 IDENTIFICATION OF VIBRATION PROPERTIES OF HEAVY DUTY MACHINE DRIVELINE PARTS AS A BASE FOR ADEQUATE CONDITION MONITORING: TORQUE CONVERTER

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Improving uptime is paramount in the heavy duty construction equipment business. Failure of critical components in the heavy duty machine may lead to unnecessary stops and expensive downtime. The torque converter, a complex component of the driveline, transmits and multiplies torque from the engine to the gearbox, and its failure may not only lead to the machine standing still but may also lead to damage of other parts of the automatic transmission.

For adequate condition monitoring of the torque converter, different sensor data are measured on a construction equipment machine during controlled driving sessions. Vibration has been measured on the torque converter. An initial investigation of the vibration measured on the torque converter has been carried out to identify its vibration properties in order to enable its health monitoring to prevent failure. Initial signal analysis of the data have been carried out using Order Power Spectrum and Order Modulation Spectrum methods. The results indicate that the torque converter vibration properties contain information relevant for early fault detection.

1. Introduction

As the requirements to improve up-time and thus to reduce costly down-time continuously increases, the construction equipment business focuses on more and new ways to increase sensitivity of early fault detection of critical components and parts in order to prevent failure.

The torque converter is a major component of the drive-line in construction equipment heavy duty machine whose faults are critical for the performance of the drive-line in a machine. Furthermore, degradation of the torque converter pollutes the lubricant and this may also result in degradation of components in the automatic transmission. Hence, a torque converter failure may result in down-time of significant cost, increased service cost and may also increase warranty cost. A torque converter
transmits and multiplies torque from the engine to the gearbox and it is regarded as one of the important parts in the automatic transmission. A torque converter consists of three major parts: the impeller, turbine and stator [1]. Dual-turbine torque converter is widely used in heavy duty construction equipment which improves the vehicle power performance and fuel economy [2]. A typical torque converter is shown in Fig. [3] Cai et al. [2] analyzed the torque distribution characteristics of the YJSW315 dual-turbine torque converter and observed that the computational fluid dynamics (CFD) method provided a reference for improving the blades of the working wheels and improving the performance. Yue Liu [1] investigated the characteristics prediction of the D350 torque converter based on CFD method and came to the conclusion that, by comparing the simulation result and the test result, the method provides a scientific basis for the design of the torque converter with respect to predicting its characteristics. Chu et al. [3] looked in to the optimization design of the cascade system of the YJSW315 dual-turbine hydrodynamic torque converter using the sliding-mesh theory, CFD and non-steady state solver. They gathered that the performance of the dual-turbine hydraulic torque converter is affected by these factors; the respective working impeller blade import and export angle, blade shape, blade thickness and the flow channel length. Furthermore they pointed out that the working wheel blade import and export angle factor had the most influence on the the dual-turbine hydraulic torque converter [3].

Even though a lot of research have been done on the design and optimization of the torque converter, the vibration properties of torque converters seems to have been overlooked. This paper concerns an initial investigation of the vibration properties of a torque converter which may contain information related to its degradation.

Furthermore, the purpose of this paper is to complement the current methods utilized to detect torque converter degradation.

2. Materials and Methods

2.1 Experimental Setup

A Volvo Construction Equipment L180H Wheel Loader was used in the experiments. The machine was warmed-up before the test cycles and the bucket was loaded with 8 tonnes of gravel. The Volvo CE test track in Eskilstuna, Sweden, was used in the experiments as driving track, using one
driver and similar driving style in all measurements. The measured parameters used in the investigation are the engine speed and the torque converter vibration. 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 LMS Scadas SCR05 Data Acquisition system, sampling frequency 6400Hz, connected to two triaxial accelerometers attached on the left side and top side of the torque converter housing. In order to adequately measure vibrations of the torque converter, the two triaxial accelerometers were mounted as close as possible to the torque converter as in Figures 2 and 3. The accelerometer on the left side of the torque converter housing was mounted using instant adhesive- Loctite 454 and the one on the top side was mounted using magnet. The engine speed from the machine CAN-bus was logged synchronously with the vibration data.

![Image of L180H Wheel Loader with accelerometer attached on the left side of the torque converter housing.]

Figure 2: L180H Wheel Loader with accelerometer attached on the left side of the torque converter housing.

2.3 Evaluation of the Torque Converter Vibration

The vibration properties of the drive-line may be investigated with the aid of order analysis techniques, frequency domain, time-frequency domain analysis, etc [4, 7]. Order analysis techniques, usually referred to as order-tracking, and are generally utilized in rotating machinery analysis where the rotational speed changes over time. Furthermore, order analysis techniques transform a non-stationary signal in the time domain into a stationary signal in an angular domain providing information about the vibration related to the changing rotational speed [5].

Order analysis is carried out by first, synchronously resampling the measured vibration based on the rotational speed measured on an reference shaft [4]. In other words, synchronous sampling adapts the sample rate of the vibration signal with the changing rotational speed of the reference shaft, thus, ensuring that the vibration is sampled at an equal angle increment [5]. Thus, the synchronous sampled vibration originating from rotating parts will basically have a fixed number of samples per cycle and this number is related to the rotational speed measure of the shaft. The synchronously resampled samples of the vibration data are said to be in the order or angle domain [4]. Synchronously resampled signals may be analyzed using different signal processing techniques, in this paper, the Order Power Spectrum and Order Modulation Power Spectrum are considered [4, 5, 6].
The Order Power Spectrum may be estimated directly via the Power Spectrum of the synchronously resampled vibration signal. While, the order modulation power spectrum is produced by first estimating the Hilbert Transform of the synchronously resampled signal and subsequently producing the Power Spectrum of the so-called analytic signal [4, 6].

2.4 Power Spectrum

In estimating spectral properties of a signal it is important to select an appropriate scaling of the spectrum estimator [11, 8]. The spectrum estimates may be scaled for either the tonal components of a signal -power spectrum (PS) estimates- or the random part of a signal -power spectral density (PSD) estimates- [11].

The Power Spectrum (PS) of a periodic sampled signal \( x(n) \) is usually computed using the Welch’s spectrum estimator [9]. 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 [12]. Thus, the original time sequence of data must be divided into data segments [10]. The Welch power spectrum estimator is given by [10, 12]:

\[
\hat{P}_{xx}(f_k) = \frac{1}{LNU_{PS}} \sum_{l=0}^{L-1} \sum_{n=0}^{N-1} x_l(n)w(n)e^{-j2\pi nk/N}^2, \quad f_k = \frac{k}{N}F_s
\]  

where \( k = 0, \ldots, N/2 \), \( L \) 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

\[
U_{PS} = \frac{1}{N}(\sum_{n=0}^{N-1} w(n))^2
\]

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 half of the Nyquist rate whereas a two-sided PS contains
the total power of the periodic components in the frequency interval from -Nyquist rate to the Nyquist rate.

2.5 Hilbert Transform

The Hilbert Transform (HT) is a useful technique for determining the instantaneous amplitude and instantaneous frequency of a signal [13]. 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 [4, 13]. The HT of a real-valued time signal $x(t)$ may be produced as [4, 13]:

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

(3)

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 $\frac{\pi}{2}$ [13]. However, HT is mostly used in envelope calculation and in creating the so-called analytic signal [4]. 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 Hilbert transform of the signal $\hat{x}(t)$ as in [13, 14]:

$$z(t) = x(t) + i\hat{x}(t)$$

(4)

In addition, the demodulated signal is the absolute value of the complex-valued analytic signal $z(t)$ obtained via the HT [14].

3. Result and Analysis

The results of the research are outlined below as a Order Power Spectrum estimation and a Order Modulated Power Spectrum of the measured vibration signal around the torque converter of the L180H Wheel Loader.

![Figure 4: Order Power Spectrum of the torque converter vibration from the accelerometer placed on the x-direction of the top side of the torque converter housing.](image-url)

The orders 29, 27 and 13 and their harmonics corresponding to the torque converter’s impeller, turbine and stator respectively are seen on Figures [3] and [6]. In addition, harmonics of the order 29 which corresponds to the impeller are more pronounced around order 87 on the order power spectrum.
Figure 5: Order Modulation Spectrum of the torque converter vibration from the accelerometer placed on x-direction of the top side of the torque converter housing.

Figure 6: Order Power Spectrum of the Torque Converter vibration from the accelerometer placed on the y-direction of the left side of the Torque Converter housing.
Also, on the order modulation spectrum on Figures 5 and 7, the order 29 which correspond to the impeller is observed to have significant peaks around order 29 and slightly lower around its harmonic at order 58. By comparing the order power spectrum and order modulation power spectrum for the vibration measured around the torque converter, it can be observed that the order modulation power spectrum seems to magnify peaks with higher amplitude and suppress peaks with lower amplitude.

4. Discussions

An initial investigation concerning torque converter vibration properties have been carried out. The above results demonstrates that the torque converter vibration in an actual heavy duty construction equipment may contain information related to degradation of the torque converter and the automatic transmission in general. Order power spectrum and Order Modulation power spectrum estimates of the vibration measured around the torque converter provides information about the features of the torque converter. Furthermore, the orders related to underlying parts of the torque converter may be identified using the order power spectrum and the order modulation power spectrum estimates. In effect, continuous monitoring of the orders related to the torque converter may prevent failure of the torque converter as potential problems are detected well in advance before a torque converter failure occurs.

In future machines, monitoring the torque converter vibration on-board via vibration sensors may enable early fault detection of the torque converter. In addition, on-board monitoring of the aluminum level in the oil may also provide an indication of the gradual degradation of the torque convert part. Practically, early fault prediction may save both money and time for the customer, and thus increase customer satisfaction. Being able to monitor, preferably on-line, critical parts and components such as the torque converter, is a pre-requisite for using result- or availability-based business models such as Industrial Product-Service Systems or Functional Products [15, 16]. These business models are becoming more interesting as additional services, software, knowledge and know-how are added to product offers [16].

Acknowledgments

This work has been partially supported by Volvo Construction Equipment and the VINNOVA Excellence Centre the Faste Laboratory at Luleå University of Technology, Sweden.
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