TRANSMISSION ERROR AND SOUND PRESSURE LEVEL OF SPUR GEARING WITH STRAIGHT AND HELICAL TEETH

TOMAS MAREK[1], PAVEL NEMECEK[2]

Faculty of Mechanical Engineering

TUL - Technical University of Liberec, Czech Republic

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e-mail: tomas.marek@volkswagen.de [1]

pavel.nemecek@tul.cz [2]

This article concerns a study of the spur gear noise (i.e. sound pressure level) of automotive gearboxes. The aim is to verify a direct correlation between transmission error and noise emission of a gearing.
The article includes a description of some gearbox noise sources and focuses on the gears itself, which is a main source of vibration and noise.
A risk analysis is performed to assess the factors influencing gear noise, to show a significance of transmission error. The main part of this article, however, concerns experimentally identified transmission error and its correlation with measured noise.

KEYWORDS

Transmission error, gear meshing, incremental rotary encoder, phase demodulation, closed loop test stand

1 INTRODUCTION

Transmissions with gears have been an essential part of the drive train of automobiles throughout their historical development. While in the early days the focus was primarily on functionality, over time the requirements for efficiency and performance were added. Quality and comfort, such as noise emission, are the decisive factors that make sales successful.
This paper deals with a gear meshing parameter called transmission error. Transmission error (TE) has been studied since the 1950s, but only today's advanced computing and measuring technologies bring a possibility of more accurate research.
Its significance in relation to vibration and noise emission is supported by numerous sources and citations, as well as by a risk analysis carried out with a team of experts.
Finally, the study presents the results of the measurements performed on straight and helical gearings. These gearings are compared in terms of transmission error and its correlation with noise emission.

2 GEARBOX NOISE SOURCES

A gearbox is a mechanical system with a periodically repeating power transfer cycle. It has concrete constructional components and can be precisely described mathematically. Periodic operation also implies periodic manifestations of vibration and, consequently, noise. The main sources of vibration and noise are:
- rotors (mainly due to residual imbalance),
- rolling bearings as a parametric source of vibration and noise,
- the gearbox housing as the surface from which the acoustic energy is radiated,
- and, above all, the gearing.

The gearing is the main source of vibration and noise in the gearbox. Vibration and noise magnitude from the gearing are mainly influenced by so-colled *gear meshing parameters*:
- Gear contact ratio and meshing stiffness variation
- Edge tooth-bearing
- Gradient of change in the applied engagement force
- Transmission error

3 RISK ANALYSIS

Since there are four identified basic gear meshing issues (see chapter 2 – *gear meshing parameters*) with an impact on gearbox vibration and noise, the next task is to evaluate these issues and prioritise solutions based on a risk analysis.
The noise and vibration of the transmission and its impact on the environment and humans was evaluated. The noise and vibration are the result of the energy transformation, transmitted by the gear into vibratory motion. This results in acoustic power radiated to the environment. The consequence of this is a reduced efficiency. The reasons can be found in:
- design of gearing,
- manufacturing technology,
- materials and heat treatment,
- quality of assembly,
- quality assessment system,
- etc.

It is possible to investigate these reasons individually (as separate sources of noise and vibrations). However, this would require experts, procedures and evaluation criteria. The result would be a quantitative or qualitative assessment and a search for appropriate limit values. However, the individual reasons cannot be seen separately. They are inter-related.
The risk analysis of gearing causing harmful vibrations and noise proves to be a useful tool. The assessment team takes all criteria into account, but the unifying theme is their common impact on noise and vibration of the gear. Each member of the team may have a different view of the reasons for the noise and vibration of the gear and may also have a different perception of the consequences of increased noise and vibration of the gear. These may be:
- the impact on the customer and their trust in a particular manufacturer or car,
- the economic impact on the production and consequently the price of the car,
- the impact on driver's attention,
- the impact on passenger tiredness.

A risk analysis of the gearing causing non-negligible vibration and noise according to EN 31010 proves to be a useful tool. A practical application in the field of mechanical engineering is described in resource [Pačaiová, Andrejiová, Balažiková, Tomašová, Gazda, Chomová, Hiji, Salaj 2021]. The results of the risk analysis according to the principles set out in the referenced norm can be used as a basis for subsequent decisions on the solution, for evaluating other gearbox characteristics or for comparing the analyses for the entire drivetrain.
Two questions were asked to assess risk:
1) what is the risk resulting in vibration and noise,
2) what is the probability of the risk occurring

Both severity and likelihood of occurrence are rated on a scale of 1 to 5 (higher scores indicate higher risk). The significance of risk R is given by the product of S•O. The team was drawn from a wider range of respondents. These included experts in the field of gearing, vehicle drivetrain, automotive vibro-dynamic, general design, gear-manufacturing technology, economics and education. In the team composition, independence in the evaluation was a major consideration. Each respondent assessed the S and O parameters independently. The significance of risk was evaluated statistically. For both parameters, the median (identical to the modus in the statistical data sets) was evaluated. The parameter R was then evaluated as the product of the medians (see Table 1).

Source of gear noise and vibration	Conseque-nce of risk S	Probability of occurrence O	Importan-ce of risk R
Gear contact ratio	4	3	**12**
Gradient of change in the applied engagement force	3	3	**12**
Edge tooth bearing	3	3	**9**
Transmission error	4	4	**16**

Table 1. Risk analysis of gear noise and vibration

The analysis shows that the gear contact ration and the gradient of change in the applied engagement force show a medium risk for vibration and transmission noise, while the transmission error is already in the high-risk category. This is the reason for the priority investigation of this topic.

4 CORRELATION OF TRANSMISSION ERROR WITH NOISE AND VIBRATION

Transmission error (TE) is the difference between the actual and expected amount of rotation of the driven wheel. There is a detailed description of the TE in the scientific paper [Marek T. 2022].

There are several studies that describe the correlation between TE and noise. Research papers [Tharmakulasingam 2009], [Munro 1990], [Gregory, Harris, Munro 1963], [Houser, Oswald, Valco, Drago, Lenski 1994], [Munro, Houser 2003] [Glover, Rauen 2003] provide a very good introduction to TE and most of them claim that TE is one of the main causes of gear noise.

The transmission error is accompanied by oscillatory meshing force, which causes vibration reactions in the transmit pathways, and these vibrating components can subsequently emit noise.

The direct relation of TE with noise is described in the work of [Henriksson 2009] and [Moravec, Dejl, Nemcek, Folta, Havlík 2009]. The transmission error is also closely related to the variation of the gear contact ratio and the meshing stiffness. [Kayama 2005] wrote that the variation of the meshing stiffness together with the transmission error are the main causes of noise and vibration of the gearbox.

5 MEASURING OF TRANSMISSION ERROR

Measuring of TE is based on sensing the rotation behaviour of the meshing gearings. The most common way of measuring TE is with incremental rotary encoders (IRC). TE is measured under load and during rotation.

The measurements were performed on the open loop test stand (see Figure 1).

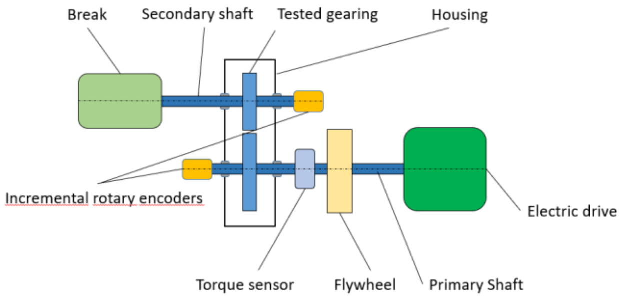


Figure 1. Scheme of the open loop test stand

TE measurement generally means a measurement of kinematic quantities (determination of time waveforms, frequency spectra). Of lesser importance are scalar quantities that replace large amounts of processed data (RMS values, equivalent values, etc.). The quality, repeatability and reproducibility of the input data is of key importance for the identification of transmission error, as well as for the minimisation of systematic and random measurement errors. The methodology of the TE measurement and TE evaluation is discussed in the literature [Tuma 2014; Tuma 2003; Marek T.2022]

There were two tested gearings with pure involute tooth flanks and without any micro-modifications. One gearing had straight teeth, the other had helical teeth. Both gearings were based on gears used in automotive transmissions with HRC teeth. The gears were very precisely manufactured, basically in etalon quality. The aim of the test was to find a correlation of the measured TE with a measured noise of each gearing.

The figures below show a detailed description of the mentioned test stand. Figure 2 shows the method of fixing the tested gears (1) via the tapered clamps (2) to the shafts (3). These are mounted in slide bearings (4) in the housing (5). The shafts are connected to the IRC (7) via safety couplings (6). The type of the IRC is IRC315/6000PB with resolution of 6000 pulses per revolution.

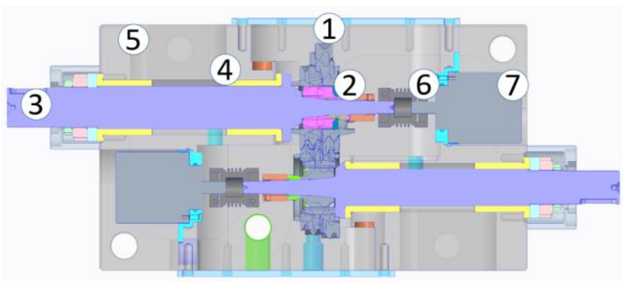


Figure 2. A detailed description of the test housing

Figure 3 shows the complete test stand. The system drives an electric motor (1) and the brake torque is induced by a wet type multiple disc hydraulic clutch (2). The power range is up to 3000 rpm and 30 Nm. It is clear, that 30 Nm is nowhere near the full realistic operating load that can be achieved in the car, around 200 Nm to 300 Nm (even more for more powerful drives). However, for the purpose of this work, these conditions were found to be sufficient in the first step. A flywheel (3) is integrated in the drive system. The braking torque is measured by a torque flange (4). Its range is up to 500 Nm and the accuracy class is 0.1%. In practice, this means an error of 0.5 Nm. This large measuring range of the sensor was chosen mainly for safety reasons. If, for example, the sliding bearings suddenly broke, the IRC could be overloaded and destroyed, even though the test stand is equipped with safety couplings. The test housing is marked (5). The whole system is mounted on a frame (6) in a floor (7) on air springs (8). An oil pressure system (9) is connected due to the slide bearings.

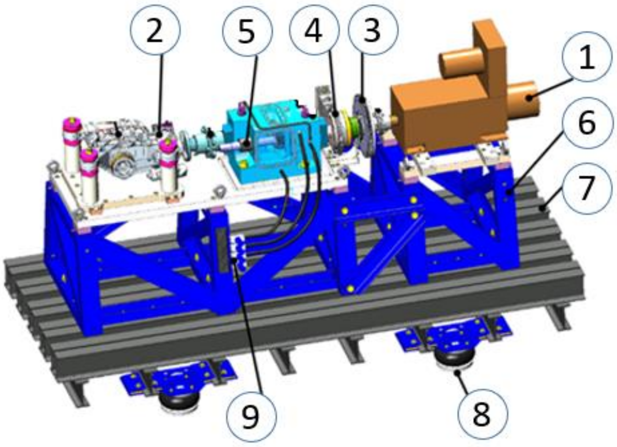


Figure 3. A detailed description of the complete open loop test stand

Figure 4. Complete test stand in the laboratory

The sound pressure level (SPL) is measured with a microphone. It is, unfortunately, not possible to place the microphone directly to the gearing as there is an oil environment. It would have to be sealed, which would cause a distortion of the measurement. Therefore, it is placed in the special acoustic tube, which is a common practice in vibro-acoustics (see Figure 5).

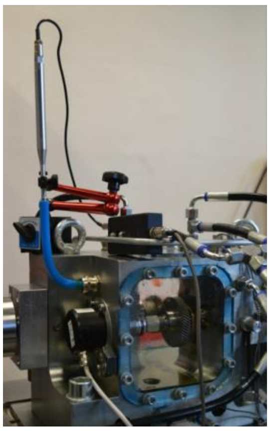


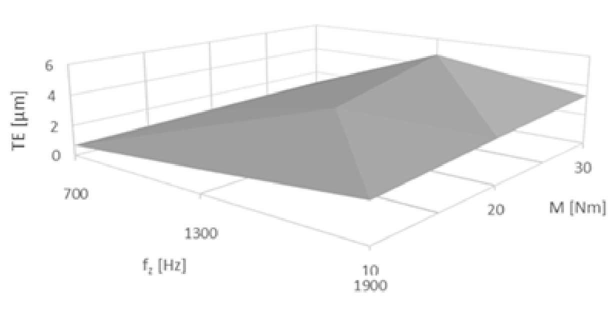
Figure 5. Test housing with a microphone for noise-measuring, inserted in a special acoustic tube

The transmission error is usually evaluated from the constant speed mode, i.e. at constant gear meshing frequency, and constant load level. The advantage of this approach is that the measurement is performed under steady conditions and any dynamic effects caused by transmission error can fully manifest themselves. The length of the time lapse record should be just long enough to allow the first tooth of the driver gear to mesh with all the driven gear teeth. Another advantage is that the results can be easily tabulated.

6 RESULTS AND DISCUSSION

The measurements carried out at different gear meshing frequencies (700 Hz, 1300 Hz a 1900 Hz) and load levels (10 Nm, 20 Nm and 30 Nm). The measured TE values were tabulated (Figure 6 and Figure 7).

TE [µm]		f_z[Hz]		
		700	1300	1900
M [Nm]	10	0,68	1,44	2,31
	20	0,92	2,82	2,84
	30	1,12	4,81	3,32



SPL [dB]		f_z[Hz]		
		700	1300	1900
M [Nm]	10	93	104	102
	20	96	106	106
	30	99	112	110

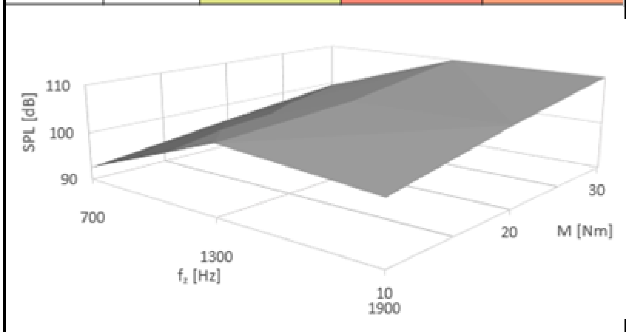
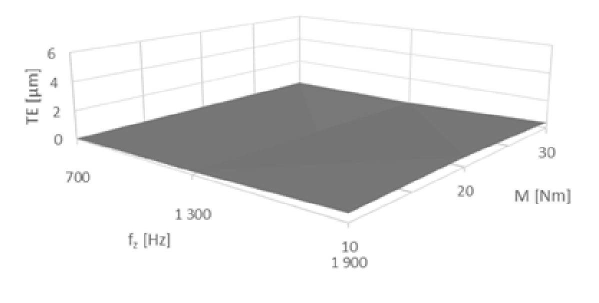


Figure 6. Measurement results. Spur gearing with straight teeth and purely involute flanks (no micro-modifications)

TE [µm]		f_z[Hz]		
		700	1300	1900
M [Nm]	10	0,04	0,19	0,53
	20	0,05	0,14	0,65
	30	0,03	0,03	0,40



SPL [dB]		f_z[Hz]		
		700	1300	1900
M [Nm]	10	76	84	83
	20	77	81	91
	30	74	84	95

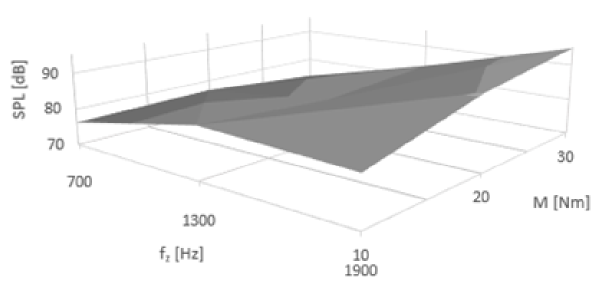


Figure 7. Measurement results. Spur gearing with helical teeth and purely involute sides (no micro-modifications)

Measured data show that the gear noise correlates well with transmission error. The transmission error and noise emission for straight gears (Figure 6) is much higher than that of helical gears (Figure 7). The colour scales of each of the observed parameters are aligned from most favourable (green) to least favourable (red). Graphical representations are also added.

7 CONCLUSIONS

At the beginning of this article, several sources of gearbox and gearing noise are listed. According to several cited scientific studies, there is a strong correlation between the magnitude of the gear noise emitted and the transmission error. Furthermore, a risk analysis carried out by a team of experts shows that the transmission error is the most significant of the listed sources of gear noises.

To investigate and confirm the correlation between transmission error and gear noise, a special test stand was developed, whose main parts are described in the paper.

The measurements were carried out on two types of spur gears, i. e. with straight and helical teeth. TE was measured under three load levels (10 Nm, 20 Nm and 30 Nm) and three constant tooth meshing frequency levels (700 Hz, 1300 Hz and 1900 Hz).

From the measurement, the following conclusions can be made. The investigated gearings show a correlation between the transmission error and noise. As expected, straight teeth show much higher values of transmission error and noise than helical teeth. For straight teeth, the maximum occurs at a tooth meshing frequency of 1300 Hz. This is due to dymanic effects induced by a transmission error. It is also reflected in the measured noise, which is significantly higher. For helical gearing, this effect is not observed at 1300 Hz. The helical gearing has an overall lower transmission error and is therefore a lot more silent.

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CONTACTS:

Ing. Tomas Marek
Faculty of Mechanical Engineering
TUL – Technical University of Liberec
Department of Vehicles and Engines
Studentska 2, Liberec, 461 17, Czech Republic
Email: tomas.marek@volkswagen.de