

Perception of Diesel Engine Gear Rattle Noise

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ABSTRACT

Component sound quality is an important factor in the design of competitive diesel engines. One component noise that causes complaints is the gear rattle that originates in the front-of-engine gear train which drives the fuel pump and other accessories. The rattle is caused by repeated tooth impacts resulting from fluctuations in differential torsional acceleration of the driving gears. These impacts generate a broadband, impulsive noise that is often perceived as annoying. In most previous work, the overall sound quality of diesel engines has been considered without specifically focusing on predicting the perception of gear rattle. Gear rattle level has been quantified based on angular acceleration measurements, but those measurements can be difficult to perform. Here, the emphasis was on developing a metric based on subjective testing of the perception of gear rattle. In the first part of the present work, a method to simulate gear rattle noise and incorporate it into a no-gear-rattle (baseline) recording was developed. That procedure enabled controlled variation of rattle within the total engine noise signal. The simulations were then used in a psychoacoustic test that was designed to quantify detectable levels, perception of growth, and increase in annoyance due to the presence of gear rattle noise. Forty subjects participated in the threshold detection tests and a paired comparison annoyance test. The responses of people who reported having experience with diesel engines were compared to those of a more general population. The subjects with diesel engine experience were found to be better at detecting gear rattle noise and found rattle more annoying than the other subjects, particularly at high rattle levels. Current work is focused on development of metrics that accurately reflect human responses to gear rattle.

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INTRODUCTION

In recent years, improvements in noise control strategies have led to a decrease in the overall level of noise produced by diesel engines. However, a decrease in overall engine noise can lead to other issues related to the sound quality of the noise produced by specific components that were previously masked by other, louder engine noises. These component noises that can now be heard contribute to the perceived overall sound quality of the engine. In some instances, this component noise may be perceived as annoying and so may negatively impact the engine's perceived sound quality. Gear rattle is one such specific component noise source.

Gear rattle is a phenomenon caused by impacts of meshing gear teeth that results in broadband, impulsive noise [1, 2, 3]. This noise is a common source of customer complaints. Current standards for assessing the acceptability of gear rattle noise are mainly based on the judgment of the engineer or other, simple measures such as overall noise levels. These objective measures are generally not connected to the human perception of the phenomenon. Thus, a way of predicting how people would assess the quality of gear rattle noise is needed.

How people perceive and respond to gear rattle noise is not well known: three subjective tests were therefore designed to explore this point. First, the levels of gear rattle required for people to detect the presence of the sound were investigated. The 'thresholds' of gear rattle noise detection in the presence of diesel engine noise were estimated by using well-defined signal detection techniques [4]. Then, the perception of growth and attenuation of gear rattle noise was investigated by estimating the 'discrimination thresholds'. The discrimination thresholds are the levels of gear rattle required for a stimulus rattle level to be perceived as different from a control rattle level. Finally, the annoyance ratings of sounds with and without gear rattle at various levels were investigated by using a paired comparison test.

MEASUREMENTS

A set of noise measurements corresponding to various gear lash settings was acquired by engineers at Cummins Inc. Measurements were made using four microphones in the far-field (in accordance with the SAE standard J1074 [5]) during steady-state and sweep engine operations at various speeds and loads. The tests were conducted in a hemi-anechoic environment to remove effects of

reverberation on the measurements. The four microphones were located one meter from the top, front, left, and right sides of the engine. The data was acquired at a sample rate of 51.2 kHz to ensure that the entire audible frequency range was captured.

The backlash of the gears in the timing gear train was varied during this testing since the level of gear rattle has been observed to increase with an increase in backlash [1]. A baseline measurement (lowest amount of gear rattle) was acquired using a specially designed gear (scissors gear) to minimize backlash and subsequent gear rattle noise. The scissors gear was replaced with a solid gear for the cases with gear rattle. The backlash of the gears was set by placing a feeler gauge with the thickness corresponding to the desired amount of backlash between meshing gear teeth. The gears were then pushed together, bolted in place to their respective shafts, and the feeler gauges were removed. The lash settings of the gears ranged from 0.002 to 0.014 inches in 0.002 inch increments (0.051 to 0.356 millimeters in 0.051 millimeter increments). The front microphone measurements were used in the analysis because they are the closest to the location of the timing gear train. The operating condition used in the analysis was the low-idle (680 RPM), no-load steady-state case because rattle is generally more pronounced at idle operating conditions. The resulting data set represented a range of signals with varying levels of gear rattle noise.

GEAR RATTLE NOISE SIMULATION

A method to simulate gear rattle noise was developed and is described in previous work [6]. This simulation method was developed for use in the subjective tests described in this paper. A block diagram of the simulation is shown in Figure 1.

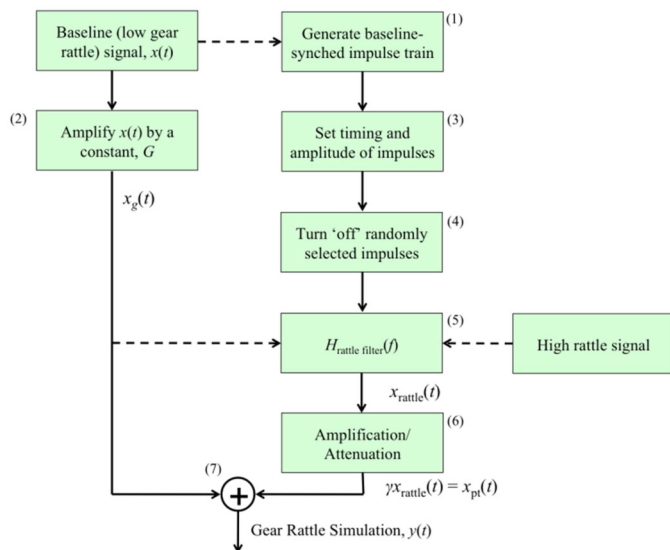


Figure 1. Gear rattle noise simulation model.

In this method, a filtered pulse-train, treated to sound like gear rattle, is added to a baseline (very low gear rattle) measurement. To generate the pulse-train, the speed of the engine in the baseline recordings is determined and used to guide impact timing. A digital filter is then designed using the difference in spectral content between the baseline and a high gear rattle case to set the spectral content of the gear rattle

impacts. The resulting gear rattle noise (filtered pulse-train) is amplified or attenuated and added to the baseline engine noise to create the overall simulation.

SUBJECTIVE TEST BACKGROUND

The subjective test was performed in an Acoustic Systems double walled sound booth in the Ray W. Herrick Laboratories. The playback system consisted of a LynxOne sound card, Tucker-Davis HB7 amplifier, and Etymotic Research ER-2 tube earphones. The sound card and earphones were chosen due to their flat frequency response and low noise floors. Subjects were tested in the sound quality booth on an individual basis. When the subjects arrived to participate in the test, they were given a brief introduction to the research, asked to read and sign the informed consent document, and asked to fill out a brief background questionnaire. The questionnaire contained questions regarding basic demographic information, previous noise exposure, knowledge of sound quality and/or noise control, and previous experience around diesel engines. The subjects that self-identified as having experience around diesel engines are referred to here as diesel engine 'experts'. The subjects were given a hearing screening before they were allowed to proceed with the test to ensure that they had normal hearing (i.e., no greater than 20 dB of hearing loss in any octave band from 125 Hz - 8 kHz). Prior to each part of the test, the subjects were played familiarization sounds and participated in a brief practice test. Three unique signals (low, medium, and high gear rattle) were chosen to represent a range of gear rattle levels and were presented to the subjects during the familiarization phase to introduce them to the types of sounds included in the test.

Forty subjects were tested in total. The subjects were 19 men and 20 women ranging in ages from 19 to 36 with a median age of 24. One subject did not respond to the question regarding gender on the background questionnaire. Thirteen of the subjects self-identified as being experienced around diesel engines.

DETECTABILITY TEST

The gear rattle simulations described previously were used in a subjective test designed to identify the detectable levels of gear rattle noise with respect to the background noise levels of a diesel engine operating without gear rattle. The gear rattle simulation method provided a way of generating gear rattle noise that could be controlled independently of the other engine noise. This gear rattle noise could be added to the diesel engine noise without gear rattle (baseline) to generate simulations of the overall engine noise with various levels of gear rattle. The detectability subjective test was designed based on the assumption that gear rattle noise could exist in a signal and have a low enough level as to be masked by the other diesel engine noise.

It was assumed that there exists an underlying psychometric function that governs an individual's ability to detect a stimulus (i.e., gear rattle in presence of background diesel engine noise). The psychometric function represents the percentage of times the subject correctly identifies the presence of a stimulus as a function of stimulus level. The two-down, one-up (2D1U) paradigm was used to

govern the change in level of the stimulus. This paradigm is used to estimate the 70.7% correct value of the psychometric function [4]. The 70.7% correct value corresponds to the level (with respect to the background noise) at which the individual correctly detected the signal 70.7% of the time. A three-alternative forced choice (3AFC) paradigm was used in the design of this test. Subjects were presented with three signals, one of which contained the stimulus, and were asked to select, "which sound was different from the other two." By using the gear rattle threshold test as an example, if the subject was able to correctly identify the signal containing the gear rattle signal as the different sound two consecutive times, the level of the rattle was attenuated for the next trial. If the subject selected one of the two baseline signals (that did not contain gear rattle), the level of the gear rattle signal was amplified for the next trial. This up-down procedure is repeated, and the values at which a change in direction occurred are stored. Each run continued until eight reversals occurred and the individual threshold for subject was calculated by averaging the last six reversal values.

Gear Rattle Threshold Test

In the test designed to determine the thresholds of gear rattle noise in the presence of the baseline engine noise, three 1.5 second sounds were presented to the subject with a 0.5 second pause in between each sound. All three of the sounds contain identical background noise signals, which is the diesel engine signal without gear rattle.

The gear rattle signal is added to one of the sounds. The selection of the window to which the gear rattle noise was added was based on a uniformly distributed random sequence. This process is illustrated in Figure 2 for the case where the sound selected for the addition of rattle was the second sound.

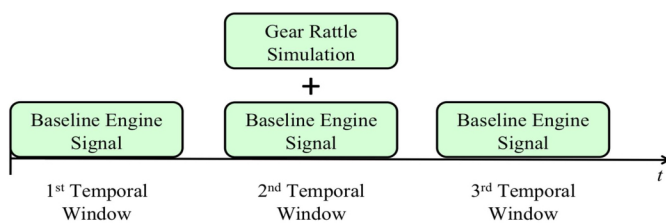


Figure 2. Illustration of a single trial in the gear rattle detectability test. The window in which the gear rattle noise simulation is placed was selected based on uniform randomly distributed sequence. In this illustration, it is added to the second signal.

Following the playback of the three sounds (one that contains the gear rattle signal and two with only the baseline signal), the subject was asked to identify "Which sound was different from the other two."

The gear rattle thresholds were estimated from three tests, referred to as Runs 1 to 3, each containing different background (baseline) diesel engine noise. The background noise for Run 1 was the baseline engine at a level of 75 dB SPL. The background noise for Run 2 was the same baseline engine noise at a lower level of 70 dB SPL. The background engine noise for the final run was a baseline noise recording from a different engine at a level of 75 dB SPL. This other engine sound was included to investigate the effect of the character of the background engine noise on the detection of the rattle. The

presentation order of the three runs was varied between subjects so that each possible order was presented before any order was repeated in order to minimize ordering effects.

An example of the results of a gear rattle detectability test is shown in Figure 3. It can be seen that at the beginning of the run, the subject was able to correctly identify the signal with gear rattle noise as being different than the other two signals four consecutive times (green squares). In the next presentation the subject identified the wrong sound (red triangle). The stimulus initially decreased in five decibel intervals to more quickly reach a level close to the individual subject's threshold. For this subject, a gear rattle level of approximately 63 dB is needed for the gear rattle noise to be perceived as being present in a baseline engine noise signal with an overall level of 75 dB.

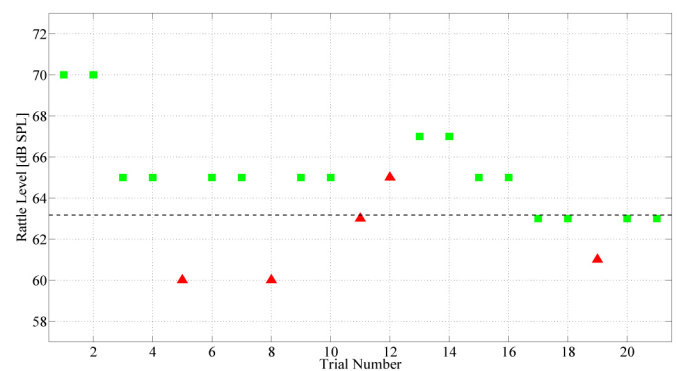


Figure 3. Tracking response data for Run 1 for an example subject. Green squares represent correct responses and red triangles represent incorrect responses. The dotted black line represents the estimated threshold.

Discrimination Thresholds of Gear Rattle

The two-down, one-up three-alternative forced-choice (2D1U 3AFC) paradigm was also used in a test designed to investigate the ability to detect differences in the level of gear rattle. Three consecutive sounds were again presented to the subject with a short pause between each sound. For the discrimination portion of the detectability tests, two of the sounds contained the baseline diesel engine noise and gear rattle noise at a level that was judged to be clearly audible. The other sound contained the 'stimulus' rattle sound that was set at a slightly different level than the rattle in the other two sounds. The subjects were again asked to identify the sound that was different from the other two. An illustration of a discrimination trial is shown in Figure 4.

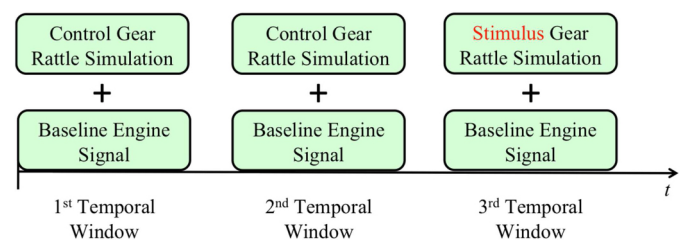


Figure 4. Illustration of a single trial in the gear rattle discrimination detectability test. The window in which the 'stimulus' gear rattle noise simulation is placed is selected based on a uniform randomly distributed sequence. In this illustration, it is in the third signal.