Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A method for variable pressure load estimation in spur and helical gear pumps

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ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form
22 December 2015
Accepted 9 February 2016

Keywords:
Gear pump
Spur gear
Helical gear
Variable pressure load
Dynamic analysis
NVH

ABSTRACT

A systematic procedure is proposed to determine variable excitation loads coming from pressure evolution inside tooth spaces in external gear pumps. Pressure force and torque are estimated with respect to the angular position of the gears, taking into account the phenomena that occur during the meshing course. In particular, the paper proposes a general methodology aiming at determining pressure force and torque components along the three coordinate axes and suitable to be applied on both spur and helical gear configuration. Firstly, the method to calculate pressure loads acting on a single tooth space during a complete revolution is given, then the total pressure force and torque loading each gear is obtained. Particular attention is addressed on the description of the helical gear scenario. As an example, the method is applied to a tandem gear pump, characterized by the presence of two stages, one with spur gears and one with helical gears. An experimentally assessed model to calculate the pressure ripple inside the tandem pump is described and the proposed procedure for pressure load estimation is applied. Eventually, the pressure loads estimated with the present procedure are compared with other estimation methods already described in the literature. The comparison shows that the present methodology is able to describe a wider range of phenomena involved in the meshing evolution and to determine all the pressure force and torque components applied to helical gears. The method gives suitable results to study the balancing and the dynamic behavior of gear pumps.

1. Introduction

Due to their features regarding the wide operating condition range, small dimensions and costs, spur gear pumps are nowadays considered as useful power sources for several applications (e.g. steering systems, automatic gearboxes and cooling systems). Within this framework, the need to improve their Noise, Vibration and Harshness (NVH) behavior without affecting their performances is becoming more and more compelling. The elasto-dynamic analysis of gear pump is a fundamental task to evaluate the pump's performances in terms of vibrations and emitted noise [1]. As it is well known, the definition of an effective dynamic model and the load determination generated by the different sources of the pumps are the two main steps to achieve this goal. When modeling the dynamic behavior of a gear pump, a number of main loads has usually to be considered: the torque transmitted by the driving motor, the meshing forces, the bearing reactions and the torque and force generated by the oil pressure evolution inside tooth spaces [2,3].

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http://dx.doi.org/10.1016/j.ymssp.2016.02.020
0888-3270/

Nomenclature

β	Helix angle of the gear, calculated on the pitch circle.
β_B	Oil bulk modulus.
ϑ	Angular position of the reference control volume.
μ	Oil dynamic viscosity.
ρ	Oil density.
ω	Angular speed in rad/s.
A	Surface used to define turbulent flows.
b	Gear width.
C_d	Discharge flow coefficient
F	Pressure force.
$F_{tot,i}$	Total pressure force applied to the gear center by tooth space i.
f_r	Rotational frequency in Hz.
h	Channel height, e.g. tooth tip/pump case clearance, tooth flank/pump case clearance.
i,j	Indexes of the reference control volumes related to the driving gear (i) and the driven gear (j).
k	Frame of calculus.
L	Channel length.
M	Pressure torque.
$M_{tot,i}$	Total pressure torque applied to the gear center by tooth space i.
n	Rotational speed in rpm.
P	Oil pressure in the reference control volume.
P_{TANK}	Oil pressure inside the tank.
Q_l	Volumetric flow rate under laminar condition.
Q_t	Volumetric flow rate under turbulent condition.
r,t	Subscripts used to indicate the radial (r) and tangential (t) component of the pressure force applied by a single tooth space.
r_{ext}	Radius of the external circle.
r_{root}	Radius of the root circle.
u	Tangential velocity.
V	Volume of the reference control volume.
V_{var}	Variable volume added to the inlet/outlet chamber.
w	Channel width.
z_n	Number of teeth.
x,y,z	Superscripts used to indicate the reference Cartesian components of the pressure force and torque.

The dynamic behavior of gear-pair systems has been widely studied during the last two decades; several authors have proposed numerical models to take into account periodic meshing stiffness, backlash and the presence of journal bearings [4–6]. These works took advantages from previous studies focused on the determination of excitation sources, e.g. the periodic meshing stiffness [7] and reactions, e.g. the journal bearing impedance [8,9]. Moreover, since the improvements in the result quality obtained by these dynamic models are strictly connected with the improvements in the excitation sources and bearing reactions estimation, various methodologies have been later presented. The meshing stiffness has been estimated by means of analytical [10] and numerical [11,12] approaches. Concurrently, efforts have been given in developing analytical models on journal bearings reaction estimation, based on approximate methods [13,14] or exact solutions [15]. Specific studies have been also focused on analyzing the journal bearing influence in gear pumps by means of experimental and numerical approaches [16–18].

From this brief review, variable pressure loads result to be the ones with the most critical determination and, thus, with a deep influence on the pump's dynamic behavior and axial balance [19,20]. A method for pressure force definition is introduced in [19] and later improved in [21], where the loading condition is calculated by a finite difference method and used to analyze the designing of bearing blocks balancing surfaces. The importance related to the determination of pressure force for investigating the performances of external gear pumps was already underlined in [22], being one of the main excitation sources for vibration of the pump case. Nevertheless, in [22] the authors did not provide a systematic method regarding their determination.

Moreover, the need to improve the NVH behavior of gear pumps has led to spread the use of helical gear pumps, mostly where low levels of pressure difference and high flow rates are required, even if, in the literature, this kind of gear pump has been rarely studied. The first works on helical gear pumps date back to the forties and they were focused on giving some slight details on the instantaneous and mean flow rate [23,24]. Later, in [25] the author provided an exhaustive explanation on the way the helix affects the theoretical outlet flow ripple. More recently, in [26] the pressure force and torque acting on helical gears has been discussed, nevertheless, the adopted approach is based on simplified hypothesis that led authors to neglect the components due to the presence of the helix, i.e. the axial pressure force and relative torque components. On the contrary, a wide effort has been put in studying external spur gear pumps, both through theoretical approaches focused on flow rate characteristics [27–29] and outlet pressure pulsation [30], and different computational techniques, such as lumped parameter modeling [31–33] and CFD modeling [34,35].

In the present work, a systematic procedure for the determination of the pressure force and torque acting on the gear shafts is introduced. The purpose is to clearly define an accurate and flexible methodology that can be easily implemented in different calculus environments and straightforwardly applied to both simulated and measured pressure data, in a wide variety of gear pumps. The outlined method is suitable to analyze both spur and helical gear pumps by determining all the spatial components of the pressure load (forces along three coordinate axes and relative torques). In order to assess this methodology, firstly an external gear pump made of two coaxial stages, one with spur gears and one with helical gears, has