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An improved technique for measuring piston-assembly friction and comparative analysis with numerical simulations: Under motored condition

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A B S T R A C T

Robust and accurate measurement techniques are essential to studying the piston-assembly friction of Internal Combustion (IC) engines. Based on the instantaneous Indicated Mean Effective Pressure (IMEP) method, this paper develops an improved measurement technique to evaluate the piston-assembly friction in engines. Wireless telemetry technology is employed in the measurement of connecting rod axial force, which greatly minimizes the engine modifications and enhances the measurement stability compared to the conventional wired way. The measurement system, which is composed of computer, data acquisition system, sampling trigger apparatus and sensors, is exploited with special attention given to the sampling synchronization of signal channels including cylinder pressure, connecting rod force and crank angle position. Engineering implementations are carried out on a four-stroke gasoline engine under motored condition. The measurement results are compared with numerical results from a newly developed numerical coupling model system, and it shows that the two agree well. In addition, the piston-assembly friction under different engine speeds and inlet lubricant temperatures are also measured, and analyses indicate that these results are in good correlation with the well-known Stribeck curve. This improved measurement technique provides an accurate and reliable option for the friction evaluation of piston-assembly components in engine designs.

1. Introduction

Nowadays, tighter vehicle emission regulations are propelling the automobile manufacturers to improve the IC engine efficiency for better fuel economy. Piston-assembly, the core power unit of a reciprocating IC engine, is reported to account for about half of the total friction of the whole engine [1–3]. It leaves a great improvement space for the friction reduction of piston-assembly/liner wall interface and numerous efforts have been devoted into the exploration and optimization of its lubrication performance in recent decades [4,5]. In order to achieve lower friction designs of the piston-assembly and liner system, accurate measurements are required to evaluate the friction dissipation in the system under actual engine operation conditions. Such measurements in engine tribological bench testing can provide rapid and cost effective information for

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screening and ranking purposes in the development process of piston-assembly and liner components as well as the lubricant-additive formulations.

However, it is still very hard to measure the piston-assembly friction under actual running state of engines. The floating liner method may be the most popular technique though it has been invented for several decades [6]. This method is to separate the cylinder liner from the engine block and axially support it by cantilever beams with mounted strain transducers [7,8]. When the piston-assembly is moving up and down, the isolated liner is loaded by the piston-assembly/liner friction force and therefore the force is measured directly. It is well known that extensive modifications are required for the specific testing engine, through which the measurement results might be very different from the actual situation of commercial engines. Besides, some problems such as combustion gas sealing, piston thrust force supporting, and liner vibration reducing are the challenges that have to be faced in this method.

The instantaneous IMEP (Indicated Mean Effective Pressure) method, an indirect measurement approach for the piston-assembly friction evaluation proposed by Uras and Patterson in 1980s [9,10], is able to settle the issues existed in the floating liner method. The principle behind this method is to calculate friction force through an instantaneous force balance under a prerequisite of known combustion gas force, connecting rod force and inertial forces from piston-assembly components. The greatest advantage of this technique is that no major engine modification is required and thus it can be applied into any commercial engine. Following the pioneer work by Uras and Patterson, Yun et al. [11], Mufti et al. [12–14] and Sethu et al. [15] also made attempts to measure the piston-assembly friction using the instantaneous IMEP method. Compared to the floating liner method, although the cost advantages are very obvious for this technique, several urgent problems that impede its engineering application and popularization remain to be solved.

The main challenge of this method is that the extremely accurate measurement of other forces acting on the piston-assembly is required, because the magnitude of the resultant friction force is much smaller than these forces [5]. Another big challenge is that a special telemetry equipment is required to transmit the strain gauge signal from moving connecting rod out of the engine block [16]. In all implementations of this technique listed above, a special device called grasshopper linkage was used to lead the signal wires, which puts some restrictions on testing engine speed and the life time of signal wires. As the engine speeds up, the signal wires are bended more frequently and fatigue failure is prone to occur, which greatly reduces the stability and reliability of the measurement system.

With the rapid development of the electronic technology, the semiconductor chips are becoming smaller in size and lower in power consumption, whereas the functions and anti-interference capacity are stronger. This now makes it possible to carry the strain gauge signal from the fast moving connecting rod out of the engine using the wireless telemetry technology. Several successful application examples of the wireless telemeter to the measurement and analysis of the piston system have been reported in recent years [17–21]. Most of these applications concentrate on the measurement of piston temperature. In the early days, the piston temperature was measured using the electromagnetic induction method [17,18]. But that method was based on the conventional radio technology, which had poor measuring accuracy and weak resistance to interference. Furthermore, the signal transmission was not continuous and the number of measurement channels was limited. Literature survey suggests that Lee et al. [20] were the few pioneers who applied the modern digital wireless telecommunication technology to the piston temperature telemetry system. In their work, the piston temperature telemetry system was designed using the Bluetooth networks, which can measure up to 56 piston nodes simultaneously. Two years later, Isarai et al. [21] also developed a measurement system equipped with new digital telemeter to measure the strain, motion and temperature of engine parts. Testing results showed that the measurement system can work steadily at high engine speed up to 6200 rpm. However, they didn't disclose the wireless communication technology used in their measurement system. Sum up of these literatures, the developed wireless digital telemeter has been proven to be capable of multipoint measurement over long periods of time under high-speed, high-load conditions, without any constraint from the wire harness.

In order to address the concern issues ever encountered in the applications of the instantaneous IMEP method, this study proposes an improved technique for the piston-assembly friction measurement, and successfully realizes its engineering implementation under motored condition. A comparative analysis between the measuring and numerical results is conducted. Furthermore, the piston-assembly friction under different engine speeds and inlet lubricant temperatures is measured. Correlating these measuring results to the famous Stribeck curve, the accuracy and reliability of the measurement system has also been proved.

2. Experimental methodology and setup

2.1. Fundamental principle of the instantaneous IMEP method

All the forces acting on the piston-assembly and connecting rod are presented on left side of Fig. 1. There are mainly combustion gas force acting on crown of piston (F_g), inertia force of piston assembly (F_{in}), friction force (F_f) and gravity ($m_{pisa}g$) of the piston-assembly and additionally the connecting rod force along its principal axis (F_{stg}), the inertia force induced by the mass of connecting rod part above the strain gauge (F_{cin}). These forces stay balance at any moment and the friction force (F_f) can be acquired once other forces are known, which is illustrated on the right side of Fig. 1. It can be directly seen from the force balance equation that there are three variables need to be measured, namely, the gas force (F_g), the connecting force (F_{stg}), and the crank angle position (θ or CA) with respect to time. In general, the gas force and connecting rod force are of the