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# Ghost Frequency Noise Reduction through Displacement Deviation Analysis

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***Abstract*—**Low gear noise is an important sound quality feature in modern passenger cars. Annoying gear noise from the gearbox is influenced by the gear design, gearbox shaft layout, manufacturing deviations in the components, assembly errors and the mounting arrangement of the complete gearbox. Geometrical deviations in the form of profile and lead errors are often present on the flanks of the inspected gears. Ghost frequencies of a gear are very challenging to identify in standard gear measurement and analysis process due to small wavelengths involved. In this paper, gear whine noise occurring at non-integral multiples of gear mesh frequency of passenger car gearbox is investigated and the root cause is identified using the displacement deviation analysis (DDA) method. DDA method is applied to identify ghost frequency excitations on the flanks of gears arising out of generation grinding. Frequency identified through DDA correlated with the frequency of vibration and noise on the end-of-line machine as well as vehicle level measurements. With the application of DDA method along with standard lead profile measurement, gears with ghost frequency geometry deviations were identified on the production line to eliminate defective parts and thereby eliminate ghost frequency noise from a vehicle. Further, displacement deviation analysis can be used in conjunction with the manufacturing process simulation to arrive at suitable countermeasures for arresting the ghost frequency.

***Keywords*—**Displacement deviation analysis, gear whine, ghost frequency, sound quality.

## I. Introduction

GEARS are popular mechanical elements in power transmission systems due to their advantages of high-power density, constant speed ratio and high efficiency. Gear designer must deal with three key characteristics relative to their application: noise, accuracy, and durability.

This paper deals with most annoying and challenging aspect of the group, gear noise. Excitations due to gear meshing generate an undesirable noise typically at tooth mesh frequency known as whine noise. Whine noise is caused by steady harmonic displacement excitation known as transmission error which is a measure of faults in current tooth place relative to the ideal position [1]. Transmission error is a result of tooth elastic deflections, tooth profile errors and operational misalignment of the gear.

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Gear noise can also be radiated at tooth mesh harmonics if these are in audible frequency range of humans. Gear rotational excitations at once per revolution frequency can generate vibration and noise from transmission and inside the car. Eccentricity and misalignment can generate low frequency modulation of the higher tooth mesh frequency noise cal1ed sidebands.

Other frequencies that are dominant but not related to gear shaft rotational frequency or gear meshing frequency are called “ghost” or phantom frequencies. These excitations exhibit high amplitudes of an individual harmonics.

To define the type of gear noise that is of concern, it is usually necessary to apply sound or vibration measurement analysis to the final application, to understand excitation frequency content. Problem frequency definition is key step to understand the type of gear noise, and to decide investigations or corrections needed to be made to the gears [2]. Application of vibration analysis for gear fault diagnosis and monitoring is well established practice in industry [3].

This paper describes methodology & technique adopted to identify source of ghost frequency gear noise from the gearbox observed during mass production of vehicle. Methodology adopted to investigate root cause of ghost frequency excitation is given below.

1. Vehicle level NVH problem definition
2. System level analysis: EOL vibration analysis
3. Sensitivity analysis for Gears
4. Gear deviation Measurement analysis
5. Vehicle Level NVH validation

## II. Ghost Frequency Investigation Methodology

“Ghost” frequency excitations are observed in geared systems in addition to the tooth meshing frequency [2]. For high production efficiency, continuous generation method is extensively used for grinding the flanks of the helical gears, and this can generate ghost frequency excitations.

Ghost frequency errors typically are a result of cyclic errors from worm wheel drive of grinding machine. These undulations get transferred to each tooth of the gear and can lead to transmission error [4]. Ghost frequency errors may also initiate from the dresser used for dressing the grinding wheel which are transferred to gear flank surface during grinding in the form of undulations (waviness) [5]. These undulations have amplitudes as small as 4 µm & wavelengths are typically 0.5 mm. It is challenging to identify the origins of ghost excitations at multiple of gear mesh frequency & identifying countermeasure to avoid these errors involves trial and error process.

## III. Vehicle Level Noise Measurement

Subjective NVH assessment during pre-production trials of vehicle with front wheel drive equipped with transverse powertrain with standard 5 speed manual transaxle highlighted presence of annoying whine noise in coast condition in few vehicles. NVH measurements were conducted to identify problem orders and analysis showed presence of orders that were not related to gear meshing frequency of engaged gears from transaxle or other rotational excitations from powertrain. Subjective and objective vehicle level assessment highlighted problem mainly in coast condition.

Figs. 1 (a) and (b) show Campbell plot of driver ear noise measurement in 5th gear in coast condition of good vehicle and problem vehicle identified during subjective assessment. From Campbell plot it was evident that in 5th gear coast condition problem vehicle had dominant 67.5 order whereas this order was absent in good vehicle. Vibration analysis of good and bad vehicle transmission indicated noise was originating from transmission.

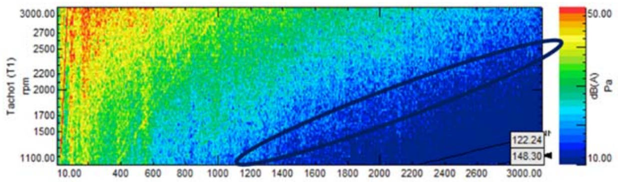

Fig. 1 (a) Driver ear noise Campbell plot: 5$^{th}$ Gear coast: good vehicle

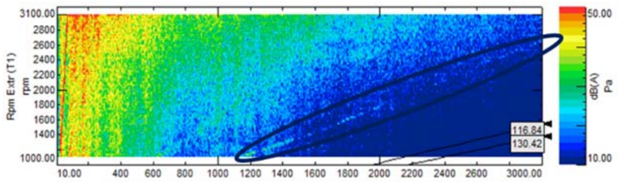

Fig. 1 (b) Driver ear noise Campbell plot: 5$^{th}$ Gear coast: bad vehicle

In-cab noise analysis of 4$^{th}$ gear coast condition highlighted the problem order at 51.75 as shown in Fig. 2 which is different from problem order identified in 5th gear condition. This meant that the problem order number changed with change in operating gear & the problem order relates to the component that was not rotating at same speed as engine speed.

## IV. Transmission End of Line Vibration Measurement

Based on vehicle level findings of whine noise problem, detailed vibration analysis of transmission End of Line (EOL) was conducted. Spectrum analysis of transmission EOL vibration demonstrated appreciable difference in amplitude of relevant ghost frequency of bad vehicle transaxle and good vehicle transaxle as shown in Fig. 3 which correlated with frequency from vehicle level noise and vibration measurements. Transaxle of bad vehicle showed significantly higher vibration of the ghost frequency relative to the good vehicle transaxle which had no whine noise. Also, it was observed that drive flank EOL vibration response for ghost frequency amplitude of bad vehicle was higher than good vehicle even though the vehicle did not exhibit problem at vehicle level measurements in drive condition.

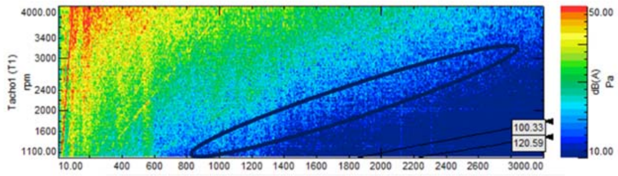

Fig. 2 (a) Driver ear noise Campbell plot: 4$^{th}$ Gear coast: good vehicle

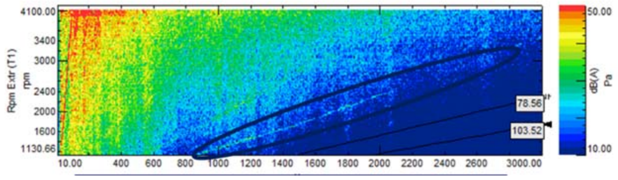

Fig. 2 (b) Driver ear noise Campbell plot: 4$^{th}$ Gear coast: bad vehicle

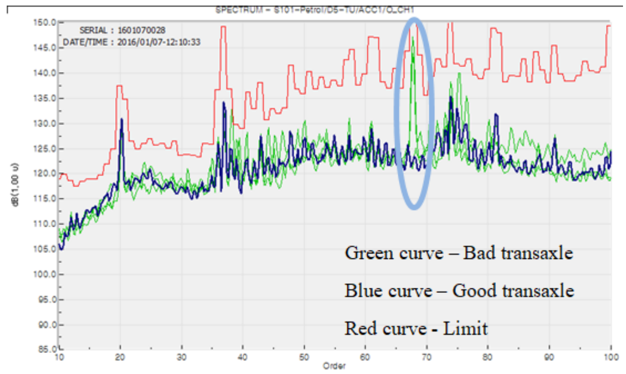


Fig. 3 (a) Transmission EOL vibration: Order plot: good transmission and bad transmission: 5$^{th}$ Gear drive condition

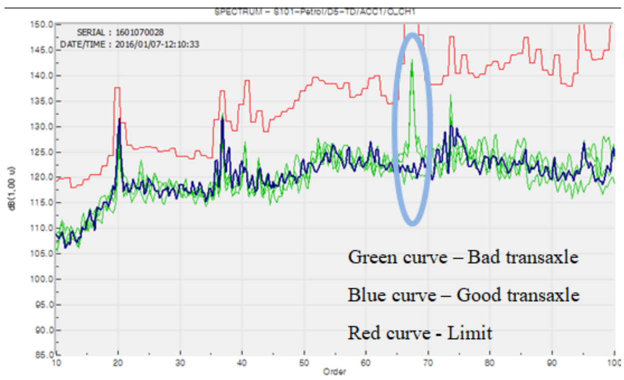


Fig. 3 (b) Transmission EOL vibration: Order plot: good transmission & bad transmission: 5$^{th}$ Gear coast condition

In 4$^{th}$ gear condition, transmission EOL vibration shown in Fig. 4 confirmed the problem order was 51.75 as identified in vehicle level noise and vibration measurements.

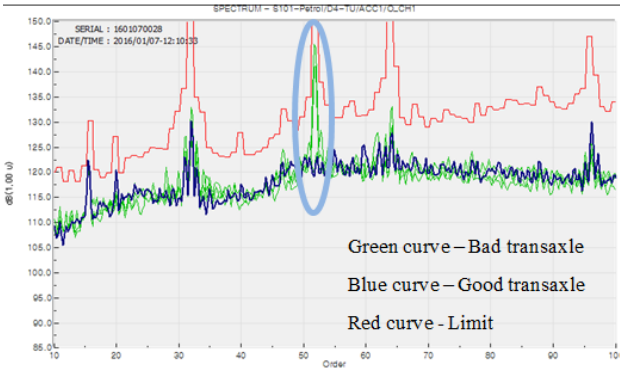


Fig. 4 Transmission EOL vibration: Order plot: good transmission & bad transmission: 4th Gear coast condition

There were two transmission variants for gasoline & diesel, albeit with different overall gear ratios. Both gasoline and diesel vehicles had been reported for the whine noise. It was observed that order with respect to output shaft remained constant in different gear engaged conditions as well as for gasoline and diesel variants indicating problem gear related to output shaft of transmission. The order based on gear teeth number turned out to be 240 with respect to output shaft speed.

In order to identify problem component of output shaft, swap analysis between good vehicle transaxle and problem vehicle transaxle was carried out It confirmed that problem moved with ring gear and had no influence of assembly or any other component or design parameters of transaxle.

As a confirmatory trial, problem gear was re-ground using different profile grinding machine and reassembled this ring gear in the problem transmission. EOL vibration analysis of this transmission confirmed the problem order of ghost frequency excitation had disappeared. These two trials confirmed the ghost noise was indeed from the ring gear.

Final drive ring gear was manufactured using generation grinding process due to high volume requirements. Gears were manufactured on multiple machines in parallel at supplier locations. It was later traced that the problem was related to ring gears ground on a specific machine. Gear ground on other machines did not show ghost frequency problem on EOL vibration and vehicle level noise measurements.

## V. Deviation Investigation of Gear

Traditional gear pair assessment based on simplified geometric tolerances does not always correlate with functional performance, especially when the deviations are of small magnitude & when few cycles of the undulation on a measured tooth trace. To identify such type of excitation source on gear flanks, high accuracy gear tooth measurements are required as surface waves as small as 100 nanometers which can create noise during operation of gears.

Precision measuring centers such as KLINGELNBERG [6] can measure these micro-deviations through wave analysis technique. All teeth of gears are typically measured for wave analysis to ensure enough frequency resolution. It is achieved by joining measuring points to form a closed curve based on angle of rotation. This curve is then used to calculate an order spectrum by means of compensatory sine functions.

If a ghost frequency is present on gears, the tooth flanks show a ripple with varying phase position, and the form changes from tooth to tooth as shown in Fig. 5.

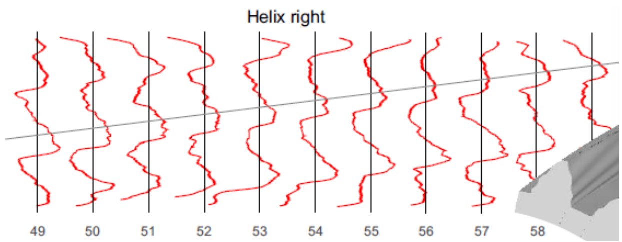


Fig. 5 Ghost frequency ripple

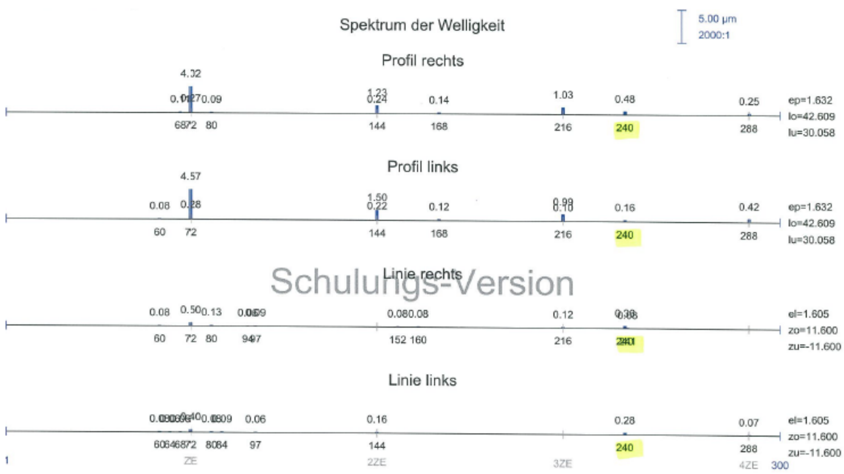


Fig. 6 (a) Deviation analysis: Ring gear: Bad transmission

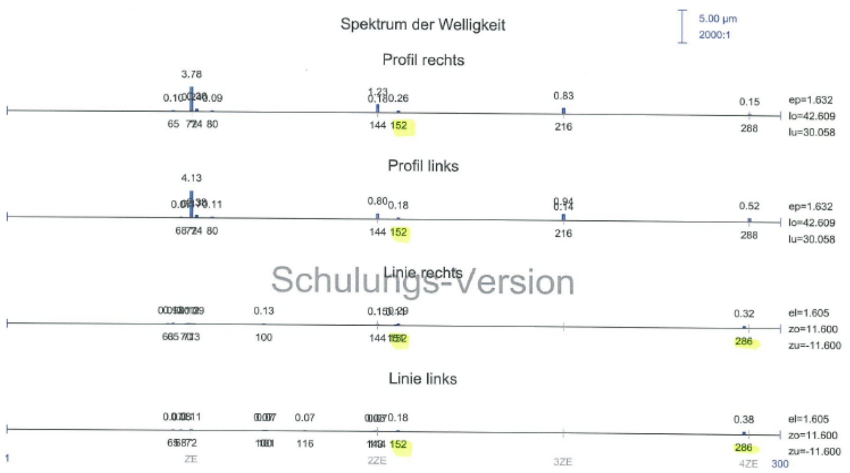


Fig. 6 (b) Deviation analysis: Ring gear: Good transmission

To identify measurable root cause leading to problem ghost order and associated amplitude of deviation, wave measurement analysis technique was conducted on ring gears of good and bad transmissions based on vehicle level and EOL vibration analysis using KLINGELNBERG machine.

Analysis of the measurement data shown in Fig. 6 (a) highlighted conspicuous 240 order deviation in bad ring gear which was absent in wave analysis of good gear as shown in Fig. 6 (b). This observation correlated with the problem order seen in EOL vibration measurement as well as in vehicle driver ear noise measurement. This measurement technique to assess gear quality was deployed in production line on batch wise random sampling basis leading to huge cost saving by avoiding repair and refitment cost of faulty gears in transmissions & vehicles.

## VI. Summary & Conclusions

This paper demonstrated the approach used for investigating the ghost frequency noise observed in vehicle. Systematic approach was used to investigate the ghost noise using the deviation analysis method on gear measuring machines. In addition, the paper explained usage of gear measurement tool and the methodology used to identify measurable root cause of excitation on gear tooth surface.

Ring gear surface undulations were demonstrated to be the excitation forces causing ghost order noise generation at driver ear location in vehicle. Subsequently, gear quality control system was established for controlling the ghost order sensitive parameters at EOL machine. NVH measurements on vehicle level, EOL vibration diagnostics along with deviation measurement techniques helped to eliminate the ghost order noise from gear inside the vehicle.

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