Online listening test to evaluate the gear mesh noise of inequidistant gearings

Philipp Neubauer, Joachim Bös, Tobias Melz
System Reliability, Adaptive Structures, and Machine Acoustics SAM, TU Darmstadt, Germany
Email: neubauer@sam.tu-darmstadt.de

Introduction

Gear noise is considered to be a major acoustic challenge in electric vehicles. Since common electric engines have their highest power density at a high rotational speed and a low torque, gearboxes are needed to transform these quantities to a lower rotational speed with a higher torque, as required at the vehicle's wheels. Due to the strictly regular arrangement of the teeth along the circumference of conventional gear wheels, the meshing is strictly periodic. This results in an excitation of periodic vibrations and, therefore, tonal noise is radiated. In the context of gear noise, this is well known as *gear whine*. The research group System Reliability, Adaptive Structures, and Machine Acoustics SAM of TU Darmstadt investigates a new approach to reduce gear whine called *the inequidistant gearing*.

However, the sound quality of the meshing noise excited by inequidistant gearings in terms of annoyance, for example, has not been evaluated yet. Hence, an online listening test was performed in order to investigate how subjects evaluate the sound quality of inequidistant gearings compared to the sound quality of conventional equidistant gearings.

Inequidistant gearings

Inspired by fans and vehicle tire patterns, where the blades and the tread bars, respectively, are positioned irregularly along the circumference to reduce tonal noise, this approach is applied to spur gears. Figure 1 shows an example of an inequidistant gearing.

Figure 1: example of an inequidistant gearing with irregular tooth thicknesses and pitches

The design of inequidistant gearings differs from that of conventional gearings in the irregular tooth thicknesses and the irregular pitches, leading to an irregular meshing. The irregularities on the gear wheel and the pinion are designed in an inverse way. A thicker tooth, for example, always meshes with a wider gap in order to ensure a uniform transmission of motion. Hence, the kinematics of inequidistant gearings does not differ from conventional gearings.

The main excitation mechanism is the variable gear mesh stiffness due to the alternating number of tooth pairs in mesh. In Figure 2 the calculated gear mesh stiffness of a conventional equidistant gearing is compared to the gear mesh stiffness of an inequidistant gearing.

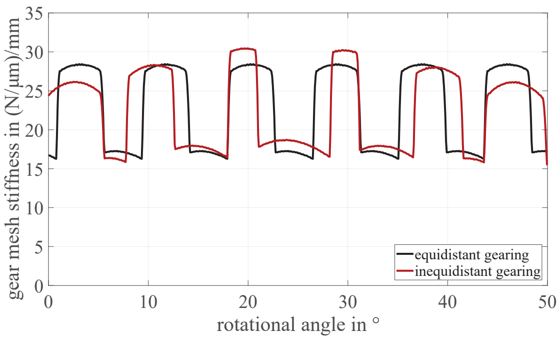

Figure 2: calculated gear mesh stiffness of a conventional equidistant gearing (black line) compared to the gear mesh stiffness of an exemplary inequidistant gearing (red line)

The periodic character of the gear mesh stiffness of the conventional equidistant gearing (black line in Figure 2) is the reason for the excitation of the tonal gear whine. The gear mesh stiffness of the inequidistant gearing (red line in Figure 2) is less periodic, resulting in a less tonal and more broadband noise.

Generation of synthetic sound samples

Sound samples from experimental investigations are not available yet. Therefore, synthetic sound samples were generated from a calculation model available at the research group SAM. Table 1 shows the geometrical properties of the gearings made from steel.

Table 1: geometrical properties of the gearings

property	gear wheel	pinion
number of teeth	42	18
addendum modification	0.1	0.4
gear module	2.5 mm	
width	20 mm	
center distance	91.5 mm	
load	100 Nm	

Furthermore, three operation points were chosen: a run-up from 0 to 1200 rpm, a run-up from 1200 to 6000 rpm, and a constant rotational speed of 2500 rpm. One conventional equidistant design (subsequently referred to as *eq*), four inequidistant designs for the run-ups, and three inequidistant designs for the constant rotational speed were used. The inequidistant designs differ in the pattern length of irregularly positioned tooth pairs. In the design called *2_in*, for example, a pattern of two tooth pairs is designed randomly irregular and repeated 21 times along the circumference of the wheel (42 teeth) and 9 times along the circumference of the pinion (18 teeth). In the designs *3_in* and *6_in* a pattern of three and six tooth pairs were designed randomly irregular, respectively. It is assumed that the gear noise becomes more broadband with a longer random irregular pattern and, therefore, might be less annoying. Additionally, another inequidistant gearing with a pattern of six irregularly positioned tooth pairs is specifically designed with the aim of a minimal tonality (subsequently referred to as *6_in,min*). Figure 3 shows the design of *3_in*. The pattern of the three tooth pairs is highlighted in red. The synthetic sound samples have a length of approximately 3 seconds. In total, 14 sound samples were created for the online listening test. All sound samples have approximately equal sound pressure levels.

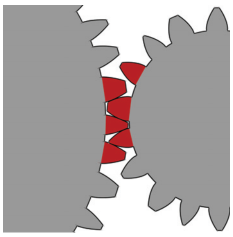

Figure 3: design *3_in* of an inequidistant gearing used for the generation of synthetic sound samples; the pattern of three irregular tooth pairs is highlighted in red

Setup of the online listening test

Online listening tests are not common since the test environment (e.g., ambient noise) and the test settings (e.g., volume settings) cannot be controlled by the examiner. Hence, uncertainties in the procedure of the listing test occur, which results in uncertainties in the results. However, an online listening test comes with the chance of a higher number of subjects. It is assumed that this compensates for the uncertainties in the test environment. To acquire a higher number of subjects, the online listening test needs to be intuitive and should not take longer than 30 to 45 minutes. Further advantages of an online listening test are that the moment of taking the listening test can be chosen by the subject and that the physical presence at the test facility is obsolete.

There are two methodologies that are suitable for conducting an online listening test: direct and indirect scales. When using direct scales (e.g., semantic differentials, grades), the subjects need to evaluate a large number of sound samples in an absolute manner over a long period of time. In practice there certainly will be changes in the environmental conditions during an online listening test, such as a change in ambient noise, for example. Indirect scales (e.g., rankings and pairwise comparisons) are characterized by a comparison of a small number of sound samples within a short period of time. The downside of this is the high number of comparisons that are needed in order to collect all necessary data. All in all, the indirect scales are assumed to be more suitable for an online listening test. Hence, the listening test presented in this article is set up as a pairwise comparison, where all sound samples are compared with each other within the same operation point. This task is very intuitive, changes in the environmental conditions affect the overall results as little as possible, and established analysis methods are available [1].

The listening test was implemented as an online survey on the platform *SoSci Survey* [2] since it is a free platform for researchers and it is possible to upload sound files. The sound samples were evaluated with the attributes *annoying, loud, rough, tonal,* and *sharp*. All attributes were introduced at the beginning of the online listening test by characteristic sound samples to ensure that the subjects get an understanding of the attribute's meanings. A screenshot of the online listening test is shown in Figure 4.

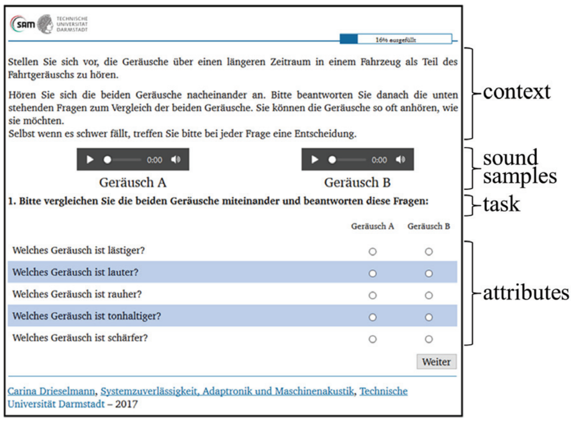

Figure 4: screenshot of the online listening test [1]

Every page of the online listening test is structured identically. At the very top the context is presented. The subjects were asked to imagine sitting in a passenger car and hearing the presented sounds as a part of the driving noise. The two sound samples for the pairwise comparison are located below the context. The sound samples can be started and stopped by the subjects in any sequence and as often as they desire. The only task is to compare both sound samples regarding the five attributes. The subjects indicate their preference by checking the radio buttons next to the five attributes. To compare the five sound samples for the run-ups and the four sound samples for the constant rotational speed, the subjects need to perform ten pairwise comparisons for each of the run-ups and six comparisons for the constant rotational speed. In total the subjects need to perform 26 pairwise comparisons resulting in a total duration of the listening test of approximately 40 minutes [1].

Implementation of the online listening test

The listening test was online for about four weeks. In that time 61 persons participated. The majority of the subjects were between 20 and 29 years old, which represents the typical age of students at the university [1].
The pairwise comparison allows for checking the consistency of the submitted answers by checking the data sets for *circular triads*, as illustrated in Figure 5. Assuming that a subject prefers A over B and B over C, the subject should also prefer A over C. If this is not the case, a circular triad occurs and the given answers cannot be used for the analysis of the results. In the listening test presented in this paper approximately 30 to 40% of the given answers were circular triads and must, therefore, be excluded from the analysis.

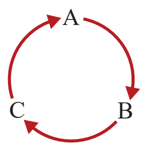

Figure 5: illustration of a circular triad

Results of the online listening test

For the analysis of the results a quantitative and a qualitative analysis method was chosen. The qualitative analysis method is a simple ranking by counting the submitted preferences of the subjects. This method is very easy to implement and very easy to interpret but a major drawback is the lack of quantitative information. Hence, a second analysis method is used – the Bradley-Terry-Luce model (BTL model). In this model a statistical distribution of the individual preferences of the subjects is assumed leading to a statistical distribution of the likelihood of the results – the score [3]. This measure allows for a quantitative investigation of the results. For the sake of this article's length only the results of the evaluated annoyance and one result of the evaluated loudness are shown. Figure 6 shows the results of the qualitative and the quantitative analysis for the constant rotational speed of 2500 rpm regarding the attribute *annoying*.

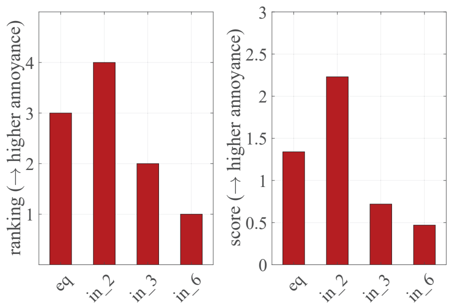

Figure 6: results for the constant rotational speed of 2500 rpm; attribute: annoying; left: qualitative analysis (ranking), right: quantitative analysis (BTL model) [1]

The qualitative results (Figure 6, left) show that the inequidistant gearing with a pattern of two irregular tooth pairs is evaluated as the most annoying sound sample for the constant rotational speed. The equidistant gearing is rated the second most annoying sample. The inequidistant gearings with longer patterns are rated less annoying. The quantitative results (Figure 6, right) show that the equidistant gearing (*eq*, score of 1.34) is rated nearly three times as annoying as the inequidistant gearing with 6 irregular tooth pairs (*in_6*, score of 0.47). Figure 7 shows the results of the qualitative and the quantitative analysis for the run-up from 0 to 1200 rpm regarding the attribute *annoying*.

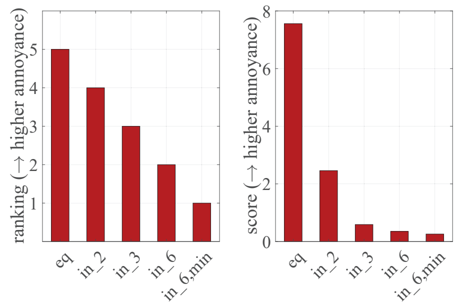

Figure 7: results for the run-up from 0 to 1200 rpm; attribute: annoying; left: qualitative analysis (ranking), right: quantitative analysis (BTL model) [1]

The results show that there is a strong trend towards a lower annoyance for a higher number of irregular tooth pairs. Furthermore, the annoyance of the gearing with six irregular tooth pairs is further reduced when the gearing is designed for minimal tonality. Hence, the well known fact that tonal noise is considered annoying [4] can also be confirmed for the noise of inequidistant gearings. The score of the BTL model suggests that the annoyance of the conventional equidistant gearing (*eq*, score of 7.56) is about 29 times as high as the annoyance of the low tonality design with 6 irregular tooth pairs (*in_6,min*, score of 0.26), which is impressive. However, taking the characteristics of the BTL model into account, this result most likely overrates the actual relations. For the run-up from 1200 to 6000 rpm, the scores for the annoyance in the BTL model become even more extreme and, therefore, less reliable (indicated by the gray color), see Figure 8.

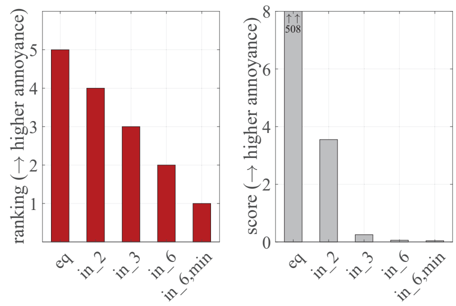

Figure 8: results for the run-up from 1200 to 6000 rpm; attribute: annoying; left: qualitative analysis (ranking), right: quantitative analysis (BTL model; extreme values) [1]

Even though the ranking (Figure 8, left) equals that in Figure 7, the scores of the BTL model greatly differ. The reason for these extreme values is that all subjects unanimously evaluated the equidistant gearing as more annoying than the inequidistant gearing with the low tonality design. On the one hand, a low tonality design obviously is evaluated much less annoying than a conventional equidistant gearing. On the other hand, this shows that the BTL model might not be the right choice to quantitatively analyze data that contain such extremal evaluations. Another interesting result is that the sound samples of some gearing designs are rated less annoying even if they were evaluated as louder, see ranking in Figure 9.

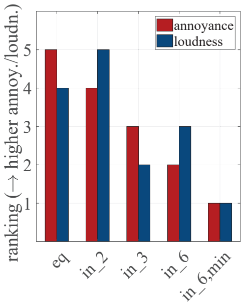

Figure 9: results for the run-up from 1200 to 6000 rpm; annoyance compared to loudness; qualitative analysis [1]

The sound sample of design *in_6* is evaluated as the second least annoying but only third least loud sample. Inverted results can be found for the design *in_3*. This is an interesting result but, of course, is not a proof for the independence of annoyance and loudness since the subjects remarked that the differences in loudness were very hard to distinguish. Overall, the results rather show the trend for inequidistant gearings with high numbers of irregular tooth pairs to be evaluated as less loud. Of course the loudness is assumed to be the major contributor to the annoyance, as is well known in literature [5]. The sound sample of design *in_6* is evaluated as the second least annoying but only third least loud sample. Inverted results can be found for the design *in_3*. This is an interesting result but, of course, is not a proof for the independence of annoyance and loudness since the subjects remarked that the differences in loudness were very hard to distinguish. Overall, the results rather show the trend for inequidistant gearings with high numbers of irregular tooth pairs to be evaluated as less loud. Of course the loudness is assumed to be the major contributor to the annoyance, as is well known in literature [5].

Summary and conclusions

Tonal noise from gearings is a major acoustical challenge. The research group SAM of TU Darmstadt develops the inequidistant gearing with the aim of minimizing tonal noise excited by gearings. The inequidistant gearing and the challenge of evaluating its sound quality is introduced. This article describes the setup of an online listening test that evaluates the gear noise from inequidistant gearings and compares it to the gear noise of conventional equidistant gearings. The generation of the synthetic sound samples, utilizing a calculation model that is available at the research group SAM, was described. A pairwise comparison of the sound samples was chosen to be an adequate method to set up online listening tests. Strengths and shortcomings of an online listening test were discussed. The test results show that the noise of inequidistant gearings is evaluated as considerably less annoying than the noise of conventional equidistant gearings. Furthermore, it can be concluded that designs with a higher number of irregular tooth pairs lead to less annoying noise, particularly for higher rotational speeds. An approach with a low tonality design shows that the annoyance is even more decreased for these designs. A louder sound does not necessarily lead to a higher annoyance. But the well-known fact that the loudness dominates the evaluation of the annoyance is not in question. However, a trend towards a lower loudness for inequidistant gearings with higher numbers of irregular tooth pairs can be concluded.
For future research the results of the online listening test will be compiled to a mathematical criterion to evaluate the gear mesh noise of inequidistant gears. Based on this criterion an optimization algorithm will be used to generate an optimal design of an inequidistant gearing. The results will be validated in further listening tests.

Acknowledgment

Many of the results in this article were taken from the master's thesis of Carina Drieselmann [1]. The authors greatly appreciate this excellent work.

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