Detecting cavitation and simultaneously occurring mechanical faults

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Abstract

Cavitation is a somewhat common and well-known phenomenon and can cause erosion in machines, such as water turbines and pumps. The detection of cavitation in different machines has been quite widely investigated. However, when cavitation occurs simultaneously with different types of mechanical faults, the task is slightly more complicated. This paper discusses the application of real order derivatives, weighted $l_p$ norms and S surfaces in order to detect cavitation, mechanical looseness, the lack of lubrication and certain combinations of these. It is shown that these methods can produce easily interpretable information on a complex situation of this kind.

Keywords: cavitation, simultaneous faults, weighted $l_p$ norm, real order derivative, fractional derivative, MIT measurement index, S surface

1. Introduction

While being harmful due to erosion of materials, cavitation causes vibration. This gives the possibility to detect it by means of vibration measurements. There is also a potential risk of mechanical damage caused by vibration induced by cavitation. In condition monitoring, a change in the vibration signal is often considered to be a sign of a deteriorating condition in the machine. However, if cavitation is taking place simultaneously, the vibrations that are induced by it should be extracted from those that are due to mechanical faults.
This requires an adequate amount of measurement data and some expertise to perform suitable signal processing for feature extraction. In the following, detecting cavitation and simultaneously occurring mechanical faults is discussed, and some results based on laboratory experiments are presented.

2. Laboratory tests

The laboratory testing was conducted at Otto von Guericke University, in Magdeburg, Germany. The test rig used was originally manufactured by G.U.N.T. Gerätebau GmbH, and was later modified at the Otto von Guericke University. The test equipment consisted of:

- Bodywork of G.U.N.T. PT 500 test rig
- 1.1 kW electric motor manufactured by EMK
- Nordac 700E frequency converter
- Mädler 41200102 bevel gearbox with transmission ratio 1:2
- Centrifugal pump for cavitation testing, manufactured by G.U.N.T.
- 2 KTR claw clutches

A photograph of the test rig is in Figure 1.

![Figure 1. The test rig](image)
At the initial stage, measurements were performed with no faults induced in order to acquire the signals that would be used as reference. After this, mechanical looseness of the pump stand and the lack of lubrication in the gearbox were caused intentionally. In the tests, the system was run with and without cavitation in all the situations mentioned above.

Cavitation was inflicted by closing the valve on the intake side pipeline of the pump. Mechanical looseness was caused by loosening the mounting bolts of the stand of the pump, and the lack of lubrication by pouring out the lubricant from the gearbox. After the oil was poured out, the gearbox was placed for about 16 hours in a position, where the residue keeps flowing out of the gearbox. The bevel gear was then run for 10 minutes with slow rotational speed to ensure minimum effect of residual lubrication.

Measurements were performed using two accelerometers, and their signals were simultaneously sampled at the sampling frequency 50 kHz. The accelerometers were IMI Sensors model 621B51 and the data acquisition card was NI 9233 manufactured by National Instruments. Before starting the measurements, the sensitivity of entire measurement equipment was determined using a calibrator.

3. Detecting cavitation and faults

Vibration is caused when cavitation occurs, as bubbles of gas in liquid collapse causing a mechanical shock\(^{(1)}\). This causes erosion in machine parts, so cavitation is normally undesired. When trying to avoid cavitation detecting it is of course useful, and there are numerous articles about this\(^{(2,3)}\). Also modelling and simulations about cavitation have been under some investigation\(^{(4,5)}\).

It is shown that detecting cavitation from acceleration signals for example in water turbines\(^{(6)}\) is possible, when signal processing is performed in a suitable way. These signal processing methods are valuable in several industrial applications\(^{(7)}\).

Detecting faults is a very common topic, and instructions on this are provided in handbooks\(^{(8)}\). When there are multiple faults, however, the situation is more complicated in this respect, but separating different sources of vibration has proved to be possible\(^{(9)}\).

4. Frequency domain signal processing

The fast Fourier transform (FFT) is very commonly used in order to create a frequency spectrum. Nonetheless, FFT can also be useful in calculating derivatives and integrals.
The real order derivative stands for a derivative, whose order can be any real number, instead of being limited to integers. The definition for real order derivative \( x^{(\alpha)} \) of function \( x = X e^{i\omega t} \) is:

\[
x^{(\alpha)} = \omega^\alpha X e^{i(\omega t + \alpha \pi)},
\]

where \( X \) is a constant, real number \( \alpha \) is the order of derivative, \( \omega \) is the angular frequency, \( e \) is the Napier’s constant, \( i \) is the imaginary unit and \( t \) is a variable representing time. This definition was introduced by Lahdelma in (10).

Furthermore, we can express (1) as follows:

\[
x^{(\alpha)} = (i\omega)^\alpha x.
\]

(2)

The FFT results in a sequence with finite number of complex components \( \{X_k\} \), which present the phase angle and the amplitude of each term of the Fourier series. This complex spectrum can be transformed to the complex spectrum of the \( \alpha \) order derivative by multiplying each term \( \{X_k\} \) by corresponding \( (i\omega_k)^\alpha \), this is to say:

\[
X_{\alpha k} = (i\omega_k)^\alpha X_k
\]

(3)

As integration is the inverse procedure of the derivation, it can be calculated as ‘a negative derivative’, which means using negative values of \( \alpha \). When desired operations on the sequence are complete, the time domain signal of \( \alpha \) order derivative can be acquired by inverse Fourier transform (FFT\(^{-1}\)). There is a somewhat similar way of filtering the signal. The unwanted frequency components can simply be multiplied by zero. This results in a filter with very sharp cut off.

5. Weighted \( l_p \) norms and measurement indices

For detecting several faults, the weighted \( l_p \) norm was applied. This norm has proved to be an effective tool in condition monitoring, and it can be applied to any type of signal(6,11,12,13,14). It is defined by:

\[
\|x^{(\alpha)}\|_{p,w} = \left(\sum_{i=1}^{N} w_i |x^{(\alpha)}_i|^p \right)^{\frac{1}{p}}.
\]

(4)

where the real number \( \alpha \) is the order of derivative, \( x \) is displacement, \( N \) is the number of samples in signal, and the real number \( p > 0 \). This is the classical \( l_p \) norm \( \|x^{(\alpha)}\|_p \) when \( w_1 = w_2 = ... = w_N = 1 \). Moreover, we end up with the formula (5), when \( w_1 = w_2 = ... = w_N = \frac{1}{N} \). It has the same form as the generalised mean,
also known as the power mean or the Hölder mean. Lahdelma has introduced in (13) the concept of the space $l_p$.

$$\|x^{(\alpha)}\|_p \equiv \left( \frac{1}{N} \sum_{i=1}^{N} |x_i^{(\alpha)}|^p \right)^{\frac{1}{p}} = \left( \frac{1}{N} \right)^{\frac{1}{p}} \|x_i^{(\alpha)}\|_p.$$  

(5)

The MIT index (15) can be used to create an easily interpretable way of determining the scope of the relative change in the value of the norm. It is calculated by

$$\tau MIT^{p_1,p_2,\ldots,p_n}_{\alpha_1,\alpha_2,\ldots,\alpha_n} = \frac{1}{n} \sum_{i=1}^{n} b_{\alpha_i} \frac{\|x^{(\alpha_i)}\|_{p_i}}{\|x^{(\alpha_i)}\|_{p_i}}.$$  

(6)

where $b_{\alpha_i}$ is the weighting factor for $\alpha_i$ order derivative, and the norms $\|x^{(\alpha_i)}\|_{p_i}$ are calculated from signals $x^{(\alpha_i)}$. The norm $\|x^{(\alpha_i)}\|_{p_i}$ is a reference, usually obtained from a machine in good condition.

6. Analysis of the measurements

The S surface (12) is a three dimensional graph, which is obtained by calculating the values of the MIT index (6) using different order derivatives and the $l_p$ norms, and plotting the results. The frequency spectra are presented using rms values.

6.1 Vibrations induced by the motor

After conducting some tests, an unusual shape in the frequency spectrum was detected in all of the measurements whether or not any faults were deliberately induced to the system. Figure 2 shows that there are multiple peaks in the intervals of 25 Hz.
One could quite easily assume that the peaks in Figure 2 are caused by misalignment, mechanical looseness, or at least some of them by electrical interference, as 50 Hz is the frequency of the power grid in Germany. In this case, these assumptions can be proved to be wrong, as can be seen in the spectrum presented in Figure 3, where there are from different frequencies, which are in fact harmonics of the rotational frequency. These peaks are showing even if the motor was not coupled to anything at all and it was ensured that it is firmly mounted on the stand.

Because the motor was brand new when the tests were started, it was not expected that the motor would cause this kind of vibration. However, despite of trying a
number of different settings for the frequency converter, the vibration did not change substantially. In the end it was concluded that there may have been some kind of defect in the motor or in the frequency converter, but as the vibration level was very low after all, this could not be considered very exceptional. In fact, the vibration can be considered to be on acceptable level, even if it is due to fault of some kind. Nonetheless, this phenomenon is not insignificant enough to be ignored in further analysis.

### 6.2 Cavitation

Acceleration signals measured from the pump with and without cavitation are shown Figure 4. The difference can be seen even if it cannot be considered very dramatic.

![Figure 4. Acceleration signals from the frequency range 3...15000 Hz measured from the pump. Rotational speed was 3000 rpm: (a) in the initial situation and (b) when there is cavitation](image)

Figure 5 shows the S surfaces calculated from the signals in Figure 4 from two different frequency ranges. It can be seen that in the originally used frequency range the maximum relative change is greater than in the case where band-pass filtering from 3 to 5000 Hz is used. It can also be stated, that the S surface in Figure 5b is rather interesting. The relative change in $l_p$ norms of the order around 4 and above is fluctuating, which can be seen as ‘ridges’ to the S surface. This is a very good example indicating that using several orders of derivative can be useful when trying to determine the best features for a certain case. It is quite obvious too why using S surface is sensible in this case, because it shows the optimum orders of norm and derivative very easily.
Figure 5. The S surfaces calculated from the acceleration signal measured from the pump when comparing the situation with cavitation to the initial situation. Rotational speed was 3000 rpm: (a) frequency range 3...5000 Hz and (b) 3....15000 Hz

6.3 Mechanical looseness

When the pump was running with the bolts loosened, the frequency spectrum in Figure 6b shows a clear change in frequencies range below 1 kHz. This is actually a somewhat expected result. On the other hand, in some cases mechanical looseness can also cause shock-like vibrations, because a loose machine can be shot up in the air for a period of time, and then slammed back on the mounting. In this case, signs of this kind of behaviour cannot be seen, but the frequency spectrum shows a quite obvious change in rotational frequency and its harmonics.
Figure 6. Acceleration spectra from 3 to 1000 Hz of the signals measured from the pump. Rotational speed was 3000 rpm: (a) in the initial situation and (b) when mechanical looseness was induced

In Figure 7, there are the S surfaces where the situation with mechanical looseness is compared to the initial situation. There is a clear change in lower order derivatives regardless of the order of the $l_p$ norm. This is quite a logical result, because it can be seen in Figure 6 that the change is most prominent at relatively low frequencies, and on the other hand it is a known fact that low frequency vibrations have the highest impact on the low order of derivatives.

Figure 7. The S surfaces acquired from the acceleration signal measured from the pump when comparing the situation with mechanical looseness the to initial situation. Rotational speed was 3000 rpm: (a) frequency range 3...5000 Hz and (b) 3....15000 Hz
6.4 Lack of lubricant

Lack of lubrication was caused to the gearbox by simply pouring out the lubricant, but not washing it off. To achieve a situation where the amount of lubricant is certainly inadequate, the gearbox was run for 10 minutes to heat it up and thus to decrease the viscosity of the oil. After this the lubricant was let to pour out of the gearbox for 20 hours. After removing the lubricant, the gearbox was run for about ten minutes at slow speed before starting the measurements. The purpose of this action was to reduce the effect of residual lubrication. The measurements analysed here were performed after the gearbox had been running for about 15 minutes and after removing the lubricant, so it is quite certain the the residue of the lubricant had minimum effect, if any.

Figure 8 shows the S surfaces calculated from the acceleration signals measured from the gearbox. In this case the signal obtained with the lack of lubrication is compared to the signal from the initial situation. The lack of lubricant causes a clear change in several features, and the highest changes of norms are comparable to the case of cavitation. It must be noted, however, that the shape of the S surface is not similar. Because poor lubrication leads to increased friction, which causes random vibrations in a wide frequency range, it is an expected result that higher orders of derivative show a change in this case. Setting the upper cut-off frequency to 5 kHz provided greater relative change than using upper cut-off frequency of 15 kHz.

However, the drop at low orders of derivative ($\alpha \approx 0...1$) is somewhat more difficult to explain. The analysis of the displacement spectra (Figure 9) shows that the main reason to this is a drop in the 25 Hz frequency component, which represents the rotational speed of the motor. It should be noted, that even if the relative change in the displacement at 25 Hz frequency was considerable, the level of vibration is very low in both the cases. Nonetheless, it can be stated that the lack of lubricant was detected in the measurements.
Figure 8. The S surfaces calculated from the acceleration signal measured from the gearbox when comparing the situation with no lubricant to the initial situation. Rotational speed was 3000 rpm: (a) frequency range 3...5000 Hz and (b) 3...15000 Hz

Figure 9. Displacement spectra from 3...200 Hz measured from the pump: (a) in the initial situation and (b) with no lubricant. Rotational speed was 3000 rpm

6.5 Combinations of cavitation and faults

Figure 10 shows the S surface from the situation where both mechanical looseness and cavitation occur simultaneously. We can see a shape that quite obviously is a combination of the shapes shown in Figures 5b and 7, where cavitation and mechanical looseness occur separately. The result can easily be found just by looking at the
S surfaces. A very similar result can be seen also in Figure 11, where the shape of the S surface looks like a combination of Figures 5b and 8b.

Figure 10. The S surface acquired from the acceleration signal measured from the pump when comparing the situation with mechanical looseness and cavitation to the initial situation. Rotational speed was 3000 rpm and frequency range 3...15000 Hz

Figure 11. The S surface acquired from the acceleration signal measured from the pump when comparing the situation with cavitation and no lubricant to the initial situation. Rotational speed was 3000 rpm and frequency range 3...15000 Hz

In Figures 12 and 13 the S surfaces represent the same situations as in Figures 10 and 11, but this time the signals are from 3 to 5000 Hz. It is quite evident that the
results are different. It can be stated that the shape indicating cavitation, which is seen in Figures 5b, 10 and 11, is not visible when the upper cut-off frequency is 5 kHz. It can nevertheless be stated, that even if the relative change in high orders of derivative due to cavitation is greater when the upper cut-off frequency is 15 kHz, it is also possible to detect cavitation when the upper cut-off frequency of 5 kHz is used. This can be seen in Figure 5a. A similar shape of S surface in higher orders of derivative as in Figure 5a can be seen in Figure 12 as well.

![Figure 12. The S surface acquired from the acceleration signal measured from the pump when comparing the situation with mechanical looseness and cavitation to the initial situation. Rotational speed was 3000 rpm and frequency range 3...5000 Hz](image-url)
Figure 13. The S surface acquired from the acceleration signal measured from the pump when comparing the situation with cavitation and no lubricant to the initial situation. Rotational speed was 3000 rpm and frequency range 3...5000 Hz

7. Conclusions

In conclusion, we can say that cavitation, mechanical looseness and the lack of lubrication can all be detected using real order derivatives and $L_p$ norms if the order of derivative and the norm are selected correctly. The frequency range used can have a significant impact to the results. Even simultaneous faults can be detected when the S surface is utilised. With this surface, it easy to conclude which of the features have changed and this information could be used in automatic condition monitoring, for example. A monitoring system could interpret the information we have presented, alert when there is significant change in any of the feature, and even indicate the type of fault by determining the shape of the S surface.

References


