

Whirl of Crankshaft Rear End, Part 2: An L4-Cylinder Diesel Engine

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ABSTRACT

Since the sizes of the flywheel and clutch have been enlarged due to downsizing of diesel engines, the mass and moment of inertia at the crankshaft rear end have increased. Consequently, the serious bending stresses have appeared in the crankshaft rear. This paper describes the characteristics of those serious bending stresses, based on the mechanism for whirl resonance. The whirl resonance is largely impacted by the mass of the flywheel and clutch and by the distance from the crank-journal center of the rear end to the center of gravity of the flywheel and clutch.

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INTRODUCTION

Several researchers reported that for the crankshaft front and rear, the bending stresses caused by whirl resonance express the significant values [1, 2, 3] and thereby the whirl resonance can impose a limit on operating speeds [1]. However, they did not discuss the mechanism for the whirl resonance and the method to prevent the whirl resonance in detail. In this paper, the mechanism for the whirl resonance is described and the method to prevent the whirl resonance is also discussed in detail. The following steps were taken to prove that the serious bending stresses in the crankshaft rear are exerted by the whirl resonance of the crankshaft rear end.

First, from the discussion of the whirl motion for a spinning top rotating with an inclination angle of θ that is the angle between the vertical axis going through the support point of the spinning top and the rotating axis of the spinning top, the authors indicated that the gyroscopic moment makes θ smaller for a forward whirl which takes place in the same direction as the rotation of the spinning top itself, and that the gyroscopic moment makes θ larger for a reverse whirl which takes place in the reverse direction as the rotation of the spinning top itself.

Second, by applying a principle of the whirl motion for the spinning top to the crankshaft rear end and by using the equation expressing the gyroscopic moment, the authors showed that the resonant frequency of the bending stress increases with an increase of the engine speed for the forward whirl, while it decreases with an increase of the engine speed for the reverse whirl.

Third, it was seen that there are two groups, from the relationship between the resonant frequencies and the resonant engine speeds of the measured bending stresses in the crankshaft rear. One is the group that the resonant frequency increases with an increase of the engine speed. The other is the group that the resonant frequency decreases

with an increase of the engine speed. Accordingly, the authors were convinced that the bending stresses are caused by the forward whirl resonance and the reverse one.

Fourth, since the second-order bending stress was the largest, they compared the second-order phase angle for the radial force acting on No.4 crank-pin which is the exciting force for the whirl resonance and the second-order phase angle for the speed fluctuation of the flywheel which causes the fluctuation of the gyroscopic moment. From the comparison of the phase angles, they found that the bending stress exerted by the fluctuation of the gyroscopic moment is added to the bending stress caused by the whirl resonance. In addition, the authors discussed the mechanism of the 2nd-order torsional vibration of the crankshaft for L4-engine, because the 2nd-order speed fluctuation of the flywheel was the largest.

Finally, the method to prevent the whirl resonance was discussed, based on the calculated three-dimensional vibrations of the crankshaft rear using AVL/Excite software.

FUNDAMENTAL OF WHIRL

Whirl of Spinning Top

Figure 1 shows a lampshade-shaped spinning top which rotates with an inclination angle of θ . The gravity force is $\mathbf{mg}$ in Figure 1, where $\mathbf{m}$ is the mass of the spinning top and $\mathbf{g}$ the gravity acceleration. The direction of rotation of the spinning top itself is counterclockwise when viewed from the upper so that the angular-momentum vector is as shown in Figure 1 by the right-hand rule. The moment $\mathbf{M}_{\text{grav}}$ caused by the gravity force is as shown in Figure 1, so that the vector of the moment $\mathbf{M}_{\text{grav}}$ is perpendicular to the paper into the paper by the right-hand rule. Accordingly, since the angular-momentum vector

whirls in a cone of angle 2θ in the same direction as the rotation of the spinning top itself, the whirl of the spinning top takes place in the same direction as the rotation of the spinning top itself.

A whirl in the same direction as the rotation of a rotor itself is called 'forward whirl'. The gyroscopic moment $\mathbf{M}_{\text{gyro}}$ is as shown in Figure 1 because the absolute value of the moment $\mathbf{M}_{\text{gyro}}$ is equal to that of the moment $\mathbf{M}_{\text{grav}}$ and the direction of the moment $\mathbf{M}_{\text{gyro}}$ is opposite to that of the moment $\mathbf{M}_{\text{grav}}$. Thus since the two moments balance, the spinning top can rotate and whirl without falling down. For the forward whirl, the gyroscopic moment $\mathbf{M}_{\text{gyro}}$ makes θ smaller.

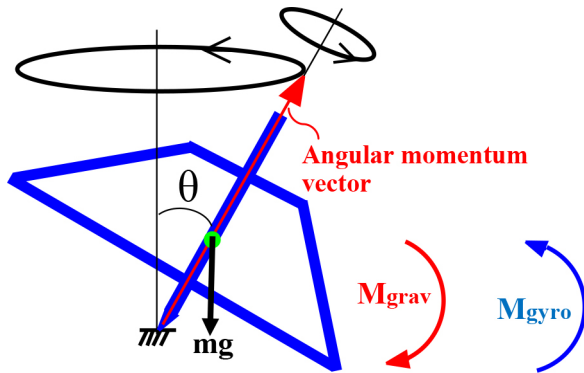


Figure 1. Forward whirl for spinning top

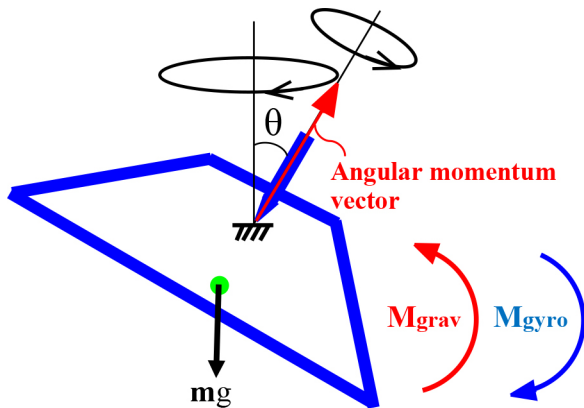


Figure 2. Reverse whirl for spinning top

Figure 2 shows a spinning top in which the center of gravity is situated beneath the support point of the spinning top. The moment $\mathbf{M}_{\text{grav}}$ is as shown in Figure 2 so that the vector of the moment $\mathbf{M}_{\text{grav}}$ is perpendicular to the paper out of the paper by the right-hand rule. Therefore, the whirl takes place in the reverse direction as the rotation of the spinning top itself and the gyroscopic moment $\mathbf{M}_{\text{gyro}}$ is as shown in Figure 2. A whirl in the reverse direction as the rotation of a rotor itself is called 'reverse whirl'. For the reverse whirl, the gyroscopic moment $\mathbf{M}_{\text{gyro}}$ makes θ larger.

Whirl of Crankshaft Rear End

It could be seen from the motion of the spinning top with an inclination angle of θ that, for the forward whirl, a whirl takes place in the same direction as the rotation of the rotor itself and the gyroscopic moment makes θ smaller. On the other hand, a whirl takes

place in the reverse direction as the rotation of the rotor itself and the gyroscopic moment makes θ larger, for the reverse whirl. Figure 3 shows the forward whirl for the crank-journal with flywheel.

The crank-journal rotates with angular speed Ω and the flywheel whirls with angular speed ω about A in a cone of angle 2θ . The directions of the rotation and whirl are counterclockwise when viewed from the right, as shown in Figure 3. Since the gyroscopic moment $\mathbf{M}_{\text{gyro}}$ makes θ smaller for the forward whirl, the moment $\mathbf{M}_{\text{gyro}}$ is as shown in Figure 3. When the moment $\mathbf{M}_{\text{gyro}}$ that makes θ smaller is a minus sign, the moment $\mathbf{M}_{\text{gyro}}$ in Figure 3 is expressed in Equation (1) [4].

$$\mathbf{M}_{\text{gyro}} = -(I_p \Omega \omega - I_d \omega^2) \theta \quad (1)$$

Where I_p is the inertia moment of the flywheel about the X axis, I_d the inertia moment of the flywheel about the Z axis.

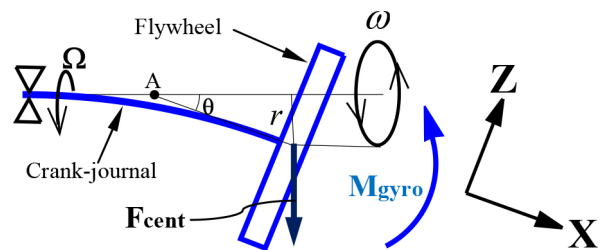


Figure 3. Forward whirl for crank-journal with flywheel

The angular speed of the whirl ω is expressed in Equation (2) by using the angular speed of the crank-journal Ω and harmonic order n for the whirl. The gyroscopic moment $\mathbf{M}_{\text{gyro}}$ is expressed in Equation (3) from Equations (1) and (2). Besides the moment $\mathbf{M}_{\text{gyro}}$, there is a centrifugal force $\mathbf{F}_{\text{cent}}$ acting on the flywheel as shown in Figure 3. The force $\mathbf{F}_{\text{cent}}$ is expressed in Equation (4).

$$\omega = n\Omega \quad (2)$$

$$\mathbf{M}_{\text{gyro}} = n\theta(nI_d - I_p)\Omega^2 \quad (3)$$

$$\mathbf{F}_{\text{cent}} = mr(n\Omega)^2 \quad (4)$$

Where m is the mass of the flywheel and r is the radius of the whirl.

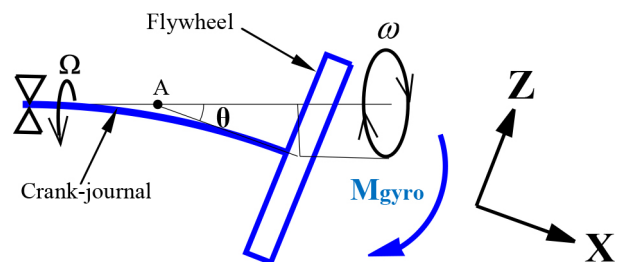


Figure 4. Reverse whirl for crank-journal with flywheel

Figure 4 shows the reverse whirl for the crank-journal with flywheel. The reverse whirl takes place in the reverse direction as the rotation of the crank-journal as shown in Figure 4. The gyroscopic moment M_{gyro} makes θ larger for the reverse whirl so that the moment M_{gyro} is as shown in Figure 4. There is also a centrifugal force F_{cent} acting on the flywheel as shown in Figure 3 for the reverse whirl.

A whirl motion for a crank-journal with flywheel is shown in Figure 5. The direction of rotation of the crank-journal in Figure 5 is counterclockwise when viewed from the rear of the engine. Therefore, Figure 5 shows the reverse whirl.

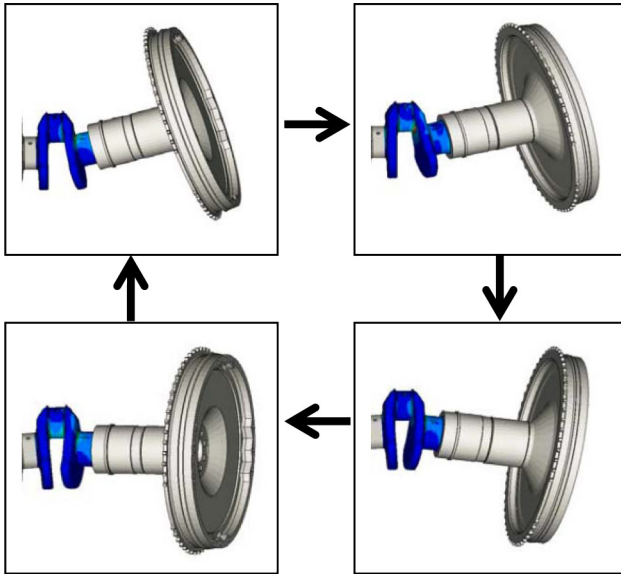


Figure 5. Whirl motion for crank-journal with flywheel

From Equation (3), it is seen that the gyroscopic moment M_{gyro} increases with an increase of the engine speed because the moment M_{gyro} is proportional to the square of the crank-journal speed Ω . Since the gyroscopic moment M_{gyro} for the forward whirl makes θ in Figure 3 smaller, the bending stiffness of the crankshaft rear can be higher by the moment M_{gyro} . Consequently, it is predictable that the bending resonant frequency, i.e., the resonant frequency of the whirl increases with an increase of the engine speed for the forward whirl. On the other hand, the resonant frequency of the whirl decreases with an increase of the engine speed for the reverse whirl.

From Equations (3) and (4), it is considered that the gyroscopic moment and centrifugal force fluctuate when the engine speed fluctuates so that the fluctuations of the moment and force cause the fluctuation of the bending stress in the crankshaft rear. Therefore, it is predictable that the significant bending stress in the crankshaft rear occurs when the resonant engine speed of the whirl coincides with that of a torsional vibration of the crankshaft.

EXPERIMENTS

The strain gauges were mounted on the fillets of the crank-pin and crank-journal, to measure the bending stress. The lead wires of the strain gauges were routed through the drill holes in the crankshaft to

the slip ring, and then the gauge signals were taken out to the front end of the crankshaft [5]. The bending stress, cylinder pressure and engine speed were measured at a full load speed of every 50 rpm.

Engine Specifications

Table 1 shows the engine specifications used for this study.

Table 1. Engine specifications

Engine type	4-stroke, turbo-charged diesel
Cylinder layout	4 cylinders in line
Bore x Stroke	$\phi 95.4 \times 104.9$ mm
Displacement	2.999 ℓ
Firing order	1-3-4-2
Maximum power	120 kW at 3600 rpm

Bending Stress in Crankshaft

The measurement locations of the bending stresses were the front fillet of No.4 crank-pin (hereinafter referred to as '4PF'), the rear fillet of No.4 crank-pin (hereinafter referred to as '4PR') and the front fillet of No.5 crank-journal (hereinafter referred to as '5JF'), as shown in Figure 6.

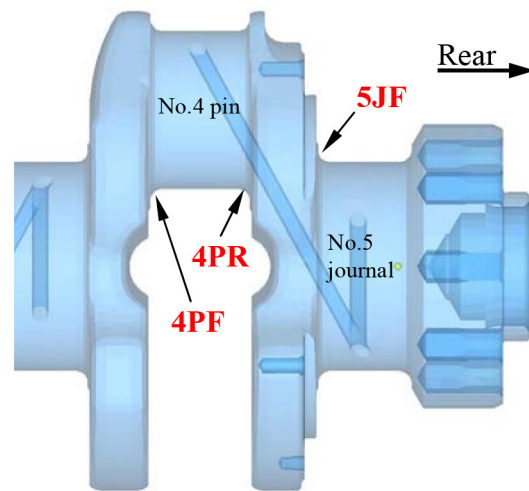


Figure 6. Measurement locations of bending stress

Figures 7, 8 and 9 show the measurement results of the bending stresses in 4PR, 5JF and 4PF. The 2nd, 3rd and 4th orders in Figures 7, 8 and 9 are the order components of the dominant peaks in 4PR. The 5th-order components are added in Figures 7, 8 and 9 because two peaks can be clearly distinguished for the 5th-order component in 4PR.

From Figures 7, 8 and 9, it is predictable that the mode of bending vibration at each resonant engine speed is an open-close mode of the webs, as shown in Figure 10. In the following, the authors focus on the bending stresses in the 4PR that are the largest in all locations.