Psychoacoustics Applied to eDrive Noise Reduction

Dr. Hermann J. Stadtfeld

Physical Effects Causing Transmission Noise

Transmissions in electric vehicles appear to require new and different mechanisms for the reduction of the high pitch noise they are emitting. If the question is asked why the frequency of the eDrives noise is significantly higher than the frequencies in conventional automotive transmissions, then the answer is that the transmission input RPM is higher by a factor 3 to 10. Basically this means the physical phenomena which generate the noise are the same phenomena that generate noise in a conventional transmission. This means the tooth mesh frequency and its higher harmonics are also responsible for the high pitch noise emitted from eDrives.

High pitch noise is recognized as more annoying than low pitch noise. Although the same effects are responsible for the noise in both conventional and electric vehicle transmissions, the same disturbance which was tolerable in a conventional vehicle with an internal combustion engine becomes now a deciding factor of why to buy one vehicle versus another. The importance of small tooth mesh impacts which were rated as acceptable in the past becomes critical in connection with an eDrive.

Cylindrical gears as well as bevel and hypoid gears have the same identical noise generation principles, and both can be reduced with the same noise reduction mechanisms.

- Chapter 9 introduces the phenomena between noise generation, analysis and recognition by the human ear. The acknowledgements and conclusion of chapter 9 are then applied to two different levels of noise reduction, Micro Topology (flank form modifications), discussed in chapter 10 and Micro Topography (surface structure modifications), discussed in chapter 11.

Main Topics of Chapter 9 are:

- Designed flank surface crowning and theoretical motion transmission
- Fourier analysis and its limits in gear noise analysis
- Gear noise and psychoacoustics
- Practical example of Fourier analysis and the residual phenomenon

Psychoacoustics. Sound is created by the vibration of mechanical elements and magnified by structures with certain surface areas and certain resonance frequency. The original or the magnified sound is transmitted through structures (structure-borne noise) and then transmitted through the air (sound pressure waves) and finally received by the human ear.

The physics of sound transmission is based on the compression and expansion of solid materials as well as fluids. The mathematical function of the compression and expansion of elastic materials is most likely always a sinusoidal function. The assumption that all sounds which are transmitted and emitted consist solely of sinusoidal elements seems reasonable.

The answers which engineers would be interested to receive from the Psychoacoustic Science regard the receiving of sound transmission by the human ear. If sound was created as a non-sinusoidal signal and also transmitted to the ear in a media which supports non-harmonic functions, how is this sound recognized by the human brain? An inverse

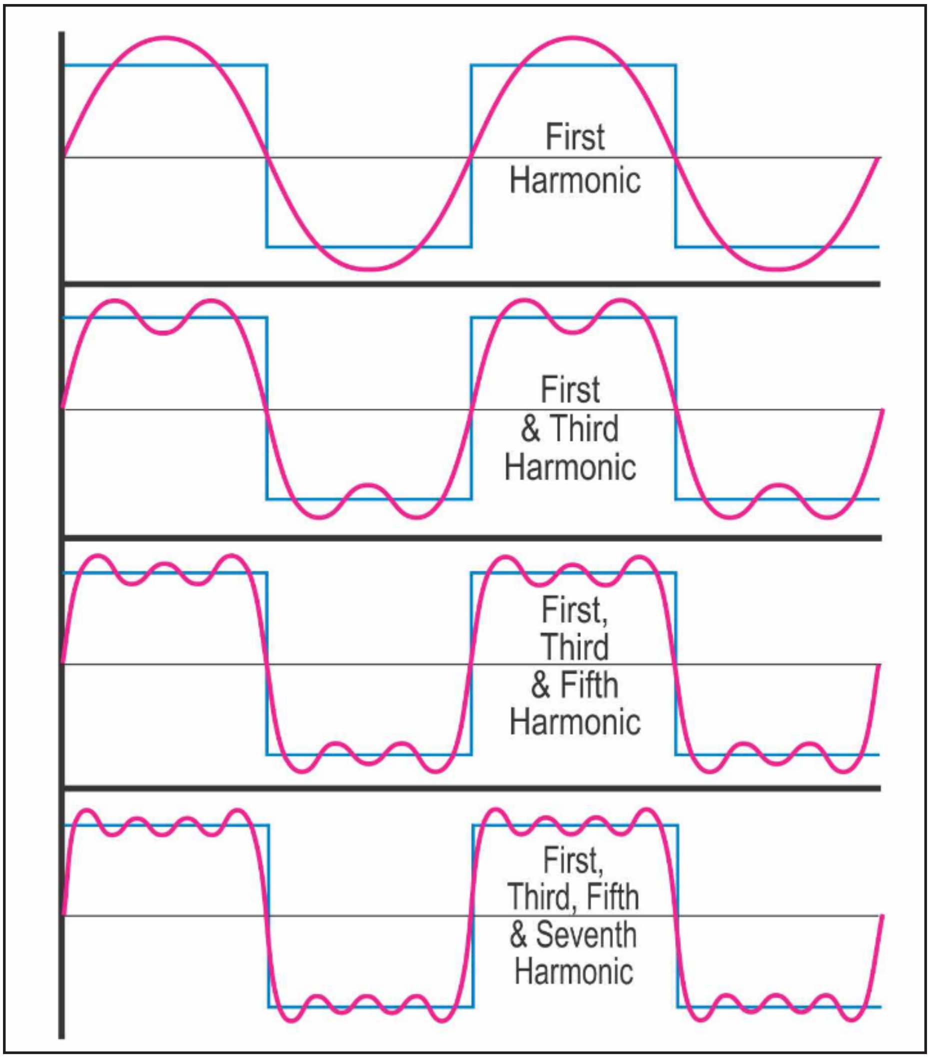

Figure 1 Fourier series development for a square wave.

question is, if our entire environment, including the laws of physics, is strictly supporting harmonic sounds. This would govern that sound sources, sound transmission, as well as the receiving and recognizing of sound by a listener, are all based on the harmonic movement of elements by certain amplitudes and with a certain frequency.

In studying the vertical sequence of the graphics in Figure 1, it is evident that according to the common acoustic interpretation a square wave would cause a listener to hear several high frequencies. This raises a number of questions:

- Is the transmission of waves through the air or other media only possible in sine waves?
- If a true square wave was received by the human ear, would the brain first recognize the received wave form and replace it with a sine wave of the same frequency and similar intensity and then substitute the higher frequencies, similar to Figure 1?
- If the human ear could hear the original square wave as a plain periodic plus-minus signal, would it sound the same as an artificial square wave which is a superimposition of four or more different frequency sine functions?

The questions above require some basic relationships between sound transmission and the psychoacoustics between the sound received by the human ear and its processing by the brain. A complete Fast Fourier Transformation (FFT) also analyzes the frequencies between the harmonics in certain Hertzian increments in order to more accurately capture the working variation. If the result of a FFT is used as the absolute measure of the noise characteristic of a gearset, then the conclusion is made that the human ear only recognizes acoustic signals or sound pressure waves in the form of true sinewaves.

The concert pitch A of 440 Hz from a tuning fork sounds different to the human ear than from a violin or from a piano. The reasons are overtones which consist of higher harmonics, side bands and/or other elements in the sound waves which might not be captured by the FFT. However, the fact that the 440 Hz can be recognized precisely by a listener is explained with the higher harmonics accompanying the fundamental frequency (Ref. 1).

The assumption that the ear tends to recognize only harmonic signals is partially correct. The outer ear acts as equalizer and compressor, which boost the sound pressure by 15 to 20 dB. The airwaves actuate the eardrum which in turn actuates the ossicles which acts as equalizer, compressor and impedance matcher such that the processed pressure waves are transferred into the cochlear fluid. The pressure waves are transmitted by the cochlea fluid to the tectorial membrane. The snail house-shaped cochlea is lined with the tectorial membrane which moves hair cells. Along the windings of the cochlea, the hair cells are sensitive to different frequencies, performing a spectral analysis of the sound signal. The hair cell neurons convert the mechanical vibration into digital electronic signals which are transmitted to the brain. The diagrams in Figure 2 show the Fourier analysis of the noise emission from a gearset and how the vibrations are converted to airborne sound which is received by the order tracking neurons in the ear. The recognized frequencies and amplitudes are similar, but different than the ones found in the Fourier transformation. One reason for this is the residual error which is not captured by the Fourier analysis.

An interesting phenomenon is that the pitch identification of ear and brain not only uses the fundamental frequency, but also employs the available (audible) higher harmonic orders. The ear still identifies, for example, concert pitch A if only the second to sixth harmonics are received, and the fundamental frequency

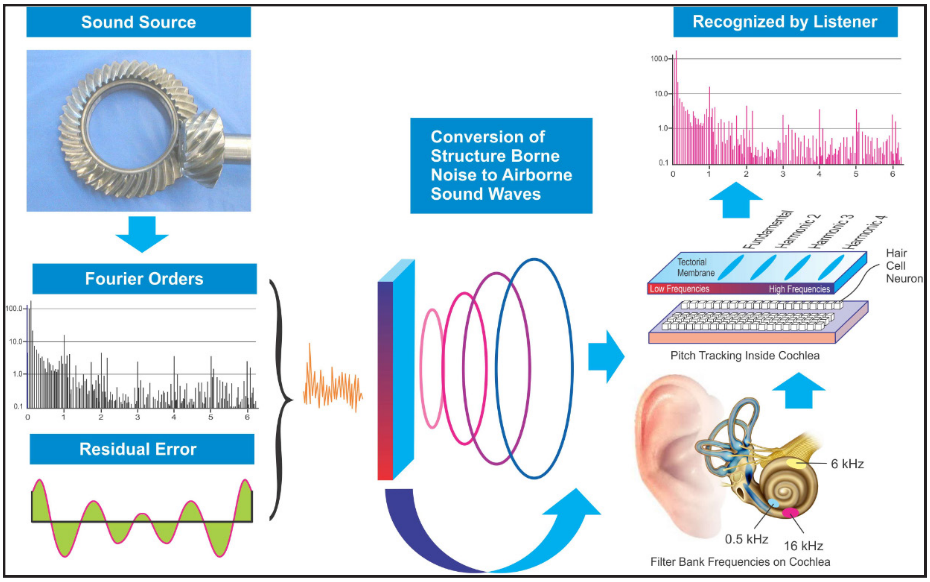

Figure 2 **From sound source human recognized sound.**

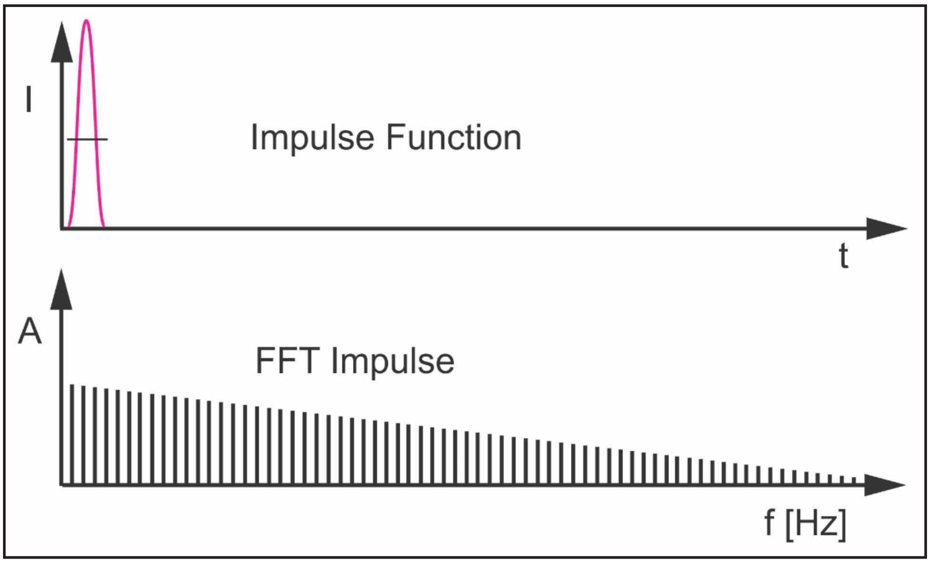

Figure 3 **Impulse recognition in Fourier analysis.**

is absent in the received sound signal (ghost fundamental). The "A-signal" without the fundamental sounds "smoother" than if the fundamental frequency was present.

The conclusion is that the ear as a pneumatic-mechanical-hydraulic-electronic system has masses, springs and dampening, and is created to recognize frequencies. It will mostly recognize harmonic air pressure changes which are received in a periodic signal. However, an impulse will also be recognized while ear and brain try to supplement the missing periodicity. The Fourier transformation of an impulse is shown in Figure 3. The impulse generates bars in the entire frequency range which die down in amplitude as the frequency increases. This means that all those frequencies have been found by the Fourier transformation, although the impulse was an isolated occurrence with virtually no frequency. The human ear will respond similarly because its design will cause an excitation of all hair cells along the windings of the cochlea and send signals of all audible frequencies to the brain.

Another interesting question is how a square wave sounds to the human ear compared to the results of a Fourier analysis. A perfect square wave which is approximated with a Fourier series shows an overshoot at the corners of the square (Gibbs phenomenon) (Refs. 2-3). Figure 1 shows a square wave which is approximated by a first, third, fifth and seventh order sine wave. The overshoot never dies out, but approaches a finite limit of 18% of the square wave amplitude as the number of orders increases. The question is if the human ear, because of its function, will basically send a similar exaggerated signal to the brain when it receives a perfect square sound wave. This question might be academic because no sound generating source is capable of creating a perfectly square signal without the overshoot. Besides this, the airwaves would not be able to transmit such a signal without distortion. The square wave has a ringing sound to the ear which is attributed to the overshoot. An additional peculiarity of the Fourier series of a square wave is that only the odd orders + 1, 3, 5 + are represented. The verification of the fundamental frequency of a square wave which the ear conducts with the higher harmonics in numerous distinct areas of the tectorial membrane is not given and a strange hearing experience is the result. The square wave not only rings, it also sounds "cold and synthetic."

Acoustical experiments with pure single frequency sine waves seem to confirm the theory that ear and brain will not complement the non-transmitted higher harmonic multiples of that sinusoidal sound. The pure single frequency sine wave sounds smooth and rather quiet compared to a same intensity square wave. This raises the question, if in case of a parabolic motion error, will the ear notice the same higher harmonic frequency levels which result in a Fourier analysis of such a motion error? The Fourier analysis mirrors in many cases the psychoacoustics of the human ear very well (e.g. music), but also fails in many cases to deliver representative evaluation results (e.g. disturbing mechanical noise).

Depending on the motion error characteristic, there are higher harmonics amplitudes in the FFT result and residual approximation errors which are ignored. It is assumed that certain residual non-sinusoidal waves are audible as distorted sine waves and certain harmonic amplitudes do not really exist in the sound waves received and processed by the ear. The non-existing harmonic amplitudes are merely a result of the Fourier summation scheme. It has been proposed to apply the smoother Fejér summation or Riesz summation or using the continuous wavelet transformation in order to gain more relevant dynamic analysis results.

Dynamic analysis results have commonly two applications. One is the mentioned audible experience by humans and the second is the conclusion to gear geometry-related manufacturing errors. The latter asks for a sufficient qualitative and a concrete quantitative interpretation in order to allow for corrections in the machining process. The fundamental harmonics and the side bands can give certain hints to machining errors. The harmonics above the fourth order point in some cases at surface structural and roughness problems. Especially the second to fourth harmonic amplitudes can lead to the belief that there is, for example, a disturbance which occurs 2, 3 or 4 times at each tooth mesh. As a matter of fact, this is possible, but it only might be the result of the Fourier summation process required to capture a particular motion graph, which only repeats its disturbing rotational transmission once per tooth mesh.

Example of Fourier analysis and the residual phenomenon. In order to approximate a realistic motion transmission graph, a parabola of the form $\Delta\varphi = a \cdot (\varphi - \varphi_0)^2$ as it is typical for bevel gearsets, is used in Figure 4 as the subject of a Fourier analysis.

As a starting point, a sine-function with suitable amplitude and a period of

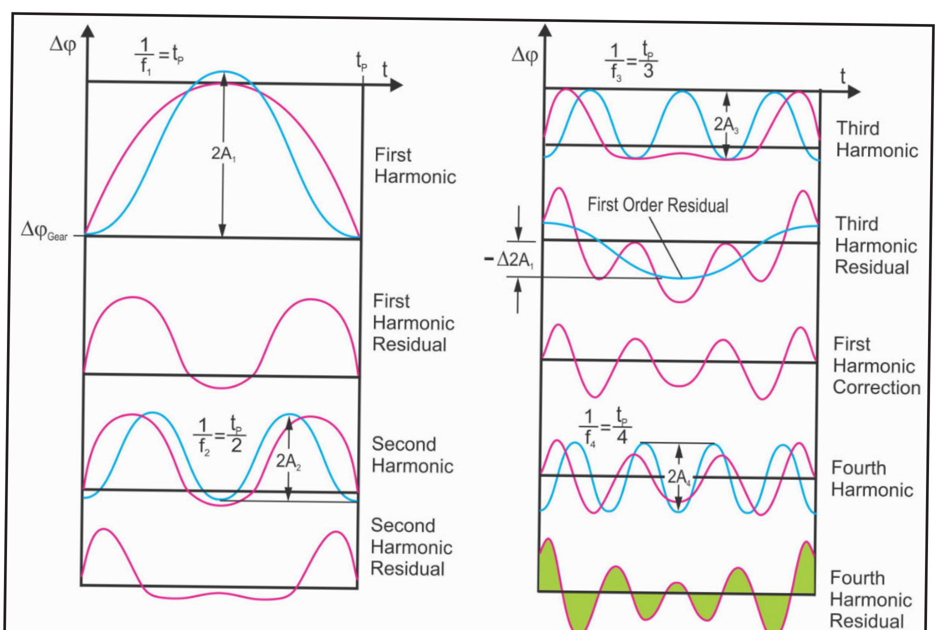

Figure 4 Fourier analysis of parabolic function.

the meshing time of one pitch are drawn into the parabola-shaped motion graph. If the first harmonic is subtracted from the motion transmission graph, the result is the first harmonic residual which has twice the frequency of the motion transmission graph itself. This does not mean that the original motion transmission graph contained any elements of double frequency, it merely means that in the attempt to approximate a parabola with a sine-function the residual will show a dominating second order. If the dynamic transmission media is capable of transmitting the original parabola-shaped sound wave, and if the receiver, e.g.— a human ear was rather capable in receiving and processing sinusoidal waves, only then would this second harmonic be noticed.

A sinusoidal function with half the period of the original function and an amplitude of about half of the residual magnitude is now used to approximate the residual function from the first harmonic. The residual from this approximation step result is shown in Figure 4 underneath the second harmonic. This graph appears to have some third- and some fourth-order elements. As a matter of fact, it requires the elimination of the third- and fourth-order harmonic elements in order to notice a visible reduction of the residual function. The unequal spacing of the waves makes it particularly difficult for a Fourier analysis to closely approximate a parabolic function. The residual error after the elimination of the third harmonic element still contains some first-order residual, which can be determined at this point and then be added to the amplitude A_1. The frequency-amplitude spectrums of the four sinewaves in Figure 4 have been plotted into the graphic in Figure 5. Although this graphic shows the amplitudes for the dynamic gearset evaluation, only the first order peak-to-peak values are relevant because they only represent the stroke of the excitation ripple and can be correlated to the transmission error. A true mechanical disturbance (e.g. + second order) would show as an amplitude above the enveloping curve (red dashed bar). There are several conclusions that came out of the experiment demonstrated with Figure 4:

- A true parabola-shaped graph was

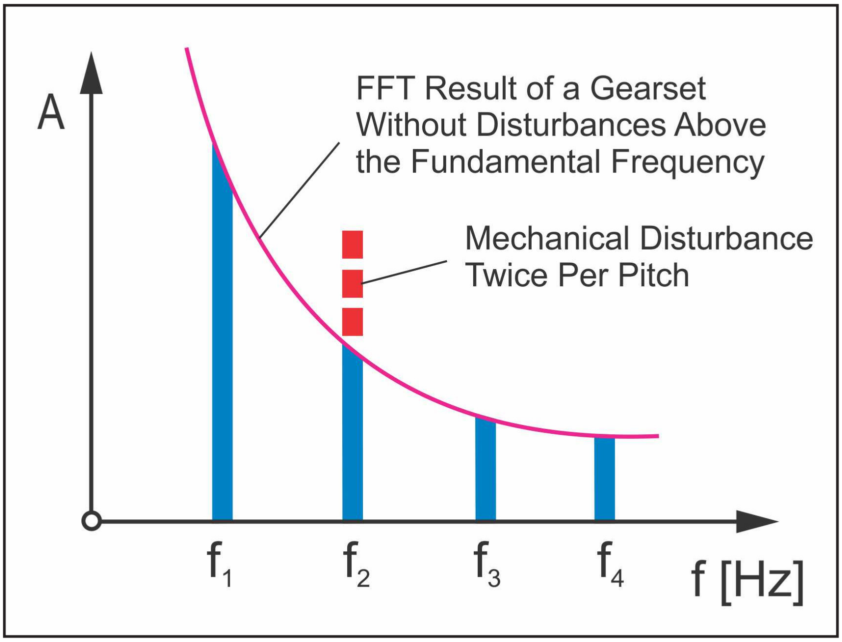

Figure 5 **Frequency-amplitude spectrum of harmonic contents of a periodic parabola.**

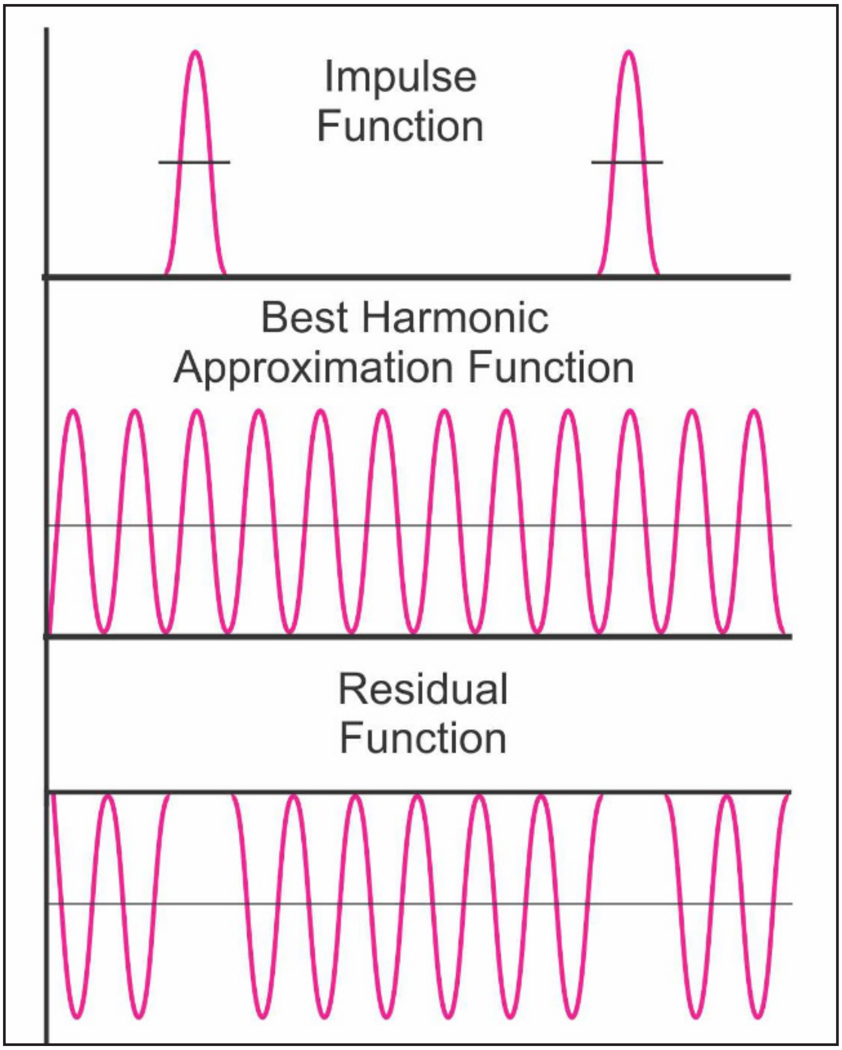

Figure 6 **Residual error in case of a periodic impulse.**

approximated. The result of a Fourier analysis of a perfect parabola-shaped motion transmission graph results in more than four harmonics of significant amplitudes. If the analysis is stopped after the four harmonic separation steps, a residual amplitude of about 50% of the original function is found.

- The value $2A_1$ is larger than the original value of the motion error $\Delta_{\varphi Gear}$
- Many gear analyses are performed with only a four harmonics analysis. The residual function is so significant for the effective noise emission of the gearset that no absolute noise rating is possible.
- FFTs have their value if they are used in the comparison of similar gearsets which have been found acceptable in their noise emission.
- FFTs are useful if the presence of low frequencies caused by pinion and gear runout should be detected. Those waves are dominated by a sinusoidal content.
- FFTs are useful if higher frequencies caused by surface texture or generating flats should be detected. Also those waves are dominated by sinusoidal contents.
- FFTs are useful in the medium frequency range (first to fourth harmonic) if the measured transmission variations have a dominating sinusoidal content.

A periodic impulse function is impossible to capture with a harmonic Fourier analysis if the width of the impulse and the period of its reoccurrence have largely different amounts, as shown on top of Figure 6. The bottom of Figure 6 shows the residual error reflects a high frequency with the amplitude of the original peak. In reality, the FFT will attempt to approximate the function and also interpret the impulse characteristic which will result in side bands in the entire frequency range.

The Physics of Sound Transmission Applied to Gears

In a constructed example, the single flank error signal in the graphic in Figure 7 consists only of sine functions. The top graphic is the recording of one ring gear revolution. In the example, a ratio of 3.00 was chosen, which means the graphs in Figure 10 will be exactly repeated for additional ring gear revolutions.

Figure 7 shows how in three steps, first the gear runout, then the pinion runout and finally the tooth mesh is filtered out. In the example, no residual amplitudes are left. It can be assumed that a listener can clearly hear all three separated frequencies. At the bottom in Figure 7 the FFT result contains bars for the gear runout, the pinion runout and the tooth mesh frequency. The side bands of the tooth mesh frequency originate from the gear and pinion runout. The side bands are spaced away from the tooth mesh frequency by their respective runout frequencies. Although the gear and pinion runout and even the generating flats commonly have a dominating sinusoidal shape, the tooth mesh in most real cases is parabolic, resulting in many additional frequency amplitudes which is attributed to the transformation algorithm that is used in Fourier analysis and does not exactly represent the audible frequencies.

In Figure 8 the motion transmission error from Figure 7 is used as an example for the separation of the elements "Gear Runout," Pinion Runout" and tooth mesh. The difference with Figure 7 is the tooth mesh motion error which is parabolic in Figure 8 instead of sinusoidal. Due to the parabolic motion error not only f_z, but also the multiples of f_z are present in the Fourier analysis result. Each of these harmonic frequency bars is surrounded by side bands caused by the gear and pinion runout. Instead of ignoring the differences between parabolic and sinusoidal function, the Fourier analysis expresses the residuals between parabolic motion graph and sine function in additional sine functions of higher orders (Ref. 4).

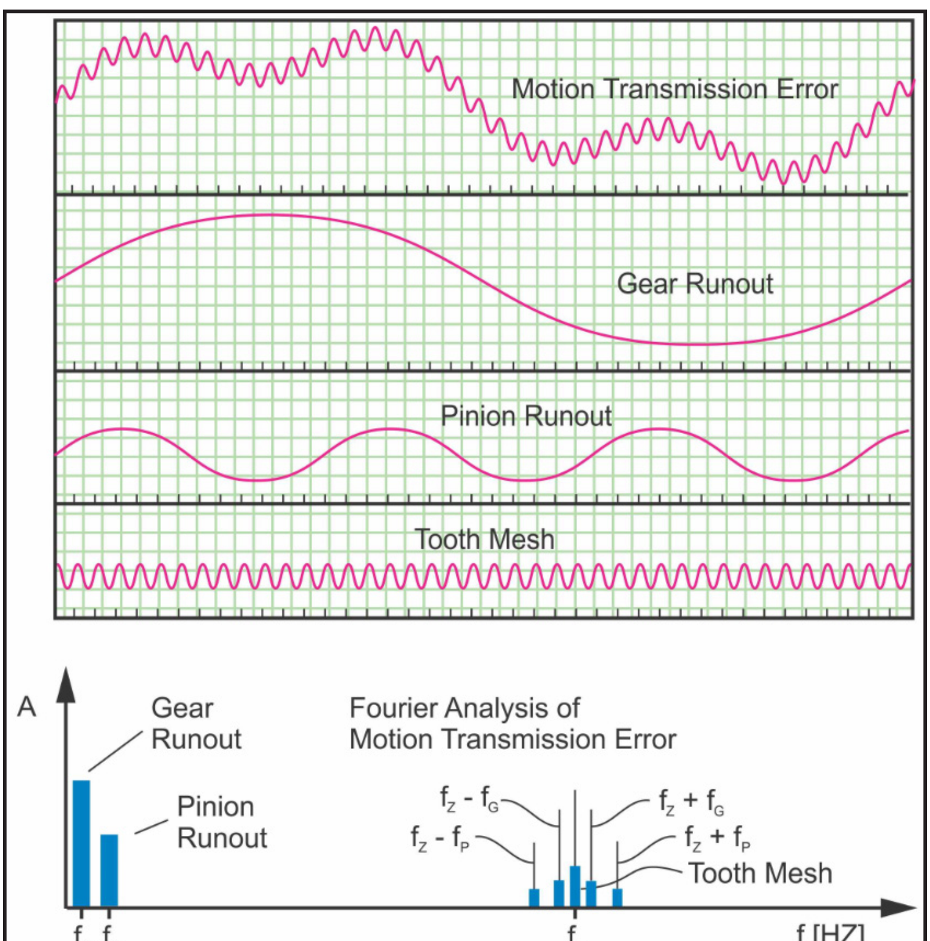

Figure 7 Separation of harmonic motion transmission elements of motion error.

Summary

Psychoacoustic science teaches that a sound source which initially has a non-harmonic excitation will be recognized as harmonic function with the initial frequency and a superimposition of an infinite number of higher frequencies with fading amplitudes. The reason is the ability of mechanical structures and the ability of air waves to transmit only harmonic signals. This phenomenon is also supported by the human ear, which processes received sound with a spectral analysis and therefore only recognizes superimposed harmonic sound signals + even if the sound waves would consist of a pure square function.

It is interesting to mention in this connection, that Jean-Baptiste Joseph Fourier published in 1807 his analysis method which uses an infinite number of sinusoidal frequencies in order to quantify a repeated function + even if the function has no sinusoidal elements. Fourier's analysis algorithm is employed since the 1960s as a computerized method and is used today to analyze vibration and sound for its contents of frequencies. Fourier's method is aligned with the sound transmission principle of the airwaves as well as with the function of the human ear. However, it is an approximation of signals like square waves which do not contain any harmonic waves at all, yet the result is a variety of harmonic frequencies and their amplitudes.

Conclusion for eDrive Noise Reduction

The higher input speed of eDrives implies that all noise-causing disturbances are multiplied by 3 to 10 compared to conventional transmissions. Therefore events higher than the third mesh harmonic would be above the human audible frequency. The conclusion from this would be that higher harmonics and surface structure effects have no influence on the audible spectrum and can therefore be ignored.

This conclusion is incorrect. Only the first stage of an eDrive has the high rotational speed. All conventional criteria like frequencies below and above the third mesh harmonic, as well as surface structure-borne frequencies, are still applicable to the final stages of electric vehicle transmissions. Another reason to use surface structure shifts (MicroShift) in addition to flank form modifications is based on the research results from structure shift investigations. A different amount of surface structure shift from tooth to tooth, following for example a sinusoidal function, will generate side bands with different frequency distances from the mesh frequency multiples. The side bands will change sensation of noise recognition from annoying to an un-disturbing, smooth buzzing sound.

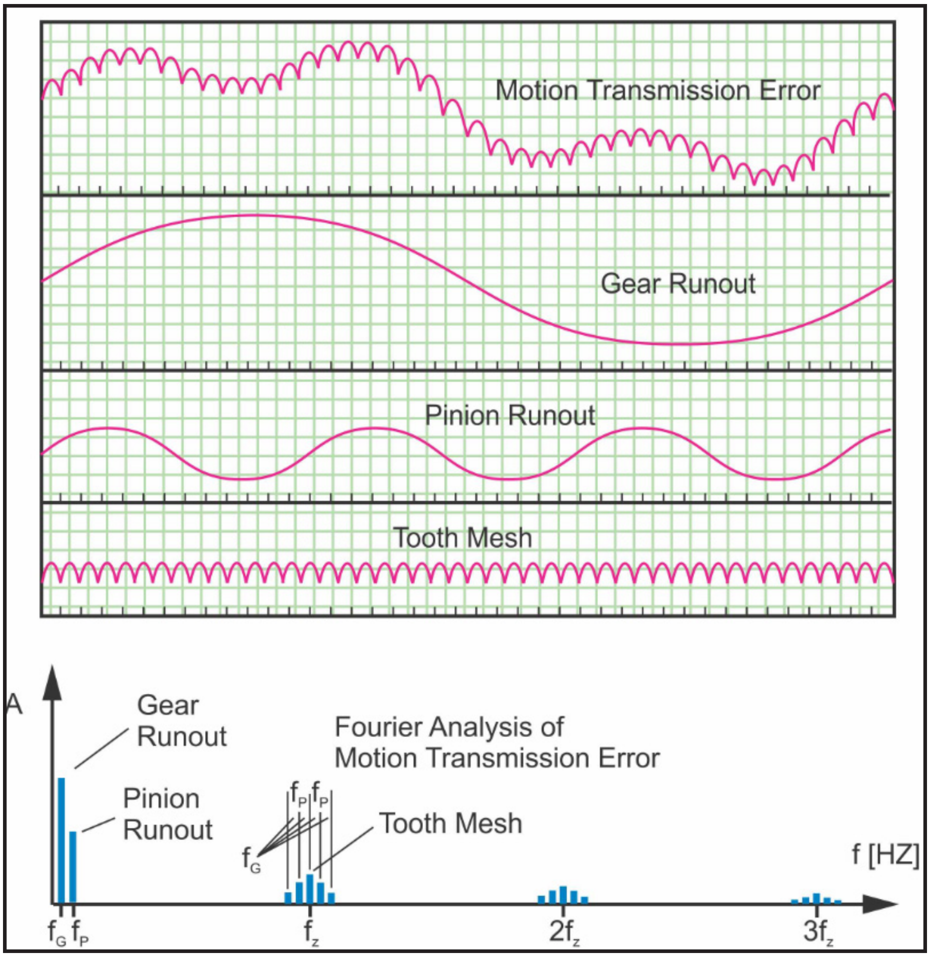

Figure 8 Separation of parabolic and harmonic motion transmission elements.

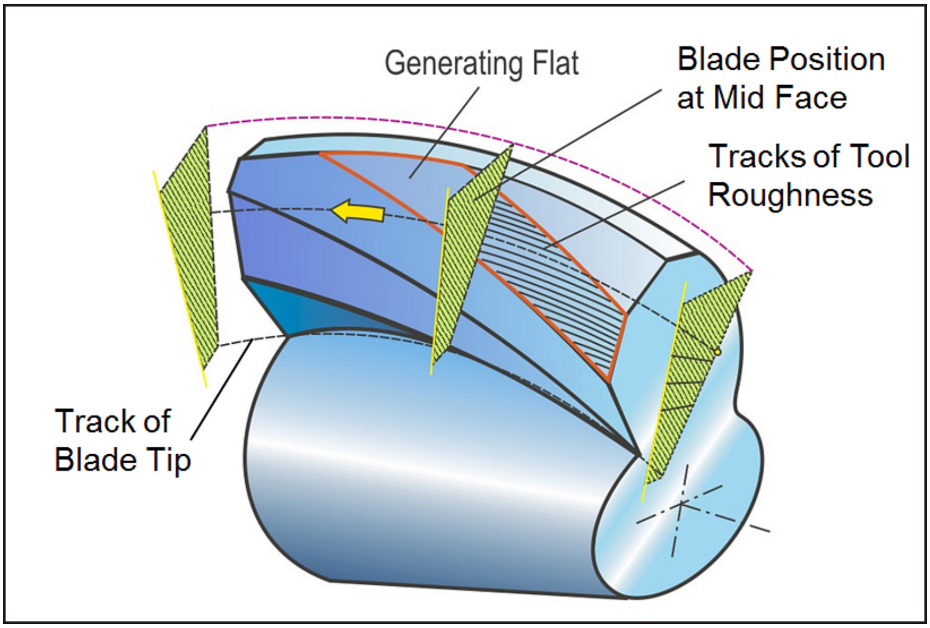

Figure 9 Noise generating flank surface effects.

All gear noise is caused from the tooth mesh impact, flank form imperfections as well as from generating flats and roughness tracks of the tool (cutting blades or grinding wheel). Generating flats and tool roughness tracks are shown in an exaggerated view in Figure 9. Depending on the direction of the contacting lines between the two mating gears and their interacting with the flank surface effects in Figure 9, medium- and high-frequency noise can be generated when the mating teeth mesh under certain, mostly low, loads.

If the tooth mesh impact and the surface effects are the cause of excitations of gearbox surrounding structures, two conclusions for their reduction or elimination are possible:

- A modified transmission function can reduce or eliminate the residuals and all higher harmonic multiples of the tooth mesh harmonic.
- Side bands surrounding the harmonic peaks will reduce the annoying character of the emitted noise.

Modifications to the transmission function can be achieved with *Universal Machine Motions* (*UMC*). Chapter 10 (see book version) discusses several possibilities of sophisticated transmission function optimizations which proved to reduce the tooth mesh impact as the major source of all gear noise.

For more information.
Questions or comments regarding this paper?
Contact Hermann Stadtfeld at *hstadtfeld@gleason.com.*

References

1. Deruty, E. "How the Ear Works, Psychoacoustics of the Human Hearing Experience," Article in *www.soundonsound.com*, November 2016.
2. Wilbraham, H. "On a Certain Periodic Function," Cambridge and Dublin Mathematical Journal 3, 1848.
3. Burkhardt, H. "Klein's Encyclopedia, Mathematische Annalen," Review of the Gibbs Phenomenon, Teubner Verlag, Göttingen, 1933.
4. Stadtfeld, H.J. "Psychoacoustic Methodology for the Noise Reduction of Bevel Gears," *AGMA, Fall Technical Meeting*, Columbus, Ohio, October 2017.

For Related Articles Search
noise
at www.geartechnology.com

Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in bevel gear technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems and gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership the world of bevel gear cutting has converted to environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower noise emission level and reduce energy consumption.

For 35 years, Dr. Stadtfeld has had a remarkable career within the field of bevel gear technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. He held a professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards — one for his high-speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015–2016 CNN featured him as "Tech Hero" on a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency.

Stadtfeld continues, along with his senior management position at Gleason Corporation, to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as professor of the Technical University of Ilmenau — thus helping to shape and ensure the future of gear technology.