Modal vibration experiments conducted on a stationary planetary gear show that elastic-body motion is active in gear modes within frequency ranges of interest. Deformable body motions of the ring gear and planet gear are measured. There is a mode with a two nodal diameter shape of the ring gear and a mode with a three nodal diameter shape of the ring gear. Each of these modes are coupled to discrete degrees of freedom of other planetary components with planar rotational/translational vibration components. An elastic-body mode with significant continuous deformation of the planet gear is coupled to various discrete-body degrees of freedom and elastic vibration of the ring gear. Finite element simulation is used to further explore the nature of planet elastic continuum vibration in this mode. The results show extensive coupling between elastic and discrete degrees of freedom. Modes with elastic continuum vibration are identified experimentally in systems with three, four, or five planet gears. Consideration is given to phase relationships between elastic and discrete degrees of freedom. The experimental results suggest that elastic vibration of certain planetary gear components is not unique or exceptional. This behavior is likely present in many systems, although it is not considered in common lumped-parameter models. It also introduces the possibility of new failure modes, most notably fatigue and crack propagation.

Keywords: planetary gear, elastic ring vibration

1. Introduction

Recent advancements in planetary gear design have produced lighter, thinner components. The added compliance of these components helps compensate for manufacturing errors, but may promote elastic continuum vibration of the gears at operational speeds. Traditional lumped-parameter models do not consider elastic-body vibration, so potentially harmful physical behavior may be overlooked in design and analysis of many gears.

Elastic ring gear deformation has been studied by finite element analysis and analytical models. Abousleiman and Velex [1] use a hybrid finite element/lumped-parameter model to include elasticity of the ring gear and carrier. Kahraman and Vijayakar [2] use a finite element approach, focusing on ring gear deformation. Wu and Parker [3, 4] use an analytical approach to model the ring gear as an elastic continuum. There is, however, little published experimental data that examines the dynamic elastic deformation of planetary components. Hidaka et al. conducted several planetary gear experiments and published a series of papers. In their second report [5], they see that elastic...
continuum deformation dominates ring gear displacement in experiments. The ring gear is deformed into a triangular form, but the deformation is caused by tooth loads from the spatial periodicity of the three planet gears, not a dynamic mode of the ring gear.

This work presents experimental results of elastic-body vibration in the ring gear and planet gears. The measured dynamic response is active within the operating range of many systems and demonstrated on an experimental setup with practical dimensions similar to a production helicopter gear. The modes discussed appear in the frequency range of, and in many cases very close to, discrete body modes predicted by lumped-parameter models, showing that there is coupled discrete and elastic motion in many or all of these modes.

2. Experimental methods

The experimental hardware and setup is discussed in detail in [6]. A spur planetary gear is stationary during testing. A static torque is applied to the carrier while the sun and ring gears are rotationally constrained by fixtures. The planetary gear is excited at a planet gear along the line of action with the ring gear by a modal shaker. Accelerometers measures the rotational/translational discrete-body vibration of the sun gear, carrier, and two planet gears, as well as the elastic-body vibration of the ring gear. Fig. 1 shows a photograph of the experimental system with the modal shaker attached directly to a planet gear. The planetary gear used in the experiments is a custom gear design, but parameters are similar to a production helicopter gear. Systems with three, four, and five equally-spaced planet are tested. Gear parameters, including masses and stiffnesses, are given in [6] for what is called “Gear B” in that paper. The modes of interest are in the 1500-3300 Hz range.

![Figure 1: Photograph of planetary gear modal testing setup.](image)

3. Experimental modes with significant ring gear elastic deformation

Modes with ring gear elastic deformation are identified at 1600 Hz and 3740 Hz. Fig. 2a shows the vibration of the ring gear at 1600 Hz. The ring gear exhibits a two nodal diameter component shape at this mode. Fig. 2b shows the same result at 3740 Hz, where the ring gear exhibits a three nodal diameter shape. These modes demonstrate that elastic-body motion of planetary gears is present at frequency ranges generally thought to characterized by discrete, lumped-parameter, motion. Prior research [6] used a lumped parameter model to explore the vibration behavior in this range. These modes are particularly important because they are dominated by deflections in the tooth meshes, where excitation from transmission error and mesh stiffness variation exists. The 1600 Hz mode was previously thought to be a discrete-body mode in [6], and the 3740 Hz mode was missed entirely. Both are within the frequency range of interest for planetary gear modes. The elastic-body vibration in these modes has similar amplitudes as discrete-body vibrations.
3.1 Phase differences among planet configurations

Experiments on systems with three, four, and five planets show that the behavior illustrated in Fig. 2 exists in all of these configurations. The phases of planet gear discrete-body vibration at these modes, however, change with different numbers of planets. Table 1 summarizes the state of the planet gear discrete-body degrees of freedom for the 1600 Hz mode when the elastic-body vibration of the ring gear is in the same maximum deflection (as in Fig. 2a). The orbital trajectory of the planet gear also changes, reflecting differences in relative magnitude of the translational degrees of freedom among the different planet configurations.

Table 1: State of discrete-body degrees of freedom in the 1600 Hz mode with different planet configurations when the elastic-body vibration of the ring gear is in the maximum deflection state shown in Fig. 2a.

<table>
<thead>
<tr>
<th></th>
<th>Three planets</th>
<th>Four planets</th>
<th>Five planets</th>
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<tbody>
<tr>
<td>Planet rotation</td>
<td>maximum CCW</td>
<td>maximum CCW</td>
<td>maximum CW</td>
</tr>
<tr>
<td>Planet x-translation</td>
<td>maximum (-)</td>
<td>maximum (+)</td>
<td>maximum (-)</td>
</tr>
<tr>
<td>Planet y-translation</td>
<td>0</td>
<td>maximum (+)</td>
<td>maximum (-)</td>
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The deflected ring gear shapes are also similar in all three planet configurations for the 3740 Hz mode, but the phases of the planet gear discrete-body vibration change with different numbers of planets too. Table 2 summarizes the state of the planet gear discrete-body degrees of freedom for the 3740 Hz mode when the elastic-body vibration of the ring gear is in the same maximum deflection state (as in Fig. 2b) for the 3740 Hz mode. Planet gear rotational motion is near equilibrium in all three cases, but the translational components have opposite phase relationships in the four-planet gear system compared to the three-planet and five-planet systems. The tangential component is maximized in the four-planet gear system, but it is zero in the three-planet and five-planet systems. Likewise, the radial component is at a maximum negative value in the three-planet and five-planet gear systems,
but it is zero in the four-planet system. The orbital trajectories of the planet gear in those figures are reasonably similar; they all show more vibration in the tangential ($y_p$ component) direction than the radial ($x_p$ component) direction. This observation differs from that for the 1600 Hz mode, which shows more significant variation in the orbital paths among the different planet configurations. In total, the experiments show complex phase relationships between components.

Table 2: State of discrete-body degrees of freedom in the 3740 Hz mode with different planet configurations when the elastic-body vibration of the ring gear is in the same maximum deflection state shown in Fig. 2b.

<table>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>maximum (-)</td>
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<td>Planet $y$-translation</td>
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</table>

4. Experimental mode with significant planet gear elastic deformation

The elastic-body deformation of the ring gear noted above is interesting, but it is not entirely surprising. Ring gear elastic-body deformation is expected in many applications, though usually in designs that are lighter and operating at higher speeds that the gear we are studying. Planet gear elastic-body deformation, however, is a surprising result. In an experimental setup not designed to study elastic deformation, we see the elastic-body ring gear deformation discussed above and elastic-body deformation in the planet gear in another mode. Experiments show expected gear modes predicted by lumped parameter models below 4000 Hz, but a large resonance at 5860 Hz indicates significant vibration behavior not predicted by discrete-body modeling.

We suspect that there is a significant amount of planet gear elastic-body vibration in the 5860 Hz mode because (1) it is not predicted by the lumped parameter model, (2) is most active in the planet gear and local radial elastic-body deformation of the ring gear, and (3) exists at a frequency higher than modes predicted by a lumped parameter model or modes containing elastic-body ring gear deformation. Our experiments are not equipped to measure planet gear elastic-body vibration, but we can observe other aspects of this mode, including elastic-body ring gear deformation, at this frequency.

Fig. 3 shows experimentally measured discrete-body vibration of the 5860 Hz mode. This figure shows the rotational/translational motion of the excited planet gear, sun gear, carrier, and one other planet gear. It also shows the radial elastic-body deformation of half the ring gear with five accelerometer measurement points located by the solid dots. Dashed lines indicate the equilibrium position of the planetary gear with the straight ones showing the nominal rotational position of planets and central members. The magnitude of discrete-body rotational vibration of the central members and two planet gears is indicated by a solid line for each body. This line is tied to the mass center trajectory of each of the four discrete-body components. The sun gear orbit is too small to see. The carrier trajectory is almost a diagonal line, indicating in-phase vibration and little damping in this component. The images in Fig. 3 are created by animating the measured vibration from accelerometers during steady-state excitation of the 5860 Hz mode. Carrier translation is the most prominent central member vibration. The active discrete-body degrees of freedom in the 5860 Hz mode are planet rotation, planet translation, and carrier translation. Neither this mode nor the 3740 Hz mode with significant ring gear elastic deformation are predicted by lumped parameter modeling.

Computer simulation tools are used to determine if the planet gear experiences elastic-body deformation in the 5860 Hz mode. A finite element/contact mechanics software developed by Vijayakar
[7][8] can give the discrete-body motion of gear components along with the elastic-body deformation at finite element nodes. A simulation of the experiments shows that the planet gear experiences two nodal diameter component deformation in this 5860 Hz mode. A two nodal diameter elastic-body vibration of the planet gear clearly dominates the response. Some rotational discrete-body motion is noticeable, which was an important piece of the experimental measurements.

5. Conclusions

Modal vibration experiments reveal interesting elastic-body vibration modes in planetary gears on a test stand originally designed to quantify discrete-body motion. One of these modes has significant planet elastic-body vibration, and the other two involve principally elastic-body ring gear vibration. A finite element model is used to further define this behavior. This research shows the importance of considering elastic-body vibration in planetary gear research and design. The test planetary gear, which is closely based on a helicopter planetary gear, is not intentionally designed to highlight this behavior, so these types of modes are likely active in numerous practical systems, especially in lightweight high-speed applications or systems with intentional compliance to improve load sharing or robustness against manufacturing errors.

6. Future Work

A more comprehensive, expanded version of this work is in preparation for journal publication.

REFERENCES


