Non-linear dynamic behaviour of compound planetary gear trains: model formulation and semi-analytical solution

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Abstract: A discrete, non-linear, time-varying, torsional dynamic model of a multi-stage planetary train that is formed by any number of simple planetary stages is proposed in this study. Each planetary stage has a distinct fundamental mesh frequency and any number of planets spaced in any angular positions. The model allows the analysis of the gear train in all possible power flow configurations suitable for various gear drive ratios. It includes periodic variation of gear mesh stiffnesses as well as clearance (backlash) non-linearities that allow tooth separations. Equations of motion for the general case are formulated and solved semi-analytically using a hybrid harmonic balance method (HBM) in conjugate with inverse Fourier transform. Relative mesh displacements along lines of action of individual gear pairs were used as the continuation parameters to pass singular points and ill-conditioned equations in their proximity. At the end, a case study of a two-stage planetary train is used to demonstrate the effectiveness of the model and solution methods. The HBM solutions are compared to those obtained by a direct numerical integration method to assess their accuracy.

Keywords: multi-stage planetary gear trains, non-linear dynamics, torsional model, time varying, harmonic balance method, inverse discrete Fourier transform

1 INTRODUCTION

Planetary gear sets are widely used in many applications including automotive transmission, rotorcraft, wind and gas turbine gearboxes, as well as other marine and industrial power transmission systems. Planetary gear trains have many advantages over fixed-centre counter-shaft gear systems. The flow of power via multiple-gear meshes increases the power density, helping to reduce the overall size of the gearbox. The axi-symmetric orientation of the planet gears reduces the radial bearings loads and in many cases allowing its central members (sun gear, ring gear, or the planet carrier) to float radially. This reduces the effect of gear and carrier manufacturing errors on planet load sharing. Finally, the ability of multi-stage planetary sets in providing multiple speed reduction (gear) ratios has been the main reason for their extensive use for automatic transmission applications. Compound planetary trains are obtained from a number of single-stage planetary gear sets whose central members are connected according to a given power flow configuration. Input, output, and fixed (stationary) member assignments are made to certain central members to achieve a given gear ratio.

Most of the published planetary gear train dynamic models were limited to single-stage planetary gear sets. Early models were of linear time-invariant type (no backlash and constant mesh stiffness) where the eigen solutions and model summation techniques were used to predict the natural modes and the forced response [1–4]. These models were extended to study the neutralization or cancellation of excitations at each gear mesh through proper phasing of the gear meshing by specifying the planet position angles and numbers of teeth of gears [5–7].