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A transient tribodynamic approach for the calculation of internal combustion engine piston slap noise

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ABSTRACT

An analytical/numerical methodology is presented to calculate the radiated noise due to internal combustion engine piston impacts on the cylinder liner through a film of lubricant. Both quasi-static and transient dynamic analyses coupled with impact elasto-hydrodynamics are reported. The local impact impedance is calculated, as well as the transferred energy onto the cylinder liner. The simulations are verified against experimental results for different engine operating conditions and for noise levels calculated in the vicinity of the engine block. Continuous wavelet signal processing is performed to identify the occurrence of piston slap noise events and their spectral content, showing good conformance between the predictions and experimentally acquired signals.

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1. Introduction

Internal combustion (IC) engines have been extensively deployed in various configurations for transportation (vehicles, ships, motorcycles etc.). There have been ever increasing concerns with regard to their radiated noise levels, fuel consumption and emissions. These concerns, together with the growing competition have forced industry to increase investment in research and development. As the parasitic losses of piston – cylinder system account for 6–9 percent of fuel consumption [1], including friction and errant dynamics, their investigation has been regarded as beneficial.

One effect of errant dynamic behaviour is the induced noise, which is regarded as a sign of poor quality. Piston slap due to secondary piston inertial dynamics is one such noise propagating concern. The generated noise is due to piston impact on the cylinder liner, which has been a problem for the research community for a long time. The noise generation mechanism can be analysed in three phases: (i) vibration excitation at the source, (ii) energy transfer through a structural path and (iii) noise radiation from the vibrating surfaces [2]. In vehicular powertrains, noise can originate from processes and associated components, such as combustion, piston slap, fuel injection, gear teeth contacts, oil pump and valve impacts. Fig. 1 shows the contributions to the total engine noise levels from the aforementioned noise sources for a three-cylinder,

Abbreviations: ATS, Anti-thrust side; ABDC, After bottom dead centre; ATDC, After top dead centre; BDC, Bottom dead centre; BBDC, Before bottom dead centre; BTDC, Before top dead centre; COG, Centre of gravity; CWS, Continuous wavelet spectrum; EHL, Elasto-hydrodynamic lubrication; EVC, Exhaust valve closure; EVO, Exhaust valve opening; IVC, Inlet valve closure; IVO, Inlet valve opening; NVH, Noise, Vibration and Harshness; SPL, Sound pressure level; SPL_T, Total sound pressure level; TDC, Top dead centre; TS, Thrust side

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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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List of symbols

A_r	surface area of noise radiating source
A_v	surface area of impacted structure
a	distance between the pin-bore and top of piston skirt
b	distance between the piston centre of gravity and top of piston skirt
C	nominal clearance between piston and cylinder liner
c_a	wave propagation speed in air
d	combined effect of instantaneous clearances; e_t and e_b
d_{COG}	offset between the piston centre of gravity and the pin-bore
d_p	offset between point of action of gas force and the pin-bore
e_b	eccentricity at the bottom of piston skirt
e_t	eccentricity at the top of piston skirt
$\overline{F}$	average lubricant reaction between two consecutive time steps
F_f	piston – cylinder conjunctional friction
F_G	gas force
F_{hyd}	lubricant reaction
F_L	connecting rod force
$F_{pin,x}$	pin reaction along the x coordinate
$F_{pin,z}$	pin reaction along the z coordinate
F_t	lateral (side) force acting on the piston
h	lubricant film thickness
h_t	thickness of the structure
I_{pis}	piston inertia
L	piston skirt height
L_w	sound power level
M_f	viscous friction moment
M_{hyd}	viscous reaction moment due to load
M_s	tilting moment due to pin or crankshaft offset
m_{pin}	mass of piston pin
m_{pis}	mass of piston
P	elasto-hydrodynamic pressure
P_a	acoustic power
P_{ref}	reference acoustic power
P_v	impact power
R	radius of piston crown
R_b	distance from the block surface
r	piston profile
S	overall skirt deformation
$\bar{s}_0$	acoustic field characteristic
t	time
U_{av}	speed of entraining motion of the lubricant
V_{av}	lubricant side leakage velocity
v	lubricant film squeeze velocity
v_r	surface vibration velocity
v_v	impact velocity
W	transferred energy
x	coordinate along the axis of the cylinder
Y	impact mobility
Z	impact impedance
z	coordinate transverse to the axis of the cylinder

Greek letters

η	lubricant dynamic viscosity
$\eta_{a/v}$	structural attenuation ratio
η_0	atmospheric dynamic viscosity of the lubricant
Θ	lubricant temperature
Θ_0	bulk oil temperature
θ	crank angle
ρ	lubricant density
ρ_a	density of air
ρ_v	density of the impacted structure
ρ_0	atmospheric density of lubricant
σ	surface radiation efficiency
ϕ	connecting rod obliquity angle

water-cooled gasoline engine at a speed of 2500 rpm [2]. As can be seen, combustion and piston slaps are significant contributors with their cumulative share representing about 80 percent of the total engine noise output [2]. Piston slap represents the most significant mechanical noise source, comparable with the combustion-induced noise [2–4].

Piston slap occurs due to the differing load conditions between the piston skirt and the cylinder wall. The type of contact is determined by the regime of lubrication, which can be hydrodynamic, elastohydrodynamic, mixed, or even boundary, depending on the prevailing kinematics/loading, geometry and lubricant rheological state [5]. The noise transfer mechanism from the piston assembly to the surface of the engine block is shown in Fig. 2. Piston slap depends on the variations of the cylinder pressure and the inertia of the piston assembly. The vibrations generated reach the engine block through the cylinder liner. Surface vibrations of the block induce sound propagation into the environment. The forces acting on the piston assembly originate from three main sources: (a)- the cylinder pressure, (b)- component inertia and (c)- the lubricant film. Numerous studies have been reported in modelling the cylinder pressure analytically [6,7], whilst this is commonly measured for piston-slap investigations [3,8,9]. Models describing piston dynamics usually exclude its tilting motion through piston pin rotation [10,11] or simply use constrained Lagrangian dynamics to include the component reactions due to piston rotation [8,12]. Methodologies involving multibody dynamics and Finite Element Analysis (FEA) software, such as MSC ADAMS and NASTRAN, have been reported for the study of piston secondary motion [13–16].

In earlier studies of piston dynamics, the effects of lubrication were generally neglected [10,11]. Later, a coefficient of friction was included in the equations of motion to account for the frictional losses [17]. In order to add the effect of lubricant film damping, spring-damper arrangements in parallel and/or in series have been considered [12,18–20]. A more accurate representation of lubricant behaviour is obtained through the solution of Reynolds equations [15,16, 21]. Cho and

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