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Systematic Approach for the Psychoacoustic Analysis of Dynamic Gear Noise Excitation

By C. Brecher, M. Brumm, and
C. Carl, RWTH Aachen University

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Dr. Christian Brecher, Markus Brumm, and Christian Carl, RWTH Aachen University

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

The sound quality of technical products is an increasingly important quality criterion and has a significant influence on the product acceptance. But sound quality does not only depend on the physical attributes of the sound signal. It is defined to a large extent by human sound and noise perception. This perception is based on a physiological and psychological signal processing. These aspects depend on complex properties of the physical signal like the spectral distribution and a relative comparison. However, today the sound design of gearboxes is mainly based on the physical reduction of the noise level that is detected by absolute and objectivized parameters. The noise oriented gear design is based on physical key parameters like the reduction of transmission error in compliance with achievable manufacturing tolerances. Nevertheless, these design rules may lead to a minimal sound pressure level but cannot solely be applied for an optimal sound quality in every case. Under economic and technical aspects there is no excitation free gear set. Furthermore, modern tendencies such as lightweight design and masking noise reduction (engine downsizing and electrification) lead more and more to scenarios where the sound of a gear set, which is only designated to have low transmission error, can be perceived as annoying. This requires design guidelines which take also the human related aspects of gear noise into account. Nowadays the gear design does not yet consider human noise perception sufficiently.

Thus, a research project at the WZL has been established that investigates the correlation between gear mesh excitation and the evaluation of gear noise. The objective of this project is to deduce a method for the consideration of perception-based noise evaluation already in the stage of gear design. Therefore, psychoacoustics metrics are used to analyze the gear noise of different gear sets in the dimensions of air-borne noise, structural vibration and the excitation due to meshing. The aim of this paper is to discuss the correlation between the signal properties of the excitation and the radiated noise in order to investigate the possibilities to transfer the perception related evaluation from sound pressure to the gear mesh excitation. The paper firstly shows central psychoacoustic parameters that are most relevant for the properties of gear noise. Furthermore, a new test fixture will be introduced that allows a dynamic measurement of gear mesh excitation directly adjacent to the meshing. Regarding these aspects two different gear sets are discussed concerning the calculated transmission error and the experimentally determined excitation, surface vibration and noise radiation. These aspects are accordingly examined with respect to human noise perception, which is described by psychoacoustics. It is shown that operating conditions, order distributions as well as the gear geometry are the main influences on the signal evaluation. The influence of dynamic aspects and especially the influence of resonance effects on the noise characteristics are additionally considered.

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American Gear Manufacturers Association
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Alexandria, Virginia 22314

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Introduction and objectives

The main objective of the gear design process is to meet the specifications and requirements on fatigue and wear resistance considering the defined product life cycle. Nevertheless, beside this aspect the generated and radiated noise of the gearbox becomes increasingly important in terms of acoustic quality and product acceptance by the customer. This leads to an increasing demand for powertrains and gearboxes with a low vibrational and acoustic output. In order to achieve and ensure a high quality rating acoustic design is therefore a central challenge for gearbox development.

Today the acoustic development process of gearboxes is based on absolute and objectified analyzing methods that allow a physical minimization of excitation and vibration. Nevertheless, a total reduction of gear noise cannot be achieved by reasonable effort taking into account practical requirements and manufacturing boundary conditions. In compliance with these boundary conditions scenarios occur when physical reduction and optimization of the excitation cannot solely lead to an improved acoustic quality rating of the gearbox [1] [2] [3]. The origin for the discrepancy between design and acoustic quality can be found in the signal processing of human noise perception that is not only determined by the physical sound pressure level but more by its spectral distribution and psycho-physiological (psychoacoustic) aspects [4]. Moreover, it can be observed that improvements of manufacturing quality may even lead to a worse acoustic quality rating, since the reduction of randomly scattered excitation effects can lead to more emphasized tonal aspects of gear noise [5] [6] [7]. Therefore, an extended source-path-receiver approach is required for achieving optimal acoustic quality of a gearbox powertrain, Figure 1.

This systematic approach needs to consider the entire gear noise origination process from the gear sets specific properties to the noise radiation and its perception under dynamic operating conditions. This is an augmented consideration of the conventional source-path-receiver model as described by [8]. The quasi-static gear mesh excitation is the foundation for the radiated noise. It is a gear set specific dimension that depends on aspects like load, macro and micro geometry, manufacturing deviations and several others more.

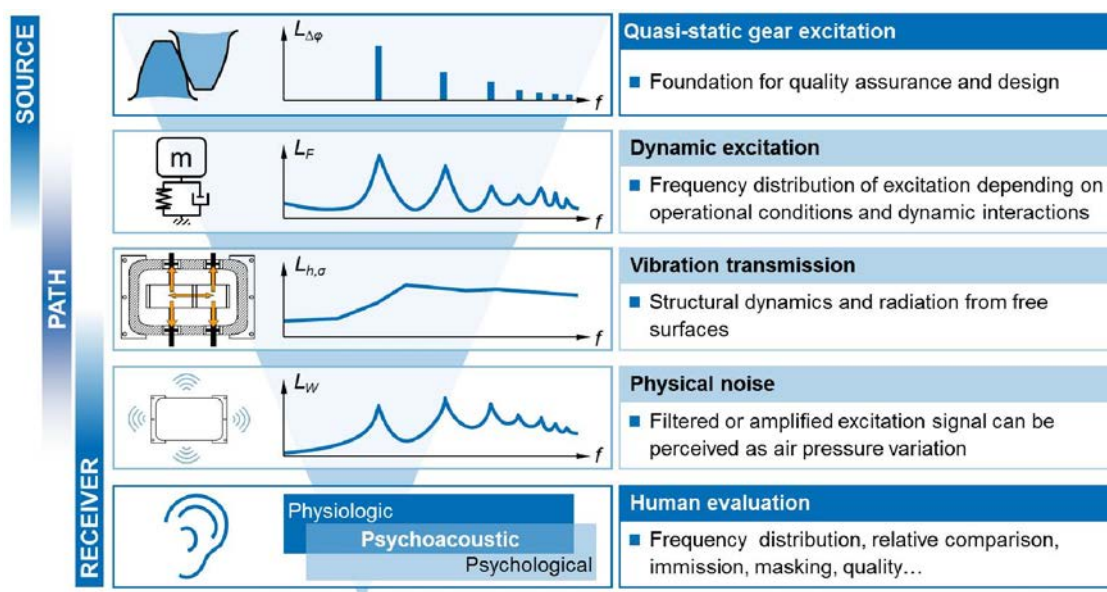


Figure 1. Augmented source-path-receiver model for gear noise excitation and perception

Today a gear set is designed with the objective to have a low transmission error as an indicator for low noise excitation, which is mainly distributed in discrete tonal harmonics of the gear mesh frequency. It can be quality controlled by e.g., topographic measurements or rolling tests. At operating conditions interactions between the gear set excitation and eigendynamics of the powertrain lead to a dynamic force excitation that is transmitted by structural vibrations in the shaft-bearing-housing system and radiated from free surfaces as airborne noise. The powertrain noise is evaluated by human perception as a result of a physiologic and psychological signal processing. Today already several calculation parameters are available and also partially standardized that allow considering this signal processing by objectified metrics. These psychoacoustic metrics can be used for an acoustic target design of powertrains [9] [10] [11] [12] and also as a detection tool for condition monitoring objectives [13].

However, today a method is not yet available for an adequate consideration of human noise perception in terms of the acoustically oriented gear design. Thus, the aim of this research activity is to analyze the perception related correlation between gear mesh excitation, structural vibrations and radiated airborne noise. This will allow defining a procedure to integrate the psychoacoustic signal processing into the gear design process in order to develop gear transmissions that have an increased acoustic quality rating. This paper firstly discusses the transfer of psychoacoustic metrics on the signal properties along the augmented source-path-receiver model of two different recently tested gear sets. Thereby, an analysis of the physical vibration signals is followed by a psychoacoustic discussion of these signals in an averaged way and at specific operating conditions. The latter one shows how the excitation order distribution influences the psychoacoustic rating in interaction with dynamic aspects and the transfer path at operating conditions.

Psychoacoustic evaluation parameters

Human perception of noise is neither objective nor absolute. A lot of the physiologic and psychological reasons are not yet entirely explored. But it can be determined that the perception is not only defined by the physical level. Moreover, classifications of annoyance require a more sophisticated approach of signal analysis. Psychoacoustics metrics have been development in recent past and already partially standardized that allow evaluating an airborne noise signal with respect to different perception aspects. These metrics rate a signal considering the annoyance and even euphony regarding those perception aspects. Figure 2 gives an overview on central psychoacoustic metrics that are described in the following paragraphs.

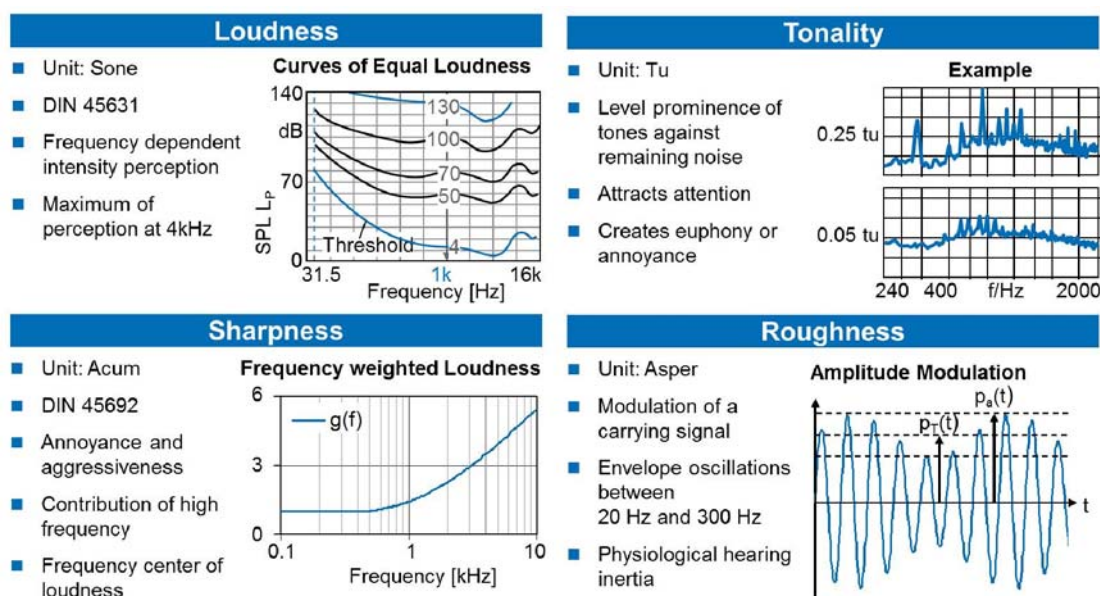


Figure 2. Overview on central psychoacoustic metrics

Loudness

Loudness is the psychoacoustic description of human intensity perception. It depends mainly on the frequency content of the signal but also on the exposition duration [14]. Effects of masking and critical bandwidths take into account the interference between single tones and narrow bandwidth noise in the frequency domain. The maximum of perception is for single sinusoidal tones at about 4 kHz. The curves of equal loudness are shown in Figure 2. Above and beneath this frequency region the intensity perception decreases significantly. In effect the sound pressure level needs to be higher there to cause the same intensity or loudness perception as for 4 kHz.

There are two different scales that describe loudness perception: *phon* and *sone*. They can be transferred into each other in a non-linear way. The *sone*-scale is the actual psychoacoustic one, because doubling the *sone*-value means a doubling of intensity perception. The *phon*-scale is historically used for a technical rating. The *phon* and *sone* rating scales have in common a fix point at a sinusoidal tone with a frequency of 1 kHz and a sound pressure level (SPL) of 40 dB. This sound is rated per definition with 1 *phon* and 1 *sone*. The evaluation method for loudness is standardized in DIN 45631 and DIN 45631/A1:2010 [15]. The supplementation A1 is for the loudness calculation of time-variant sounds. The calculation of loudness according to DIN 45631 is based on a method that determines the loudness of a complex noise as an equivalent loudness rating of a single tone. The calculation procedure can be divided into three steps. In the first step the frequency spectrum of the noise is dissected into critical frequency groups of hearing and weighted according to the frequency dependency of loudness. In the second step the effect of masking thresholds are considered and a frequency group dependent curve of specific loudness $N'(z)$ is determined. In the last step this curve is integrated across all the frequency groups. The resulting integral corresponds to the loudness N of the entire, complex noise signal. Two different aspects of the loudness calculation procedure should be mentioned at this point and considered for the analyses in the end of this paper. First, two neighboring tones, which occur within a distance lower than a critical frequency group bandwidth, contribute to the same specific loudness. Second, tones, which have a level lower than the masking threshold of adjacent frequency groups, contribute with the masking threshold of the adjacent frequency group level to the specific loudness.

Tonality and prominence ratio

Tonality of sound and noise signals is an important psychoacoustic feature that determines the annoyance or euphony of its signal. Thereby, tonality describes the dominance of single tones or narrow-bandwidth noises in comparison to the remaining noise level of the signal. Depending on the interest of the receptor in the sound event increasing tonality can lead to increased euphony or annoyance. The perception of tonality is frequency-dependent and the maximum of perception can be observed at a frequency of 700 Hz. Depending on the field of application there are several standards and definitions of tonality. The tonality evaluation method, proposed by Terhard [16] and Aures [17], gives a time-dependent single value for the airborne noise signal. This evaluation is based on short-time frequency spectra that are evaluated regarding prominent tones and narrow-bandwidth within critical bandwidths [18]. For each of the prominent components a tonal penalty level is calculated against the remaining noise. The single tonality value is finally determined with a non-linear function of all these penalty values.

In comparison to the summarizing evaluation with the previously described method there are several approaches that describe the perception of tonality in a spectrally resolved way. These approaches use a similar method to identify the existence of prominent tones and narrow-bandwidth noises as the approach by Terhard and Aures. But they give spectral prominence ratios or tone-to-noise ratios that allow evaluating the relevance of frequency regions for the tonal perception of the signal. The evaluation method in DIN 45681 [19] is a most generalized approach for this objective. This approach can similarly found in standard ISO/IEC 61400-11 [20] for wind turbines and in ECMA 74-Annex D [21] for information technology and telecommunications equipment. Generally it can be stated that all tonality evaluation methods have in common that they determine a level surplus, respectively a penalty level, of specific tones within a critical bandwidth in comparison to the remaining noise.

Sharpness

The psychoacoustic parameter sharpness describes the noise perception that correlates with the dominance of high frequencies. With increasing sharpness a noise is rated more aggressive and unpleasant. The sharpness rating depends on the loudness rating. The unit for sharpness rating is *acum*. There are several approaches for calculating sharpness rating. All of them use the specific loudness distribution of the noise signal. The standard DIN 45692 [22] describes a method for the calculation of sharpness by using the specific loudness distribution $N'(z)$ according to DIN 45631 [15]. This specific loudness is weighted by a function $g(z)$ that puts progressively emphasis on higher frequency. By normalizing the weighted specific loudness distribution to the entire loudness of the signal a weighted frequency center of loudness is determined. The resulting value defines the sharpness S [14].

$$S = 0.11 \frac{\int_{z=0}^{z=24 \text{ Bark}} N'(z) g(z) z/\text{Bark} dz}{\int_{z=0}^{z=24 \text{ Bark}} N'(z) dz} [\text{acum}] \quad (1)$$

Roughness

Signals, especially sound and noise signals, are often modulated in amplitude or frequency in order to transmit information. Spoken language is a typical example for this phenomenon. But when the receptor is not interested in the information, the modulation can lead to high annoyance, since it attracts attention. Hence, modulation is an important psychoacoustic aspect. When the sound signal is modulated by frequencies below 20 Hz, human perception can follow envelope fluctuations [18]. Above 20 Hz the fluctuation transforms to a perception of roughness. This perception reaches up to modulation frequencies of 300 Hz. Above 300 Hz the sideband effects of amplitude modulation cause a perception of individual tones. With an increased roughness the noise is perceived with an increased aggressiveness and annoyance. The maximum of roughness perception can be observed for a test tone at $f_T = 1$ kHz that is amplitude modulated with a modulation frequency of $f_m = 70$ Hz and a modulation degree of $m = 1.0$. The common unit for roughness is *asper*. Amplitude modulation can be found in the frequency spectrum as sideband in a frequency distance of the modulation frequency. As a result also two single neighboring tones within the required distance can cause roughness perception without the existence of modulation. The perception of roughness is nearly independent of the test tone level.

At the moment there is no standard for evaluating roughness. In [14], a general approach is proposed, which is adopted in [18] where two calculation approaches are described. Among these, the model “Gehörmodell Rauigkeit über Zeit” has proven to describe the perception phenomenon most adequately [23]. At first the time signal is filtered to simulate the influence of the external and the middle ear. Afterward, the signal is filtered and dissected into the critical frequency groups. After dissection and filtering, the envelope of each signal is determined by using the Hilbert transformation [18]. The following application of combined low- and high-pass-filters models the previously mentioned dependency of roughness perception on the modulation frequency. The overall roughness of the noise signal is finally determined by integrating the resulting and afterward weighted signals over the frequency.

Interpretation considering gear noise

Considering the previously described psychoacoustic aspects and their calculation metrics, first influence conclusions can be drawn for the gear noise excitation. Figure 3 gives an overview to these conclusions. These conclusions should be considered as first interpretations that have to be verified by the upcoming investigations.

Psychoacoustics <u>Linear</u> , objectified correlation between Noise characteristics and perception			
Parameter	Perception	Signal analysis	Gear relevance
Loudness	Intensity perception depending on frequency	Integral over the frequency specific loudness in frequency groups	Excitation level, Resonances, speed, number of teeth
Tonality/ Prominence ratio	Attention concentration due prominent tones	Level surplus of tones and narrow-bandwidth noises against remaining signal	Speed, number of teeth, manufacturing quality, order distribution, background noise
Sharpness	Frequency center of intensity perception	Weighted frequency center of loudness	Speed, number of teeth, order distribution of excitation
Roughness	Envelope fluctuations between 20 and 300 Hz	Envelope and modulation analysis	Low-order modulation (pitch errors, eccentricities , etc.)

Figure 3. Relevance of psychoacoustic metrics for gear noise evaluation

Loudness is mainly influenced by the frequency-dependent intensity of the noise signal. Therefore, mainly the excitation level influences the loudness rating of gear set in interaction with resonance effects. Additionally, also the combination of number of teeth and operating speeds has influence on the loudness rating, since these parameters define the excited mesh frequencies and their higher harmonics. The aspect of tonality is defined by the level and the prominence of single excitation frequencies. Therefore, increasing manufacturing quality can lead to an increased tonality, as also described in [5] [6]. But also the excitation level and its spectral distribution on to the mesh frequency and its harmonics have a significant influence on the tonality rating in combination with the background noise level. Since a high sharpness rating is caused by a dominance of high frequencies this psychoacoustic is mainly influenced by the operating speed in combination with the number of teeth. These two aspects define the mesh frequencies and thereby the frequency level of noise excitation. Furthermore, the spectral order distribution and hence the level of higher mesh harmonics define the dominance of higher excitation frequencies and the sharpness rating. The perception of roughness is an effect of low-order modulations. Generally, low-order modulations of gear noise excitation are caused by pitch errors or eccentricities. Therefore, increasing manufacturing quality reduces the modulation and hence the roughness rating, but can also lead to an increased tonality.

Quasi-static loaded gear mesh excitation

As mentioned in the introduction the quasi-static gear mesh excitation is a foundation for gear set design and also for quality assurance. With some restrictions, it is a gear set specific dimension and independent from the designated powertrain, in which the gear set will operate. But nevertheless, there is a strong correlation between the properties of the quasi-static gear set excitation and resulting gear noise in the powertrain, as sketched by Figure 1. There are many means to influence the level and the properties of gear mesh excitation. One central objective of this research project is to investigate various excitation characteristics as well as their influences on the physical noise signals and the perception related evaluation by psychoacoustic metrics. This investigation concentrates on the geometric parameters as shown in Figure 4. Thereby, central macro and micro geometric parameters are discussed that are well-known having significant influence on gear noise. Additionally, gears will be included that are hard-finished by either continuous worm-grinding or discontinuous profile grinding. Both manufacturing processes differ in the resulting bias of the flank topology that can influence the load distribution and hence the noise excitation [24] [25]. In total there are 22 different gear sets that have been designed and manufactured and will be investigated within the project. This paper discusses the analysis of the first two gear sets that are described in the lower row of Figure 4. The gear sets differ significantly with respect to the number of teeth and the tooth width but have similar modules, helix angles and total contact ratios.