Experimental Study on Torsional Vibration of Engine Crankshaft and Cylinder Block

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Abstract. Engine cylinder block vibration usually does not consider the influence of torsional vibration of crankshaft. Because cylinder block and crankshaft vibrate separately, crankshaft torsional vibration may have a coupling effect on the vibration of the cylinder block, especially when the crankshaft torsional vibration is very large when engine is idling. In order to evaluate the coupling effect, a pilot test program was designed and developed under idle no-load condition. The torsional vibration of the crankshaft comes from the encoder sensor, and the torsional vibration of the cylinder block comes from the calculation of two acceleration sensors arranged on the cylinder block. This paper derives the formula for extracting the torsional vibration signal of the cylinder from two acceleration signals. Data analysis of spectrum and coherence reveal that the torsional of the crankshaft is greater than the cylinder block at the engine 3rd order frequency 35Hz, and the torsional vibration signals of the two have strong coupling at integer multiples of the 0.5th order frequency of the engine in the range of 100Hz that is prone to vibration problems. Through the above tests and data analysis, it is more accurate to consider the influence of crankshaft torsional vibration when studying engine vibration.

1. Introduction

Engine is the main vibration source of various mechanical products, and the vibration generated by it directly affects product reliability and comfort. Therefore, it is of great engineering significance to study the vibration of the engine. Engine vibration is transmitted to other parts through cylinder block. The noise generated by cylinder block vibration also accounts for an important part of engine noise. Therefore, the vibration of cylinder block is an important aspect of engine vibration. In general, when calculating the vibration response of the cylinder block, the coupling between the cylinder block and other parts is ignored. The load on the cylinder block is obtained by the method of multi-body dynamics, and response calculation and vibration prediction are carried out by using the finite element method, and weak parts of the cylinder block are found and modified to carry out the virtual design of low-noise engine [1-10].

The vibration generated by the crankshaft is three-dimensional vibration [11, 12]. Between the crankshaft and the engine block, the force can be transmitted through the combustible gas in the cylinder, and can be transmitted through the bearing of the crankshaft. Therefore, the possibility of
coupling between the two is very high. For many engines, subtle differences in the size of pulleys and flywheels can lead to dramatic changes in engine structure noise and vibration [13].

At present, rare documents about the torsional vibration coupling of cylinder block and crankshaft have been published. The coupling between the crankshaft and the drive system of the front-end accessory is studied only in some literature [14].

Considering the complexity of the theory, this article intends to do a test to find possible coupling relationship between crankshaft and cylinder block. As for test condition, the diesel engine's torsional vibration during idling is relatively large [15]. Therefore, idling condition was selected.

The torsional vibrations of the crankshaft and cylinder block of an engine were obtained by sensors of encoder, laser sensor and accelerometers, and the spectrum and coherence were analysed. The data show that the crankshaft torsional vibration is larger than the cylinder during idle speed, and the crankshaft and cylinder block torsional vibration are strongly coupled at integer multiples of the 0.5th order frequency of the engine. Therefore, it is more accurate to consider the influence of crankshaft torsional vibration when studying engine vibration.

2. Test Plan Design

In order to find the coupling relation through actual test data, the data have to be obtained through synchronous test in idle and no-load condition.

The crankshaft torsional vibration signal is achieved by the encoder mounted on the crankshaft belt pulley [16]. Vibration technology can provide useful information for diesel engine fault detection [17], and the torsional vibration of the cylinder block in this test is achieved by the appropriate calculation of the data of two acceleration sensors installed on the cylinder block. For phase reference, a laser sensor is arranged near the crankshaft belt pulley, that is, a reflective strip is pasted on the pulley. When the crankshaft turns one turn, the laser sensor will generate one impulse voltage signal, as shown in figure 1.

![Figure 1. Testing sensors and measuring points.](image)

According to the plane analysis, there are 3 degrees of freedom, namely, horizontal direction, represented by X, vertical direction, represented by Y, and rotation direction, represented by $\theta$.

The angular acceleration signal of the cylinder block is calculated from the acceleration signals at two points, point A and point B. Schematic diagram of torsional vibration test and calculation is shown in figure 2.
Figure 2. Schematic diagram of torsional vibration test and calculation.

\( \vec{r} \) is the vector from point A to point B, and \( \vec{\epsilon} \) is the angular acceleration vector of the cylinder block, because of their vertical relationship, their norm of vector product is:

\[
| \vec{\epsilon} \times \vec{r} | = | \vec{\epsilon} | | \vec{r} |
\]  
(1)

The magnitude of \( \vec{\epsilon} \) multiplied by the magnitude of \( \vec{r} \) equals the magnitude of the tangent acceleration \( \vec{a}_{BA} \) :

\[
| \vec{\epsilon} | | \vec{r} | = | \vec{a}_{BA} |
\]  
(2)

In the above formula, \( \vec{a}_{BA} \) refers to the relative acceleration from point A to point B, and \( \vec{a}_{BA} \) is its tangential vector which can be obtained through the projection in the tangential direction of the acceleration \( \vec{a}_{BA} \) :

\[
\vec{a}_{BA} \parallel = \vec{a}_{BA} \cdot \sin \alpha
\]  
(3)

Where, \( \alpha \) refer to the angle between \( \vec{a}_{BA} \) and \( \vec{r} \).

The above expression can also be expressed as the vector product of \( \vec{a}_{BA} \) with a unit vector \( \frac{\vec{r}}{|\vec{r}|} \):

\[
\vec{a}_{BA} \parallel = \vec{a}_{BA} \times \frac{\vec{r}}{|\vec{r}|}
\]  
(4)

Combine the above formulas, the following formula can be obtained:

\[
| \vec{\epsilon} | = \frac{| \vec{a}_{BA} \times \vec{r} |}{| \vec{r} |^2}
\]  
(5)

\( \vec{a}_{BA} \) and \( \vec{r} \) are respectively defined as:

\[
\vec{a}_{BA} = \vec{a}_B - \vec{a}_A = \left[ (a_{Bx} - a_{Ax}), (a_{By} - a_{Ay}) \right]
\]  
(6)
\[ r = \left( (r_{bx} - r_{ax}), (r_{by} - r_{ay}) \right) \]  \hspace{1cm} (7)

Where, \( \vec{a}_A \) and \( \vec{a}_B \) refer to the acceleration vector of point A and point B respectively, \( a_{Ax} \) and \( a_{Ay} \) refer to X and Y direction of \( \vec{a}_A \) respectively, \( a_{Bx} \) and \( a_{By} \) refer to X and Y direction of \( \vec{a}_B \) respectively, \( r_{Ax} \) and \( r_{Ay} \) refer to the X and Y coordinates of point A respectively, and \( r_{Bx} \) and \( r_{By} \) refer to the X and Y of point B respectively.

The formula for calculating the calculated angular acceleration of the cylinder is as follows [18, 19]:

\[ \ddot{\theta} = \frac{(a_{Bx} - a_{Ax})(r_{By} - r_{Ay}) - (a_{Bx} - a_{Ax})(r_{Bx} - r_{Ax})}{(r_{Bx} - r_{Ax})^2 + (r_{By} - r_{Ay})^2} \]  \hspace{1cm} (8)

The cylinder block vibrates on three degrees of freedom in the plane, X, Y and \( \theta \). The acceleration sensor is consolidated with the cylinder block, so the measured data contains the part caused by the torsional vibration of the cylinder block and the part caused by the overall vibration signal in the X and Y direction. What we need is to extract the torsional vibration signal. By the calculation of two acceleration differences, signals only due to vibrations in the X and Y directions are eliminated, and the torsional vibration signals are extracted, as shown in equation (8). At the same time, the encoder does not collect vibrations in X and Y directions, so the torsional vibration of the crankshaft and cylinder block is not affected by the overall vibration of the engine in the X and Y directions.

The test object is an engine mounted on the passenger car, and the external accessory belt connected to the engine is completely disconnected, that is, the engine is in independent operation.

The relevant parameters of the engine and test instruments are given in Table 1.

**Table 1. Main parameters of the engine and sensors.**

| Engine/sensors | Parameter(units) | Value |
|----------------|------------------|-------|
| Engine         | Type of fuel     | Diesel |
|                | Cylinder arrangement | in-line |
|                | Number of strokes | 4     |
|                | Number of cylinders × bore diameter (mm) × stroke(mm) | 6×105×130 |
|                | Piston displacement (L) | 6.75L |
|                | Compression ratio | 18:1  |
|                | Rated power (kW) / rotational speed (r/min) | 180/2300 |
| Encoder        | Pulses per revolution, PPR | 100   |
|                | Maximum rotational speed(r/min) | 18000 |
|                | Maximum Frequency \( f_{\text{max1}} \) (kHz) | 100   |
| Laser sensor   | Measuring range (r/min) | 1-250,000 |
|                | Signal output    | TTL(same as the input voltage) |
When PPR value of the encoder is large and the maximum speed pulse frequency of the data acquisition front end is low, the speed may exceed the maximum allowable speed of the entire system. The maximum speed $N_{max}$ by the combination of the encoder and the data acquisition front end is calculated according to formula (9) [20]. After calculation, the test speed did not exceed the value of $N_{max}$.

$$N_{max} = 60\min\left(f_{max1}, f_{max2}\right)/PPR$$  \hspace{1cm} (9)

The sampling frequency was 20480Hz, the frequency resolution was 0.5 Hz, and the window function is hanning window. The time domain data obtained by measurement and calculation are shown in Figure 3.

![Figure 3](image_url)

Figure 3. The time signals obtained through testing and calculation.

3. Test Results and Analysis
When conducting spectrum analysis, the vibration was expressed in the form of vibration speed. With the laser sensor as the reference signal, the obtained time-domain signal can be used to calculate the torsional vibration spectrum of the cylinder block and crankshaft, which are shown in the bode diagram in figure 4.

As can be seen from the figure 4, the torsional vibration of the crankshaft and the cylinder block at the idle speed of 700rpm is mainly reflected in the 35Hz of the third order of the engine. Crankshaft torsional vibration amplitude and phase respectively are 0.7 rad/s, 121°, cylinder block torsional vibration amplitude and phase are 0.059 rad/s, 153°. It can be seen that the crankshaft torsional vibration is larger than the cylinder block, and the amplitude ratio is about 11.9.

![Torsional vibration spectrum of the cylinder block and crankshaft](image.png)

**Figure 4.** Torsional vibration spectrum of the cylinder block and crankshaft in idle condition.

The coherence is utilized to detect the correlation of two signals in frequency domain [21, 22]. The definition of the (squared) ordinary coherence of signal $X_i$ and signal $X_j$ is shown in equation (10), where $\bar{S}_{ij}$ is the average crosspower, $\bar{S}_{ii}$ and $\bar{S}_{jj}$ are the average autopowers. The range of coherence is between 0 and 1, and a high value (close to 1) indicates that the output is almost entirely due to the input.
\[ \gamma_{ij}^2 = \frac{|S_{ij}|^2}{S_{ii} \times S_{jj}} \]  

(10)

The result of the coherence analysis of the torsional vibration signal of the encoder and the torsional vibration signal of the cylinder block is shown in figure 5. At 700rpm, half order frequency is 5.84 Hz. As can be seen from figure 5, in the range of 100Hz that is prone to vibration problems, the coherence coefficients of half order frequency are all within the range of 0.9~1, while other frequencies are significantly lower. This indicates that the two signals have a strong internal connection at half order frequency, that is, the crankshaft has a strong coupling relation with the cylinder block. Therefore, if the coupling effect is not considered, there will be a certain error in the torsional vibration of the cylinder block.

![Figure 5](image_url)  

**Figure 5.** The coherence coefficient of torsional vibration signal of cylinder block and crankshaft.

![Figure 6](image_url)  

**Figure 6.** Change of the crankshaft and cylinder block third order of torsional vibration spectrum when the speed increases.
Figure 6 shows the third order of torsional vibration spectrum within a commonly used speed range of 700-1600rpm. It can be seen that, when the speed increases, the torsional vibration of the engine crankshaft and the cylinder block changes, in which the torsional vibration of the cylinder block steadily decreases, while the torsional vibration of the crankshaft has a tendency to decrease while a larger fluctuation occurs.

4. Summary
Taking the signal of laser sensor as reference signal, the torsional vibration of an engine's crankshaft and cylinder block was tested and calculated in two working conditions of idle and no-load condition and rising speed condition, and the spectrum and coherence of the two signals were analyzed. The research conclusions are as follows:

- The torsional vibration of the crankshaft and cylinder block is mainly manifested in the 3rd order 35Hz, and under this condition the crankshaft torsional vibration is larger than the cylinder block, and the amplitude ratio is about 11.9.
- In the range of 100Hz that is prone to vibration problems, the coherence coefficients of integer multiple of the engine's half-order are all within the range of 0.9–1, while other frequencies are significantly lower. This indicates the crankshaft has a strong coupling relation with the cylinder block.
- According to the above analysis, it is more accurate to consider the influence of crankshaft torsional vibration when studying engine vibration.

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