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Tools and Methods for Product Sound Design of Vehicles

Roland Sottek, Winfried Krebber
HEAD acoustics GmbH

G. (Randy) Stanley
HEAD acoustics Inc.

ABSTRACT

Interior vehicle sound is an important factor for customer satisfaction. To achieve an optimized product sound, subjective evaluation methods as well as analysis and prediction tools must be combined to provide reliable information relevant to product quality and comfort judgments. Toward this end, the European project OBELICS (Objective Evaluation of Interior Car Sound, BRITE-Euram 96-3727) was devised. It was carried out between 1997 and 1999 by a consortium of two European car manufacturers, three engineering companies active in automotive sound evaluation, and two universities. The main idea behind the OBELICS project was to understand the basis of sound perception and associated descriptive language and to derive tools for objective evaluation. Within the project, a vehicle interior sound database and 'psychoacoustic dictionary' were developed, and three subject-centered methods for the evaluation of interior car sounds were investigated. The three methods include Semantic Differential (SD), Multidimensional Preference Analysis, and Exploration of Associated Imagination on Sound Perception (AISP). This paper gives a short overview of the OBELICS project results and improvements made during the last five years in associated engineering tools and methods for vehicle product sound design.

INTRODUCTION

Product sound has a significant influence on the market position of car manufacturers. To achieve an optimized product sound, it is normally not sufficient to consider only the A-weighted sound pressure level or the loudness. This has been done in the past, but now, where "silence is the standard" (at least for luxury cars) the foundations have been laid for sound design. Occasionally, annoying sounds which have been masked in formerly louder cars become audible: e.g. squeak and rattle events or noise of small electric motors. These disturbing noises are unwanted and must be removed before sound design begins. Subjective evaluation of the interior sound can be used as a suitable method to provide reliable information relevant for product quality and comfort judgments.

The interior sound of vehicles not only characterizes the product but also influences customers' purchase behavior. Consequently, sound design and sound quality may be seen as two important disciplines for corresponding improvements with respect to subjective sound evaluation. Since the start of the OBELICS project, a significant increase in the interest for the underlying topics has been observed.

The perception of sound is not limited to the hearing sensation; it is also linked to vibration and visual perceptions. New technologies help provide more information about the complete auditory context. Product sound evaluation of a sporty car is more than just listening to the engine sound. It is important how the car responds acoustically under certain driving conditions. Besides all the physical aspects that sound, vibration, haptics, and optics entail, cognitive and emotional aspects are of great importance for the benchmarking of vehicles and for the definition of target sounds.

The target sound for a specific car can be defined by a car sound itself: For example, the Porsche sound, once developed, has been very much enjoyed by its drivers. It became a characteristic that sound engineers aimed to maintain over the years, even when the technology of the vehicle changed. This has been a great technical challenge. Other car manufactures are still looking for the right customer-accepted sound. In this time of globalization, the market is changing, and the product sound must also consider the varying expectations of different nations and cultures. That means that the challenge of finding the right target sound is becoming increasingly important.

Below, the most important results of the OBELICS project are first summarized, and then recently improved tools and methods for target sound definition are described from a technical viewpoint.[1]

MAIN RESULTS OF THE OBELICS PROJECT

SOUND DATABASE

A sound database that covers the typical stationary and instationary driving conditions of 15 vehicles has been built. It can be used as a reference for the development of new analysis methods for automotive sound engineering.

AUDITORY DESCRIPTORS

A four-language psychoacoustic dictionary has been set-up. It is a useful tool for improving the communication between engineers, foreign partners and psycho-acousticians.

To achieve a multi-method sound evaluation design, three methods were combined for subject-centered evaluation of different interior car sounds:

- Semantic Differential method [4] [10] (SD, for 15 items in 4 languages),
- Multidimensional Preference Analyses,
- Associated Imaginations on Sound Perceptions method (AISP) [11]. The AISP-method was introduced to analyze systematically and improve understanding of the emotional effects of sounds.

Some applications of the Multi-Dimensional Scaling (MDS) techniques showed evidence of the inherent multi-dimensional structure of the subjective auditory space; nevertheless, the results of the overall investigation proves that, on the whole, sound quality perception for automotive products is dominated by sound level, i.e. the subjective sound intensity feeling [9]. In most cases, the best available “level” index corresponds with Zwicker loudness.

The correlation research between physical parameters and sound quality perception lead to the definition and implementation of new and relevant parameters for the automotive context. It reveals that only “elementary” perceptions, e.g. loudness, can be linked with parameters and that “complex” perceptions, e.g. sportiness, need to be projected on elementary perceptions to be explained.

Concerning environmental influences, road/driving situation, car class, and type have been found as main dimensional factors. External (non-acoustic) sources of information also contribute to the assessment of auditory perceptions. A physical sound event is the most important but not the only criterion for an auditory event assessment, which is in actuality made by the listener. Thus, cognitive aspects play an important role.

The influence of intercultural differences with respect to the evaluation of vehicle sounds was investigated by Semantic Differential Tests [3], as well as Preference Tests in Germany, Italy and France. The tests validate comfort, power, and sonority as essential factors. The factor analysis on the adjective pairs shows that in all three countries, the adjective pairs unpleasant/pleasant, strenuous/relaxing, exciting/calming, ugly/nice, rough/smooth, and loud/soft explain the first factor (comfort). Concerning the second and third factor, there are no similarities between the Italian, French and German data. AISP-clustering can give hints for naming of factors, however.

PHYSICAL AND PSYCHOACOUSTIC PARAMETERS

A number of analysis techniques have been used to quantify particular physical characteristics in the sound. Emphasis has been placed on identifying the presence of tonal components in the sounds. For accurate order calculation, adaptive RPM-synchronous resampling was needed. It was observed that in general, the pitches determined using the algorithm of Terhardt [23] corresponded to the pitches actually heard in the sounds. It allows identification of the harmonic components that are important for perception. The algorithm of Aures [1] for the calculation of tonality defines the level of perceived tonality in a complex signal containing multiple tonal components.

In addition to this, it was observed that much of the difference between car sounds is due to variations in higher frequencies. A number of parameters were proposed for quantification of this higher frequency contribution.

For analysis of start sounds, Short Fast Fourier Transform and Wavelet analysis techniques are proposed.

In addition, a list of psychoacoustic parameters was established and calculated. The parameters were calculated for a subset of sounds that were also used in the subjective tests.

Using the results of the correlation analysis, a tool has been developed that creates a list of adjectives that relate most to the perception of an arbitrary stationary automotive sound.

Loudness has been shown to be the most important parameter in preference tests (time-varying loudness for non-stationary sounds). Sound sets have been created using modified sounds with increased/decreased

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[1] In [26] the historical development of car sound evaluation techniques, the recent shift towards subjective methods of testing and the controversies surrounding these methods, using the case study of the OBELICS project, is investigated under the perspective of Science & Technology Studies.

amounts of tonality, high frequency content, and/or roughness. The results of expert tests show that tonality, sharpness, articulation index, and roughness are important in the judgment of unpleasantness.

Using the tools developed within the project, it is not yet possible to predict perceived sound quality of a noise only from an analysis of its characteristics. For the creation of target sounds, the results of subjective tests must be included.

NEW ANALYSIS PARAMETERS

Relative Approach

The Relative Approach method [5] is an analysis tool developed to model a major characteristic of human hearing. This characteristic is the much stronger subjective response to patterns (tones and/or relatively rapid time-varying structure) than to slowly-changing levels and loudnesses. It is assumed that human hearing creates for its automatic recognition process a running reference sound (an “anchor signal”) against which it classifies tonal or temporal pattern information moment-by-moment. It evaluates the difference between the instantaneous pattern in both time and frequency and the “smooth” or less-structured content in similar time and frequency ranges. In evaluating the acoustic quality of a patterned situation, the absolute level or loudness is almost completely without significance. Temporal structures and spectral patterns are important factors in deciding whether a sound makes an annoying or disturbing impression.

This approach has been applied to the following interior noise phenomena: cold start, aerodynamic noise, squeak and rattle. Figure 1 shows the comparison between subjective data and relative approach results for wind noises of 8 vehicles. Both subjective ranking and Relative Approach results divide the 8 vehicles clearly into two clusters with totally different values.

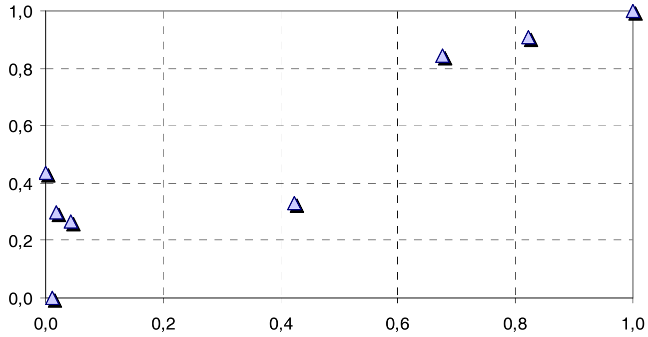

Figure 1: Comparison between Relative Approach results (vertical axis) and subjective preference (horizontal axis) for wind noises of 8 vehicles.

The Relative Approach has recently been expanded in scope. Various time-dependent spectral analyses can be used as pre-processing for the Relative Approach: FFT-based analyses and the successive application of a nonlinear transform take into account the nonlinear relation between sound pressure and subjective perceived loudness according to the Hearing Model of Sottek [19] or time-dependent specific loudness patterns.

Recent extension of the method gives the user a choice of combining time-sensitive and frequency-sensitive procedures, with adjustable priority weighting between the two and independent settings choices for each. In this way, both time and frequency patterns in a sound situation may be displayed in the same measurement result (please see Figure 2).

The Relative Approach algorithm objectivizes pattern(s) in accordance with perception by resolving, or extracting, them while largely rejecting pseudostationary energy. At the same time, it considers the context of the relative difference of the “patterned” and “non-patterned” magnitudes. On the measurement units: Due to the nonlinearity in the relationship between sound pressure and perceived loudness, the term “compressed pressure” in compressed Pascals (cPa) is used to describe the result of applying the nonlinear transform.

Although developed to model the pattern-sensitive evaluation of human hearing, the method has wider engineering applicability in quantifying patterns in noise and potentially also in vibration [2].

The following windshield wiper example compares absolute-value measurements with adaptive relative-value (pattern-sensitive) quantifications:

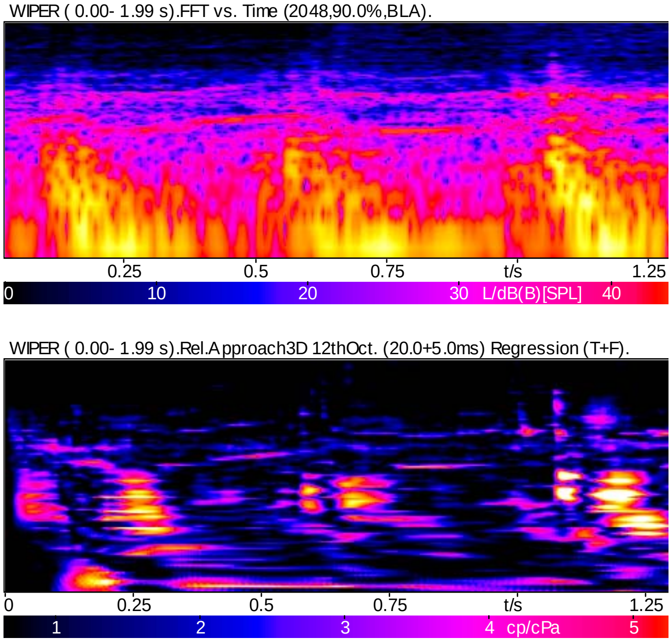

Figure 2: Windshield wiper, two cycles. Upper graph: conventional FFT spectrum vs. time with best choice of block size for resolving both tonal and “thump” patterns. Lower graph: Relative Approach, with variation analysis optimized for sensitivity to both temporal and tonal patterns. Time scale is horizontal, frequency vertical; color indicates magnitude.

Figure 3 shows the block diagram of the different Relative Approach Analyses. It should be noted that the algorithms applied within OBELICS are only first steps; time- and frequency-sensitive results not yet considered.

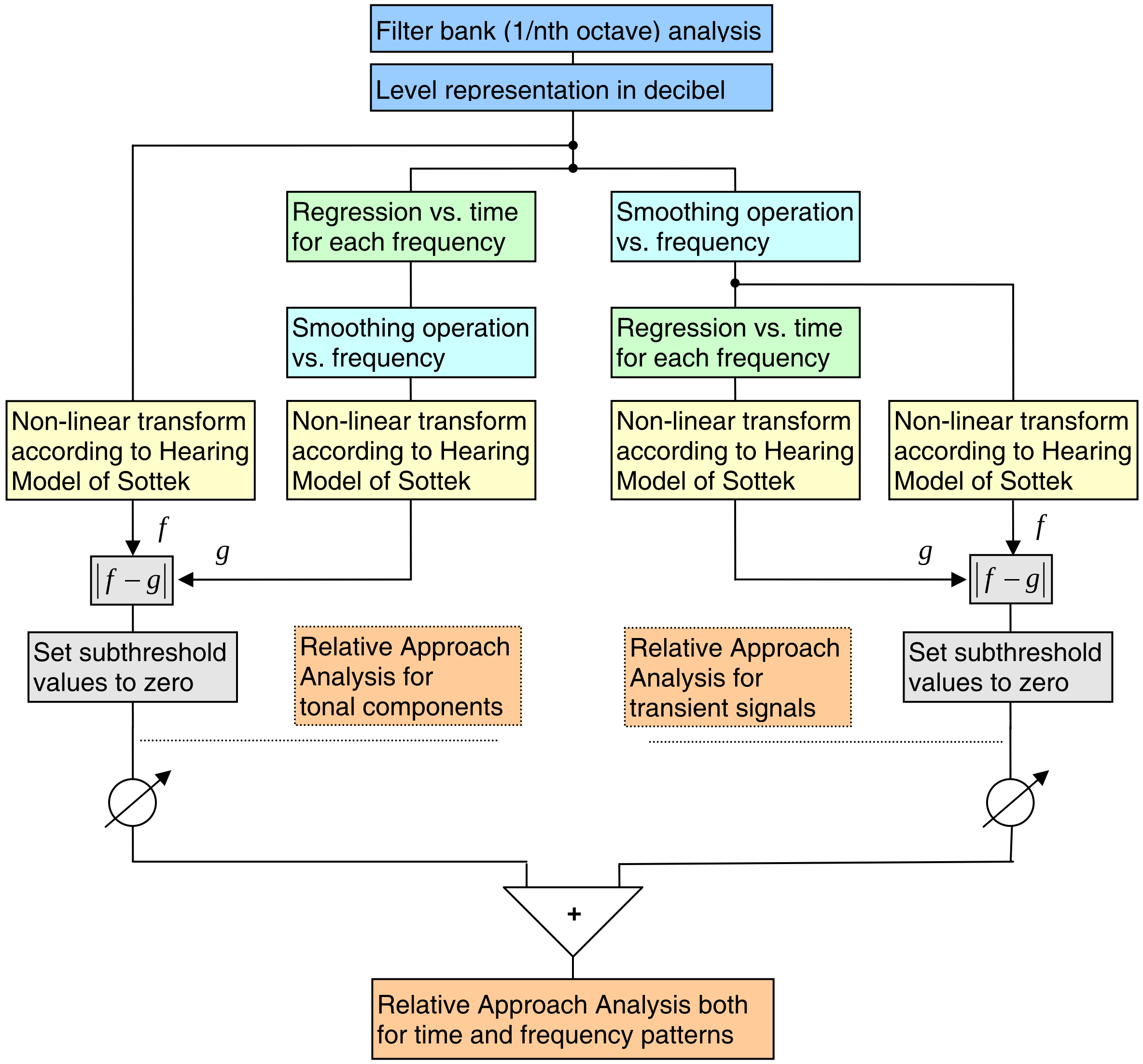

Figure 3: Block diagram of Relative Approach Analyses.

Impulsiveness based on Hearing Model of Sottek

Subjective listening tests have been carried out to describe the perception of impact events that lead to a formulation of the "impulsiveness parameter". Applying this parameter to the description of cold start conditions reveals that it does not correspond in all cases with the global judgement. Improvements could be achieved by using the Relative Approach method.

RPM - related High Resolution Spectral Analysis

The High Resolution Spectral Analysis (HSA) [18], [19] was developed to model how human hearing is able to use pattern recognition to pull the tonal components out of noisy or short duration signals. The HSA uses a method of iterative reconstruction to extrapolate the dominant carrier and modulation frequencies of a signal without any of the leakage and smearing which results from other spectral analysis techniques. The application of HSA is appropriate if a spectrum includes clear, tonal components.

It can also be advantageously applied to the analysis of tonal components in non-stationary signals. The application within the OBELICS project was extended to RPM-related HSA based on the idea that the RPM information provides the analysis algorithms with additional information concerning relevant frequencies. This has been proven with engine run-up recordings.

ADVANCED TOOLS

The results of the subjective tests carried out within the project confirmed the need for reliable sound design tools, capable of creating specific "target sounds" aimed to well defined market groups. Some first steps could be realized within the project. For steady state sounds, a tool for harmonic / non-harmonic part extraction and recomposition has been developed. This allows separate listening to that part of the sound related to the engine sound or that part related to road and aerodynamic sound. Time Domain Transfer Path Analysis (TDTPA) [25] has been developed for transient sounds. A psychoacoustic parametric synthesizer (PPS) [24] aims at the creation of artificial (car) sounds with controlled psychoacoustic features. The SoundCar [6] [15] [16] concept (calibrated vibroacoustic playback device in a car cabin) provides the possibility to listen to the sound and to simultaneously feel the realistic vibration of the seat and steering wheel.

ENGINEERING TOOLS FOR SOUND EVALUATION

OVERVIEW

Multi-modal stimuli must be taken into account in the context of a realistic interior vehicle sound perception. In the last decade, the SoundCar was developed as a first step in this direction. The next step was to make the playback of car sounds in the SoundCar interactive using H3S, the “HEAD 3D Sound Simulation Software”. This development, in collaboration with several car manufactures, led finally to the construction of a Sound Simulation Vehicle. The Sound Simulation Vehicle, equipped with the H3S software, enables the judgment of sound via headphones while actively driving a real car along a road. This concept has been technically refined further, resulting in “H3S mobile”. In joint work with the Technical University of Berlin, a new strategy for conducting and evaluating the results of “operator-in-the-loop tests” is being developed. It is based on AISP for the definition of target sounds [14] [17].

There are yet possibilities for improvements: Whereas sound and vibration can be modified in the SoundCar, the “H3S mobile” always includes the inherent vibration of the specific car used for the drive evaluation. It is a significant technical challenge to develop a car with “user-defined” vibration. But for the moment, the evaluation of vehicle sound under realistic driving conditions delivers more insight about the judgments of test subjects than a test in the SoundCar. The different concepts are explained in the following section.

BACKGROUND

The first subjective sound evaluations took place in laboratories using playback via loudspeakers or headphones. Jury tests on interior car noise have shown that to achieve realistic results, it is not enough to present only the original recorded airborne sound via headphones to the evaluator sitting in an office. It is indeed necessary to present the sounds in an environment, where the tester feels immersed in the actual situation of driving. And even this is not quite sufficient. It is absolutely necessary to add the realistic structure-borne vibrations to the presented airborne sounds, in order to get results which are comparable to judgments made during real driving situations.

In order to accomplish this, the simulation system must be capable of independently reproducing each required vehicle sound (air- and structure-borne) component upon demand, with an optimum balance between fidelity and real-time performance. It has been found that the best way to achieve this balance is with appropriately pre-processed and indexed vehicle sound components. Additional real-time synthesis, switching capabilities, and filtering tools enable a wide array of NVH design and jury assessments within the same simulation environment.

INTERIOR VEHICLE SIMULATION MODEL

To achieve a realistic virtual auditory environment for driving simulations, the reproduced sound must capture not only each sound characteristic, but also the spatial attributes of each sound within the cabin. The automotive industry has long relied on binaural recordings to capture such spatial information. In the semi-diffuse acoustic environment of a vehicle cabin, it has been found that a binaural recording has the capability to best capture the directional characteristics of the semi-diffuse sound in the same manner as individuals hear it.

Binaural reproduction is quite possible without the use of constraining headphones which could detract from the sense of realism. This is achieved through careful loudspeaker timing and equalization inside the vehicle cabin. Synchronization of airborne and structure-borne cues is guaranteed by careful timing of all transducers.

Localization studies have shown that appropriately positioned, timed, and equalized four loudspeaker arrays inside reverberant rooms are quite capable of good binaural reproduction [12]. In the semi-diffuse acoustic environment of a vehicle cabin, such loudspeaker reproduction can even provide slightly improved localization over headphones for a large number of directions. This is partially attributed to the fact that many in-vehicle driving sounds emanate from the front or rear of the vehicle, where localization via loudspeaker playback is best.

The virtual vehicle cabin playback environment, with appropriately timed and equalized loudspeakers, is shown in Figure 4. It is a combination of real and virtual sounds. The real sounds could be from existing vehicle cabin components such as the radio or dashboard warning chimes. Virtual sounds are those directly related to motion and the physical driving process. These may be stationary or moving with respect to the driver. As shown in Figure 4, a driving simulation system requires external control and a driving dynamics model. The driving dynamics model includes vehicle specific definitions of engine power vs. RPM and gearbox adaptation to changing load conditions. Currently, the described simulation audio system is given commands via TCP/IP network interface. This interface offers more than sufficient speed for the described system. For system testing and demonstration purposes when actual driving via “H3S mobile” is not possible, a laptop control program with a simplified driving dynamics model has been created.

The SoundCar concept is being increasingly requested by users in the automotive field. Sound quality engineering, sound design, as well as troubleshooting, has been based up to now on laboratory playback systems using headphones. From the OBELICS project, however, much has been learned about the context-sensitivity of subjective results and the need for realistic immersive environments. Thus, there is a need for advanced playback systems as SoundCar and the context of interactive driving made possible with H3S.

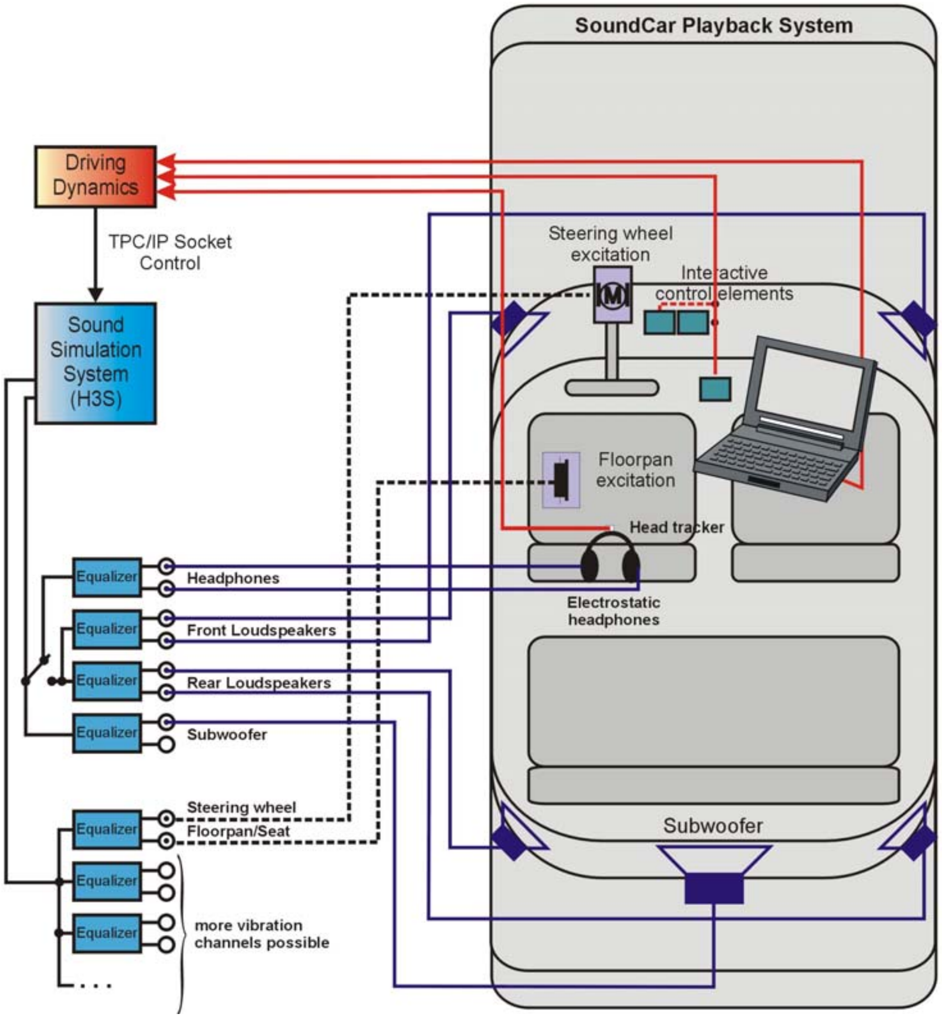

Figure 4: Audio simulation control concept and SoundCar playback environment.

INTERACTIVITY REQUIREMENTS

An interactive driving simulation will require on-demand reproduction of vehicle sound components. Independent reproduction of required vehicle sounds is achieved through playback of an indexed and catalogued database. Wind and tire noise are primarily dependent upon speed, while engine noise depends upon the simultaneous variables of RPM and load. A basic vehicle sound simulation should contain, at minimum, the following sound components:

- Engine sound, dependent on engine type, RPM, and load
- Tire noise, dependent on tire model, vehicle speed, and road conditions
- Wind noise, dependent on air and vehicle speed
- Special sounds such as individual road bumps, dependent on speed
- Virtually moving sounds produced by other vehicles; dependent on direction, distance and speed relative to the driven vehicle
- Background sounds
- Instructions intended to be provided to the driver

In order to provide good reproduction of vehicle sounds without unnatural repetitive cycling and to limit the required number of files, different crossfading techniques and processing algorithms are used for playback of each vehicle sound component. This, in effect, simplifies the database model and the processing required for creation. For a very realistic simulation, the resulting database for engine, tire, and wind noise consists of 25-30 actually recorded and processed sound files.

VEHICLE SOUND COMPONENTS

Engine noise is the most complex sound in a vehicle noise database [13]. This is due to the fact that its sound characteristic varies according to at least two different variables and is the most difficult to index and playback without audible artefacts. The most important variables are engine speed (RPM) and the load condition. This results in the need for a matrix of sound files indexed by RPM and load. In order to playback optimally sized engine sound segments without such distortion, one must find appropriate crossfading points. This can be done in a pre-processing step via calculation of the dominant engine orders. The precise processing and crossfading technique has been achieved through a large number of subjective listening tests and ongoing refinement over some years.

Tire noise, also being dependent on several factors, requires some processing. Generally, noise is generated by the interaction between a road surface, e.g. smooth/worn concrete or asphalt, and a given tire tread pattern. Tire noise contributions are generally most prominent at low frequencies, but can reach higher frequencies during tire ringing events such as caused by road impacts. The tire noise spectrum changes shape with vehicle speed (rate of interaction with road surface), and consequently, it is important to define tire noise adequately so that changes in road speed are not audible. Changes in tire (tread pattern) or road texture typically require new database definitions for accurate reproduction.

Wind noise reproduction is also critical for realistic driving simulation audio. Due to the inherent random characteristics of wind noise, any repetition of recorded wind sounds can be quite audible without careful processing. Consequently, playback of wind noise is best achieved through careful pre-processing or continuous online filtering for correction of changing spectral shape and level. Increasing computing capabilities have made it possible to perform this filtering with sufficient resolution in real time.

Road bump sounds present a particular challenge to simulation audio. Because individual road bump sounds often need to be synchronized with driving simulation video, these need to be recorded as special sounds for playback upon demand. Additionally, because road bump sounds are made up of a variety of sound sources, some of which do not vary consistently with speed, they typically need to be recorded for a sufficient number of road speeds. These sounds include both excitation to the vehicle body and tire ringing sounds.

Another form of special sound is provided by **tire squeal**. In the H3S simulation system, a tire squeal, groan, or scraping sound is first recorded for a given tire position. Each may be modified on demand via user-modifiable level and modulation settings. Finally, it may be desirable to record driver **instructions** which are repetitive or are anticipated to occur at specific positions within a driving simulation scenario.

The aforementioned sounds remain stationary in space with respect to the driver position, and consequently, certain assumptions can be made for recording and playback. It is helpful to record the sounds binaurally at the position of the driver, thus capturing the spatial cues as the driver hears them. This adds significantly to the sense of realism experienced by the driving simulation user. Some stationary sounds internal to the vehicle cabin and unrelated to the physical driving process, such as warning chimes or radio, can also be implemented using actual components inside the vehicle.

OUTSIDE SOUNDS

Other sounds which move with respect to driver position are more difficult to implement. These could include persons, animals, or other vehicles, for example. Among these, other vehicles, particularly oncoming ones, move quickly enough with respect to the simulation vehicle to cause significant audible Doppler shifts. These Doppler pitch shifts must be reproduced accurately to provide sufficient realism to the simulation user.

The Doppler shift ratio f/f_0 can be obtained using the following equation, where f is the Doppler shifted frequency, f_0 is the rest frequency, and c is the speed of sound. The radial component of listener (driving simulation) vehicle velocity v_L and sound source vehicle velocity v_S are considered toward each other. Negative velocities result from radial motion away from each other.

$$\frac{f}{f_0} = \frac{c + v_L}{c - v_S}$$

In order to generate a fully realistic sound for pass-by vehicles in any direction, distance, or relative speed, pass-by vehicles need to be recorded and processed as monaural sounds. To achieve good in-cabin binaural reproduction, these factors should be taken into account:

- Directivity of sound sources (if different from recording)
- Inverse pressure squared attenuation with distance
- Doppler shift due to relative speeds
- Reverberation (if needed), i.e. due to tunnels or reflective structures
- Direction dependent cabin attenuation (filter)
- Binaural sound field synthesis

Doppler shift must therefore be calculated based on vector position, direction of motion, and relative velocities. Doppler shifts for each sound are implemented using a time-varying up/downsampling algorithm before binaural synthesis is performed. Binaural synthesis is accomplished via convolution of the monaural sound with head-related impulse response (HRIR) functions in the appropriate direction.

Other pass-by sounds can also be readily implemented using the aforementioned factors and binaural processing of monaural recordings with vector positions. This could include individuals shouting, thunder, train crossings, train horns, truck back-up beepers, and other warning signals. Ambient sounds are also available and implemented. A flowchart showing the described vehicle sound database and applied signal processing is shown in Figure 5.

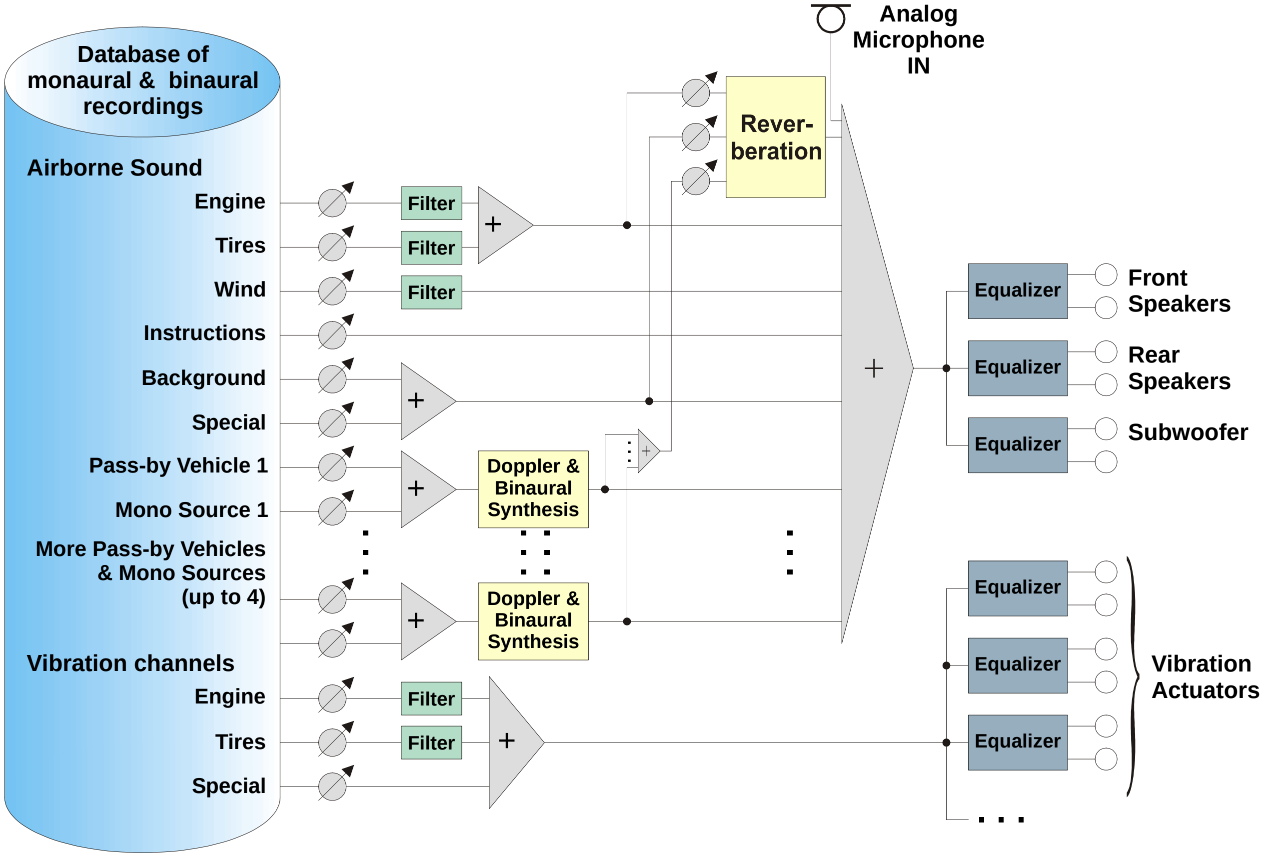

Figure 5: Vehicle sound database and signal processing flowchart for simulation system.

SIMULATION ENHANCEMENTS

It has been shown that vehicle audio simulation is greatly enhanced by the addition of low frequency acoustic and vibration excitation. Most vehicles have prominent low frequency cabin resonances which are readily excited by the appropriate stimulus. In addition, the driver expects to feel some amount of tactile vibration in the seat and steering wheel, at minimum. This is not limited to road texture and prominent road bump events, but is also expected during vehicle startup and stationary idle.

There are two means of vibration possible in the H3S driving simulation audio system. The first simplified approach involves low pass filtered acoustic signals for vibration excitation. When carefully timed, equalized, and adjusted in level, this can provide substantial vibration which adds significantly to perceived user realism. The second approach involves closed loop playback of actual recorded vibration signals. This can be accomplished via multichannel acquisition of vibration simultaneous with the binaural acoustic signals. This approach enables good synchronization for all airborne and structure-borne signals reproduced by the simulation system.

While simulation is certainly possible via headphone playback in a laboratory environment, the SoundCar playback environment shown in Figure 4 provides the important environmental context for driving. Just as individuals react to the reverberance of their office environment for assessment of room size and location, drivers respond to the size of the vehicle cabin and the visual proximity of controls. For this reason, the semi-diffuse acoustic environment created by a vehicle cabin having a combination of reflective (windows) and absorptive surfaces (seats) is critical to the driving experience. When the interactive simulation system and the SoundCar are combined, the result is a complete virtual auditory environment for driving simulation as shown in Figure 6.

Another possibility for improving the contextual realism of binaural playback is a head tracking headphone system. Originally developed for situations where loudspeaker playback would be impractical or where existing sounds must be replaced (as with “H3S mobile"), a head tracker offers some unique advantages. Because head elevation angle and azimuth is tracked via a radio transmitter, special filters can be used to modify the binaural recording based on known HRIR functions. Consequently, the head can be rotated without simultaneous rotation of the sound field (the perceived sound field remains stationary). Thus the wearer experiences a more accurate headphone simulation because head movements do not intrinsically distort the reproduced sound field.

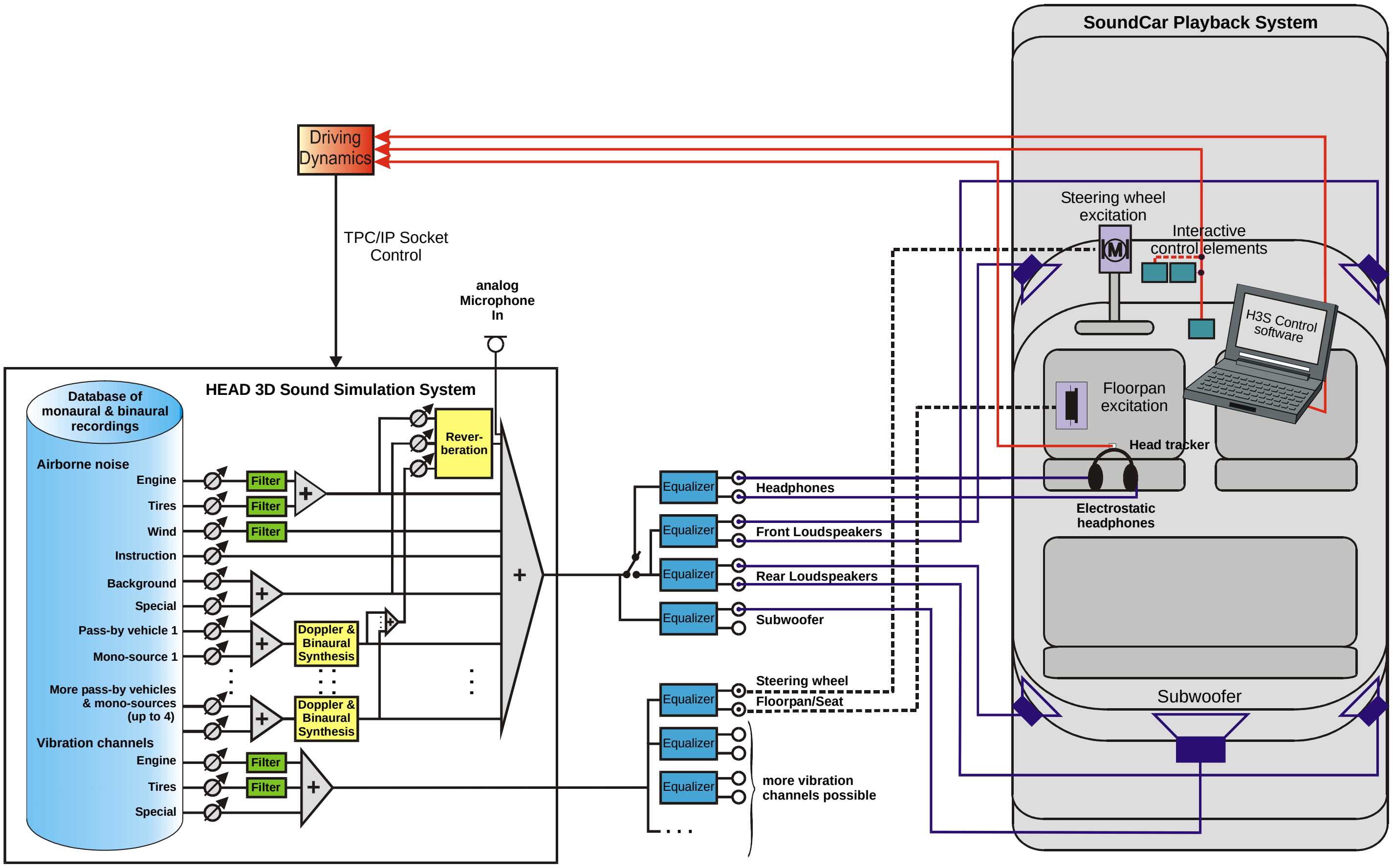

Figure 6: Combination of simulation system and SoundCar for complete virtual auditory environment.

BTPA/BTPS

Binaural Transfer Path Analysis (BTPA) was originally developed for assessment of the binaural contributions of individual vehicle noise paths [7]. It is a powerful modeling tool enabling engineers to identify causative mechanisms for noise transfer by distinguishing between excitation source strengths and the transfer behavior of individual elements. The method is well known for powertrain noise analysis, including both point coupled structure-borne and identified airborne source paths to a receiver location. Binaural Transfer Path Synthesis (BTPS) is the process of creating listenable vehicle interior noise data based on a BTPA model or modifications to it.

Recent improvements to the BTPA/BTPS methodology involve new techniques for measurement of transfer paths [20] [21] and the replacement of intricate time-consuming measurements with simulations using computer models [22].

The listenability of BTPS results makes BTPA/BTPS one of the best sound quality (SQ) design tools available for vehicle noise assessment. However, in order to ensure correct judgments, one must ensure a correct context. When BTPS results can be connected to the SoundCar playback environment and the driving simulation system, this offers potential to complete the equation by allowing the user to experience the sound interactively in the same manner and context [8] as a driver, thus termed a "driver-in-the-loop" experience.

SOUND DESIGN APPLICATIONS

The described audio simulation system contains a number of features for specific applications. These applications include vehicle sound quality design, noise and vibration harshness (NVH) assessment, and consumer benchmarking.

The features include the ability to switch on/off and control the level of any vehicle sound component instantaneously, thus making it possible to isolate any particular sound contribution for assessment. Wind noise can be filtered in real time using a predefined filter array that varies with speed. Using this capability, a calculated change in wind sound spectrum could readily be used to create a new filter without re-recording the wind sound itself. This can also be used to quickly set up direct A/B comparisons of wind noise in real-time based on measurements or CAE predictions.

It is possible to load up to three engines simultaneously for similar real-time switching. This permits comparative A/B assessments of different pre-recorded or pre-calculated engine sounds. As mentioned above, engine sounds can be pre-calculated using BTPS technology and then auditioned in a virtual vehicle driving environment (SoundCar). The potential for engineer design, management assessment, or consumer benchmarking of engine sounds is quite large.

The next extension for auralization of binaural transfer path results may lie in the ability to load a large number of selectable transfer path sounds which could be summed in real time. The requirement for synchronization may necessitate that they be processed and indexed simultaneously; however, the signal summation portion is certainly possible given existing computational capabilities.

Order synthesis and channel selective real-time filtering of acoustic or vibration sources offer added possibilities. Currently, up to ten online filters can be activated simultaneously. The filter options include fixed highpass, lowpass, bandpass and parametric filters. In addition, variable filters are possible. For wind and tire, tracking filters may be varied with speed. For engine sound, order or other tracking filters may be varied with both RPM and load. Amplitude values for the variable filters can be specified via Excel spreadsheet. The simulation system is capable of interpolating between the specified values in two dimensions.

Online filtering may be used for auralizing the result of CAE design predictions or measured changes. Pre-calculated variable order filters from engine test bench data can readily be implemented for audible assessment of engine design changes. This calculation process would be relatively trivial using existing software tools, and this would likely take less time than re-recording an entire new engine database. Similarly, order synthesis could be used to create a new engine sound or augment certain orders in an existing engine database.

SIMULATION CALIBRATION

Calibration is important to ensure correct context and to enable good judgments. Equalization of the vehicle cabin playback environment (SoundCar) for binaural playback is accomplished via a combination of FIR and IIR filters. These filters are implemented in DSP-based equalization boxes capable of serial port synchronization with the simulation computer. Using this interface, the simulation computer is not taxed by the relatively constant external equalization requirements, and it is able to send new timing or filter selection commands for different potential playback scenarios as needed. This could include loudspeakers + subwoofer, headphones + subwoofer, headphones only, or some other combination of these elements. For equalization of low frequency vibration channels, the DSP-based boxes have the capability to implement the required FIR filters at low sampling rates, thus resulting in better equalization at such frequencies.

H3S MOBILE

“H3S mobile” is the most recent Sound Simulation Vehicle development. It can be used under actual (fully realistic) driving conditions. The driving dynamics come from an actual vehicle drive.

Figure 7: “H3S mobile”.

The H3S hardware and software are placed in the trunk. The sound environment is generated and presented in real-time via equalized headphones with additional ANR (Active Noise Reduction).

It is possible to modify the acoustic behavior of the car, i.e. to change the engine, tire and/or wind noise while driving; however, the vibration cannot be changed. Nevertheless, with “H3S mobile”, the most realistic playback is possible. This is essential for getting reliable data for sound evaluation [14].

CONCLUSION

Using tools available now, it is not yet possible to predict the perceived sound quality of a noise from only a precursory analysis of its characteristics. For the creation of target sounds, subjective test results must be considered. The OBELICS project has helped to increase understanding of customer responses and perception of target sounds. The customer responses and the desired image of the car manufacturer help to determine the target sound. It is a marketing task to define this 'target sound'. It is up to the sound quality engineer to monitor the quality of the vehicle-powertrain project. The described tools, including vehicle sound simulation, support this activity.

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