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Enhanced model of gear transmission dynamics for condition monitoring applications: Effects of torque, friction and bearing clearance

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ABSTRACT

Gear transmissions remain as one of the most complex mechanical systems from the point of view of noise and vibration behavior. Research on gear modeling leading to the obtaining of models capable of accurately reproduce the dynamic behavior of real gear transmissions has spread out the last decades. Most of these models, although useful for design stages, often include simplifications that impede their application for condition monitoring purposes. Trying to filling this gap, the model presented in this paper allows us to simulate gear transmission dynamics including most of these features usually neglected by the state of the art models.

This work presents a model capable of considering simultaneously the internal excitations due to the variable meshing stiffness (including the coupling among successive tooth pairs in contact, the non-linearity linked with the contacts between surfaces and the dissipative effects), and those excitations consequence of the bearing variable compliance (including clearances or pre-loads). The model can also simulate gear dynamics in a realistic torque dependent scenario.

The proposed model combines a hybrid formulation for calculation of meshing forces with a non-linear variable compliance approach for bearings. Meshing forces are obtained by means of a double approach which combines numerical and analytical aspects. The methodology used provides a detailed description of the meshing forces, allowing their calculation even when gear center distance is modified due to shaft and bearing flexibilities, which are unavoidable in real transmissions. On the other hand, forces at bearing level were obtained considering a variable number of supporting rolling elements, depending on the applied load and clearances. Both formulations have been developed and applied to the simulation of the vibration of a sample transmission, focusing the attention on the transmitted load, friction meshing forces and bearing preloads.

1. Introduction

Gear transmissions remain as one of the most complex mechanical systems from the point of view of noise and vibration behavior. They are applied in several ways i.e. for speed changes, for torque gain, torque reduction or power split among others. The future foresees higher torque levels with a global increment in the power density, a reduction in energy

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consumption, better endurance and lower noise and vibration levels [1]. To cover these demands the industry should carry out a great effort on understanding the dynamics of these kinds of systems. In order to achieve this task, better theoretical models should be developed, which might be able to accurately reproduce the dynamic behavior of real gear transmissions.

Moreover, gear transmissions are critical components on a wide range of machinery i.e. helicopter transmissions, wind turbines and aerospace applications having a great impact on the final success of the whole system. As an example, in the case of wind turbines, gearboxes represent an important percentage of the final cost of the machinery but they are also a component especially susceptible to develop expensive failures, which have a great impact on the final profit in operation [2].

Therefore, besides its utility on the improvement of the gear transmissions design stage, the development of specific models capable to reproduce the dynamic behavior in operation, arise as a very interesting goal to their application in condition monitoring applications. This possibility has been suggested by some researchers such as Bartelmus [3], who proposed the use of a model of gear transmissions as an aid for diagnostics or Ho and Randall [4] who applied these kinds of tools for the case of bearings. Following this approach, during last years several authors have addressed the simulation of different kinds of faults in gear transmissions, such as gear cracks [5–7], tooth breakage [8], surface pitting and/or spalling [9,10], among others.

However, most of these models tend to present a lot of simplifications, without a detailed description of the most critical aspect involved in gear dynamics, which is the role played by the parametric excitation due to the variable number of meshing tooth pairs [11], as well as its inherent non-linearity.

On top of the variable meshing stiffness, gear transmissions are usually supported by rolling bearings, which undergo the same kinds of dynamic phenomena described for gears: a parametric excitation due to the variable number of rolling elements transmitting the load to the support. This variation in the number of rolling elements effectively supporting the load causes a variable stiffness in the bearings, and will result in the appearance of vibrations. These vibrations are characterized by multiples of the so-called Ball Pass Frequency (BPF) which is obtained as the product of the number of rolling elements by the cage rotation frequency. The consideration of the variable stiffness due to the angular position of the cage, and therefore of different numbers of contacting elements, was proposed by Gupta [12]. Later, Fukata et al. [13] developed a two-dimensional model including the effects of clearances, contact stiffness and parametric excitation. Nevertheless, the inclusion of bearing flexibility in gear dynamic models has been simply approached by considering bearings as time invariant flexible supports [14].

On the other hand, a reduced number of researchers have proposed advanced models combining gear and roller bearing dynamics, including the parametric excitation due to both elements in order to analyze the interaction between these elements and its consequences on the dynamics and vibratory behavior. An interesting example is the model proposed by Lahmar and Velex [15], who combines the gear model developed in [16] with a non-linear formulation for ball and roller bearings including the variable compliance of these elements. This formulation was linearized carrying out static and dynamic analysis in order to compare the results obtained with the original non-linear approach. Moreover, Sawalhi and Randall [17] developed a model for spur gear transmissions, focusing their attention on the inclusion of ball bearings with several types of faults.

Nevertheless, real transmissions present some features usually neglected in the mentioned models, such as the coupling among successive tooth pairs in contact and the non-linearity linked with the contacts between surfaces. These phenomena have implications in the load sharing between teeth pairs, and as a consequence in the actual contact ratio, due to the fact that the deformation values will be greater than the estimated ones from purely kinematic approaches, as those applied in previous models. Furthermore, shafts and bearings interact with gears, increasing the complexity of transmission dynamics. Depending on the level of the transmitted torque, those elements suffer deflections and hence the gear center distance becomes greater. Thus, the tooth engagement process is modified and consequently the meshing stiffness provides a different dynamic response for different torque levels. As a consequence, transmissions working under different load conditions result in a problem for conventional condition monitoring applications, as the alarm levels and the system set up must consider several working conditions.

Aiming to cover this gap, the authors developed an advanced model, combining rolling bearings and gears, for quasi-static analysis [18] showing the consequences in gear center orbits, transmission error and meshing stiffness when several levels of transmitted torques are applied. The computational features of the procedure for calculation of meshing forces based on a hybrid approach combining numerical and analytical tools were presented in [19] and subsequently applied on the quasi-static simulation of tooth defects like pitting and tooth cracks [20]. Afterwards, in [21] the model was extended to dynamic analysis and applied to simulate the impact of profile deviations, while in [22] index and run out errors were considered. This paper describes the enhancement of the model towards on condition monitoring applications by showing the interaction between the non-linear behavior of bearing and gears, assessing the consequences of meshing friction, bearing clearances and the level of the applied torque.

2. Model description and dynamic equations

Fig. 1 illustrates a schema of the sample transmission used, consisting of a couple of spur gears mounted on elastic shafts, which are supported by two ball bearings each. Each wheel is modeled as a rigid disk with lumped inertia at the center,