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Transmission error model-based optimisation of the geometric design parameters of an automotive transmission gearbox to reduce gear-rattle noise

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ABSTRACT

The optimisation of gearbox geometric design parameters to reduce gear-rattle noise in an automotive transmission based on a transmission error model is presented. Towards this aim, a four-degree-of-freedom torsional vibration model for the geared system is obtained. Differential equations of the pinion gear-wheel gear system are obtained. The state-space forms of the differential equations are obtained. The transmission error of the gear system is calculated via a state-space model. An empirical model is used for rattle noise calculation for the five-speed gearbox. The transmission error is considered as the objective function, and bending stress, contact stress and the constant distance between gear centres are considered as constraint functions. By optimising the geometric parameters of the gearbox, such as the module, number of teeth, axial clearance, and backlash, it is possible to obtain a gear structure with high bending and contact strength and to minimise the torsional vibration, transmission error and gear-rattling noise. It is concluded through optimisation that minimising the transmission errors of the gearbox leads to reduced vibration and noise levels of the gearbox. It is determined that the optimised geometric design parameters reduce the calculated rattle noise level by 10% [dB] compared with the sample five-speed gearbox. Furthermore, a 95% reduction in transmission error results in a 12% decrease in rattle noise. All optimised geometric design parameters are significant for the required constraints.

1. Introduction

The optimisation of gearbox geometric design parameters to reduce gear-rattle noise in automotive transmissions based on a transmission error model is presented. The purpose of this study is to reduce gear-rattle noise by minimising the transmission error. Transmission errors are calculated based on torsional vibration equations via state-space equations.

Transmission error results both from manufacturing inaccuracies and from design inaccuracies. Therefore, transmission error is an important parameter during significant gear design.

Gear motion causes gear-rattling noise and gear-clattering noise, and a low noise level is required for high comfort in the automotive design. Hence, reducing gear-rattling noise and gear-clattering noise in the automotive transmission is necessary to increase the comfort level in car design.

The following results on rattling noise are presented in the literature:

The main transmission noises are rolling contact noises of gear pairs under load, which can be described as whining noises. Tooth rigidity changing with the meshing position causes the whining noises. A second kind of noise is gear-rattle noise, which may occur with automotive transmissions if unloaded gear wheels are excited by torsional vibration [1].

The maximum rotation between the two gear wheels indicates the beginning of the gear-rattle limit and the beginning of double-sided impacts. Gear rattle starts at the point where the rotation becomes greater than zero [1].

Gear-rattling noise in change-over gears of automobiles is an unwanted phenomenon and causes comfort problems. The torsional vibrations of the transmission system cause excitation at the entrance of the gearbox [2].

Gear-rattling and gear-clattering noises are caused by torsional vibration. The internal combustion engine causes this torsional vibration. If the transmission is in neutral, it is called gear-rattling noise. If the gear is under power, it is called clattering noise, which was concluded in [3].

Gear rattling and gear clattering are caused by the torsional vibration of loose parts. Idler gears and synchroniser rings are loose parts in the neutral position, which was concluded in [3].

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The amplitude of angular acceleration is a crucial operational parameter for the torsional vibration in automotive transmissions [4].

The formation of a hydrodynamic lubrication film between gear teeth also reduces the rattling noise in automotive transmissions [4].

The tribological parameters have only a small influence on whining noise but strongly determine the lubrication conditions and, therefore, the lifetime and efficiency of the transmission [1].

Optimisation of the macro-geometry for gear teeth with a high contact ratio leads to reduced noise levels. Optimisation of the micro-geometry for gear teeth with profile corrections generally leads to lower transmission noise, which was concluded in [5].

Increasing the module and the number of teeth results in high rattle noise level. Similarly, axial clearance causes increased rattle noise level, up to a maximum axial-clearance value. In contrast, backlash causes reduced rattle noise until a maximum value of backlash, and then, the gear-rattle noise increases, which was concluded in [6].

The following results on transmission error are presented in the literature:

The large dynamic transmission error amplitudes also result in large dynamic force. Furthermore, dynamic transmission error increases both vibration and noise behaviours, which was concluded in [7].

Increasing the geometric design parameters of gears results in increased stiffness coefficient K_e of the gear tooth and increased Rayleigh damping D_e and thus reduces transmission error TE, which was noted in [8].

To achieve further reductions in gear noise, one of the methods is optimisation of the geometry to minimise the transmission error TE [μm] and, hence, minimise noise, which was concluded in [9].

Experiments show that decreasing TE [μm] results in decreasing transmission sound level, which was noted in [10].

2. Gearbox mechanism

A five-speed manual gearbox mechanism is shown in Fig. 1, where Z_{1p}, Z_{2p}, Z_{3p} and Z_{4p} denote the 1 st-speed pinion gear, the 2nd-speed pinion gear, the 3rd-speed pinion gear and the 4rd-speed pinion gear, respectively; Z_{Cp} and Z_{Rp} denote the constant-speed pinion gear and the rear-speed pinion gear; Z_{g1}, Z_{g2}, Z_{g3} and Z_{g4} denote the 1 st-speed wheel gear, the 2nd-speed wheel gear, the 3rd-speed wheel gear and the 4rd-speed wheel gear, respectively; Z_{Cg} and Z_{Rg} denote the constant-speed wheel gear and the rear-speed wheel gear; and S_1, S_2 and S_3 denote synchronisers.

3. Gear-rattle noise model

An empirical model is used for the rattle noise calculation of a five-speed gearbox for a five-speed automotive transmission.

3.1. Rattling noise sources

Rattling noise sources are idler gears in both neutral position and under power. Gears responsible for rattling noise are summarised in Table 1.

When an automotive transmission is in the 1 st-speed position, all gears except for 1 st-speed gears are responsible for rattling noise. For the 2nd-speed position of the automotive gearbox, all gears except for 2nd-speed gears cause rattling noise. For the 3rd-speed position, all gears except for 3rd-speed gears are sources of rattling noise. While the automotive transmission gearbox is in the 4th-speed position, 1st-, 2nd-, 3rd-, 5th- and rear-speed gears are responsible for rattling noise. In summary, for each speed position, all unloaded gears are responsible for rattling noise.

To reduce rattling noise, optimisation of the geometrical parameters of gears that play effective roles in rattling phenomena is a crucial method.

3.2. Design parameters for a gearbox

General definitions and specification factors for gears are given in DIN 868 as follows:

3.2.1. Module m

The module m is the basic parameter for the linear dimensions of gear-tooth systems. It is found by dividing the pitch p by the number π. It is determined by the dimensions of the datum surface and the number of teeth; see Fig. 2a.

3.2.2. Number of teeth z

The number of teeth z of a gear is the number of teeth present on the full circumference of the gear or feasible for a chosen pitch; see Fig. 2b.

3.2.3. Face width b

The face width b is the distance between the two end surfaces on the datum surface of a gear-tooth system; see Fig. 2c.

3.2.4. Helix angle β

The helix angle β is the angle between the helix line and horizontal axis; see Fig.2d.

3.2.5. Backlash s_v

The backlash s_v is the clearance between the gear pair of non-contact when the working flanks are in contact with one other; see Fig. 2e.

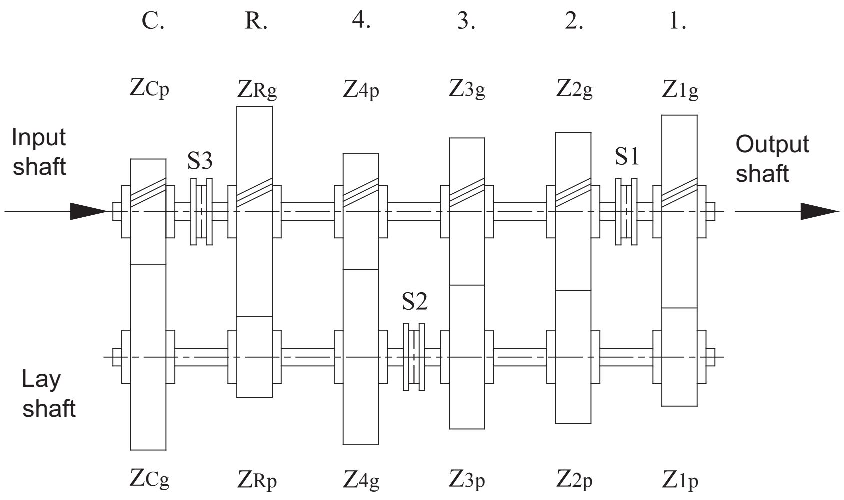

Fig. 1. Five-speed gearbox for automotive transmission.