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Modelling dynamic behaviour and noise generation in gear pumps: Procedure and validation

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ABSTRACT

The paper presents a methodology for noise and vibration analysis of gear pumps and its application to an external gear pump for automotive applications. The methodology addresses the use of a combined numerical model and experimental analyses. The combined model includes a lumped-parameter model, a finite-element model and a boundary-element model. The lumped-parameter (LP) model regards the interior parts of the pump (bearing blocks and gears loaded by the pressure distribution and the driving torque), the finite element (FE) model regards the external parts of the pump (casing and end plates), while the boundary element (BE) model enables the estimation of the emitted noise in operational conditions. Based on experimental evidences, attention has been devoted to the modelling of the pump lubricant oil: the fluid–structure interaction between the oil and pump casing was taken into account. In the case of gear pumps all these important effects have to be considered in the same model in order to take their interactions into account. The model has been assessed using experiments: the experimental accelerations and acoustic pressure measured in operational conditions have been compared with the simulated data coming from the combined LP/FE/BE model. The combined model can be considered a very useful tool for design optimisation.

1. Introduction

Noise, vibration and harshness (NVH) is an important attribute in vehicles. It is usually among the top five attributes in terms of its priority in the design of any vehicle type [1]. Like other attributes of safety, performance, dynamics and fuel economy, this attribute has to be considered closely in the design process. The attempts to reduce vibrations and radiated noise, while improving system performance, have become of increasing interest for the automotive industry in order to achieve high level of comfort in vehicles. Each vehicle component should produce low level of noise and vibration. Thus, a proper design of gear pumps used in the vehicle steering is crucial to control the emitted noise and vibration in operational conditions, maintaining high overall pump performance. Gear pumps use a very simple mechanism to generate flow and consist of a low number of parts. They combine good performance and low costs. The simplicity of their design translates into higher reliability as compared to other positive displacement pumps using more complex designs. However, gear pumps are often accompanied with noise levels that are generally higher than other types of pumps. Such noise levels are the consequence of the dynamic forces within the system, related with the flow and pressure ripple as well as the variable meshing stiffness and gear errors. Thus, in the hydraulic systems using this pump as a power source, taking countermeasures for noise and vibration reduction is one of the key points. In this scenario, numerical or analytical analyses can be useful to study the dynamics of gear pumps.

In the literature, several authors have addressed efforts to study gear pump dynamics. Refs. [2–9] contain a good description of the lumped parameter (LP) models used to simulate the pressure distribution and variable pressure forces acting on gears. In [10–14], the computational fluid dynamics (CFD) has been used for the development of numerical models of gear pumps in order to estimate the pressure distribution around the gear in operational conditions; a few of these works use structured mesh in each time step for the simulation, others dynamic non-structured mesh. With this latter technique, the mesh is adapted, through a spring-based algorithm, to the new geometry in each time step. In order to keep the mesh quality above a certain limit, cells are created and agglomerated where necessary. Li et al. in [15] have developed a dynamic model of gears which takes into account the contribution of the trapped oil in order to estimate the gears acceleration in an external spur-gear pump. In such a work the contribution of the journal bearing is not considered. Refs. [16,17] contain a good description of the mathematical models used to simulate the meshing stiffness

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Nomenclature

Latin symbols

B_{oil}	oil bulk modulus
C_T	torsional viscous damping coefficient of the driving shaft
h, l, w	height, length, width of a generic fluid film element
f_{bxk}, f_{byk}	bearing reaction applied to gear k in directions X and Y, respectively
f_{mg}	meshing force
f_{pxk}, f_{pyk}	pressure force applied to gear k in direction X and Y, respectively
$F_{ecX'}$, $F_{ecY'}$	external forces applied to pump casing and plate in direction X'_1 and Y'_1, respectively.
$F_{gcX'}$, $F_{gcY'}$	forces applied to pump casing and plate from gears in direction X'_1 and Y'_1, respectively
$F_{icX'}$, $F_{icY'}$	inertia forces concerning pump casing and plate in direction X'_1 and Y'_1, respectively
$F_{igX'}$, $F_{igY'}$	inertia forces concerning gears in direction X'_1 and Y'_1, respectively
J_k	moment of inertia of gear k
K_T	torsional stiffness of the driving shaft
M_{ecO_1}	external moment applied to pump casing and plate about point O_1
M_{gcO_1}	moment applied to pump casing and plate from gears about point O_1
M_{icO_1}	inertia moment concerning pump casing and plate about point O_1
M_{igO_1}	inertia moment concerning gears about point O_1
m_k	mass of gear k
M_m	motor driving torque
M_{pk}	pressure torque applied to gear k
N	maximum number of isolated tooth spaces
P_b	base pitch
p_i	pressure in control volume i
V_i	volume of control volume i
t	periodic time ($0 \leqslant t < T$)
T	meshing period ($T = 60/nz$, n is the rotational speed in rpm)
(x_k, y_k)	coordinates of the centre of gear k in reference frame O_k-X_kY_k

Greek symbols

α_w	pressure angle in operational conditions
Δp	pressure drop between adjacent control volumes
ΔQ	difference between the volumetric flow rate, coming into control volume i and coming out
θ	angular coordinate
θ_p	angular pitch
μ	oil dynamic viscosity
ω	angular speed

Subscripts

$i = 1 \ldots N$	denotes isolated tooth space volumes (control volumes)
$k = 1, 2$	denotes gears

phenomena in gear coupling; the majority of the simulations to date are based on rigid-body lumped-parameter models with the meshing teeth assimilated to a lumped variable stiffness. The simulation of the dynamic behaviour of a speed-increasing gearbox was also carried out using finite element (FE) methods in [18], where a 3D-contact FE model is used to model the time variable meshing stiffness of the gears, while the gearbox housing is modelled using tetrahedral solid elements. The combined analyses of gears and oil bearings have been developed in the literature using several oil bearing formulations. In particular, in Ref. [19] the dynamics of a spur gear pair supported by journal bearings was studied using the theory proposed in [20]. Gearbox vibrations have been widely studied in the literature by using several methods; in [21] by using a torsional vibration model, in [22,18] by using an FE model, in [23,24] by using a multibody model. Moreover, the noise and vibration behaviour of a gearbox has been modelled by using FE methods in [22]. The emitted noise of gear pump has also received attention in [25–27].

Thus, works that specifically deal with the dynamic phenomena occurring in gear pump were found in the literature, as mentioned above; however such effects have been shown and discussed separately; on the contrary, in the case of gear pumps all these important effects have to be considered in the same model in order to take their interactions into account. In fact, it has to be underlined that, gear accelerations, which can be estimated by LP models, are not directly related to noise and vibration emitted, due to the presence of the pump casing dynamics and noise propagation issues. Moreover, the flow pulsation and the variable pressure field around the gears, which can be foreseen by CFD or LP models, are not the only source of fluid borne noise. Several studies such as [28] show that there is a relation between flow ripple and air borne noise, at least in many operating conditions. It is also true that other phenomena related to the meshing process, bearing dynamics or casing resonances also contribute to noise emissions. For this reason, a complete methodology for noise and vibration analysis of gear pumps including the dynamic behaviour of gear pairs, the pressure evolution in a gear tooth space during the pump rotation, the journal bearing behaviour, the dynamic response of the external casing, the noise propagation as well as experimental verification has been developed, since it cannot be found in the literature.

In this work an external gear pump for vehicle steering is studied. The most usual configuration has two twin gears (see Fig. 1), which are assembled by a couple of lateral floating bearing blocks that act as seals for the lateral ends. Gears and floating bearing blocks are jointly packed inside a casing that encloses all the components and defines the isolated spaces that carry the fluid from the low to the high pressure chamber. The bearing blocks act as supports for the gear shafts by means of two hydrodynamic bearings, which are hydraulically balanced in order to avoid misalignments between gear shaft and journal bearing. Power is applied to the shaft of one gear (gear 1) and transmitted to the driven gear (gear 2) through their meshing. The driving shaft is connected by an Oldham coupling with an electrical drive. This pump works with a pressure ranging from 3.5 to 100 bar and angular speed ranging from 1500 to 3400 rpm. These authors have already developed and experimentally assessed a lumped-parameter model of such a pump [29–34]; the lumped-parameter (LP) model regards the internal parts as gears and bearing blocks. The LP model is a non-linear kineto–elastodynamic model and includes the most important phenomena involved in the pump operation, as time-varying oil pressure distribution on gears, time-varying meshing stiffness, gear errors and hydrodynamic journal bearing reactions [29–31]. The LP model was used in order to analyse the influence of a few design and operational parameters on the pump dynamic behaviour. In particular, the effect of operational pressure and speed, the influence of the clearance in the journal bearing and between tooth tip and pump casing, and the effect of the dimension of the relief grooves in the bearing blocks have been thoroughly discussed [32]. As model results, this analysis gives the gear