24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

IDENTIFICATION OF VIBRATION PROPERTIES OF WHEEL LOADER DRIVELINE PARTS AS A BASE FOR ADEQUATE CONDITION MONITORING: BEARINGS

Källström Elisabeth
Department of Engineering Sciences and Mathematics, Luleå University of Technology, Luleå, Sweden and Volvo Construction Equipment, SE-63185 Eskilstuna, Sweden
email: elisabeth.kallstrom@volvo.com

Lindström John
ProcessIT Innovations, Luleå University of Technology, 971 87 Luleå, Sweden

Håkansson Lars
Department of Mechanical Engineering, Linnaeus University, 351 95 Växjö, Sweden

Karlberg Magnus
Department of Engineering Sciences and Mathematics, Luleå University of Technology, Luleå, Sweden

Öberg Olof
Volvo Construction Equipment, SE-63185 Eskilstuna, Sweden

In order to reduce costly downtime, adequate condition monitoring of the automatic transmission components in heavy duty construction equipment is necessary. The transmission in such equipment enables to change the gear ratio automatically. Further, the bearings in an automatic transmission provide low friction support to its rotating parts and act as an interface separating stationary from rotating components. Wear or other bearing faults may lead to an increase in energy consumption as well as failure of other related components in the automatic transmission, and thus costly downtime. In this study, different sensor data (particularly vibration) was collected on the automatic transmission during controlled test cycles in an automatic transmission test rig to enable adequate condition monitoring. An analysis of the measured vibration data was carried out using signal processing methods. The results indicate that predictive maintenance information related to the automatic transmission bearings may be extracted from vibrations measured on an automatic transmission. This information may be used for early fault detection, thus improving uptime and availability of heavy duty construction equipment.

Keywords: Automatic Transmission, Adaptive Line Enhancer (ALE), Bearings, Order Power Spectrum, Order Modulation Spectrum, Recursive-Least-Squares (RLS) and Vibration.

1. Introduction

The heavy duty construction equipment industry seeks to continuously upgrade its offers by improving availability which increases customer satisfaction and reduces warranty cost for the provider. In particular, sufficient monitoring of bearings located in driveline parts is an important way of reducing downtime and improving uptime in heavy duty construction equipment since most major breakdowns of driveline parts are a result of bearing faults [1]. Early fault detection, monitoring and predictive maintenance are all important aspects in emerging business models based on contract parameters such as result, performance or availability. The bearings in an automatic transmission provide low friction support to its rotating parts and provides an interface separating stationary from rotating components. In addition, different bearings are designed to support certain types of load depending on the direction in which the force is applied. Furthermore, wear or other bearing faults may lead to an increase in energy consumption as well as failure of other related components in the automatic transmission.

There are different types of bearings available and they are classified based on the type of load and type of contact. Usually, antifriction bearings, also known as rolling contact bearings, are used in automatic transmissions [2]. Further, a rolling contact bearing consists of four major parts: the rolling element (which is made of hardened steel), an inner race, an outer race and a retainer (separator or cage) [1]. A typical roller bearing is illustrated in Figure 1. In this study, torque converter bearings are considered.

Figure 1: A Roller Bearing 3-D view.

Different techniques concerning the condition monitoring of bearings have been reported. Immovili et al. [3] compared the capability of using electric current and vibration signals for bearing fault detection in induction machines. They concluded that vibration signals are a robust indicator for detecting faults in a bearing provided a suitable signal analysis method is utilized [3]. Abdusslam et al.[4] via a simple bearing test rig analyzed vibration data for bearing fault detection using Fast Fourier Transform (FFT) of the signal and an envelop analysis of the signal. Further, the bearing test rig comprises of a 3-phase electrical induction motor, a dynamic break, four shafts connected by three flexible couplings, two bearing housings and an amplifier [4]. They concluded that the envelope analysis was more reliable in revealing the faults [4]. Randall et al. [1] stated that bearing frequency components are cyclostationary due to random slip which is dependent on the ratio of the axial load to the radial load. After a review of different techniques, Randall et al. [1] recommended the envelope spectrum for bearing fault detection. Brkovic et al. [2] utilized the wavelet transform for ball bearing feature extraction. They carried out this study using a simple experiment setup which involves installing a ball bearing in a motor driven mechanical system [2]. The setup comprises of a three-phase induction motor connected to a dynamometer and a torque sensor, and an accelerometer attached to the motor housing [2].

To sum-up, although a lot of research has been carried out for bearings in most parts of rotating machinery, the torque converter bearings seem to have been ignored. In this paper the torque converter bearings are considered with the purpose to prevent torque converter failure as a result of bearing faults. Furthermore, the objective is to increase availability and improve uptime. The Adaptive Line Enhancer (ALE), Order Power Spectrum and Order Modulation Spectrum are techniques utilized in this study.

2. Materials and Methods

2.1 Experimental Setup

A Volvo Construction Equipment L90H automatic transmission test rig was used in the experiments. The oil temperature in the transmission was steady at 82^0C when the test was running.

The measured quantities used in the investigation are the engine speed and the vibration of the structure around the torque converter. The experiment was controlled and an adequate number of recordings were made.

2.2 Measurement Equipment and Setup

The vibration signals were recorded using a SOMAT eDAQ Data Acquisition system, sampling frequency 5000 Hz, connected to a triaxial accelerometer attached on the top side of the torque converter housing close to the torque converter shaft. In order to adequately measure vibrations of the torque converter, the triaxial accelerometer was mounted as close as possible to the torque converter as in Figure 2. The accelerometer was mounted using instant adhesive Loctite 454. The engine speed from the machine CAN-bus was logged synchronously with the vibration data.

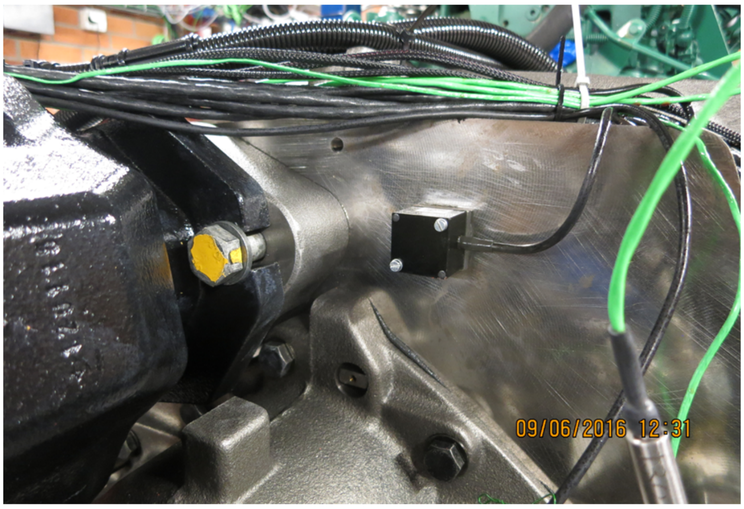


Figure 2: L90H Transmission Test Rig with accelerometer mounted on the top side of torque converter housing.

2.3 Vibration Analysis of the Torque Converter's Bearing

The frequencies of the inner and outer race, the cage frequency and the ball/roller spin frequency reveal defects in the respective parts of a bearing and they are produced as [1, 5].

$$f_{inner} = \frac{n}{2} f_{sh} \left\{ 1 + \frac{D_{ball}}{D_{pitch}} cos\phi \right\} \tag{1}$$

$$f_{outer} = \frac{n}{2} f_{sh} \left\{ 1 - \frac{D_{ball}}{D_{pitch}} cos\phi \right\} \tag{2}$$

$$f_{cage} = \frac{1}{2} f_{sh} \left\{ 1 - \frac{D_{ball}}{D_{pitch}} cos\phi \right\} \tag{3}$$

$$f_{spin} = \frac{D_{pitch}}{2D_{ball}} \left\{ 1 - (\frac{D_{ball}}{D_{pitch}} cos\phi)^2 \right\} \tag{4}$$

where f_{inner} is the inner race frequency, f_{outer} is the outer race frequency, f_{cage} is the cage frequency, f_{spin} is the ball/roller spin frequency n is the number of balls/roller, f_{sh} is the shaft speed, D_{ball} is the ball/roller diameter, D_{pitch} is the pitch circle diameter and ϕ is the contact angle.

In rotating machinery, since the rotational speed is changing over time, order analysis technique is suitable [6]. Furthermore, order analysis technique transforms a signals non-stationary components whose vibration frequencies are related to the rotation speed in the time domain into stationary signal components in the angular domain and thus provides information about the vibration components related to the changing rotational speed [7, 8]. In order analysis, the vibration data is first synchronously resampled with the rotational speed of a reference shaft ensuring sampling at an equal angle increment with reference to the rotating shaft [6, 8, 9]. The signal is said to be in the order or angle domain after resampling and may be further analyzed using relevant signal processing techniques suitable for the component of interest. It is important to note that bearings in an actual transmission exhibits stochastic behavior with low frequencies [1, 10]. The measured vibration data is a combination of the deterministic signal (gears, turbine, impeller, stator etc) and the stochastic signal [13].The deterministic part of the signal tends to mask the bearing signal, hence the need to separate the stochastic part from the deterministic part after the vibration signal has been synchronously resampled to the order domain [6, 13]. An Adaptive Line Enhancer (ALE) steered with a Recursive-Least-Squares (RLS) adaptive algorithm was utilized to make this separation before further signal analysis is performed [11, 12]. For adequate signal separation the time delay, filter order and the convergence must be carefully selected [11, 12]. The delay of the ALE should be longer than the correlation length of the random part of the signal [11, 12, 14].

In this paper, further signal analysis of the separated signal is performed using the Order Power Spectrum and the Order Modulation Spectrum [6, 7, 15].

2.4 Hilbert Transform

The Hilbert Transform (HT) is a useful technique for determining the instantaneous amplitude and instantaneous frequency of a signal [16]. HT is not a transform between domains in contrast to other integral transforms like Fourier transform, wavelet transform, etc, rather, it produces a new signal in the same domain as the original signal by assigning a complementary imaginary part to a given real part, or vice versa, by shifting each components of a signal by a quarter of a period [6, 16]. The HT of a real-valued time signal $x(t)$ may be produced as [6, 16]:

$$\widehat{x}(t) = \pi^{-1} \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \ = x(t) * (\pi t)^{-1} \tag{5}$$

HT corresponds physically to a special type of linear filter with all the amplitudes of the spectral components left unchanged and the phases shifted by $\frac{\pi}{2}$ [16]. However, HT is mostly used in envelope calculation and in creating the so-called analytic signal [6]. Furthermore, the analytic signal is a complex-valued signal $z(t)$ whose real part is the original signal $x(t)$ and its imaginary part is provided by the HT of the signal $\widehat{x}(t)$ as in [16, 17]:

$$z(t) = x(t) + i\widehat{x}(t) \tag{6}$$

In addition, the demodulated signal is the absolute value of the complex-valued analytic signal $z(t)$ obtained via the HT [17].

2.5 Power Spectrum

In estimating spectral properties of a signal, it is important to select an appropriate scaling of the spectrum estimator [18, 19]. The spectrum estimates may be scaled for either the tonal components of a signal -power spectrum estimates- or the random part of a signal -power spectral density (PSD) estimates- [19].

The Power Spectrum (PS) of a periodic sampled signal $x(n)$ is usually computed using the Welch's spectrum estimator [20]. The Welch spectrum estimate is obtained by averaging a number of periodograms. Each periodogram is based on segments of a time sequence $x(n)$, each segment consisting of N samples [21].

Thus, the original time sequence of data must be divided into data segments [22] The Welch's power spectrum estimator is given by [21, 22]:

$$\widehat{P}_{xx}^{PS}(f_k) = \frac{1}{LNU_{PS}} \sum_{l=0}^{L-1} \left| \sum_{n=0}^{N-1} x_l(n) w(n) e^{-j2\pi nk/N} \right|^2, \; f_k = \frac{k}{N} F_s \tag{7}$$

where $k = 0, ..., N/2$, L is the number of periodograms, N is the length of the periodogram, l is related to the overlapping increment (usually $0 - 50\%$ of the periodogram length), F_s the sampling frequency, $w(n)$ is a suitable window and

$$U_{PS} = \frac{1}{N} (\sum_{n=0}^{N-1} w(n))^2 \tag{8}$$

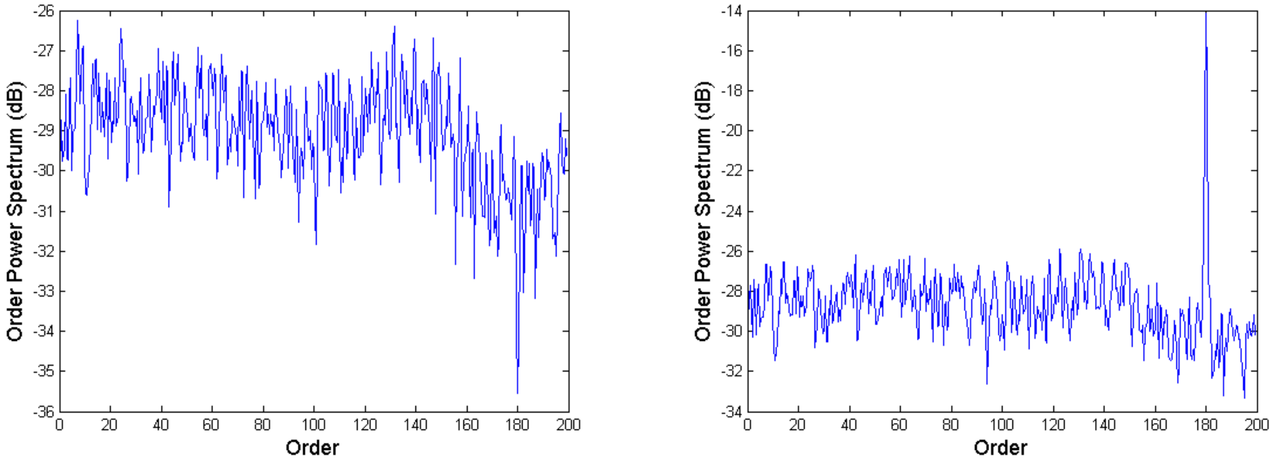
is the window-dependent magnitude normalisation factor.

Further, a one-sided PS contains the total power of the periodic components of a signal in the frequency interval from direct current (DC) to $F_s/2$, where F_s is the sampling frequency, whereas a two-sided PS contains the total power of the periodic components in the frequency interval $[-F_s/2 : F_s/2]$.

3. Result and Analysis

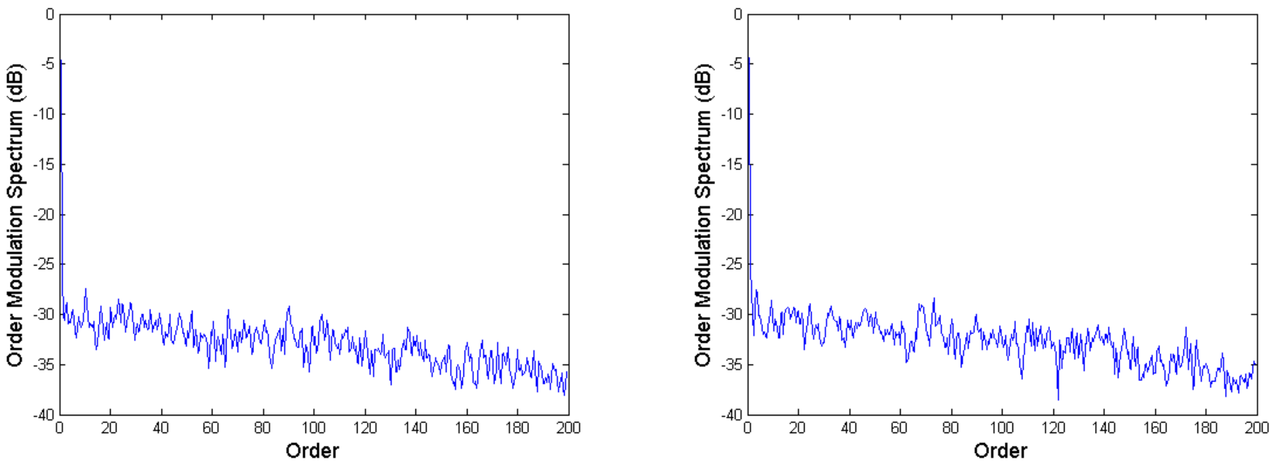
The results of the research are outlined below as ALE, Order Power Spectrum estimation and a Order Modulated Power Spectrum estimation of the measured vibration signal around the torque converter of the L90H automatic transmission test rig. Some of the orders of the bearings of the torque converter and their harmonics are identified.

The orders of the bearings and their harmonics are; the ball bearing 6.5, 8.4, 0.4, 4.1, the roller bearing; 16.9, 19.1, 0.47, 7.9, the cylindrical roller bearing 12.9, 15.1, 0.46, 6.5, the needle bearing 19.2, 20.8, 0.48, 12.6 and the cylindrical roller bearing 7.2, 9.8, 0.4, 3.2. The Order Power Spectrum of the torque converter stochastic vibration from the accelerometer mounted on the x-direction as in Figure 3a shows a deep at order 180 which correspond to the peak on the deterministic vibration as in Figure 3b, order 180 represents the harmonic of a gear with 45 teeth directly connected to the torque converter shaft into the gearbox. The orders of the bearings and their harmonics are visible on the stochastic signal Order Power Spectrum. The Order Modulation Power Spectrum of the torque converter stochastic vibration from the accelerometer mounted on the x-direction as in Figure 4b also



a) b)

Figure 3: a) Order Power Spectrum of the Stochastic Signal. and b) Order Power Spectrum of the Deterministic Signal.



a) b)

Figure 4: a) Order Modulation Spectrum of the Stochastic Signal. and b) Order Modulation Spectrum of the Deterministic Signal.

reveals the the bearing orders. Thus, the results above indicates that the stochastic part of the vibration which is related to the torque converter bearings may be separated from the deterministic part using ALE and the internal features of the bearing may be identified with Order Power Spectrum and Order Modulation Spectrum.

4. Discussions

The paper has presented two methods for analyzing the vibration properties of the torque converter bearings of the L90H automatic transmission. The measured vibration signal was re-sampled to the angle domain and subsequently an ALE was used for the separation of the stochastic part and the deterministic part of the angle domain vibration signal. Order Power Spectrum and Order Modulation Power Spectrum estimates of the separated stochastic part of the angle domain vibration signal provide information on the health status of the torque converter bearings.

Monitoring such vibration features on-board may enable to prevent failures of the torque converter. Thus, in this way, uptime can be improved and costly downtime, replacements and repairs can be minimized. The results of this paper are necessary for emerging business models and offers which will be hard to duplicate for competitors. Examples of such emerging business models, which may have contract parameters based on an agreed-upon level of result, performance and availability, are Industrial Product-Service Systems [23] and Functional Products [24]. This is required as the global competition on the construction equipment market forces the providers to add more value than products and services do. In addition, the emerging business models offer additional value to the customers by transfer of responsibility and risks to the provider. Thus, the provider needs to be compensated for that in order to achieve a long-term sustainable win-win situation between the customer and the provider sides.

REFERENCES

1. Randall R. B., and Antoni J., Rolling Element Bearing Diagnostics-A tutorial, *Mechanical System and Signal Processing*, **25**(2), 485–520, (2011).

2. Brkovic A., Gajic D., Gligorijevic J., Savic-Gajic I., Georgieva O. and Di Gennaro S., Early Fault detection and Diagnosis in Bearings for more efficient Operation of Rotating Machinery, *Energy*, (2016).

3. Immovilli F., Bellini A., Rubini R. and Tassoni C., Diagnosis of Bearing Faults in Induction Machines by Vibration or Current Signals: A Critical Comparison, *IEEE Transactions on Industry Application*, **46**(4), 1350–1359, (2010).

4. Abdusslam S.A., Gu F. and Ball A., Bearing Fault Diagnosis based on Vibration Signals, *Proceedings of Computing and Engineering Annual Researchers' Conference*, University of Huddersfield, Huddersfield, ISBN 9781862180857, 93–98 (2009).

5. Tuma J., *Vehicle Gearbox Noise and Vibration: Measurement, Signal Analysis, Signal Processing and Noise Reduction Measures*,John Wiley & Sons, Ltd, ISBN 978-1-118-79761-7, 77–83, (2014).

6. Brandt A., *Noise and Vibration Analysis: Signal Analysis and Experimental Procedures*, ISBN 978-0-470-74644-8, pp 263-283,379–384 John Wiley & Sons, (2011).

7. Källström E., Lindström J., Håkansson L., Karlberg M., Öberg O., Renderstedt R., and Larsson J., Identification of Vibration Properties of Heavy Duty Machine Driveline Parts as a Base for Adequate Condition Monitoring: Torque Converter, *Proceedings of the 23th International Congress on Sound and Vibration*, Athens, Greece, (2016).

8. Junsheng C., Yu Y. and Dejie Y., The Envelope Order Spectrum Based on Generalized Demodulation Time-Frequency Analysis and its Application to Gear Fault Diagnosis, *Mechanical System and Signal Processing*, **24**(2), 508–521, (2010).

9. Källström E., Lindström J., Håkansson L., Karlberg M., Renderstedt R., and Larsson J., Identification of Vibration Properties of Heavy Duty Machine Driveline Parts as a Base for Adequate Condition Monitoring: Axle, *Proceedings of the 23th International Congress on Sound and Vibration*, Athens, Greece, (2016).

10. Giannakis G. B., *"Cyclostationary Signal Analysis" Digital Signal Processing Handbook*,CRC Press LLC, (1999).

11. Widrow B. and Stearns S.D., Adaptive Signal Processing, *Prentice-Hall*, (1985).

12. Haykin S., Adaptive Filter Theory, *Prentice-Hall*, **third edition**, (1996).

13. Randall R. B., Sawalhi N., and Coats M., A Comparison of Methods for Separation of Determinstic and Random Signals, *International Journal of Condition Monitoring* , **1**(1), 11–19, (2011).

14. Ho D. and Randall R. B., Effects of Time Delay, Order of FIR Filter and Convergence Factor on Self Adaptive Noise Cancellation, *Fifth International Congress on Sound and Vibration* , (1997).

15. Randall R. B., *Vibration-based Condition Monitoring: Industrial, Aerospace and Automotive Applications*,John Wiley & Sons, Hoboken, NJ, (2011).

16. Feldman M., *Hilbert Transform Applications in Mechanical Vibration*, ISBN 978-0-470-97827-6 John Wiley & Sons, (2011). (2004).

17. Chen G. and Lin S.,*Design, Implementation and Comparison of Demodulation Method in AM and FM*, Master of Science Thesis, Graduate Program in Electrical Engineering, Blekinge Institute of Technology, Sweden, (2012).

18. Bendat, J. S., and Piersol, A. G., *Random Data Analysis And Measurement Procedures*, John Wiley & Sons, third edition, 2000.

19. Harris, F., On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform, *Proceeding of the IEEE*, vol. 66, (1978).

20. Andren, L., Håkansson, L., Brandt, A. and Claesson, I., Identification of Dynamic Properties of Boring Bar Vibrations in a Continuous Boring Operation, *Mechanical Systems and Signal Processing*, **18**(4), 869–901, (2004).

21. Källström E., *On-board Feature Extraction for Clutch Slippage Deviation Detection*, ISBN: 978-91-7583-496, Licentiate thesis, Luleå University of Technology, (2015).

22. Welch, P. D., The use of fast fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms, *IEEE Transactions on Audio and Electroacoustics*,70–73, (1967).

23. Meier, H., Roy, R., and Seliger, G., Industrial Product-Service Systems - IPS2, *CIRP Annals Manufacturing Technology*, 1–24, (2008)

24. Lindström, J., Plankina, D., Nilsson, K., Parida, V., Ylinenää, H., and Karlsson, L., Functional Products: Business Model Elements, *Proceedings of 5th CIRP International Conference on Industrial Product-Service Systems*, (2013).