrum/Time signals is to identify the shock source and to use them for relative measurements (trending), so do not pay too much attention to the absolute values in the Y direction. The important values for absolute measurements are HDm and HDc.

4 A couple of interesting patterns in spectrums

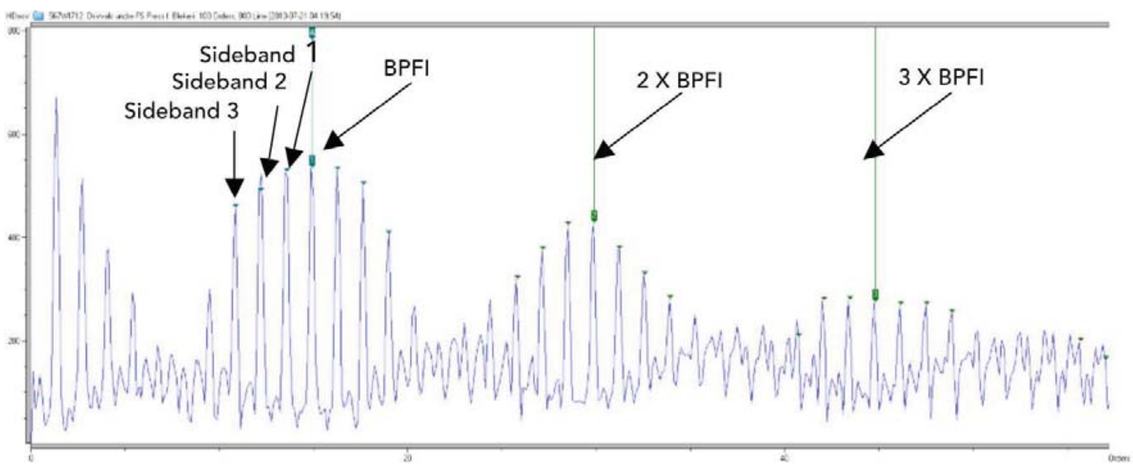
As a result of the SPM HD algorithms, the Time signals and Spectrums HD are unusually crisp and clear, increasing the demand for interpretations of different spectrum lines. Sometimes, finding a physical explanation to some of the patterns in the spectrums is complex. Listed below are some typical spectrums and some that need further evaluation of the machine before a decision is made to replace a bearing.

4.1 Typical inner race problem

A cracked inner race, time signal (spherical roller bearing from a twin wire press, approximately 10 RPM):



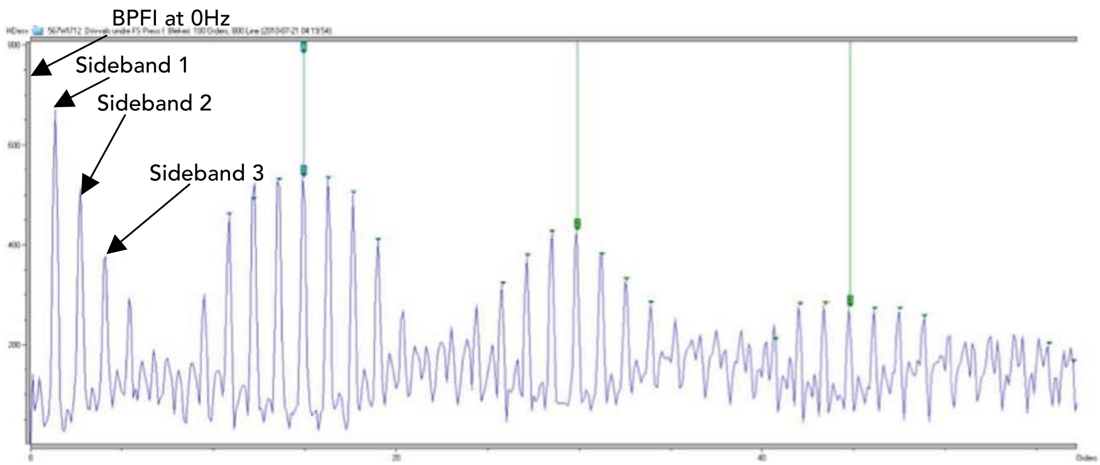
Same cracked inner race as above but in the spectrum domain. Note the extremely clear sidebands with a spacing of 1 times the RPM (Order 1):



If you find time signal like this, you can be fairly sure that this is an inner race damage. The typical pattern in the time domain is a result of the crack on the inner race entering and leaving the loaded zone. Use the HDm value before decision to replace the bearing.

Note that the pattern in the time domain is repeated for every revolution, and that the distance between the small peaks equals BPFI (ball pass frequency inner race). The resulting spectrums show a line at BPFI and sidebands with order 1.

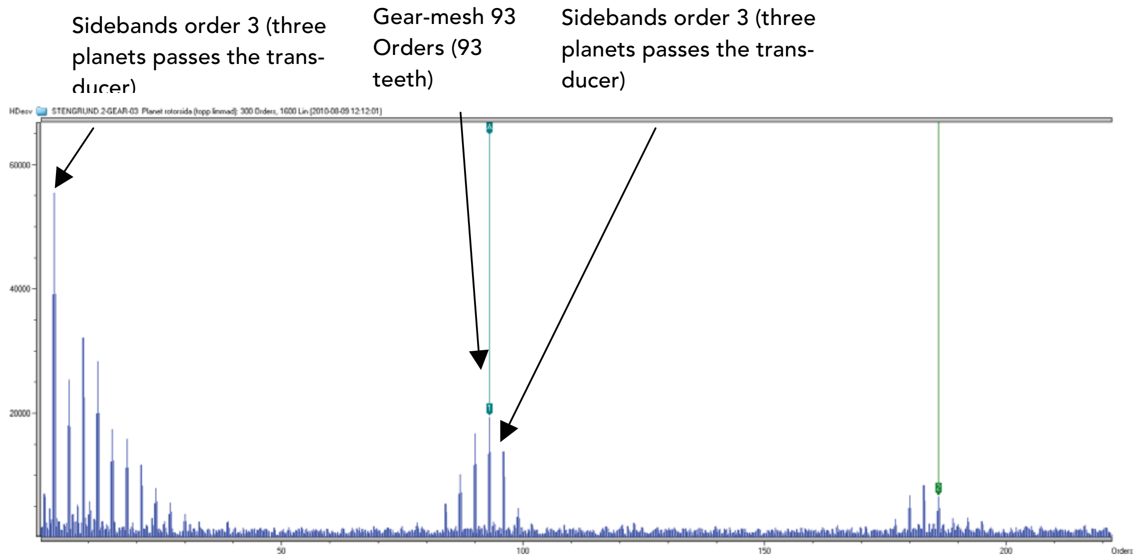
Studying the same spectrum again reveals another interesting detail. There is actually a BPFI peak at 0 Hz as well. It is not shown in the spectrum, but what is visible are the right hand sidebands to the 0 Hz line. This is an effect of the enveloping process as such. A raw SPM signal is normally symmetrical around 0. There are both positive and negative peaks, and taking an average of this signal will be close to 0. But in the enveloping process the signal is rectified and enveloped and the signal is no longer symmetrical; it has a DC shift. A DC shift means that there is a 0 Hz frequency component with sidebands. This is exactly what we see in the spectrum. Please note that this is also true for vibration enveloping techniques, but not for vibration without enveloping. Looking at the first line, it is positioned exactly at order 1 (1 times RPM).



It is a common misconception that a 1 X peak in the SPM Spectrum HD always means something impacting once per revolution. This may be the case, but much more common is that there is an inner race problem and the 1 X peak is the first sideband or something else that is modulated with 1 X.

4.2 Planetary gearbox with planet modulation

In a planetary gearbox for a wind turbine there are normally three planets. These planets are turning along with the main shaft, meaning that at a specific point, three planets pass this point in the course of one main shaft revolution. If an SPM transducer is placed on this point (for example glued to the outside of the ring gear), the shock pulse transducer will normally pick up the gear mesh from the teeth in the ring, and the strength of the gear mesh will regularly increase and decrease with the passage of the planets.



This is also an example where there is a DC component at 0 Hz not visible but the right hand side-bands are. This does NOT mean that there are shocks at order three, its just modulation.

Suspicious line at BPFO

As described in section 3.4, '*Effects of anti-aliasing filters and modulation on SPM Time Signal HD/SPM Spectrum HD*' earlier, a high frequency shock rate can be modulated to a lower frequency. Studying the resulting signal (the blue line in the picture), it can be seen that the signal has become "soft" with no sharp edges. If a Fourier Transform is applied to this signal, the result is a single peak with no harmonics in the spectrum.

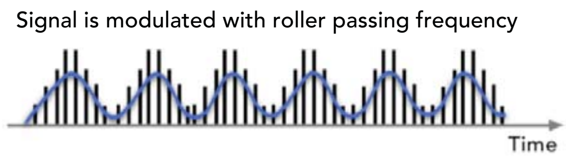
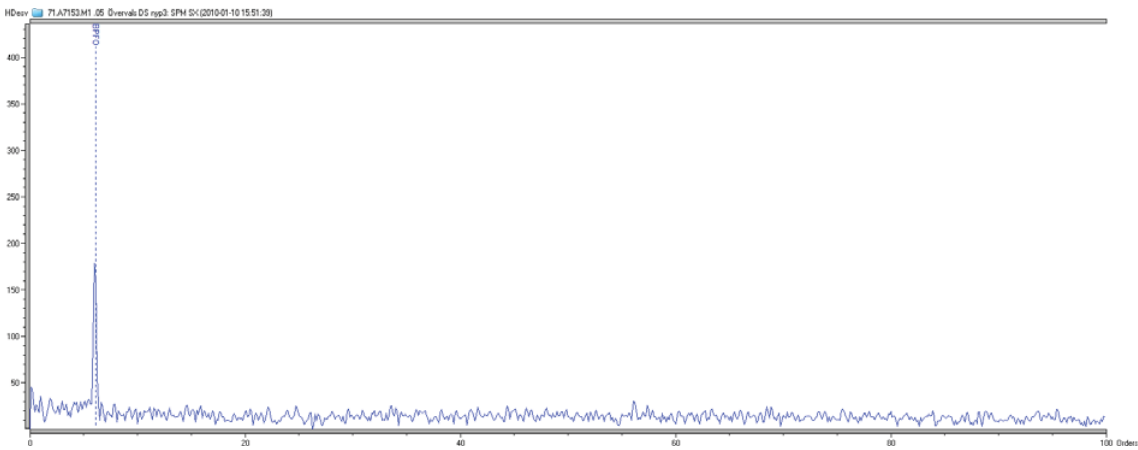


Fig. 20 *Modulation with BPFO*

A spectrum at BPFO with no harmonics may mean that the rollers are creating small shocks at the interface between the outer race and the rolling element each time a roller passes close to the transducer. The shocks are modulated with BPFO. This could indicate dry running or a rough surfa-ce but no severe damage.

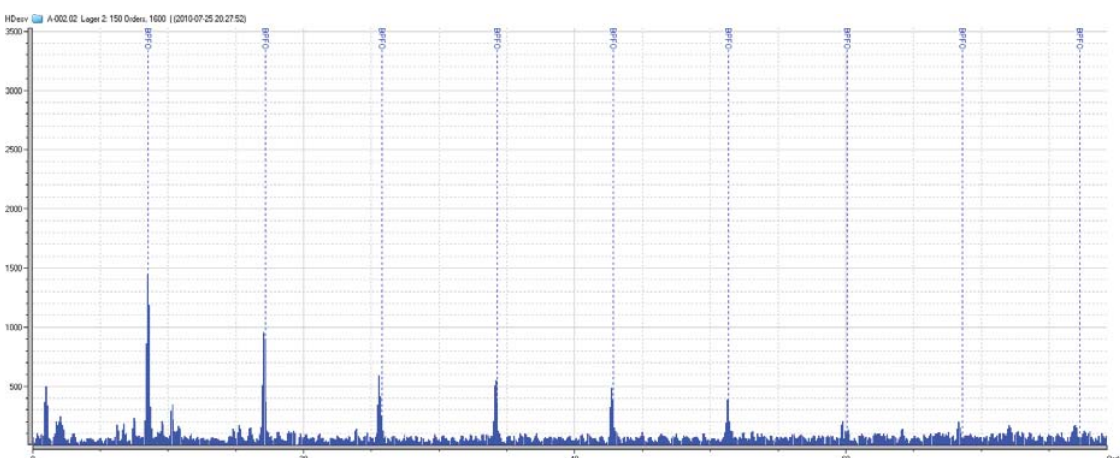
Example of a spectrum from a low RPM application with one peak at BPFO. This spectrum is no indication of damage on the outer race. In many cases, a single line matching a BPFO can be a good sign, indicating that the signal is of good quality; the transducer has good mechanical contact.

Twin wire press, approximately 10 RPMs



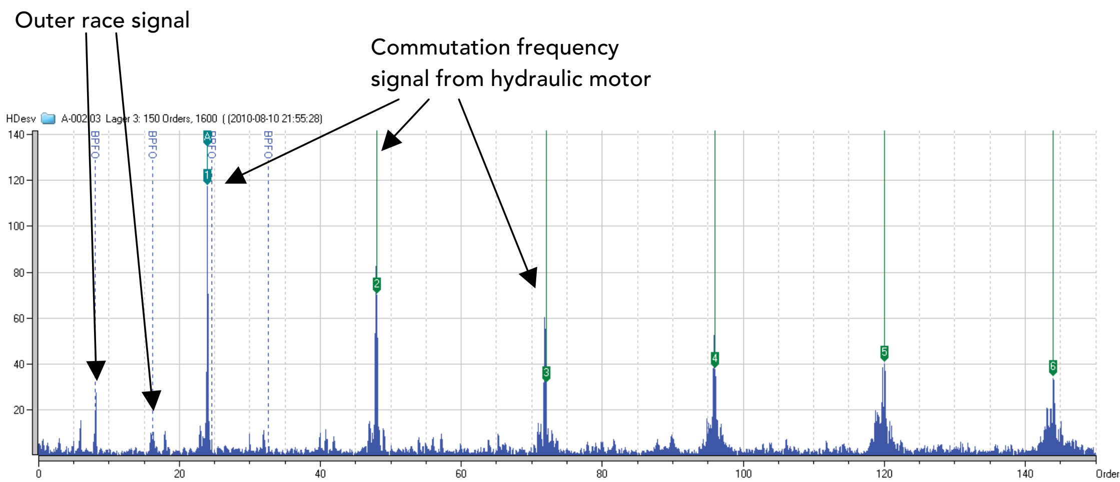
4.3 Typical outer race spalling with harmonics

A typical damage on an outer race involves higher order harmonics. This example is from a Swedish paper mill washing roller at 11 RPM. The leftmost line is the main BPFO frequency component with clearly visible harmonics to the right. Generally, a damage with sharp edges, typically from a spalling, results in very sharp shock pulses. A typical result contains a high content of harmonics.



Hydraulic motor

A hydraulic motor shows a typical pattern in the SPM Spectrum HD. The commutation frequency in the motor emits shocks that are easily detected. In some cases, the commutation frequency is not easily visible but this is related to the motor brand and how it is mounted. The example here shows a strong impact at 24 - 48 -70- 94-120-144 orders. Impacts from commutation frequency should create lines at whole numbers contrary to bearing related signals that are not whole numbers. In the spectrum also BPFO with at least two harmonics are visible. In some cases the signal from the deteriorating bearing is several magnitudes higher than the commutation frequency signal and HDm can be used directly. Otherwise band trending should be used.



5 Typical trends for deteriorating bearings at low RPMs

During the extensive SPM HD method field tests, we were able to study trends over long periods of time (more than a year) and a typical pattern, common for all the successful bearing damage detection during the test period, could be observed. The values of both HDm and Spectrum band values showed clear periods of increasing shock amplitudes followed by periods of decreasing amplitudes followed again by increasing values. The mean values were steadily increasing.

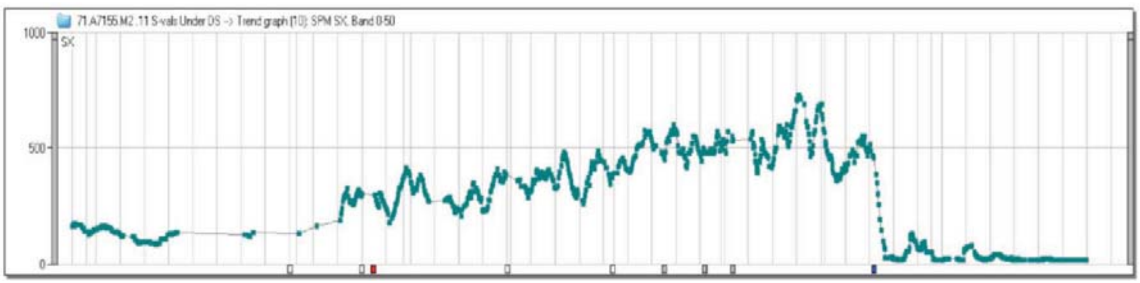
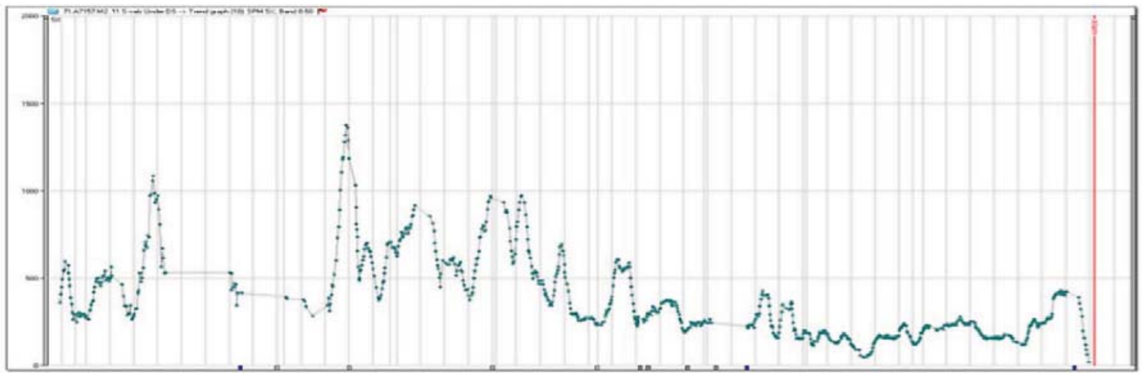


Fig. 21 *SPM Spectrum HD band values (proportional to the energy in the spectrum) spanning over six months, for a twin wire press bearing. RPM from 8 to 15. Note the typical pattern where periods of increasing values are followed by decreasing values while the mean value shows a clearly increasing trend. The dramatically decreasing values were after bearing replacement.*

The physical explanation to this behavior can be found in the interface between the raceways and the rolling elements. When the surfaces are subject to high pressure, microscopic cracks can be developed. When these very small cracks grow, entire areas of the raceway surfaces (or the surface of the rolling elements) can become loose, thus creating a spall. Even though the spall can be very small, it has sharp edges and when the rolling elements hit these edges, strong shocks are emitted from the contact points, thus affecting the shock pulse transducer. This results in a clear increase of shock pulse values. After some time, depending on the forces, these edges become less and less sharp due to the “smearing” effect of the rolling elements and the shock values goes down. A first spall is typically followed by new spalls and this process continues until the bearing is severely damaged. In the picture above, the time between two peaks is roughly five to ten days, but this will differ between applications.

This behavior is also the secret to the very long damage forewarning times when using the SPM HD method. The method detects even the first, very small spalls and the typical increasing/decreasing values can be observed very early in the damage process. Traditional vibration analysis is unable to detect this as early as the SPM method. This is because vibration transducers are sensitive to lower frequency mass movements and this movement is so extremely small that it will go undetected. Later on in the deterioration process, when the damage has become so severe that it involves mass movements (rolling elements “falling” into the grooves and /or displacement of the shaft), it can be detected with vibration analysis. Using vibration enveloping however, simulating the tuned SPM transducer can reveal details relatively early (see chapter 6, ‘*Comparison with vibration enveloping techniques*’).

In some cases, when a severely damaged bearing has been used for a long time, there is a high probability that the edges of spalls and possibly cracks have become so soft (edges with increasing radius) that the shocks emitted are decreasing in amplitude. Preceding this stage is a period of high shock levels.



April 2009 February 2010

Fig. 22 *Example of a severely damaged bearing with a decreasing trend due to softening of edges. The time period spans over ten months. The decreasing trend was preceded by a period of very high values. The bearing was replaced at the end of the trend graph. The probability of total malfunction was very high during this ten month period.*

6 Comparison with vibration enveloping techniques

The advantage of detecting elastic waves (shock pulses) in rigid material for early damage detection and lubrication evaluation for bearings is obvious. There are other methods which, to a varying degree, can be used to detect these elastic waves. One of them is vibration enveloping, another is PeakVue®[2]. It is important to point out that both of these methods aim at the same goal – to detect shock pulses. There are many similarities and some differences between vibration enveloping, PeakVue® and the SPM method.

When a rolling element in a bearing collides with a damage on a raceway, a shock pulse is created at the point of impact. The shock pulse propagates in the material by affecting nearby molecules, and is spread by the speed of sound in the material (the speed of sound in steel is approximately 5000 m/s). When this wave front propagates in the raceway material, eventually spreading out in the machine itself, it will trigger oscillations at the natural frequency of the machine structure. The natural frequency of a steel structure, for example, will be different depending on whether it is a small sturcture or a big one, if the shape is round or square, etc. A big steel structure has a lower natural frequency than a small steel structure. In the case of the SPM method, the resonating structure is built into the transducer itself, while the vibration enveloping techniques and PeakVue® rely on the structural natural frequencies mentioned above. This is the first and maybe the most important difference between the SPM method and the other methods: the "ringing" structure is built in into the transducer itself in the case of the SPM method, while the other methods use the ringing structure of the bearing or machine itself. Typically, the natural frequencies for bearings and machines can be found from 2 kHz to 8 KHz, but it can vary widely depending on the application.

When the shock pulse wave front hits a metal structure in the machine, the oscillation starts at the natural frequency of the structure. If an accelerometer is mounted at the "ringing" structure, the oscillations from the structure will be detected and hence can be measured. These oscillations are normally much smaller in amplitude compared with the signal energy from low frequency signals like unbalance and misalignment.

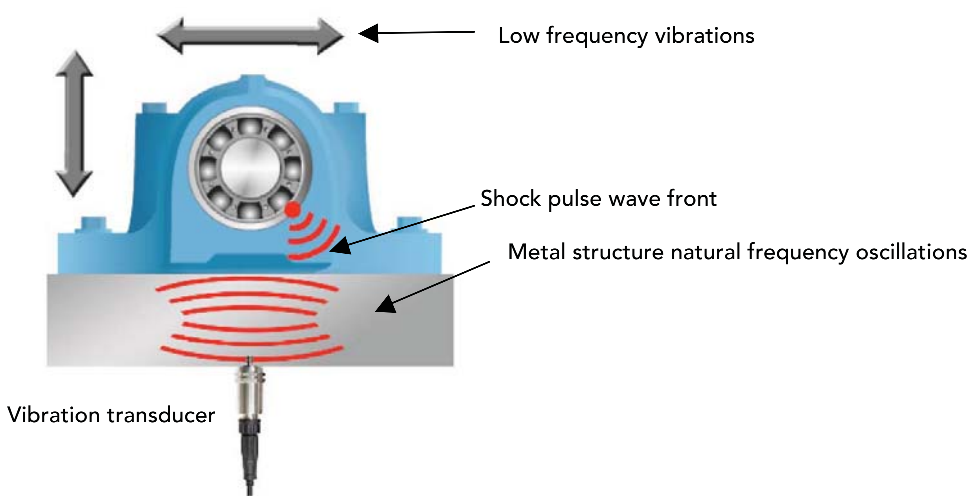


Fig. 23 *A simplified picture of a machine with an outer race damage in a bearing. The shock pulses propagate in the machine and triggers a metal structure. The metal structure oscillates at its natural frequency. An accelerometer mounted on the structure will measure the oscillation. The double arrowed arrows represent low frequency vibrations that are normally dominate the signal completely.*

2) PeakVue® is trademark of CSI Technology, Inc.

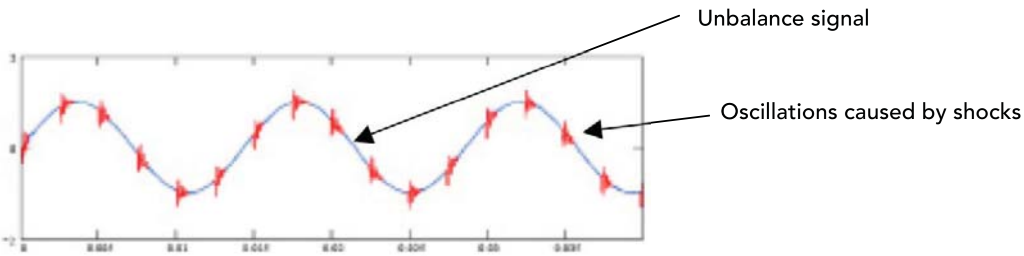


Fig. 24 *Typical signal from the accelerometer. A low frequency signal originating from an unbalance is dominating the signal. Superimposed on this low frequency signal, small oscillations from shock pulses are visible.*

To be able to extract the small ”ringing signals” from the overall signal, a band pass filter or a high pass filter needs to be applied.

Because the ”ringing” structure has different natural frequencies, varying from bearing to bearing and machine to machine, finding out exactly at which frequency the oscillation occurs is essential. When that frequency has been identified, the center frequency of the band pass (or high pass) filter can be adjusted to this frequency. In the SPM method, this step is not necessary because the ringing structure inside the transducer is always 32 KHz. A typical approach to finding out the natural oscillation frequency is to take a broad band frequency spectrum and try to identify a so-called ”haystack”. A typical appearance of such a spectrum is high amplitude peaks at low frequencies, originating from unbalance or other low frequency sources. Higher up in the spectrum, a broad group of frequency lines with normally significantly lower amplitude can be seen: a haystack. Once the haystack is identified, the next step is to apply the filter so the haystack is contained inside the pass band of the filter. The result after the filtering is a signal containing only the oscillation triggered by the shocks.

This signal will then be rectified and enveloped, very similar to the SPM technique.

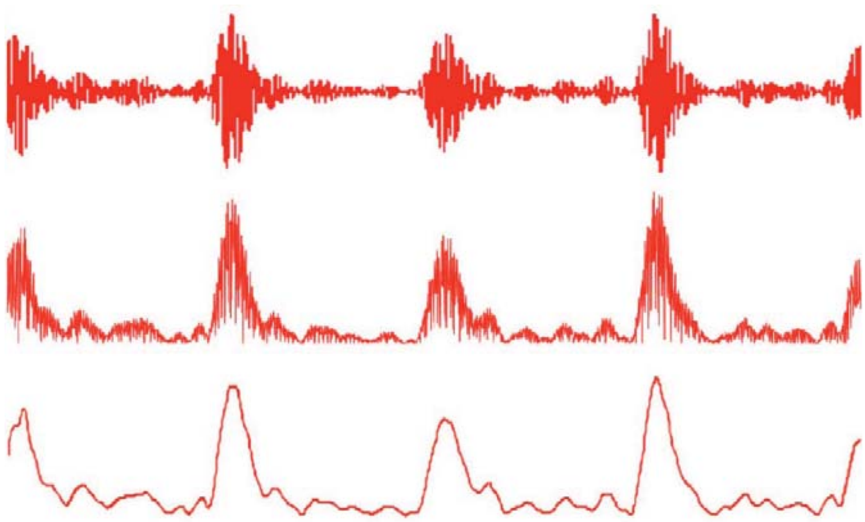


Fig. 25 *Top: the vibration signal after the band pass (or high pass) filtering step. Middle: the signal after rectification. Bottom: the enveloped signal. Note the similarity with the SPM method principles at these stages.*

Contrary to the SPM method, the resulting enveloped signal amplitude can not be judged in absolute terms because it is depending on where the transducer is placed and what type of transducer is used. As mentioned in previous chapters, the "ringing" time for accelerometers are normally longer than for SPM transducers (not indicated in the picture above). This makes it hard to resolve shocks that are coming too closely; they will be added up into one big peak instead of several smaller peaks. This is a clear advantage of the SPM method. Especially for lubrication condition measurement, where the shocks are small and many, it is important to resolve individual shocks.

The enveloped signal is then treated in the "normal" way, by applying FFT algorithms and studying spectrums.

The step when the rectified signal is enveloped is very critical. The normal approach is to use a low pass filter to extract the envelope. The consequence of this is that the amplitude in the signal is dampened. To avoid this distortion of the amplitude, the PeakVue®[3] method extracts the envelope from the rectified signal in a different way: instead of using a low pass filter, PeakVue® divides the rectified signal into a number of time slots (the width of each time slot depends on frequency range and number of lines). Within each timeslot, the instrumentation uses a high sampling rate to find the highest peak. When all time slots are processed, a very accurate envelope is extracted with minimal amplitude distortion. The drawback is that when a high sampling rate is being used, the aliasing filters are set very high (or not used at all), creating aliasing problems, especially when several strong signals exist at the same time (like an outer and inner race damage or multiple damages on one raceway). The name PeakVue® may be an acronym for the process of finding the highest peak within the time window – viewing the peak PeakVue®.

The SPM HD method uses the low pass filtering method to avoid aliasing, but as a consequence the amplitude is affected. However the HDm value is an accurate value for the amplitude maximum value, so you could say that SPM HD is the best of both worlds.

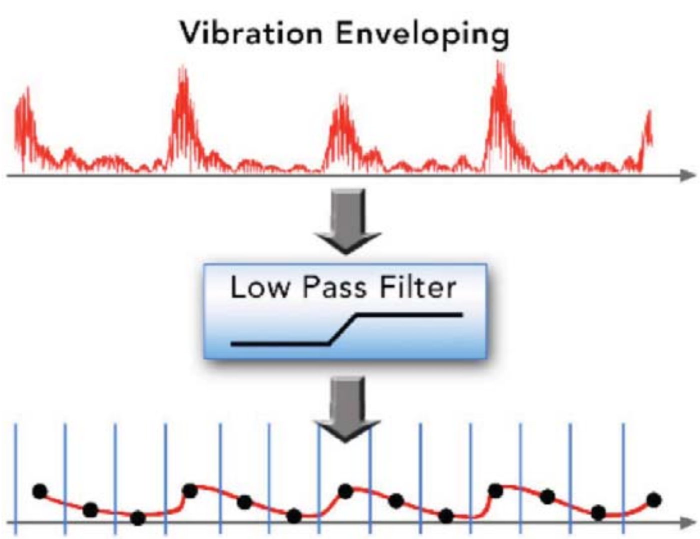


Fig. 26 *A standard envelope process. The rectified signal is passed through a low pass filter. The amplitude is affected but the signal does suffer from alias problems.*

3) PeakVue® is trademark of CSI Technology, Inc.

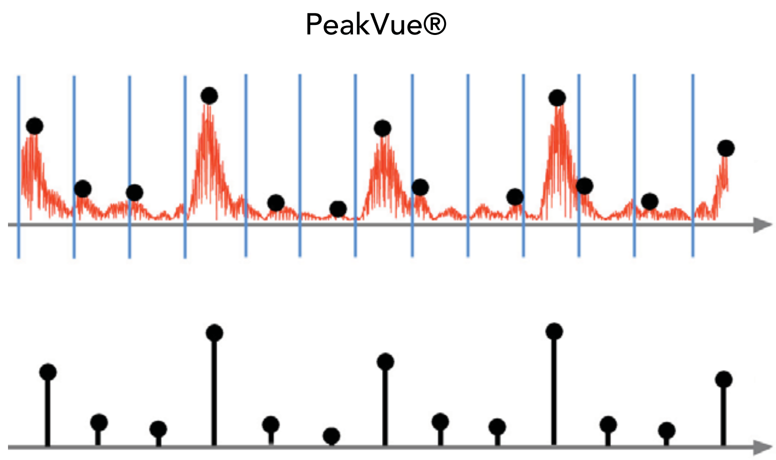


__Fig. 27__ The same process using PeakVue®. Within each time window, the highest peak in the signal is identified. The amplitude is preserved.

6.1 Summary

There are similarities between the SPM method, vibration enveloping and PeakVue®[4]: they all look for elastic waves (shock pulses). The shock pulses trigger resonant structures. In the case of SPM, this structure is built in into the transducer, always having a resonance frequency of 32 KHz. In vibration enveloping techniques, this ringing structure is found in the machine. A filter (band pass or high pass) needs to be tuned to find a suitable frequency to remove the low frequency contents.

The major advantages of the SPM method is the fact that the tuned transducer is tailor-made to detect elastic waves. It responds in a predefined way when exposed to a specific elastic wave, thus enabling an absolute scale for bearing operating condition.

4) PeakVue® is trademark of CSI Technology, Inc.

Example of Condmaster Nova parameter setup

The parameter settings required in Condmaster to start measurement with SPM HD are limited. Besides the obvious settings for measurement channels, measuring interval etc., there are a couple of settings unique to SPM HD:

Measuring time HDm/HDc: The default setting is 50 revolutions. If the measuring time available is limited, this number can be decreased. The HDm values can become more unstable if this number is reduced by too much. Try to avoid decreasing it below ten revolutions. If the number of revolutions is increased to 1000, for example, the measuring time will of course increase, but some stability can be gained. Selecting the "Same as FFT measurement" setting means the measuring time for HDm/HDc will be forced to be equal to the SPM Spectrum/Time signal HD.

Short time memory and Long time memory settings: We strongly recommend using "Time signal and FFT" for both long and short time memory if possible. The time signal HD is very valuable in the analyzing process. The reason for supplying the option to save only FFT and peaks is to limit the size of each result, thus keeping the database size under control. If the database size is not an issue, it is good practice to also save time signals in long time memory.

Upper frequency: Frequency can only be specified in orders. One order equals RPM/60 Hz (if RPM=120, then 1 order equals 2 Hz). It is very convenient to work with orders once you get used to it; bearing signals and gear mesh are easily identified. Order tracking is used by default. The lower frequency is always 0, while the default value for the upper frequency is 100 orders. As a rule of a thumb, you should select a frequency range that covers the main frequency of interest together with five harmonics. Typical values for BPFO, BPFI are around ten, adding five harmonics and some extra room gives 100 orders. Of course this number should be adapted to the application. In a typical wind turbine application, we use 100 orders for all measuring points except the planetary gearbox, where we use 250 orders in order to cover gear mesh from the ring.

Please note that increasing the upper frequency will decrease the measuring time for SPM Spectrum/Time signal HD (see chapter 3.3, '*Measuring times for HDm/HDc and SPM Spectrum/Time signal*'), but the resolution will decrease.

Lines in spectrum: The default value is 800 lines, which is sufficient in most cases. It is possible to select up to 12.800 lines, but be careful: the measuring time as well as the computing time will increase dramatically for SPM Spectrum/Time signal, especially if a high symptom enhancement factor is used (see chapter 3.3, '*Measuring times for HDm/HDc and SPM Spectrum/Time signal*'). If measuring time is not critical, 1600 lines can reveal some more details. For planetary gearboxes in wind turbine applications, 1600 lines is recommended.

Symptom enhancement factor: The default value is 5. This works in most cases. Increasing this factor to 10 increases the signal to noise ratio by 3 dB, but measuring time then almost doubles. The allowed range for the factor is 1 to 10. For more details, see chapter 3.8, '*Symptom enhancer*'.