Simulation of gear rattle to aid in the development of sound quality metrics for diesel engine component specification

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ABSTRACT

Noise produced by components in a diesel affect the quality of the engine noise. One component source related to consumer complaints is gear rattle. Gear rattle is caused by gear tooth impacts resulting from fluctuations in differential torsional acceleration of the driving gears. Previous work in this area has focused on rating the overall sound quality of diesel engines without specifically focusing on models for predicting the perception of gear rattle. Here, a method to generate sounds having different levels of gear rattle is described. First, diesel engine noise recordings were analyzed to determine the engine speed time histories; they were then used to guide gear impact timing and to generate gear noise components. The gear noise transfer paths were then tuned to improve the quality of the gear noise predictions. The gear noise simulation tool is presently being used to generate sounds for subjective tests designed to quantify the detectability, perception of growth, and annoyance of gear rattle. The noise prediction coupled with the sound quality models based on the analysis of the subjective data will provide a way to predict how people perceive gear rattle so that component noise targets can be set directly related to human perception.

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(See `http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf`.)

1. INTRODUCTION

Sound quality is an important factor in the design of competitive diesel engines. The noise produced by specific components and mechanisms in the engine can play a significant role in determining the perceived quality of the overall noise. The goal of the present research is to characterize the sounds produced by gear rattle to develop a model that can be used to assess gear rattle noise in a way that connects directly with human perception. In this paper a gear noise simulation method is described. This simulation approach will be used to generate sounds for subjective tests designed to quantify the detectability, perception of growth, and annoyance of gear rattle noise.

Gear rattle noise is caused by the repeated impacts of gear teeth resulting from torsional vibrations of the driving gears. The backlash of the gears, drag torque on the driven gear, oil level and oil viscosity, and the level of torque pulsation through the gear system are examples of key factors that have an influence on the level of rattle [1]. Rattle is also generally more pronounced at low speed, low load engine conditions. Rattle simulations have been developed by researchers to gain an understanding of the gear rattle phenomenon and to aid in the design of the overall gear systems by including the previously discussed factors in their complex models [2, 3], but these models have been focused on predicting individual component influences on the level of rattle and not on generating time histories for listening experiments. Gear noise simulations were performed by Becker and Yu [4] for use in their subjective tests which were designed to investigate the threshold above which people can detect gear whine, but not gear rattle. Singh describes a [1] noise simulation model that requires extensive knowledge of the gear system and gear angular acceleration measurements. A model that can be used to simulate diesel engine combustion noise based on timing and amplitude of combustion events has been developed by Hastings [5] and has aided in the development of the gear rattle noise simulation model used in this research.

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2. MEASUREMENTS

A set of gear lash testing data was initially acquired by engineers at Cummins, Inc. Measurements were made using four microphones in the far-field (in accordance with the SAE standard J1074) during steady-state and sweep engine operations at various speeds and loads. The backlash of the gears of the timing gear train were varied for this testing. The lash settings of the gears ranged from .002 to .025 inches. The baseline measurement (lowest gear rattle) was acquired using a specially designed gear (scissors gear) to minimize backlash and gear rattle noise.

The present simulation model was developed using the difference between measurements with high and low amounts of gear rattle as a guide. The data set with the gear backlash setting of .010 inches was chosen for the "high rattle" measurement because this was judged by diesel engine noise engineers to represent an example of a high level of gear rattle. The scissor gear data were selected as the baseline for the simulation because it contained the lowest amount of gear rattle among the available measurements. The far-field noise measurement normal to the timing gear train (i.e., on the front side of the engine) was selected as the measurement location to be used in the simulation because this was the location in which the gear rattle would be the most prominent. A no-load, low-idle engine operating condition was selected for the simulation because gear rattle is, in general, more pronounced at idle.

3. GEAR RATTLE SIMULATION

As illustrated in Figure 1, the simulations comprised two parts: the noise of a low gear rattle engine which was used to create the background engine noise, and the noise caused by gear teeth impact events. The simulation was designed using noise measurements of a diesel engine at idle with very low gear rattle. The simulation process consists of the following seven stages, the details of which are described in the subsections below.

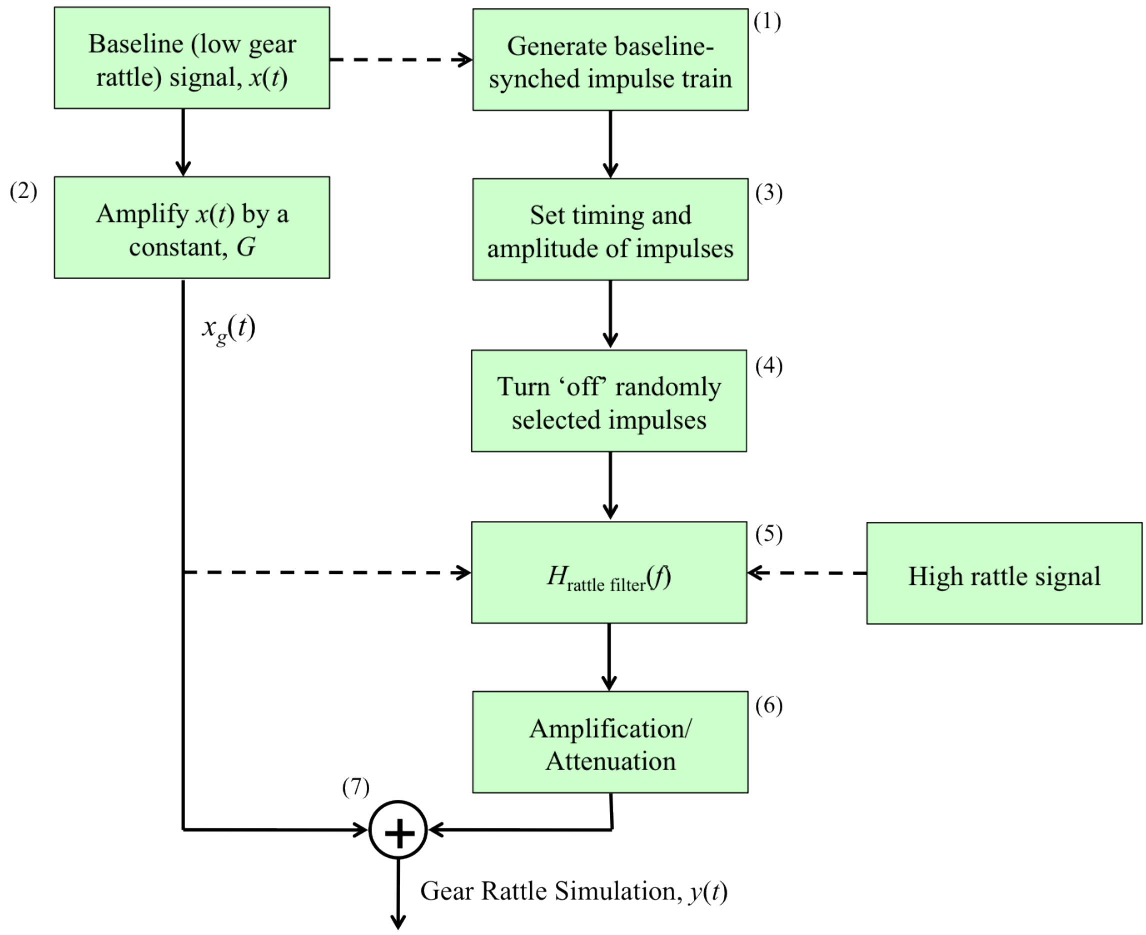

Figure 1 – Gear rattle noise simulation model.

1. An impulse train is generated that is synched to the low gear rattle noise measurement by using the instantaneous operating speed of the engine in the noise measurement. The instantaneous operating speed is determined from an estimation of the instantaneous frequency of the tone related to the fundamental

firing frequency of the baseline engine.

2. The low gear rattle noise measurement is amplified by a factor, G, to account for the observed increase in diesel engine noise that is not directly caused by the gear rattle impact events in the high gear rattle noise measurements. It was determined that an amplification factor of 1.2 approximates the increase in background engine noise well.
3. The timing and amplitude of the gear rattle impulses are set. Primary impulses (pulses occurring quickly following a firing event) are set using the engine-synchronized impulse train as a guide. The primary pulses are set with a random timing and amplitude variation. A second set of impulses related to the reengagement of the gear teeth after they have lost contact is added to the impulse train (there could be multiple impacts). These impulses quickly follow the original impulses by a percentage of the period between primary pulses. A random timing and amplitude variation is also added to the second impulses.
4. Some gear rattle impulses are removed (i.e., amplitudes set to zero). The selection of the impulses to be removed is based on samples from a uniformly distributed random process that produces values between 0 and 1 (the output of rand in MATLAB). If $100a\%$ of the impulses are to be removed, then an impulse is removed if the corresponding random variable sample is less than a. This step was added to the simulation to mirror the variations that are typically present in engine sounds when rattle is present. Without this step, the sound are too regular and sound artificial.
5. The impulse train is filtered using a finite impulse response (FIR) filter that is designed using the power spectral densities of the high and the amplified low gear rattle measurements. The damping characteristics of the filter are altered to add a 'metallic' sound to the impact events.
6. To vary the level of gear rattle noise, x_{rattle}, present in the simulated signal, x_{rattle} is amplified or attenuated.
7. The filtered gear rattle impact train, x_{rattle}, and the amplified low gear rattle measurement, $x_g(t)$, are summed to create the engine noise.

3.1 Baseline Synchronized Impulse Trains

The timing of the gear rattle impacts is guided by the speed of the engine in the baseline measurement [1]. In summary, impact events occur due to the fluctuations of the differential acceleration of the driving gears. Rattle occurs when the inertial torque of the driving gear is greater than the drag torque of the driven gear. In these instances, the driven gear and the driving gear lose contact. Two impact events can occur when the gears lose contact. The first impact can occur when the leading edge of the driven tooth impacts the trailing edge the tooth on the driving gear. The second impact occurs when the correct gear teeth reengage. The diesel combustion firing events are a possible cause of the fluctuations in the inertial torque that force the gears to lose contact. Therefore, the timing of the rattle impacts in this simulation is related to the timing of the combustion events, and subsequently the instantaneous operating speed of the engine.

The instantaneous operating speed of the engine in the baseline measurement was estimated by calculating the instantaneous frequency of the tone related to the fundamental firing frequency of the engine. The firing frequency is the inverse of the time between sequential combustion firing events. The frequency variation of the firing frequency tone is therefore related to the variation in engine speed. The baseline measurement was band-pass filtered around the firing frequency of the engine prior to the instantaneous frequency calculation. The band-pass filter should have lower and upper cut-off frequencies that are far enough apart to capture most of the range of frequency variation of the tone. In the example shown later, the tone related to the firing frequency in the baseline measurement was approximately 32.5 Hz. A third-order Butterworth band-pass filter was designed with 30 Hz and 35 Hz lower and upper cut-off frequencies, respectively. A Hilbert Transform approach was used to estimate the instantaneous frequency by using the expression

$$f(t_n) = \frac{1}{2\pi}\frac{\dot{\hat{x}}_{\text{BP}}(t_n)x_{\text{BP}}(t_n) - \dot{x}_{\text{BP}}(t_n)\hat{x}_{\text{BP}}(t_n)}{x_{\text{BP}}(t_n)^2 + \hat{x}_{\text{BP}}(t_n)^2}, \tag{1}$$

where $x_{\text{BP}}(t_n)$ is the low gear rattle noise measurement band-pass filtered around the firing frequency of the engine, $\hat{x}_{\text{BP}}(t_n)$ is an estimation of the Hilbert Transform of the band-pass filtered signal, $\dot{x}_{\text{BP}}(t_n)$ and $\dot{\hat{x}}_{\text{BP}}(t_n)$ are estimates of the derivatives of the band-pass filtered signal and the estimated Hilbert Transformed signal, respectively. Also, $f(t_n)$ is the instantaneous frequency and t_n are the discrete times at which the signals are sampled. The estimations of the Hilbert Transform and the differentiated signals were constructed using 255 and 121 point digital finite impulse response filters, respectively. The FIR filters were designed using the Parks-McClellan algorithm [6] (firpm function in MATLAB).

An infinite impulse response digital filter that simulates integration was used to generate the instantaneous phase of the signal, $\phi(t_n)$, from the instantaneous frequency, $f(t_n)$, and a sinewave of the form:

$$x_{\text{guide}}(t_n) = \sin(\phi(t_n)) \tag{2}$$

was generated to help in the assigning of the timing of the impulsive events that occur during gear rattle. The time of a firing event was determined by visual inspection of the time history of the baseline measurement, and the corresponding value of the $x_{\text{guide}}(t_n)$ signal at that time is noted. In the example shown in Figure 2, this value is close to the maximum of the $x_{\text{guide}}(t_n)$ signal and is denoted by a red cross. A program was written to take this information and then automatically determine the times at which the $x_{\text{guide}}(t_n)$ signal passes through this value, and these times are used to estimate the cylinder firing times, $T_{\text{sync}}(n)$. Note that while it is not obvious in the short segment of signals shown in Figure 2, the time between cylinder firings vary throughout the signal even though the engine is running at a nominal constant speed.

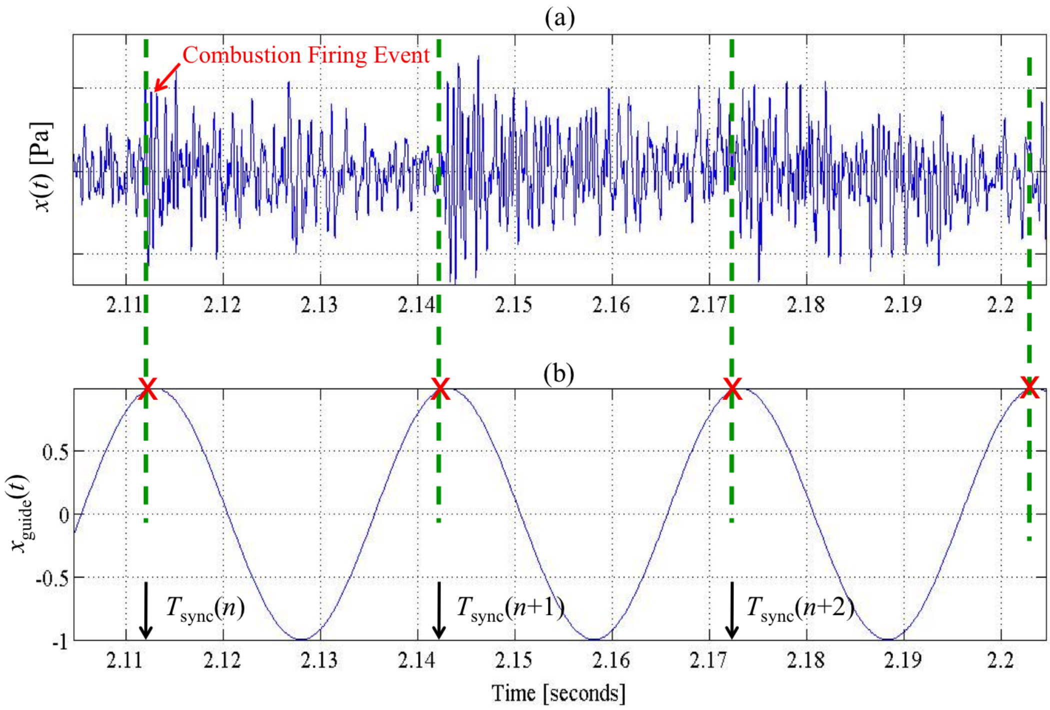

Figure 2 – Synchronizing the gear rattle primary pulse train with the (a) baseline noise measurement by using (b) a sine wave with a frequency variation of the instantaneous engine speed.

A vector of times, T_{sync}, was generated corresponding to the time of the firing events and was synchronized to the engine operating speed in the baseline noise measurement.

3.2 Setting the Timing and Amplitude of the Gear Rattle Impulses

The times of the gear rattle impact events is next determined. Multiple gear impact events may occur between cylinder firing events. These events are categorized as the primary and secondary impulses. The primary impulse is an impacting event that quickly follows a cylinder firing event. The secondary impulses are a series of impacts that occur sequentially after the primary impulse. In the example in this paper, it was determined that including the primary impulse and one secondary impulse between cylinder firing events sounded the most realistic.

The location of the impulses in the time history is a function of both deterministic (related to the cylinder firing times, $T_{\text{sync}}(n)$) and random elements. A random delay is included to account for the non-deterministic nature of the gear rattle impacts. A schematic of the timing of the two impulses between two consecutive cylinder firings is shown in Figure 3. The shaded regions are the ranges of possible locations for the primary and secondary pulses.

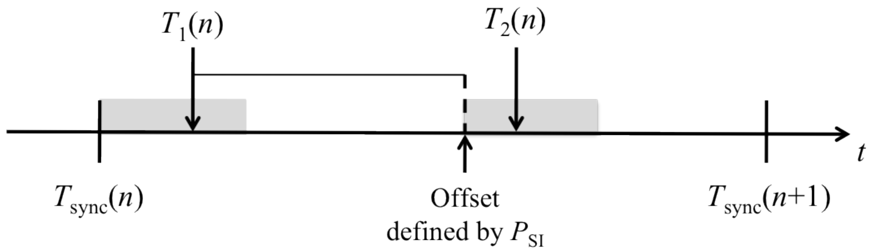

Figure 3 – Illustration of setting gear rattle impact times. The shaded areas represent the possible locations of the gear rattle impact events due to the random delay.

The amount of delay is limited to a fraction of the current period between impacts. The time of the primary impulse is

$$T_1(n) = T_{\mathrm{sync}}(n) + R_1(n)[T_{\mathrm{sync}}(n+1) - T_{\mathrm{sync}}(n)], \tag{3}$$

and for the secondary impulse is

$$T_2(n) = T_1(n) + (P_{\mathrm{SI}} + R_2(n))[T_{\mathrm{sync}}(n+1) - T_{\mathrm{sync}}(n)], \tag{4}$$

where $T_1(n)$ is the time of the n^{th} primary impulse, $T_2(n)$ is the time of the n^{th} secondary impulse, and $R_1(n)$ and $R_2(n)$ are selected from a uniformly distributed random process that allows for the control of the amount of random variation of the timing of the primary secondary impulses. In addition, P_{SI} is the fraction of the period that the second impact occurs after the first impact. In the case with multiple secondary impacts, P_{SI} would become a function of the number of secondary impacts. Care should be taken when setting these parameters so that no gear impacting event is allowed to occur after the next (n+1) cylinder firing event. The amplitudes of the primary and secondary gear impact events are uniformly distributed and are constrained to a percentage of variation denoted by $\mathrm{R}_{\mathrm{A}_{\max}}$.

3.3 Turn 'Off' Random Impulses

There might also be combustion events that do not cause a gear rattle impact event. To account for these cases, some primary and corresponding secondary impulse times are removed from the vector of gear impact times. The decision to remove impacts is guided by whether values taken from a uniformly distributed random process that generates numbers between 0 and 1 are less than a preset value (P_{off}). Next, this reduced vector of impact times (containing both the first and second impacts) is used to generate a signal of the same sampling frequency as the measurements. The signal generated is zero everywhere except at the impact times. The impulse amplitudes are uniformly distributed across a present range with a maximum value of 1.

3.4 Gear Rattle Filter

A difference in the power spectral densities between the low gear rattle and high gear rattle measurements was observed. To account for this difference in spectral content, a finite impulse response (FIR) filter was designed to shape the gear rattle impact simulation. When it is assumed that the gear rattle noise is a noise source independent of the normal (baseline) engine noise, the gear rattle spectrum can be written as

$$S_{x_\mathrm{R}x_\mathrm{R}}(f) = S_{x_\mathrm{HR}x_\mathrm{HR}}(f) - S_{x_\mathrm{D}x_\mathrm{D}}(f), \tag{5}$$

where $S_{x_\mathrm{HR}x_\mathrm{HR}}(f)$ is the power spectral density of the high gear rattle measurement which contains both the baseline diesel engine noise and the gear rattle impact noise, $S_{x_\mathrm{D}x_\mathrm{D}}(f)$ is the power spectral density of the amplified baseline measurement (little or no rattle), and $S_{x_\mathrm{R}x_\mathrm{R}}(f)$ is the estimate of the power spectral density of the rattle part of the signal. In the present case, $S_{x_\mathrm{R}x_\mathrm{R}}(f)$ was estimated using the available high rattle and low rattle measurements. The spectral resolution of the power spectral densities used in this example was 6.25 Hz with 371 averages. Hann windows were used with 50% segment overlap. The frequency response of the rattle filter is set to

$$|H_{\text{rattle filter}}(f_k)| = \sqrt{\frac{S_{x_\mathrm{R}x_\mathrm{R}}(f_k)}{S_{x_\mathrm{PT}x_\mathrm{PT}}(f_k)}}, \tag{6}$$

where $S_{x_\mathrm{PT}x_\mathrm{PT}}$ is the power spectral density of the previously discussed gear rattle impulse train and f_k are the frequencies at which the power spectral densities were calculated. This filter was made to be minimum phase by using the Hilbert Transform relationship between the minimum phase of a system and the log of the magnitude of the frequency response [7]. This procedure was implemented using FIR digital filters. The impulse train was passed through this filter to generate an estimate of the gear rattle impact noise.

When the impulse train was passed through this filter to generate an estimate of the gear rattle impact noise, the gear rattle impact events sounded dull. This may have been a result of the spectral estimation smoothing of the lightly damped features in the frequency response function. By decreasing the damping of some of the rattle filter impulse response components, the impact events could be make to sound more metallic. Reducing the damping of all components did not help. The selection of features to modify was guided by some additional measurements on the diesel engine gear train.

Tap tests on gears on the engine and the front cover of the timing gear train were conducted at Cummins to identify the resonant characteristics that an impact event might excite. Frequency response functions (FRFs) were estimated and a corresponding impulse response was calculated. A Prony series analysis was performed on the impulse response of the radiated acoustic energy from an impact of the loaded gears through the front cover to a microphone one meter normal to the gears. The Prony analysis decomposes a signal into a series of damped exponentials and sinusoids [8] (see [9] for an overview of this well known technique), and the amplitude, damping, frequency, and phase of the components can be determined.

A Prony series model of order 450 was found to produce a good match to the data when 4,110 data point of the impulse response were used in the estimation of the parameters (shown in Figure 4(a)). The components related to the resonant features of the gear system were determined by selecting the components with the highest energy (determined over 0.3 seconds at the start of the signal) and having small estimated damping coefficients. The characteristics of the components were used as a guide in the modification of the gear rattle filter.

A similar Prony analysis was then performed on the impulse response of the rattle filter. The frequencies of the components in this model that were closest to the component frequencies identified in the tap test were selected for modification; the damping of those (three) components was decreased, but was not set to the low damping of the components identified in the tap test. This was because doing so led to a prominent 'ringing' feature that is not heard when listening to the gear rattle measurements. The adjustment of the damping characteristics for the components that were modified in the example simulation in this paper is shown in Table 1. The original and modified impulse responses rattle filter impulse response are shown in Figure 4(b). The decreased damping causes the modified impulse response to 'ring' longer than the original impulse response.

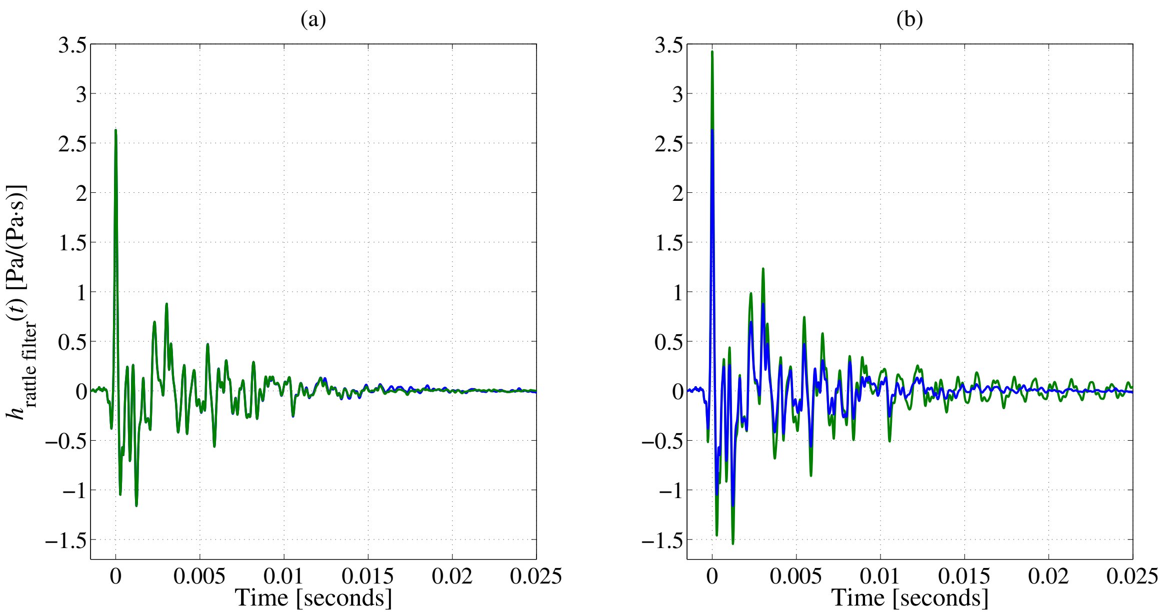

Figure 4 – (a) The original gear rattle impulse response (blue) and the Prony series model (green) and (b) the original gear rattle impulse response (blue) and the impulse response with decreased damping of various components (green). See Table 1 for parameter values.

The gear impact impulse train was filtered with the modified gear rattle filter to simulate the impact events associated with the gear rattle phenomenon. Gear noise levels were increased or decreased by amplifying the rattle components before adding them to the amplified baseline (low gear rattle) measurement.

Table 1 – Adjustment of damping characteristics of the gear rattle filter.

Gear System Tap Test			
Gear System Resonance, Hz	885	2340	3853
Damping Ratio, ζ	0.004	0.002	0.002
Gear Rattle Filter			
Mode Frequency, Hz	880	2364	3847
Damping Ratio, ζ	0.039	0.011	0.008
Adjusted Damping Ratio, ζ	0.013	0.004	0.003

3.5 Tuning the Simulation

The selection of the values for the parameters controlling the timing and amplitude variations previously described has a large influence on the overall character of the gear rattle sound. The random delay of the first impact, the delay of the second impact, the randomness of the second impact, the randomness of the amplitudes of the impulses, and the fraction of pulses that are turned off are all adjustable variables in this simulation. Extensive work was performed to investigate the effect of these individual parameters on simulated noise. Each parameter was varied through a range of values while all other parameters were held constant. Sound quality metrics were calculated to investigate how they were influenced by the parameter variations. Metrics examined were Zwicker (DIN 45631) Loudness, Roughness, Sharpness, and Tonality [10]. These sound quality metric values were then compared to the sound quality metrics determined from the high gear rattle measurement.

In the gear lash study, the roughness and loudness metrics were found to increase with an increase in backlash. Roughness was the most useful metric to guide optimization of the parameter settings in the simulation. The simulation parameters that provided the best reproduction of the high rattle measurement are shown in Table 2. Too small of a variation in cycle to cycle gear impulse timing lead to simulations that sounded too regular. Spacing the primary and subsequent impulses uniformly lead to audible pitch changes not present in the measurement. Turning off pulses was found to be important to avoid simulations that sounded too regular, but turning off too many impulses made the sounds too irregular.

Table 2 – Optimized simulation parameters.

Adjustable Parameter	Value
$R1_{\max}$	0.10
P_{SI}	0.35
$R2_{\max}$	0.10
$R_{\mathrm{A}\max}$	80%
P_{off}	0.02

4. SIMULATION RESULTS

Sample measurements and simulations are shown in Figure 5. The time histories of the high gear rattle measurement and the simulation appear to have similar overall levels. The baseline signal is smaller in amplitude than the measured and simulated high rattle signals. The impacts can be clearly seen in the high gear rattle simulation (c) and appear to have larger amplitude than the impacts seen in the high gear rattle measurement. The impulses used in the timing train were all positive, and a possible modification would be to randomly switch the signs of the pulses to create a more even distribution about the mean of the signal.

The corresponding power spectral densities of the signals are shown in Figure 6. It can be seen that the design of the rattle filter ensures that the spectral content of the simulation is in good agreement with the spectral content of the high rattle measurement.

In addition to listening to the sounds, a variety of sound quality metrics were used to compare the high gear rattle simulation to the high gear rattle measurement. The Head Acoustics Artemis software was used to calculate the roughness, loudness, tonality, and sharpness metrics for the various signals. The values of the sound metrics exceeded five percent of the time for both the simulation and the measurements are shown in Table 3.

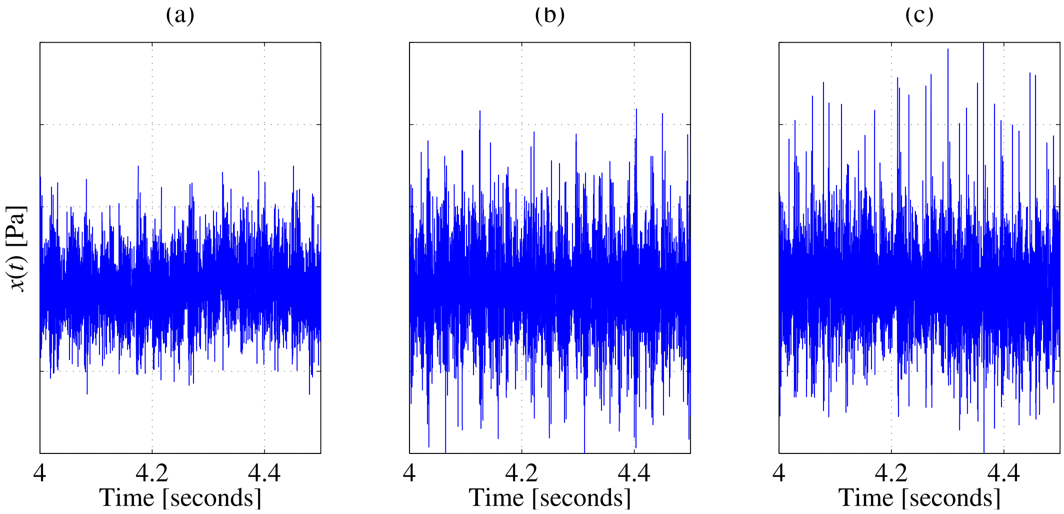

Figure 5 – The time histories of (a) the low gear rattle measurement, (b) the high gear rattle measurement, and (c) the high gear rattle simulation.

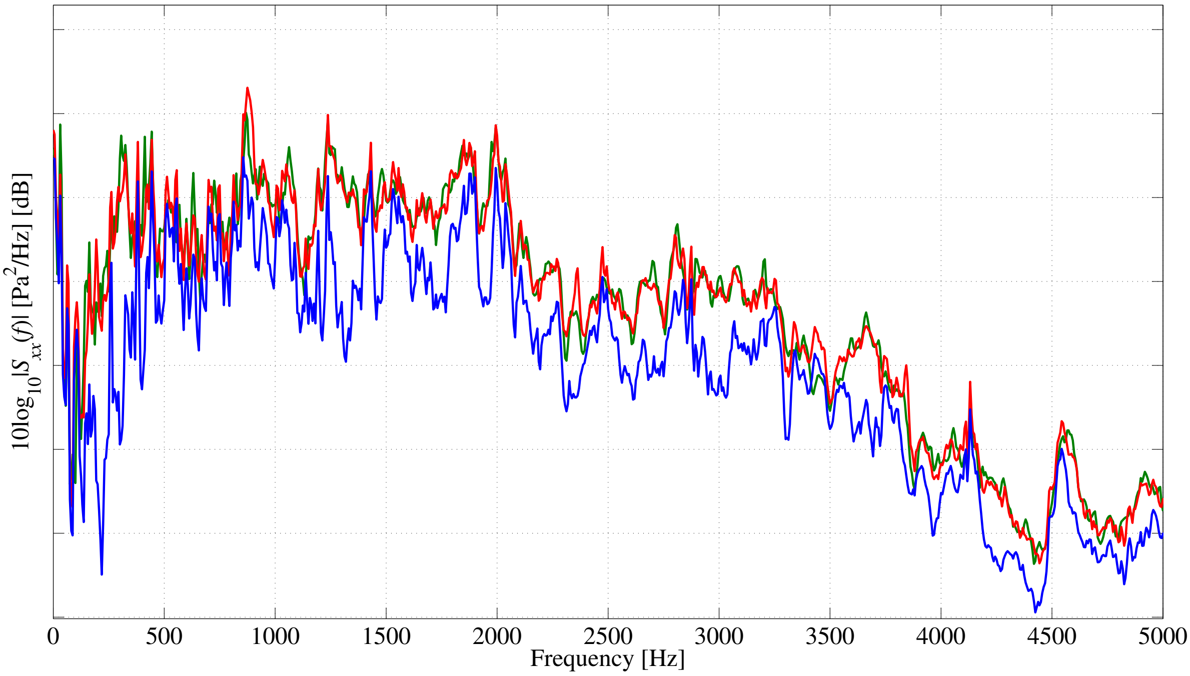

Figure 6 – Power spectral densities of the low gear rattle measurement (blue), high gear rattle measurement (green), and high gear rattle simulation (red). Each tick mark is a 5 dB increment.

Table 3 – Sound metrics. N_5, R_5, S_5, and K_5 are, respectively, Loudness, Roughness, Sharpness, and Tonality exceeded 5% of the time.

Signal	SPL, dBA	N_5, sones	R_5, asper	S_5, acum	K_5, TU
Low Gear Rattle Measurement	85.1	59.3	5.8	1.51	0.10
High Gear Rattle Measurement	88.0	72.0	7.2	1.48	0.07
Gear Rattle Simulation	87.8	71.8	6.7	1.48	0.08

The sound quality metric values for the high gear rattle measurement and simulation are in close agreement. The overall level of the signal and the loudness are the same between the two signals. The roughness metric (R_5) is the most sensitive to simulation parameter settings (timing of the impacts and random variations). The fundamental frequency is approximately 32.5 Hz and the introduction of two pulses per period creates fluctuations at around 65 Hz. Without the damping adjustment in the rattle filter, the roughness value was even closer to that for the high rattle measurement. However, the quality of the gear rattle was judged to be better (by engineers studying gear rattle phenomena in diesel engines) with the decreased damping.

5. CONCLUSIONS AND FUTURE WORK

This simulation method has proven successful at creating realistic sounding time histories with varying levels of gear rattle. The independent control of the level of the gear rattle events will be a useful tool in determining thresholds at which gear rattle may be detected and for understanding the way people perceive growth of gear rattle. Gear rattle simulations created as described here were used in a subjective test designed to quantify detectable levels of gear rattle; the results of that test will be reported later. Decisions that were made during the development of the method that improved the sound of the simulations from a listening perspective but degraded the sound quality metric comparison between the simulated and real signals highlight the importance of listening to the sounds and not relying solely on sound quality metrics during the simulation process. The understanding gained from the development of this simulation process may help to guide the development of a gear rattle metric using noise measurements.

In recent work, it has been observed that gear rattle might affect the operation of the engine. It was previously mentioned that the presence of gear rattle tends to amplify the 'background' noise (engine noise not related to gear rattle impact events). An improved simulation might implement feedback that more accurately simulates how gear rattle affects the operation of the engine.

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