International Journal of New Developments in Engineering and Society
ISSN 2522-3488 Vol. 3, Issue 5: 139-147, DOI: 10.25236/IJNDES.2019.030516

Dynamic Lubrication Analysis of Main Bearing Coupling Based on Fluid-Structure Coupled Heat Transfer

Peng Huo *, Huihua Feng , Weizheng Zhang , Li Wei , Liting Wang

Beijing Institute of Technology, Beijing, China
**Email: penghuo1991@hotmail.com*
**Corresponding Author*

ABSTRACT. *The internal combustion engine is one of the most important power machinery in the world today, and it provides tremendous impetus for the progress and development of human civilization. During the working process, the internal combustion engine is subjected to various excitation forces, and the vibration of the internal combustion engine is often caused by the excitation force of various frequencies. In the past, due to limited computing power, people often used the dynamic external load of the bearing as the fixed input when performing the oil lubrication analysis of the crankshaft main bearing. In the system dynamics analysis, the influence of oil film lubrication is often neglected or simple. The linear model is replaced. In order to ensure the reliability of the work, the design of the internal combustion engine requires the crankshaft to have high strength, stiffness and good dynamic and static characteristics. Based on the principle of fluid-structure coupled heat transfer, the lubrication problem of the main bearing of internal combustion engine is discussed. The dynamic characteristics of the component under the coupling of system dynamics and fluid dynamic lubrication are simulated.*

KEYWORDS: *Internal combustion engine, Oil film, Lubrication, Bearing, Fluid-solid coupling heat transfer*

1. Introduction

The internal combustion engine is one of the most important power machinery in the world today, and it provides tremendous impetus for the progress and development of human civilization. The internal combustion engine is the leading power equipment for transportation, national defense equipment, engineering machinery, agricultural machinery, marine machinery, petroleum machinery, etc. The internal combustion engine industry is an important basic industry [1]. During the working process, the internal combustion engine is subjected to various excitation forces, which often cause vibration of the internal combustion engine under the excitation force of various frequencies [2]. Although the focus of economic development in developed countries has shifted to the high-tech industries of the service industry and the electronic information industry, due to the important strategic position of the internal combustion engine industry, developed countries still attach great importance to it. The motion state and dynamic performance of each component in the system are not only related to the system dynamics of the system, but also related to the tribological dynamics between them [3]. With the increasing attention to environmental protection, people have put forward higher and higher requirements for the vibration, noise and running stability of internal combustion engines [4]. When the internal combustion engine is working, the gas pressure of the combustion chamber pushes the piston to move along the axis of the cylinder liner, which drives the crankshaft to make a rotary motion and simultaneously outputs the torque [5]. During this cyclic motion, the lubricating oil in the lubricant between the piston skirt and the cylinder liner, between the piston and the piston pin, in the bearings at both ends of the connecting rod, and in the main bearing of the crankshaft forms a fluid lubricant film. During the entire power transmission process, the lubricating oil membrane acts as a dynamic coupling between different parts [6].

In the development of internal combustion engines, how to avoid the adverse effects caused by resonance is a must for designers. In the past, due to limited computing power, people have isolated the tribological problems and system dynamics problems [7]. For example, in the dynamic lubrication analysis of the crankshaft main bearing oil film, the dynamic external load of the bearing is often used as a fixed input, while in the system dynamics analysis, the influence of oil film lubrication is often neglected or replaced by a simple linear model [8]. Unlike the friction between solids, the friction between the oil films is the friction behavior of the lubricating film having a low shear strength between the inner surfaces of the oil film. The tribological characteristics of the main bearing are closely related to the vibration noise of the internal combustion engine, and strongly affect the dynamic performance of the internal combustion engine, which in turn affects the vibration characteristics of the internal combustion engine [9]. In order to ensure the reliability of the work, the design of the internal combustion engine requires the crankshaft to have high strength, stiffness and good dynamic and static characteristics [10]. In fact, there is a strong coupling between tribological behavior and dynamic behavior, so the coupling analysis of tribology and system dynamics is of great significance for solving tribological problems and dynamics. Based on the principle of fluid-structure coupled heat transfer, the lubrication problem of the main bearing of internal combustion engine is discussed. The dynamic characteristics of the component under the coupling of system dynamics and fluid dynamic lubrication are simulated.

2. Main Bearing Lubrication Analysis Model Based on Internal Combustion Engine Shafting Dynamics

ISSN 2522-3488 Vol. 3, Issue 5: 139-147, DOI: 10.25236/IJNDES.2019.030516

2.1 Basic Principles of Lubrication Analysis Based on the Dynamics of the Internal Combustion Engine Shafting

Conventional internal combustion engine plain bearings are not used singly, and are generally used in groups to support the crankshaft shafting of an internal combustion engine that is subjected to periodic cylinder explosive forces. The heat transfer of the combustion chamber components of the internal combustion engine mainly includes solid structure heat conduction, gas side heat transfer, cooling water chamber side heat transfer, piston oil chamber oscillation heat transfer and heat transfer between the moving pairs. If the large amount of friction in the internal combustion engine is neglected, the vibration problem is studied from a single angle, which not only does not conform to the actual working state of the internal combustion engine, but also affects the source of the vibration [11]. If a part of the object in the multi-flexible body system can be treated as a rigid body and a part of the object can be treated as a flexible body, the system is a rigid-flexible multi-body system, which is the most common model in a multi-body system. When the engine is running under stable conditions, although the humidity in each cycle varies greatly, the humidity of the solid only fluctuates within a very thin thickness range, and the internal temperature of the structure is basically stable.

The physical quantity of feedback of each bearing is the axis motion parameter of the journal. The feedback result is the oil film reaction force generated by the bearing and the oil film counter-torque change. The movement of the shaft system changes the state of the oil film. The change of the oil film state will affect the oil film reaction force and the oil film reverse. The moment, the oil film reaction force and the counter torque further change the movement of the shafting. If the additional benefit from collaboration in multi-case optimization can be assigned among the participants, it is called payment-transferable multi-case optimization. On the contrary, it is called multi-case optimization that the payment cannot be transferred. Fig.1 shows the scanning velocity modulation architecture of the coupled dynamic prediction model.

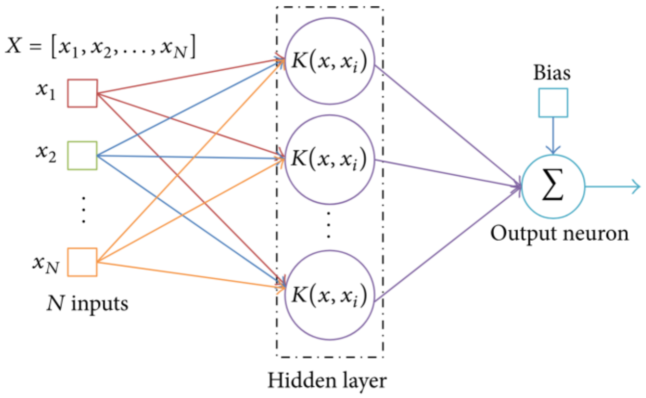

Fig.1 Scanning Speed Modulation Architecture of Coupled Dynamic Prediction Model

For basic information about internal combustion engines, production managers can manage them in a timely and dynamic manner. It can be seen from Table 1 that the numerical simulation of the natural frequency of the internal combustion engine and the natural frequency calculated by the finite element does not exceed 5%. The comparison between the two proves the accuracy of the description of the elastic deformation.

Table 1 Comparison of Results

Order	Numerical simulation frequency (Hz)	Calculate the modal frequency (Hz)
1	15.616	15.842
2	89.544	88.593
3	182.158	186.842
4	256.515	271.605

The heat balance calculation of the working process of the cylinder takes the volume enclosed by the bottom surface of the cylinder head, the wall surface of the cylinder liner and the top surface of the piston as the control body. Because the combustion of the internal combustion engine gas is very fast, the explosion will generate tremendous pressure within the range of the power stroke and generate complex pressure changes. Lubrication parameters such as oil film reaction force, oil film counter torque, frictional resistance and lubricating oil flow rate can be obtained based on the oil film pressure distribution of the radial sliding bearing. Multi-flexible deformation and spatial displacement occur simultaneously and as a fundamental feature of multi-flexible dynamics, which makes the dynamic model different from multi-rigid dynamics and structural dynamics. Numerically calculating the iterative equation to convergence yields a set of discrete pressure valuescorresponding to the mesh. Due to the large number of degrees of freedom, it takes a lot of time to simulate dynamic load conditions. Therefore, for vehicle system components with fewer load cases, finite element analysis is suitable for obtaining detailed information. For lighter weight components, the flexible deformation cannot be ignored and in order to maintain a small numerical force [12]. As the degree of superheat increases, the initial heat flux density gradually rises from a steep rise to a sharp rise, and then reaches a high point. The corresponding angle of the maximum oil film pressure is related to the deviation angle. The larger the axial center deviation is, the larger the corresponding oil film pressure becomes. When the superheat degree is increased, the heat flow density will drop sharply, that is, enter the transition boiling area.

2.2 Basic Model of Lubrication Analysis Based on Engine Shaft Dynamics

In the multi-body system, there are a large range of rigid body motion and elastic deformation between the members, so the dynamics of the rigid-flexible system is closely related to the dynamics and structural finite element analysis of the multi-rigid system. When considering the oil film dynamic lubrication of the bearings in the system, the corresponding constraints between adjacent components are replaced by the corresponding lubricant film forces. Since the heat transfer between the gas side of the cylinder and the wall surface of the combustion chamber is affected by the physical and chemical processes such as air flow in the cylinder, spray wall, and combustion process, the lack or incompleteness of any one of the factors may result in heat transfer in the cylinder. Take thousands of miles. For the internal combustion engine crankshaft, the crankshaft is subject to a large variable torsional load and bending moment load. The material of the shaft is generally carbon steel or alloy steel with elastic deformation properties, and the journal must have a slight flexural deformation. The general modeling process involves building a complete engine model of the internal combustion engine, building a template-based subsystem, and building an assembly that can be used for system simulation. As the power density of internal combustion engines is getting higher and higher, the thermal load is more serious, and the phenomenon of boiling heat transfer in the cooling water chamber becomes more prominent. When considering the oil film dynamic lubrication of the main bearing of the crankshaft, the rotational joint between the cylinder and the crankshaft is replaced by a dynamic lubricating oil film force.

Project quality control refers to the control of the progress level of each stage and the final completion time of the project during the project implementation process. The process duration is subject to a lognormal distribution. Fig. 1 shows the results of the key chain method planning.

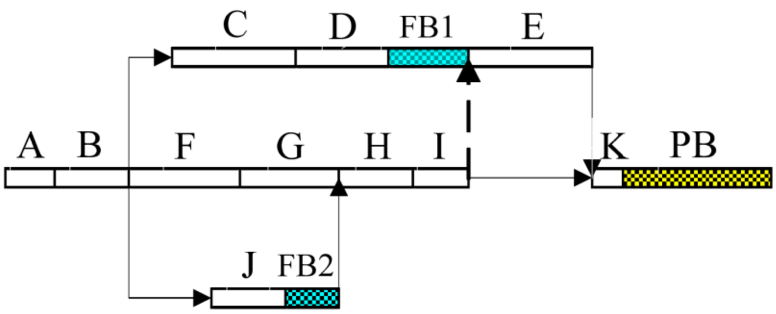

Fig.2 Key Chain Method Planning Results

Ignore the momentum conservation equation. In practice, the mass flow is usually a variable we are interested in, so the mass flow m is used here to reflect the flow rate u of the fluid. will $m = \rho u A$ The mass conservation equations brought into the fluid will result in:

$$\frac{\partial A\rho}{\partial t} + \frac{\partial m}{\partial z} = 0 \quad (1)$$

Since the working medium is in the process of pressurizing the working medium, the burning value of the working medium will increase, and this process can be considered as an adiabatic process. By setting the efficiency coefficient ηp of the working medium, the working medium is discharged at the pump outlet. The devaluation can be expressed as:

$$h_{p,o} = h_{p,i} + \frac{u_p (P_{po} - P_{pi})}{\eta_p} \quad (2)$$

Where up is the average specific volume of the working fluid. Therefore, the steady state model of the working fluid pump is obtained, which can be expressed by the following equation:

$$y_p = f_p(u_p) \quad (3)$$

The components around the combustion chamber of the engine are subjected to the high temperature and high pressure of the combustion chamber gas. To ensure the temperature level and strength, reasonable cooling must be achieved. The frequency at which vibration occurs and the mode shape at a particular frequency depend on the physical characteristics of the system. When excited at a particular frequency, the modes experienced by the system correspond to the so-called intrinsic modes or regular modes. The development of today's internal combustion engines requires continuous improvement of their power density, and the explosion pressure and thermal load in the cylinder are significantly improved, so it is required to be compact. The oil film reaction force of the main bearing and the oil film counter-torque act on the crankshaft shaft system, which combines the cylinder explosive force, the inertial force of the crankshaft shaft itself and the crankshaft load to affect the movement of the crankshaft shafting [13]. Due to the periodicity of diesel engine operation and the combination of various unbalanced inertial forces, the radial load on the crankshaft bearings and journals of internal combustion engines is complex and variable. Not only does the size of the load it is subjected to becomes more complicated, but the direction of the load it receives also changes more frequently. To calculate the frequency response, the program applies a dynamic load at the additional point to replace the static load. Such dynamic loads are time coordinated, meaning that they act on the additional points at the frequency of the excitation. When the temperature of the wall surface of the cooling water chamber is low and the coolant does not reach the saturation temperature generated by the bubble, only forced convection heat transfer is performed between the coolant and the solid wall.

3. System Dynamics and Oil Film Dynamic Coupling Numerical Analysis Process

The relative description is to select a dynamic reference system for each object in a certain way. The shape of the object is determined relative to its own dynamic reference system. These dynamic reference systems are usually non-inertial. Only when the minimum oil film thickness of the sliding bearing is greater than the sum of the coarse sugars of the sliding bearing and the bearing surface of the bearing bush, hydrodynamic lubrication is possible between the two contact surfaces of the sliding bearing. The mainstream liquid is affected by the bubble phase change heating, the heat flow density is high, and the temperature rises rapidly. The axis moves periodically along a certain trajectory, and the position of the axis changes continuously, so that the thickness of the oil film at various points on the bearing surface also changes continuously. The bearings of multi-cylinder diesel engines are simultaneously subjected to the combined action of different gas pressures, and their comprehensive stress conditions are relatively more complicated. The gas explosive force in the cylinder is the main force of the crankshaft movement. The combined action of these forces and the supporting force of the main bearing makes the crankshaft work normally. Since the combustion velocity of the combustible gas is very fast, a large burst pressure and a complicated gas pressure change occur in the range of the power stroke.

The dynamic coupling of the lubricating oil film can make the force of each part of the cylinder tend to be uniform, which greatly reduces the maximum force of the parts. When the critical heat flux density point is exceeded, the heat transfer state in the engine water chamber will briefly enter a boiling state after a brief transitional boiling. The heat transfer status partitioning is shown in the Table2.

Table 2 Heat Transfer State Partition

Heat transfer zone	Status flag	Interval starting point
Forced convection zone	0	
Partial development of nucleate boiling zone	1	q_{OPDNB}
Fully develop nucleate boiling zone	2	q_{OFDNB}
Critical margin area 3	q_{OSAC}	
Transition and membrane boiling zone	4	q_{OTFB}

In the finite element program, the deformation of the flexible body is described by the motion of the finite element mesh nodes. In mechanical systems, traditional motion analysis treats the mechanism as a rigid body, and the flexible body characteristics of the mechanism itself will have an important impact on the analysis results of the entire system. In general, a node can perform a translational motion, and for a shell element and a beam element, its nodes can also perform a rotational motion. If the heat transfer in the water chamber is in the forced convection zone and part of the nucleate boiling zone is developed, the engine has the potential to increase the thermal load on the premise that the water cavity structure is unchanged. The circulation of lubricating oil and cooling water of the diesel engine is generally driven by the crankshaft to drive the timing gear or the pulley to realize the power supply, and the accompanying generator is also driven by the rotation of the crankshaft. While the engine is operating under steady conditions, although the temperature in each cycle varies greatly, the temperature of the solid only fluctuates within a very thin thickness range. In the kinematic analysis, if the influence of the flexible body is not considered, a certain error will be caused. The calculation results of the radial load of the bearing of the diesel engine crankshaft bearing system are mostly used for the lubrication calculation of the main bearing of the crankshaft of the internal combustion engine. The accuracy of the radial load received by the crankshaft bearing of the internal combustion engine has an extremely important influence on the lubrication of the main bearing.

4. Conclusion

The dynamic coupling of the lubricating oil film can make the force of each part of the cylinder tend to be uniform, and the maximum force of the component is greatly reduced. The rigid-flexible coupling model is basically consistent with the trend of the main bearing load change in the rigid body model. The rigid-flexible coupling model will have multiple peaks and the difference between the maximum and minimum valuesof the load will be smaller than that of the rigid body model. In the part strength design, the component design with the maximum force of the component calculated without considering the oil film dynamic coupling has an excessive safety margin. Considering the coupling of system dynamics and oil film dynamics, the dynamic characteristics of the components have changed greatly. The dynamic coupling of the lubricating oil film can make the force of each part of the cylinder tend to be uniform, and the maximum force of the component is greatly reduced. The lubricating oil membrane dynamic coupling function has the effect of reducing the force and the force difference of the main thrust surface of the cylinder, and reduces the local stress shock peak. Increasing the width of the bearing helps to increase the bearing capacity of the bearing, resulting in a lower maximum oil film pressure. Choosing the right bearing width is very positive for ensuring a good lubrication of the bearing. In the design of internal combustion engine components, it is necessary to consider the coupling of tribology and system dynamics.

References

[1] Garcia-Atance Fatjo, G., Smith, E. H. , & Sherrington, I. . (2014). Mapping lubricating film thickness, film extent and ring twist for the compression-ring in a firing internal combustion engine. Tribology International, vol. 70, pp.112-118.

[2] Zavos, A. B. , & Nikolakopoulos, P. G. . (2015). Simulation of piston ring tribology with surface texturing for internal combustion engines. Lubrication Science, vol.27, no.3, pp.151-176.

[3] Thomas, W. , Ulrike, C. B. , Claudia, L. , Ditrói Ferenc, Takács Sándor, & Johannes, S. B. , et al. (2018). Wear of different material pairings for the cylinder liner – piston ring contact. Industrial Lubrication and Tribology, vol.70, no.4, pp.687-699.
[4] Dey, A. R. , & Misra, R. D. . (2017). Effect of infiltration of bio-lubricant on the performance of a compression ignition engine fuelled with biodiesel blends. Clean Technologies and Environmental Policy, vol.19, no.2, pp.553-563.
[5] Liu, Z. , Wei, M. , Song, P. , Emhardt, S. , Tian, G. , & Huang, Z. . (2018). The fluid-thermal-solid coupling analysis of a scroll expander used in an orc waste heat recovery system. Applied Thermal Engineering, vol138, pp.72-82.
[6] Shetab Bushehri, M. R. , Ramin, H. , & Salimpour, M. R. . (2015). A new coupling method for slip-flow and conjugate heat transfer in a parallel plate micro heat sink. International Journal of Thermal Sciences, vol. 89, pp.174-184.
[7] Koren, C. , Vicquelin, R. , & Gicquel, O. . (2017). Self-adaptive coupling frequency for unsteady coupled conjugate heat transfer simulations. International Journal of Thermal Sciences, vol. 118, pp.340-354.
[8] Xu Z G, Qin J, Zhou X, et al.(2018) Forced convective heat transfer of tubes sintered with partially-filled gradient metal foams (GMFs) considering local thermal non-equilibrium effect. Applied Thermal Engineering, vol. 137:pp.101-111.
[9] Chen, X. , Zhou, P. , Kang, R. K. , & Dong, Z. G. . (2016). Numerical study on thermal deformation characteristic of water-cooled mirror with interdigitated channels. Applied Thermal Engineering, vol. 98, pp.357-364.
[10] Xu, L. , Cheng, L. , Cai, Y. , Liu, Y. , Wang, Q. , & Luo, Z. , et al. (2016). Heat flux determination based on the waterwall and gas–solid flow in a supercritical cfb boiler. Applied Thermal Engineering, vol. 99, pp. 703-712.
[11] Su, H. , Rahmani, R. , & Rahnejat, H. . (2016). Thermohydrodynamics of bidirectional groove dry gas seals with slip flow. International Journal of Thermal Sciences, vol. 110, pp.270-284.
[12] Khuong, L. S. , Masjuki, H. H. , Zulkifli, N. W. M. , Mohamad, E. N. , Kalam, M. A. , & Alabdulkarem, A. , et al. (2017). Effect of gasoline–bioethanol blends on the properties and lubrication characteristics of commercial engine oil. RSC Adv., vol.7, no.25,pp. 15005-15019.
[13] Tomic, M. , Savin, L. , Micic, R. , Simikic, M. , & Furman, T. . (2014). Possibility of using biodiesel from sunflower oil as an additive for the improvement of lubrication properties of low-sulfur diesel fuel. Energy, vol. 65, pp.101-108.