KU Leuven
Department of Mechanical Engineering
LMSD (Mecha(tro)nic System Dynamics)
Celestijnenlaan 300 - box 2420
B-3001 Heverlee, Belgium

Proceedings of

ISMA2024

International Conference on
Noise and Vibration Engineering

USD2024

International Conference on
Uncertainty in Structural Dynamics

9 to 11 September, 2024
Editors: W. Desmet, B. Pluymers, D. Moens, J. del Fresno Zarza.

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Rattle detection in gearing systems by noise and vibration measurements

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Abstract

Rattle noise in a gear train is defined as an undesirable noise that occurs due to the impact between the gear teeth. This work aim to apply methodologies for detecting rattle noise in powertrain transmissions through the processing of microphone and acceleration signals. An experimental campaign was conducted on an off-road vehicle within a truck that was capable of reproducing the real operational conditions. Two kind of operational conditions were investigated: the constant velocities and the time instants of changing gears. The campaign employed experienced operators to identify scenarios with and without rattling. Consequently, rattle indices were applied to the experimental measurements of acoustic pressure and acceleration. The results allowed for the identification of rattle noise conditions, especially if applied to vibration data. Furthermore, the effectiveness of a modified configuration has been tested, both with subjective evaluations and, thus, with the rattle indices.

1 Introduction

Rattle noise in a gear train refers to an undesirable noise that occurs due to the impact between the gear teeth. This phenomenon typically happens during certain operating conditions, such as when there are fluctuations in speed, load, or torque in the gear system. The study of gear rattle noise is crucial for advancing the state-of-the-art in gear design and optimization. By unraveling the contributing factors to rattle noise, engineers can develop innovative solutions to minimize its occurrence and enhance system performance. Consequently, a comprehensive understanding of gear rattle noise is not only a pursuit for acoustic comfort but a fundamental step towards achieving robust, reliable, and efficient mechanical systems in diverse applications, from automotive transmissions to industrial machinery. This work aims to contribute to this understanding.

In order to gain insight into the rattle phenomenon, several studies have sought to identify the primary parameters that contribute to its appearance. Sakai [1] explored the effect of the lubricant by concluding that higher oil viscosity helps in reducing rattle phenomena. Thus, Barthod et al. [2] reached the conclusion that rattle phenomena are promoted by three main factors: larger gear backlashes, loose gears with higher inertias and reduced drag torques. This was achieved through the use of lumped parameter models.

In addition, several researches have been conducted with the objective of identifying methods to reduce unpleasantness caused by rattle phenomena. One of the most significant parameters in the appearance of rattle noise are the torsional oscillations of the input velocity. It has been demonstrated that the optimisation of the torsional characteristics of clutch plates ([3],[4],[5]) has a significant impact on the reduction of torsional oscillations of the input velocity. Furthermore, within this context, Park and Kim [6] developed a mathematical model for optimising the torsional damper parameters with the objective of reducing gear rattle noise and verifying the model both with numerical and experimental tests.

A number of studies have been conducted with the purpose of identifying objective indices capable of characterising the vibro-impact phenomena. Sakai et al. [1], Singh et al. [7] and Rigaud and Perret-Liaudet [8] proposed rattle indices and thresholds based on the analysis of quantities such as gear inertia, angular acceleration and drag torque. Pizzolante et al. [9] developed a lumped parameter model model suitable for investigating the rattle behaviour of multiple branch geartrains proposing an index based on the same quantities. In addition to the aforementioned criteria, other considerations were based on the knowledge of the instantaneous velocities of the gears ([10], [11], [12]), which allowed for the presence of an optical encoder mounted on each analysed gear. Given the difficulty of acquiring the requisite quantities in real operational conditions, Cristofori and Mucchi [13] propose the use of rattle indexes based on quantities such as vibration data and microphone data, which are verified through the use of a lumped parameter model.

The objective of this study is to employ two rattle indices proposed in [13] in a real-world scenario to investigate the signal of one accelerometer and two microphones. In addition to distinguishing between rattle and no rattle conditions, the efficacy of a modified configuration was also investigated with the aforementioned indices, with the objective of determining the ability of the proposed rattle indices to detect potential differences.

The following Section 2 presents an investigation of the studied system, an account of the experimental setup, and a description of the instrumentation employed. The employed rattle indices are described in Section 3, with particular attention paid to their applications to the acquired signals. Furthermore, the experimental campaign to verify the rattle indices accuracy is detailed in Section 4. Concluding remarks are reported in Section 5.

2 System under investigation

A gearbox mounted on an off-road vehicle is subjected to a detailed examination. For reasons of confidentiality, the transmission details cannot be disclosed. However, a simplified scheme is shown in Figure 1. It is worth noting that in addition to the baseline configuration, a modified configuration was subjected to testing. The scheme was depicted in Figure 2. With this regard, a comprehensive literature review revealed that the implementation of modifications designed to reduce torsional oscillations was capable of mitigating the rattle issues. Thus, in the modified configuration the mass of the flywheel was increased and an additional anti-rattle mass was added.

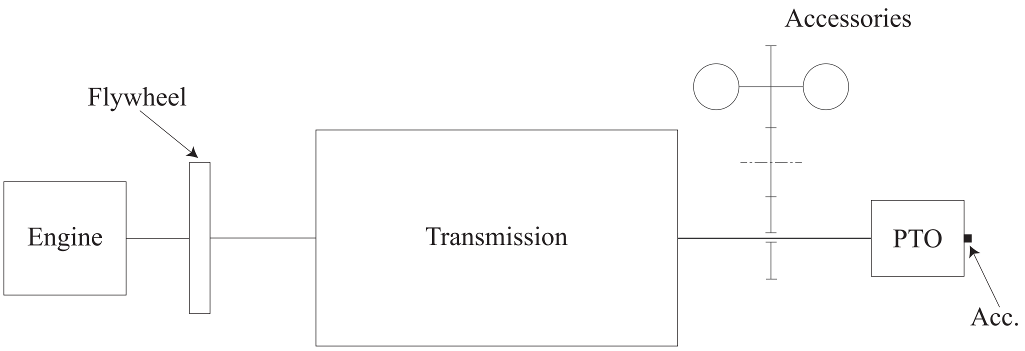


Figure 1: Baseline configuration of the transmission.

2.1 Test set-up

Two different kinds of tests have been conducted, both for the baseline and the modified configuration, differing from the input profile velocity. The aforementioned tests were conducted on a dedicated truck, which allows for the reproduction of the real operational conditions.

- **Idle**: the idle speed test involves maintaining a constant velocity for 40 seconds while driving the off-road vehicle. The aforementioned test was conducted for each engaged gear individually.
- **Powershift**: this test enables the off-road vehicle to be driven at constant velocities and to change engaged gears during the tests, allowing the irregularities caused by changes in flow during operating conditions to be evaluated.

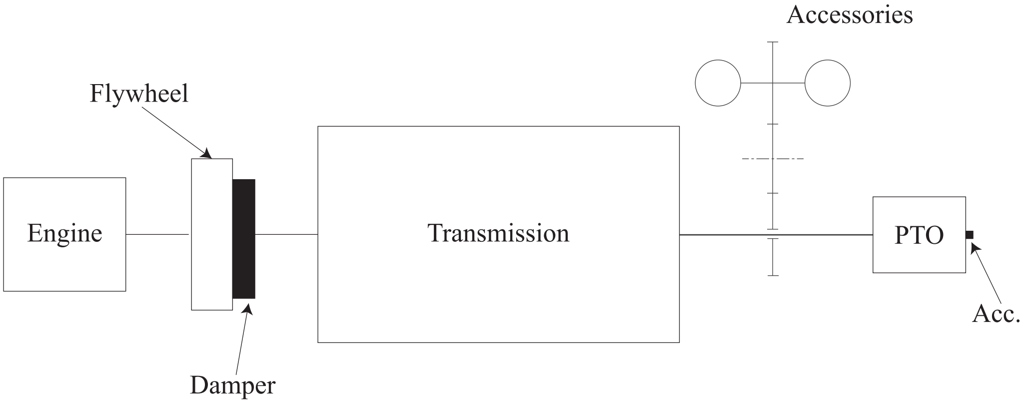


Figure 2: Modified configuration of the transmission.

While idle tests were necessary to verify the effectiveness of the indices and to give rattle thresholds, powershift tests allow to investigate also non-stationary conditions related to the change of the gears.

2.2 Instrumentation

A piezoelectric accelerometer (model PCB 356B2) with a sampling frequency of 25600 Hz and a resolution of 1 Hz was mounted on the gearbox housing in close proximity to the power take-off (PTO), with the reference scheme taken from Figures 1 and 2. Two microphones (model PCB 378B02, sampling frequency 51200 Hz and 1 Hz resolution) were used to record the sound pressure signals. The external microphone was positioned 30 cm from the transmission engine of the off-road vehicle, while the internal microphone was located inside the driver's cab. In addition, a pick-up sensor has been fitted to the input shaft of the gearbox to detect changes in engine speed, which can also be used to detail gear change during powershift tests.

2.3 Subjective evaluations

Initially, it was crucial to evaluate the subjective assessments of the rattle noise weight in the experimental test. Within this framework, four operators with expertise in the assessment of rattle noise were tasked with evaluating each engaged gear. Three distinct conditions were identified, as illustrated in Table1: rattle ($\vee$) and no-rattle ($\times$) conditions, as well as the incipient rattle ($\sim$) condition, which represents a situation where the rattle noise is minimal. Table 2 summarises the results of the idling tests, with the letters A to J indicating the different gears engaged, which is different from the power flow, but at the same input speed. It has been observed that tests with high engaged gears increase system irregularities and produce rattling noises. With regard to the discrepancies between the baseline and the modified configuration, the assessments do not indicate any significant divergences, except for the gears F and G. Nevertheless, the operators observed a reduction in the rattle noise disturbance, despite the rattle remaining present.

Table 1: Details of the experimental configurations tested.

Symbol	Evaluation
$\vee$	with rattle
$\times$	without rattle
$\sim$	incipient rattle

Table 3 summarises the results of the powershift tests. In addition to the constant velocity evaluations, the shift conditions were also assessed, with the rates displayed between the gears from A to J. It was observed that the shift conditions are of critical importance, as the rattle also occurs also in low gears. To illustrate, even if the Gears E and F did not exhibit rattle at constant velocity in the baseline configuration, the change between these two demonstrated vibro-impact phenomena that may be perceived as an annoyance.

Table 2: Subjective evaluations on the idle tests.

Configuration	A	B	C	D	E	F	G	H	I	J
Baseline	×	×	×	×	×	∼	∨	∨	∨	∨
Modified	×	×	×	×	×	×	∼	∨	∨	∨

Table 3: Subjective evaluations on the powershift tests.

Configuration	A		B		C		D		E		F		G		H		I		J
Baseline	×	×	×	×	×	×	×	×	×	∨	×	∼	∼	∨	∨	∨	∨	∨	∨
Modified	×	×	×	×	×	×	×	∨	×	∨	∼	∨	∨	∨	∨	∨	∨	∨	∨

3 Rattle criteria

This section is dedicated to the description of the indices employed to detect rattle noise. These criteria are based on the processing of both acoustical and vibration signals. In order to provide further clarification, examples of signal processing applied to the acquired signals will be presented.

3.1 RI$_1$

The first index benefits from the signal processing methodology employed to identify bearing faults. In particular, RI$_1$ is based on the envelope spectra analysis, proposed by Randall et al. in [14]. This decision is based on the understanding that the rattle noise is an impulsive phenomenon. The flowchart in Figure 3 outline the signal processing to obtain RI$_1$.

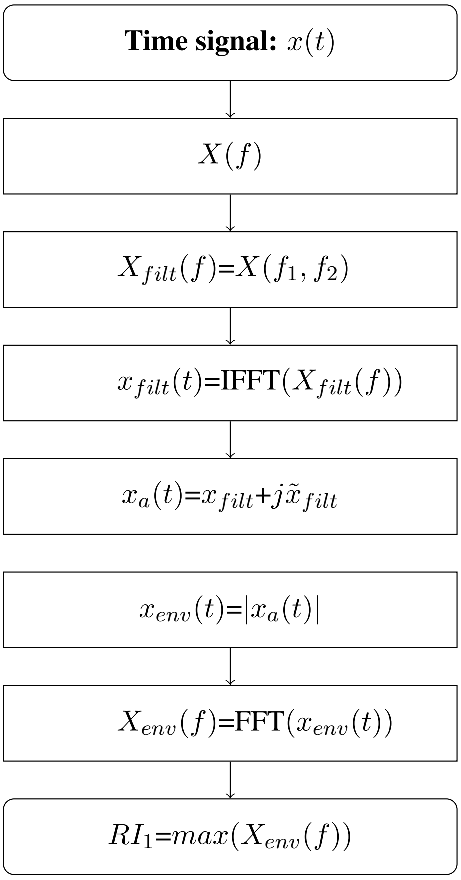
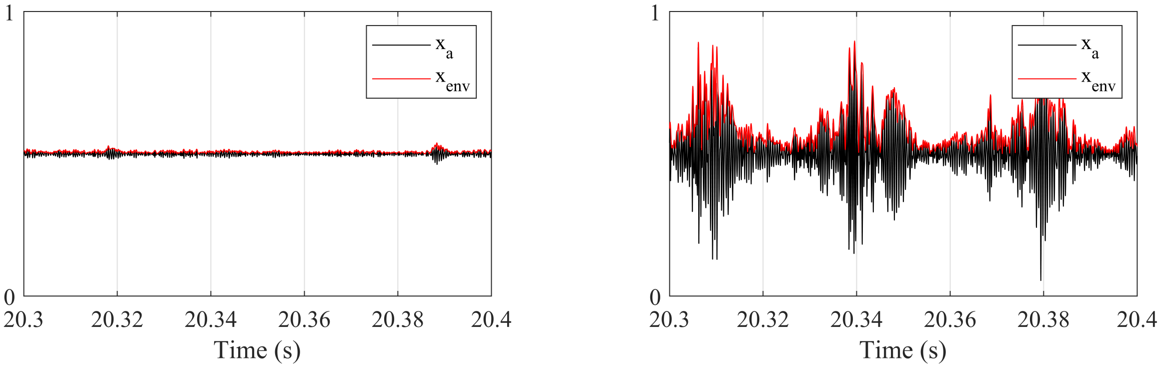


Figure 3: Flowchart for the RI$_1$ evaluation.

The initial acquisition of the acceleration and the acoustical pressure was conducted in the time domain. The frequency spectrum is then computed and bandpass filtered. The objective of this choice is to prevent the frequency characteristics of the signal from obscuring the rattle signal. Thus, it is necessary to select a frequency filter that is appropriate for the specific task. In a generic gear train, the signal must be bandpass filtered at frequencies above the meshing frequencies. Within this specific example, the signal must be filtered between 3000 Hz and 6000 Hz, which correspond to f_1 and f_2 in the flowchart, respectively. Therefore, the filtered time signal was obtained through the use of the Inverse Fast Fourier Transform (IFFT) algorithm and the analytic signal (x_a) was derived, whose imaginary part is the Hilbert transform ($\tilde{x}_{filt}$) of the real part of the signal. Eventually, the envelope of the analytic signal was computed. Figure 4 illustrates the analytic signal (depicted in black) and the relative envelope (shown in red) of Gear A (without rattle) and Gear J (with rattle). Within this context, the data being processed are the acceleration data. In order to maintain confidentiality, the y-values of the graphs were normalised.

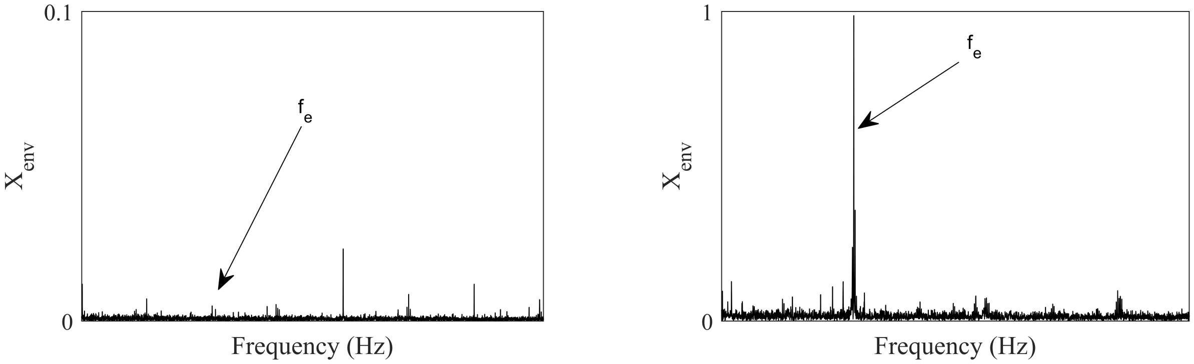


(a) Gear A: without rattle

(b) Gear J: with rattle

Figure 4: Analytic signal of the vibration data and relative envelope of the baseline configuration during Idle tests.

Finally, RI_1 is identified as the maximum value of the envelope spectrum of the analytic signal as the signals with rattle display the frequency components of the excitation. In particular, given that the engine in question is a two-stroke combustion engine, the excitation frequency is twice the rotational frequency. Figure5 illustrates the envelope spectra of Gear A and Gear J, demonstrating that the signal with rattle exhibits the excitation frequency that was previously concealed within the starting signal.



(a) Gear A: without rattle

(b) Gear J: with rattle

Figure 5: Spectra of the analytic signal envelope of the vibration data of the baseline configuration during Idle tests.

3.2 RI$_2$

RI$_2$ is defined as the RMS value of the signal filtered at high frequencies (Eq.1). As the literature review in [13] indicates, when teeth impact, their behaviour is analogous to that of a series of hammers, resulting in system excitation with flat spectra in a wide frequency range. The frequency filter is the same as that used in the signal processing of RI$_1$.

$$RI_3 = RMS(x_{filt}) \tag{1}$$

4 Application of the rattle indices

This section presents the results of applying the aforementioned rattle indices to the gearbox under examination. It examines the ability of the indices to detect rattle noise and to distinguish between different configurations. The signal processing will initially be applied to the vibration data, followed by the acoustical pressure data.

4.1 Acceleration data

Initially, the tests conducted in idle conditions were employed to assess the efficacy of the proposed indices and to establish thresholds for differentiating between rattle and no-rattle conditions. The thresholds were selected based on the Baseline configuration during idle tests. It is worth noting that, for the sake of brevity, only the radial direction of the accelerometer was considered as the most emissive direction. Nevertheless, the other directions give analogous results.

Figure 6 illustrates the resulting values of the RI$_1$ and RI$_2$ for the baseline configuration in the idle test. For reasons of confidentiality, the values of the y-axes were normalised. In order to facilitate comprehension, three areas pertaining to the evaluations of Table 1 were delineated. The red colouration signifies tests with rattle, the yellow colouration indicates incipient rattle, while the green colouration represents tests conducted without rattle. The evaluations in Table 2 help in defining the rattle thresholds. It is important to highlight that the resulting values permit an objective differentiation between different rattle scenarios, especially RI$_1$.

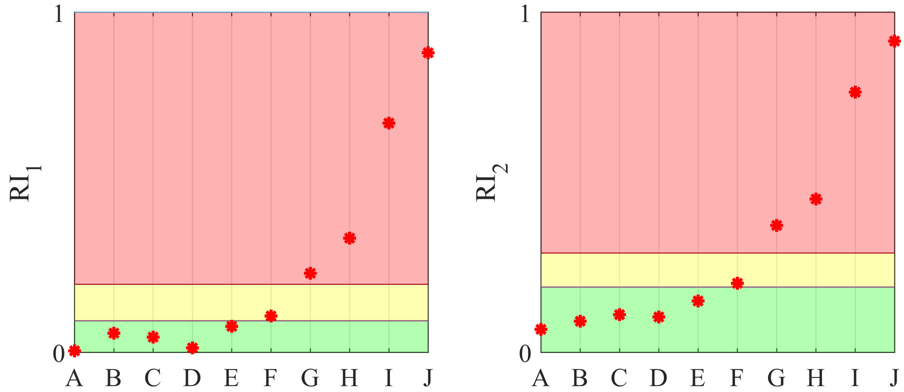


Figure 6: RI$_1$ and RI$_2$ results on the accelerometer data for the baseline configuration in Idle tests.

Once the effectiveness of the rattle index was confirmed, the modified configuration was subjected to further testing. Figure 7 shows the results of the comparison. The proposed rattle criteria permit the objective evaluation of rattle both in the baseline and the modified configuration within the same thresholds set within the baseline configuration. Furthermore, it is demonstrated that the indices exhibit reduced values for the modified configuration, thereby maintaining the capacity to distinguish rattle. These results were in accordance with the subjective evaluations.

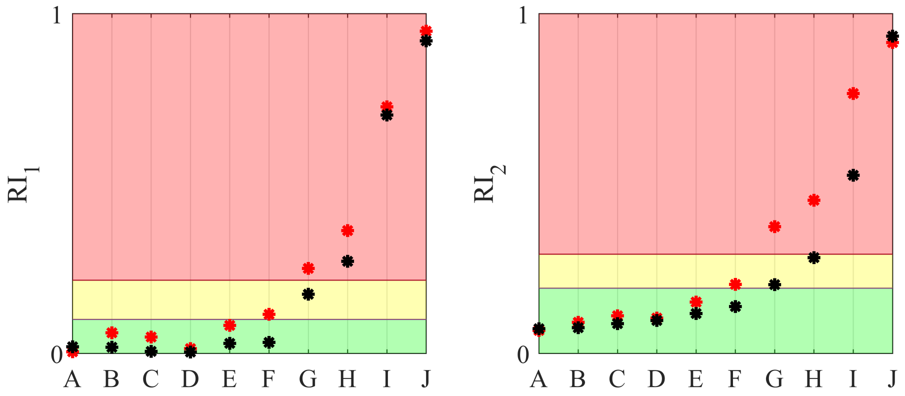


Figure 7: RI$_1$ and RI$_2$ results on the accelerometer data for the baseline (red) and the modified (black) configuration in Idle tests.

Figure 8 shows the RI$_1$ results of the powershift test, while the Figure 9 shows the RI$_2$ results. Within these graphs, the asterisk symbol represents a constant velocity, while the circle symbol represents the instants of shifting between two gears.

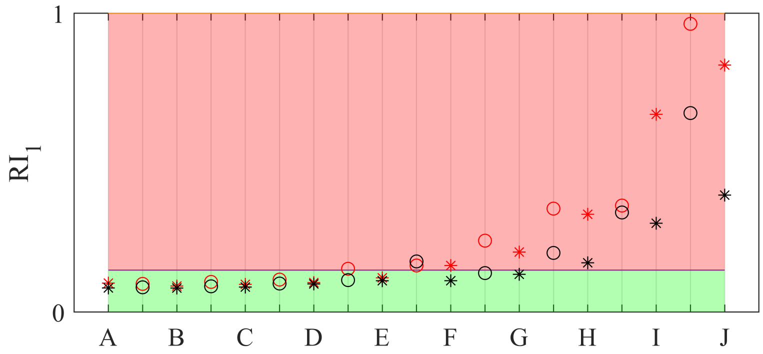


Figure 8: RI$_1$ results on the accelerometer data for the baseline (red) and the modified (black) configuration in Powershift tests.

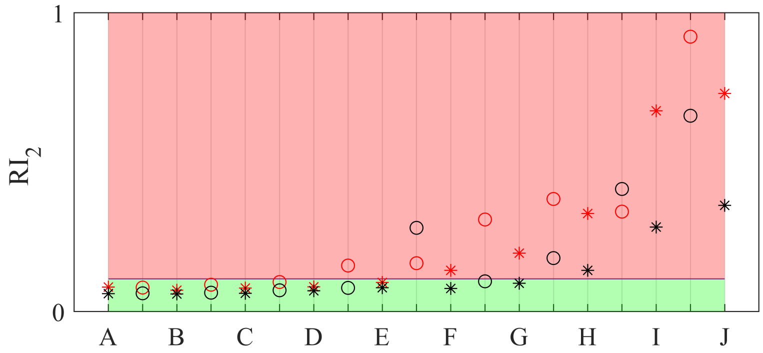


Figure 9: RI$_2$ results on the accelerometer data for the baseline (red) and the modified (black) configuration in Powershift tests.

It is evident that the employed indices are capable of differentiating between the conditions of rattle noise. The results are in good accordance with the subjective evaluations presented in Table 3. Moreover, the indices permit differentiation between the baseline and modified configurations, also in non-stationary tests. It is therefore of interest to note that the indices can be used to evaluate the critical condition of changing gears in situations where the acoustic issues related to the vibro-impact phenomena become important.

4.2 Microphones data

In addition to the results of the acceleration data, the rattle indices have also been tested on the microphone data. Firstly, the signal of the internal microphone positioned within the driven cabin was analysed. The results of the rattle indices for the baseline configuration are presented in Figure 10. RI_1 was unable to detect the rattle, whereas RI_2 demonstrated an increasing trend. Nevertheless, it was not possible to determine a threshold value to evaluate critical conditions, given the low differences in the RI_2 values. It can be observed that only gears I and J exhibit a slight increase in RI_2 value. It can be assumed that the driver's cabin may serve to filter certain noises and may mask those instances of rattling noise that are inherent to the vehicle.

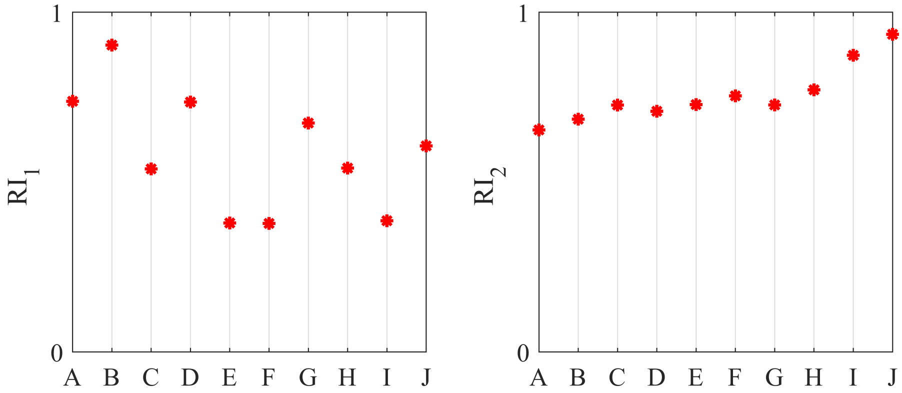


Figure 10: RI_1 and RI_2 results on the internal microphone data for the baseline configuration in Idle tests.

The rattle indices were then applied to the acoustic pressure of the microphone outside the driver's cabin. As illustrated in Figure 11, in both proposed indices, it has been possible to set a threshold, despite the relatively minor differences between the rattle and no-rattle scenarios with respect to the vibration data results. A comparison of the two rattle indices revealed that RI_1 was more effective when applied to acoustical pressure data. Nevertheless, it was not possible to identify the incipient rattle of the gear namely F.

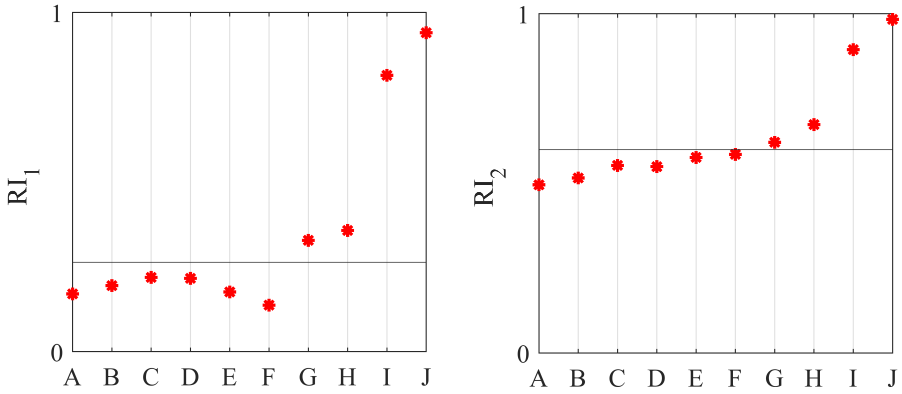


Figure 11: RI_1 and RI_2 results on the external microphone data for the baseline configuration in Idle tests.

Thus, the differences between the baseline and the modified configuration were analysed in Figure 12. It was observed that the rattle indices, when applied to the acoustical pressures of the external microphone, did not differentiate between the baseline and the modified configurations. For real, no discernible pattern emerged that could differentiate between the two configurations, for either of the employed indices.

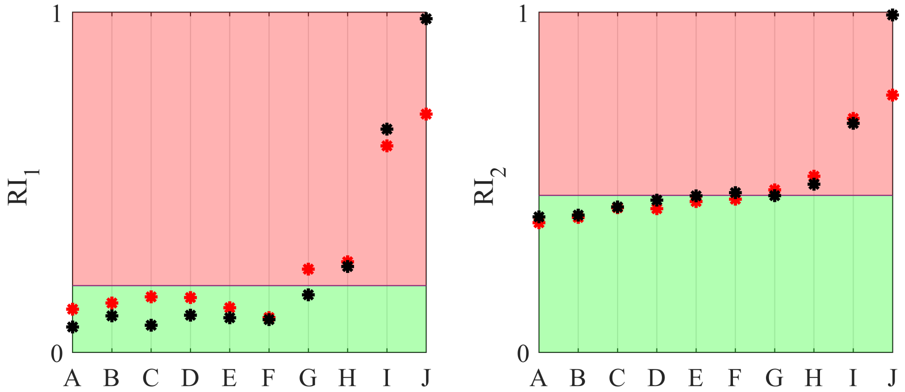


Figure 12: RI_1 and RI_2 results on the external microphone data for the baseline (red) and the modified (black) configuration in Idle tests.

5 Summarizing remarks

The objective of this study was to investigate a gearbox of an off-road vehicle with a view to evaluating the conditions that give rise to rattle noise and to assess the impact of a modified transmission configuration. In particular, the modified configuration incorporates an additional mass to the flywheel and an additional damper.

When applied to the internal microphone signals, both the rattle indices were unable to detect those conditions of rattle noise. With regard to RI_2, the outcomes of the internal and external microphones were comparable. Only minor discrepancies were observed between the various rattle scenarios, which rendered the application of the aforementioned indices to the acoustical pressure signals ineffective. Instead, the RI_1 of the external microphone gives good results with reference to the ability of detecting vibro-impact phenomena. Nevertheless, it was unable to differentiate between the two configurations investigated.

In terms of rattle noise detection, both RI_1 and RI_2 were found to be effective when applied to the acceleration signals. As for the microphone signals, RI_1 allows for a better differentiation between different rattle conditions. In addition to this, the proposed results indicates that the rattle indices are sensitive to the improvement provided by the modified configuration in mitigating rattle issues. Moreover, these indices were found to be effective not only in the stationary conditions, but also in those non-stationary conditions of shifting gear.

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