Vibration based condition monitoring under fluctuating load and speed conditions

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Abstract
While the benefits of vibration based condition monitoring was initially primarily realized in industries where equipment run for long periods, under more or less constant speed and load conditions, there is a growing need for extending the application of vibration based condition monitoring techniques to include machines where the speed and load conditions fluctuate widely. It remains a significant challenge to analyse vibration data that are generated under such fluctuating operating conditions. This is especially true for situations where relatively little prior knowledge regarding the specific gearbox is available. This paper explores a range of techniques which have been developed at the University of Pretoria to deal with such situations, and introduces the techniques by considering various practical applications.

Keywords: Condition monitoring, fluctuating load and speed, machine health monitoring, order tracking, vibration monitoring

1. Introduction

Our physical assets are aging and operational life is continuously pushed to new limits for financial and environmental reasons. Condition monitoring is increasingly becoming an important tool in the optimal operation and management of these assets. In this process traditional monitoring techniques are forced into new applications where the assumptions underlying conventional monitoring methodologies are sometimes violated and new approaches are required.

This paper briefly reviews specific vibration based condition monitoring applications where existing approaches fall short and new methodologies had to be developed. The Dynamic Systems Group (DSG) at the University of Pretoria has been exploring various aspects of this general problem over the past decade. These developments have been prompted by real industrial problems, and include diverse applications such as fluctuating load conditions on gearboxes, road condition monitoring and electrical machines. The work forms part of a continued programme to enhance reliability and availability of physical assets through condition monitoring. The importance of this field may be expected to grow, as these assets grow in scale, complexity and cost on the one hand, and sensing and computational technologies become more mature, while communication technology is rapidly enabling continuous and remote monitoring on the other hand. This enables fresh approaches and fuels new interest in specialized condition monitoring applications.
2. Fluctuating load and speed conditions on gearboxes

Conventional gearbox vibration monitoring techniques are based on the assumption that changes in the measured structural response are caused by deterioration in the condition of the gears in the gearbox. However, this assumption is not necessarily valid under fluctuating load conditions, since the fluctuating load will amplitude modulate the measured vibration signal and cause the rotational speed of the system to change. Generally, the monitoring of machines subjected to varying load conditions is dealt with by attempting to monitor during periods of constant load, or alternatively during unloaded conditions. Typical practical examples of such applications can be found on draglines [1]. The drag motor and gearbox which control the motion of the bucket in conjunction with the hoist motor and gearbox, is exposed to highly fluctuating load conditions as well as continuous reversals in the direction of rotation. Further, the cutting head of a continuous miner is driven through a gear transmission subjected to highly variable loads as the coal is sheared from the coal face. These cutting heads are critical and replacement costs high.

The need to improve the management of assets such as these, has given rise to the need for signal processing and diagnostic techniques which will enable continuous online monitoring throughout the fluctuating load conditions, to ensure a constant flow of reliable information on the condition and integrity of the assets under consideration. In our initial work the DSG developed a three pronged approach to this problem.

Firstly a load demodulation procedure was developed to remove the modulation caused by the fluctuating load conditions and obscures the detection of incipient faults [2]. A rotation domain averaging technique is implemented which combines the ability of computer order tracking and time domain averaging to suppress the spectral smearing caused by fluctuations in speed, as well as suppress the amplitude of vibrations which are not synchronous with the rotation of the gear shaft. This procedure essentially filters a measured acceleration signal by using the low pass filtered modulation obtained using the Hilbert Transform, and then dividing the original signal by the filtered modulation to obtain a load normalized acceleration signal. The procedure relies on the fact that the load modulation frequencies are generally lower and narrower than the modulation cause by tooth defects. A pseudo-Wigner-Ville time-frequency distribution of the load-normalised acceleration signal may subsequently be calculated to identify the deteriorating fault condition, despite the fluctuating load conditions. Using various statistical parameters and other features, linear separation of the values for a range of fault conditions can be obtained after the normalization has been applied, and a monotonic increase in these parameters may be obtained for various selected load conditions (constant, sinusoidal, step, chirp) on a computer controlled test rig, as the fault severity increases. This separation does not occur for the non-normalized distributions.

Secondly the use of instantaneous angular speed of a gearbox shaft was advanced as a sensitive indicator of the condition of a gear [3]. The instantaneous angular speed is less susceptible to phase distortions introduced by the transmission path, compared to conventional gearbox casing vibration measurements. This was explored by applying the load demodulation procedure described above on a gearbox casing. Deterioration in gear condition usually goes hand-in-hand with reduced tooth stiffness, which in turn affects the instantaneous angular speed (IAS) of the gear. A detailed investigation [3] showed that the IAS provides a more sensitive parameter than linear vibration for gearbox vibration monitoring purposes, because it is less susceptible to the transmission of forces from other
rotating components in the immediate vicinity. In many cases rotational speed needs to be measured anyway, and under these circumstances one less response channel is required. These factors simplify the diagnosis of gear fault conditions and advance the utilization of IAS as an attractive option for the monitoring of gear condition.

During this investigation the importance of distinguishing between synchronous and non-synchronous load modulation was identified. Rotation domain averaging (RDA) will suppress the load modulation for non-synchronous fluctuating load conditions. The modulation caused by gear defects will however always be synchronous with the rotation of the shaft, and will not be suppressed, but rather emphasized by the RDA process.

Lastly, a novel method was developed to overcome the phase distortion effects by employing a phase domain averaging approach [4]. In practice, while the fault excitation always remains perfectly synchronous with the shaft rotation, the response is altered through the frequency dependent transfer function of the structure on which the measurements are conducted, while the vibration signal is transmitted through the structural transmission path on the gearbox. The transmission of the actual excitation force due to a fault in the system, to the corresponding vibration response at the vibration monitoring location, is therefore always subjected to relative phase variations because of the dynamic characteristics of the structure through which the signal is transmitted. In the techniques described above, synchronous averaging is employed. A signal which is synchronous with the rotation of the shaft of the gear being monitored, is measured to obtain a reference which is synchronous with the rotation of the shaft. This reference therefore remains synchronous with the excitation when the shaft rotation speed changes. The measured response is however not synchronous with the reference signal, because of the non-linear phase changes imposed by the transmission path when the rotational frequency changes. This obviously also happens when RDA is performed, even though the order content remains correct.

This phase shifting effect has been overcome by introducing a phase domain averaging procedure for use under fluctuating load conditions [4]. This entails representing the signal as a function of its phase, instead of the angle of rotation. The process is far more efficient and requires fewer data to obtain a converged synchronized average representation of the signal. This amplitude versus phase representation displays less erratic modulation than the conventional RDA and simplifies diagnosis of an incipient gear problem. This issue was recently quantitatively explored further, to identify the magnitude and the extent of the order domain distortions introduced by the transfer function distortions, as a function of the relative frequency domain distance between the excitation and natural frequency of a system [5].

In the DSG this general interest in fluctuating loads and operating speeds was recently further explored [6]. A Bayesian based adaptive time series model was proposed to obtain a sensitive residual signal which is more robust to fluctuating conditions. In this approach the regular components (such as normal gear meshing) are removed from the vibration signal so that a residual signal is obtained which is more sensitive to gear faults and robust to changes in operating condition. This residual signal is generated as the difference between the output from a time series regression model and the observed waveform. The regression model is composed of the weighted average of an assembly of autoregressive (AR) models which are iteratively updated based on the Bayesian model selection framework. The time series regression is run both forwards and backwards to obtain two
residual signals which are subsequently merged into a final residual signal, by pointwise selecting the smaller of the two. This residual signal can be shown to be much more capable to localise irregularities caused by faults in the measured signals.

A statistical framework was subsequently proposed to extract and interpret diagnostic information embedded in the structure of the residual signal. This makes it possible to localize the fault induced signal deviations and offers insight into the nature of the gear damage. It is interesting to note that the proposed methodology is somewhat analogous to synchronous averaging of the residual signal. The methodology requires minimal physical knowledge of the system and is essentially a highly generic pre-processing technique which allows normalisation of signals with respect to the fluctuating loads and speeds, without the need for manual classification. The proposed methodology was tested on two sets of simulated data. Firstly the Stander and Heyns [3] spring-damper-mass single stage gear model was used with an improved representation of the gear mesh stiffness, to approximately simulate the structural response of a gear casing under various loading and gear damage conditions. Secondly data were obtained from an accelerated gear life test in which a single stage gearbox was run to failure under constant speed and loading. The results indicate that the methodology is not only sensitive to gear damage but robust to significantly fluctuating operating conditions, and suggests an intuitive and cost-effective approach to the monitoring of assets which are exposed to highly fluctuating operation conditions.

3. Road condition monitoring under fluctuating conditions

Maintenance management of highly used road infrastructures such as mine haul roads is often inadequate, leading to over-maintenance or failure to recognise significant road deterioration [7]. In earlier investigations the DSG [8] explored the feasibility of using inverse dynamic vehicle models to determine the road profiles from measured acceleration responses on the vehicle. This was successfully accomplished, but the approach requires experimental characterisation of vehicle properties such as tyre and suspension system inertia, stiffness and damping. This can be very difficult and expensive, especially for large vehicles such as dump trucks. To eliminate these practical system characterisation problems, supervised learning through artificial neural networks was utilised to reconstruct road profiles [7]. The network essentially performs the reconstruction by learning the system input-output patterns, and mapping the outputs to related inputs. This approach offers the advantage that non-linearity can readily be dealt with. This methodology was numerically demonstrated on a linear pitch plane vehicle model, for classifying road damage with varying roughness grades, emerging surface defects, under varying conditions of noise, vehicle payload and speeds.

In many practical cases knowledge of the exact road profile may not be necessary and a simpler response-type metric, which is indicative of the adverse effect of the road on the vehicle, may suffice. Heyns, Heyns and De Villiers [9] explore this in the context of haul roads which are traversed multiple times by either the same or similar vehicles. They then estimate how a speed-standardised response-type road-roughness measuring system may be devised by means of regression functions which express the response measurement metric as a function of vehicle operating conditions. Unique regression functions are estimated for individual road intervals, to reflect the spectral properties of that specific interval. The regression functions are subsequently evaluated at a standardised vehicle operating condition to allow for consistent comparison of the condition of different road
intervals. The regression functions are estimated by means of Bayesian estimation. This allows for the incorporation of a strong prior over the range of expected values. This prior reflects the experience which was gained where good quality data is available. The prior subsequently renders it possible to obtain more robust parameter estimates. This methodology was investigated on experimental data obtained from response measurements on a utility vehicle in a coal mine. RMS acceleration was used as metric in this case. Using the Bayesian framework made it possible to estimate a standardised RMS value for different sections of the road in a robust way, even if only a limited number of measurements are available.

In a subsequent paper, vehicle response normalisation is accomplished using Gaussian Processes [10]. The implemented methodology again requires no prior knowledge of the vehicle, and standardised results are significantly more consistent compared to the uncalibrated severity measurement. While the reported study focused on haul roads it is anticipated that the procedure could also be applied to urban roads and extended to be normalised not only for speed but also with respect to different operating conditions such as varying vehicle mass, or significant changes in the underlying condition of the traversed road (speed dependency of vehicle response differs when it traverses a smooth road compared to a road with a hump).

4. Improved order tracking of rotors under fluctuating conditions

Conventional rotating machine vibration monitoring techniques are based on the assumption that changes in the measured structural response are caused by deterioration in the condition of the rotating machine. However, due to fluctuations in the rotational speed, the measured signal may be non-stationary and difficult to interpret. For this reason, order tracking is commonly introduced. One of main advantages of order tracking over traditional vibration monitoring lies in its ability to clearly identify non-stationary vibration data and to a large extent exclude the influences of the fluctuating rotational speed. In recent years, different order tracking techniques have been developed. Each of these has their own pros and cons in analyzing rotating machinery vibration signals. The DSG investigated three existing order tracking techniques combined these to further explore their abilities in the context of condition monitoring.

Firstly, computed order tracking was examined. This allows non-stationary effects due to the variation of rotational speed to be largely excluded. However, this technique was developed to deal with the entire raw signal and therefore loses the ability to focus on each individual order of interest. Secondly, Vold-Kalman filter order tracking was considered. This technique overcomes many of the limitations of other order tracking methods and extracts order signals into the time domain. However because of the adaptive nature of the Vold-Kalman filter, the non-stationary effects due to the rotational speed will remain in the extracted order waveform, which is not ideal for conventional signal processing methods such as Fourier analysis. Yet, the strict mathematical filter (the Vold-Kalman filter is based upon two rigorous mathematical equations, namely the data equation and the structural equation, to realize the filter) gives this technique an excellent ability to focus on the orders of interest. Lastly the empirical mode decomposition method was studied. This technique is claimed to be an effective diagnostic tool for various kinds of applications including diagnosis of rotating machinery faults. Its unique empirical way of extracting non-stationary and non-linear signals allows it to capture machine fault information which is intractable by other order tracking methods. But since there is no precise mathematical
definition for an intrinsic mode function in empirical mode decomposition and no published assessment of the relationship between an order and an intrinsic mode function, this technique has not been properly considered by analysts in terms of order tracking. As a result, its abilities have not really been explored in the context of order related vibrations in rotating machinery. In the DSG research, the relationship between an order and an intrinsic mode function was discussed and treated as a special kind of order tracking method.

Through combination, exchange and reconciliation of ideas between these order tracking techniques, three improved order tracking techniques were developed for the purpose of enhancing order tracking analysis in condition monitoring. The techniques are Vold-Kalman filter and computed order tracking (VKC-OT), intrinsic mode function and Vold-Kalman filter order tracking (IVK-OT) [11,12] and intrinsic cycle re-sampling (ICR) [13]. These improved approaches contribute to current order tracking practice, by providing new order tracking methods with new capabilities for condition monitoring of systems which are intractable by traditional order tracking methods, or which enhances results obtained by these traditional methods.

To demonstrate the abilities of the improved order tracking techniques, two simulation models were established. One is a simple single-degree-of-freedom rotor model with which VKC-OT and IVK-OT techniques are demonstrated. The other is a simplified gear mesh model through which the effectiveness of the ICR technique is proved. Finally two experimental set-ups in the Sasol Laboratory for Structural Mechanics at the University of Pretoria were used for demonstrating the improved approaches for real rotating machine signals. One test rig was established to monitor an automotive alternator driven by a variable speed motor. A stator winding inter-turn short was artificially introduced. Advantages of the VKC-OT technique are presented and features clear and clean order components under non-stationary conditions. The diagnostic ability of the IVK-OT technique of further decomposing an intrinsic mode function is also demonstrated via signals from this test rig, so that order signals and vibrations that modulate orders in IMFs can be separated and used for condition monitoring purposes.

The second experimental test rig is a transmission gearbox. Artificially damaged gear teeth were introduced. The ICR technique provides a practical alternative tool for fault diagnosis. It proves to be effective in diagnosing damaged gear teeth.

5. Conclusions

The Dynamic Systems Group at the University of Pretoria have been exploring techniques to deal with the all too common practical situation of trying to monitor vibrations under fluctuating load and speed conditions for diagnostic purposes. These fluctuations violate the normal tacit assumption of stationarity and requires improved approaches which are robust to these changes. This problem has been studied in the context of gearbox vibration monitoring, road condition monitoring and rotating machinery and useful results have been obtained, details of which are reported in the list of references.

References


