Modeling of Modulation Sidebands of Planetary Gear Sets

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Dissertation Research Motivation:

Vibration and noise spectra from automotive planetary transmissions commonly exhibit components at distinct frequencies around the gear mesh (tooth passing) frequency and its higher harmonics, called modulation sidebands. These sideband components constitute a significant portion of the vibration and noise generated by the transmission. Sidebands have significant influence on noise quality measures as well as having great potential to provide valuable clues in regards to manufacturing errors present in the gear set and in diagnostics of defects and fatigue failures. First critical step in designing and controlling the sideband activity of a planetary transmission is to develop a comprehensive model to predict modulation sidebands as well as describing the mechanisms causing sidebands. As the power transmission literature lacked such a comprehensive model, this doctorate dissertation research aimed at developing a family of planetary gear dynamics models to bring a phenomenological understanding to planetary sidebands.

Technical Methodology and Major Findings:

Two major root-causes of modulation sidebands are identified in this research as (i) amplitude modulations at fixed locations due to rotation of the planet carrier, and (ii) amplitude and phase modulations of gear mesh dynamic forces due to gear errors and unequal planet load sharing. The first mechanism was tackled by developing a simplified semi-analytical force transmission path model where the gear mesh forces are amplitude modulated based on their proximity to a fixed measurement point, as illustrated in Fig. 1. This model has shown that three sets of parameters define the sidebands caused by the rotation of the carrier: (i) the number of planets in the gear set, (ii) planet spacing angles around the sun gear, and (iii) number of teeth of gear components. These parameters determine the relative phase angles of dynamic forces at each gear mesh as well as planet spacing conditions. As a result, this model was used to classify planetary gear sets in five distinct groups based on their modulation activity: (1) equally-spaced and in-phase planets, (2) equally-spaced and sequentially phased planets, (3) unequally-spaced and in-phase planets, (4) unequally spaced and sequentially phased planets, and (5) unequally spaced and arbitrarily phased planets. Rules for the sidebands for each type of gear set were developed, including the spacing, frequencies and relative amplitudes (symmetric or asymmetric about the gear mesh frequencies) of the sideband components.

The second model focused on prediction of dynamic gear mesh forces of planetary gear sets having various manufacturing errors in the form of gear eccentricities, spacing and pitch-line run-out errors, and planet carrier pin hole position errors. The time-varying changes to the gear mesh excitations due to these errors were quantified by using a deformable-body model under quasi-static conditions and a discrete two-dimensional dynamic model of a planetary gear set was developed to predict dynamic gear mesh forces with such errors. It was shown that each error type provides a different set of sidebands at its signature frequencies. This dynamic model was coupled with the first model to include the amplitude modulations caused by the rotation of the carrier.

An extensive experimental study of planetary modulation sidebands was also carrier out for validation of the model predictions. A power-recirculation type test set-up shown in Fig. 2 was designed to test gear sets from each of the five categories identified above. The experiments were shown to confirm not only this qualitative classifications of the model, but also

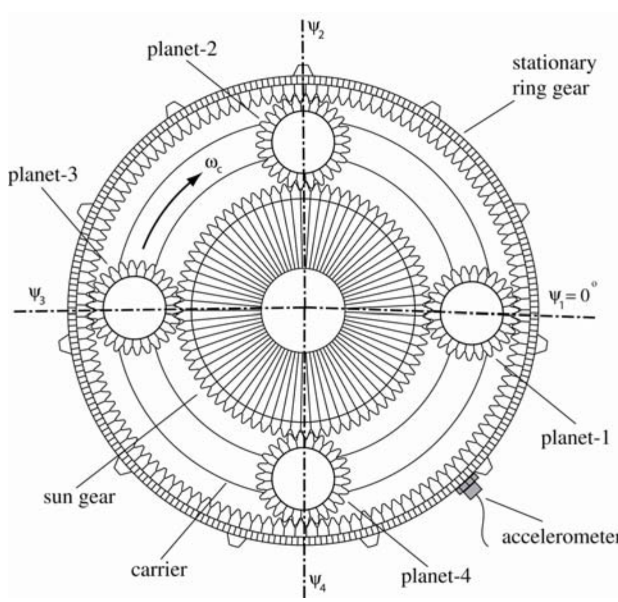

Fig. 1. A planetary gear set with four planets and a sensor mounted on the stationary ring gear.

demonstrated to match the predicted spectra quantitatively as illustrated in measured and predicted acceleration spectra displayed in Fig. 3.

Major Contributions to the State-of-the-Art:

This study provides the first published comprehensive methodology for modeling sidebands of planetary gear sets, fully describing the two major mechanisms of sidebands. The model allows a complete classification of planetary gear sets for their expected sideband behavior based on their basic design parameters. It also provides the foundation for future diagnostics, prognostics and sound quality studies on planetary transmissions. The experimental database formed in this study can be viewed as one of the most extensive databases focusing on planetary gear sidebands, which will be instrumental in validating and guiding future modeling efforts.

Journal Publications Based on the Dissertation Research

- M. Inalpolat, A. Kahraman, A theoretical and experimental investigation of modulation sidebands of planetary gear sets, *Journal of Sound and Vibration*, **323,** 677-696, 2009.
- M. Inalpolat, A. Kahraman, A dynamic model to predict modulation sidebands of a planetary gear set having manufacturing errors, *Journal of Sound and Vibration*, doi:10.1016/j.jsv.2009.09.022, 2009.
- M.Inalpolat, A. Kahraman, Dynamic modeling of planetary gears of automatic transmissions, *IMechE, Part K: Journal of Multi-body Dynamics*, **222**(3), 229-242, 2008.

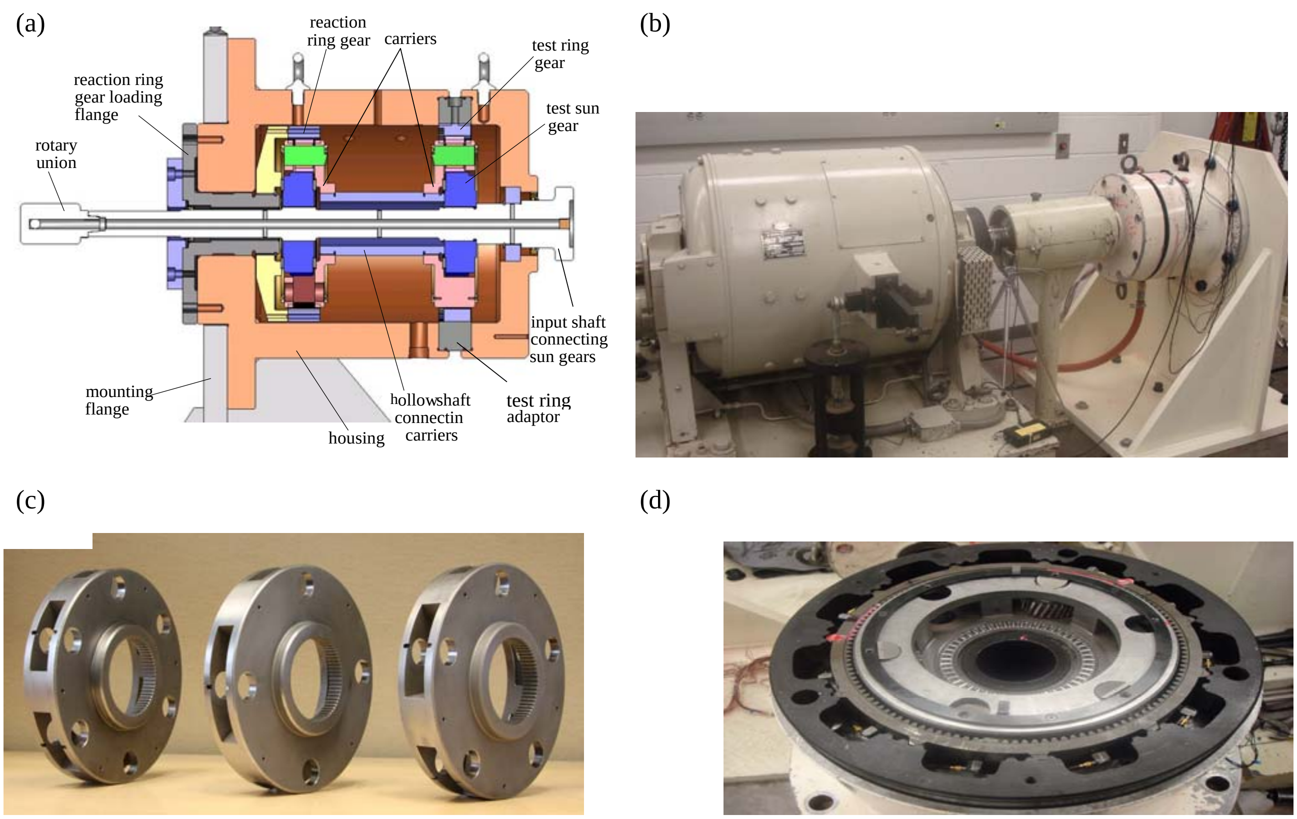

Fig. 2 (a) Cross-section of the back-to-back planetary test fixtures, (b) the test set-up on a transmission dynamometer, (c) 3, 4 and 5 planet carriers used in this study, and (d) accelerometers mounted radially on the outside surface of the test ring gear.

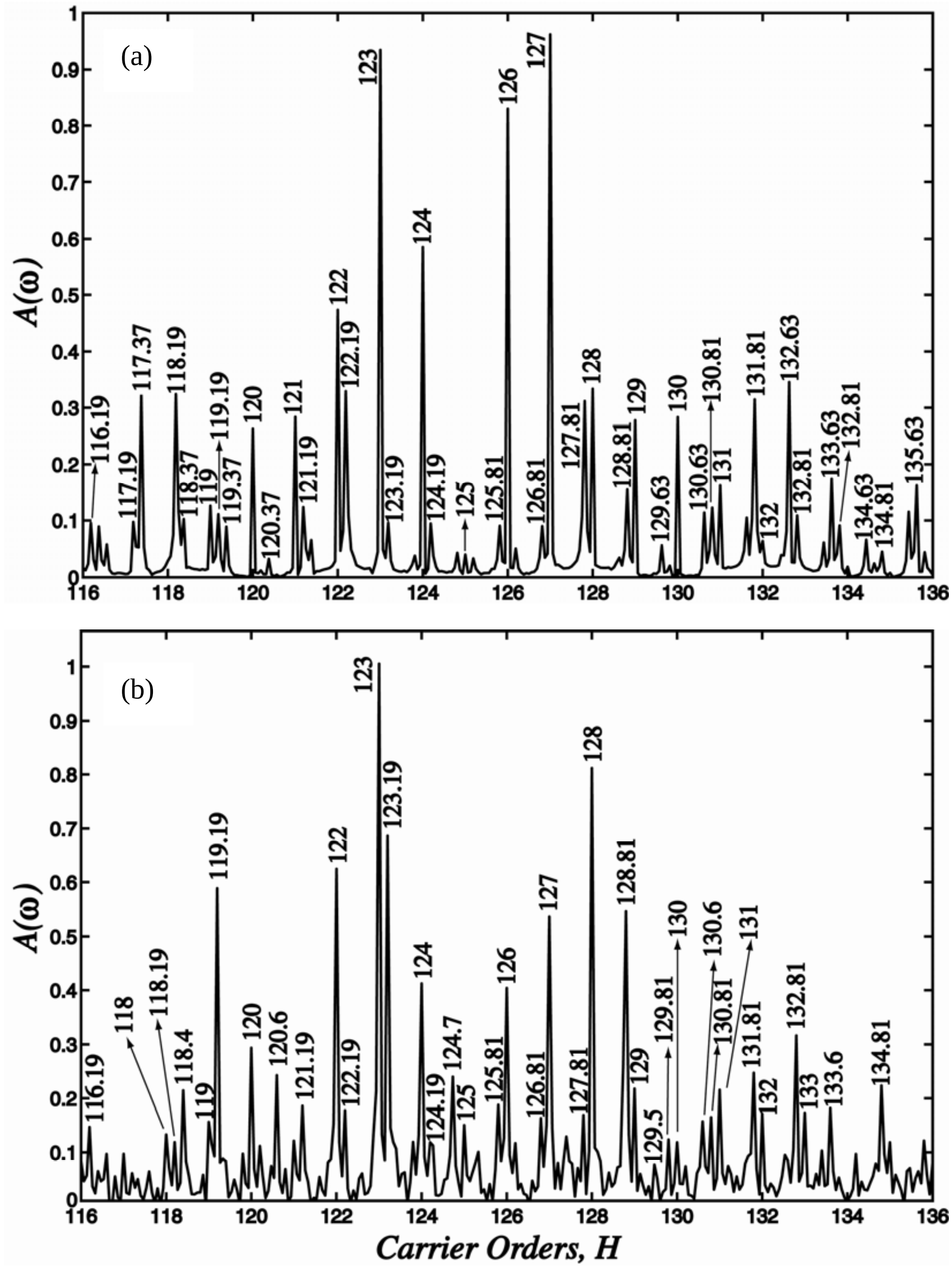

Fig. 3. (a) Measured and (b) predicted acceleration spectra from a 4-planet planetary gear set.