Research Report

Visualization and Measurement of Oil Flow in Transparent Oil Passage of Crankshaft

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主軸受油路流れの可視化と油量測定

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Abstract

Minimizing the oil pump capacity of an engine while maintaining reliability is one of the most effective ways of reducing mechanical loss of an engine. Care is required to assure reliability, because an excessively low oil flow may result in poor lubrication that can cause engine components to seize.

The oil flow was observed by visualization and the pressure was measured in two types of oil passage that link main bearings and con-rod bearings, namely, "V type" which has an oil passage in the main journal, and "I type" which does not have this passage. The oil flow in the passage was observed using a CCD camera and a crankshaft made of acrylic resin. The oil flow rate was measured at the same time as the flow was observed. The pressure at which the oil supply failed due to the occurrence of aeration differed with the oil passage types.

Then, the oil flow rate from the oil pump through the main bearing to the con-rod bearing was predicted by using a model that combined a mass-conserved elastohydrodynamic lubrication calculation with an oil flow equation to calculate the effect of the oil supply conditions on aeration. Consequently, the validity of the model was confirmed by attaining a good agreement with the measured oil flow rates, as well as the limit pressure without aeration in the two oil passage types.

Keywords: Engine, Bearing, Visualization, Oil flow, Oil passage, Supply pressure, Aeration, Elastohydrodynamic lubrication model

要　旨

エンジンの信頼性を確保しつつオイルポンプ容量を最小限にすることは，エンジンの機械損失を低減する重要な手法の一つである。しかし，潤滑油不足は焼付きなどの問題に直結するため十分な配慮が必要である。

ここでは，エンジン主軸受からコネクティングロッド大端部軸受（以後，コンロッド軸受）間の油流れ可視化と給油圧の測定を，貫通路のある″V形油路″と貫通路のない″I形油路″の2種類の油路形状について行った。主軸受はアクリル製とし，コンロッド軸受間の油路内流れをCCDカメラで観察した。その結果，エアレーションによってコンロッド軸受への油供給ができなくなる限界給油圧は，油路形状によって異なることがわかった。

そこで，ポンプから主軸受を通してコンロッド軸受に流れる油流量を，質量保存弾性流体潤滑モデルと油路流れの式を連立したモデルを作成し，エアレーションの影響を考慮して予測した。この予測結果からエアレーションを発生しない限界給油圧は油路形状で異なることがわかり，実験と良い相関が得られた。

キーワード　エンジン，軸受，可視化，油流れ，油路，給油圧，エアレーション，弾性流体潤滑モデル

1. Introduction

One of the most effective ways of reducing mechanical losses in an engine is to minimize the capacity of its oil pump. At the same time, however, careful attention must be paid to assure reliability, because oil starvation can directly lead to lubrication problems, such as seizure. Therefore, the oil supply rate should be reduced only with great care. In particular, the connecting rod big-end bearings (hereinafter, the "con-rod bearings") are central to the reliability of the engine, such that several studies have been conducted to examine the lubrication characteristics of these bearings.[1-4)]

Lubricating oil is supplied from the oil pump to the con-rod bearings through a long passage, that is, through the main oil hole, the main bearings, and the oil passages in the crankshaft that rotates at high speed. To prevent bearing seizure, therefore, it is necessary to predict the supply conditions in the long passages of real engines. Also, a well-known problem that must be considered is the aeration that occurs as a result of centrifugal force in the oil passage of the crankshaft.

In this study, aeration was investigated by varying the oil supply pressure and the oil passage type. First, the oil supply rate was measured for a given oil supply pressure, and the oil flow in the oil supply passage was observed. Next, the oil supply rate from the oil pump to the con-rod bearing through the main bearing was predicted using a model that combined the oil passage flow with mass-conserved elasto-hydrodynamic lubrication (EHL).

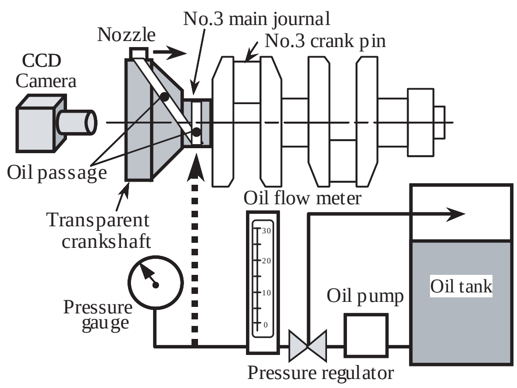
2. Equipment and conditions

2. 1 Test engine

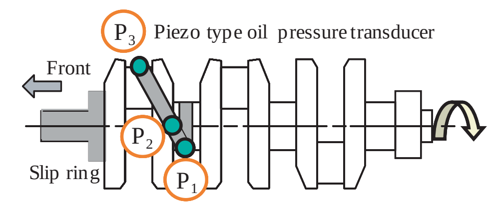
A mass-produced, in-line, four-cylinder, water-cooled, four-cycle engine with a displacement of 1600 cm^3 was used in the experiment. To allow us to observe the oil passage between the main bearing and the con-rod bearing, the reciprocating parts were removed from the No.1 and No.2 cylinders, and the engine was run using only the No.3 and No.4 cylinders. The setup is shown in **Fig. 1**. To observe the oil flow in the oil passage, a transparent acrylic resin part was used to replace the No.3 main bearing. A CCD camera was positioned towards the front of the engine where it could "see" through the transparent part (Fig. 1(a)). A nozzle with an equivalent diameter to the clearance of the con-rod bearing was attached to the end of the oil passage. Specifically, the inner diameter was 1.0 mm, which corresponded to the total area of the bearing clearance of 60 μm. The pressure in the oil passage of the crankshaft shown in Fig. 1(b) was measured at the the main bearing inlet (P1), the shaft center (P2), and at the crankpin outlet (P3). The pressure was measured using piezo-electric type transducers (Kulite XP-700). The signal from the pressure transducers was taken out through a slip ring attached at the position of the No.2 main journal bearing. The oil flow rate in the part being measured was controlled independently, isolated from the original supply system of the engine, and was measured using a volume-type flow meter.

2. 2 Experimental conditions

The experiment was conducted under the operating conditions listed in **Table 1**. Low-viscosity oil was used to simulate high-temperature operation at room temperature. The oil temperature was held at about 30°C to avoid a change in the bearing dimensions (bearing profile, minimum



(a) Crankshaft for visualization in oil passage



(b) Crankshaft for measurement of oil pressure in oil passage

Fig. 1 Equipment.

clearance) and the amount of air dissolved in the oil. Two types of oil passages that are commonly used in main bearings was investigated, shown in **Fig. 2**. Specifically, they are the type with a passage-crossed main journal (Fig. 2(a), hereinafter referred to as the "V type") and the type without one (Fig. 2(b), hereinafter referred to as the "I type").

3. Experimental results

3. 1 Pressure history in the oil passage

Figure 3 shows the measured oil pressure at the main bearing inlet for each oil passage type when the engine was running at 1800 r/min. The "V type" oil passage exhibits an almost constant pressure history throughout one revolution.

On the other hand, the "I type" oil passage exhibits a large pressure change every half-revolution. This result depends on the existence of the oil passage across the main journal, as shown in Fig. 2. From the above results, the oil supply rate through the "I type" oil passage seems to be smaller than that through the "V type" oil passage, because the former is supplied with oil only every half-revolution.

Table 1 Operating conditions.

Engine speed	1000, 1800, 3000 r/min
Oil kinematic viscosity at 30°C	5mm^2/s
Load	Motoring
Water temperature	30 ± 2°C
Oil temperature	30 ± 2°C

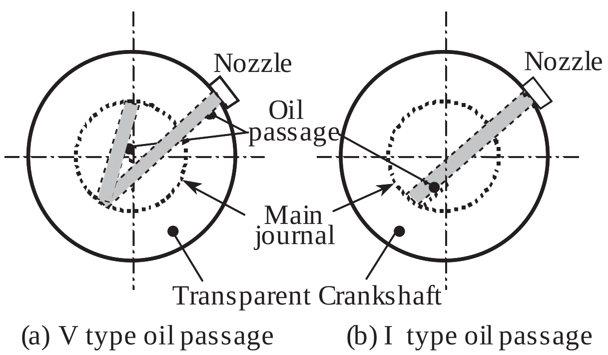


Fig. 2 Oil passage types.

3. 2 Oil passage type and oil flow rate

The oil pressure history seems to indicate that the oil flow rate is greatly influenced by the oil passage type. Therefore, the influence of the oil passage type on the oil flow rate was investigated. **Figure 4** shows a comparison between the oil flow rate as measured at the nozzle, which corresponds to the oil flow rate for the crank pin, through both the "V type" and "I type" oil passages at different supply pressures while the engine was running at 1800 r/min.

The oil flow rate at the nozzle (hereinafter, the "oil flow rate for the crank pin") was calculated as the difference between the oil flow rate measured in the entire oil passage with the nozzle both open and closed. From Fig. 4, the oil flow rate for the crank pin with the "I type" oil passage is smaller than that

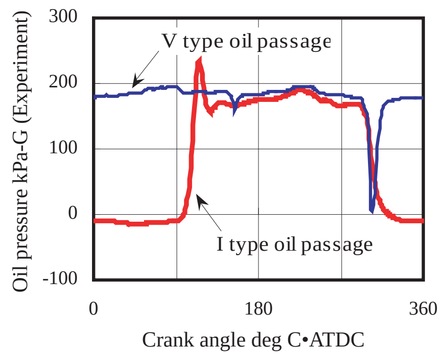


Fig. 3 Comparison of oil supply pressure between V type and I type oil passages (1800 r/min, oil supply pressure = 196 kPa-Gauge, nozzle diameter = 1 mm)

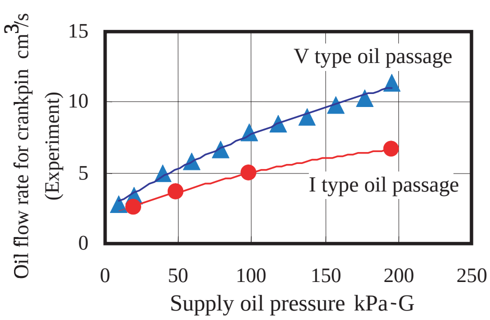


Fig. 4 Comparison of oil flow rate between I type and V type oil passages (1800 r/min, nozzle diameter = 1 mm)

for the "V type" oil passage, despite the oil supply pressure being the same. When the oil supply pressure was reduced, aeration[5] of air bubbles generating in the oil passage was observed. An example of the aeration observed is shown in **Fig. 5**. When the oil supply pressure was lowered even further, the oil supply failed altogether, with no oil being observed in the passages.

Figure 6 compares the oil supply pressures at which aeration occurs for the two types of oil passage. Aeration occurred at a higher supply pressure with the "I type" oil passage than with the "V type" passage. The reason for this seems to be the difference in the oil flow rate that is caused by the existence of the through passage in the main journal, as shown in Fig. 4.

4. Prediction of oil flow rate using lubrication system model

4. 1 Lubrication system model

A lubrication system model was devised. The object part of the model consists of the hole through the main bearing and the oil passage to the con-rod bearing of an actual engine. The model incorporates a mass-conserved EHL model[6, 7] that is used to calculate the oil flow rate from the oil hole to the bearing and an equation for determining the flow in the passage (hereinafter, the "oil passage model").

The former model was created by combining a modification of Elrod's cavitation algorithm with the EHL calculation.[8] The combined model is called the "Lubrication System Model." That is, the EHL calculation is performed for each of the main bearing and the con-rod bearing, and the oil flow rate in the oil passage between these bearings is solved by combining the two calculations. The model is illustrated in **Fig. 7**.

Precise calculation using the bearing dimensions, oil passage dimensions, oil supply pressure and the like as input conditions is very time consuming. Using this model, the oil flow rate for a range of supply pressures for bearings with constant dimensions, to create a data-base of oil flow rates was first calculated. Then, the oil flow rate through each of the oil passages was calculated , followed by

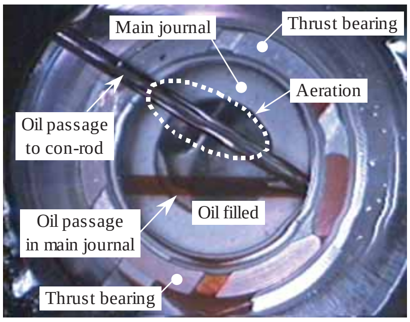


Fig. 5 Aeration in V type oil passage.

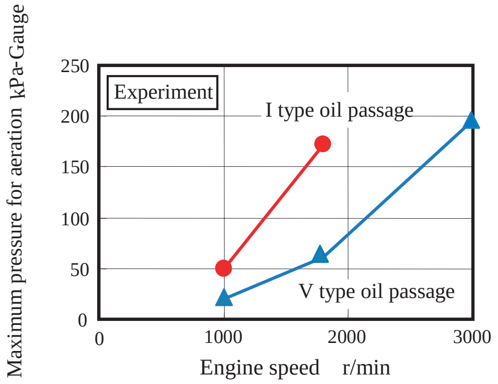


Fig. 6 Difference in aeration limit between I type and V type oil passages (nozzle diameter = 1 mm)

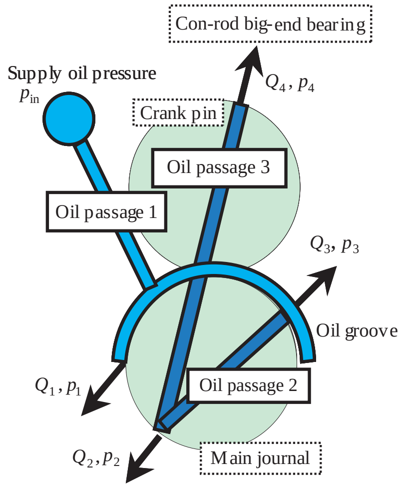


Fig. 7 Lubrication system model.
Oil passage 1 : oil passage from main bearing to main oil hole
Oil passage 2 : oil passage in main journal
Oil passage 3 : oil passage from main bearing to con-rod bearing
Q_1, Q_2, Q_3, Q_4 : oil flow rate
p_1, p_2, p_3, p_4 : oil pressure

the oil supply conditions, by combining the created data-base with the oil passage model.

4. 2 Relationship between experiment and model

4. 2. 1 Pressure history in oil passage

The oil pressure history at each point of the "I type" oil passage was calculated using the oil passage model at a rotational speed of 1800 r/min and a supply pressure of 297 kPa-A (absolute). **Figure 8** compares the calculated results with the results of the experiment. The oil supply pressure measured in the engine was used for the inlet pressure of the main bearing.

The oil pressure history calculated for each position using the oil passage model seems to simulate the experimental results well, except at that position at which the pressure rises rapidly, which corresponds to the instant at which the oil passage to the con-rod bearing aligns with the oil groove of the main bearing.

4. 2. 2 Oil flow rate in oil passage

Figure 9 shows the calculated oil flow rates for each oil passage type and supply pressure for a rotational speed of 1800 r/min and a nozzle diameter of 1.0 mm. The calculated results correspond well with those obtained by experiment for all the supply conditions, thus proving the validity of the model for calculating the oil flow rate.

4. 3 Prediction of aeration

The relationship between the oil supply to the oil passage and aeration was investigated using the lubrication system model. It has been reported that aeration is effected by the amount of air dissolved in the oil.[10] With the model, air cavity was created and aeration occurred when the oil passage pressure was less than 0 kPa-Abs.

Figure 10 shows the calculated oil flow rates with "I type" and "V type" oil passages for different supply pressures. The oil flow rate of the "V type" oil passage increases with the engine rotational speed for all supply pressures (147, 196, and 294

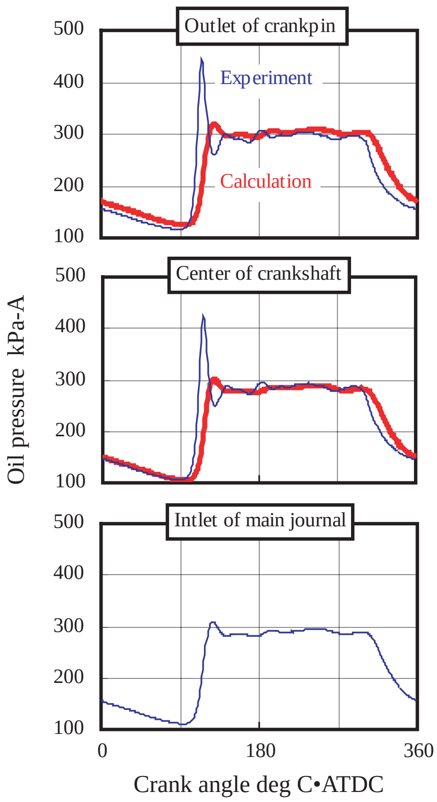


Fig. 8 Comparison of results obtained by experiment and with the oil passage model for a given oil pressure (1800 r/min, I type oil passage).

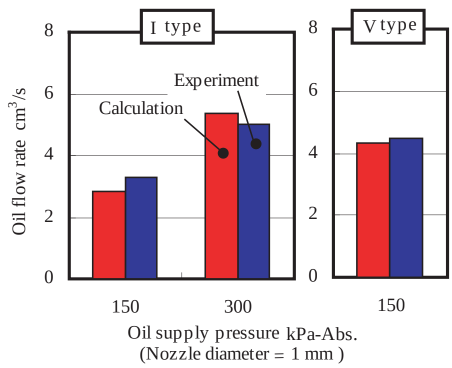


Fig. 9 Comparison between experiment and calculation by the lubrication system model for oil flow rate (1800 r/min).

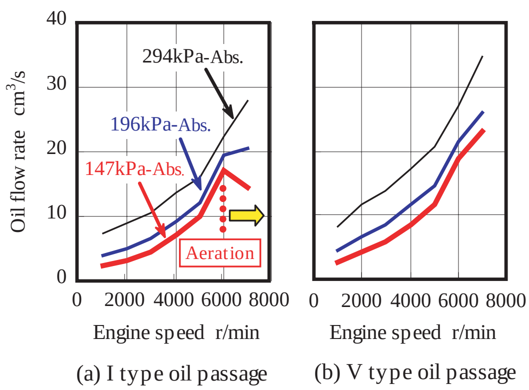


Fig. 10 Relationship between oil flow rate and oil passage type.

kPa-Abs.)(Fig. 10(b)). On the other hand, the oil flow rate of the "I type" oil passage falls at high rotational speeds in excess of 6000 r/min at supply pressures of less than 196 kPa-Abs. (Fig. 10 (a)).

This drop in the oil flow rate seemed to caused by the lower supply pressure failing to fill the oil passages, which we observed with the CCD camera. Then, the degree of cavitation (hereinafter, the "rate of oil filling") generated in the oil passage was calculated in the high-speed region in which different flow rate characteristics appeared for the different oil passage types.

Figure 11 shows the effect of the oil passage type on the rate of oil filling at the journal center (rotation center) of the oil passage in the No.1 main bearing for a range of supply pressures at 7000 r/min.

With the "V type" oil passage, the passage is always filled regardless of the supply pressure. With the "I type" oil passage, on the other hand, the rate of oil filling falls with a reduction in the supply pressure. Thus, the situations in which aeration occurred could be predicted.

5. Conclusion

Based on experiments with the oil passages in an engine crankshaft and predictions using the "lubrication system model", we were able to clarify the following.

(1) For any given oil supply pressure, the oil flow rate in the "I type" oil passage is smaller than that in the "V type" oil passage.

(2) An aeration in the "I type" oil passage first appears at a higher oil pressure than in the "V type" oil passage.

(3) The calculated oil flow rate corresponded well to the measured rate, which proved the validity of the "lubrication system model".

(4) The model predicted that the supply oil pressure with no aeration differed depending on the oil passage type.

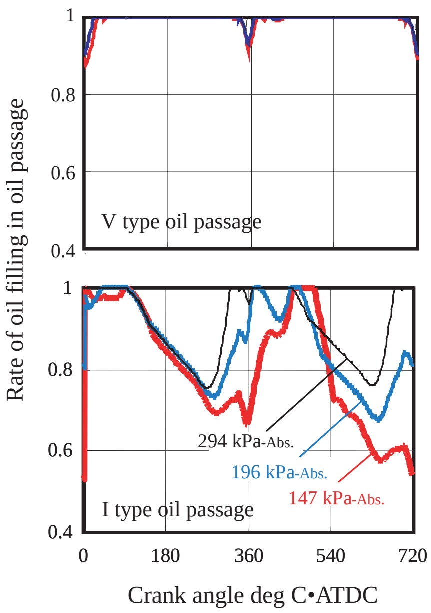


Fig. 11 Effect of oil passage type on aeration (7000 r/min, No.1 main journal).

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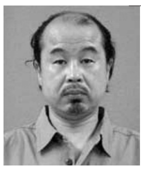

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