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Advanced Binaural Transfer Path Analysis

- New Theoretical Approaches and Their Benefits in Practical Applications -

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Binaural **T**ransfer **P**ath **A**nalysis and **S**ynthesis techniques have been developed for the prediction of vehicle interior sound in the time domain. These methods not only allow the prediction of order levels, spectra and vibrations but also the binaural auralization. Recent method extensions permit the combination of measured and simulated excitation data for the time domain approach of BTPS using a newly developed order generator considering phase synchronization of all input data. This paper describes advanced engineering tools and improved methods developed for vehicle sound design and comfort judgments by means of a BTPS model of a Nissan vehicle.

Key Words: Noise, Simulation, Research/ Binaural Transfer Path Analysis (14)

1．Introduction

'Binaural Transfer Path Analysis and Synthesis' techniques have been developed for predicting vehicle interior sound. These methods not only allow predicting order levels and spectra, but also the binaural auralization of various driving conditions and the prediction of vibrations at essential contact points of the driver to the vehicle. The synthesized interior sounds can be realistically experienced in the acoustic driving simulator.

During the development process of new engines, prototypes are rarely available and cost-intensive. However, it is important to have detailed and reliable information about NVH-issues in the early design phase. Therefore, recent extensions of BTPA and BTPS concern the use of simulated excitation data for airborne and structure-borne contributions permitting the combination of measured and simulated excitation data. Acoustic simulation software allows the prediction of level and phase values of sound pressure or vibrations, generally for steady-state conditions at certain rpm values. These data cannot be used directly for the time-domain approach of BTPS, which is essential with respect to auralization. Therefore, an order generator has been developed, considering adequate phase synchronization of all input data to ensure a correct summation of the contributions from the different sources.

2．Binaural Transfer Path Analysis and Synthesis

Binaural Transfer Path Analysis (BTPA) was originally developed for assessing the contributions of individual vehicle noise paths [(1)]. It enables engineers to identify causative mechanisms for noise transfer by distinguishing between excitation source strengths and transfer behavior of individual elements. The method is well-known and acknowledged for powertrain noise analysis, including both point-coupled structure-borne and identified airborne source paths to a receiver location.

2.1 Measurement of Transfer Functions

For structure-borne sound, transfer functions from engine mount to each ear are measured for each individual noise path (Fig. 1). For airborne noise, acoustic transfer functions are similarly determined. For the latter, all relevant sound sources must be known, especially because no discrete reference points exist as they do in the case of structure-borne sound.

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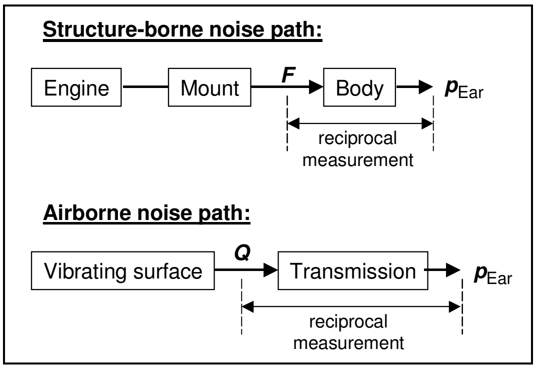

Fig. 1: Transfer functions measured by BTPA

The transmission of airborne and structure-borne sounds to the driver's ears can be measured reciprocally using a recently-developed binaural volume velocity transducer [(2)] in the driver‘s seat and microphones or accelerometers at the noise source positions. The basic requirement to apply the reciprocity method is that directional patterns of source and receiver are the same. [(3)] The advantages of using reciprocal measurements of acoustic transfer functions is that time is saved since all paths can be measured simultaneously and that less space is required for sensors than for sources. Thus, the measurement positions can be chosen almost without restriction, leading to higher accuracy.

2.2 BTPS Model

Binaural Transfer Path Synthesis (BTPS) is the process of creating vehicle interior noise data based on a BTPA model (Fig. 2) or modifications of it, which can be completely auralized. For engine and transmission mounts, vibration signals in all three directions (x, y, z) are considered. Each individual path or combination of paths can be auditioned independently to assess their respective impact on the overall sound quality. Paths can be modified to simulate countermeasures and their effects on the interior noise. Operating data measured on different sources, such as an engine test rig, may also be put into the model to predict how interior noise is influenced by the different sources [(4)].

Input data for the binaural interior noise synthesis are the measured airborne and structure-borne excitations. The airborne radiation of the engine is acquired with several microphones around the engine and at the intake and exhaust system. The structure-borne excitations are measured with triaxial sensors at the attachment points of the engine mounts.

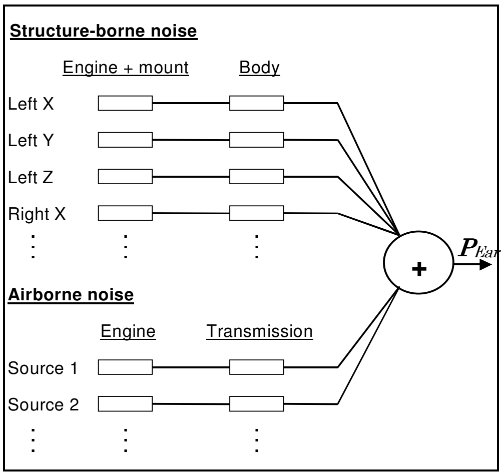

Fig. 2: Binaural synthesis based on airborne and structure-borne sound transfer paths

All input signals are measured time-synchronously in one measurement to guarantee accurate phase relationship between the transfer paths. In order to combine several measurements or include simulation data, suitable time synchronization is essential. Recent improvements to the BTPA/BTPS methodology include new techniques for replacing complex and time-consuming measurements with simulations using computer models [(5)].

3. Method for Order Modification

There are different methods for order modification. Well-known methods involve order filtering using tracking filters. Filter parameters such as the center frequency vary as a function of rpm. The accuracy depends on the rpm resolution and on the update-rate of the filter parameters. Very fast changes of filter parameters may cause audible noise due to transient effects. But also, very fast changes of center frequency are difficult to manage. There is always a trade-off between the resolutions in the frequency and time domains. Narrow filter bandwidths mean longer transient responses of the filter. Thus, it is almost impossible to modify a single order without influencing other orders (or partial orders) in its vicinity. Thus, in case of BTPS, where time data is generated with a certain phase relation to other measured or simulated data, the common tracking filter is not suitable. Normally, minimum-phase filters are used: their phase depends on their amplitude and cannot be adjusted independently. For the sum of several paths the resulting processing errors due to erroneous phase relations may become very high. To correct the situation, FIR (finite impulse response) filters could be used. They allow for independent control of magnitude and phase. But, it is difficult to update the parameters of FIR filters continuously. Normally, averaged rpm values are used for order tracking, leading to unwanted order-level fluctuations due to the mismatch of actual signal frequency and center frequency according to frequency-dependent order filter characteristic. Thus, a method based on order analysis and synthesis using a high rpm resolution and a non-linear resampling technique is proposed for order modification.

4. Order Analysis and Synthesis

The process of order analysis, modification and synthesis is schematically explained in the following. It starts with the recorded audio signal (e.g. from the intake). After applying a nonlinear resampling technique the pressure curve for each camshaft cycle on a linear angle scale is obtained. By means of the fourier transform the order spectrum can be calculated. The resolution of the order spectrum is very high, because of the improved resampling technique in combination with a high angular resolution based on high pulse rate of the crankshaft sensor signal provided by the engine control unit. Fig. 3 shows the magnitude and (unwrapped) phase curves of the 2^{nd} order of the intake signal (left). This forms the basis for further modifications (e.g. change of order levels, phase values, or exchange of orders with results from simulation). Normally, the results of simulation programs (e.g GT-Power) are magnitude and phase values as a function of rpm. Thus, another mapping process from camshaft angle to rpm and vice versa is done. Here for demonstration purposes the 2^{nd} order of the intake signal is reduced 4 dB level (resulting from the reduction in magnitude and phase vs. rpm).

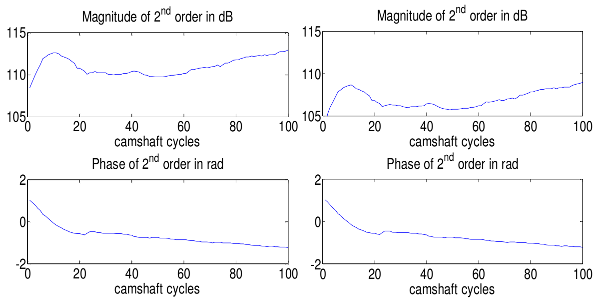

Fig. 3: Magnitude and phase of 2nd order of intake signal (left) and magnitude and phase of modified 2nd order (4 dB reduction) (right) as function camshaft cycles

The next processing step realizes the transformation from rpm to camshaft cycles. For each camshaft cycle the level and phase of the modified orders must be adapted (Fig. 3, right). By means of inverse fourier transform the order spectrogram is converted to a pressure signal vs. camshaft angle containing all modifications applied to the different orders. The final processing step results in a modified audible sound file using a nonlinear mapping from camshaft angle to time. The results show no audible noise due to errors caused by signal-processing steps.

5. Application Examples

5.1 Interior Noise Synthesis

A sub-compact front-wheel-driven car was investigated. The interior noise was synthesized using the above-described BTPS methodology for complete load and rpm. Thus, it was possible to calculate a complete dataset for the acoustic driving simulation system. For the interior noise synthesis the structure-borne vibration transmitted through the engine mounts and the torque rod was taken into account for three directions (x-, y- and z-direction: front-to-rear, left-to-right and bottom-to-top). Additional considered structure-borne paths were left and right drive shaft as well as the air conditioning refrigerant pipe. Thus, the model includes 18 structure-borne transfer paths. The engine airborne noise radiation was acquired by 8 microphones around the engine and one microphone each at the intake orifice and the tailpipe, resulting in 10 airborne transfer paths. Fig. 4 shows the comparison of the left artificial head channel of the synthesized (right) and measured interior noise (left) for a run-up measurement.

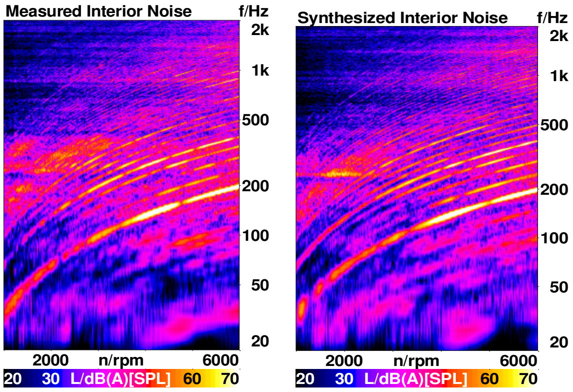

Fig. 4: Spectra of the left artificial head (AH) channel of the measured (left) and synthesized (right) interior noise

The diagrams indicate good agreement, especially with respect to the noise pattern mainly characterizing the interior noise (2^{nd} and 4^{th} engine order, and half-orders leading to engine roughness). Further investigations with engine modifications have proven the validity of the synthesis model. Thus, the described BTPS model covers the most relevant transfer paths and is adequate to evaluate the vehicle interior noise.

5.2 Vibration Data from Excitation

Based on the existing BTPS model, the interior noise of a modified engine built into the investigated vehicle could have been predicted. Since this engine was not available in hardware, the engine mount vibrations were simulated using `Excite´. The airborne noise radiation was assumed to remain unchanged due to the implemented modification. The order level and phase data for the half engine orders from 0.5th order to 8.5th order were simulated for steady-state conditions each 100 rpm. Using the described order-synthesis technique these order level and phase data were used to calculate new input data for the interior noise synthesis. The measured torque mount vibration in x-direction of the original engine as an input measurement was used to synthesize the new input data of the modified engine. Therefore, the simulated order level and phase data were imported from Excite into the BTPS Software tool. Using order synthesis, the original order level and phase data were replaced by the simulated data. Fig. 5 illustrates the general procedure of calculating new input data for the BTPS using order synthesis.

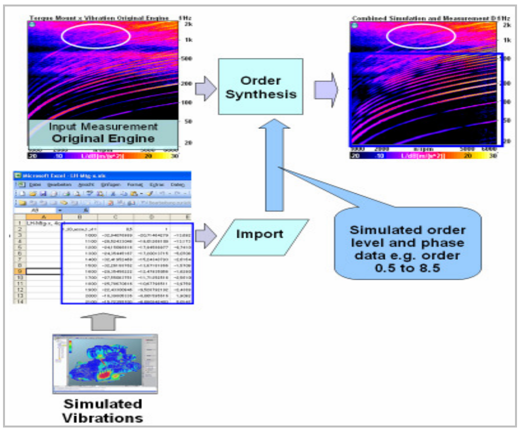

Fig. 5: General procedure of calculating new input time data for BTPS using a combination of measurements and simulations

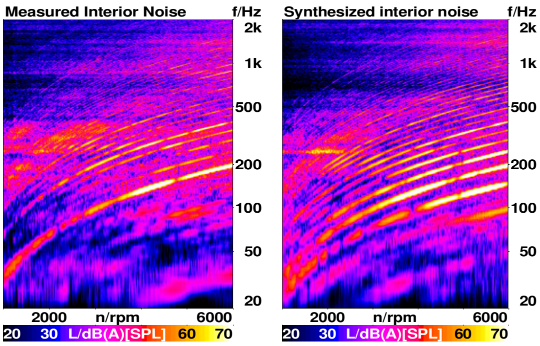

Fig. 6: Spectra of left AH-channel of measured (left) and synthesized interior noise (right) using simulated excitation data

This new signal is time-synchronous to the other measured input signals and, thus, can be used for noise synthesis. This new input time signal is free of any audible artifacts. The resulting interior noise for the modified engine can be calculated. Here, the changes leads to higher half engine order levels, thus to higher engine roughness (Fig. 6).

6. Conclusion

Using presently-available tools, it is not only possible to predict the perceived interior noise sound quality from measurements, but also to use data from acoustic simulation software for a hybrid approach combining simulated excitation signals with measured transfer paths from the different source locations (e.g. at powertrain) to the receiver positions (such as driver's ears). The described method based on order analysis and synthesis delivers extraordinarily results using a high rpm resolution and a non-linear resampling technique. It also allows for merging different measurements within the scope of 'Binaural Transfer Path Analysis and Synthesis'. Only paths of interest need to be considered, instead of measuring the modified vehicle once again and so reducing project duration and cost.

Finally, a dataset for an acoustic driving simulator (sound and vibration) is available at very early stages of vehicle development - even without having a prototype -, helping to increase understanding of customer responses. For it, acoustic driving simulations (H3S) (6) have been developed for stationary or mobile use to investigate sound quality. The `H3S mobile´ allows the modification of vehicle sound, i.e. to change engine, tire, wind noise while driving. This is essential for obtaining reliable data for sound evaluation. (7)

7. References

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