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电动车尾门电动推杆用低音调齿轮的开发与验证

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摘要: 高速电动机目前被广泛用于汽车自主驾驶系统。由于高速电动机采用小质量设计,因此为了使转速和输出扭矩达到目标值,通常将渐开线齿轮组和它配套使用。然而,传统的渐开线齿轮在工作中噪声较大,因此一种新型的具有不规则轮齿设计的低音调(Low-Tone)齿轮被开发,以减少齿轮传动装置的噪声。通过优化算法,开发设计了一种Low-Tone齿轮,并应用于一个驱动电动车尾门启闭的电动推杆系统。之后在该系统运行期间,对使用Low-Tone齿轮和使用传统齿轮所产生的声压进行测量对比。结果表明,Low-Tone齿轮对于噪声有较好的抑制作用,其优势特别体现在音调特性方面。

关键词: 低音调齿轮;噪声降低;音调特性
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Validation of Noise Reduction Using Low-Tone Gearing on a Push-Rod System

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Abstract: Electric motors with very high speeds are used widely for highly automated and autonomous driving. A low weight design of high-speed electric motors can reduce the demand for environmentally harmful materials. However, due to the regular involute gears, which are usually used with high-speed motors to bring the rotation speed and output torque into target values, a noticeable and extremely annoying tonal noise occurs, which compromises the comfort of passengers significantly. Thus, an innovative low-tone gearing with irregular design of tooth is introduced to reduce the noise of gear transmissions. To obtain a low-tone gearing design for an electric push-rod system, which operates the tailgate of vehicles to either open or close, an optimization is conducted. Then for comparison, the sound pressure of the low-tone gearings and a regular design is measured during the operation of the push-rod system. Finally, the reduction of noise by using the low-tone gearing, especially from the aspect of the tonality, is validated by analyzing the measured data.

Key words: low-tone gearing; noise reduction; tonality

1 Introduction

The sound characteristics of E-automobiles are becoming increasingly relevant. In the subjective noise assessment by users, a system that does not sound “good” is often associated with malfunctioning and thus often leads to complaints[1-2]. Particularly, in the case of vehicles, noise emission is playing an increasingly important role due to the growth of electrified powertrain. The elimination of the combustion engine makes the noise of transmission more prominent because of the lack of the masking effect[3-4]. Furthermore, the high-speed motor has gained more and more attention recently because it needs less magnets and is therefore lightweight[5]. On the down side, the high-speed motor leads to an unpleasant high frequency tonal sound characteristic, which is evaluated by the human perception as very disturbing[6]. The highly periodic excitation of force during gear meshing is responsible for the tonal transmission noise[5].

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In order to reduce the tonal noise, we introduce irregularity into the transmission design. The use of irregularity for noise reduction has been widely researched previously. The optimization of irregularly arranged blades in propellers and fans are discussed in several publications[7-8]. Batjargal et al. evaluate the noise reduction of rail vehicles with random sleeper spacings numerically[9]. For transmission system, we focus on the low-tone gears developed by Neubauer et al., more precisely the approach of using an uneven tooth geometry for the purpose of tonal noise reduction[10-11]. This research is conducted by Research Group System Reliability, Adaptive Structures, and Machine Acoustics SAM TU Darmstadt in the Project "Validation of Inequidistant Gearings for Autonomous Driving", which is funded by Pioneer Fund program of TU Darmstadt.

In Section 2, the concept and design approach of low-tone gearing are further presented. Different from the regular gears, the position and thickness of gear teeth become variables, which are optimized using Monte-Carlo simulation (MCS) and neighborhood search. The experimental validation of low-tone gearing with a push-rod system is described in Section 3. Based on the analysis of the measurement data in the aspects of sound pressure level and tonality, the advantage of low-tone gears for the noise reduction is validated. In Section 4, the summary and outlook are delivered considering the perspective and challenge of low-tone gearing.

2 Low-Tone gearing

2.1 Design of Low-Tone gearing

Neubauer et al. introduce uneven mesh stiffness in the design of low-tone gearing in order to bring irregularity into the structural dynamic excitations while gear meshing[11]. Because of uneven tooth thickness and tooth space, an arbitrary pair of tooth and tooth space of matching gears are no longer guaranteed to be compatible. Thus, a pattern-wise design with a length of Φ teeth is conducted. Several identical patterns are repeatedly arranged for both gears to achieve the desired gear ratio.

In order to fully describe the variations of tooth position and thickness, Neubauer et al. use the relative dimensionless factors, i. e., position factor ΔQ_j and thickness factor Δs_j for tooth j regarding the regular centered circular pitch $p_{c,0}$, which is defined as the relative position between the centers of two adjacent teeth of a regular gear[11-12]. The absolute circular position of tooth j is described as:

$$Q_j = Q_{j,0} + \Delta Q_j p_{c,0} \quad (1)$$

where $Q_{j,0}$ is the absolute circular position of the regular gear. Because the tooth positions are defined related to a specified position on pitch circle, the ΔQ_1 of the first tooth in a pattern to zero to establish a reference point for tooth positions[11]. Similar to the tooth positions, the absolute tooth thickness for tooth j is defined as:

$$s_j = s_0 + \Delta s_j p_{c,0} \quad (2)$$

where s_0 is the absolute regular tooth thickness[11]. If the pattern on one of the matching gears are defined, the tooth positions and tooth thicknesses on the mating gear are also determined[11]. Thus, a low-tone design can be described with $2\Phi - 1$ parameters, i. e., $\Phi - 1$ position factors ΔQ_2, ΔQ_3, $\cdots$, ΔQ_Φ and Φ thickness factors ΔQ_1, ΔQ_2, $\cdots$, ΔQ_Φ.

2.2 Optimization of parameters

Based on a regular gear, the low-tone gear is defined with $2\Phi - 1$ parameters, as described in Section 2.1. Thus, total $2\Phi - 1$ parameters should be altered in the simulation of sound pressure level (SPL) for optimization. The peak $K_{\max}$ in the order spectrum of SPL is selected as the criterion of optimization in order to spread the sound energy into a large number of orders. This criterion has been validated on listening tests[10]. The optimization takes place by a two-step procedure, as shown in Fig. 1.

In the first step, use Monte-Carlo simulation globally to find the optimal position in full search space of $2\Phi - 1$ parameters. After 10,000 times of random iterations of MCSs, the solution that has the lowest $K_{\max}$ is selected for the second optimization, which is the neighborhood search. In this step, the optimal solution is searched with an increment of ± 0.01 for each parameter iteratively, until no reduction of $K_{\max}$ is achieved. By doing this, the optimal parameters for low-tone gearing in Tab. 1 are finally determined.

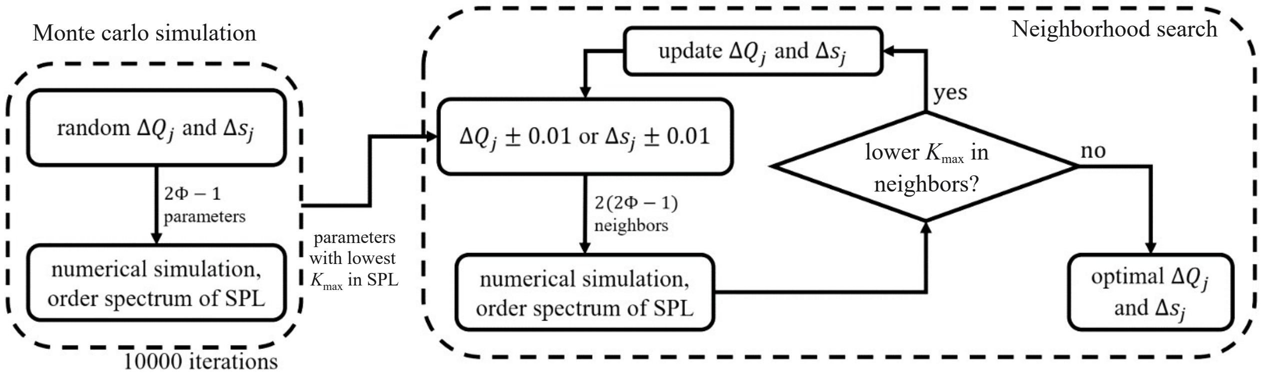

Fig.1 Procedure of optimization

Tab.1 Optimal parameters after two stages of optimization

j	1	2	3	4	5	6	7
ΔQ_j	0	0.0662	0.0988	0.1223	−0.1492	−0.0663	0.0686
Δs_j	−0.0780	−0.1414	−0.0389	0.0312	−0.1222	−0.1031	−0.0977

3 Experimental validation

3.1 Push-rod system

The experimental validation of the low-tone gearing is conducted in a compact push-rod system with four stages of gearing transmission. In real application, this push-rod system is used to operate the tailgate of vehicles to open and close. Its motor rotates up to 2 400 r/min to push the rod for a range of about 55 mm. In order to simulate the real application scenario, a test bench is constructed based on a tailgate simulator of a vehicle which is provided by the automotive supplier (see Fig. 2). The first stage of gears is going to be optimized, because the pinion on the motor shaft has the highest rotation speed in this push-rod drive system.

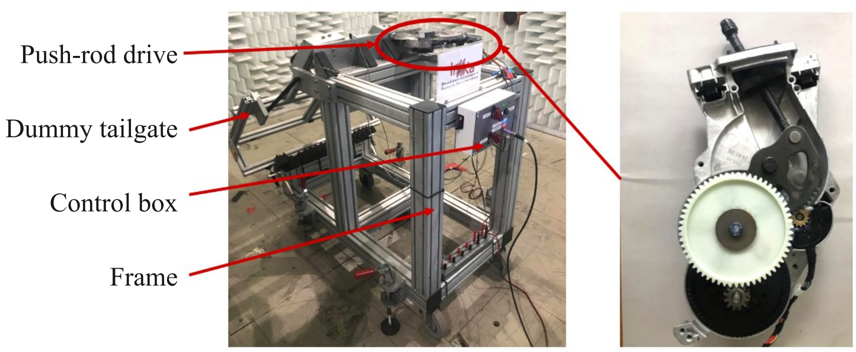

Fig.2 Construction of test bench

3.2 Results of optimization

The large gear and the small pinion at the first stage of transmission are made out of different materials, i. e., Polyoxymethylene (POM) and brass respectively. These are helical gearing with teeth numbers $z_a=14$ and $z_b=83$. For a simple manufacturing, we change these gears to spur gears so that the gears can be prototyped by waterjet cutting technique quickly. In order to put a pattern of gear teeth into the gears without changing the transmission ratio too much, the number of teeth on large gear z_b is raised from 83 to 84. Therefore, a pattern of seven teeth can be implemented. The pattern on the large gear repeats twelve times and the pattern on the small pinion repeats two times along the circumference.

After two stages of optimization, a design of low-tone gearing for the first stage of push-rod drive is obtained (see Fig. 3). Compared to the regular gearing, the simulated SPL of low-tone gearing shows a significant reduction of the maximum value from 79.4 dB to 66.9 dB in order spectrum (see Fig. 4). Besides, the curve of low-tone gearing is smoother without peaks every 14 orders, which means that the sound pressure spreads over more orders and the tonality in sound pressure is lower.

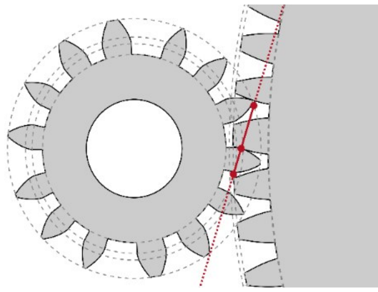

Fig.3 Layout of low-tone gears

3.3 Evaluation of measurement data

First, the order spectrum of the sound pressure is to be evaluated during the opening operation of the test stand. In Fig. 5, the regular and low-tone gearing have similar curves in low order area up to 42nd order. The maximal SPLs of both types are equal to 53 dB. From 42^{nd} to higher orders the low-tone gearing shows an advantage, i. e., its SPL is lower than the curve with regular type.

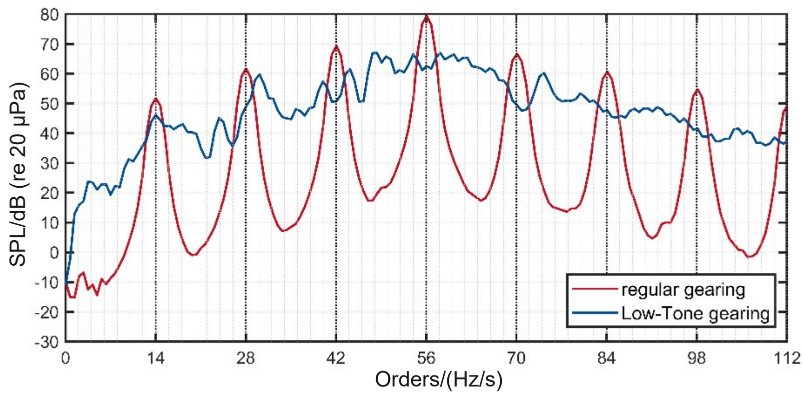

Fig.4 Comparison of regular and low-tone gearings in order spectrum of simulations

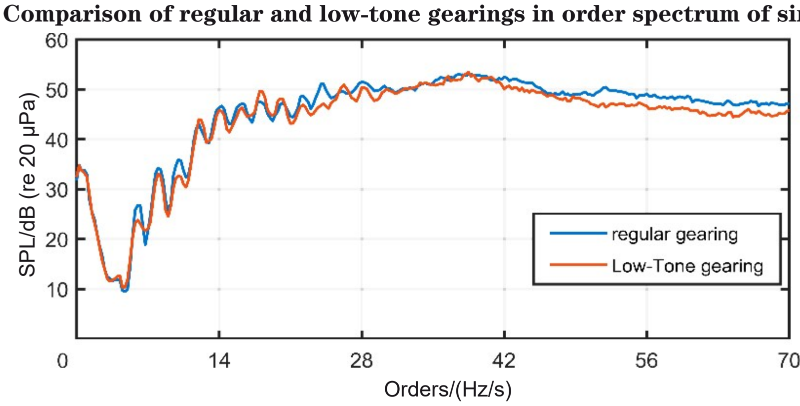

Fig.5 Order spectrum of regular and low-tone gearing

Then, the total SPL over time can be evaluated with the Fig. 6. Except for the time interval from 2 s to 3 s, the low-tone gearing has a significantly lower SPL. At the beginning and end of the opening maneuver, the actuator is loaded less than during the period between 2 s and 3 s because the length of the lever arm of the tailgate is shorter. Therefore, the low-tone gearing gives a better performance in terms of the overall SPL.

The tonality quantifies the strength of a single tone from a sound. Using the Artemis SUITE software, the tonality was calculated according to the ECMA-74 standard (see Fig. 7) [13]. In the time interval from 2 s to 4 s, low-tone gearing shows an advantage with low tonality level. The maximum value is reduced by using low-tone gearing from 1.14 tu_{HMS} to 0.67 tu_{HMS}. In contrast, low-tone gearing shows little advantage earlier than 2 s and after 4 s. At the 4.5s time point, the peak occurs with the low-tone gearing, which is 0.75 tu_{HMS}. By comparing the peaks of both types, it can be found that the low-tone gearing reduces the maximum value of the tonality from 1.14 tu_{HMS} to 0.75 tu_{HMS}, i. e. by 34%.

Due to the reduction of the SPL and the tonality of the low-tone gearing, its advantage for the noise reduction is validated, especially in the aspect of

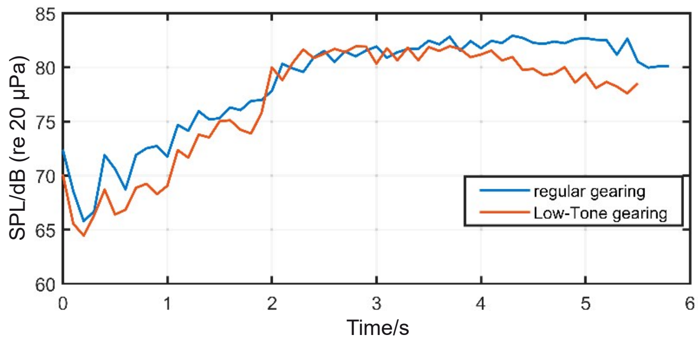

Fig. 6 Sound pressure level of regular and low-tone gearing versus time

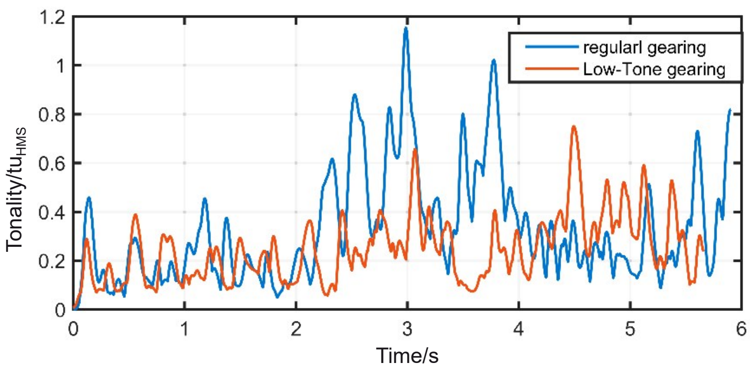

Fig. 7 Tonality of regular and low-tone gearing versus time

tonality. However, the advantage in the low order range of the order spectrum is not clearly recognizable. A potential reason is a reduced manufacturing quality of the gears, whose teeth have shape deviations, more specifically the almost straight tooth flanks. These shape deviations make the regular gear teeth irregular, which should be the concept of low-tone gearing. Because of the common irregularity of both prototypes, the reduction of SPL by low-tone design in particular order range is not clear to identify.

4 Conclusion and outlook

In order to validate the reduction of SPL and tonality by using low-tone gears on electrically driven systems in automobile industry, we redesign the first stage of gears in a compact push-rod system with uneven teeth positions and thicknesses. A pattern with seven gear teeth on each matching gear is numerically optimized in a two-step procedure. In the first step, a Monte-Carlo simulation searches a prominent solution with 10 000 iterations in the full searching space. In the second step, a neighborhood search updates the optimal parameters around the last optimized solution locally. Manufactured by waterjet cutting, the low-tone gears and the regular gears are tested and compared on a test bench, which is a tailgate simulator of vehicles. The low-tone gearing gives overall less noise in terms of the SPL and tonality. However, the advantage of low-tone gearing in order spectrum of sound pressure occurs primarily in high orders (>42^{nd} order). The reason for this can be a reduced manufacturing quality of the gears, which narrows the geometric difference between the low-tone gears and regular gears.

In further work, the manufacturing quality should be improved. A more precise geometry of gears can be achieved by manufacturing with CNC-milling. Moreover, the durability should be further researched. Because the low-tone gears have uneven teeth thicknesses and spaces, several teeth are thinner than the tooth with regular design, which can compromise the strength of teeth and the durability of the gear. Additional systems such as integrated sensors can be implemented to monitor the structural healthiness of low-tone gears. Therefore, the gear near the end of lifespan could be identified and replaced in time. The data regarding the weariness of low-tone gears can also be gathered and analyzed for research and improvement of the durability in the future.

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