# Vibration study of the gearbox of hydro-mechanical continuously variable transmission based on Mean Filter Method

Xiao Maohua*, Zou Fan, Zhang Haijun, Xiao Dengsong, Lu Zhixiong, Zhang Cunyi

(*College of Engineering, Nanjing Agricultural University, Nanjing 210031, China*)

**Abstract:** Hydro-mechanical continuously variable transmission (HMCVT) is an important drive assembly part of high-horsepower tractors. Its loading ability changes violently under various conditions. Additionally, starting shifting or barking of hydraulics will cause more violent vibration, which may greatly influence the lifetime of the gearbox. Therefore, effective test and analysis of the vibration of different parts will play an important role in ensuring the system's reliable operation. A Mean Filtering Method was used in this paper to calculate and analyze the vibration of the gearbox's important parts. The vibration signal data was filtered by Mean Filtering Method, and was changed from Time Domain Waveform into Frequency Domain Waveform by Fourier Transform Method. The filtering effect can be shown clearly by comparing the two different frequency range charts with or without filtering. Root-mean-square vibration speed in each point was sought by Matlab. Vibration intensity level in each part then was judged according to rotating machinery vibration standard (SHS 01003-2004). Combined with the construction and transmission route of the HMCVT, a prioritization scheme that changed two output semi-axes into one output axis using layer-stepping type and casting type gearbox body was proposed, and the control system on the body surface was installed.

**Keywords:** vibration, HMCVT, high-horsepower tractors, Mean Filter Method

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## 1 Introduction

Hydro-mechanical continuously variable transmission (HMCVT) is an important drive assembly part of high-horsepower tractors, and its loading changes due to different working conditions (Ji et al., 2009). The drive system vibrates violently, which influences greatly on transmission's service life, with pure hydraulic starting, shifting and braking. Although in the ideal working condition, forced vibration due to the engine's periodic speed fluctuations maybe coused, since the transmission is delivering power with its engine. Therefore, by testing, analyzing and improving every single part's vibration, it plays a great role in ensuring the transmission body's reliability service.

The study on HMCVT was relatively late in China, and up to now, there is no commercialized HMCVT products in the market. Liu (1998), a professor in Beijing Institute of Technology, is a predecessor of researching on HMCVT in China. The analysis on hydrodynamic mechanical transmission system in Liu's book built a systematical research of HMCVT (Liu et al., 1998). Hu et al. (2008) had come up with a two-stage scheme which had been applied to high-speed tracked vehicle. And also, a three-stage scheme was invented by Zhang et al. (2007); Ji et al. (2009), Zhang et al. (2011) and Tian et al. (2011), who are from Jilin University, mainly focused on HMCVT's application in engineering vehicles. Ni (2013); Wang et al. (2014); Shi et al. (2011) in Nanjing Agricultural University had come up with a four-stage transmission scheme, which helped to do the theoretical analysis and experimental research on transmission's shifting and efficiency characteristics. They even created

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* **Corresponding author: Xiao Maohua**, Ph.D., Associate Professor of College of Engineering, Nanjing Agricultural University, Nanjing, 210031, China. Email: xiaomaohua@njau.edu.cn, Tel: 025-58606623, Fax: 025-58606580.

the sample prototype (Lu et al., 2009; Tao et al., 2013). The paper, vibration and noise analysis of transmission (Dong et al., 2000), analyzed the reasons for some abnormal vibration and noises of a transmission. It tested and analyzed the sample prototype's vibration and noise signal under different conditions by arranging four experimental points in the transmission body. At the same time, by creating a model of transmission shell, it did a modal analysis on the front side of transmission shell and calculated each wheel gear's gear-mesh frequency, with which to estimate how the results influence the peaks in vibration and noise-based power spectrum. The final analysis result revealed that it would decrease vibration and reduce noise if we changed the original cast iron materials of transmission shell into pressure-casting aluminum. Furthermore, with the creation of three-dimensional transmission body, Li et al. (2009) had got an idea that if the outer casting vibrated slightly, the thickness of the outer casting could be redesigned. Besides, it got more amplitude in inside ribs and partitions, thus some parts of the body can be reinforced on.

Ashwani Kumar et al. (2014) studied a truck's free vibration of transmission shell, which was made of FG260. The author concluded that the inherent frequency variation of the gear box side connection bolt based on the constrained boundary condition was 2954-1002 Hz. Also Shawki et al. (2013) studied vehicle transmission using the method of analyzing vibration. They analyzed the vehicle transmission and calculated its radiate efficiency. Tuma et al. (2009) did a research on a truck's noise and vibration. He found that heavy vibration frequency was between 500-2500 Hz by analyzing and fourier transforming the experimental results. Kumar et al. (2015) also did research on the vibration of different materials. The simulation results showed that its fixed frequency was 1002-3784 Hz.

The listed researches have solved the problems about vibration of HMCVT by changing the materials or shape of its body without considering its manufacturing technique and the effects of drive system on body vibration. The vibration of some important parts of the gearbox with a method called Mean Filter Method was analyzed in this paper. Firstly, 20 important positions were chosen as the testing points on the body surface to see their vibration signals under different situations. Secondly, the signals were filtered and their time domain waveform were changed into frequency domain waveform through Fourier transform. Then, root-mean-square vibration speed in each point was calculated through filtering with Matlab 9.0. According to (SHS 01003-2004), the root-mean-square vibration speed which varies from frequency 10 to 100 Hz was used as a symbol to represent the measured parameters of mechanical vibration. When the experimental data were shown on table and bar chart, it can be seen clearly that vibrates on gearbox body was greatest, and then on its bearing parts. The vibration on cover and bracket were smallest. Combining with the construction and transmission rout of HMCVT, a prioritization scheme which changed two output semi-axises into one semi-axis was put forward. The gearbox body was designed as layer-stepping type and casting type, and also the control system was installed on the body surface.

## 2 Mean Filter Method

According to the Rotating Machinery Vibration Standard (SHS 01003-2004), the root-mean-square vibration speed which varies from frequency 10 to 1000 Hz can be used as a symbol to represent the measured parameters of mechanical vibration. The test data which were not in the measurement range should be filtered firstly. Then the collected data should be calculated to root-mean-square, which will be the final experimental data.

In order to reduce noise of the collected signal as much as possible, Mean Filter Method was used in this paper. The time domain waveform of the signal was transformed into frequency domain waveform by Fourier transform. Then, the filtering effect was compared with the filtered frequency domain map before filtering, thus showing the filtering effect. Root-mean-square speed of each point was analyzed by Matlab 9.0 listed below:

```
s=csvread('D:\111\k_a. csv');
data1=s(:, 2);
a=1;
```

```
b=[1/20, 1/20, 1/20, 1/20, 1/20, 1/20, 1/20, 1/20, 1/20,
1/20, 1/20, 1/20, . .
1/20, 1/20, 1/20, 1/20, 1/20, 1/20, 1/20, 1/20];
data2=filter(b, a, data1);
fs=1/0. 000061;
n=0:length(data2)-1;
t=n/fs;
N=length(data2);
result = sqrt(sum(data2. ^2)/length(data2))
y1=fft(data1);
figure;
subplot(2, 1, 1);
plot((0:N/2-1)*fs/N, abs(y1(1:1:N/2))*2/N);
xlabel('frequency/Hz');
ylabel('velocity amplitude/mm/s');
title('Wave before filtering');
%frequency domain after filtering
y2=fft(data2);
subplot(2, 1, 2);
plot((0:N/2-1)*fs/N, abs(y2(1:1:N/2))*2/N);
xlabel('frequency/Hz');
ylabel('velocity amplitude/mm/s');
title('filtered frequency domain waveform');
```

## 3 Experiment and analysis

### 3.1 Distribution of the vibration test points

Twenty different important parts of the HMCVT body were picked up as the test points which were mainly distributed near each bearing holes, body cover and side walls. They were distributed evenly on X, Y, and Z axis directions. Among all of these, the first one to the eighth points were distributed mainly on Z axis direction, the ninth to the sixteenth points were distributed mainly on X axis direction and the rest points were on Y axis direction. Figure 1 shows all the points distribution. They were all representative points for the body, the cover and the bracket.

### 3.2 Experiment and results analysis

#### 3.2.1 Test method

The vibration equipment used in this test was VIBXPERT-II, which was produced by the Germany Pulu Fu company. The instrument has 102400 lines and its specific parameters are as follows:

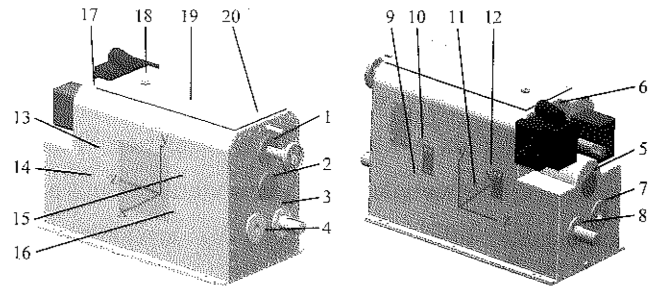


Figure 1 Distribution of the vibration test points

Frequency range: 0.8 Hz-40 KHz

Dynamic (measured / total): 96 dB/136 dB

Sampling frequency: <= 131 KHz / channel

Speed range: RPM 10-200 000 rpm / ±1‰ / ±1 rpm

Displacement: 6000 μm (p-p) / ±1%

Speed: 6000 mm/s (p-p) / ±1%

Acceleration: 6000 m/s$^2$ (p-p) / ±1%

Frequency FFT measurement range: Fmin: 0.5 Hz - 10 Hz, Fmax: 200 Hz-51.2 KHz

The engine named WP6T180E21 was equipped in the HMCVT prototype. Its rated power was 132.5 kW, and rotating range speed was between 750-2200 r/min. To ensure the integrity of the experimental data, a number of gears (corresponding to different speeds) were tested. There were three speeds selected for testing, which were named HM1 (750 r/min), HM2 (1300 r/min), and HM3 (2000 r/min ). The vibration at twenty test points were tested at the three different input speeds. The tractor would work under a big load in both paddy fields and dry lands which were complicated working environment. Therefore, the magnetic powder brake was used and the preliminary loading of the driver output shaft was set to 300 N·m while testing in the section HM2.

The engine speed and the set point were set in the test firstly, then the frequency range of the vibration measurement was adjusted between 10 to 1000 Hz. The sample period T was 0.000061 s, and the frequency f=1/T=1/0.000061=16384 Hz=16.384 kHz. To ensure the accuracy of the test, many test points were selected. Vibrations at the same point, the same level and the same speed sampled were measured at least 3 times. So, 16384 data were acquisited in every data collection, and a total of 540 groups of data were acquisited in each test. The input speed of the engine in the testing experiment was set at the beginning of the test. Then the speed of every set points can be measured and saved in form of .csv while the HMCVT experiment table worked smoothly. Finally, the saved data were transferred to PC and analyzed after all the experiments had been finished.

3.2.2 Data processing and analysis

By using the Mean Filter Method mentioned above, root-mean-square vibration speed after filtering of each point was calculated. Figure 2 showed the frequency domain contrast figure before and after filtering. It can be found that the data larger than 1000 Hz were filtered out after filtering in the figure below. So, the effective data was obtained.

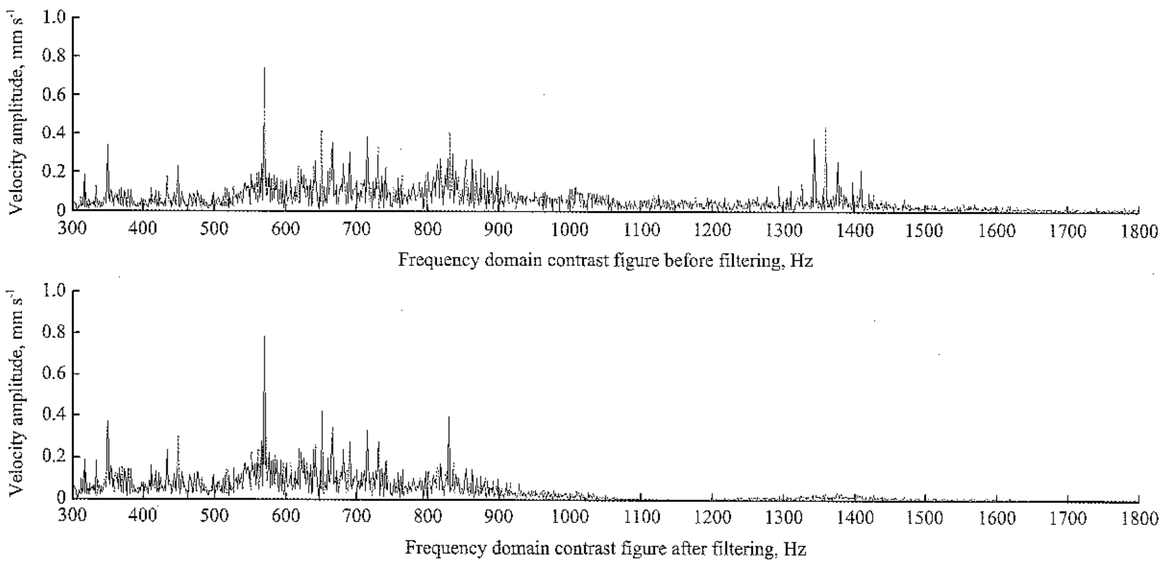


Figure 2 Frequency domain contrast figure before and after filtering

The relationship between time and vibration speed in each point under disparate input speed was measured in three different gears of HM1, HM2 and HM3. In order to judge the vibration intensity in each point, the input speed should be converted to root mean square speed RMS value. Then they were judged whether qualified according to the mechanical rotating vibration standard (SHS 01003-2004). A total of 20 points were selected in the vibration test and each point in the same rank and the same input speed was tested 3 times. The data capacity of each set was 16384 and twenty-seven sets of data were collected in the same point. The speed RMS value of each point can be obtained in various sections under disparate input speed by using Matlab function "result =sqrt(sum(data. ^2)/length(data))". Among them three speed RMS values were available in the same section under the same rotational speed. Then the arithmetic average of the three speed RMS values and the numerical value were obtained as speed RMS value of that point.

The vibration severity of each point under high band was analyzed because of a large amount of data. There were four pointsshould be analyzed in each X, Y, and Z axis direction. Point 13, 14, 15 and 16 were in X axis direction, in HM3. Their speed RMS values were listed in Table 1 and the comparison graph of root mean square value in the point 13, 14, 15, 16 was shown in Figure 3. With the same idea, point 17, 18, 19 and 20 were in Y axis direction, in HM3. Their speed RMS values were listed in Table 2 and the comparison graph of root mean square value was shown in Figure 4. Point 5, 6, 7 and 8 were in Z axis direction, in HM3. Their speed RMS values were listed in Table 3 and the comparison graph of root mean square value was shown in bar chart in Figure 5.

**Table 1 Speed rms value of the test point 13, 14, 15, 16**

| Speed rms, mm/s / r/min | Position | | | |
|---|---|---|---|---|
| | 13 | 14 | 15 | 16 |
| 750 | 2. 9063 | 3. 4828 | 3. 9008 | 2. 3412 |
| 1300 | 3. 9585 | 3. 1637 | 4. 3687 | 3. 1617 |
| 2000 | 4. 1278 | 3. 2859 | 4. 4786 | 2. 3768 |

**Table 2 Speed rms value of the test point 17, 18, 19, 20**

| Speed rms, mm/s / r/min | Position | | | |
|---|---|---|---|---|
| | 17 | 18 | 19 | 20 |
| 750 | 1. 4712 | 1. 6028 | 2. 2856 | 2. 4524 |
| 1300 | 1. 413 | 1. 5636 | 2. 4976 | 2. 3826 |
| 2000 | 1. 2628 | 1. 3315 | 2. 4678 | 2. 3317 |

**Table 3 Speed rms value of the test point 5, 6, 7, 8**

| Speed rms, mm/s \ r/min | Position | | | |
|---|---|---|---|---|
| | 17 | 18 | 19 | 20 |
| 750 | 0.8154 | 2.833 | 0.6552 | 0.7775 |
| 1300 | 1.0425 | 3.3001 | 0.6831 | 0.8486 |
| 2000 | 0.9903 | 3.445 | 0.6614 | 0.9147 |

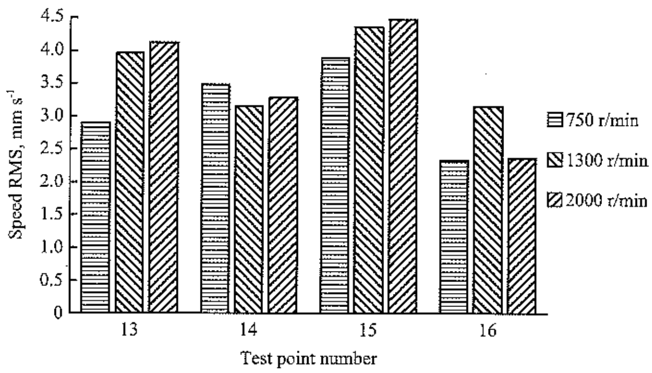


Figure 3 Comparison graph of root mean square value in the point 13, 14, 15, 16

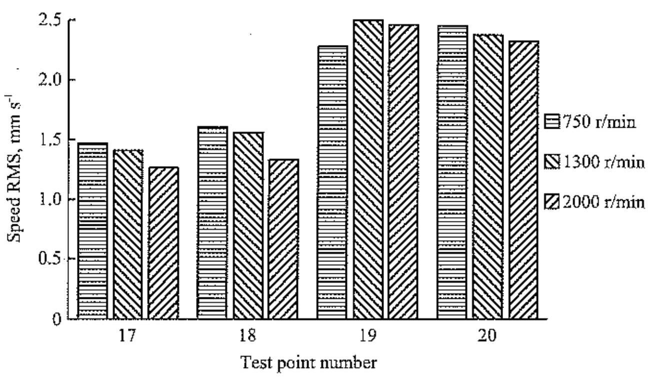


Figure 4 Comparison graph of root mean square value in the point 17, 18, 19, 20

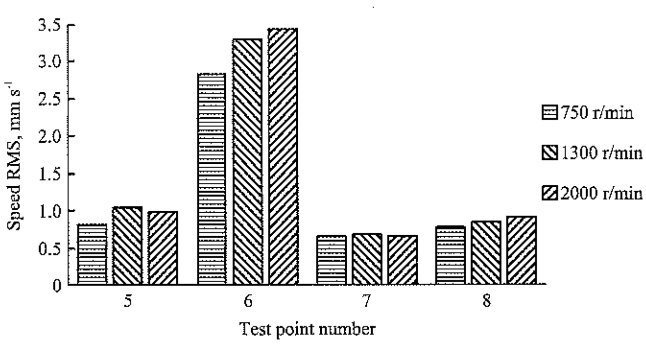


Figure 5 Comparison graph of root mean square value in the point 5, 6, 7, 8

By analyzing Figures 3, 4 and 5, most parts of the gearbox body vibrated in excellent or good situation, while just a few ones vibrated greatly and it should be improved. It also could be found that, the gearbox showed the most severe vibration, while the bearing parts showed medium vibration. Vibration in the cover and the bracket were very small. The vibration velocity at the input and output points of the test points near the shaft bearings were relatively large, while the values of the remaining sections were relatively small. The reason of the vibration speed trend could be concluded by comparing the test results, the construction and transmission route of HMCVT.

Firstly, the HMCVT applied in this research was dual planetary bus bar. The engine input power through input axle, then the power flow was divided into mechanical drive and hydraulic drive, which finally run together by the bus bar. At the same time, the dual planetary was connected by two semi-axises. It supported the whole bus bar and resisted the impact force which was produced in the process of distributaries and confluence with a sliding axle which was fixed on the gearbox body.

Secondly, the gearbox output axis was constituted by two semi-axises. It was output through the two semi-axises firstly, and then output through a long axis. In this way, it expanded the number of the gear pair. Moreover, the existing errors made a larger axial float which may be the reason of more vibration.

Thirdly, the input axle was connected to the engine with a coupling, and the output axle was also connected to magnetic powder brake with the coupling. The different loads offered by magnetic powder brake and the impact force will also cause vibration. So, much serious vibration appeared near the bearing holes.

Fourthly, the bracket of the gearbox was fixed to the rack with the bolt. The amount of the vibration resources was limited near the body cover. Therefore, the vibration speed in the cover and bracket were relatively small.

Finally, the errors produced by the wheel gears manufacturing, the technology assembly, the slight stability and so on may also cause vibration to a certain extent.

## 4 Conclusion

The vibration speed in the important parts of HMCVT was analyzed under the existing experiment platform. According to the analysis results on the vibration speed of the gear box under the different bands and engine speeds, it was found that vibration on gearbox body were the greatest, and then on its bearing parts. The vibration on cover and bracket were the smallest. Also, the existing gearbox body was unitary, and its wheel gears and axles were too huge and complex to assemble. It was not easy for the transmission to be installed, disassembled and maintained.

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