Mechanism and Machine Theory 74 (2014) 370–389

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Experimental measurement of the effects of torque on the dynamic behavior and system parameters of planetary gears

Tristan M. Ericson [a], Robert G. Parker [b,*]

[a] Assistant Professor, Department of Physical Sciences, York College of Pennsylvania, York, PA 17403, United States
[b] L. S. Randolph Professor and Head, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, United States

ARTICLE INFO

Article history:
Received 22 February 2013
Received in revised form 23 September 2013
Accepted 18 December 2013
Available online 1 February 2014

Keywords:
Planetary gear
Vibration
Torque
Gear dynamics

ABSTRACT

Experiments designed to capture the independent motion of spur planetary gear components show the influence of mean operating torque on system parameters and dynamic response. All natural frequencies increase with higher torque, but the natural frequencies of modes with significant planet bearing deflection are particularly sensitive to torque. Current lumped-parameter models do not consider the anisotropic nature of planet bearing stiffnesses, but this research shows that the accuracy of these models is increased when the radial and tangential planet bearing stiffness components are calculated separately. These bearing stiffnesses depend on the mean bearing forces in the two directions. A finite element/contact mechanics model provides accurate calculation of the anisotropic, load-dependent planet bearing stiffnesses and the load-dependent mesh stiffnesses. An analytical model using these values accurately predicts changes in the experimentally measured natural frequencies of modes with high strain energy in the planet bearings for varying mean torque. Experiments also show changes in the mode shapes and damping ratios with changing torque.

1. Introduction

Planetary gears are used in many industrial applications because their multiple load paths increase power density through load sharing. The noise and vibration generated by the many gear meshes, however, is one drawback. The complexity of planetary gears increases modeling difficulty for gear designers interested in accurate prediction of dynamic response. Lumped-parameter models can quickly and efficiently predict dynamic behavior. These models, however, require accurate estimation of system parameters to correctly obtain natural frequencies and peak response amplitudes. Bearing stiffnesses and damping parameters in these models are often roughly estimated. The anisotropic nature of planet bearing stiffnesses is often neglected, so the bearings are typically assumed to be isotropic.

Cunliffe et al. [1], Botman [2], August and Kasuba [3], and Lin and Parker [4] presented models to analyze the in-plane vibration of planetary systems with spur gears. Other models have included the three-dimensional motion of helical gears [5–7]. Abousleiman and Velex [8] added the elasticity of the carrier and ring gear in a hybrid finite element/lumped-parameter model. Wu and Parker [9–11] presented an analytical model that considers the elastic deformation of the ring gear coupled to the lumped-parameter motion of the sun gear, carrier, and planet gears. Other advanced models consider compound planetary gears [12–14], nonlinearities [15–19], and gyroscopic effects [20,21].

The influence of planetary gear parameters on natural frequencies has been considered in the literature, but no experimental work has tied stiffness variation to system torque. Some studies [22,23] examine the sensitivity of natural frequencies and vibration modes to system parameters. Velex and Flamand [6] showed that mesh stiffness is a critical parameter affecting natural frequencies, but Saada and Velex [24] found planet pin stiffness to be less influential. Botman [2], however, saw that certain

* Corresponding author.
E-mail addresses: tericson@ycp.edu (T.M. Ericson), r.parker@vt.edu (R.G. Parker).

0094-114X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmachtheory.2013.12.018

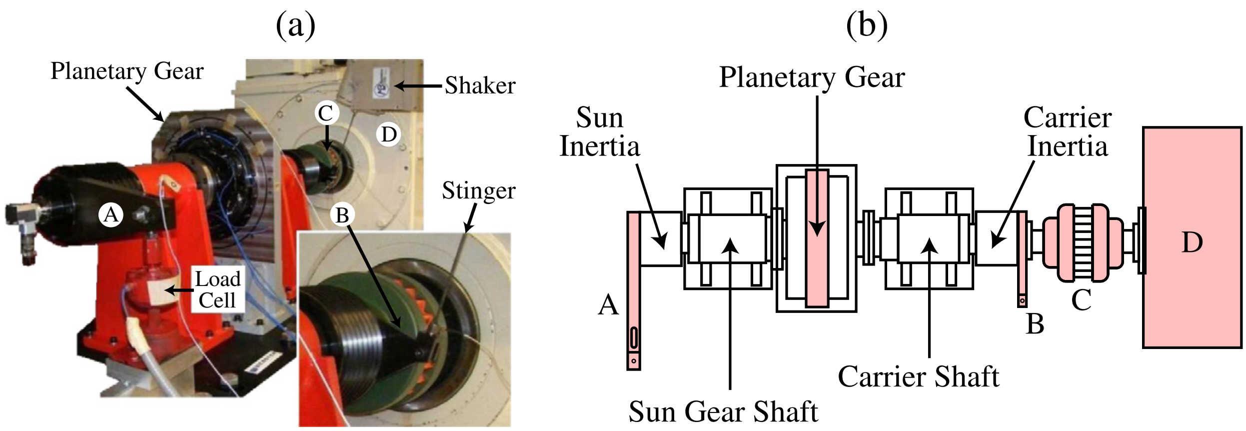

Fig. 1. Planetary gear modal testing setup (a) photograph and (b) schematic diagram showing (A) the load cell arm fixing the input shaft to the bedplate through a load cell, (B) an excitation arm, and (C) a compliant coupling that isolates the gearbox from (D) the torque actuator.

natural frequencies were more sensitive to planet pin stiffness than others. Through two orders of magnitude of planet pin stiffness variation, these natural frequencies moved from 1000–2000 Hz to 6000–7000 Hz.

Several papers consider the relationship between manufacturing errors and loading. Singh [25] showed that manufacturing errors can change the individual planet gear load sharing factors, which may cause premature wear and failure. Unequal load sharing can alter the mesh and bearing stiffnesses at the different planets. Frater et al. [26] considered unequal planet stiffnesses by comparing a nominal parameter set to a system with one mesh stiffness reduced by 50%. Toda and Botman showed that planetary gear vibration also increases with planet pin position errors [27]. Gu and Velex used a lumped-parameter model to study the dynamic effects of planet position errors [28] and eccentricity errors [29], which significantly affect the dynamic behavior.

This research experimentally investigates how the anisotropic nature of planet bearings and the load-dependent bearing and mesh stiffnesses affect the natural frequencies, mode shapes, and damping ratios of a spur planetary gear. Increasing system torque causes complex changes in dynamic behavior. Accurate estimation of the load-dependent radial and tangential planet bearing stiffnesses–which are not equal–and the load-dependent mesh stiffnesses is performed by a finite element/contact mechanics method [30]. A lumped-parameter model [4,31] using these load-dependent stiffnesses more accurately predicts the natural frequencies of the experimental system than a model with isotropic planet bearings.

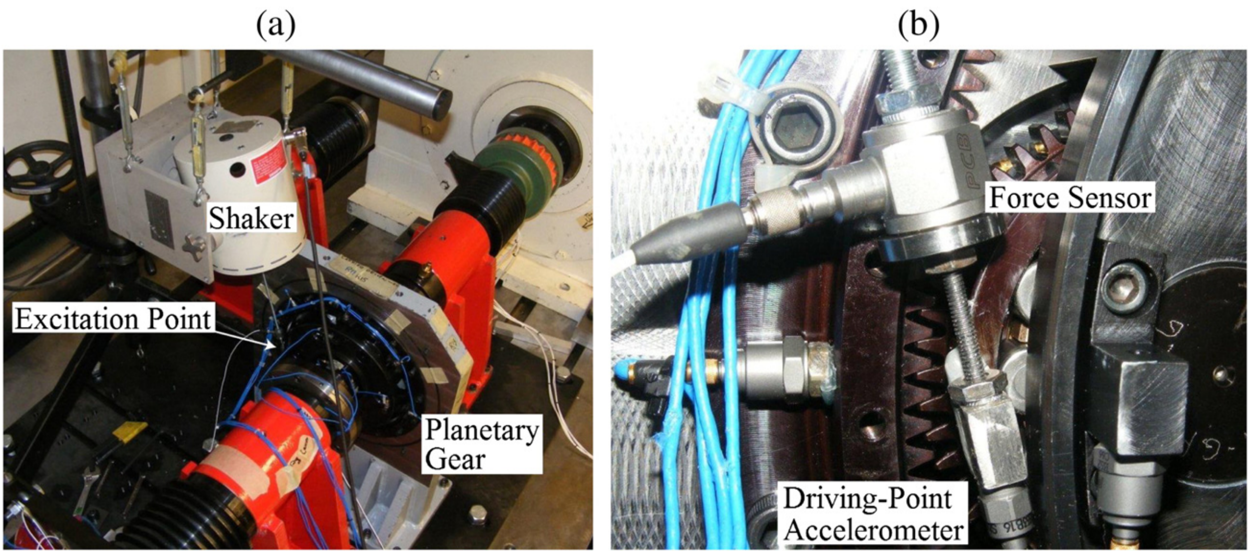

Fig. 2. Planetary gear modal testing setup photographs showing (a) the planetary gear excited by the modal shaker and (b) the shaker stinger attached to a planet gear parallel to the ring–planet line of action with a force sensor and a driving point accelerometer.