Benefit of Psychoacoustic Analyzing Methods for Gear Noise Investigation

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Management Summary

In recent years gear noise in automobiles has attracted more and more scrutiny. This is due in part to reduced interior noise levels, which make drivetrain noise more noticeable; thus the gear industry's development and quality assurance focus is on the excitation of gear sets. To ensure a constant noise quality objective, characteristics are needed to describe the noise quality of gears and gearboxes. In acoustics it is well known that sound power level and FFT (*Ed.'s note: Fast Fourier Transform—an efficient algorithm to compute the Discrete Fourier Transform—DFT—and its inverse*) analysis are not sufficient to fully describe the sound quality of noise. It is for that reason that with psychoacoustics, additional values have been developed such as tonality, roughness and sharpness to better describe the sensation of human hearing.

Our objective is to provide an overview of the benefits of using psychoacoustic characteristics for describing gear noise. And with that, human hearing and the most important psychoacoustic values will be introduced. Finally, results of noise tests with different gear sets will be presented. The tests are the basis for a correlation analysis between psychoacoustic values and gear characteristics. The conclusion will provide an outlook on further investigations.

Introduction

In the gear development process, noise reduction has always been important. Interior noise is a quality characteristic and influences customer satisfaction (Ref. 1). And while in recent years interior noise has been steadily quieted (Ref. 2; Fig. 1), interior noise reduction in fact further exposes gear noise as one of the dominant noise sources in vehicles.

To attain customer satisfaction, it is not enough to reduce the noise level of the drive train; in future the *sound design* of gearboxes will become necessary. But to date, no characteristics exist with which to evaluate transmission noise.

Within this report psychoacoustic characteristics are used to describe gear noise. A case study was conducted to investigate the correlation between gear noise characteristics and gear geometry.

Psychoacoustics

In gear development and gear production the quality-check of transmissions is based on physical values—unlike the customer who evaluates the sound quality with his hearing. Due to a difference in the performance of human hearing and noise analysis, evaluation of the same noise can differ. Psychoacoustics is one solution for this problem. In psychoacoustics, objective values such as sound level, frequency, bandwidth, duration and degree of modulation are used to calculate psychoacoustic characteristics (Ref. 3). These characteristics have a linear correlation to human noise perception and are based on extensive testing.

The anatomy of human hearing influences noise percep-

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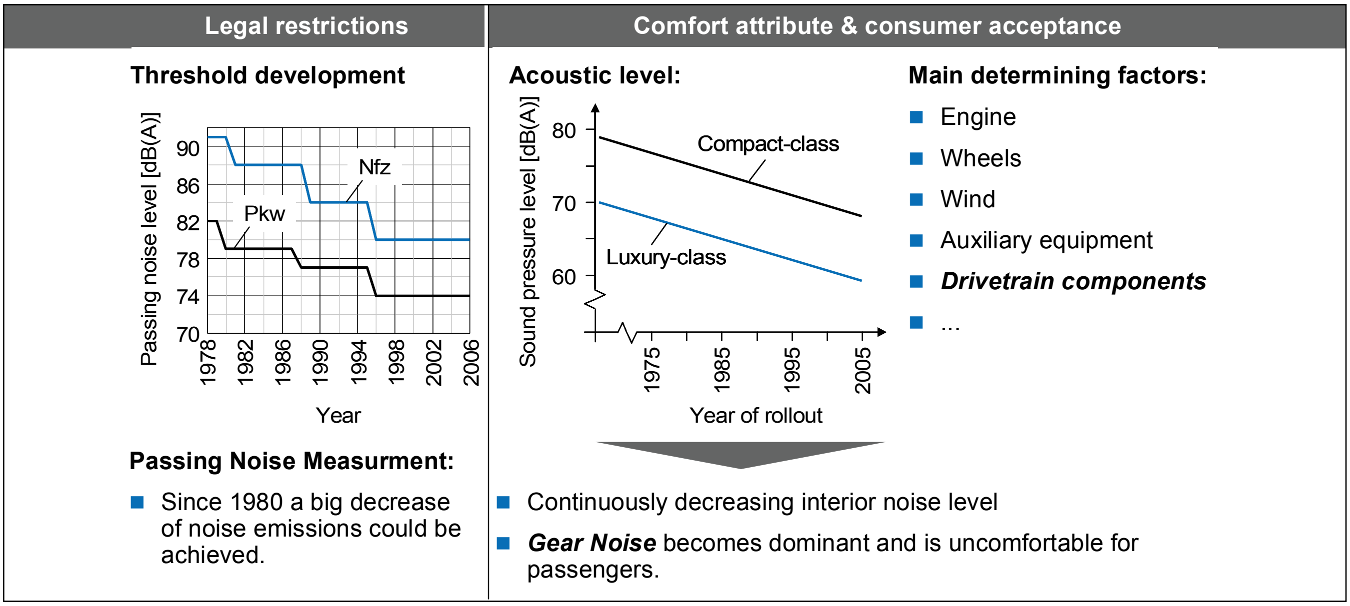


Figure 1—Motivation for psychoacoustics in gear industry (Ref. 2).

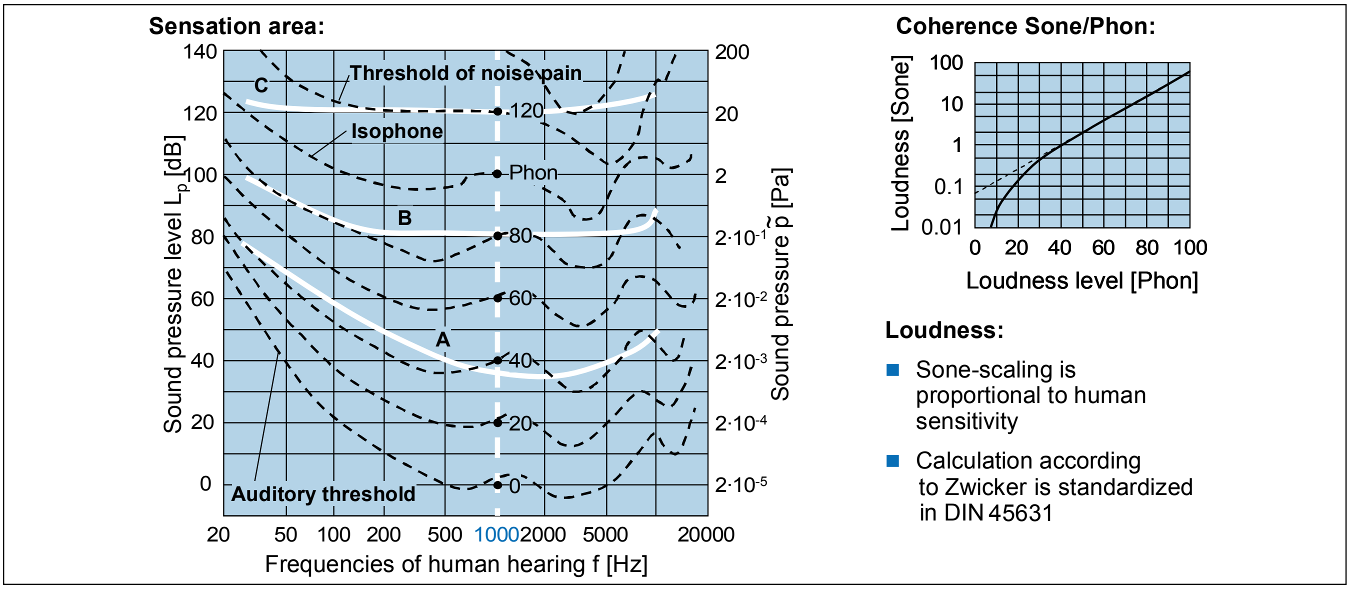


Figure 2—Loudness is a psychoacoustic characteristic.

tion. For example, the length of the outer ear canal leads to an amplification of frequencies between 2 and 4 kHz. Due to Eigen frequencies the transfer function of the inner ear is optimal for frequencies with a range of one-to-two kHz. The sensation area for human hearing is shown in Figure 2; it reaches from 16 Hz to 16 kHz, and the agility of human hearing enables sensate sound pressure from $2{\cdot}10^{-5}$ Pa to 100 Pa. Sound pressure is usually expressed with a leveled scale; the reference value is $2{\cdot}10^{-5}$ Pa. The sensation area displays the isophones (curves of constant loudness) (Ref. 4). The psychoacoustic loudness with its unit sone (a unit of subjective loudness) allows comparison of the loudness level of noise with different frequencies.

Further psychoacoustic characteristics are sharpness, tonality, roughness and fluctuation strength (Fig. 3; Ref. 3). The definition of the scale for the different characteristics takes into account that a doubling of the sensation leads to a doubling of the value.

Design of Experiments

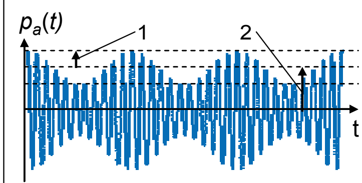
The aim of this report is the investigation of psychoacoustics to evaluate gear noise. Therefore different gear sets with different geometry will be tested in a gear set fixture (Fig. 4; Ref. 5). The fixture is equipped with angle encoders. Additionally, acceleration sensors are mounted close to the bearings and a free-field microphone is located close to the tooth mesh. The fixture enables exchange of the gear set without disassembling the fixture.

To investigate the correlation between gear geometry and gear noise, four different gear sets are tested (Fig. 5). The macro-geometry remains the same for all variants—the pinion has 25 and the gear 36 teeth; the center distance is 112.5 mm and the modulus is 3.5 mm (Ref. 5).

The topology of the first gear set—V1—is conjugated and V1 is the reference for the other variants. V2 has a pitch error that is harmonic to the gear revolution and a wavelength of one-sixth of a gear revolution; V3 has tip relief and crowning;

Tonality	Roughness	Modulation
■ Value shows whether the sound characteristic is tonal or noisy. ■ Tonal sounds occur when the excitation frequency matches the Eigen frequency of the system. ■ Unit: 1 tu (tonality unit).	■ Envelope fluctuation between 20 and 300 Hz. ■ Roughness decreases outside this frequency range. ■ Depends on sound pressure level and modulation. ■ Unit: 1 asper.	■ No psychoacoustic value. ■ Amplitude and frequency modulation are possible. ■ Amplitude of carrier wave is oscillating periodically.

Sharpness	Fluctuation Strength
■ Sensation that depends on noise contend of high frequencies. ■ Unit: 1 acum (Latin: sharp).	■ Occurs when signal amplitude is changing with very low frequency (4Hz). ■ Sounds with a high fluctuation strength call attention. ■ Unit: 1 vacil.



$$p_a(t) = \hat{p}_{carrier} \cdot [1 + m \cdot \sin(2\pi f_{mod} \cdot t)] \cdot \sin(2\pi f_{mod} \cdot t)$$

1: Changing component

2: Constant component

Figure 3—Overview of some psychoacoustic characteristics (Ref. 3).

Input

P_{max} = 220 kW

n_{max} = 4,000 rpm

M_{max} = 380 Nm

Output

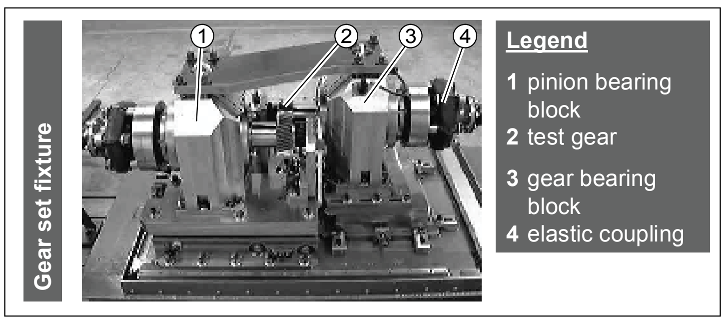
P_{max} = 155 kW

n_{max} = 2,500 rpm

M_{max} = 1,300 Nm

Measurement devices:

- CM DIGIT NoisyS32
- 4 x acceleration sensor
- 1 x microphone
- 2 x angle encoders



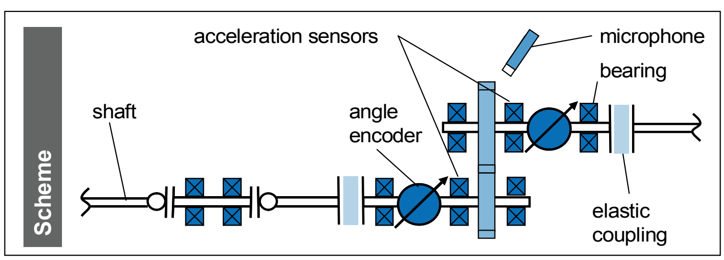


Figure 4—Test set-up.

V4 has only tip relief.

Use of Psychoacoustics for Gear Noise Investigations

What follows is a presentation of the influence of input speed and gear geometry on gear noise. The speed influence was tested by speed sweeps and therefore the input speed was increased from 200 to 3,200 rpm. During one speed ramp, the load was kept constant. Figure 6 shows the influence of the input speed on the gear noise characteristics.

The Campbell graph (Fig. 6) in the upper left corner shows the rising frequencies of tooth mesh harmonics over speed; it also shows the increasing magnitudes of gear noise over speed. The rising sound power level over speed leads to a spike in loudness; the sharpness of the gear noise is also increasing over speed due to the rising mesh harmonics. The lower-right graph (Fig. 6) shows that the tonality of the gear noise is almost independent of speed.

The influence of gear geometry on noise characteristics is seen in Figure 7. Comparison of the noise of the four different gear designs (Fig. 5) is based on the order spectra (sound and vibration) of structure-borne noise and airborne noise. The noise of V1 is characterized by relatively small magnitudes of the mesh harmonics (36th, 72nd). The tip relief of V4 leads to an increase of the magnitudes of the mesh harmonics. The noise signals of V3 show the highest magnitudes of the mesh harmonics. The pitch error of V2 leads to many harmonics of the 6th order referred to gear revolution. This is caused by the wavelength of the pitch error; it has a wavelength of one-sixth of a gear revolution.

The comparison between the order spectra of impact

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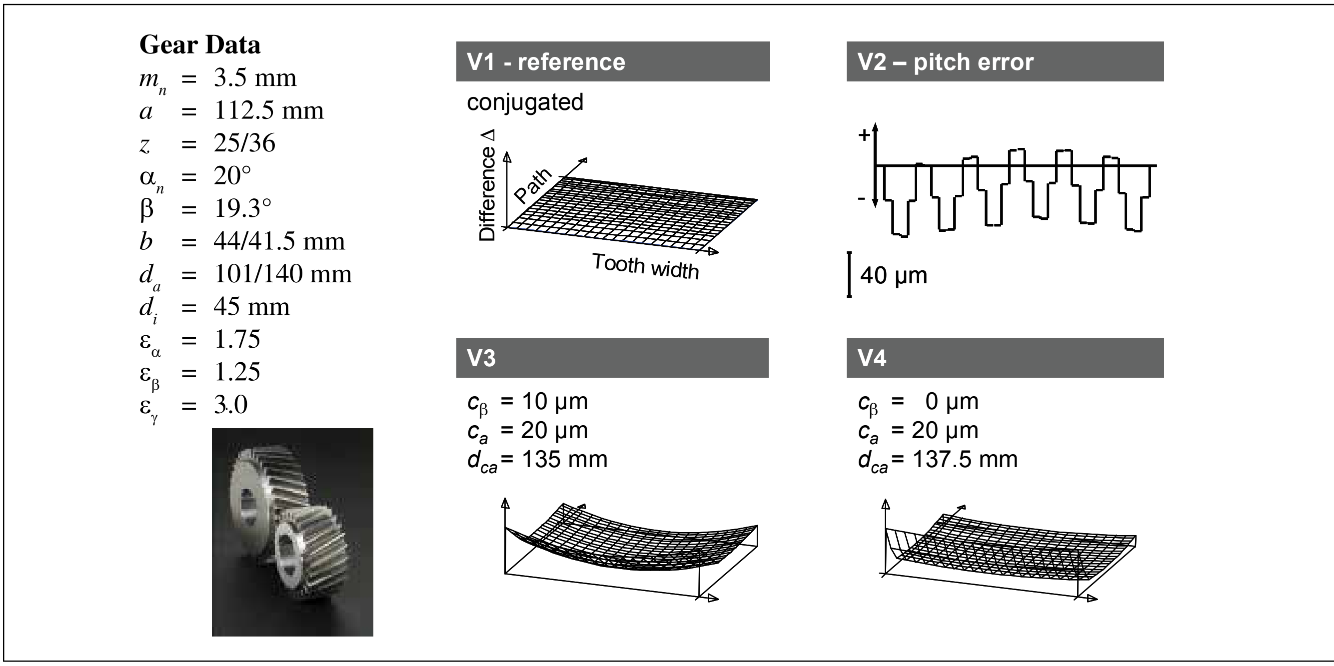

Figure 5—Gear sets.

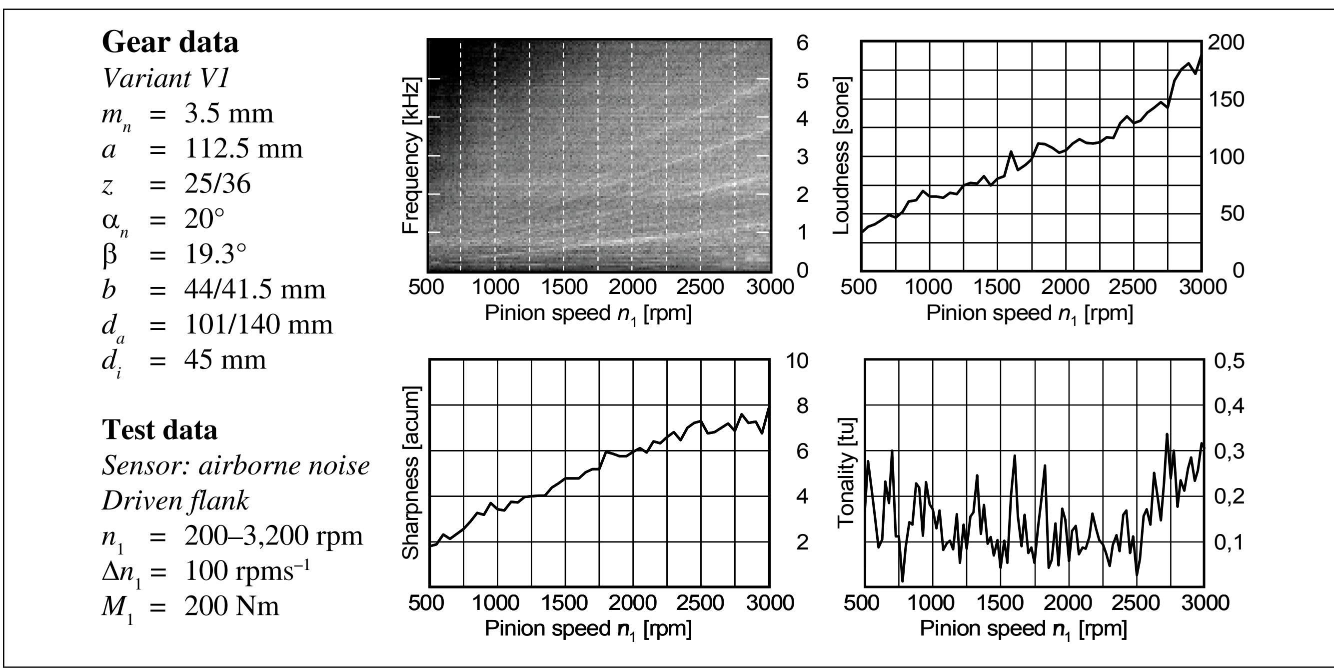

Figure 6—Noise analysis of a speed ramp.

noise and airborne noise shows that the characteristics of both sounds are similar. Dominant frequencies occur in the structure-borne noise signal and in the airborne noise signal—leading to the question of whether psychoacoustic calculations can also be used for structure-borne noise.

Figure 8 shows an overview for the psychoacoustic characteristics of loudness, sharpness and roughness for the airborne noise of the four gear sets. The top-left diagram presents the order cuts of the mesh frequency. The amplitudes of the mesh order differ depending on the variant. The reference gear set (V1) with the conjugated topology has the lowest mesh frequency. V3 radiates noise with the highest content of the tooth mesh order.

Although the tooth mesh amplitude of the noise from V3 is highest, the loudness of the noise from V2 is higher. This is caused by the content of harmonics to the sixth order of the gear revolution in the signal. The excitation caused by the pitch error leads to an increase of the loudness by 50%. Besides V2, the loudness of V3 is also higher than the loudness of the other variants.

The influence of the geometry on sharpness value is very little; the noise of all variants has similar sharpness values and the characteristic roughness is influenced by the pitch deviation.

For the impact-noise sharpness, loudness and roughness are presented in Figure 9. Although the psychoacoustic characteristics are only defined for structure-borne noise, the calculations show a similar trend as do the values for the airborne

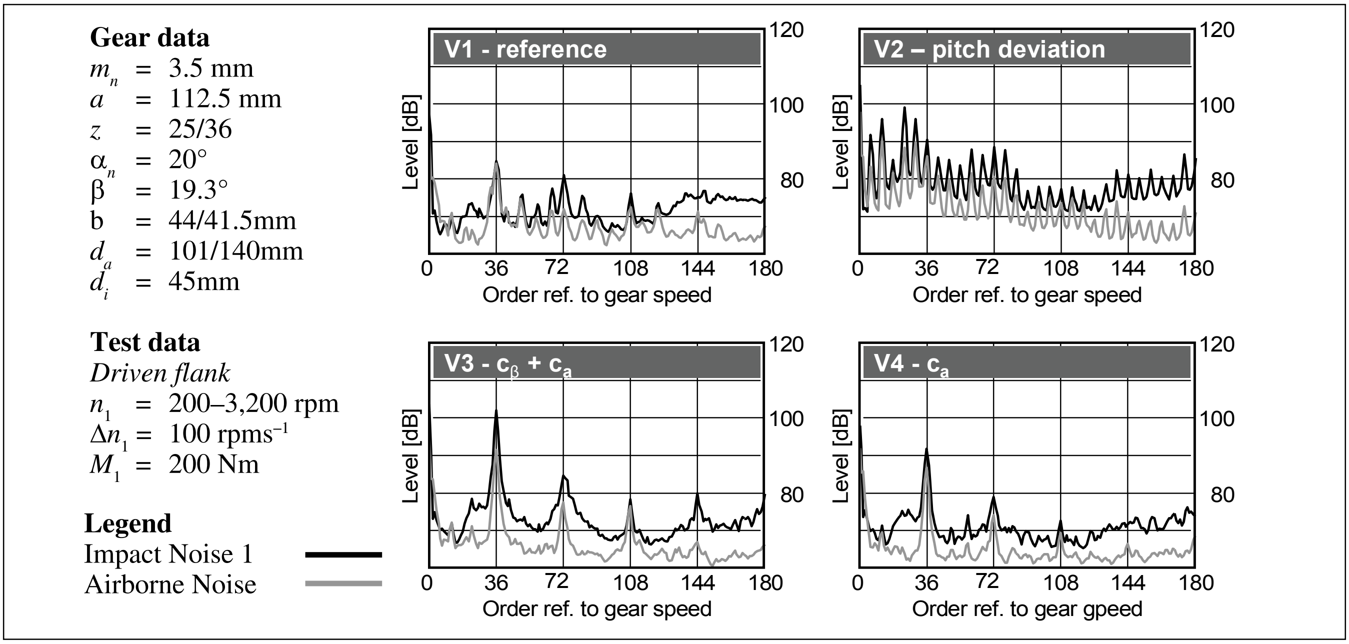

Figure 7—Fourier analysis of impact and airborne noise.

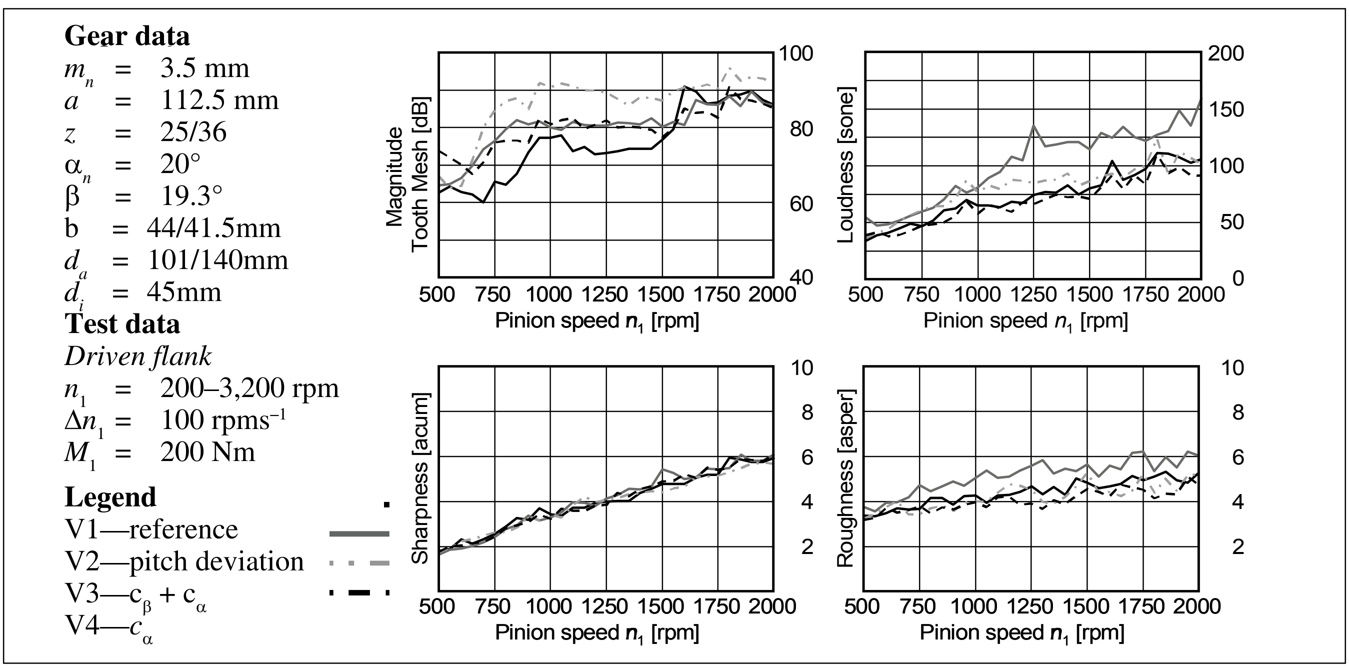

Figure 8—Psychoacoustic evaluation of airborne noise.

noise in Figure 8.

The ranking of the order cut of the mesh frequency of the structure-born noise is the same as the corresponding ranking for the airborne noise. The calculation of the loudness is also influenced by the pitch error. V2 shows the highest loudness level followed by the loudness of V3; the roughness also shows the same ranking for structure-borne noise and airborne noise. By using psychoacoustic calculations for impact noise, the separation effect is even higher than the resolution for airborne noise. One possible reason: the influence of environmental noise in the airborne noise signal. The influence on the structure-borne noise is almost avoided by dampers and elastic couplings.

The example shows that the characteristic of the airborne noise is already included in the impact noise. Due to the transfer path, all frequencies and modulations in the airborne noise are radiated from the surface of the test fixture; thus the oscillation of the surface must already include all the information.

Figure 10 answers the question—Why is V2 noisy and why is its noise so rough?

In comparison to the envelope curve of the reference gear set (V1), the flow of the mesh amplitude of V2 is modulated higher. This signal was recorded at constant speed and constant torque. The signal of the reference gear set is modulated with a dominant frequency of one pinion revolution. The signal of the gear set with the pitch error shows a modulation frequency that meets the sixth order referred to gear speed.

continued

Gear data
m_n = 3.5 mm
a = 112.5 mm
z = 25/36
α_n = 20°
β = 19.3°

Test data
Sensor: acceleration sensor
Driven flank
n_1 = 200–3,200 rpm
Δn_1 = 100 rpms^{-1}
M_1 = 200 Nm

Legend
V1—reference
V2—pitch deviation
V3— $c_\beta + c_\alpha$
V4—c_α

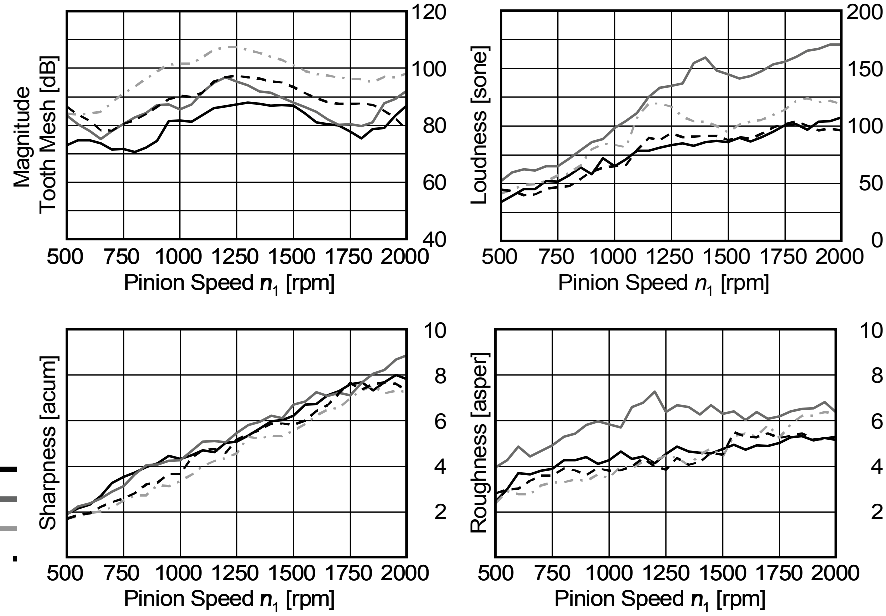

Figure 9—Psychoacoustic evaluation of impact noise.

Gear data
Variants V1&V2
m_n = 3.5 mm
a = 112.5 mm
z = 25/36
α_n = 20°
β = 19.3°
b = 44/41.5 mm
d_a = 101/140 mm
d_i = 45 mm

Test data
Sensor: microphone
Driven flank
n_1 = 1,000 rpm
M_1= 200 Nm

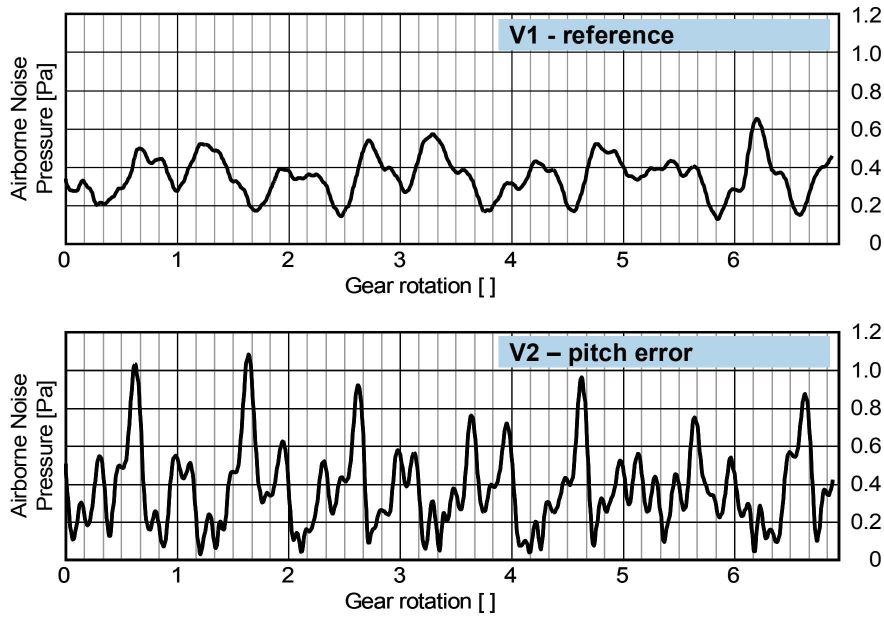

Figure 10—Envelope curve of the mesh frequency.

This strong modulation leads to an increase of the roughness.

The comparison of Figures 8 and 9 shows that all the information included in the airborne noise already exists in the structure-borne noise; the structure-borne noise is exacerbated by oscillating forces in the tooth mesh. For further investigations it is necessary to do a correlation analysis between the transmission error in tooth mesh and the structure-borne noise. The goal of these investigations should be to find possibilities to optimize the noise characteristic by changing the transmission error.

Summary and Outlook

The interior noise level of vehicles continues to decrease; thus noise from gearboxes is not masked by other sounds as in the past and requirements on gear noise quality are rising.

For gear design and quality objectives, physical characteristics are used.

In reality, the consumer rates interior noise subjectively. For that reason evaluation of the same noise can differ.

Psychoacoustics can be one solution. Within this report psychoacoustic characteristics have been introduced and first analyses have been done on gear noise. Therefore different gear sets with a variation of micro-geometry and pitch deviations have been chosen. Noise measurements have been done with these gear sets to investigate the relationship between gearing and gear noise. Sweeps have been done to investigate the speed influence on gear noise. The results show that loudness is not only rising with the rotational speed; noise sharpness is also rising—proportional to the speed.

The result of the comparison of the different gear designs is that the roughness of the gear noise is a characteristic value to determine the pitch deviation of a gear set. It was also possible to transfer the results from airborne noise to structure-borne noise. For the investigated gear sets the psychoacoustic characteristics have been calculated for airborne noise as well as for structure-borne noise. The values show similar results for both signals.

At the end of this report a method was defined to use an input and output synchronous analysis to determine the reason for noise phenomena.

In future investigations:

- The coherence between gearing parameters and noise patterns will be further investigated.
- Different gear designs will be manufactured.
- A variation of micro- and macro-geometry will be done, as well as a variation of run-out and pitch error.
- Psychoacoustic values will be referred to the results of tooth contact analysis to find correlations between psychoacoustic value and tooth contact. Based on this functionality, orientated analyzing methods for gear noise can be developed.

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