Research about vibration characteristics of timing chain system based on short-time Fourier transform

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Abstract. Vibration characteristic of timing chain system is very important for an engine. In this study, we used a bush roller chain drive system as an example to explain how to use multibody dynamic techniques and short-time Fourier transform to investigate vibration characteristics of timing chain system. Multibody dynamic simulation data as chain tension force and external excitation sources curves were provided for short-time Fourier transform study. The study results of short-time Fourier transform illustrate that there are two main vibration frequency domain of timing chain system, one is the low frequency vibration caused by crankshaft sprocket velocity and camshaft sprocket torque. Another is vibration around 1000Hz lead by hydraulic tensioner. Hence, short-time Fourier transform method is useful for basic research of vibration characteristics for timing chain system.

1. Introduction
As an important component of engine, a well timing chain system could ensure good timing performance, reduce radiated vibration and noise value of engine front end. It attracts much more attention in recent years. There are three main typical analysis methods for timing chain system investigation. The First method is dynamic analysis. T.Schaffner, M. Sopouch established bush roller chain dynamic model and silent chain dynamic model separately to discuss the vibration character of engine for different chain type [1]. Martin Sopouch, Wolfgang Hellinger from AVL List GmbH, and Peng from Chang’ an Auto Global R&D Center used dynamic method as well to study noise excitation due to timing chain drive [2-3]. The second one is finite element analysis method. Wang from Shandong University established a finite element model by ANSYS software to simulate horizontal fluctuation of chain [4]. The last one is acoustic analysis. Luo from Taiwan propose a simulation procedure and correction method of acoustic field of chain system [5]. Sun from Jilin University suggest an impact noise prediction method of silent chain drive system using acoustic boundary element theory [6].

Dynamic characteristics of timing chain system could be got by dynamic simulation easily, but these data could not reflect vibration feature directly. Due to the accuracy problem of simulation, both finite element method and acoustic analysis need high quality elements and high performance computers, leading to a long calculation time. However, the advantages of vibration characteristics analysis method based on STFT (short for short-time Fourier transform) introduced in this paper are fast analysis speed and reliable analysis results, make it is suitable for basic research.

2. Short-time Fourier transform theory
Because of Fourier transform can only analyse data in the frequency domain, Gabor (1946) proposed the short-time Fourier transform, in this method the signal is divided into many small intervals, which
can be analyzed by the Fourier transform to determine the frequency of the existing intervals [7-9], that is the basic idea of STFT, the formula is illustrated as below.

\[
S(\omega, \tau) = \int_{\tau} f(t) g^*(t) e^{-j\omega t} dt
\]  

(1)

In formula (1), \( g(t) \) is a function with a compact set, \( * \) is a complex conjugate and \( f(t) \) is an analyzed signal. The "time window" determined by \( g(t) \) that can move with time \( \tau \) on the \( t \) axis and is analyzed by \( f(t) \) gradually. Then \( g(t) \) is often called the window function, the relative content of \( f(t) \) is "signal component" at \( \tau \) time and the \( \omega \) frequency is mainly reflected by \( S(\omega, \tau) \). So the expansion of the signal on the window function can be expressed in the state of the region \([\tau - \delta, \tau + \delta]\) and \([\omega - \epsilon, \omega + \epsilon]\), this region is called the window, \( \delta \) and \( \epsilon \) are called as the window of the time width and bandwidth separately, which express the resolution in the time-frequency analysis. The smaller the window width, the higher accuracy of the resolution.

In a word, STFT can be understood as: add a short window Fourier transform, which window function is intercepted by the window function, then move along the time axis, so that the entire time signal short-time Fourier transform can be completed.

3. Dynamic analysis of timing chain system

There are two excitation sources of timing chain system. One is internal excitation sources, caused by meshing and polygon effects. The other is external excitation sources, which is caused by crankshaft sprocket velocity fluctuation, camshaft sprocket torque vibration and hydraulic tensioner. The vibration characteristics of timing chain system caused by external excitation sources at 1000rpm is studied in this paper.

This chain drive comprise 112 chain link assemblies, a 21-tooth crankshaft sprocket, a 42-tooth camshaft sprocket, a hydraulic tensioner, a fixed guide and a tension guide(show in figure 1.). Each chain link assembly in this model further comprises a cylindrical roller, a bush, a pin and two link plates. Figure 2 illustrate multibody dynamic analysis model.

In this analysis, the crankshaft sprocket velocity (figure 3) and camshaft sprocket torque (figure 4) have been inputted as calculation boundary condition to reflect the real working condition. Tensioner plunger velocity is shown in figure 5 which is the data base of tensioner plunger velocity STFT transform spectrum.
The changes in chain tension force during a marked link rotation in four circles (figure 6) at 1000 rpm is analyzed by multibody dynamic analysis software RecurDyn. The marked link comes in contact with the tension guide at the beginning of the first cycle. The maximum chain tension force is 736N in this moment. Then, the marked link meshes with the camshaft sprocket, after this stage, marked link starts to come in contact with the fixed guide as the crankshaft sprocket rotates, and the maximum chain tension force is approximately 1136N. Finally the marked link engaged with crankshaft sprocket. The maximum tension force of this cycle is 1136N less than ultimate strength that conforms to the force regularity. All of these data calculated in dynamic analysis are used to STFT for further study.

4. Vibration characteristics of timing chain system based on STFT

Tension force STFT transform spectrum is illustrated in figure 7, energy period distribution in time domain that conforms to chain tension force distribution rule. Energy mainly concentrated in two area in frequency domain. One is in the low frequency area and the other is around 1000 Hz. It means that this timing chain system includes low frequency vibration and higher frequency (around 1000Hz) vibration.

Tensioner plunger velocity STFT transform spectrum (figure 8) points out that the maximum energy concentrate on 1000Hz domain, which is the same with tension force STFT transform spectrum, and indicates that hydraulic tensioner is the excitation source which caused vibration of timing chain system around 1000Hz. Both camshaft sprocket torque STFT transform spectrum (figure 9) and crankshaft sprocket velocity STFT transform spectrum (figure 10) depict that their largest
energy are at low frequency domain which accord with tension force STFT transform spectrum data. In another word, camshaft sprocket torque and crankshaft sprocket velocity are the main reason that lead to low frequency vibration of timing chain system.

Figure 7. Tension force STFT transform spectrum

Figure 8. Tensioner plunger velocity STFT transform spectrum

Figure 9. Camshaft sprocket torque STFT transform spectrum

Figure 10. Crankshaft sprocket velocity STFT transform spectrum

5. Conclusion
A multibody dynamic simulation model is established in this paper, the external excitation sources of timing chain system, including camshaft sprocket torque, crankshaft sprocket velocity and hydraulic tensioner are taken into consider to reflect real working condition, improving the accuracy of calculate data. The curve of tension force shows that this timing drive system conforms to the force regularity, and all of these selected data are the data base of STFT.

A time-frequency domain analysis method, STFT, is used to explore vibration characteristics of timing chain system in time-frequency domain. Hydraulic tensioner is the excitation source caused vibration of timing chain system at 1000Hz band, and camshaft sprocket torque, crankshaft sprocket velocity are the reason lead to low frequency vibration.

In conclusion, a method based on STFT is useful for analyzing the influence of external excitation sources on timing chain system vibration characteristics. This method not only indicates energy distribution, but also points out the reason caused these vibration in frequency domain, and it could provide analysis basis for further research about vibration characteristics of timing chain system.
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