Abstract

For improving the reliability of main bearing in large 2-stroke marine diesel engine, it is indispensable to grasp the journal movement behavior in main bearing with high accuracy. We have studied to disclose the journal movement behavior. Firstly, the journal movements of actual engines were measured. The journal center locus and the journal tilting angle were clarified. Secondly, a theoretical calculation model has been developed in order to simulate the journal movement behavior under uneven alignment between two adjacent main bearings. For confirming the validity of the model, calculated results were compared with measured results. The model was proved effective to simulate the journal movement in high accuracy. At last, by indicating an actual bedplate deflection owing to the loading of a vessel, the calculated journal movement results under the uneven alignment is compared with measured results. As the results, the developed model is able to simulate the journal movement under the uneven alignment. As mentioned above, the model was proved effective to simulate the journal movement with high accuracy. The developed simulation technique of journal movement behavior has been applied in practical machinery design for high reliability.

1. Introduction

Recent large 2-stroke marine diesel engine has been developed for more powerful, longer strokes, lighter weight and in a more compact size. As for main bearing of the diesel engine, the higher degree of specifications is required. A careful adjustment of alignment between crankshaft and main bearings is also needed more strictly than before.

When replying the demands and improving the reliability of the main bearing, it is vital to make better techniques both to grasp the journal movement behavior in main bearing and to keep the
alignment under optimum conditions free from damage.

This discussion provides a theoretical calculation model in order to simulate the journal movement behavior \(^{(1)}\). Alternatively, journal movement measurements were also carried out at typical commercial engine \(^{(2)}\). The journal center locus as well as journal tilting angle was clarified. By comparing the calculated results with the measured results, the validity of the theoretical model is confirmed. Furthermore, for the quality control of engine installation on a vessel, a method of determining the optimum alignment in bearing height has been developed by use of service experiences and results \(^{(3)}\).

In this paper, the technology for simulation of journal movement in main bearing is described with comparison between calculated results and measured results. Furthermore, by indicating an actual engine bedplate deformation under various vessel conditions, an influence of alignment on dynamic journal movement is discussed.

2. Measurement in Actual Engine

2.1 Journal Center Locus and Journal Tilting Angle

Fluctuation load due to gas pressure and inertia force of cylinder and crank throw acts on main bearing of engine. It leads to journal tilt and bearing deformation. Journal tilting causes edge contact between journal and bearing. Figure 1 shows the schematic image of journal center and journal tilting angle. These items are measured in this study.

2.2 Main Bearing for measurement

Figure 2 shows the main bearing for measurement. Journal movement behavior is detected by four
gap sensors fitted in an upper part of bearing. Thermocouples are used for compensation of the gap sensors.

Journal center locus during cycles is measured as an eccentricity from bearing center to journal center. Journal center is calculated by outputs of 2 gap sensors buried in along with the same circumference both fore and aft sides of bearing width (the combination of the sensors are G1-G2 or G3-G4 as shown in figure 2). In calculation, it is assumed that the distance between the gap sensor position and the center of the bearing is invariable and that there is no bearing deformation. As the results of the two journal center points, relative journal tilting angle between the journal and the bearing is calculated.

2.3 Specification of Engine and Operating Condition

A seven-cylinder marine diesel engine (Hitachi MAN B&W 7S50MC Mk.6) was selected for this measurement. The measurement was carried out during the delivery test operations. The operating condition was 100% engine load based on propeller law characteristics.

2.4 Measurement Bearing Position in Engine

Figure 3 shows the installed position of measurement main bearing. The measurement bearings were installed in No.1, No.2, No.4 and No.8 bearing. The reasons why these are selected are as follows. On the bearings installed fore and aft end of the engine, bearing failure has occurred more frequent than other bearings. The feature of the No.4 bearing is influenced by the sequential combustion, so the loading for the bearing is severe.
2.5 Measurement Results

Figure 4 shows the journal center locus in each main bearing for measurement on full load operation. A plotted point on polar diagram is equivalent with an eccentricity from bearing center to journal center. The figures are view from aft end of engine. Since two journal center points both at fore side and at aft side of the bearing are measured at the same time by this measurement, the both loci are plotted. When measured each journal center traces almost the same locus during 9 to 10 cycles, a locus during only one cycle is plotted. The plotted values are crank angle assuming that the top dead center of No.1 cylinder is 0 deg.

Each feature of journal movement behavior is discussed as follows.

2.5.1 No.1 Main Bearing

As shown in figure 4(a), journal in No.1 bearing moves widely along the lower part of the bearing between starboard and port side. The fore end journal reaches the upper bearing port side for a short period. However, journal center locus moves always in lower part of the bearing throughout cycles.

2.5.2 No.2 Main Bearing

As shown in figure 4(b), journal center locus in No.2 bearing is smaller than the locus in No.1 bearing. The journal moves near the bottom of the bearing.

2.5.3 No.4 Main Bearing

As shown in figure 4(c), journal in No.4 bearing moves widely along the lower part of the bearing between starboard and port side. Eccentricity is larger during 330 deg to 360 (0) deg and near 150 deg. On the other hand, the eccentricity is smaller at 206 deg and 257 deg of crank angle, where those angles are the combustion of No.4 and No.3 cylinder, respectively.

2.5.4 No.8 Main Bearing

As shown in figure 4(d), journal in No.8 bearing moves circular along the bearing clearance. Only at 51 deg of crank angle, combustion of No.7 cylinder influences on the locus.

As the results, journal movement behavior has large variety in each main bearing. A theoretical
calculation model that is able to simulate journal movement behavior is described as follow section.

3. Theoretical Calculation of Journal Behavior

3.1 Theoretical Calculation Model

Figure 5 shows the schematic model of theoretical calculation in order to simulate journal movement behavior. The full model consists of engine and propulsion shaft system on a vessel. The following items are deliberated and examined for developing the model.

(1) Crankshaft Figure 5 shows the schematic model of crankshaft. To simplify the calculation, crankshaft is assumed as a multiple connection of straight beam. Stiffness of crankshaft can be calculated by approximate formula with only principal dimension of crankshaft.

Deformation of crankshaft due to torsional moment is taken into consideration in this model. The relation between deformation and torsional moment is also approximately formulated by calculating
the torsion of crankpin and deformation of crank arm.

(2) Bearing support As shown in figure 5, bearing support is modeled by spring with both transversal and rotational stiffness. The stiffness is determined by finite element analysis results. An initial bearing height is the relative height against standard design height.

(3) Lubrication of bearing In order to calculate journal center locus in bearing, mobility method is used for approximate solution of the Reynolds equation. Journal center locus and maximum oil film pressure is able to be calculated in a short calculation time.

(4) External force on crankshaft The forces acting on the crankshaft are as follows: (a) Centrifugal force of crank throw, (b) Inertia force of reciprocating mass, (c) Centrifugal force of rotating mass, (d) Gas pressure force, (e) Weight of shaft.

Fig. 5 Schematic model of dynamic journal movement calculation

3.2 Procedure for Theoretical Calculation

In order to calculate journal tilting angle and bearing load, the series of connected beam model is solved by the use of transfer matrix method. Four components of a state vector, which are deflection, angle of deflection, moment and shearing force at each bearing and at the middle of each crank throw, are calculated by considering the boundary conditions on calculation model. In this calculation at the middle point of each crank throw and at each main bearing, the following methods are introduced.

At the middle point of each crank throw, a torsional deformation of a torque is replaced as a jumped deformation. The deformation acts on 90 degrees forward against rotating direction of crank arm.
External forces as shearing force are also added at the point.

In each main bearing, sum of a relative bearing height and journal eccentricity is translated to a shearing force by multiplying a stiffness of a bearing.

In time loop step, crankshaft distortion is calculated beforehand, and then bearing load and journal tilting angle are calculated by transfer matrix method. Based on the bearing load results, the eccentricity of journal is calculated by mobility method. Until the deviation of eccentricity between at 0 deg and at 360 deg of crank angle is less than the convergence criterion, this calculation is repeated. Usually, a calculation time is only a few seconds in each bearing.

The validity of the model is confirmed by comparing calculated results and measured results.

### 3.3 Comparison of Calculated Results with Measured Results

#### 3.3.1 Journal Center loci

Figure 6 shows the calculated and the measured results of journal center loci. A frame of reference represents a view from aft-ward in the same way as figure 4. The measured result is the average of the locus at fore side and aft side of bearing by referring to figure 6(a). The calculated journal locus is equivalent to the locus in the middle of bearing width.

The horizontal eccentricity of measured result is wider than the calculated result. The reason is presumed that the difference of bearing clearance appeared. While the clearance of the theoretical calculation is assumed circumferential symmetry, the one of the measurement bearing is like lemon shape. Nevertheless, except for the difference of clearance, all calculated loci are agreed qualitatively with all measured results. Furthermore, eccentricity position at each crank angle shows good coincidence with calculated results in each corresponding measured locus. As a result, the theoretical simulation is effective to predict a journal position at each crank angle in a main bearing.

#### 3.3.2 Journal Tilting Angle

Figure 7 shows the journal tilting angle for vertical direction of calculated and measured results. Plus (+) sign indicates fore side of journal in a bearing towards top and aft side towards bottom. Horizontal axis is equivalent of 1 cycle. When No.1 piston position is at top dead center (T.D.C.), crank angle equals 0 deg. The number on top of each figure shows each cylinder number at T.D.C.
In the beginning, characteristics of measured result of journal tilting angle are described as follows.

1. No.1 main bearing  
   Journal always tilts with fore side of journal in the bearing towards top and aft side towards bottom during 1 cycle. Maximum tilting angle occurs at T.D.C. of No.1 piston, crank angle 0 deg. Therefore, gas pressure is a great influence on journal tilting.

2. No.2 main bearing  
   Maximum tiling angle in ‘plus’ and ‘minus’ occurs at 0 deg and 103 deg, respectively. Those correspond to T.D.C. of adjacent, No.1 piston and No.2.

3. No.4 main bearing  
   Maximum tilting angle occurs at 206 deg and 257 deg of crank angle, at which combustion of adjacent cylinders is taken place. Maximum tiling angle in ‘plus’ and ‘minus’ occurs sequentially. Therefore, change of journal tilting angle is grater than other journals.

4. No.8 main bearing  
   Journal tends to tilt with fore side of journal in the bearing towards bottom and aft side towards top during 1 cycle. Those are reasoned that combustion force of No.7 cylinder located on fore side of No.8 main bearing acts on journal towards bottom, and that tension force on chain wheel between No.8 bearing and No.9 acts on journal towards top.
Fig. 7 Comparison between measured results of journal tilting angle and calculated results

The tendencies of journal tilting angle of calculated and measured results coincide with each other very well. The results indicate that maximum values are obtained when the adjacent cylinder combustion force become maximum. As a result, this model is effective to simulate the journal tilting behavior and to predict the maximum value for practical use.

4. Actual Engine Bedplate Deformation under Various Vessel Conditions

For applying the journal movement simulator to a commercial engine, it is necessary for the analysis of journal movement behavior to simulate by considering installed main bearing height at static alignment.

4.1 Measurement Method of Engine Bedplate Deformation

An engine bedplate in a hull deflects towards convex deformation (HOG deformation) caused partly by hull deflections due to cargo load, and partly by thermo deformations due to the heating-up of the engine and certain tanks.
Figure 8 shows an image of a measurement method of engine bedplate concave deformation (SAG deformation) at shipyard installation. An engine bedplate deformation is measured with piano wire supported with both fore and aft sides of engine, and represents the direct distance from the bedplate to the piano wire by compensating the natural hanging curve at given tension force of the piano wire.

4.2 Measured Results of Engine Bedplate Deformation

Figure 9 shows an example of bedplate deformation measured results. Vertical axis represents a bedplate deformation against engine bedplate length. Horizontal axis represents bearing supported positions. Nowadays, when installing an engine, SAG of the bedplate is introduced in order to counteract the bedplate HOG deformation. As shown in figure 9, after the installed engine with pre-SAG bedplate deformation, the deformation towards HOG in both ballast and full loaded condition is reduced.

By using the theoretical model that described previous chapter, the dynamical movement of journal is able to be calculated against static alignment by engine bedplate deformation.

An example of both theoretical and measured journal movement results against static alignment is described as follow section.

4.3 Influence of Alignment on Dynamic Journal Movement
Figure 10 shows a result of maximum tilting angle of journal against static alignment of bearing height. Vertical axis represents the maximum value of absolute tilting angle, and horizontal axis does the relative changed value of bearing thickness against standard thickness in the lower part of No.1 main bearing. 0 mm is equivalent to standard thickness. Tested engine is the same engine (Hitachi MAN B&W 7S50MC Mk.6) which is described previous chapter. Simulated results of journal tilting angle of No.1 to No.3 journal are shown in three kinds of lines. Measured results are plotted in two kinds of symbols; ○ sign represents the journal tilting angle in No.1 main bearing, □ sign is in No.2 main bearing. As shown in this figure, simulated results are good coincidence with measured results. As the results, the journal movement simulator is able to calculate the journal behavior under static alignment, and estimate of main bearing installed condition for the maintenance.

5. Conclusions

In this paper, the technology for simulation of journal movement in main bearing is described with comparison between calculated results and measured results. Furthermore, by indicating an actual engine bedplate deformation under various vessel conditions, an influence of alignment on dynamic journal movement is discussed. The summary is as follows:

(1) Journal movement in each main bearing behaves the same locus during each cycle by measurement. Furthermore, the feature of journal movement is different in each main bearing by the influence of firing order.

(2) Theoretical calculated results of journal center loci are qualitatively good coincidence with measured results by actual engine. Especially, it is shown in the relationship between crank angle and eccentric position of journal center.

(3) Theoretical calculation is also able to simulate the complicated journal tilting angle with good correspondence quantitatively.
Journal movement simulator can also successfully predict the journal movement behavior under static alignment due to cargo load of the vessel.

The mentioned above, the theoretical calculation model is an efficient method to grasp the actual journal movement, and to estimate main bearing installed condition for the maintenance.

References


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