



Analysis of vibrational comfort in car equipped with a modified 3-cylinders engine

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Summary

In order to improve engines in a way that reduces emissions and consumption of future cars, automobile manufacturers are developing innovative drivetrains like new 3-cylinders engines. In spite of improving the consumption and emissions, these modifications imply a new vibrational and acoustical environment in the car interior which can affect the comfort of drivers and passengers. Indeed the engine presents unusual harmonics at low frequencies and drivers may consider its sounds and vibrations as unpleasant or even uncomfortable. The aim of our study is thus to analyse the vibrational comfort in the particular case of a 3-cylinders engine whose harmonics are much lower in frequency and higher in magnitude than a common engine. We work on the analysis of modifications and their consequences to propose organic or digital solution to improve the vibro-acoustic comfort like modification of the wheels horizontal suspension to lower the vibration's magnitude. Another axis of improvement is a sonification solution that enhances the engine sound. The study takes place in a driving simulator where modal parameters of a car horizontal suspension - amplitude and central frequency of the mode - can be changed and proposed to several testing subjects. This allowed us to determine the acceptability threshold and the couple of parameters which gives the best results in terms of comfort. Moreover, by testing two different sounds of the same engine, it has been showed how a better quality sound influences the evaluation of vibrational comfort.

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1. Introduction

This study takes place in a project of evaluation and improvement of vibro-acoustic comfort for new drive trains. Several combustion strategies are being considered among witch we are interested in simulating cylinders deactivation in a 3-cylinders engine. In cars equipped with such an engine, the vibrational and acoustic environment is strongly modified. The aim is to evaluate the influence of modal behaviour of horizontal wheels suspensions on the perception and comfort linked to vibrations transmitted through the driver seat.

This paper presents the results of a perceptual experiment conducted on a driving simulator. 39 participants were asked to evaluate the vibrational comfort of different synthetized accelerations simulating different suspensions versions. Two engine sounds are presented during the experiment in order to see if the evaluation of vibration is influenced by the sound. Models for prediction of comfort evaluation from modal factors of suspension and global signal indicators are presented.

2. Context and analysis

2.1. Engine specification

This study aims at improving the specific case of a 3-cylinders engine with deactivation. That means that for each engine cycle some explosion will not occur. To analyse the vibro-acoustic behaviour, of the engine, measurements are done on a circuit in full load accelerations in a straight line. Vibrations transmitted to the car seat are measured thanks to a tri-axial accelerometer placed on the right driver's seat runner and a manikin located on the

passenger's seat recorded the acoustic field in the occupant compartment. z-axis is the vertical direction and x-axis is defined as the longitudinal direction and directed to the back on the car.

Figure 1 represents the spectrograms of accelerations measured on the seat runner in the x-direction (left picture) and the z-direction (right picture).



Figure 1. Spectrogram of acceleration measured on the sear runner (left: *x*-direction, right: *z*-direction)

We can focus on the first two principal harmonics of this engine called H_{i1} and H_{i2} . They are the most energetic and their frequencies would be easily transmitted through the seat to the car occupants. The first resonance in H_{i1} in xdirection creates vibrations felt as uncomfortable by passengers. It corresponds to the horizontal wheels suspension mode called SHR excited by this harmonic.

Two improvement solutions can be investigated. The first one consists in changing component to reduce inconvenient due to vibrations. The second one is to numerically enhance the engine sound to create a better atmosphere inside the vehicle.

2.2. Vibro-acoustic simulator

The experiment is conducted on a vibro-acoustic simulator illustrated in figure 2. It is composed of a car seat mounted on a rigid platform. This structure is excited by two electrodynamics shakers, one for each. Sound reproduction is provided by headphones and a subwoofer is located in front of the seat.



Figure 2. Vibro-acoustic simulator.

3. Perceptual experiment

A perceptual experiment is thus realized to evaluate the influence of modal modifications on this suspension on the vibrational comfort evaluation.

The aim is to simulate changes of the central frequency and the magnitude of this mode to get the couple of parameters which gives the most comfortable situation and an evaluation of the acceptability thresholds depending of these two parameters. Moreover, we would like to evaluate the influence of the sound acts on the vibrational comfort evaluation. For thispurpose, we presented to the participants two sounds, one is the regular engine sound and the other is an enhanced sound.

3.1. Design of experiment

The aim of the experiment is to determine how comfort varies with frequency and magnitude of the suspensions. As the current configuration is uncomfortable and not acceptable in a vehicle, we consider that it will be the worst case of possibilities. Values of factors magnitude and frequency will be chosen lower than the current ones. Indeed it seems to be reasonable to reduce the vibration magnitude to improve comfort. Moreover, in normal circumstances, this mode is not excited because of its central frequency tuned to be lower than the lowest frequency of the first engine harmonic. In the case of deactivation, the harmonic frequencies lower than a regular engine leading to an unusual SHR excitation. Reducing the central frequency would then attenuate this excitation. The experimental design adapted to quantitative factors (magnitude and frequency) aiming at describing another quantitative value (comfort rating) is a centered composite plan represented in figure 3.



Figure 3. Centered composite plan.

This plan is built from 5 values of each factor centered between leading at 9 points: 4 points are from the complete plan, 4 are the star points and the central point is repeated 5 times. Consequently 13 vibratory stimuli are presented following an equilibrated presentation plan. The plan is presented twice for each subject with two sounds played alternatively: odd subjects begun with sound number 1 and even with sound number 2.

3.2. Stimuli synthesis

3.2.1. Vibrations

We choose to synthesis only the two first engine harmonics for the vibrational excitation in both directions x and z. Harmonics with higher orders are less energetics and their respective frequencies are too high to be transmitted to the driver from the seat. Harmonics are synthetized with filtered sine sweeps to match the measurements and their spectrograms are plotted on figure 4 in both directions (x on the left – z on the right).



Figure 4. Spectrograms of synthesed acceleration.

The vertical excitation will always be the same for the nine stimuli and the area surrounded on the horizontal spectrograms corresponds to the SHR mode that is modified on this experiment. The frequency and magnitude of the SHR mode are modified according to the experimental design. This implies 9 different time dependent shape of the first harmonic represented on figure 5. The second one is unchanged as well as the vertical excitation.

3.2.2. Sound

As well as for vibrations, the acoustic stimuli are created from a harmonic analysis based on measurement in the vehicle. The level of each harmonic is extracted from the measurement at specific rpm values. The wind and road noise are obtained by removing of the harmonic part from the sound. A correspondence between rpm, harmonic level and noise is then established.

The acoustic synthesis consists in following an engine speed linear variation from 1,000 to 4,000 rpm and playing back the corresponding noise by granular synthesis plus the different harmonics.

The sound obtained is then the synthesis of the regular engine sound and will be presented in the experiment as the sound number 1 its spectrogram is plotted on figure 6.



Figure 6. Spectrogram of sound number 1.

A second sound in figure 7 is created by increasing the level of three harmonics in order to have a better sound quality.



Figure 7. Spectrogram of sound number 2.



Figure 5. Time dependence of magnitude for the first longitudinal harmonic

3.3. Participants

39 participants (7 women and 32 men) aged between 20 and 54 (average 30) volunteered to the experiment. This leads to a balanced presentation plan of the 13 stimuli.

3.4. Evaluation task

Subjects were asked to seat comfortably on the simulator and imagine themselves driving a car through acceleration from 20 to 80 km/h.

After this acceleration, they should report on a tablet their evaluation of the comfort linked to the vibrations only on an eleven-point scale from 0 to 10 with the following specifications:

- 0 corresponds to a vibration they consider like absolutely not comfortable,
- 5 is the acceptability limit between vibrations they can accept in a car or not,
- 10 correspond to a vibration they consider like very comfortable.

Each stimulus can be repeated if the participant needs it.

4. **Results and discussion**

4.1. Preliminary results

A principal component analysis made for each sound reveals a consensus among subjects around an axis representing up to 45% of the global inertia. This allows us to consider only one group of subjects and to keep each response without excluding anyone.

4.2. Analysis of Variance

The weights of the factors subject, sample and sound and their interactions are analyzed with an ANOVA (Analysis Of Variance). This reveals a significant effect of subject, sample and the interaction between sound and subject. The effect of sound is thus not significant here as well as its interaction with sample.

Indeed, the averaged ratings for each sample are the same for sounds 1 and 2. Nonetheless, the averaged ratings given by each subject seems to be different depending of the sound. This illustrates the significant effect of the interaction between sound and subject but globally the effect of sound is not significant in this study.

Figure 8. Averaged ratings for each subject depending



of the sound.

Consequently, to establish a model of the comfort evaluation, we consider the average of the rates given for both sounds even though some subjects seem to be more sensitive to sound than others; this question will be treated in a further study.

4.3. Responses modeling

This kind of experimental design allows the modeling of the responses with a surface depending on the two factors, their square value and their interaction. This modeling shows a significant effect of the factors magnitude a and frequency f. Nevertheless, it seems to be reasonable to consider than a linear relation between magnitude and frequency could be an efficient approximation of the comfort evaluation as describes equation 1.

$$y_{calc} = b_0 + b_1 * a + b_2 * f$$
(1)

The coefficients b_0 , b_1 et b_2 calculated on normalized and centered factors indicate that SHR central frequency has twice the weight as the magnitude. Then, reducing the central frequency of the suspension could significantly improve comfort.

The regression between the calculated and experimental ratings plotted on figure 9 presents a coefficient of determination (r^2) of 0.8 which confirms that the linear model is efficient enough to predict the comfort rating.



Figure 9. Averaged ratings for each subject depending of the sound.

Both coefficients b_1 and b_2 are negative thus the lower the magnitude and frequency, the higher the comfort. This had been expressed by several subjects who were more likely to accept higher vibrations at the beginning of the signal (corresponding to a lower frequency in this case of engine speed increase) which is coherent with a regular behavior of a car.

4.4. Acceptability threshold

The optimal comfort is thus reached for the lowest values of magnitude and frequency. Nevertheless, the model can provide a relationship between magnitude and frequency in equation 2 leading to an average rating above 5 meaning that subject would evaluate this situation as the limit of acceptability.

$$y_{calc} \ge 5$$
 (2)

$$a \le A * f + B \tag{3}$$

Where

$$A = (5 - b_0)/b_1 = -0.04$$
$$B = b_2/b_1 = 0.82$$

This model is particularly useful to know how those modal parameters acts on the comfort and can lead to organic changes on suspensions to lower the central frequency or attenuate the transmission. Nevertheless, those factors are not easily measurable and a model based on signal metrics is more relevant to predict the vibrational comfort from accelerometric measurements.

4.5. Signal metrics

International Standard ISO 2631.1 [1] advocates the calculation of some indicators on weighted signal. The frequency weightings are defined depending on the vibrational axis rely on the sensitivity of whole-body to acceleration [2]. Figure 10 shows those weightings in both directions x and z.



Figure 10. Frequency weightings in directions x and z.

The indicators advised by the standard are

- RMS value and vibration level in dB with reference $a_0 = 10^{-6} m. s^{-2}$
- Peak amplitude and crest factor defines as the ratio between the peak value and the RMS level of the signal It is calculated on the total length of the signal
- Vibration Dose Value VDV is more sensitive to the peak of acceleration than RMS value.

The total value of vibration is calculated as the quadratic sum of RMS values in both directions with a respective factor equal to 1 in the case of comfort evaluation in equation 4.

$$a_{\nu} = (k_x^2 a_x^2 + k_z^2 a_z^2)^{1/2}$$
(4)

These indicators are computed for x, z and total value for weighted and unweighted signals.

4.5.1. Influences of frequency weightings

The weighting defined in standard ISO-2631 applies a low pass filter to signals with a cut-off frequency around 3 Hz in x (W_d weighting) and around 16 Hz in z (W_k weighting).

In this experiment, the excitation signals present frequencies higher than 10 Hz meaning that W_d weighting severely attenuates the x signal and flatten all the variations between stimuli. Thus indicators calculated on weighted signal bring less information than those calculated on the raw signal explicating how subject evaluate comfort.

Indeed the coefficient of determination get with weighted RMS values is 0.70 whereas with unweighted RMS values it is 0.86.

Consequently, in this case, it is more pertinent to keep indicators calculated on raw signal to analyze the comfort rating. RMS value in x is the one with the best correlation with comfort plotted in figure 11. A linear model is thus defined in equation 5 between comfort and acceleration level.



Figure 11. Linear model between comfort rating and rms value of the signal.

5. Conclusion

This experiment has been held on 39 subjects on a vibro-acoustic simulator in order to evaluate the influence of modal modifications on suspensions on the evaluation of vibratory comfort. 9 different vibratory stimuli were presented with two engine sounds. This study demonstrated that people evaluated the vibratory comfort depending more on central frequency than on its magnitude. A linear model has been established between those modal parameters. Another model has been constructed from global RMS value of the signal itself instead of modal parameters acting on one engine harmonic only. This indicator has been

calculated on the raw signal and not on the weighted one as requested in standard ISO-2631 which is not really adapted to the study of comfort in automotive cases. Moreover, the effect of sound on vibratory comfort is also studied. It has been showed that with those two sounds merely close to each other, no effect was really significant on the evaluation of vibration. Nevertheless, this only means that this kind of sonification is not efficient enough to make vibrations acceptable, but the overall comfort in the car can be improved by sound enhancement.

Acknowledgement

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Reference

- [1] ISO, Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole-Body Vibration, ISO 2631-1, 1997.
- [2] M.J. Griffin: Handbook of human vibration. Academic Press, New York, 1990.