ANALYSIS OF AUTOMATIC TRANSMISSION VIBRATION FOR CLUTCH SLIPPAGE DETECTION

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Heavy duty construction equipment is generally equipped with automatic transmission enabling to change gear ratio automatically. The clutches in an automatic transmission transfer torque from the engine to the gearbox and clutch failures may result in costly downtime of construction equipment. To prevent costly downtime of construction equipment, condition monitoring in combination with condition based maintenance may be utilized. Different sensor data are collected on a machine that enables condition monitoring. Vibration have been measured on an automatic transmission in a construction equipment machine during controlled driving sessions, with and without clutch slippage, on a test track. An initial investigation of the vibration measured on the automatic transmission have been carried out with the purpose to find out if the vibration may contain reliable information related to clutch slippage considered to be abnormal. Initial signal analysis of the data have been carried out using Spectrogram and Spectral Kurtosis methods. The results indicate that information related to abnormal clutch slippage may be extracted from vibration measured on an automatic transmission in a construction equipment machine.

1. Introduction

Ways of improving up-time and reducing down-time are paramount in the construction equipment business. Automatic transmission clutch failure results in costly downtime, which also increases service cost and may also increase warranty costs. Multiple disc wet clutches are considered to be the backbone of Automatic Transmissions. The function of the clutch is to enable the disconnection
of a driving shaft and a driven shaft during gear shifts, and to connect and transfer of torque between the shafts when being in gear. \cite{1,2}. Furthermore, multiple disc wet clutches allows slipping, which means that the shafts can be connected while there is a large difference between the rotation speed of the two shafts \cite{2}.

A typical multiple disc wet clutch pack and its components is illustrated in Fig. \ref{fig:clutch}. The clutch plates are arranged in such a way that one of the discs type is driven by the hub and the other by the drum \cite{5}. The drum and hub are driven by a joint that allows axial movement such as splines and lugs \cite{5}. The multiple disc wet clutch is equipped with an electro-mechanical hydraulic actuator, comprising of e.g piston, returning spring, a control valve, oil pump etc, which enables the engaging and disengaging of gear.

![Multiple Disc Wet Clutch pack 3-D view](image)

**Figure 1: Multiple Disc Wet Clutch pack 3-D view**

Multiple disc wet clutch pack are designed to slip for a defined period of time (slip time) so that too much heat is not generated at the clutch plates interfaces burning the clutch material due to excessive friction \cite{8}. Clutch failure occurs when the the clutch can no longer transmit the desired torque. Hence, clutch slippage is a result of diminishing frictional characteristics of the clutch system \cite{10}.

Clutch degradation is often accompanied by drive-line vibration \cite{12,8,9}. Friction induced vibration, also referred to as "Judder", is influenced by the coefficient of friction of the clutch system \cite{12}. Yuzuru et al \cite{4} investigated the presence of torsional vibration during clutch engagement in an experiment where he used paper-based friction material and connected two accelerometers, one around the clutch pack and the other on the bottom end of the input shaft, he observed that torsional vibration of the input shaft occurred during engagement. Agusmian et al \cite{11} utilizing modal parameters developed a monitoring method aimed at monitoring the change in post lock-up dynamic behavior of the drive-line due to wet clutch induced vibration. Berglund et al \cite{8} observed that the degradation of wet clutches is often associated with the presence of drive-line vibration, he also showed that the frictional characteristics of an ageing clutch may induce drive-line vibrations \cite{8}. Fatima et al \cite{9} clearly pointed out that the torsional vibration of wet clutches occurs when the static coefficient of friction is greater than the dynamic coefficient of friction thus leading to a reduction in the coefficient of friction, she went on to investigate the influence of output shaft stiffness and inertia, on wet clutch vibration. She observed that vibration was higher for a clutch with low stiffness and low inertia of the output shaft, which results in a loss in the coefficient of friction in the wet clutch \cite{9}. Centea et al \cite{12} showed that the level of torsional vibration (judder) depends on the coefficient
of friction characteristics of the friction material lining of the clutch system. He also stated that selecting a friction material with good friction characteristics is one way of reducing vibration in the clutch system [12].

To sum-up, drive-line/torsional vibration has been observed both during clutch engagement and clutch degradation but the vibration signals has not been utilized for the detection of clutch slippage with the aim to provide an indication of the health of the wet clutch system. This paper concerns an initial investigation with the purpose to find out if drive-line vibration may contain information related to clutch slippage. It is based on recorded accelerometer data measured on the transmission of a Volvo L90F Wheel Loader. Further, the purpose of the paper is to extend the current methods to detect clutch slippage based on vibration features.

2. Materials and Methods

2.1 Experimental Setup

The Volvo Construction Equipment L90F Wheel Loader was used in the experiments. To induced clutch slippage the Wheel Loader was slightly modified by installing two manual needle valves on the pressure outlet of clutch 1 and 2 as in Fig. 2. The clutch 1 and 2 were considered based on reported cases of clutch failure [13]. The manual needle valves can be fully opened and fully closed, when both valves are fully opened oil leakage is simulated in both clutches. A steep hill was used in the experiments as driving track, with one driver and similar driving style in all measurements. The measured parameters used in the investigation are the clutch pressures, the clutch vibration, gear shift from 1 to 2 and 2 to 1. 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 SQuadriga 1369 Data Acquisition system, sampling frequency 6kHz, connected to a triaxial accelerometer attached on the automatic transmission. The triaxial accelerometer was mounted as close as possible to the clutch 1 and 2 to measure vibration as in Fig. 3. The accelerometer was mounted using instant adhesive- Loctite 454. The clutch Pressures and the gear signals were recorded using two CAN-buses, the IPETronic CAN-bus and the Machine ECU CAN-bus. The clutch pressures were logged using a IPETronic M-SENS 8, and signals which gave an indication of a gear shift such as engaged gear were logged using the ECU CAN-bus. The data from these two CAN-buses were broadcast to a third bus and displayed using the CANalyzer VN1630.

2.3 Evaluation of the Gear Box Vibration

The properties of drive-line vibration may be investigated by applying frequency domain, time-frequency domain analysis, etc. Frequency domain analysis of a signal can be carried out directly with the aid of the Fast Fourier Transform or generally more reliable and robust via Power Spectrum/ Power Spectral Density estimates, depending on the underlying properties of the signals. While, the time-frequency domain analysis involves signal processing methods that provide information about the time and frequency domain at the same time. Furthermore, the time-frequency domain analysis may be estimated directly via the Short Time Fourier Transform (STFT) or its squared magnitude regarded as Spectrogram, Spectral Kurtosis, (which is based on STFT), wavelet transform etc. [15] [14]. The time-frequency domain analysis is often preferred when analyzing non-stationary signals to extract information regarding a signals frequency content as a function of time. Physical quantities, such as vibration, may have non-stationary stochastic behavior, this makes their spectral properties change over time [15].
2.4 Spectral Properties

2.4.1 Spectrogram

The Spectrogram is a time-frequency signal processing technique which provide information about a signal in both the time and the frequency domain at the same time [15]. The Spectrogram is based on the squared magnitude of the Short Time Fourier Transform (STFT). The STFT is a windowed Fourier Transform whose window has fixed length [15]. The discrete time STFT of a sampled signal $x(n)$ may be produced as [15]:

$$X(k, lD) = \sum_{n=0}^{M-1} x(n)w(n - lD)e^{-j2\pi \frac{k}{N}(n-lD)}$$  

where $k = 0, ..., N/2$, $w(n)$ is a suitable window with length $N$, $lD$ is the starting point for each periodogram, $D$ is the overlapping increment and $D < N$, $M$ is the length of the time series. The Spectrogram may be produced according to:

$$\text{Spectrogram}(k, lD) = \frac{1}{F_s \sum_{n=0}^{N-1} (w(n))^2} \left\langle |X(k, lD)|^2 \right\rangle_t$$  

Where $\langle \cdot \rangle_t$ is the time averaging operator and $F_s$ is the sampling frequency.

2.4.2 Spectral Kurtosis

The Spectral Kurtosis (SK) is a higher order statistical tool which can handle non-Gaussian components of a signal showing their location in the frequency domain [18]. SK is a powerful tool to use for detecting transients in a signal and thus complements the PSD which may remove non-stationarities in a signal [18]. Furthermore, SK is suitable for analyzing signals corrupted with Gaussian noise since higher-order statistics are blind to Gaussian measurement noise [20, 18]. The SK may be estimated with the aid of the STFT according to [18]:

$$\overline{SK}_X(k, lD) = \frac{\left( |X(k, lD)|^4 \right)_t}{\left( |X(k, lD)|^2 \right)_t^2} - 2$$
where $X(k, lD)$ is the short time Fourier transform of the signal $x(n)$, $|X(k, lD)|^4$ is the fourth power of the magnitude of signals short time Fourier transform and $|X(k, lD)|^2$ is the second power of the magnitude of signals short time Fourier transform. Care should be taken when choosing overlapping increment $D$ with concern to aliasing and when choosing window length $N$; basically the window length $N$ should be longer than the signals correlation length providing sufficient spectral resolution and sufficiently short to resolve temporal variation in its spectral properties [18]. Furthermore, with increasing window length the STFT approaches Gaussianity according to central limit theorem and thus the spectral kurtosis will approach zero [18].

3. Result and Analysis

The results of the research are outlined below as a Spectrogram estimation and a Spectral Kurtosis estimation of measured vibration data with clutch slippage and without clutch slippage. In Fig. 4 a) spectral kurtosis for gearbox acceleration for clutch slip is shown in a 3-D plot and in Fig. 4 b) a spectrogram for the corresponding gearbox acceleration is shown. For the case with no clutch slippage Spectral Kurtosis for gearbox acceleration is shown in a 3-D plot in Fig. 5 a) and a Spectrogram for the corresponding gearbox acceleration is shown in Fig. 5 b). From the figures, the time and frequency domain axes provides an indication on how the clutch frequencies vary over time during a gear shift. Furthermore, the results also shows that clutch slippage vibrations exhibits non-stationary stochastic behavior.

By comparing the Spectrogram results for the case of clutch slippage and the case of no clutch slippage, a more broadband spectrum can be observed when there is no clutch slippage as compared to when there is clutch slippage. Also, with no clutch slippage two ridges in the spectrogram are more pronounced as compared to the case of clutch slippage. Also, around 0.01 seconds the frequency peaks at about 1688Hz is higher when there is clutch slippage unlike when there is none. further, at about 0.58 seconds on the Spectrogram, the frequency peak at about 1875Hz is higher when there is no clutch slippage.

The Spectral Kurtosis for the case with clutch slippage and no clutch slippage also shows a variation; high peak around 2625Hz for no clutch slippage case and no peak at around 2625Hz for the clutch slippage case. Also, about 0.7 second to 1 seconds, the Spectral Kurtosis peaks around 750Hz and 1500Hz frequency range seems to be more pronounced and thus higher for the clutch slippage case.
case compared to the case of no clutch slippage.

Figure 4: a) Spectral Kurtosis of gearbox acceleration, with clutch slippage and b) Spectrogram of gearbox acceleration, with clutch slippage.

Figure 5: a) Spectral Kurtosis of gearbox acceleration, without clutch slippage and b) Spectrogram of gearbox acceleration, without clutch slippage.

4. Discussions

An initial investigation concerning clutch slippage detection using driveline vibration have been carried out. The above results demonstrates that automatic transmission vibration in an actual heavy duty construction equipment may contain information related to degrading clutch slippage. Spectrogram and Spectral Kurtosis estimates of automatic transmission vibration seems to provide features related to degrading clutch slippage. The results also indicates that automatic transmission vibration during clutch slippage exhibits non-stationary behavior. Furthermore, the measured vibration originates from the off-going and on-going clutches during a gear shift. In addition, the implication from
the results shows that time-frequency domain analysis using the Spectrogram and the Spectral Kurtosis reveals the frequency components over time during a gear shift in a vibration signal corrupted with noise. This indicates that it is possible to detect wet clutch failure via vibrations.

In future machines, it might be of importance to monitor the driveline vibration on-board via vibration sensors, complementing other on-board monitoring sensors in early fault detection of the clutch systems and other component parts. Practically, early fault prediction may save both money and time for the customer as potential problems are detected well in advance before a clutch failure occur, gearbox failure occur, etc.

An industrial application of the vibration analysis is that it together with other methods to monitor and analyze key components, which have high impact on the level of availability, enable further advanced business models than products and services. This is crucial as the global competition force providers of for instance construction equipment or production equipment to provide additional value than products and services do. If the level of availability and key components can be monitored, in order to enable predictive and proactive maintenance, further advanced business models such as Product-Service Systems [21] and Functional Products [22] can be offered. These business models can potentially offer more value to the customers by e.g., transfer of responsibility and risks to the provider. However, the provider needs to be compensated for that to reach a sustainable and long-term win-win situation between the customer and the provider sides.

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