Using computed order tracking to detect gear condition aboard a dragline

by B.L. Eggers*, P.S. Heyns*, and C.J. Stander*

Synopsis

This study investigates the application of computed order tracking with subsequent rotation domain averaging and statistical analysis, to the drag gearbox of a dragline used in a mining environment. Computed order tracking is a fault detection method developed to deal with the varying speed conditions often found in industry and has been proven effective in laboratory conditions. Its application to real situations, however, requires some adjustment to deal with issues such as inadequate speed data and the fact that the drag gear rotates in two directions. This provides a unique opportunity to observe the performance of the order tracking method in a bi-directional rotating environment, allowing an investigation of the relationships between the results obtained from each operating direction.

A monitoring station was set up aboard the dragline and data was captured twice daily for a period spanning approximately one year. The data captured consisted of accelerometer and proximity sensor data. The key on the shaft triggers the proximity sensors, allowing speed and direction to be measured. The measured speed is interpolated by using various speed interpolation techniques. Then the interpolated speed is used to complete the order tracking procedure that resamples the vibration data with reference to the speed. The results indicate that computed order tracking can be successfully employed in real environments. Furthermore it is shown that the rotation direction that opens the gear-tooth crack gives a better indication of incipient failure. It is therefore important not to disregard either direction when monitoring rotating machinery of this kind.

Introduction

Vibration monitoring is commonly used to detect changes in the operating condition of rotating machinery. During the monitoring process, the speed and load should ideally remain constant so that a change in the vibration signal can be attributed to developing fault conditions[1]. Since this is not always possible, there is a need for vibration analysis methods which can indicate deterioration under fluctuating conditions. Synchronous averaging, a preprocessing method, removes noise from periodic signals by the ensemble averaging of successive samples of repetitive signals, such as those caused by gear meshing. McFadden[2] assumes that constant speed and load conditions apply, leaving the problem of varying speed conditions largely unexplored. However McFadden's[3] matched-difference approach might be successful for small variations in speed and load.

Another approach used in condition monitoring is the analysis of the modulation and demodulation of signals. White[4] indicates that frequency modulation of the gear-mesh frequency (GMF) in gears can occur because a gear is eccentric on its shaft, causing it to drive the other gear at varying speeds.

When driving a load, the varying speed also causes variations in the tooth forces, resulting in amplitude modulation. However, Ma and Li[5] point out that using only a single tooth-meshing harmonic and its sidebands to find the modulation signal, blunts the effectiveness of the procedure, since all meshing harmonics carry information about modulation signals.

When applying demodulation techniques, it is often assumed that constant load and speed conditions apply[5–7]. Order tracking is the only vibration analysis method directly seeking to address the effect of varying speed on fault detection performance. Order tracking uses analogue hardware to sample vibration data at a rate proportional to the shaft speed, so vibration analysis is based on multiples of the running speed (orders), instead of frequency.

Fyfe and Munck[8] note that this approach is prone to problems, given rapidly changing shaft speeds, and suggest computed order tracking (COT), which samples at a constant rate and then uses software to resample the data at constant angular increments. These authors found that accuracy was improved by higher sampling rates on the key phasor and data signals and the use of higher-order interpolation techniques in the resampling process.

---

* *Dynamic Systems Group, Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, South Africa.*

© *The Southern African Institute of Mining and Metallurgy, 2007. SA ISSN 0038–223X/3.00 + 0.00. Paper received Sep. 2006; revised paper received Feb 2007.*

Bossley *et al.*[9] introduced a hybrid order tracking method, which makes use of hardware to measure the key phasors found in the traditional order tracking technique, and employed interpolation techniques to resample the vibration data. Based on simulated data, they show that this hybrid COT approach is superior.

Groover *et al.*[10] make use of the COT method as a kind of rotation component filter. Using the fact that a fixed frequency component changes orders as the running speed varies, the unvarying rotational-related components can be eliminated in the order domain.

To address the high frequency sampling necessary for good resolution of the key phasor, Bonnardot *et al.*[11] suggest the use of vibration signals only in the COT method. The shaft speed can be estimated by investigating the location of the GMF and its harmonics, given the number of teeth on the gear of interest. Its drawback is that only a very small speed variation is tolerated, causing a problem when the harmonics of the GMF are used for speed estimation.

Bonnardot *et al.*[11] used solely the acceleration signal in performing COT. These authors processed the gear contact shocks in order to locate the position of the gear with respect to time. Interpolation was then used to estimate the angular acceleration required to perform COT. However, they mention that, although this approach is cheap as it does not need the hardware required by traditional order tracking methods, it is vulnerable to high fluctuations in angular speed.

Order tracking is the only vibration analysis method that directly seeks to address the effect of speed on the performance of fault detection methods. By making use of order tracking, Stander *et al.*[12] developed a method to measure the condition of gears operating under varying speed conditions. After load demodulation, the statistical parameters were calculated from a pseudo-Wigner-Ville distribution. These parameters could then be monotonically trended to indicate fault progression. This methodology has proven effective in detecting seeded gear damage when tested under laboratory conditions and needs to be applied to an industrial environment, such as that of the drag gearbox pinion aboard an operating dragline.

The methodology employed by Stander *et al.*[12] does need to be adjusted to suit the mining environment, however. The shaft encoder used in the original work was not robust enough and was replaced by two proximity sensors. This decreased the shaft location pulses from 1 024 points per revolution to 2 points per revolution, suggesting the use of higher-order interpolation techniques to gain acceptable data on shaft speed. Stander *et al.*[12] made use of vibration segments from 276 shaft rotations; these segments were averaged to remove noise. Due to frequent changes in the pinion rotating direction, significantly fewer shaft rotations will be useable. The rotating directions are described with reference to the dragline bucket motion, which either moves outwards away from the dragline, or inwards towards the dragline. The effect on the rotating direction on this methodology was also investigated.

Data acquisition

The monitoring station

A monitoring station was set up aboard the largest dragline in the southern hemisphere, a Dresser 8200 Marion dragline operating at the Syferfontein Colliery in South Africa. The station consisted of sensors capable of relaying speed, direction and vibration. Two 100-mV/g integrated circuit piezoelectric accelerometers were used to measure vibration, each requiring a signal conditioning box to amplify the output. The accelerometers were mounted with studs onto aluminium platelets that were bonded to the pinion housing in the radial and axial directions.

Two inductive proximity sensors capable of switching at 1 000 Hz were used to measure both direction and speed. The proximity sensors were mounted on a bracket close to the pinion shaft, and sensed the passing shaft key.

An 8th order Butterworth low-pass filter, with a cut-off frequency of 2 500 Hz, was used to prevent any aliasing of the measured vibration data. This cut-off frequency included the first four gear-mesh harmonics. A 12-bit analogue-to-digital (A/D) conversion card capable of a 200 kHz aggregate sampling frequency was used to accept the data relayed by the sensors. Each of the four input channels was sampled at 50 kHz. A personal computer, mounted in an industrial case to protect the A/D card and the hard drives, completed the hardware complement of the monitoring station.

The software was capable of sustained data capturing over an indefinite period of time, and could store the data with informative file names. Based on preoperative tests, a 120-second sample was chosen as a good trade-off between the sample length and loading time required prior to processing. This sample time allows roughly two complete cycles of the dragline activity to be captured.

Relating dragline activity to measured data

Video footage was taken of the operating dragline, synchronous to the two-minute sample, to gain a better understanding of the data captured aboard the dragline. The vibration signal was converted to a short-time root mean square (RMS) representation to aid in analysis. The vibration RMS points were then plotted, yielding a smoothed view of the vibration intensity. Speed estimation software was also developed to convert the pulse signal from the proximity sensor to an indication of the pinion speed. The program differentiated the pulse data, giving a signal with clear spikes, which indicated the start and end of each pulse. The time taken between two spikes, indicating the start of two pulses, was then divided into the traversed rotational angle between the spikes, yielding the average speed over one shaft revolution.

Figure 1 illustrates a common cycle of the dragline, consisting of dropping the bucket and then dragging it through the ground to shovel dirt into the bucket (A to C), and Figure 2 depicts the corresponding RMS vibration and pinion speed histories. The bucket is then hoisted and the dragline swings to the dumping position where the drag-cables are paid out to dump the dirt (D to G). Then the dragline returns to the pick-up point (H) to start the cycle again.

The vibration RMS fluctuation plot, shown in Figure 2(a), illustrates the vibration intensity levels. Different peaks correspond to different dragline actions. An understanding of the dragline cycle and its constituents significantly aided in the development of an online monitoring technique and also improved the ability to detect flaws and inconsistencies within the captured data sets.

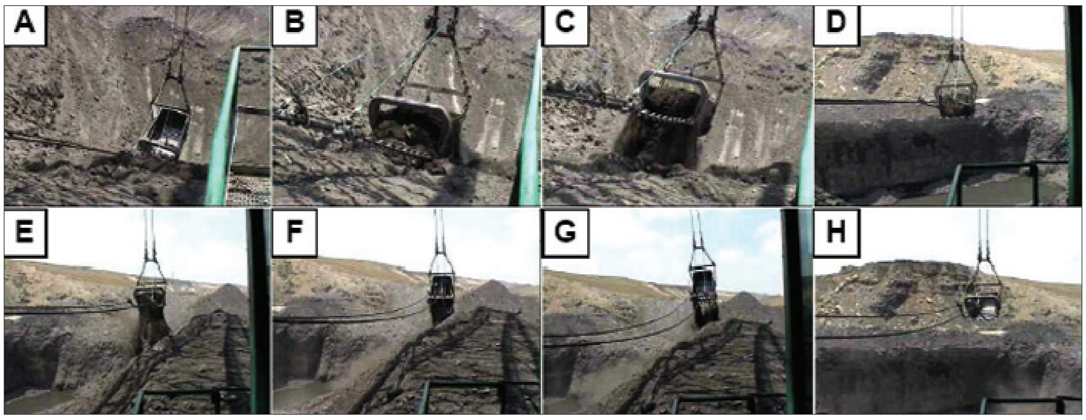

Figure 1—A series of stills taken from the dragline operation video

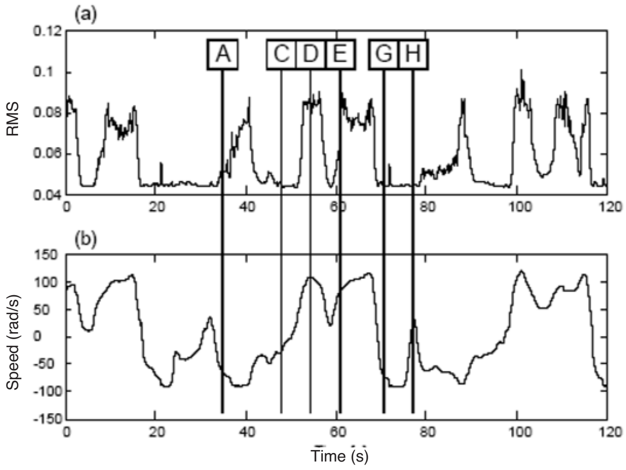

Figure 2—(a) The RMS fluctuation over one data sample. (b) The pinion speed fluctuation over one sample

Processing the pinion speed

Order tracking

Order tracking requires accurate speed data so that the accompanying vibration data can be accurately resampled with reference to shaft rotation. Using simple statistical methods, the order-tracked vibration data can then be used to give an indication of gear fault progression. Since 1 024 pulses per revolution were used to estimate shaft speed, Stander *et al.*[12] did COT by assuming that the speed between pulses remained constant. However, as the monitoring station aboard the dragline received only two pulses per revolution, higher-order interpolation techniques were employed with the aim of getting a better approximation of shaft speed. Existing COT software was modified to use linear, cubic and moving window order tracking (MWOT) interpolations. Displacement-driven velocity interpolation (DDVI), a speed correction procedure, was also added.

Interpolation techniques

The simplest interpolation technique assumes that the shaft speed remains constant over each revolution. The time taken to complete one shaft revolution is converted to an average speed, which is then assumed to hold true for the entire revolution. The principal shortcoming of this method is that it disregards the intra-revolutionary speed fluctuation of the dragline pinion, which can change by as much as 9%. The linear interpolation method assumes that shaft acceleration is constant. Bossley *et al.*[9] state that linear interpolation is the cheapest and one of the most popular methods of signal interpolation. Although this interpolation technique is an improvement on the assumption that constant speed applies across one revolution, there are cases where cubic interpolation is required. These interpolation techniques were used to estimate the rotational speed of the pinion aboard the dragline.

Moving window order tracking

All the interpolation methods mentioned so far employ only the proximity sensors' data converted to continuous real speed values as primary input. However, the vibration data itself can also be a valuable source of information about rotational speed[11]. The location of the GMF within the frequency domain fluctuates as the pinion speed changes, making the location of the GMF an alternate source of shaft speed information. So MWOT, a hybrid method that takes vibration data into account, was developed and used along with the traditional interpolation methods. In MWOT the approximate GMF location within the frequency domain is obtained from a linear interpolation of the two pulses per revolution from the proximity sensors' data. From observation, a precise frequency is not required since the GMF should be the dominant phenomenon for a bandwidth of at least 50 Hz. The shaft speed can then be determined by simply dividing the number of teeth on the pinion into the GMF.

During MWOT the available acceleration data is windowed into segments small enough to make the speed variation across the segment insignificant. This avoids smearing the GMF across several frequencies. Smaller windowed sections lead to a higher resolution in determining the speed, but if the segment is too small there are not enough tooth-on-tooth impacts, causing the amplitude of the GMF to dwindle in comparison to resonance frequencies.

To minimize the effect of detecting a false GMF, the first, second and third GMFs were identified and used to compute the average shaft speed, which was used in COT. Figure 3

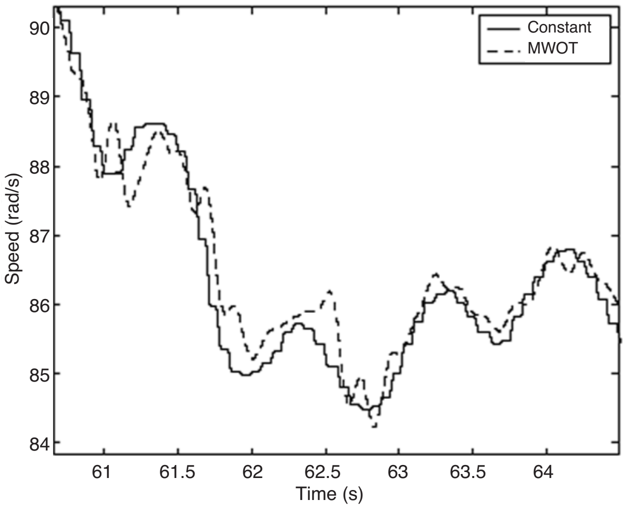

Figure 3—The difference between constant speed per revolution interpolation and MWOT data, using windowed segments with a length of 4 096 points

shows an approximately 3-second section of the speed as calculated by MWOT and as interpolated assuming constant speed per revolution.

The MWOT method is sensitive to intra-revolutionary speed change. In essence, normal interpolation techniques apply estimates of the speed dynamics within a revolution and then generate this data. With MWOT, every fluctuation in speed can be traced back to the measured data, giving it greater credibility than the data from other interpolation techniques. In cases where minimal information is available about direct speed, such as the case of the two proximity sensors aboard the dragline, the additional information gained from the vibration data will enhance the accuracy of the speed signal used for order tracking.

Displacement-driven velocity interpolation

With MWOT, however, there is a chance that a non-GMF peak may be chosen. To rectify this, it is necessary to add an additional process to the pre-COT procedure that will retain the speed profile and ensure accurate speed. This is possible if DDVI is used.

DDVI exploits the fact that the angle rotated by the shaft between two consecutive pulses from a proximity sensor is precisely 2π radians or 360 degrees. To determine whether the speed data attained after processing holds true, it is necessary to inspect the angle indicated by the interpolation techniques between adjacent pulses received from the proximity sensor, by integrating the area beneath the indicated speed graph. The area beneath a speed graph relates to the angle spanned and should be 2π radians. The largest deviations in rotation angle occur when the shaft speed approaches 0 rad/s because the drag motor may cycle back and forth between the pulses and indicate only one revolution. Therefore the angle traversed between pulses at low speeds is not necessarily 2π radians. Consequently, the speeds approaching 0 rad/s within the data sample were not used to do COT. However, it is clear from Figure 4 that using DDVI would also be advisable for higher speeds.

Figure 4 clearly indicates that there are rotation angle fluctuations from pulse to pulse even at higher speeds. This is mainly due to the interpolation scheme used for giving a closer approximation of the real speed, but which still introduces small errors in the real speed. To rectify the speed, consecutive segments of the speed are integrated and compared to 2π radians. Then a deviation value is calculated by subtracting the integration result from 2π radians. A boxcar windowing function is employed to adjust the speed. This window has the same number of entries as the speed vector of each segment, and is adjusted every time a new segment is being analysed. An adjustment factor is determined to ensure that the correct result is obtained. If multiplied by the window function, the adjustment factor will result in the correct area beneath the window function.

Figure 5 depicts the changes that DDVI made to the speed signal after it underwent cubic interpolation. One revolution is the smallest data size that DDVI analyses and adjusts. The speed segment corresponding to each revolution is adjusted as a whole, independently of other segments. It is therefore

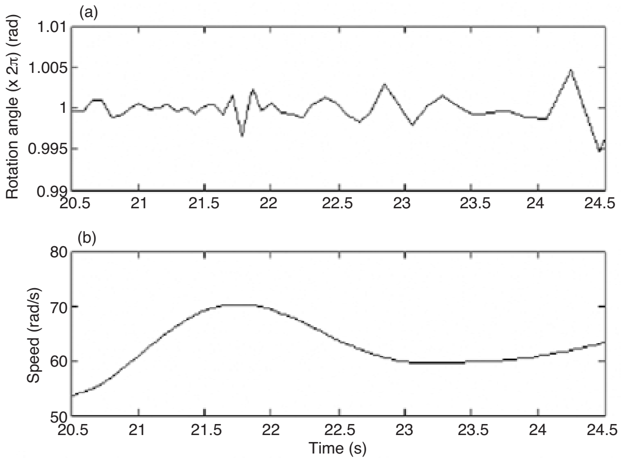

Figure 4—(a) A view of the rotation angle between pulses. (b) The corresponding speed graph

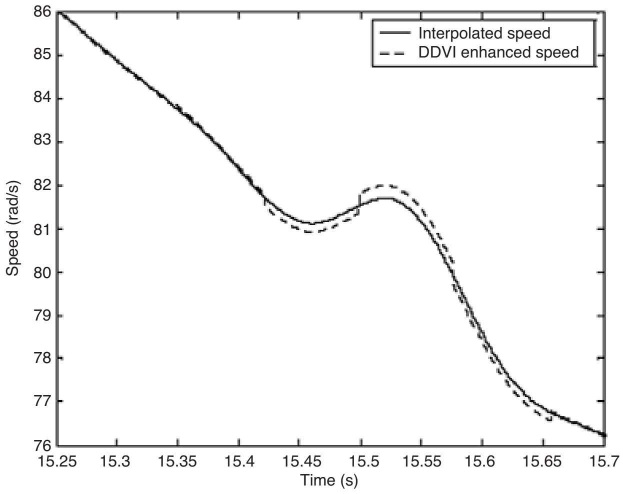

Figure 5—The effect of DDVI when applied to a cubic interpolation of the shaft speed

possible that a DDVI may adjust one speed segment upwards and the next downwards, as is clearly displayed in Figure 5. This is why the border between these two speed segments shows a clear discontinuity. This approach guarantees that the profile of the original interpolated speed is maintained. The discontinuities do not affect the COT process as it resamples the vibration data per revolution so that only the data between the discontinuities are used during COT.

Order tracking

Rotational domain averaging (RDA) can begin once the speed data has been captured and interpolated. Specific data blocks from each 120-second data set are selected on the basis of the number of pinion rotations completed in one direction. Each vibration segment in the selected data block, corresponding to one pinion revolution, is then resampled with reference to the interpolated speed in that revolution. Then a number of these resampled monodirectional rotational domain segments are averaged to complete the COT process. Typically each 120-second data set will yield two vectors related to the vibration measured in one pinion revolution, one in each pinion direction. A number of these vectors originating from 120-second data sets and captured throughout the year, are statistically analysed to obtain an indication of wear progression. Prior to obtaining the results, the number of rotational averages and the MWOT window size were determined.

Determining the number of rotational averages

The number of rotational averages that can be taken per 120-second data set is limited by the time that the pinion spends on rotating in a single direction. Figure 6 indicates the largest number of rotations available in both directions for each 120-second data set. It would be difficult to use more than 200 rotational averages, since this would make an even distribution of qualifying 120-second data sets throughout the measuring period impossible, and would hamper the ability to show wear progression.

Determining MWOT window size

The MWOT method determines the rotational speed of the shaft by calculating the GMF of consecutive segments of the vibration data. The window size affects accuracy, as it is indirectly proportionate to speed sensitivity and directly proportionate to spectrum resolution. Several spectra were generated from the captured data to determine which window size to use. It became clear that the GMF would be difficult to pinpoint if a spectrum of less than 1 024 points was generated. Four different window sizes were then chosen, ranging up to 8 192 points. Then the speeds generated by MWOT for each window size were compared. The distance between the starting positions of each window was 1 000 points. Therefore, as the window size increases, every segment of data is evaluated more often, creating a smoothing effect as the window size is increased. The 4096-point spectra perform as well as 8 192-point spectra, so eliminating the use of 8 192-point spectra because this would increase the processing time with little or no gain in accuracy. Consequently, a window size of 4 096 points was chosen for estimating shaft speed by means of MWOT.

Convergence in the rotational domain

The test for convergence indicates how fast the order tracking method being used settles down to a stable RDA. To this end, a data block is split into two equally sized daughter sets. The daughter sets are then incrementally averaged. After each incremental average, the resulting RDA from each daughter set is subtracted from the other and evaluated using RMS to get a single value. Then the RMS values are plotted to obtain the convergence graph. The convergence of the RDA using MWOT was checked in both of the pinions' rotating directions. The method converged satisfactorily. Figure 7 shows one of the convergence graphs generated in this way.

The convergence of the RMS difference is an indication that COT was correctly applied. Furthermore, Figure 7 indicates that convergence occurs at about 80 rotational averages, well within the 200 averages chosen earlier for this investigation.

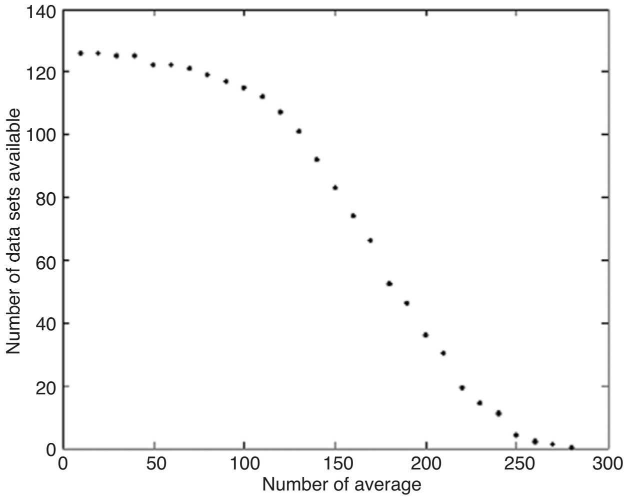

Figure 6—Available data sets as a function of required averages

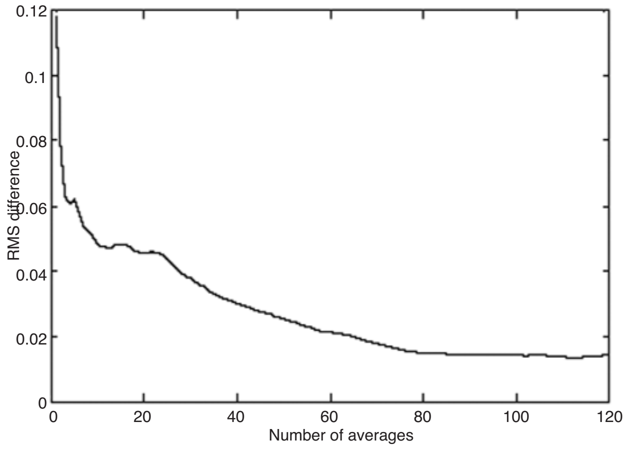

Figure 7—The convergence results of MWOT in the outward bucket motion direction with gear damage present

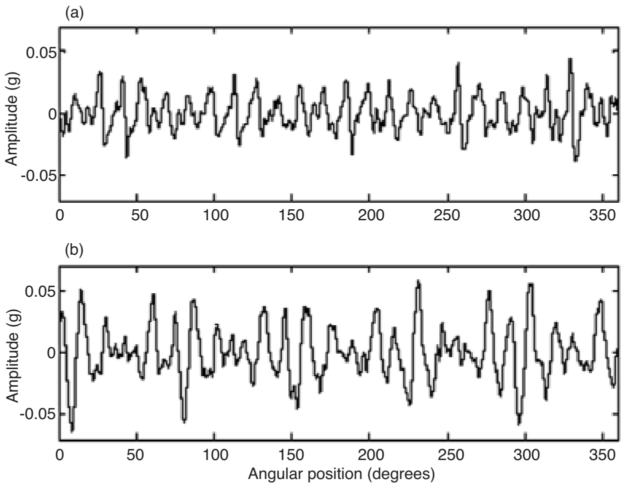

Figure 8—The RDA using MWOT, (a) without and (b) with damage. The dragline bucket motion is inward

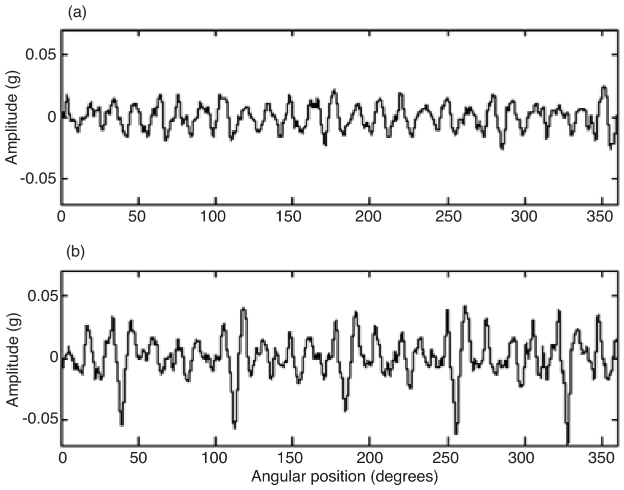

Figure 9—The RDA using MWOT, (a) without and (b) with damage. The dragline bucket motion is outward

Results

Rotation domain averaging

The RDAs shown in Figures 8 and 9 clearly indicate a difference between relatively little gear damage and gear damage present shortly before the pinion was removed.

The periodic signal evident in Figures 8(a) and 9(a) has 25 peaks, corresponding to the tooth impacts of the pinion. Figures 8(b) and 9(b) indicate the data was taken with damage present. The effect of the damage is clearly visible as the RDA has increased in amplitude and shows clear amplitude modulation. The slight distortion of the tooth impact peaks is probably due to the fact that the pinion is a double helix gear. This means that the manufacturing tolerances of the gear could affect the RDA, especially if the teeth from the two sides do not mesh in complete unison. RDA would not filter out this type of distortion since it is periodically synchronous with the shaft rotation. The slight amplitude modulation seen in the undamaged cases is probably caused by gear misalignment.

Cascade plots

The MWOT RDAs stretching over the pinion lifetime were evaluated using fast Fourier transforms (FFT) and are presented in Figures 10 and 11 as cascade plots.

An increase in vibration levels across the order spectrum indicates a faulty gear. The GMF at 25 orders is also clearly visible. The sidebands show significant increases, giving a clear indication of fault progression. The sidebands are visible at 5 orders on either side of the first and second gear-mesh frequencies. The modulating frequency causing the sidebands is clearly visible in the advanced wear RDA graph depicted in Figures 8(b) and 9(b). Loading does not cause this modulation, because the load profile of the dragline is not consistent across one shaft revolution. A local tooth defect would certainly increase the extent of the modulation but would not account for the slight modulation seen early in

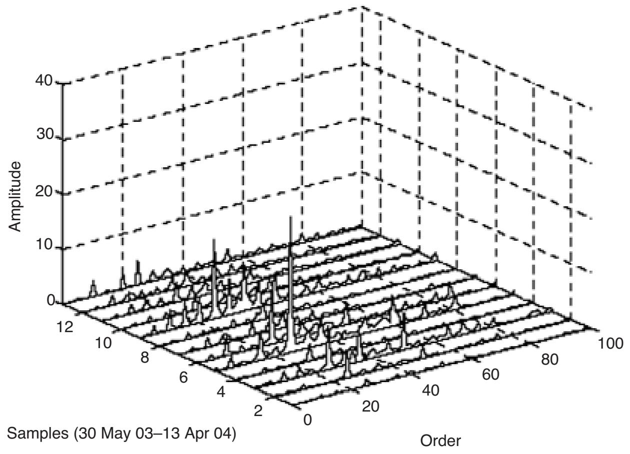

Figure 10—The cascade plot of 180 RDAs generated using MWOT. The bucket motion is inward

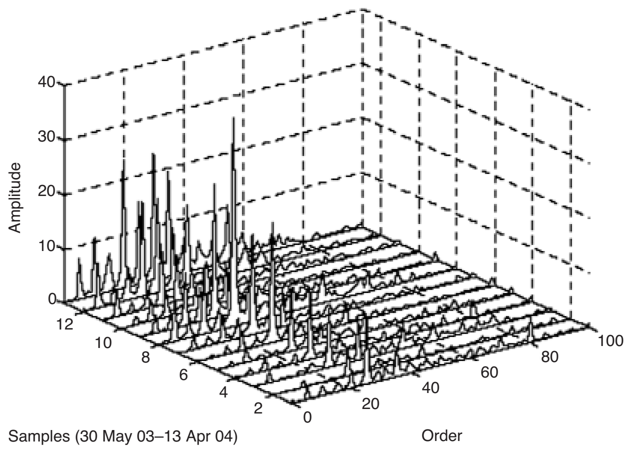

Figure 11—The cascade plot of 180 RDAs generated using MWOT. The bucket motion is outward

the pinion life span, as shown in Figures 8(a) and 9(a). The misalignment of the pinion is a more likely root cause of the modulation. This misalignment could have imposed higher stresses on a small number of teeth, causing them to break. In turn, the broken teeth would accentuate the modulation. The cascade plot of the inward bucket motion has approximately half the amplitude of the plot of the outward bucket motion, and shows no indications of a uniform increase in vibration levels. The lack of increased vibration in the inward motion is most probably because the inward bucket motion for the most part does not carry a load, as opposed to the outwardly moving bucket which is mostly filled. Furthermore, the vibration intensity while the bucket is being filled is less intense than when the bucket is emptied, as evidenced in Figures 1 and 2.

When the gear system was removed from the dragline, the pinion and the bull gear driven by the pinion both showed damage. The monitored pinion shown in Figure 12 shows severe spalling on two adjacent teeth on the left set of teeth. The right set showed minimal pitting damage.

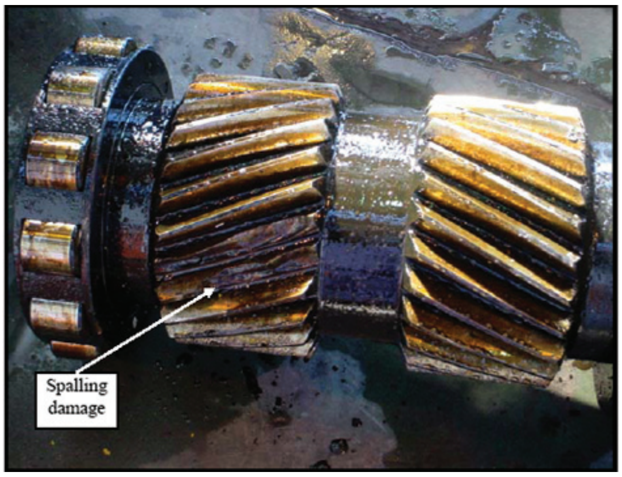

Figure12—Spalling damage on the pinion

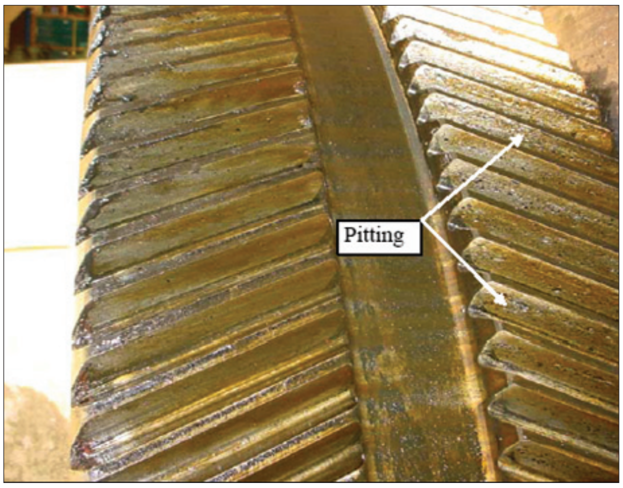

Figure 13—Pitting damage on the bull gear

The bull gear in Figure 13 showed severe pitting on only one set, whereas the other remained relatively unscathed. The fact that the bull and pinion gear showed preferential damage to one set only is a strong indication that misalignment is probably the root cause of the damage to the gears in this system, and supports the possible failure mechanism gleaned from the cascade plots in Figures 10 and 11.

Although the cascade plots are interpretable, a more intuitive portrayal of the progression of gear wear is necessary.

Deterioration graphs

Trending a number of components from the cascade plots and plotting these separately allows the wear progression to be observed clearly. The maximum peak amplitude is a rough indication of gear fault, on the premise that overall vibration intensity will increase with fault progression. The RDA modulation resulting from gear fault as shown in Figures 8 and 9, can be analysed by trending the first and second GMF sidebands in the cascade plots. Figures 14 to 16 show the trends of the above-mentioned components.

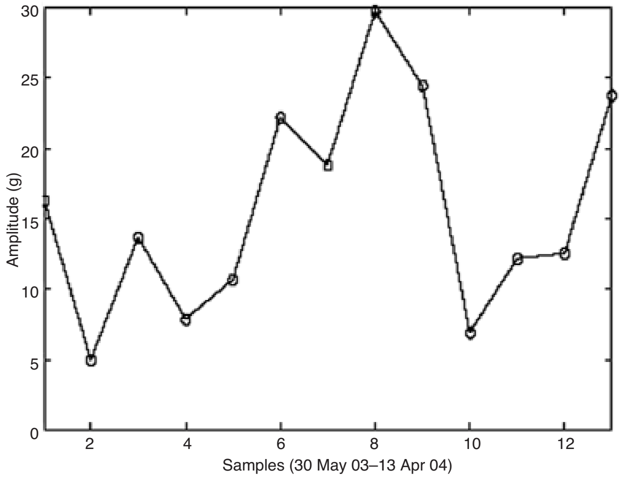

Figure 14—The maximum amplitude of the FFT in the outward bucket direction

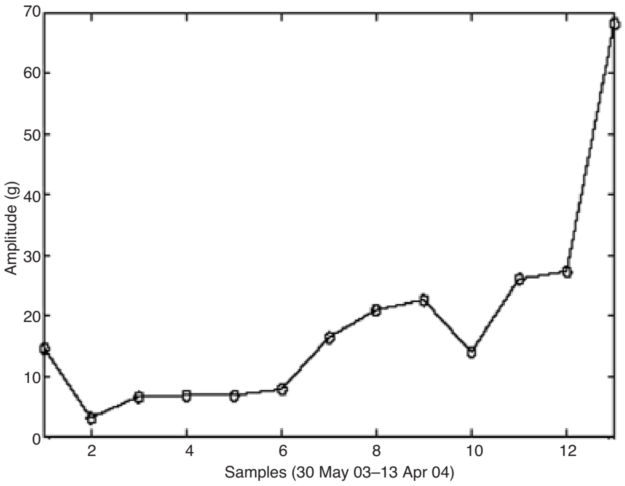

Figure 15—The sum of the first GMF sidebands in the outward bucket direction

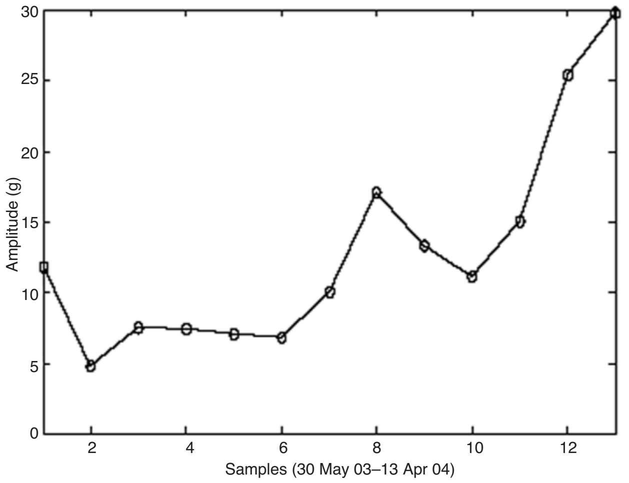

Figure 16—The sideband amplitudes surrounding the second GMF with the bucket moving outwards

If trended, the maximum peak amplitude does give an indication of the gear fault progression. However, the maximum peak is likely to vary with load, thus rendering this manner of determining the deterioration unreliable. The first GMF sideband amplitude gives a better indication than the overall maximum amplitude. Figure 15 clearly shows the rapid increase in gear damage towards the end of the gear's lifespan. The second GMF sidebands amplitudes, shown in Figure 16, are comparable to those generated from the first GMF sidebands. The peak observed at set number 8 might indicate that one tooth has been broken. This assumption is supported by the fact that the sideband levels are higher for sets 9 to 11 than those from the sets prior to set 8. The drop in sideband amplitude from set 8 to set 10 is probably due to the break 'wearing in', thus creating lower vibration levels. There is a higher amplitude present at the first GMF than at the second, making the deterioration graph composed from the first GMF sideband amplitude in the outward bucket motion the premier indicator of fault propagation.

Conclusion

It has been shown that COT can be successfully employed to detect fault progression in a pinion gear in the drag gearbox of a dragline. In order to exclude human error and obtain reliable vibration data, an automated online monitoring station was set up. This equipment was stationed on the dragline for the approximate lifetime of the drag pinion. The vibration data was related to the dragline activity by means of video footage and RMS analysis so as to facilitate an understanding of the specific environment and to enable quicker error detection during the development process.

MWOT was developed by making use of the speed information inherent in the vibration data, coupled with the limited information about the shaft rotation. This speed interpolation technique makes use of the shaft pulse to locate the likely position of the GMF in the FFT of a small part of the vibration data. Then the GMF is pinpointed and converted back to speed information.

DDVI was also developed to aid with the interpolation techniques. DDVI uses the fact that if the motion of the pinion is in one direction, the angular displacement between two pulses is precisely 2π rad. Therefore the integration of the speed-time graph, between two time instances related to two pulses, should be a multiple of 2π. If this is not the case, the DDVI adjusts the speed accordingly.

The minimum number of RDAs required to yield satisfactory results were determined. The ability of MWOT to yield stable results was also tested. A relationship between the different rotating directions was established. It was clear that one direction was more sensitive to fault progression. This indicates that care should be taken when taking the vibration measurements of gears rotating in two directions, since the early detection of gear faults could be hampered if the less sensitive direction is chosen.

Cascade plots were drawn up to show changes in the FFT of the RDA data over the lifespan of the pinion. The increase in the vibration power of the GMF and its sidebands was clearly visible, indicating fault progression. To get a clearer picture of the progression in pinion wear, a number of components of the cascade plot were plotted separately. The power at the first GMF sidebands proved the best indication of fault progression.

References

1. Baydar, N., Chen, Q., Ball, A., and Kruger, U. Detection of incipient tooth defect in helical gears using multivariate statistics. *Mechanical Systems and Signal Processing*, 2001, vol. 15, no. 2, pp. 303–321.
2. McFadden, P.D. Examination of a technique for the early detection of failure in gears by signal processing of the time domain average of the meshing vibration. *Mechanical Systems and Signal Processing*, 1987, vol. 1, no. 2, 1987. pp. 173–183.
3. McFadden, P.D. Detection of gear faults by decomposition of matched differences of vibration signals. *Mechanical Systems and Signal Processing*, 2000, vol. 14, no. 5, 2000. pp. 805–817.
4. White, G. Amplitude Demodulation—A new tool for predictive maintenance. *Sound and Vibration*, September 1991, pp. 14–19.
5. Ma, J. and Li, C.J. Gear defect detection through model-based wideband demodulation of vibrations. *Mechanical Systems and Signal Processing*, 1996, vol. 10, no. 5, 1996. pp. 653–665.
6. McFadden, P.D. and Smith, J.D. A signal processing technique for detecting local defects in a gear from signal average of the vibration. *Proceedings of the Institution of Mechanical Engineers*, 1985, vol. 199, no. C4, 1985. pp. 287–292.
7. McFadden, P.D. Detecting fatigue cracks in gears by amplitude and phase demodulation of the meshing vibration. *Journal of Vibration, Acoustics, Stress, and Reliability in Design*, April 1986, vol. 108, 1986. pp. 165–170.
8. Fyfe, K.R. and Munck, E.D.S. Analysis of computed order tracking. *Mechanical Systems and Signal Processing*, 1997, vol. 11, no. 2, 1997. pp. 187–205.
9. Bossley, K.M., McKendrick, R.J., Harris, C.J. and Mercer, C. Hybrid computed order tracking. *Mechanical Systems and Signal Processing*, 1999, vol. 13, no. 4, 1999. pp. 627–641.
10. Groover, C.L., Trethewey, M.W., Maynard, K.P. and Lebold, M.S. Removal of order domain content in rotating equipment signals by double resampling. *Mechanical Systems and Signal Processing*, vol. 19, 2003. pp. 483–500.
11. Bonnardot, F., ElL Badaoui, M., Randall, R.B., Daniere, J., and Guillet, F. Use of the acceleration signal of a gearbox in order to perform angular resampling (with limited speed fluctuation). *Mechanical Systems and Signal Processing*, vol. 19, 2005. pp. 766–785.
12. Stander, C.J., Heyns, P.S., and Schoombie, W. Using vibration monitoring for local fault detection on gears operating under fluctuating load conditions. *Mechanical Systems and Signal Processing*, 2002, vol. 16, no. 6, 2002. pp. 1005–1024.

◆