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AUTOMATIC IDENTIFICATION OF NOISE ANNOYANCE FEATURES FROM ENGINE RUN-UP SOUNDS

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Abstract

This paper presents a noise annoyance identification tool that was developed to assess the interior noise quality of passenger cars on an objective basis. The tool automatically extracts resonances, masking effects, order non-linearities, booming phenomena and amplitude modulations from a vehicle run-up sound and visualizes these features on the rpm-frequency spectrogram of the sound.

A unique order-based approach is used. In a first stage, an automatic order detection algorithm is employed to detect the significant engine orders in the run-up sound. An advanced order tracking technique is then used to accurately track these order components in amplitude and phase. Once this is achieved, the noise annoyance features are automatically extracted from the order data and displayed in the rpm-frequency colormap of the sound.

The noise annoyance identification tool is interesting and useful for two reasons: (1) it can largely reduce the vehicle evaluation time and efforts when compared with traditional subjective jury test methods; and (2) it informs the sound engineer which parts of the sound need to be modified in order to improve the interior sound quality.

INTRODUCTION

One of the main concerns in the development process of cars is the acoustic comfort for driver and passengers. The interior sound of passenger cars becomes a more and more important marketing aspect for increasing the market share of its own brand. The success of a vehicle on the market depends on how well the sound fits the customer’s expectations. This particular sound needs to be provided in the acoustic development of the car.

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This paper presents a noise annoyance identification tool that was developed to assess the interior noise quality of cars on an objective basis. The tool automatically extracts resonances, masking effects, order non-linearities, booming phenomena and amplitude modulations from a vehicle run-up sound and visualizes these features on top of the rpm-frequency spectrogram of the sound. The use of such tool in conjunction with a Virtual Car Sound (VCS) synthesis environment [1] will help sound engineers and designers to assess the sound quality of various design alternatives in a short period of time without the need for extensive subjective jury testing.

The extraction of noise annoyance features from a vehicle run-up sound is achieved in three major steps. In a first step, an automatic order detection algorithm is employed to identify the significant engine orders in the run-up data. These orders are then accurately tracked in amplitude and phase with an advanced time-varying DFT order tracking method. Finally, the various noise annoyance features of interest are automatically extracted from the order data in the third stage of the approach. This three-steps approach will be described and discussed in more detail in the next sections. The engine run-up data in figure 1 will be used to illustrate the approach.

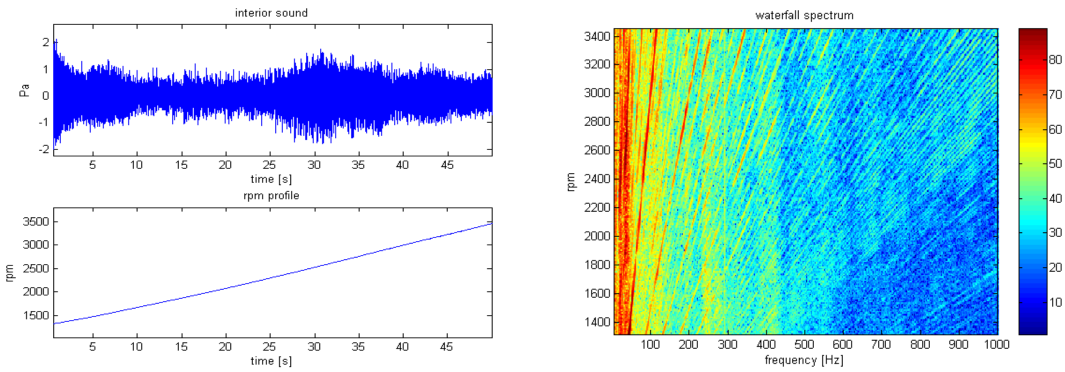
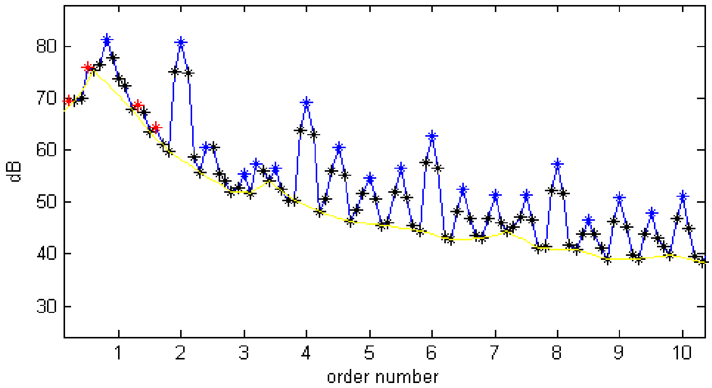


Figure 1 - A typical engine run-up: (left) measured interior sound and rpm profile; (right) rpm-frequency spectrogram.

STEP 1: AUTOMATIC ORDER DETECTION

The first stage of the approach concerns the automatic detection of the significant orders in the run-up sound. This is based on adaptive resampling. The measured tacho pulse train is used to convert the sound data from the time-domain to the angle-domain. Once this is achieved, a tracked spectral processing is done on the angle-domain data. From the obtained rpm-order spectrogram, a mean order spectrum (up to order 20 in steps of 0.05) is calculated, from which the significant orders can be automatically identified. Figure 2 shows the mean order spectrum and automatic order detection results for the engine run-up data in figure 1. The detected significant orders are marked with a blue star. These are local maxima that exceed the noise floor (yellow curve) with more than 3 dB (detection threshold).



0.8	7
2	7.5
2.4	8
3	8.5
3.2	9
3.5	9.5
4	10
4.5	
5	
5.5	
6	
6.5	

Figure 2 - The automatic order detection results for the run-up in figure 1. The detected significant orders are marked with a blue star and listed in the table.

STEP 2: ADVANCED ORDER TRACKING

Once the signifiant orders are detected, the time-varying DFT transform [2] is used to accurately track their amplitude and phase as a function of rpm. This advanced TVDFT order tracking method performs much better than the classical FFT-based approach, especially with respect to phase. As an example, figure 3 visualizes the order 2 and order 4 tracking results for the considered engine run-up. For more details we refer to [3].

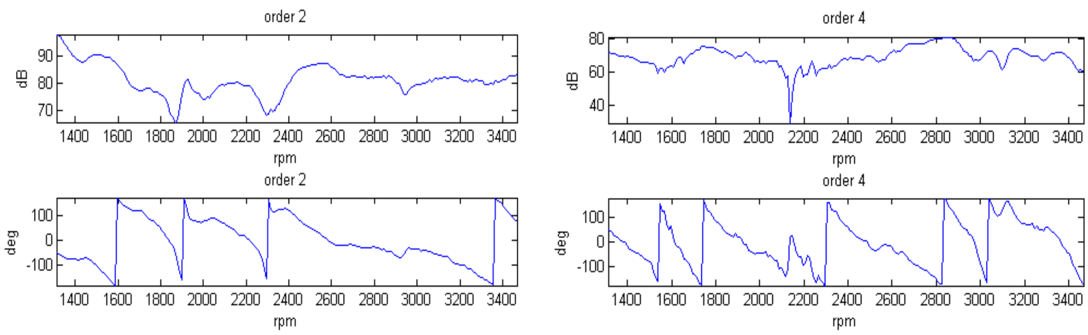


Figure 3 - Order tracking results for orders 2 and 4.

STEP 3: ORDER-BASED FEATURE EXTRACTION

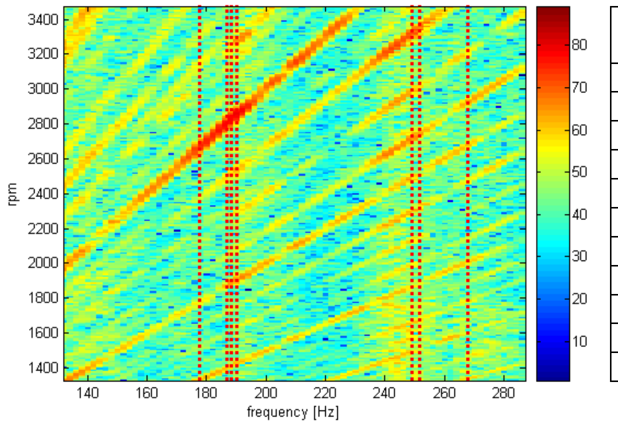
Resonances

An engine run-up can be considered as a multi-sine sweep excitation, exciting a broad frequency band. Under such excitation, the system resonances or modes can be identified from the order data with operational modal analysis. As discussed in [3], this is achieved in different steps:

- The frequency range of interest is first split into a number of adjacent, partially overlapping frequency bands. For each frequency band, a modal model is then identified by using the PolyMAX parameter estimation method [4]. Such model is identified from those orders that fully lie in the frequency band.

- A stabilization diagram is then constructed by fitting models of increased number of modes to the order data. An automatic pole selection algorithm [5] is finally used to select the stable modes from the stabilization diagram.

For the run-up example in figure 1, six frequency bands were considered: (1) 40-140 Hz, (2) 120-220 Hz, (3) 200-300 Hz, (4) 280-380 Hz, (5) 360-460 Hz and (6) 440-540 Hz. The resonance identification results are shown in figure 4. The left graph visualizes the most significant modes on top of the rpm-frequency spectrogram. The table presents the frequency, mean level and damping of the different modes.



Nr.	Frequency [Hz]	Level [dB]	Damping [%]
1	121.74	67.21	1.231
2	177.56	69.86	0.956
3	186.95	74.12	0.520
4	188.47	74.83	0.500
5	190.07	75.29	1.872
6	249.00	50.15	0.070
7	251.52	48.06	0.265
8	267.63	54.01	1.258
9	324.34	47.04	1.236
10	341.17	48.07	1.927
11	355.73	45.20	0.915

Figure 4 - (left) Visualization of the most significant modes on top of the rpm-frequency spectrogram; (right) List of modes with their frequency, mean level and damping.

Masking

A run-up sound is a complex signal in which some orders are masked by the presence of adjacent orders and background noise. Based on the work of Voran [6] and others, a masking algorithm was developed which calculates a masking threshold curve for each rpm point of the spectrogram. Only the orders that exceed the masking threshold are audible, the others are masked. The left graph in figure 5 visualizes the masking results on the rpm-frequency spectrogram for the run-up under study. The sound engineer can immediately see which order parts are audible during the run-up and need to be further considered in the sound engineering and design process. The right graph, which shows the masking threshold curve, the audible and masked orders for a specific rpm, gives a better idea on how dominant some of the orders are.

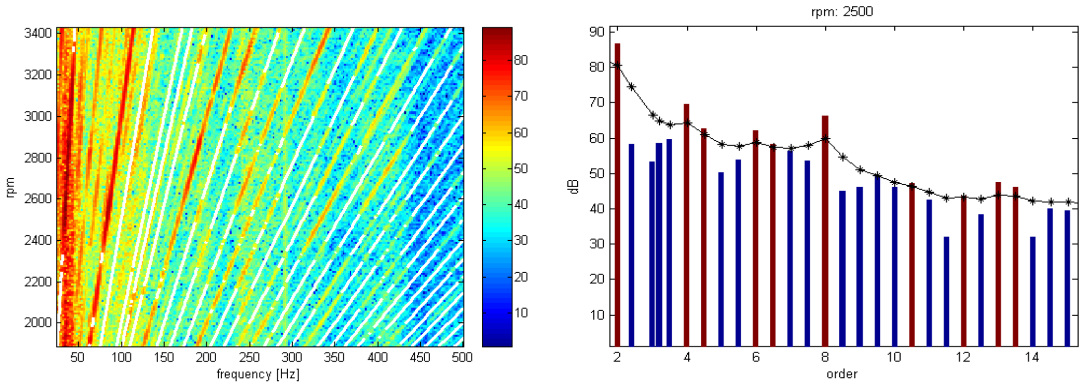


Figure 5 - (left) Visualization of the masking results in the rpm-frequency spectrogram. The masked orders are drawn in white; (right) The masking threshold curve (black) and the masked (blue) and audible (red) orders at 2500 rpm.

Order non-linearities

Non-linearity is an important aspect affecting the sound quality during acceleration. The acoustic signature of a run-up sound must increase linearly with increasing speed or rpm. A sudden drop after resonance can be for example very annoying, especially in sporty cars. Not only the total sound pressure level (SPL) but also the individual order levels must be as linear as possible. The partial effect (in %) of linearizing an order on the standard deviation of the total SPL is calculated as a measure of order non-linearity. The left graph in figure 6 presents the results of this calculation for the different orders of the run-up under study. This graph is very useful as it indicates which orders need to be linearized in the first place to achieve a more linear profile of the total SPL. The orders that are finally considered as non-linear are those that affect the standard deviation of the total SPL with more than 5 %. These are orders 2 (32.09 %) and 4 (12.93 %) in our example. The right graph in figure 6 shows the effect of linearizing these orders on the total SPL.

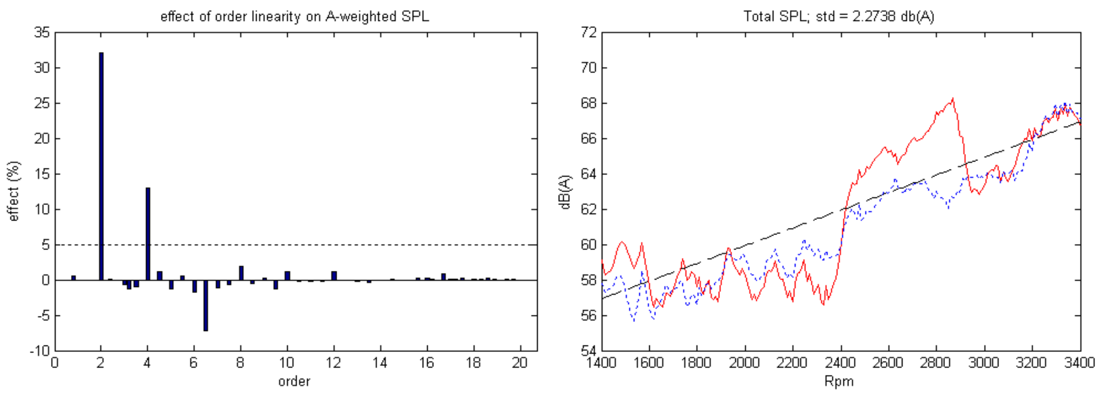


Figure 6 - (left) Partial effect of linearizing individual orders on the standard deviation of the total A-weighted SPL; (right) Total A-weighted SPL profile: original (full line) and when orders 2 and 4 are linearized (dotted line).

Not only linearity in level is important, also linearity in pitch must be considered. It is for example possible that the total SPL is quite linear, but that the dominant frequency in the sound is all the time changing over different engine orders during acceleration. In such case, the perceived sound quality might be poor as well. Figure 7 gives a clear view on pitch non-linearity. For each rpm point of the sound spectrogram, the order with the highest dB(A) value is indicated with a blue star. A black star is used when the order is absolutely dominating. If we look at the pitch map, we can see that the pitch content is continuously varying over a number of orders during acceleration and not just following the firing order 2.

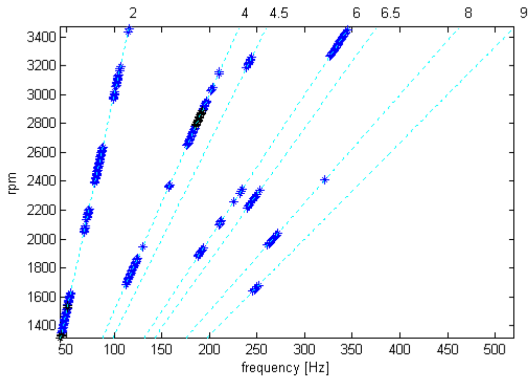


Figure 7 - Pitch map with clearly varying pitch content during acceleration.

Booming

Booming noise a an order-based, low-frequency phenomenon below 250 Hz. A booming area is automatically identified in the rpm-frequency spectrogram of a run-up sound when a single, low-frequency order is absolutely dominating and pushing up and down the A-weighted total SPL with at least 3 dB(A). Figure 8 presents the booming extraction results for the considered run-up. Order 2 and 4 related booming areas were identified from the order data. These booming areas are shown on the A-weighted SPL profile (left graph) and spectrogram (right graph) of the sound.

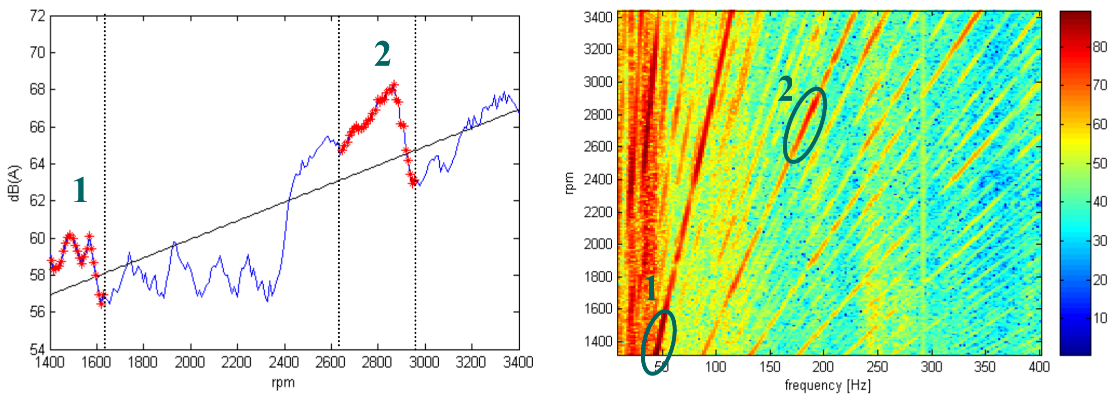


Figure 8: Visualization of the booming identification results on the A-weighted SPL profile (left) and rpm-frequency spectrogram (right) of the run-up sound.

Amplitude modulations

The auditory perception of roughness is determined by temporal fluctuations in the envelope of the sound. It is known from psycho-acoustic literature that modulations related to adjacent integer and half integer engine orders contribute to the roughness of a vehicle run-up sound. Classical roughness models use critical band filters with fixed centre frequency. These models provide a good prediction of the perceived roughness of stationary sounds, but do not correlate well with the subjective perception of run-up sounds. This may be due to the fact that the auditory filters of the human hearing system adapt to the time-varying frequency content of the sound [7]. For this reason, we are using an order-based algorithm with rpm-dependent critical band filters. This algorithm includes several steps.

- The complete run-up is first split into different rpm segments. The sound per rpm segment is then filtered in various, overlapping critical bands. A critical band is considered around every order component of the sound.

- The algorithm then calculates the sound envelope (Hilbert transform), the modulation spectrum (FFT processing of the sound envelope) and partial roughness (subsequent processing based on psycho-acoustics literature) per critical band. These calculations are done for every considered rpm segment.

- The partial roughness per critical band and rpm segment is finally presented in a colormap and the main modulation areas are visualized in the rpm-frequency spectrogram. The results are shown in figure 9.

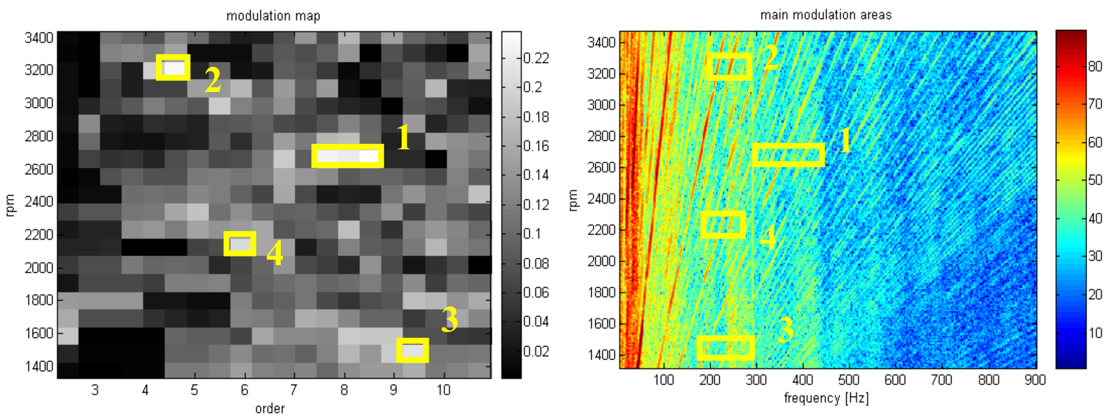


Figure 9 - Partial roughness map and main modulation areas on the sound spectrogram.

Overview

Figure 10 presents an overview of the noise annoyance identification results for the run-up under study. It gives a fully objective evaluation of the interior noise quality without the need for a jury test.

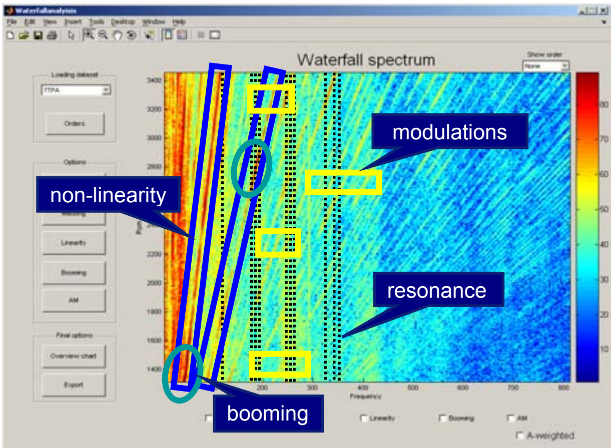


Figure 10 - Overview of noise annoyance identification results.

CONCLUSIONS

An automatic noise annoyance identification tool was developed to assess in-vehicle noise quality on a fully objective basis. The tool automatically extracts resonances, masking effects, non-linearities, booming effects and amplitude modulations from a run-up sound and visualizes these features in the sound spectrogram. The tool is of great help in a sound engineering and design context. It automatically pinpoints the rpm-frequency regions that need to be modified to improve interior sound quality.

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