

Setting Up a Measuring Device to Determine the Friction of the Piston Assembly

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ABSTRACT

This SAE Technical Paper gives a summary of the essential findings in the development and operation of a test engine dedicated to the measuring of the friction between the piston group and the liner. Firstly the fundamental demands on the high-precision and close to real engine operation friction measuring are laid out. Subsequently the basic engine, the measuring system based on the floating liner method including a gas balance device, as well as the implemented measuring technique are specified. Major influencing variables on the friction of the piston assembly and its interference variables are also summarized. Extensive information about the systematic and strategies for the test engine's operation startup are given in acknowledgement of influencing and interference variables. This strategy reduces the developmental and startup process of an engine dedicated to the measuring of piston group friction.

INTRODUCTION

In the course of the CO₂ reduction legislation the automotive industry in particular has come under pressure to reduce their vehicles' fuel consumption. This can be effectively achieved by reducing the losses in the combustion engine. Apart from thermodynamic losses, mechanical losses play a decisive role. The largest part of mechanical losses are caused by the piston assembly, thus offering the biggest potential for reducing fuel consumption through tailored further development. As a complex tension field is active in the range of the piston assembly, the research requires a holistic approach that takes target parameters such as friction, oil consumption, blow-by and wear into account.

For some time reliable methods for the determination of the target parameters blow-by, oil consumption and wear in

customer-relevant engine operation have been at engine developers' disposal. Yet the determination of the friction losses proved to be extremely laborious. In literature there are some rare mentions of measuring engines that allow for the adequately accurate identification of the piston assembly's friction losses during the combustion run. Due to the operating principle those measuring systems are tailored to a concrete application. As the piston group friction is largely dependent on the application, a tailored measuring system needs to be established for advancements towards minimal friction.

Yet the piston assemblies vary between gasoline engines and diesel engines, between common automobiles and race cars and they are depending on bore and stroke. This means that effective advancements require the setup of a specially built measuring engine that is attuned to the respective geometries and necessities.

At the Technische Universität München's Chair of Combustion Engines such a measuring engine, dedicated to the high-precision determination of the piston assembly friction of a gasoline engine with 0.5 l displacement was assembled and successfully initiated. This paper gives an extensive summary of the experiences that were made during this laborious and time-consuming development process. Within the framework of this research an exemplary approach was developed regarding the minimal number of steps that are necessary for the launch and the subsequent clearing of the measuring system for the developmental operation. Design aspects as well as the measuring technology's choice and application at the measuring engine were optimized during the startup process.

CHALLENGES OF THE PISTON ASSEMBLY FRICTION MEASUREMENT

The challenges of measuring friction parameters at the piston group of a combustion engine are rooted in various causes. Firstly the tribological circumstances considerably vary during the combustion run. Secondly the ratio of occurring gas- and mass-forces is rather large in comparison to the friction forces that need to be examined.

Notably in the area of the rings and the liner, mixed friction as well as hydrodynamic friction does occur likewise. Mixed friction mainly occurs with large loads as well as at the dead center at low rotation speeds. Between the dead centres and especially at high engine speeds hydrodynamic friction prevails. For the detailed analysis of the tribological conditions, the friction needs to be detected with adequately high resolution and sample rates. This is the only way to measure both friction varieties. Particularly suitable is the floating liner method that has been applied in Japan by [2] since the 1970s.

In the single cylinder engine used in the tests, the gas forces working on the piston in axial direction are 58 kN at full load. The high pressures of 110 bar that are required in the combustion chamber also work on the floating liner. This results in high axial forces on the liner even on small areas, in comparison the friction at the piston assembly is only several hundred Newton, see [4], [5] and [8]. This renders the decoupling of gas-forces and friction within the framework of the measuring process an absolute necessity. A wide variety of methods are mentioned in literature, mostly based on the gas balance method. See examples in [1] and [3].

Experimental Device

The single cylinder friction measuring engine is based on a reference engine, which is a four-cylinder automotive gasoline engine. It features 82.5 mm of bore and 92.8 mm of stroke. This yields to a displacement of approximately 0.5 l. In the area of the piston assembly, standard engine parts are used; the piston cooling is identical to the one in the reference engine. In combination with the actual cylinder head's geometry this is an important prerequisite for the transferability of the results from the measuring engine to the reference engine. A Lancaster mass balancing of the first and second order and a correspondingly inert flywheel are used to reduce the vibration excitation and to raise the quality of the measuring. The reference engine's degree of irregularity was taken into account in the dimensioning of the flywheel. 3D acceleration sensors allow for the supervision of the vibration behavior at different points of the basic engine and the measuring system during the friction measuring. This enables conclusions about the smoothness and the mass balancing's performance, if engine parts are changed. The synchronous

vibration measuring allows conclusions about their influence on the measured friction run. The measuring engine is built modular and flexible. It can be conditioned externally at the test bench and is connected to a three-phase asynchronous motor. This way a wide range of parameter variations and component tests is possible.

For the high-precision measurement of the friction forces between the piston assembly and liner in correlation to the crank angle, the floating liner method with a gas balance device is used, see [Figure 1](#). Depending on the configuration, two or four load cells are employed. A more rigid and accordingly less vibration-sensitive setup of the measuring system is achieved by the use of four load cells. Yet this configuration is inferior regarding the reproducibility of the measurings after a complete disassembly of the system. The use of two load cells results in a lower grade of static overdetermination, which leads to reduced tensioning in the buildup. So the use of two load cells improves reproducibility. A so-called radial support is used for retaining the piston side forces. They feature a very low axial rigidity and a high radial rigidity. Their axial force shunt is extremely low and thus hardly influences the measuring. Instead a large percentage of the occurring piston side forces are directly diverted from the liner to the block. This significantly reduces the shear loads and the moment loads working on the 1D load cells. In the measuring system's layout it was ensured that no vibration-reducing elements, such as parts with hysteresis, or sealing elements were placed in the force flow of the measuring. Because of their pronounced non-linear behavior they would otherwise compromise the measuring.

Due to its additional volume the gas balance device alters the compression ratio. For a gas force compensation that is as complete as possible, notably in dynamic operation, the channels to the lower compensational face and the sealing face must have an aerodynamic design. A flow channel design that is too narrow causes strong throttling effects, thus resulting in pressure differences on the compensation faces. In consequence the measuring signal shows an interference that is non-proportional to the pressure curve and is therefore difficult to record. The gas balance device's aerodynamic design hence requires adequate flow diameters, which lead to a reduced compression ratio. Compared to the reference engine the compression ratio in the operated measuring systems are reduced by factor 1.7 and 2.7. Under operating conditions it is thus necessary to equip the thermo-dynamical process with external conditioning units. This way pressure curves and tribological conditions close to the reference engine can be achieved and the results can be transferred.

Influence of the Operating Parameters

Representative studies require the retention of parameters that influence the piston assembly's tribology. This paper mainly

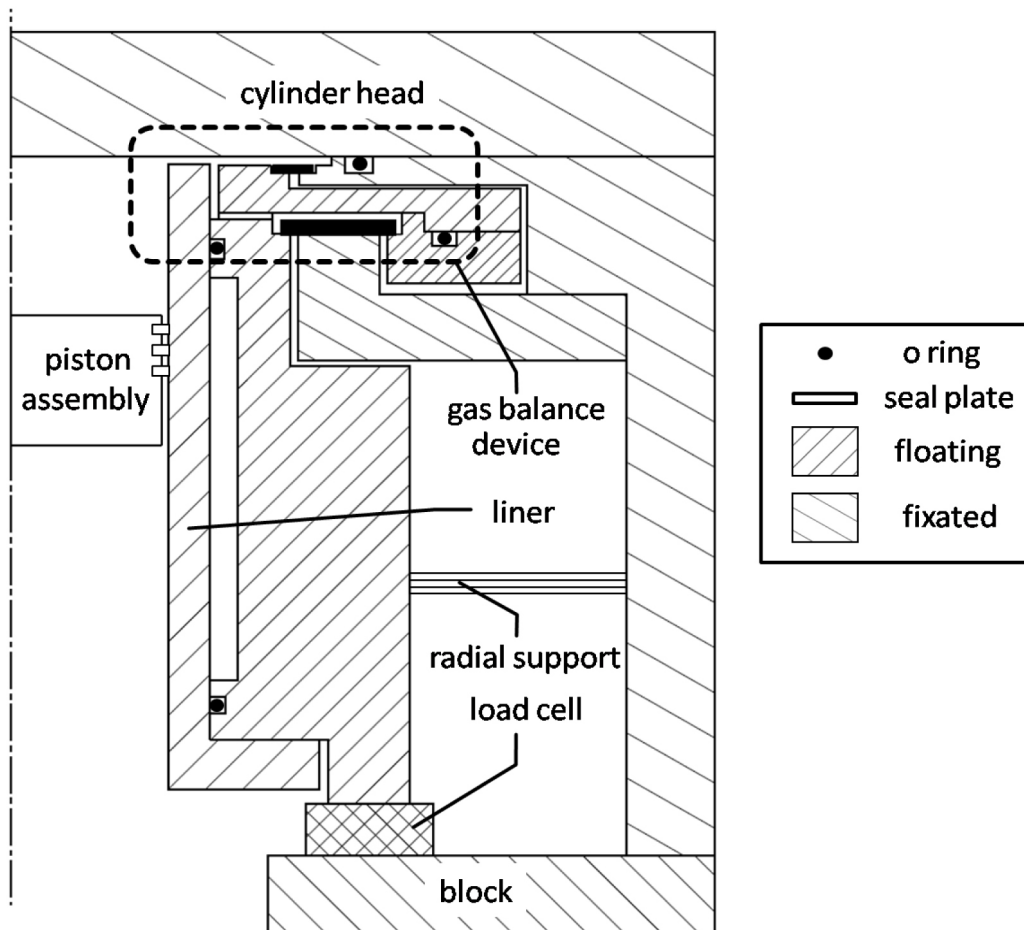


Figure 1. Schematic diagram of the measuring device

focuses on the parameters pressure, engine speed and temperature. This is a huge challenge, but is nevertheless prerequisite for the transferability of the measuring engine's results to the engine development. Yet some of these parameters do have a negative influence on the measuring resolution. Due to that the test operation as well as the interpretation of the data is hindered. In the following the main influential parameters of the engine are shown according to their tribological affect as well as according to their influence on measuring accuracy.

The engine speed has a considerable influence on all existing friction varieties. It defines the piston assembly's residence time and with it the piston rings' potential for penetrating the oil film. Lower piston speeds, among others, are the cause for mixed friction. In absolute terms, the residence time in dead center is shorter under higher engine speeds. The time span in which the rings can penetrate the oil film is shorter. If the speed is increased further, the squeeze effect occurs and the oil film is completely maintained. Apart from the reduced friction, the abrasive wear is also minimized significantly as no solid-body contact is made. In the area of hydrodynamic lubrication the engine speed also significantly affects the

friction between the piston assembly and the liner. This is shown by the model of two parallel boards that move with constant speed U relative to each other, separated by an oil film with a height h and a viscosity of η , see [Figure 2](#). According to [10] the formal correlation for this friction is as follows:

$$F = \tau \cdot A, \text{ with } \tau = \eta \cdot \dot{\gamma} = \eta \frac{U}{h}$$

Formula 1 Hydrodynamic friction between two parallel boards in relative movement to each other

With rising speed the shear stress τ also increases and with it the friction force F . In this form of friction too, the engine speed has a considerable effect on the resulting friction forces. At the same time the friction also causes vibrations of the measuring system. Besides the radial support the floating liner is exclusively suspended on load cells in axial direction; no cushioning elements are used. As the piston changes its direction in the dead center, the direction of the axial friction on the liner is reversed. Due to this alternating stress a forced axial vibration develops at the measuring system. With increasing engine speed the excitation frequency changes, as

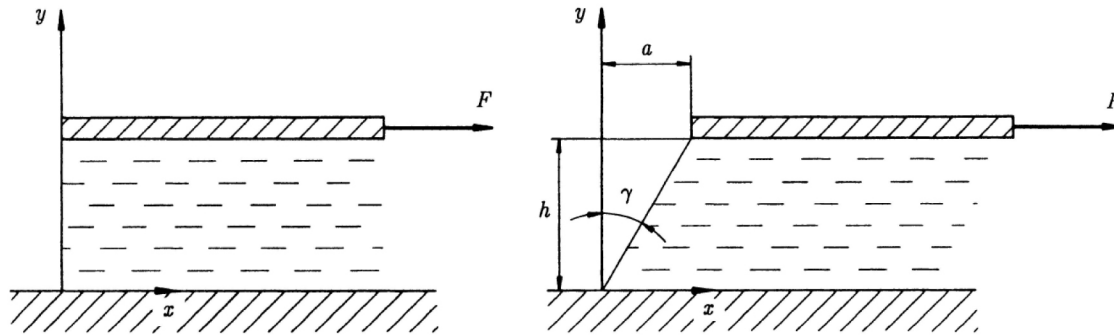


Figure 2. Hydrodynamic friction between two moving boards, see [10]

well as the exciting force, as the friction forces strongly depend on the engine speed. The vibrations of the floating liner are detected at the load cells, super-imposing the measuring record of the examined friction. The engine speeds to be tested are pre-defined by the engine operation and must not be changed in order to guarantee the measuring transferability. In order to minimize the vibrations following given excitations, it is essential to adjust the natural frequency of the measuring device through mass and rigidity. Accordingly, the engine speed is one of the main influencing and disturbing parameters for the friction that is supposed to be measured.

The load, apart from the engine speed, is a major influencing factor of the piston assembly friction. Generally, the combustion chamber pressure increases with rising loads. The high pressure level yields higher piston side forces. Thus the piston, notably in the area of the piston skirt, is pressed more strongly against the liner and the friction increases, see [7]. Furthermore the pressure also acts behind the rings, especially at the top ring. This way an increased normal force builds up between ring and liner at increasing loads, resulting in increased friction forces. The gas balance device on the liner is also subject to the combustion chamber pressure. As the gas balance device does not achieve a full equilibrium in praxis, there will always be some residual axial interference on the liner. This is recorded by the load cell and superimposed with the friction. The main reasons for the incomplete equilibrium are slightly dissimilar gas balance faces due to manufacturing tolerances. The resulting interference on the measuring signal can be physically allocated and is proportional to the pressure curve. Therefore it is admissible to retroactively eliminate those disturbing forces on the measuring data. Here again the pressure respectively the load are the cause for friction and disturbance.

Temperature is a further parameter. It affects the friction due to the lubricant's viscosity. It also determines the temperature extension of piston and liner. As a rule, aluminum pistons are used in automobile engines due to their small weight. For financial reasons and due to its good dry-running behavior

the liner is often manufactured in gray cast iron. Compared to gray cast iron, aluminum is defined by a significantly higher thermal expansion coefficient. The piston heats up significantly more than the liner, as it is not subject to a coolant flow-through. These conditions lead to a decrease in the gap between piston and liner with increasing temperatures. This gap, like the rings, regulates the thickness of the oil film between the piston assembly and the liner and thus directly affects the friction. With further expansion of the piston interference may result. Then the diameter of the piston surpasses the liner's diameter, if the thermal extension would not be constrained. This results in significantly increased friction forces and must be detected by a friction measuring engine and, in consequence, must be avoided by, e.g. an increase in cold run gap. Large temperature gradients lead to tensioning in the measuring device, thus causing further disturbing forces. Furthermore, most of the common gas balance devices feature Viton seals. Viton is permanently applicable for temperatures up to ca. 280° C. With full load, significantly higher temperatures occur in the engine's combustion chamber. Apart from forced test breaks, the frequent replacement of the seals leads to diminishing reproducibility. Accordingly the temperature is not only one of the main influencing factors of the piston assembly friction, but also of other disturbing forces. Not to mention its negative influence on reproducibility.

APPLICATED MEASUREMENT TECHNIQUE

The state of the art piston assemblies generally feature low frictions of only a few hundred Newton, [4], [5] and [8]. The measuring of further improvements requires a resolution of adequate precision. Three common measuring techniques lend themselves to the collection of liner friction data: piezoelectric force measurement, extension measurement and optical distance measurement. Due to the operating principle the application of strain gauges as well as the optical distance measurement requires defined movements of the liner. As the measuring device tends to vibrate, as stated above, those methods are not advisable. As the required movements of the piezoelectric force measurement are significantly smaller