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Signal Analysis Techniques to Identify Axle Build Errors

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ABSTRACT

Typical NVH signal analysis methods have been used for some time to offer pass/fail criteria for axle end-of-line test stands. Assemblies that are rejected are often scrapped or re-built without further analysis of the NVH signature to determine actual root cause for the failure. Of more interest to both product development and manufacturing activities is the ability to understand the root cause of the failures. This information can improve the manufacturing process by eliminating errors, streamlining re-build activities, and aiding in product design improvements.

This paper describes the activities used to identify specific build errors for a rear axle application through signal analysis of end-of-line test stand data. Measurements of both nominal and intentionally mis-built axles, with known build characteristics, were used to develop the analysis techniques. Gear mesh fundamental frequencies, harmonics, and side-band characteristics of the NVH signatures were used to identify the specific failure mode for each of the mis-built axles, which included both pinion shim and/or backlash errors.

1. INTRODUCTION

Noise and vibration measurements conducted on final assemblies at manufacturing facilities can be used in great detail to extract information regarding the product, including the quality of the components and the quality of the assembly process. The retrieval of this information is often times difficult due to improper measurements or more often due to incomplete data analysis. The noise and vibration signature generated by a product contains countless pieces of information that can be used to characterize the assembly. This is of great importance, particularly in manufacturing environments to further understand the effectiveness of the processes used to develop and assembly the final products.

This holds particularly true for axle development. End-of-line testing is often used to characterize the noise and vibration performance of axle assemblies prior to shipment to the end user. The data is typically analyzed to understand the quality of the final assembly, but can also be used to further understand the manufacturing processes. If an assembly does not pass the end-of-line test stand it is extremely useful to understand the reason for the failure and to have the knowledge of which portion of the assembly process was responsible for the failure.

2. IDENTIFICATION OF APPLICATION

A manufacturer of automotive axles set out to determine if it was possible to identify specific build errors from existing vibration data from an end-of-line vibration test stand. At the time, the vibration signatures being collected were not analyzed specifically to identify these particular errors. Teardown analysis of failed axles often indicated particular mis-build conditions that were the primary cause of the reject. The purpose of this investigation was to identify the proper analysis techniques to identify and separate assemblies with these errors from the rest of the assembly population.

To begin the investigation, several axles were assembled with intentional mis-build conditions. These axles, along with nominally built assemblies were run on the end-or-line test stand and the standard vibration measurements were conducted. The specific mis-build conditions included backlash errors and pinion shim errors. In total twelve assemblies were utilized for this study, including four with backlash errors, five with pinion shim errors, and three nominally built assemblies.

3. ANALYSIS TECHNIQUES

A. Fundamental Gear Mesh Frequency

The test events of the end-of-line test stand used for this investigation included a run-up condition between 1500-2800rpm (input speed) at a constant torque, followed by a brief cruise event as the torque is reversed, and finally a coast-down event. Vibrations were measured using an accelerometer located at the axle pinion nose. Initial data analysis used order analysis of the primary meshing frequency to determine if the mis-built axles could be identified from the nominal axles. Data was analyzed for both the drive-up and coast-down events. It was determine that a pass/fail criteria set solely on the primary meshing frequency would begin to reject nominal build axles before it rejected all of the mis-built axles. The conclusion was reached that additional analysis techniques were necessary to identify the two mis-build conditions.

B. Gear Mesh Sideband Energy

The next analysis technique investigated concentrated on the vibration content of the sidebands of the fundamental meshing frequency. Sidebands of the gear mesh frequency are caused by frequency modulations and can be very useful to diagnose defects. The modulations can be caused by gear misalignments, eccentricities, and/or tooth spacing errors[1]. These errors cause the mesh point between the ring and pinion gears to wander during operation, causing the speed of the gears and shafts to accelerate and decelerate (modulate). This causes the gear mesh energy to increase and decrease with the rotation of the eccentric shafts. By monitoring the sideband energy, faults can not only be identified, but also associated to specific gears and shafts. For this rear axle application, the sidebands associated with the pinion gear and ring gear will occur at:

Primary gear mesh order: $N_{GearMesh} = 11^{th}\ order$

Pinion gear sideband orders: $N_{GearMesh} \pm i \times N_{InputShaft}$

Ring gear sideband orders: $N_{GearMesh} \pm i \times N_{OutputShaft}$

For:

$$N_{InputShaft} = \mathit{Input\ Shaft\ Order} = 1\ (\mathit{if\ using\ input\ shaft\ as\ reference})$$
$$N_{OutputShaft} = N_{InputShaft} / \mathit{Axle\ Ratio}$$
$$i = 1, 2, 3\ldots$$

The two mis-build conditions used for this investigation, pinion shim errors and backlash errors, both cause conditions that can be directly monitored by sideband energy. These errors cause the gear mesh point to wander on the tooth surface, causing gear speed modulations. For this application, a rear axle with 39 ring gear teeth and 11 pinion teeth, the primary gear mesh order and sideband orders are calculated below. These sidebands can also be identified in Figure 1, displaying the vibration signature of the rear axle in the order domain.

$$\text{Primary gear mesh order: } N_{GearMesh} = 11^{th}\ order$$
$$\text{Pinion gear sideband orders: } 11 \pm i \times 1 = \ldots 9, 10, 12, 13, \ldots$$
$$\text{Ring gear sideband orders: } 11 \pm i \times 1 \times {}^{11}\!\!/\!_{39} = \ldots\ 10.43, 10.72, 11.28, 11.56, \ldots$$

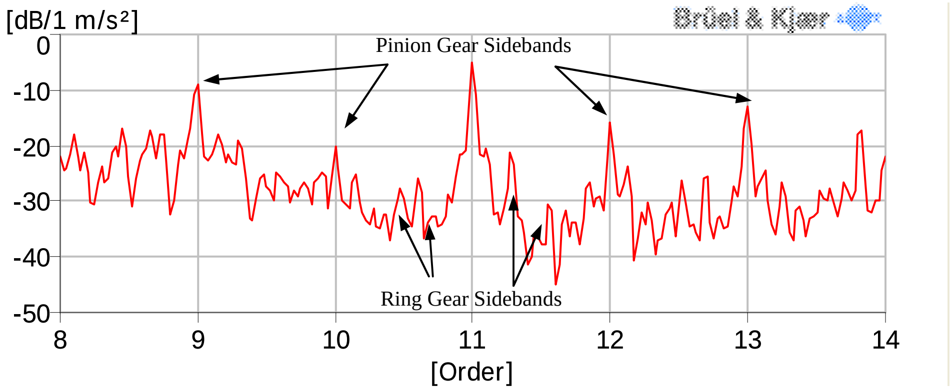

Figure 1: Order Spectra of Axle Vibration

Order analysis was conducted on the sidebands of both the pinion gear and the ring gear to determine if the content could be used to separate the mis-build axles from the nominal axles. The results indicated that for the drive-up event a pass/fail limit placed on the first upper sideband of the pinion gear, in this case the 12th order, would reject all of the backlash errors and pass all of the nominal builds for backlash. This identified an analysis technique to separate backlash errors from nominal builds, however pinion shim errors were not captured using this particular sideband and pass/fail criteria.

Similar techniques were used to determine the proper analysis methods and acceptance criteria to separate the pinion shim errors from the nominal builds. Pinion shim errors can be two-sided, meaning that the shim errors can place the pinion gear either too deep to too shallow relative to the ring gear. For this reason the analysis methods and acceptance criteria identified to locate pinion shim errors were separate for the “positive” shim errors and the “negative” shim errors. Negative shim errors were identified by monitoring the 13th order sideband of the pinion gear during the drive-up event of the test cycle. The positive shim errors were identified during the coast-down cycle through monitoring of the 12th order sideband of the pinion gear. Using this technique, pinion shim errors were separated from nominal build assemblies.

C. Separation of Build Errors

The analysis techniques and pass/fail criteria described above provide a method to ensure that all of the mis-built axles would be rejected by the end-of-line test stand. It was desired, however, to have additional information that could be used to separate the two failure modes.

For this reason, additional data analysis was conducted to identify which of the two build errors was present in a particular axle assembly. This information would allow the manufacturer to further understand the variability in the manufacturing processes and help to focus efforts to improve the overall process. Additionally the information could be used to streamline re-build activities for assemblies that initially fail the end-of-line test stand.

D. Gear Mesh Harmonic Energy

Continued data analysis efforts identified that in addition to differences in the fundamental mesh frequency and sideband energy, the harmonic content of the gear mesh frequency was noticeably different between the nominal builds and the high backlash assemblies. These differences are noted in Figure 2, which displays the vibration spectrum during a run-up event for a nominal build assembly, an assembly with backlash error, and an assembly with a pinion shim error.

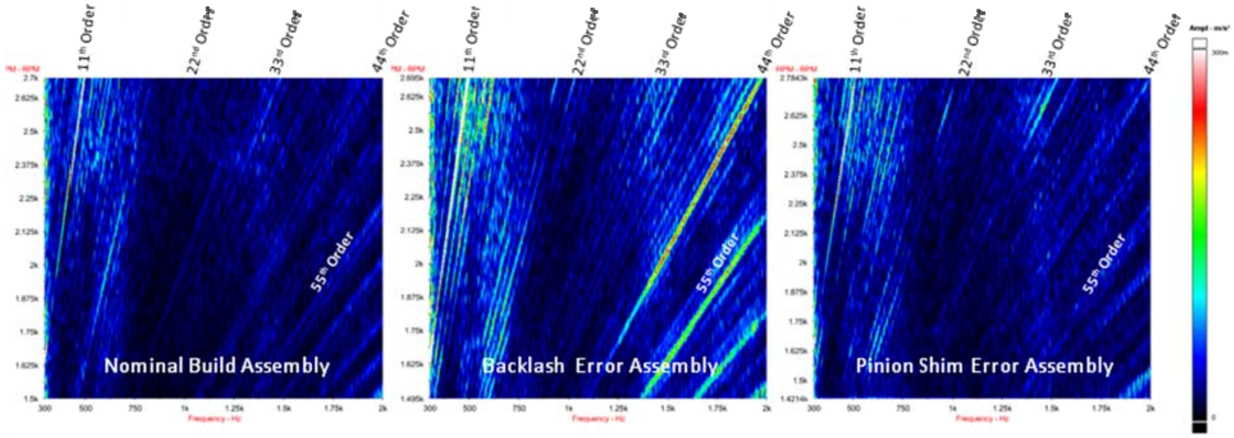

Figure 2: Vibration Spectra – Run-up Event

Harmonics are frequencies that are an exact whole number multiple of the fundamental meshing frequency. Harmonics are always present, however when the contact pattern between two mating gears are not ideal, the vibration energy of both the fundamental frequency as well as its harmonics typically increases. For this investigation the errors introduced into the axle assemblies, backlash errors and pinion shim errors, cause conditions in which the mesh point between the two gears is not ideal. This can cause the interaction between the mating gears to degrade, thus increasing the harmonic energy content.

For this application, the harmonic content of the assemblies with backlash errors was significantly higher than for the nominal and pinion shim error assemblies. This information was used to develop a pass/fail strategy to identify and separate all of the backlash error assemblies from the population. The pass/fail limit utilized the sum of the first four harmonics of the primary meshing frequency, namely the 22nd, 33rd, 44th, and 55th order energy. This limit provided an additional method to identify and separate backlash errors from the population.

4. PROCESS IMPLEMENTATION

With analysis methods defined to identify each of the failure modes for this study, the next step was to implement these methods into the production process. This process provides additional checks to ensure that assemblies with build errors are contained within the production process and not released to the end customer. Implementation of this process provides manufacturing engineers with additional data to continue to improve the assembly processes, as well as provide product engineers with data to continue to improve the product design processes. Additionally this data can be used to streamline re-build activities for assemblies determine to have build errors.

Obtaining the information to identify each of the mis-build conditions is particularly significant because it does not require any additional testing or manufacturing cycle time, it simply requires analysis of data that already exists within the end-of-line test stand. The analysis techniques developed for this particular application can very easily be carried over to additional product lines to provide similar benefits. Specific pass/fail criteria will likely be unique for each application, however analysis methods will likely be similar.

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