Dynamic Coupling Characteristics of the Crankshaft System

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Abstract. The nonlinear dynamic model of the marine diesel crankshaft system with a propeller and 6 cranks is established, in which the variable moment of inertia of the linkage and the piston, coupling effect between torsional and axial vibration, the actuating force applied on the piston, the actuating torque and force applied on the propeller is included. By numeric simulation, the dynamic response of the system to initial displacement and initial speed, variable moment of inertia, the pressure applied on the piston by combustion gas, the torque and the axial force applied on the propeller by fluid is researched respectively. According to the research results, the variable moment of inertia and coupling effect between torsional and axial vibration are the fundamental reason for nonlinear vibration. Different actuating factors can not only result in different frequency components of the response, but make the same frequency component have different vibration amplitude.

Introduction

In order to improve the efficiency of the marine diesel engine with large power and low speed, its stroke and length of the crank is longer obviously than the length of other engines, which results in lower stiffness in the torsional and axial direction of the crankshaft system, but its bending stiffness is enhanced. Therefore, when the crankshaft is connected with a propeller, torsional, axial and coupled vibration caused by the torque and the force applied on the propeller and by the pressure applied on the piston is the fundamental behavior.

In the research on coupled torsional and axial vibration, the phenomenon of coupled torsional and axial vibration is not only explained by Li, but its principle is also studied by means of theoretical and testing method [1-3]. In order to establish coupled torsional and axial vibration model, Zhang employed equivalent coupling stiffness, equivalent acceleration and speed coefficients [4]. According to the characteristics of the modern ship’s crankshaft with long stroke and lower axial stiffness, Ying studied coupled vibration model, examples and vibration absorption method. His model is frequently used as the later Ref. [5-7]. Over the years, in order to economize energy, the marine diesel engine with long stroke has taken great progress, therefore more attention is paid to coupled torsional and axial vibration [8-10].

Because there is not an ideal mathematical method, the dynamic model involved in above research is a linear model under the most conditions, and a few nonlinear dynamic models are simplified greatly. In the paper, the marine diesel crankshaft 4-6S60MC-C is used as an object. In the case of the consideration of a propeller, variable moment of inertia of the linkage and the piston, and coupling effect between torsional and axial vibration, the nonlinear dynamic model of the system will be established. The response of the marine diesel engine crankshaft system
with a propeller to all kinds of actuating factors will be studied in order to reveal its dynamic characteristics.

**Coupled Torsional and Axial Vibration Model**

In terms of kinetics of the diesel engine, the moment of inertia of the crank and the linkage mechanism can be approximated to as follows.

\[
I(\omega t + \phi) = I_0 \left[ 1 - \frac{r}{l} \cos 2(\omega t + \phi) \right].
\]  

(1)

\[
I_0 = I_A + \frac{1}{2} \left( m_B + m_l l_A / l \right) r.
\]  

(2)

In Eq. 1, \( r \) is the radius of the crank, \( l \) is the length of the linkage, \( \omega \) is the speed of the crankshaft, \( t \) is time, \( \omega t + \phi \) is the angle between the crank and moving direction of the piston, \( \phi \) is the initial phase, \( m_B \) is the mass of the piston, \( m_l \) is the mass of the linkage, \( l_A \) is the distance from the linkage centre of the mass to centre of the linkage journal, and \( I_A \) is the moment of inertia of the crank and the equivalent mass of the linkage about rotating centre.

If \( k_{x} \) is supposed to be the axial stiffness of the unit crank system. According to Ref. [8], the pressure applied on the piston is transmitted to the linkage journal through the linkage, by which the equivalent axial force is caused.

\[
P_x = k_{x} \frac{r P f_{p}^2}{8 EI}.
\]  

(3)

In Eq. 2, \( l_p \) is the length of the crank pin, \( EI \) is the bending stiffness of the crank pin, and \( P_r \) is the radial force applied on the linkage journal.

A crankshaft system with a propeller and 6 cranks is shown in Fig. 1. The lumped method is used to establish the dynamic model. The mass and moment of inertia is simplified and added on the centre of the bearing journals. The model is used to study the relative torsional vibration and the relative axial vibration of the propeller and the mass plate. The centre of the bearing between the propeller and the crank is used as a boundary.

![Figure 1. Model of the crankshaft system with a propeller and 6 cranks.](image-url)
Because moment of inertia of the system varies with the phase angle of the crankshaft, and the axial vibration and the torsional vibration are coupled, and the nonlinear function appears in the elastic force of the dynamic equation, it is a strong nonlinear and non autonomous system. Because there is not an ideal mathematical method, the governing equation is only solved by means of numerical method, and its analytical formulas can not be got. The governing equation of the system is expressed as matrix form as follows.

\[ M\ddot{X} + C\dot{X} + KX = F. \]  

In order to make the inertia force and moment of the crankshaft balanced by itself, the phase difference among the 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} crank, among the 4\textsuperscript{th}, 5\textsuperscript{th} and 6\textsuperscript{th} crank is 120°, the phase difference between the 3\textsuperscript{rd} and 4\textsuperscript{th} crank is 60°. When the diesel engine with 6 cranks operates, there is phase difference among the force applied on every piston.

**Model Response Analysis**

**Response to Variable Moment of Inertia**

Except variable moment of inertia, other actuating factors are not exist, i.e., the actuating force \( F = 0 \) at the right side of equation (4). Because there are not torsional actuating factors, and initial speed and initial displacement are also equal to zero, the torsional vibration does not appear, and its response is equal to zero. The amplitude of the torsional vibration is actually zero, but the amplitude of the axial vibration is not zero. The frequency spectra are shown in Fig. 2. In the frequency spectra of the axial vibration, fundamental frequency component and 6 times frequency component appear and their amplitude is large. Although 43 times frequency component is also appear, but its amplitude is very small.

Fig. 2 denotes that the same frequency component of the axial vibration of the crankshaft can not only be aroused, but other frequency components can also be aroused by the inertia force caused by the reciprocating movement of the piston and the translation of the linkage. If the initial torsional state of the crankshaft is not disturbed, and any torsional actuating factor is not applied, the torsional vibration is not aroused. But this phenomenon can not appear actually, because all kinds of actuating factors always exist in practice.

![Figure 2. Frequency spectra of the response to variable moment of inertia.](image-url)
Response to Initial Displacement and Initial Speed

In this case, the actuating torque and the force caused by combustion gas, applied on the piston, are zero, and the actuating force caused by fluid, applied on the propeller, is zero too. When initial displacement and initial speed exist, the time history of the system is shown in Fig. 3, and the frequency spectra corresponding to the time history are shown in Fig. 4. $\beta_1$, $\beta_2$, $y_1$ and $y_2$ are respectively the time history of the relative torsional and the axial vibration displacement between the propeller and the 1st crank, between the 1st and 2nd crank.

If Fig. 4 is compared with Fig. 2, it is found that, because of the influence of initial displacement and initial speed, although there is only variable moment of inertia, the torsional vibration is caused by coupling effect between torsional and axial vibration. According to the frequency spectra, the torsional vibration is not periodically, but is obviously gust characteristics. The fundamental frequency component and 6 times frequency component still appear in the axial dynamic response, but 13 times and 20 times frequency components are new components. The phenomenon means that the influence of initial displacement and initial speed on the dynamic response can not be neglected. Initial displacement and initial speed make the vibration amplitude of the fundamental frequency component descended, and make the vibration amplitude of 6 times frequency component ascended.

Because the frequency components of the system are changed by initial displacement and initial speed, the vibration energy corresponding to each frequency is redistributed. The energy of the axial vibration decreases, therefore the amplitude of the fundamental frequency component of the axial vibration descends obviously.

Figure 3. Time history of the response to initial displacement and initial speed.

Response to the Pressure of Combustion Gas

Initial displacement and initial speed of the system are equal to zero. The fluid force applied on the propeller is also equal to zero. The actuating torque and the force caused by combustion gas exist only. The frequency spectra of the system response to the actuating torque and the force caused by combustion gas are shown in Fig. 5. In this case, because the variable pressure applied on the piston can arouse the torsional vibration, even if initial displacement and initial
speed are equal to zero, the relative torsional angle between any two cranks is zero, therefore coupled torsional and axial vibration is caused.

![Frequency spectra of the response to initial displacement and initial speed.](image1)

![Frequency spectra of the response to pressure of combustion gas.](image2)

In the frequency spectra of the system, there are fundamental frequency component, 2 times frequency component, 6 times frequency component and 20 times frequency component. If Fig. 5 is compared with Fig 2 and Fig. 4, it is found that, in the frequency response of the relative torsional vibration between the propeller and the 1st crank, the amplitude of 2 times frequency component is obviously increased and is larger than the amplitude of other frequency components. In the frequency response of the relative axial vibration between the propeller and the 1st crank, the fundamental frequency component is obviously decreased, and 6 times frequency component is increased appreciably, and 20 times frequency component is new. This phenomenon denotes that the dynamic response of the system to different actuating factors is different from each other.
Summary

(1) The variable moment of inertia and coupling effect between torsional and axial vibration are the fundamental reason for nonlinear vibration. Even if there is not any outer actuating factor, the variable moment of inertia makes the system vibrate.
(2) Although the dynamic characteristics of the system is not affected obviously by initial displacement and initial speed, but the influence is not neglected.
(3) The different actuating factors can not only cause different frequency components, but can also make the amplitude of the same frequency component changed.

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References


