Order-Tracking with and without a tacho signal for gear fault diagnostics

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ABSTRACT

Order-tracking is a method to remove speed fluctuations from a varying frequency signal allowing constant frequency based Machine Condition Monitoring (MCM) analysis techniques to be employed. Even small amounts of speed variation have to be compensated for by order-tracking when fine analysis is to be carried out, such as time synchronous averaging (TSA) for gear diagnostics. Some machines, such as wind turbines, have much more widely varying operating speeds, and so order-tracking is necessary before even basic diagnostics can be conducted. This paper describes a method whereby angular resampling can be carried out with and without a tacho signal, using progressive iterations in a multi-stage approach, even in the case of large speed variations. Measurements were made on a gear test rig with a faulty gear, with speed varying over a number of different ranges up to ±25%. Results show that speed fluctuations could be removed successfully allowing subsequent TSA and gearmesh demodulation techniques to correctly diagnose a seeded tooth root crack.

1 INTRODUCTION

Order-tracking is a method to remove speed fluctuations from a varying frequency signal allowing constant frequency based Machine Condition Monitoring (MCM) analysis techniques to be employed. Most machines have a small amount of speed variation with variations in load, even at nominally constant speed, and this has to be compensated for by order-tracking when fine analysis is to be carried out, such as for time synchronous averaging (TSA) for gear diagnostics. Some machines such as wind turbines have much more widely varying operating speeds, and so some form of order-tracking is necessary before even basic diagnostics can be conducted. Order-tracking normally requires some sort of tacho signal to allow resampling in the rotation angle domain.

Existing Order-Tracking methods have been unable to both compensate for large speed variations and simultaneously give the fine resolution high frequency components necessary for the subsequent implementation of many current gear diagnostic techniques.

This paper describes a method whereby order-tracking can be carried out with and without a tacho signal, using progressive iterations in a multi-stage approach, even in the case of large speed variations of up to ±25%. This method results in fine resolution high frequency components suitable for use in gear diagnostics. The method presented here is based on the Single Record Order-Tracking (SROT) method as described by Coats (2006) and Coats and Randall (2010), which is a resample based order-tracking method.

Resample based order-tracking is a method which resamples a varying speed signal from equal time increments to equal phase increments. This results in a signal whose spectrum is scaled in harmonic orders, allowing the subsequent employment of constant frequency MCM techniques.

The SROT method is based on phase demodulation, extracting the phase of the first harmonic of shaft speed from a coupled tachometer signal, giving a map of the phase (rotation angle) vs. time of a rotating component of interest. This map can then be used to resample a corresponding vibration signal into a signal with stable harmonic frequency components of interest.

In this paper, firstly the SROT method is summarised covering the factors relevant to the extended method developed for this work.

The methodology for a new method to order-track a signal using progressive iterations in a multi-stage process is discussed.

The multi-stage method is then used to order-track multiple variable speed vibration signals with associated tachometer signals, captured from a gearbox testrig which contained a faulty gear with a seeded tooth root crack. Results of the order-tracking of signals with ±10% and ±25% speed variation are presented here. These signals are then analysed using Time Synchronous Averaging (TSA) and gearmesh demodulation to show the correct detection of the gear fault.

Finally, the multi-stage method is used to order-track the same vibration signals as above, without the use of the associated tachometer signals. A reference signal is instead extracted directly from a vibration signal. Results of the order-tracking as well as subsequent TSA and gearmesh demodulation are shown.

2 SINGLE RECORD ORDER-TRACKING

The basic SROT method was developed with the goal of providing a resample based order-tracking method which could operate with larger speed variations than traditional time based order-tracking approaches. The SROT method was intended to be used in cases where an acceleration signal and a directly coupled tachometer were available. It can however be used with any signal type where there is a corresponding reference signal mapping time and phase of the reference component, including a reference signal extracted from the primary signal itself.

The SROT method consists of two main steps. The first step is that phase demodulation is used to extract a phase vs. time map from a reference signal. The second step is that the phase vs. time map is used to determine time values corresponding to equi-spaced phase values to be used for the new phase based sampling, and the order-tracked signals are produced by determining the values of the original signals at the new sample times by interpolation.

It was found that all the relevant operating limits to the new method proposed here were imposed by the phase demodulation procedure. These operating limits are summarised in the section 2.1.

Finally, the order-tracking results following the application of the basic SROT method are shown in section 2.2, which necessitated the development of a multi-stage approach as shown in this work.

2.1 Operating Limits of SROT Method

The operating limits of the basic SROT method are primarily imposed by the use of phase demodulation.

The phase demodulation procedure is used to extract a phase vs. time map of the reference component to be used in the order-tracking procedure, which can be used to then produce the order-tracked result.

The method of phase demodulation has been discussed in detail in many works. From the frequency spectrum of a signal a specific band is selected, and the phase found of the components within that band. The procedure used by the SROT method is almost identical to that described by Randall (2011), with the addition that the linear phase of the carrier frequency is re-added to form the phase vs. time map.

To produce the correct phase vs. time map, the frequency band selected must encompass the reference component to be used. Typically, a reference component will be a member of a harmonic series, and so it is necessary to demodulate just one harmonic of the harmonic series.

As the phase demodulation procedure is blind, the phase produced will represent everything inside the selected frequency band selected. This means that ideally the frequency band should contain just one harmonic of the reference component series, but no other frequency information of any kind. Any extraneous components encompassed by the band, such as noise or other signal components, will degrade the order-tracking result.

The simplest type of reference signal to work with is generally a tachometer signal, as they are usually free of significant noise and only contain one component of interest. In signals without extra components, the limiting factor is due to overlapping of harmonics of the same series.

All suitable reference signals for order-tracking can be considered to be frequency modulated signals (even if they are simultaneously amplitude modulated). General frequency modulated harmonic series (above a certain modulation index) have the property that the bandwidth of each (smeared) harmonic is proportional to its harmonic order, such that the bandwidth of the second harmonic is twice that of the first and so on. The largest non-overlapping bandwidth possible is then from the first harmonic, at the point where it just meets the bandwidth of the second harmonic. Figure 1 shows this specific case, and it can be seen that provided the second harmonic does not overlap the first, higher harmonics will also not encroach the bandwidth of the first harmonic.

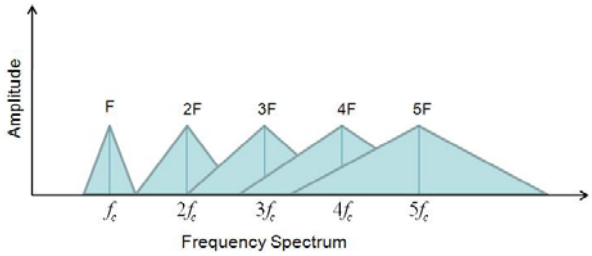

Figure 1. Extent of bandwidth of higher harmonics when harmonic 1 bandwidth is maximised

Solving algebraically, it is found that the maximum non-overlapping bandwidth for the first harmonic is ±33% of the carrier (centre) frequency f_c around f_c. The bandwidth of the first harmonic can then be related to the speed variation and rate of speed variation giving the maximum allowable parameters which can be used for the SROT method.

Traditionally a frequency modulated (FM) signal is defined as a constant frequency carrier signal modulated by a message signal. The simplest type of FM signal is a frequency modulated sinusoidal wave with sinusoidal modulation as shown in equation (1)

$$y(t) = A_c \cos[2\pi f_c t + 2\pi f_d \int \cos(2\pi f_m t)] \quad (1)$$

Where $y(t)$ is the FM signal, A_c is the magnitude of the carrier signal, f_c is the carrier signal frequency, f_d is the frequency deviation corresponding to the speed variation, f_m is the modulation frequency or rate of frequency variation.

The spectrum of the FM signal defined in equation (1) consists of a carrier frequency component, and an infinite number of sidebands tending to zero magnitude, resulting in a practically finite bandwidth. The magnitude of the components is expressed using Bessel functions of the first kind, $J_n(\beta)$, where β is the modulation index defined by equation (2). β is also the phase deviation from the carrier in radians.

$$\beta = \frac{f_d}{f_m} \quad (2)$$

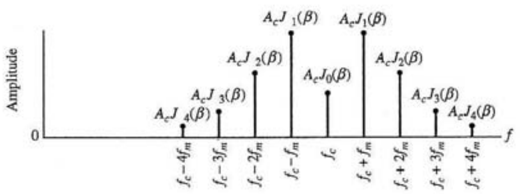

Figure 2. FM signal spectrum in terms of Bessel Functions (Ziemer and Tranter, 2002)

Figure 2 shows the spectral components of an FM signal as defined in equation (1), showing the first 4 sidebands.

As the spectrum has an infinite number of sidebands, a definition of significant sidebands must be used to give a finite bandwidth. For the SROT method as used with vibration signals a significant dynamic range of 40 dB is used, where a sideband is only significant if it is within 40 dB of the largest sideband. This is shown in Figure 3.

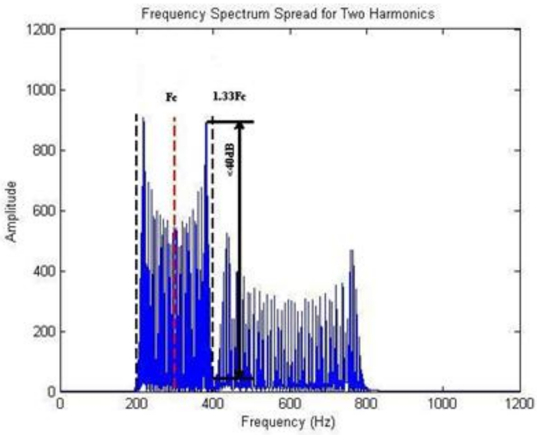

Figure 3. Significant sideband definition, for limiting ±33% bandwidth case

By expressing f_d and f_m as a percentage of f_c, $f_{d\%c}$ and $f_{m\%c}$, it is possible to find values of $f_{d\%c}$ and $f_{m\%c}$ which result in a bandwidth of equal to or less than the limiting bandwidth of ±33% of f_c. Figure 4 shows the allowable combinations of $f_{d\%c}$ and $f_{m\%c}$ producing an acceptable bandwidth.

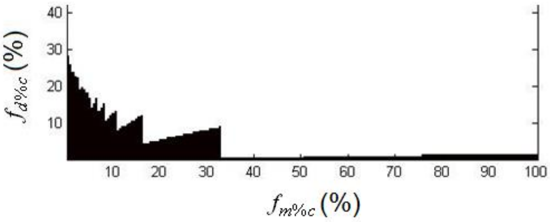

Figure 4. Combinations of speed change and rate of speed change permissible with the SROT method

The discontinuous steps in Figure 4 result from the step changes in bandwidth as individual sidebands change from being significant to non-significant.

These permissible values are only for basic FM with sinusoidal modulation. It is however possible to use them for more general cases by replacing f_d with *D*, the peak speed deviation away from the carrier, and f_m with *W*, the baseband bandwidth of the speed deviation (Ziemer and Tranter, 2002)(Schwartz, 1990). Using *D* and *W* with Figure 4 gives conservative bandwidths for any general varying speed case.

From Figure 4 it can be seen that the approximate maximum permissible speed range is ±28% for cases of very low rates of speed change. As the rate of speed change increases, the maximum permissible speed variation decreases. However for many machinery examples, such as with wind turbines, the relatively high inertia of rotating components mean that typically only *D* or *W* is high, not both parameters at the same time.

These are the maximum permissible speed ranges in an ideal case, assuming no noise or other frequency components present in the demodulated band.

When using a tachometer as a reference signal, the spectrum is generally free of noise and other components. When using other signals as a reference signal the permissible speed ranges will generally be smaller due to the presence of other components or noise. Generally the maximum speed range permissible for non-tachometer reference signals is highly signal dependent, and each application needs to be evaluated separately.

2.2 Order-tracking results from SROT method

The results of using the SROT method were shown by Coats and Randall (2010).

Testing using simulated signals showed extremely accurate order-tracking when using FM sine waves, which only contained one harmonic rather than a harmonic series.

Experimental testing however showed that the SROT order-tracking method was accurate only to a certain degree.

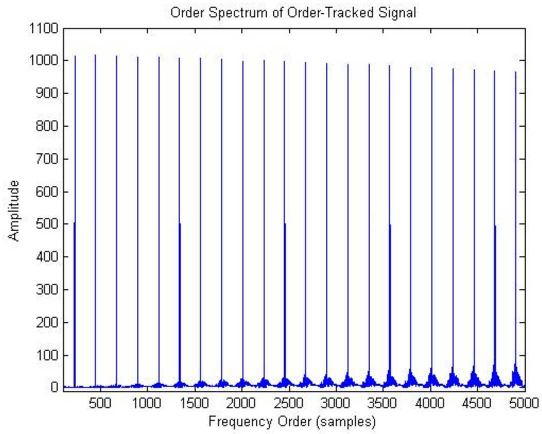

Figure 5. Order-tracked Tachometer signal showing progressive error at higher harmonics

Figure 5 shows the results of order-tracking using the SROT method. This is from a signal with ±20% speed variation and ±1% rate of speed variation. The tachometer signal was used to order-track itself, as this gives a clearer visual picture than looking at the corresponding acceleration signal. If the signal had been correctly order-tracked, every harmonic would resolve into a discrete (order) frequency. Figure 5 shows the first 22 harmonics of the tachometer, and it can be seen that only the first harmonic has resulted in a discrete frequency. As the harmonic order increases, there are increasing amounts of frequency variation which have not been correctly compensated for.

Investigation showed that the SROT method provides extremely accurate order-tracking up to the harmonic order used to perform the order-tracking. If the first harmonic of the reference signal was used, only frequency components up to the first harmonic of the reference signal would be completely order-tracked. Higher frequency components would contain progressively larger amounts of residual frequency modulation.

Using a higher harmonic of the reference signal increased the frequency range of the correctly order-tracked components, but consequently reduced the permissible speed range which could be order-tracked due to the larger bandwidth spreading of higher frequency harmonics. The allowable speed ranges would approximately decrease based on the harmonic order, so using the 2nd harmonic would decrease allowable speed ranges by 2, and using the 100th harmonic would reduce the allowable speed ranges by a factor of 100.

Coats and Randall (2012) found that by using the basic SROT method on the first harmonic, a bearing fault could be correctly detected for speed ranges of up to ±25% in a vibration signal, in spite of the residual frequency modulation on higher harmonics. This was true when using a tachometer as a reference signal as well as using the signal itself as a reference signal. This is because of the general possibility of detecting bearing faults in signals even in the presence of 1-2% residual speed variation, as only the first few harmonics are required to make the diagnosis.

Analysis requiring extremely accurate speed compensation with large speed variations is however not possible with the basic SROT method, such as for gear fault detection using TSA, where high-frequency components must be correctly order-tracked. The solution presented in this work was to implement a multi-stage approach using progressively higher harmonics for order-tracking.

3 MULTI-STAGE ITERATIVE APPROACH TO ORDER-TRACKING

As discussed in section 2.2, it was found that the basic single-stage SROT method is not suitable for order-tracking signals which require detailed analysis of high-frequency components. The SROT method can either correctly order-track high frequency components, or order-track signals with large speed variations, but not both simultaneously, at least perfectly.

In 2009 Coats and Randall (2009) investigated order-tracking of minor speed fluctuations from a gas turbine engine to perform subsequent TSA, in cases where a directly coupled tachometer was not available. As part of this work an iterative process of using phase-demodulation based order-tracking was developed to utilise primarily the signal itself to perform order-tracking. This method was shown to successfully allow order-tracking to compensate for frequency fluctuations even for high frequency components.

In order to successfully order-track a signal, the process was conducted in multiple stages. For the first stage, the first harmonic of the shaft of interest was used as it was found to be clearly separable from the rest of the signal spectrum. The resulting order-tracked signal had most of the frequency modulation removed. As a second stage, the highest separable harmonic of the shaft of interest in the order-tracked signal was now found to be the 43rd harmonic. This was used to order-track the signal a second time. A third stage of order-tracking was now conducted using the 141st harmonic of the shaft, as it was now separable after the first two stages of order-tracking. The final result could successfully be used to perform TSA.

As this methodology had proven successful in removing minor speed fluctuations from a nominally constant speed signal, it was investigated for use in the presence of large speed variations.

In order to use the multi-stage approach, order-tracking at each stage is conducted on both the signal of interest as well as the corresponding reference signal. The order-tracked reference signal is then used as the basis of the next stage of order-tracking.

Figure 6 graphically shows the procedure for order-tracking, extended to N stages. Any number of stages could be utilised to progress to higher and higher frequency values. The only consequence would be a compounding of errors introduced

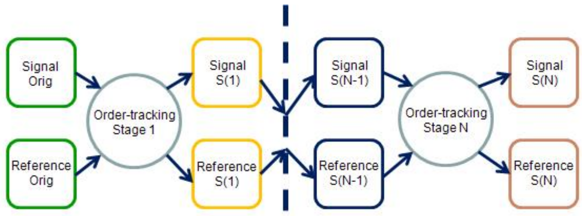

Figure 6. Multi-stage approach to Order-Tracking

by the order-tracking process itself. These errors however have been shown to be many orders of magnitude smaller than the residual modulation typically remaining, and have been a negligible issue in any multi-stage testing conducted at this time.

The general method assumes the use of a separate reference signal; however it can equally be applied in cases where a reference signal can be extracted directly from the recorded signal of interest.

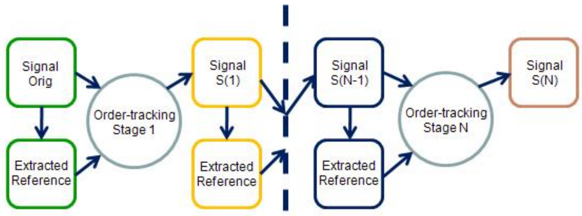

Figure 7. Multi-Stage approach to Order-Tracking using an Extracted Reference Signal

Figure 7 shows the procedure for using an extracted reference signal to perform multi-stage order-tracking, extended to N stages. It should be noted that a new reference is extracted at each stage, rather than the initially extracted reference signal being used for all stages. This is a result of higher harmonics being generally more accurate, as they have a larger bandwidth and hence a finer spectral resolution which results in finer detail of the frequency variation.

4 MULTI-STAGE ORDER-TRACKING WITH A TACHOMETER

In order to test the multistage order-tracking method while using a tachometer signal as a reference, various experimental signals were captured from a gearbox testrig.

The gearbox was operating with two 32-tooth spur gears at a mean shaft speed of 6 Hz, with various amounts of speed variation including ±10% and ±25%. The period of the frequency sweep was 5s, making the modulation frequency f_m = 0.2 Hz. The signals analysed had nominal 25 Nm torque load applied with the machine running at 6 Hz constant rotation before speed variation was commenced. The rig had a seeded gear fault, a tooth root crack, introduced on one of the two spur gears. An acceleration signal was captured from an accelerometer mounted on the gearbox casing. A synchronously recorded once-per-rev tacho signal was available, as was a 900-per-rev shaft encoder signal. For this analysis only the tacho signal was used as a reference signal. The signals were captured for 60 seconds, and initially sampled at 65536 Hz. The signals were decimated to 13107.5 Hz before analysis was begun. This was done purely to reduce the signal size and improve processing time.

In order to evaluate the order-tracking process, it was first used to order-track the experimental signals in multiple stages.

The order-tracked signals were then subsequently used in further analysis commonly used for gear fault diagnosis. Firstly the signals were averaged with TSA as described by McFadden (1987), to show that the extracted deterministic components correctly show the meshing of all 32 teeth on the gears. The TSA results were then demodulated at one of the gearmesh harmonics to produce phase and amplitude plots of the gearmesh which has been shown by McFadden (1986) to detect tooth root cracks, to see that the gear fault could be correctly detected in a signal containing speed variations.

4.1 Results of Order-Tracking with a tachometer

In order to evaluate the success of the multi-stage order-tracking method multiple experimental signals were order-tracked. Results shown here are for firstly the ±10% speed variation case, and then the ±25% speed variation case.

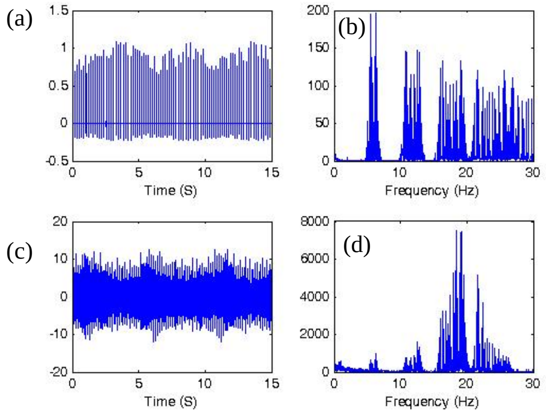

Figure 8. Signals with ±10% speed variation (a, b) tacho (c, d) acceleration, (a, c) time signals (b, d) spectra

Figure 8 shows the initially captured signals for the ±10% case. Only 15 seconds of the 60 second signals are shown in the time domain for visual clarity. From the spectra (b) and (d) it can be seen that the shaft harmonics are clearly modulated due to the speed variation. From (b) it can also be seen that the first harmonic of the reference signal is separable, and can be used for order tracking. It can also be noted that the acceleration signal (c) shows clear amplitude modulation at f_m with a period of 5 s visible.

For the first stage of the multi-stage order tracking the first harmonic of the tacho is used.

Figure 9 shows the result of the order tracked tachometer signal. The ideal order-tracking would result in a single discrete component for each harmonic present. As can be seen, the first harmonic has been order-tracked to one discrete value, and there are progressively increasing residual modulation sidebands at the higher harmonics, as was expected from one stage of order-tracking.

Figure 10 shows the spectrum of the corresponding acceleration signal after one stage of order-tracking.

Figure 10 firstly shows that the frequency modulation has been primarily removed when compared to Figure 8(d). The remaining modulation sidebands are primarily due to the amplitude modulation present in the signal. The large smeared component between orders 8 and 9 in Figure 10(b) is

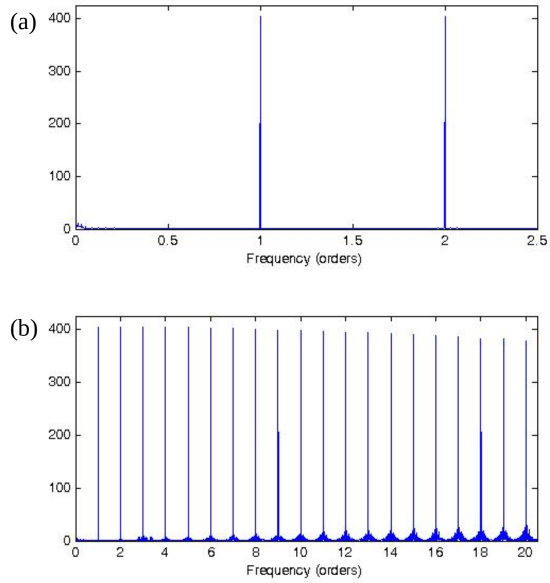

Figure 9. Spectrum of order-tracked tacho after 1 stage for ±10% case (a) showing first 2 harmonics (b) showing first 20 harmonics

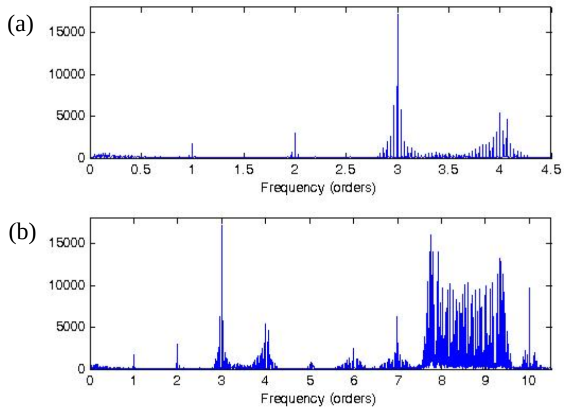

Figure 10. Spectrum of order-tracked acceleration signal after 1 stage for ±10% case (a) first 4 orders (b) first 10 orders

a constant frequency 50 Hz component which becomes smeared in the order domain. Ideally constant frequency components should be removed before order-tracking to prevent this as it can mask order components.

The signal was completely order-tracked using 4 stages of order-tracking. The multiple stages used the 1st, 5th, 21st and 151st harmonics in order.

Figure 11 clearly shows the progressive improvement of the higher harmonics in later stages of order-tracking. As the harmonics become less modulated and tend to discrete values they increase in amplitude because the total energy of each harmonic becomes concentrated in one frequency line. This can be seen in the overall amplitude of the order spectrum, with later stages providing smaller improvements in the order-tracking.

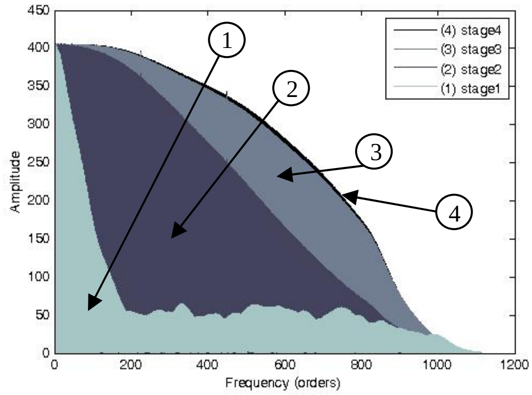

Figure 11. Comparing Spectra of order-tracked tacho from all four stages for ±10% case

Figure 12 shows the change of order 650 of the tachometer signal for all four stages of order-tracking, and it can clearly be seen that the component becomes increasingly discrete in the later stages as the order-tracking becomes more successful.

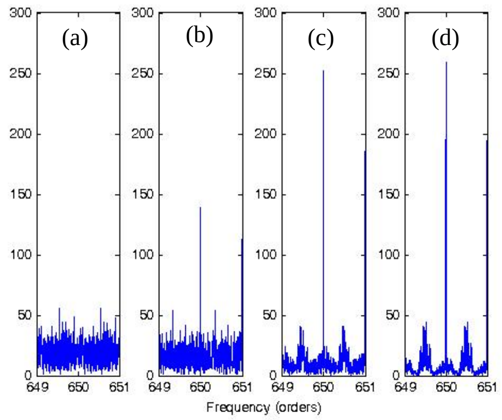

Figure 12. Comparing Spectra of order-tracked tacho from all four stages for ±10% case for the 650th order. (a) stage 1, (b) stage 2, (c) stage 3, (d) stage 4

The values present at the half orders are present between every harmonic. These are believed to be modulation sidebands not included in the selected bandwidth during the first stage due to being judged negligible at the time. These components at every half-order also become more discrete after each stage and increase in amplitude. The exact nature and impact of these half-order components is the subject of ongoing research.

Figure 13 shows the original signals for the ±25% case, and in (b) the larger speed variation is clearly visible.

This signal was again completely order-tracked using 4 stages of order-tracking. The multiple stages used the 1st, 5th, 21st and 151st harmonics in order.

Figure 14 clearly shows the progressive improvement of the higher harmonics in later stages of order-tracking in the ±25% case, showing comparable results to the ±10% case. The lower increase in amplitudes with later stages for the ±25% case is believed to be due to the presence of greater amplitude modulation in the tacho, as visible in Figure 13 (a).

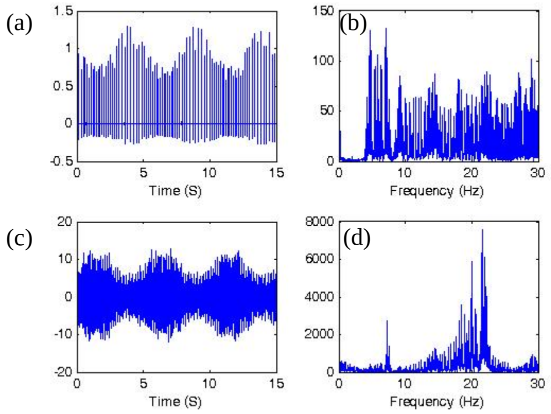

Figure 13. Signals with ±25% speed variation (a, b) tacho (c, d) acceleration, (a, c) time signals (b, d) spectra

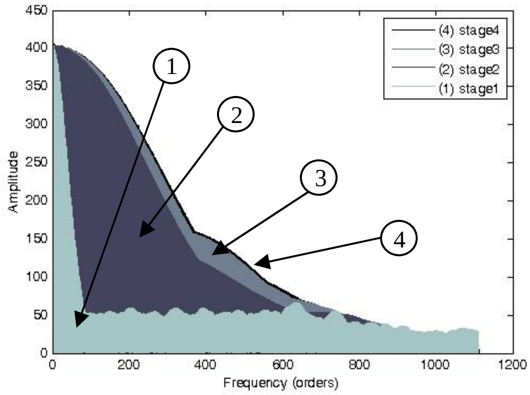

Figure 14. Comparing Spectra of order-tracked tacho from all four stages for ±25% case

From the results of the multi-stage order-tracking for both the ±10% and ±25% speed variation signal, the multistage approach appears to have order-tracked the signals successfully.

4.2 Results from using TSA and Gearmesh Demodulation for gear analysis

In order to further evaluate the success of the multistage order-tracking process, the order-tracked results from section 4.1 were subject to further analysis common for gear analysis.

The first analysis process was to use the Time Synchronous Averaging process on the order-tracked signals as described by McFadden (1987). The TSA method produces an averaged signal for one period of rotation of the component of interest. By conducting the TSA for one period of rotation of the gears in the signal, the gearmesh of the 32 gear teeth should be visible as 32 equally spaced peaks if the prior order-tracking was successful, and the gear errors were completely uniform. Note that the triggering for TSA was linked to the rotation angle of the gears, and not synchronised in any way with the speed variation. Thus the results of TSA represent the average amplitude in each rotation cycle, averaged over twelve periods of the speed variation.

Figure 15 shows the results of the TSA. The figures shown were low pass filtered to just above the 4th gearmesh harmonic (128th order) in order to improve the visual clarity of the gearmesh. In the TSA one pulse per tooth is clearly visi-

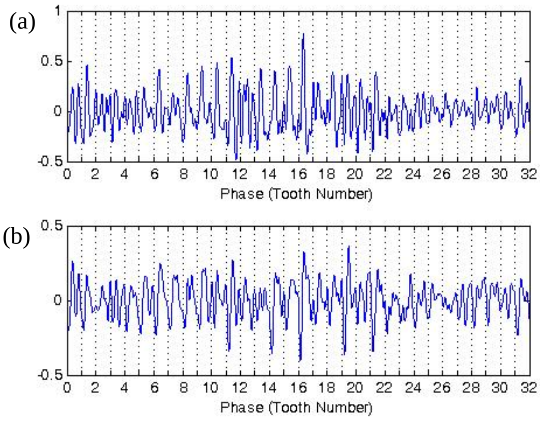

Figure 15. TSA results (a) ±10% case (b) ±25% case

ble, showing the meshing of each individual tooth. In this case two pulses per revolution are also seen in some zones. This corresponds to the fact that the second harmonic of gearmesh is greater than the first. That the gearmesh can be correctly identified in the TSA results is a clear indication that the multi-stage order-tracking process is suitable for gear analysis when a tachometer is available.

To further evaluate the order-tracking process the technique of demodulating the gearmesh in the TSA was used, as described by McFadden (1986). The 2nd gearmesh harmonic was demodulated, and a bandwidth of ±15% of the 2nd harmonic of gearmesh was found to give optimum visual results.

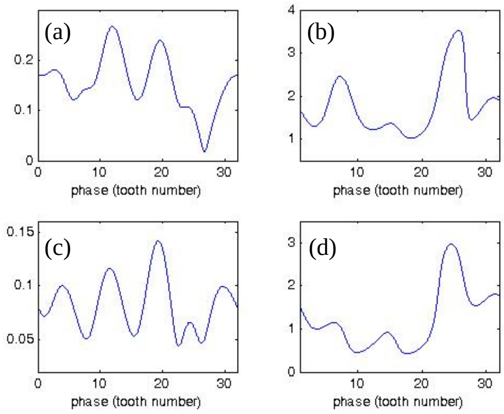

Figure 16. Demodulated gearmesh amplitude and phase (a, b) 10% case, (c, d) 25% case, (a, c) amplitude (b, d) phase

From Figure 16 (b) and (d), it can be seen that there is a large phase change at tooth number 25 in both speed cases. This change in phase is typical for a gear tooth root crack, the seeded fault. That the fault can correctly be located in the demodulated gearmesh phase is further indication that the underlying multi-stage order-tracking process was successful.

5 MULTI-STAGE ORDER-TRACKING WITHOUT A TACHOMETER

In order to evaluate the multi-stage process of order-tracking in a case where a tachometer is not available, the same acceleration signals from section 4 were used. The ability to perform order-tracking without a separate tachometer is desirable for situations where a tachometer cannot be mounted on the rotating component of interest due to size constraints or hazardous (to sensors) environments. As an acceleration signal can generally be captured from the outside casing of a piece of equipment it is often possible to capture only an acceleration signal, and it would still be desirable to perform order-tracking.

For nominally constant speed signals, Bonnardot et al. (2005) demonstrated that a phase demodulation based order-tracking could be performed using a reference signal extracted from a high order shaft component directly. Coats and Randall (2009) subsequently showed that a multi-stage approach could be used in cases where the higher harmonic was initially unseparable, where speed fluctuations were larger but still nominally constant. For this work a multi-stage approach was investigated for situations where large speed variations are present.

5.1 Results of Order-Tracking without a tachometer

For the ±10% case, for a first stage the 3rd shaft harmonic from the acceleration signal was used. From Figure 8(d) it can be seen that the first 2 shaft harmonics are too low in amplitude to be used for order-tracking. Generally the first harmonic of a machine would be suitable, and in this case the low amplitude is attributable to the machinery being recently refurbished including balancing and realignment.

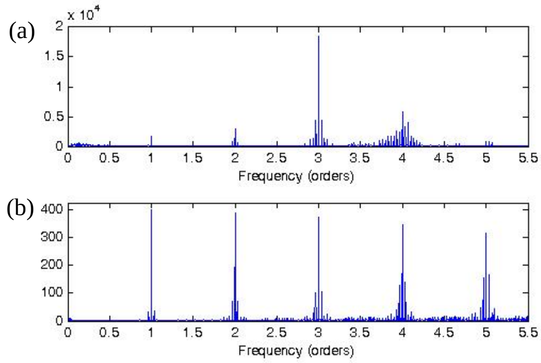

Figure 17. Spectrum of order-tracked signals after 1 stage for ±10% case, 5 orders (a) acceleration (b) tacho

Figure 17 shows the results of using the first stage of order-tracking. The tacho was also order-tracked using the same process for comparison. As can be seen the order-tracking has been relatively successful and order components can be seen, however both spectra contain significant modulation sidebands. As sidebands are also visible in the tachometer, and not just the acceleration signal, this is believed to indicate residual frequency modulation and not just amplitude modulation.

For a second stage multiple higher harmonics which were separable were tried for suitability; however it was found that all the visually separable higher harmonics available in this signal gave a slightly worse order-tracked result than from that gained from the first stage, with lower amplitude centre components and larger and more numerous sidebands. This initially appears to be a consequence of the large amplitude modulation present in the acceleration signal, which is a direct result of the large variation in speed. This could however be due to the addition of more extraneous components at higher harmonics due to the larger bandwidth necessary to encompass higher harmonics. Investigating the failure of these higher harmonics to provide more accurate order-tracking in the presence of large speed variations, when they provide more accurate results for nominally constant speed cases is the subject of ongoing research.

Unfortunately due to the weak first harmonic, the ±25% variation signal did not contain any separable harmonics suitable for order-tracking, as seen in Figure 13(d), and could not be tested. This highlights the increased difficulty of using the signal itself rather than a separate tachometer signal.

5.2 Results from using TSA and Gearmesh Demodulation for gear analysis

In order to evaluate the success of the first stage of order-tracking for the ±10% variation case, the signal was again further analysed with both TSA and gearmesh demodulation, similarly to section 4.2. Although a multi-stage process could not be fully implemented, the results of just the first stage were checked to see if the gearmesh was visible and if the gear fault could be detected.

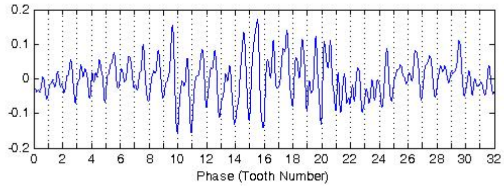

Figure 18. TSA results for ±10% case

Figure 18 shows the results of the TSA. The figure shown was low pass filtered to just above the 4th gearmesh harmonic in order to improve the visual clarity of the gearmesh. In the TSA one pulse per tooth is visible, and while not as clear as with the tachometer order-tracking cases, still shows the meshing of each individual tooth indicating that the order-tracking was successful enough for basic TSA analysis.

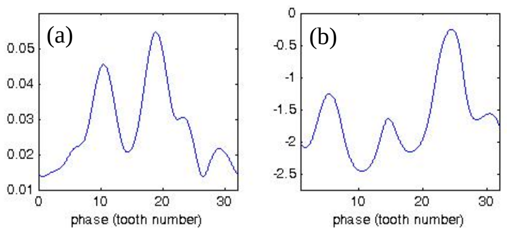

Figure 19. Demodulated gearmesh amplitude and phase (a) amplitude, (b) phase

From Figure 19 (b), it can be seen that there is again a large phase change at tooth number 25. This change in phase is typical for a gear tooth root crack, the seeded fault. That the fault can correctly be located in the demodulated gearmesh phase is further indication that the results of one stage of the order-tracking process, while not ideal, were successful enough to allow basic gearmesh demodulation analysis for gear fault detection.

6 CONCLUSIONS

This paper has shown that a multistage iterative approach to phase demodulation based order-tracking can successfully be used for gear fault detection in the presence of large speed variations of up to ±25%.

With a coupled tachometer as a reference the method can successfully order-track accurately up to high frequency values by using multiple stages. A gear fault could then be successfully detected in subsequent TSA and gearmesh demodulation analysis.

When using the signal itself as a reference, a multi-stage approach was shown to be more difficult to implement in the presence of large speed variations than when a tachometer is available. However, the first successful stage of order-tracking while not ideal, still allowed the gear fault to be successfully identified in basic TSA and gearmesh demodulation analysis.

Compensating for the corresponding amplitude modulation present in signals with large speed variations appears to be the next hurdle in allowing analysis of machinery with increasingly greater operational speed variations, and is the subject of ongoing research.

This work gives promise that it will become easier to perform gear fault diagnostics in the presence of large speed variations in the future, for machinery such as wind turbines which have widely varying operational speeds and loads.

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