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Research paper

Planetary transmission load sharing: Manufacturing errors and system configuration study

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ABSTRACT

This paper addresses the effect of manufacturing errors such as eccentricity and planet pin positioning errors on the quasi-static behavior of a 3 planet planetary transmission, taking into account different configurations regarding the bearing condition of the sun gear shaft. The aim of the paper is to shed light on some untouched aspects of the load sharing behavior of planetary transmissions, such as the effect of radial positioning errors of the planets when different pressure angles are used, and the impact of the different loadings per planet on the actual load per tooth.

A modeling approach is employed, and physical explanations and simplified graphs are provided to help understand the behavior of the transmission when the sun is allowed to float and errors are introduced. The model used, developed by the authors and presented and validated in previous works, hybridizes analytical solutions with finite element models in order to compute the contact forces.

The results obtained show that the teeth loads are much lower than expected compared to the planet uneven loads, both in the non-defected and defected transmission, and that radial positioning errors have non-negligible effect on the load sharing ratio under certain operating conditions.

1. Introduction

One of the main advantages of planetary transmissions is its compactness. For high torques, instead of enlarging the wheels and thus its load capacity, planetary transmissions split the load into a number of paths. In this manner, the power is divided among several pinions, so that loadings per unit facewidth remain below nominal values while the torque is multiplied. Besides, planetary transmissions present coaxial input and output and large reduction ratios, with the most compact and lightest possible drives [1]. Under ideal conditions, each path in a planetary transmission carries an equal amount of load. Nevertheless, as in real systems there are inevitable manufacturing deviations due to errors and tolerances, the load is not equally shared amongst the different sun/planet/ring meshes, which can be a problem in terms of both durability (higher loadings per unit facewidth than expected) and dynamic behavior (vibrations due to changing loads, etc.).

The load sharing problem in planetary transmissions has been discussed in a number of publications, assessed by means of experimental tests [2,3], but mainly based on transmission modeling, from simpler analytical models [4] to more complex models including hybrid semi-analytical and finite element techniques [5].

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Due to its spatial configuration, planetary transmissions are complicated to model, but the critical importance of these gear systems in aerospace and energy generation applications makes the effort worth it. The main feature that characterizes the dynamic behavior of gear transmissions is the change in the number of teeth couples simultaneously in mesh. The meshing stiffness is therefore variable, and induces a periodic excitation in the system. Thus, the characterization of this periodic excitation is crucial in order to achieve better simulated results [6]. In a first step to increase modeling realism, the static transmission error has been used as excitation to predict dynamic behavior of planetary transmissions [7–9]. Nevertheless, more recent studies point that this approach, whilst remaining relatively valid for ordinary transmissions, may not be applicable to multi-mesh transmissions such as planetary ones [10]. With a higher degree of accuracy, at a second step evolution, there are gear models with time-varying stiffness. They give better off-resonance responses, but they are also used to identify regions of large amplitude vibration near resonances, where damping and other nonlinear phenomena strongly affect the behavior [11–13]. The latest and more advanced planetary transmission models are those based on computational approaches, frequently including FEM techniques in combination with different contact models [14]. In some cases, completely flexible bodies are considered in real time simulation [15]. Depending on the particular application of the model, different emphases are given to each modeling aspect [16], as is the case of non-stationary operation [17].

Studies on load sharing have usually been focused on the behavior of the transmission when defects are present, evaluating the effect of different configurations on the resulting load sharing, trying to find methods of improvement. As latest works, in [18] the effects of gravity, ring support stiffness and bedplate tilt angle of a wind turbine on the load sharing are studied through modeling approaches. In [19] and again in the wind turbine field the load sharing behavior of a compound planetary gear transmission in the presence of multiple-errors is analyzed, adding experimental results to verify the model approach. The effect of floating the sun gear in a planetary gearbox has been studied by [20], in order to absorb the consequences of geometrical imperfections.

In this paper, a planetary model is used to study the load sharing in quasi-static conditions, with the aim of shedding light on some untouched aspects of the load sharing behavior of 3 planet planetary transmissions, such as the effect of radial positioning errors of the planets when different pressure angles are used and the impact of the different loadings per planet on the actual load per tooth. Specially in this last case, the new information can improve the understanding of the tooth load per unit length when uneven LSR occurs, and therefore to produce better gear design processes. Although this new design insight is a direct consequence of the study carried out, the ultimate goal of the planetary gear modeling research presented here is the accurate reproduction of the transmission behavior in real conditions for on-condition monitoring assessment. The model used hybridizes analytical solutions with finite element models in order to compute the contact forces, making unnecessary the use of mesh stiffness waveform approximations or static transmission error excitation assumptions. The mesh model is based on previous work by the authors [21,22], extended and improved towards the planetary modeling as it can be found in [23]. Coupling through gear body deformations is also given a special attention, due to the multiple meshes per wheel. With respect to the contact point location and geometric overlap modeling approach used in this work, it has been conceived to allow for the almost direct inclusion of additional modeling features, such as tooth profile modifications (with an approach used in [24]) or the use of shifted gears [25].

2. Planet load sharing

There are many variations of planetary gear trains. However, whether simple or compound, with straight or helical gears, the vast majority of planetary transmissions designs share a fundamental quality: their compactness. This compactness can be understood in two different ways. The first has to do with the kinematic configuration of the planetary transmission (with a rotary planet carrier), which provides much higher ratios than those provided by conventional transmissions. Additionally, this configuration allows coaxial inputs and outputs, which is a plus for many applications, also economizing space. The second reason for which a planetary transmission can be seen as compact is the load capacity. The load capacity of a gear is ultimately determined by the size of their teeth, so that, in general, a large workload necessarily implies large gears accordingly. However, as planetary transmissions divide the total load on a variable number of paths (sun–planet and planet–ring pairs), the size of the gears can be reduced in the same proportion as the number of load paths used with respect to an ordinary transmission.

Ideally, each of the planetary load paths should transmit the same fraction of the total transmitted load. However, there are a number of reasons for which the load distribution may not be even in the actual operation of the planetary transmissions, the main two are the different path stiffness and the errors in the manufacturing and assembly process. Thus, there will be fluctuations in the working conditions of the various components, running out of the design conditions and causing overloads, in addition to the expected consequences on the dynamic behavior.

With this uneven load sharing among the different paths being highly undesirable, the first of the two sources mentioned above could be easily avoided. The variable meshing stiffness is an inherent characteristic of gear transmissions. An unbalanced load share among the planetary paths can be caused by the different phase of the meshing cycle between paths, and the direct way to avoid this would be the synchronization of the meshing paths. When this design is adopted, another problem arises: the differences between simple and double contact for each mesh of each path would pile up in the complete transmission error or apparent stiffness of the total planetary transmission, magnifying their peak-to-peak fluctuation and becoming a great source of vibration and noise. Because of this, the choice of synchronized planet design is not usual and, on the contrary, a softened shape of the global transmission error signal is desired, for which the different meshing paths are phased out $2\pi/n$ (where n is the number of paths or planets).

With respect to the second source of uneven load sharing it is not easily avoidable, as it is related to all the errors in the manufacture or assembly of the various components of the planetary transmission. The present work focuses on these and particularly on the errors in the planet positioning.