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On the identification of piston slap events in internal combustion engines using tribodynamic analysis

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ABSTRACT

Piston slap is a major source of vibration and noise in internal combustion engines. Therefore, better understanding of the conditions favouring piston slap can be beneficial for the reduction of engine Noise, Vibration and Harshness (NVH). Past research has attempted to determine the exact position of piston slap events during the engine cycle and correlate them to the engine block vibration response. Validated numerical/analytical models of the piston assembly can be very useful towards this aim, since extracting the relevant information from experimental measurements can be a tedious and complicated process.

In the present work, a coupled simulation of piston dynamics and engine tribology (tribodynamics) has been performed using quasi-static and transient numerical codes. Thus, the inertia and reaction forces developed in the piston are calculated. The occurrence of piston slap events in the engine cycle is monitored by introducing six alternative concepts: *(i) the quasi-static lateral force, (ii) the transient lateral force, (iii) the minimum film thickness occurrence, (iv) the maximum energy transfer, (v) the lubricant squeeze velocity and (vi) the piston-impact angular duration.*

The validation of the proposed methods is achieved using experimental measurements taken from a single cylinder petrol engine in laboratory conditions. The surface acceleration of the engine block is measured at the thrust- and anti-thrust side locations. The correlation between the theoretically predicted events and the measured acceleration signals has been satisfactory in determining piston slap incidents, using the aforementioned concepts. The results also exhibit good repeatability throughout the set of measurements obtained in terms of the number of events occurring and their locations during the engine cycle.

1. Introduction

The ever increasing importance of fuel efficiency, noise reduction and engine performance is forcing researchers to better understand the mechanism and effective parameters of piston dynamics. The piston assembly plays a key role in the generation of engine mechanical losses, including noise [1]. The latter is well known as piston impact (also slap) noise. In order to better study the occurrence of slap noise events, one should carefully monitor the piston's secondary motion, which

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[1] Research data for this paper are available on request from Dr. Stephanos Theodossiades (S.Theodossiades@lboro.ac.uk).

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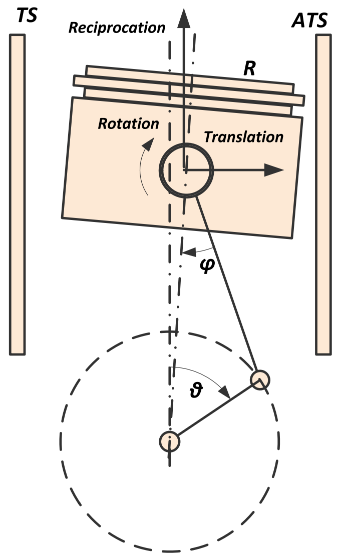

Fig. 1. Primary and secondary piston motions inside the cylinder.

leads to skirt-to-cylinder liner contacts. The excitation conditions (forces and moments) on the piston are responsible for the secondary motion, which occurs laterally within the clearance (translation) and around the piston pin (rotation). The schematic of these motions is given in Fig. 1. ϑ and ϕ are the crank and connecting rod angles, respectively [2]. R is the piston crown radius (later used to calculate the crown area). When the crankshaft rotation is clockwise, the left side of the cylinder liner is called the thrust side (TS) and the opposite side is known as the anti-thrust side (ATS). Piston impacts can occur on either side of the liner. Piston slap excites the engine block and manifests itself in the form of surface vibrations, which are eventually radiated as noise in the vicinity of the engine. In addition to the perceived benefits for engine NVH, good understanding of the number and location of piston slap events can be helpful for fuel efficiency purposes through improved system tribodynamics [2].

Previous numerical/analytical and experimental studies on piston slapping differ with regard to the way they consider lubrication effects, piston's rotation and piston skirt deformation. The common aspect in all these approaches is that they determine piston slap events (number and angular position of occurrences). In general, three approaches have been proposed in the literature to identify piston slap events based on the secondary motion of the piston. In the most simplified approach, the effects of lubrication and piston rotation are neglected. In this case, the piston's secondary motion (translation) is directly investigated using the contribution of forces in the primary direction [3–5]. This method will be referred to as *quasi-static lateral force* in this paper. Nevertheless, accurate investigation of the piston's secondary motion requires inclusion of the piston's angular motion and oil-film hydrodynamic effects. In this approach, a coupled simulation of piston dynamics and engine tribology (tribodynamics) is necessary prior to the extraction of the secondary motion [1,6,7]. Thus, the piston dynamics equations of motion are described using Lagrange's method and are coupled to the Reynolds equation for the piston skirt-liner conjunction [8]. The piston side force is extracted from the tribodynamic solution. The direction change in the side force can be used to identify the initiation of piston-slap events. Therefore, this method will be referred as *transient lateral force* in the present study. Finally, the third approach exploits the same tribodynamic analysis. In this method, the *minimum film thickness occurrence* is considered as the criterion for slap events instead of the lateral force. When the film thickness takes its minimum value (at either TS or ATS), it can be inferred that piston-liner interaction is intensified and piston slap occurs [9]. Perera et al. studied the piston-cylinder film thickness utilising the multi-physics model of a single cylinder engine. However, they considered the piston as a rigid body in their approach. The effects of friction and bearing load were included in their studies [10,11]. Three new approaches to identify piston slap events based on the tribodynamic analysis are also investigated in this study. The first approach utilises the film thickness and force variations together to calculate the transferred energy to the cylinder wall. Whenever the maximum energy is transferred, piston slap occurrence is assumed. This method will be called *maximum energy transfer*. In another approach, the rate of change in the minimum film thickness is traced to pinpoint the initiation of piston slap. As the minimum film thickness velocity changes from positive to negative, film squeeze action initiates and piston slap is assumed. This method is referred as *lubricant squeeze velocity*. The final method differs in that piston slap is indicated within a crank angular interval, whose limits are defined by the initiation of the squeeze action and the minimum film thickness occurrence methods. This interval represents the initiation and completion of piston slap. The method will be called *piston-impact angular duration*.

The six approaches chosen for investigation of the piston's secondary motion involve numerical/analytical calculations. Up to 16 potential slap events can be identified theoretically but only about 6 to 10 impacts in each cycle are observed in practice [4,12]. In order to validate the position and number of events, the experimental set-up of a single-cylinder, 4-stroke Honda petrol engine is utilised. A common practice is the attachment of accelerometers on the engine block surface. There

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