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Experiment Study on the Influence of Lubricant Viscosity and Solid Additives on Irregular Cavitation Noise in the Oscillatory Squeeze Film

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Abstract

In view of irregular abnormal cavitation noise in main bearing of engine under the dynamic load from engine spindle, this paper is devoted to finding effective factors that can reduce this cavitation noise. The experiments are carried out in the oscillatory parallel-plate squeeze film test apparatus which can simultaneously collect five kinds of signals including vibration, displacement, sound pressure, force and images of cavitation. The influence of lubricant viscosity and three different solid additives (carbon black, molybdenum disulfide, hexagonal boron nitride) on the cavitation noise were investigated experimentally. The experimental results show that as the viscosity of the lubricants increases, the cavitation area increases significantly, and the cavitation noise is more likely to occur. For eliminating the irregular cavitation noise, three different solid additives were added to the experimental lubricant base oil separately. The results show that after adding molybdenum disulfide, the occurrence of cavitation noise become intense dramatically. And hexagonal boron nitride does not have obviously effect on cavitation noise reduction. However, the cavitation noise reduces prominently after the carbon black is added, and this suppression effect enhances as the carbon black concentration increases. The noise reduction mechanism of carbon black is that the carbon black increases the cavitation nucleus in the lubricant and disperse cavitation, which reduce the chances of connecting with the atmosphere in the process of cavitation collapse and realize the effect of noise suppression.

Keywords

main bearings, engine, irregular noise, cavitation, fluid lubrication, lubricant viscosity, additives

1 Introduction

Engine is the power source for vehicles and also the most complex part. With the progress of automobile NVH (noise, vibration and harshness) technology, the noise level of engine pistons and gears mesh had declined gradually [1]. However, the irregular noise like a typewriter in the main bearing oil film that was originally covered by these noises gradually appeared. Figure 1 shows the location of irregular abnormal noise source for main bearings. It was found that when the engine was in an idling state, the irregular abnormal noise occurred in its main bearings. The noise of engine operating at idle speed is an important noise evaluation criterion for both commercial vehicles and passenger cars [2]. Therefore the noise has attracted the attention of many researchers. Toyota’s engineer Aoyama first publicly studied the main bearing noise of diesel engines [3, 4]. By comparing the theoretical and experimental results, it was found that the abnormal noise of the engine was related to cavitation in the main bearings and the noise occurred when cavitation connected with the atmosphere. It was also found that cutting the annular groove on the bearings which can prevent cavitation from connecting with the atmosphere was an effective way to solve this noise problem. However,
this approach will change the engine structure and reduce the bearing capacity of the main bearing. Kimura [5] used engine simulation analysis software to calculate the load and combined with the Reynolds equation to obtain the influence of a series of parameters such as engine speed, oil film thickness and oil film pressure on noise. The simulation also found that the noise was related to cavitation in oil film of engine, and when the oil temperature was lower than 100°C or the rotation speed was higher than 1500 rpm, there was no noise. However, these conclusions are obtained through simulation and calculation, so further experiments are needed to verify them. In 2018, our team [6] study the relationship between this irregular noise with cavitation by experiments and reduce this noise by changing experimental conditions. But it is not practical for the engine. By adding carbon black into 5W-30 fully synthetic lubricants, this noise was reduced [7]. As a commercial oil, 5W-30 fully synthetic lubricant is added with a lot of additives, which may interfere with the results, and further research is needed.

In fact, the cavitation in oil film of engine was discovered and discussed long time ago [8-10], but the research mainly aimed at the damage of the cavitation to the bearings surface, and did not pay attention to the noise of the cavitation. There are two kinds of cavitation [11-14], gaseous cavitation and vapor cavitation. Gaseous cavitation is a gas that dissolves in the surrounding lubricant. When the pressure drops below atmospheric pressure, the solubility also decreases, so the gas escapes to form cavitation. Vapor cavitation is that when the pressure drops quickly, a part of the lubricants undergoes a phase change and becomes oil vapor. So, the type of the cavitation in the lubricants can be gaseous cavitation, vaporous cavitation, or a combination of both [15].

Lubricants of different viscosities have different abilities to dissolve gases and release gases. Also, under the change of oil film pressure, the ability of lubricants of different viscosities to form vapor cavitation is also different. It was found that the cavitation area decreases in high viscosity lubricants comparing with that in the high viscosity lubricants [16]. However, only lubricating performance and cavitation area of bearings under different viscosities were studied. The relationship between cavitation noise and viscosity of lubricants was not involved. Therefore, it is necessary to study the effects of different lubricant viscosity on cavitation noise.

Solid additives are generally formulated as a colloidal suspension in a solvent to improve heat resistance, increase load resistance, reduce wear, and reduce noise [17]. Common solid lubricants include carbon black (C), molybdenum disulfide (MoS₂), hexagonal boron nitride (hBN), polytetrafluoroethylene powder (PTFE), melamine cyanurate (MCA), etc. Normally, solid lubricants have been added to lubricants as additives for use in harsh lubrication conditions such as high temperatures and high loads [18-24]. However, most researches on solid additives are discussing how to improve the lubrication performance, while few studies the effect of solid additives on reducing cavitation noise. If an effective additive can be found which can not only improve the lubricating properties but also suppress the cavitation noise, it will be of great significance.

The aim of this paper is to study this irregular cavitation noise experimentally by the oscillatory parallel-plate squeeze oil film test apparatus which can simultaneously collect five kinds of signals including vibration, displacement, sound pressure, force and images of cavitation. The influence of lubricant viscosity on the cavitation noise were studied experimentally. And three different solid additives (carbon black, molybdenum disulfide, hexagonal boron nitride) were used to detect whether they had effects on cavitation noise.

2 Test apparatus and experimental method

2.1 Oscillatory parallel-plate squeeze film test apparatus

The main bearing of the engine is in an extremely complicated working condition under the dynamic load of the piston. Meanwhile, noise can also be generated from other parts of the engine and the cavitation itself is an interdisciplinary and complex phenomenon [25, 26], which brings great challenges to the experimental research of main bearing noise of the engine. However, related research shows that the dynamic load plays an important role in the generation and collapse of the cavitation [27]. The oscillatory oil squeeze film experiment is an effective way to study the change of cavitation in dynamic load [28-32]. In fact, Aoyama also conducted oscillatory oil squeeze film experiment to study this irregular noise [4]. As a result, an oscillatory parallel-plate squeeze film test apparatus was designed to better understand the fundamental phenomenon of the irregular abnormal cavitation noise in the main bearing of engine. The schematic view of the apparatus, its photograph and the associated testing system are shown in Figs. 2 and 3.
The squeeze oil film was between two flat horizontal plates, the lower thrust plate (8) made of steel and the upper plate (11) made of transparent K9 optical glass, approximately 25 mm in thickness and 50 mm in diameter. The vibration sensor (9) was mounted on the lower thrust plate which was fixed on the base plate (6). During the experiment, the lower thrust plate was submerged in an oil pool confined by the wall of oil pool (10). The clear image of the oil film passes through the transparent upper plate and is reflected by the mirror (12) placed at 45 degrees, and finally is captured by the high-speed camera (14). An adjustable coupling between the electromagnetic exciter (1) and the movable frame (5) made it possible to set the initial oil film thickness. And the movable frame was driven by the electromagnetic exciter. The force sensor (13) is fixed in the middle of the electromagnetic exciter and movable frame and is used to measure the actual force produced by the exciter. The maximum range of force sensor is ± 450 N. The upper transparent plate was constrained to vertical motion by a system of spring wires (3), one end of which was attached to the movable frame and the other end was attached to the stationary housing. Three displacement sensors (7) were installed on the base plate which was fixed to the stationary housing (2). As shown in Fig. 2, MPA 321 sound pressure sensor with a sensitivity of 42.1 mV/Pa was placed 10 cm away from the source to detect sound in real time. The digital output signal, vibration acceleration signal, force signal and images of cavitation. The data of the vibration sensor, the displacement sensors, the force sensor and the sound pressure sensor are collected by a high-speed synchronous data acquisition card, and this high-speed synchronous data acquisition card ensures the synchronization among these signals. It should be noted that the sound pressure sensor is located at 10 cm of the noise source, and sound travels slowly in the air (340 m/s) compared with electricity, which will cause a certain lag for the sound signal. In the next analysis of this paper, the time axis of the sound pressure signal will subtract the time it takes for the sound to travel through this distance (0.00029 s). The images are collected by the picture acquisition card, so the synchronization of the two systems is critical to the experiment. A trigger program is used to ensure that the two acquisition systems are triggered synchronously. Before experiments, the time difference between the image and the vibration signal has been compared several times by the knockign of the test apparatus to correct the program and finally to realize the synchronous acquisition of the five kinds of signal data.

When noise occurred, the sound pressure, displacement, force, vibration signal and cavitation images acquired synchronously are shown in Fig. 4. It can be seen from Fig. 4 that when noise occurs (point 2), the sound pressure instantaneously increases to a maximum value of 4 Pa, at which time the displacement instantaneously decreases, the vibration increases to a maximum value, and the exciting force suddenly increases. This is because the vibration sensor is mounted on...
the lower thrust plate, and when the noise appears, there is a large sound pressure that causes the vibration of the lower plate. The force suddenly increases while the sound appears, and then quickly drops to the original value. By observing the cavitation images at points 1, 2, and 3 in Fig. 4, it can be seen that the cavitation volume increases and reaches the outside atmosphere, at which time the noise is generated. Then the cavitation gradually disappears, and the sound pressure reduces to a normal value.

After many repeat experiments, it was found that when the noise occurred, the sound pressure was generally greater than 0.5 Pa, as shown in Fig. 5. It could be found that noise occurred irregularly. Noise of different sound pressures has different sound intensities, as shown in Fig. 5, the maximum sound pressure value reaching 2.5 Pa. To make the experiment comparable easily and accurately, sampling point distributions were used to estimate the noise appearance. The sound pressure absolute value is divided into three ranges: 0.5-1 Pa; 1-2 Pa; more than 2 Pa. Only samples with an absolute value larger than 0.5 Pa were calculated. Ratio of the number of sampling points in a specific range was defined by the following equation:

\[
\text{Ratio of the number of sampling points in a specific range} = \frac{\text{The number of sampling points in a specific range}}{\text{Total number of sampling points}}
\]

3 Results and discussion

3.1 Influence of lubricant viscosity

Six different viscosity lubricant base oils are used in the experiment. The detailed viscosity information is shown in Table 2. The experimental conditions are the same as those in Table 1 except for the difference in lubricant. In the experiment, the viscosity has a significant effect on the noise, resulting in different noise phenomena. The experimental results are as follows.

3.1.1 Sound pressure

As shown in Fig. 6, with the increase of lubricant viscosity, the number of cavitation noise appearances increase, which indicates that the higher the viscosity is, the easier cavitation noise will appear. By observing the sound pressure signals of different lubricants, it is found that the noise pressure of the high viscosity lubricants is generally higher than that of the low viscosity lubricants.

However, only the percentage of noise sampling points in the two sound pressure intervals (1-2 Pa and greater than 2 Pa) is analysed in Fig. 6. This is because no cavitation noise occurs even if the sound pressure at the sound pressure sampling point exceeds 0.5 Pa, in the experiment of the low-viscosity lubricant (VG 20 and VG 30), as shown in Fig. 7. This phenomenon only occurs in the VG 20, 32 oil, while the VG 46, 68, 100 and 158 oil are consistent with previous data, when noise occurs. In order to avoid the influence of the sampling point of the sound pressure range of 0.5-1 Pa noise on the experiment, only the noise with the sound pressure in the range of 1-2 Pa and more than 2 Pa was compared in the experiment.

Also, the minimum oil film thickness of different viscosity lubricant base oils is different, as shown in Fig. 8.

This is because in the process of squeeze, the higher lubricant viscosity will provide greater damping effect, thereby increasing the minimum oil film thickness. So the minimum oil film thickness of VG 158 oil is nearly twice than that of VG 20 oil.
3.1.2 Cavitation morphology

Analysis of the relationship between the vibration, displacement, sound pressure, force signals and images of oil film cavitation obtained in the experiment is the main method to study the cavitation problem. So, the cavitation images of different viscosity lubricants are shown in Fig. 9. Since the camera system of the test machine can collect 500 photos per second, this paper selects images of 0.012 s and 0.024 s before the noise occurrence time and 0.012 s after the noise occurrence time. The time when the noise occurs is defined as zero time, so the time at which the cavitation images selected are -0.024 s, -0.012 s, 0 s and 0.012 s. And the selected noise moment is the maximum noise moment in each group of lubricant experiments and the maximum sound pressure was shown in the Fig. 9.

Since there is no noise in the experiment of VG 20 and VG 32 oil, the moment when cavitation rupture is defined as 0 s.

It can be seen from Fig. 9 that as the viscosity of the lubricant increases, the cavitation becomes more obvious and the cavitation area is getting larger especially in VG 158 oil experiment where the cavities cover almost the entire lower plate. It shows that the higher the viscosity is, the larger the cavitation area forms. At 0 s, the time when noise is generated,
it can be clearly seen that the cavitation reaches the outside atmosphere. At this time, the cavitation reaches the outside atmosphere and ruptures instantly, causing obvious noise. There is a significant difference in the size of the cavitation area at the time of 0 s among different viscosity lubricants. It can be concluded that the larger the volume of the cavitation is, the greater the sound pressure value of the noise will be.

On the other hand, it can be clearly seen from the cavitation images of the low viscosity lubricants (VG 20, 32 and 46 oil) that the cavitation almost collapsed within 0.12 s of the noise occurrence time. However, at the same time, the cavitation of the high viscosity lubricants (VG 68, 100 and 158 oil) did not completely collapse. Therefore, it is concluded that as the viscosity increases, the duration of cavitation will be longer.

In addition, two different noises, single cavitation noise and continuous cavitation noise, were observed in the experiment, as shown in Fig. 10. The experimental results show that the continuous cavitation noise is easily observed in the high viscosity lubricants. When continuous noise occurred, the sound pressure was much larger than single noise. And the continuous cavitation noise lasts a period of time. The duration of continuous noise is irregular and can range from a few seconds to tens of seconds. However, the single cavitation noise lasts only 0.1 s or even shorter. Figure 11 (a) is an image when single cavitation noise occurred, and Fig. 11 (b) is an image when continuous cavitation noise occurred.

3.2 Influence of solid additives

The addition of solid additives (Carbon black, hBN, MoS$_2$, etc.) improves the load-carrying ability and results in good anti-wear performance when used in lubricant. Carbon black which was used in the experiments is graphite powder with a carbon content of more than 99.99%. Molybdenum disulfide (MoS$_2$) is a gray-black solid powder with metallic lustre, which has a strong affinity for metal surfaces and can adhere to many metal surfaces. The hexagonal boron nitride (hBN) has a crystal structure similar to that of carbon black and MoS$_2$ and has good lubricity at high temperatures. Therefore, carbon black, MoS$_2$ and hBN are selected as solid additives to study the effects of different solid additives on cavitation noise. The basic properties

![Fig. 10](image-url) Sound pressure signal of two different noise

![Fig. 11](image-url) Images of cavitation when single and continuous noise occurred
Lubricating oil solution configured as described above, which the solid additives concentration in the high-concentration 14 times, so the concentration of each experiment was: out after thorough stirring, and then the process was repeated 5 ml of the prepared high-concentration lubricating oil mixed solution was put into the oil pool. The experiment was carried 5 ml of lubricating oil at 40°C. Experiments conditions are consistent with those in Table 1. In order to solve the problem of uneven dissolution, the lubricating oil mixed solution of high concentration solid additives was first formulated. 0.69 g of solid additives was added to 100 mL of VG 100 oil. After sufficient agitation, the ultrasonic vibrating rod is placed in the mixed solution to prevent aggregation effects between solid additives particles. In each experiment, 5 ml of lubricating oil was taken from the oil pool with a quantitative pipette, and then 5 ml of the prepared high-concentration lubricating oil mixed solution was put into the oil pool. The experiment was carried out after thorough stirring, and then the process was repeated 14 times, so the concentration of each experiment was:

\[
\frac{c_n}{V_{oil}} = 5 \times c_{dense} + (V_{oil} - 5) \times c_{n-1}
\]

Where \(c_n\) is the concentration of solid additives in the \(n\)-th experiment in lubricating oil, the unit is g/mL, \(c_{dense}\) is the solid additives concentration in the high-concentration lubricating oil solution configured as described above, which is \(6.9 \times 10^{-3}\) g/mL, \(V_{oil}\) is the volume of lubricating oil in the oil pool, the value is 222.2 mL. Through the above equation, solid additives concentration in the lubricants can be calculated for each experiment, and the concentrations of the fourteen times experiments are shown in Table 4.

The effect of different solid additives on sound appearance frequency is shown in Fig. 12. It can be seen from Fig. 12 (a) that with the increase of MoS₂ concentration the occurrences of cavitation noise do not decrease but shows an increasing trend. And the Fig. 12 (b) shows that with the increase of hBN concentration the number of occurrences of cavitation noise is fluctuant. So, the hBN does not have obvious effect on cavitation noise reduction. However, the experimental results of the carbon black show a positive reaction. With the increase of the carbon black concentration, the frequency of cavitation noise decreases obviously, and the curve shows a steady downward trend. It has been confirmed that the carbon black has stable and effective noise suppression, and the best noise reduction rate is over 80%.

Figure 13 shows the cavitation images for different additive experiments at an additive concentration of 11.5×10⁻⁴ g/mL. It is found that the area of each bubble becomes larger after the addition of MoS₂ than that without adding additives.

Meanwhile, MoS₂ is very easy to precipitate. As a result, MoS₂ aggregates to form large particles, thereby producing large cavitation, which causes the cavitation to easily connect with the atmosphere and increases the frequency of occurrence of cavitation noise. From the cavitation images of hBN experiments, it shows that hBN has no significant effect on the cavitation. However, after adding carbon black in the experiment, the frequency of cavitation noise decreases significantly with the increase of the concentration of carbon black. The cavitation images of the carbon black experiment show that when the number of bubbles increases, and the area of each bubble becomes significantly smaller.

The effect of carbon black on suppressing cavitation noise should be related to the specific physical structure of its surface. There are many irregular pores on the carbon black surface. Although both MoS₂ and hBN have a similar layered structure to the carbon black, MoS₂ and hBN do not have a porous structure. Some specific sites on a solid surface will have the optimum geometry to promote the growth and appearance of cavitation [7, 33]. Such locations are called nucleation sites. Furthermore, as the pressure decreases, these sites will generate

Table 3 Basic properties of solid additives

<table>
<thead>
<tr>
<th>Project</th>
<th>Carbon black</th>
<th>Molybdenum disulfide</th>
<th>Hexagonal BN</th>
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<tr>
<td>Chemical symbol</td>
<td>C</td>
<td>MoS₂</td>
<td>hBN</td>
</tr>
<tr>
<td>Relative density Kg/m³</td>
<td>2.23-2.25</td>
<td>4.8</td>
<td>2.27</td>
</tr>
<tr>
<td>Moth’s hardness</td>
<td>1-2</td>
<td>1-3</td>
<td>2</td>
</tr>
<tr>
<td>Coefficient of friction (in the atmosphere)</td>
<td>0.05-0.3</td>
<td>0.006-0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>Coefficient of friction (in vacuum)</td>
<td>0.4-1.0</td>
<td>0.001-0.2</td>
<td>0.8</td>
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<tr>
<td>Thermal stability/°C (in the atmosphere)</td>
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<td>350</td>
<td>700</td>
</tr>
<tr>
<td>Thermal stability/°C (in vacuum)</td>
<td>-</td>
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<td>1587</td>
</tr>
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<td>Color</td>
<td>Black</td>
<td>Gray</td>
<td>White</td>
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Table 4 Additive concentration

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Addition volume of suspensions (mL)</th>
<th>Additive concentration (10⁻⁴ g/ml)</th>
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</tr>
<tr>
<td>2</td>
<td>5</td>
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</tr>
<tr>
<td>3</td>
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<td>7</td>
<td>30</td>
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<td>35</td>
<td>10.2</td>
</tr>
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<td>40</td>
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</tr>
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<td>55</td>
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<td>60</td>
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</tr>
<tr>
<td>14</td>
<td>65</td>
<td>17.7</td>
</tr>
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</table>
and release bubbles to the body of lubricants. These nucleation sites increase the cavitation nucleus in the liquid. Under this effect, the formation of cavitation is no longer like a cauliflower spreading out from the center to the outside, but is a process of gathering the bubble groups, as shown in Fig. 13. These bubble groups do not easily aggregate to form large cavitation, which reduces the possibility of cavitation connecting the atmosphere. Therefore, the frequency of occurrence of cavitation noise decrease.

4 Conclusions

In this paper, experiments are conducted to investigate the influence of lubricant viscosity, solid additives on irregular cavitation noise in the oscillatory squeeze film. The obtained results and analysis are as follows:

1) As the viscosity of the lubricants increases, the cavitation noise occurred more frequently. The cavitation area for the high viscosity lubricants is larger than that for low viscosity lubricants. Therefore, the low viscosity lubricants can effectively reduce the occurrence of cavitation noise.

2) The results show the occurrence of cavitation noise become intense dramatically that after adding MoS2. And hBN does not have obvious effect on cavitation noise reduction. However, the cavitation noise reduces prominently after the carbon black is added, and this suppression effect enhances as the carbon black concentration increases.

3) The noise reduction mechanism of carbon black is that the carbon black increases the cavitation nucleus in the lubricant, which causes bubble groups in the oscillatory squeeze film. And these bubble groups do not easily aggregate to form large cavitation, which reduce the chances of connecting with the atmosphere in the process of cavitation collapse and realizes the effect of noise suppression.

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