# Gearbox Noise & Vibration Prediction and Control

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**Abstract -** This paper will review practical techniques and procedures employed to quiet gearboxes and transmission units. The author prefers solving the gear noise problem at the very source to introduce an enclosure as a means to reduce radiated noise, which seems to be easy but its effect on the sound pressure level is small. The gearbox noise problem solution is focused on the improvement of gear design; on the verification of its effect on the radiated noise and the determination of the gears' contribution to the truck's or car's overall noise levels and on the analytical and/or numerical computer-based tools needed to perform the signal processing and diagnostics of geared axis systems. All of the analytical methods are based on the time and frequency domain approach. Special care is addressed to the smoothness of the drive resulting from the transmission error variation during a mesh cycle. This paper will review the progress in technique of the gear angular vibration analysis and its effect on gear noise due to the self excited vibration. This presentation will include some examples of the use of such approaches in practical engineering problems

***Key Words***: Gear Noise, Gearbox Vibration, Taguchi Method, Tools for Gearbox vibration analysis, etc .

## 1.INTRODUCTION

The general performance of laser beam printers can be expressed in terms of the printing speed, resolution, image quality with regard to the vibration, First-Print-Out-Time (FPOT), and printing noise [1]. As the printing speed of laser beam printers becomes faster, reducing the printing noise is a prerequisite for research of laser beam printer. Laser beam printers feature less noise and vibration than the impact type (e.g., dot-matrix printers) printers. However, they have many rotating parts such as OPC, belts, rollers, and gears, and their power is delivered mostly from a brushless DC (BLDC) motor by gears, which are the main machine element of power transmission. Although the speed of revolution of the gears varies with the printing speed, most gears in low-end laser beam printers (printing speed of 20 ppm) rotate at 100~300 rpm. The pinion on the BLDC motor revolves at more than 1000 rpm. However, a high-speed printer (printing speed of 40~60 ppm) has power transmission gears that rotate at 500rpm.In this research, plastic gears have been optimized through Taguchi's analysis to reduce the printing noise. Further more, the sound quality resulting from the optimization of the gears has been evaluated. The sources of printer noise can be classified into three categories: driving noise, paper noise, and mechanical noise. Driving noise is produced by the operation of rotating parts such as motors, gears, the laser scanning unit (LSU), and fans. Paper noise is caused by friction and the impact of paper through the paper path of the laser beam printer. Finally, mechanical noise is produced in the pick-up, actuator, clutch, cam, etc., which all control the rotating parts. A dominant source of driving noise is the vibrations due to transmission error (TE) of the gears. TE of the gears has been studied extensively in attempts to reduce printer noise and vibration. Usually, the gear noise that results from the meshing of gear teeth is transmitted via forces and motions to the shafting, bearing, and transmission housing where it is then radiated to the surroundings, as depicted in Fig. 1 [2, 3]. Non-measurable factors for gear design such as temperature and material humidity are not major contributors to TE. However, both TE and noise are influenced by the load on the gears [4]. In this sense, Houser designed optimal gears that gave minimum noise and stress by using a unique method such as Run-Many- Cases [5]. Also, an attempt was made to reduce the gear noise by either reducing the excitations at the mesh via minimizing the dynamic forces due to TE or by reducing the force transmissibility from the mesh to the noise-radiation surface [6].

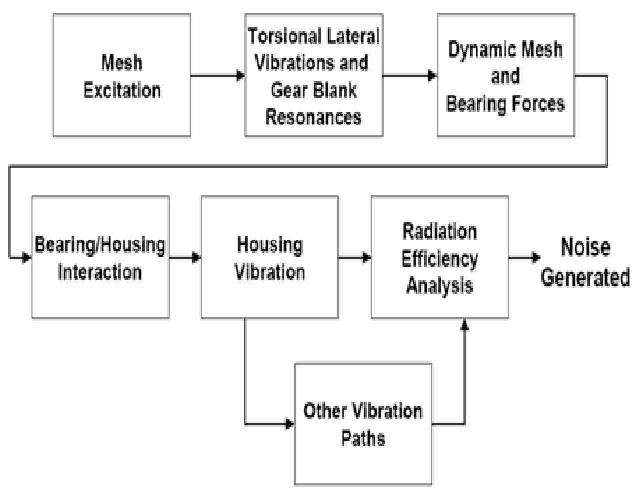



**Fig.1.Path of Gear noise transmission**

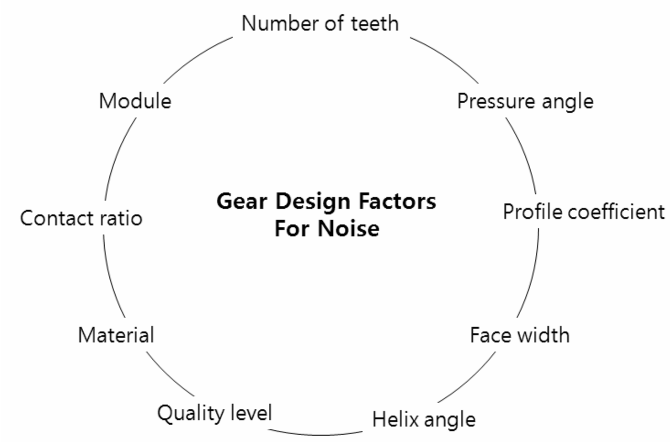



**Fig.2 Factors related to Gear noise**

## 2. Gear noise

The gear noise generated from the meshing of gear teeth is externally emitted through the gear-noise transmission path.(See Fig. 1) The main gear noise is produced at a specific frequency that corresponds to the natural mode of vibration of the gear's main frame under flexure. The gear noise also results from the noise at the mesh frequency, which is produce from each tooth of the gear pairs. In addition, the aerodynamics of rotating gears may be the reason for the gear noise. However, the noise at the mesh frequency and the noise due to sliding friction and wear arise mainly because a lubricant is normally not used for the plastic gears in laser beam printers. Usually, plastic gears are more advantageous than metal gears in terms of material cost, noise, and design flexibility. However, in light of the increasing requests from consumers with regard to product noise, there has been much effort to reduce noise in plastic gears. The gears that are used in office automation appliances, such as laser beam printers, fax, and copier should yield only low noise at low-torque conditions of operation. In general, the noise can be reduced greatly by greasing the gears in polyacetal or poly-amide gear driving. Also, provided that there is no problem of gear strength in the high-speed domain of operation, the application of pinions made of soft material would considerably reduce the noise. In addition, the noise level tends to be low when the accuracy of the gear is getting higher.

However, if the accuracy of the gear exceeds JGMA 6, noise cannot be reduced markedly. In this case, improving the surface roughness of gear teeth would be more effective than improving the accuracy of gear for the noise-reduction. The noise-reduction methods that are described above have limited applicability in high-volume mass production because of the resulting increase in production cost. Hence, considering cost, it is the most desirable to employ a method that changes the design of the gear teeth to reduce noise. Several gear-design factors among others are the module, number of teeth, pressure angle, profile shift, face width, temperature, torque, speed of revolution, and helix angle shown in Fig. 2.

TE is the most dominant characteristic in gear noise. It is definedas "the difference between the actual position of the output gear and the position it would occupy if the gears were perfectly conjugate" and can be expressed either in angular units or as a linear displacement along the line of action. TE is illustrated graphically in Fig. 3.

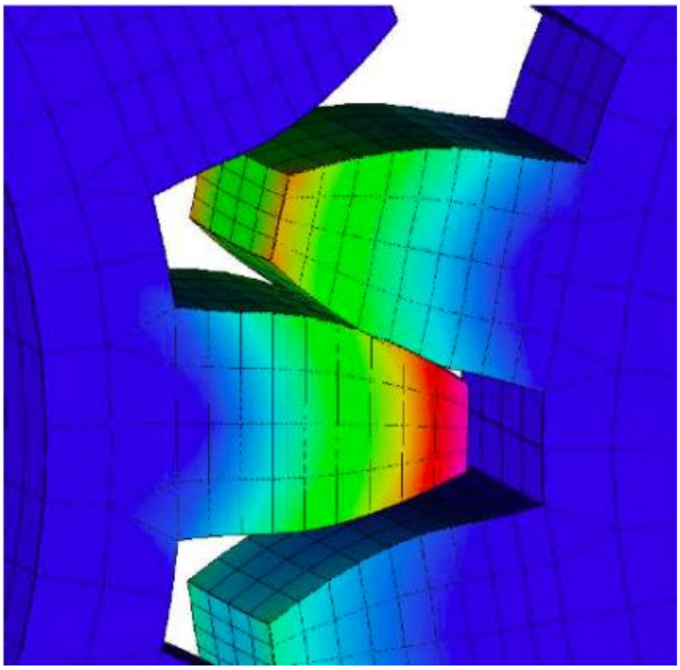
θ denotes the angular position of pinion, 2
θ denotes the angular position of gear, 1 $Z$ denotes the number of teeth of pinion, 2 $Z$ denotes the number of teeth of gear, 1 $R$ denotes the radius of pitch circle of pinion, and 2 $R$ denotes the radius of pitch circle of gear.

**Methods to Reduce Gear Noise and vibration:**

Gearbox noise can be attributed to 3 general phenomena: Whining, Rattle, and Hammering. Vibrates is an expert in researching and understanding the mechanisms behind each of these phenomena and has developed a complete methodology for understanding the excitations and dynamic response of the gearbox casing responsible for gearbox whine. Gearbox whine is the result of vibration generated by the meshing process itself, which depends on Material properties, plus the Macro and Micro Geometry of the pinions reacting to the speed and torque placed upon them. This vibrational energy is then transmitted to the gearbox casing and, depending on its dynamic behavior, radiated as airborne noise via the casing or via structure borne transmission to other components (vehicle interior, equipment skid etc.). The following presents a general step by step method for understanding the relevant mechanisms involved in unwanted gearbox whine.

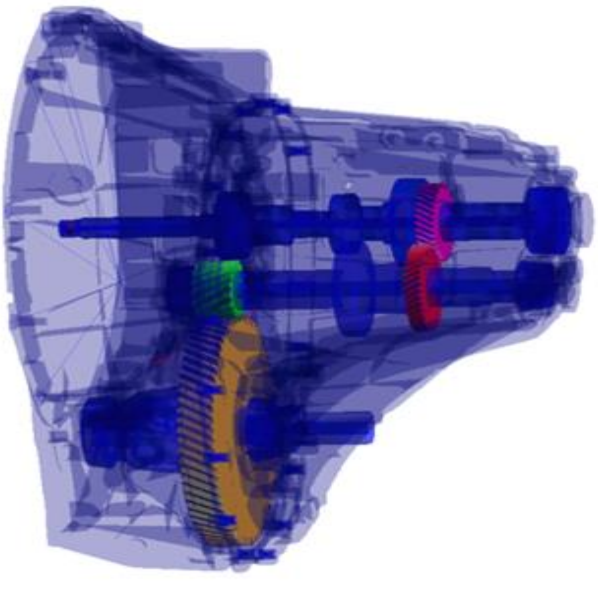
### 1. TRANSMISSION ERROR

Typically it is necessary to determine the Transmission Error of the gears and the fluctuation of the gear stiffness. Simplistically the transmission error corresponds to the difference between the actual position of the driven gear and its theoretical position. This difference is governed by the bending of the gear teeth from the torque placed upon them, defects and the dynamic behavior of the gearbox at the rotational speeds considered. Typically, the lower the transmission error, the lower the whining noise generated by the gearbox. Calculations for this element of the process are relatively straightforward for engineers involved in gearbox design. Vibratec has developed specific algorithms to optimize the tooth profile modifications for a range of torque.



## 2. GEAR (MESH) STIFFNESS

The fluctuation of the gear stiffness (mesh stiffness) is a primary excitation mechanism and is a function of the Transmission Error (and the number of active teeth), which varies with time. This calculation is again relatively straightforward but necessary to couple properly the gears involved in the dynamic model.



## 3. CALCULATE DYNAMIC RESPONSE

Using the Mesh Stiffness, it is possible to determine the Dynamic Response of the full gear system based upon the inputs from the Static Transmission Error and the Gear (Mesh) Stiffness fluctuations. Typically it is not possible to use standard Finite Element Models to accurately predict such a response using these input parameters, however, Vibratec has developed specific solvers to allow such models to be created. By analyzing the dynamic response of the system it is then possible to correlate structural modes of the gearbox casing with specific modes generated by the geared system. In such cases this re-enforcement of modes will often result in unwanted (whining) noise.

By understanding the dynamic response of a Gearbox system in this manner, it is possible to investigate the optimization of the gear tooth profiles and the geometry of the system to best reduce the degree of excitation generated by the system. This can be done for a range of torques. Similarly for any of the modes of the system that generate unwanted noise, structural modifications of the casing design can be incorporated. This overall approach allows potential modifications to be made in an efficient manner to allow the optimum solution to reduce unwanted gearbox whining noise problem, though it has not yet led to a resolution. Comparative analysis of trace files is clearly not a manual activity. SvPablo and TAU can also be used for the iterative process of (f) detailed performance debugging, i.e., identifying and tracking performance problems down to individual routines and lines of code. When performed by hand, detailed performance debugging is time consuming and fraught with problems due to instrumentation perturbation and global effects (e.g., load imbalances) masquerading as local performance problems.

## 4. SOURCES OF GEARBOX NOISE AND VIBRATION

Gearbox noise is tonal. This means that the noise frequency spectrum consists of sinusoidal components at discrete frequencies with low-level random background noise. The frequency that is the product of the gear rotational speed in Hz International Journal of Acoustics and Vibration, Vol. 14, No. 2, 2009 3 Tuma, J.: GEARBOX NOISE AND VIBRATION PREDICTION AND CONTROL Figure 3. TATRA truck (T815-2) gearbox arrangement and the number of teeth are referred to as the base tooth meshing frequency or gear meshing frequency GMF . A simple gear train (a pair of meshing gears extended optionally by idler gears) is characterized by only one tooth meshing frequency. All the basic spectrum components are usually broken down into a combination of the following effects7: low harmonics of the shaft speed originating from unbalance, misalignments, a bent shaft, and resulting in low frequency vibration, therefore, without influence on the gearbox noise level; harmonics of the base tooth meshing frequency and their sidebands due to the modulation effects that are well audible; the noise and vibration of the geared axis systems originated from parametric, self-excitation due to the time variation of tooth-contact stiffness in the mesh cycle, the inaccuracy of gears in mesh, and non-uniform load and rotational speed;_ ghost (or strange) components due to errors in the teeth of the index wheel of the gear cutting machine, especially gear grinding machines employing the continuous shift grinding method that results in high frequency noise due to the large number of index-wheel teeth, these ghost components disappear after running-in; components originating from faults in rolling-element bearings usually of the low level noise except for fatal bearing faults as the cracking or pitting of the inner or outer race or of the rolling element itself.

## 5. GEARBOX NOISE AND VIBRATION PREDICTION AND CONTROL

Figure3 . Running noise autospectra of the gearbox noise in RMS. harmonics of all the gear trains under load on the input-shaft rotational speed for the 3N gear are shown in Fig. 5. Except for the 5R gear, only three pairs of the engaged gears, whichare designated by N, 3, and SG (Secondary Gearbox), are under load. The panels of the diagram in Fig. 5 titled Gear N, 3, and SG, corresponds to the mentioned gear pairs. The curve in these panels marked by 'Sum' is a sum of the power contributions of 5 harmonic components resulting in the noise level excited only by the appropriate pair of the gears. As the pass by vehicle noise test is based on the maximum of the overall SPL, the maximum of the gearbox overall SPL (Max Tot) and a maximum of the 5 tonal components SPL (Max Sum) can be chosen as a gear quality criterion. Optionally, the maximum is evaluated for the input shaft rotational speed range either from 1000 to 2200 RPM or for an interval corresponding to the engine rotational speed during the pass-by tests. Due to the low rotational speed of the secondary gearbox gear train, its contribution to the overall (Total) SPL is negligible. The right lower panel in the diagram in Fig. 5 compares the contribution of all the gear train under load to the overall SPL of the gearbox. The minimum of the difference between the overall SPL and the contributions of the N, 3, and SG gears for the mentioned RPM range is designated by MinDiff. As was noted in the introduction section, the main sources of the gearbox noise are gears under load.7 Figure 5. Overall (Total) SPL and level of the of 5 toothmeshing harmonics of all the gear trains under load for the 3N gear vs. input-shaft rotational speed. to the time interval of one tooth pitch rotation. In this way, filtered signals are called average tooth mesh signals.12 The average tooth mesh acceleration measured on the gearbox housing close to the shaft bearing is proportional to the dynamic forces acting between the teeth in mesh. The average tooth mesh is a tool to represent the average mesh cycle. It can be observed that both the average tooth mesh signals corresponding to meshing gears have the same shape (see Fig. 6).This fact follows from Newton's third law. To assess a uniformity of tooth meshing during a complete gear rotation, an International Journal of Acoustics and Vibration, Vol. 14, No. 2, 2009 5 Tuma, J.

**Conclusion:**

The paper reviews the effect of the most efficient improvements reducing noise excited by gears, as well. Concerning the gearbox noise problem, one can conclude that a low noise gearbox requires sufficiently rigid housing, shafts and gears, and the HCR gears and the tooth surface modification for design load. The positive effect of introducing the HCR gears depends on the gear quality class. Gears finished by grinding are needed. All these improvements introduced by the TATRA company result in a decrease of the gearbox noise, which was measured on the test stand at the distance of 1 m by 8 dB at minimum. The TATRA truck gearboxes do not require an enclosure to fulfil the requirements given by the vehicle noise legislation. Noise and vibration measurement and signal analysis are important tools when experimentally investigating gear noise because gears create noise at specific frequencies, related to number of teeth and the rotational speed of the gear.

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