1 - ABSTRACT

Virtual auditory environments (VAE) are becoming more and more important for the development phase of vehicles. Interactive simulation introduces a quite new dimension in comparison to laboratory listening tests. In order to achieve an immersive VAE, all relevant sound components have to be realized in a realistic way and updated in real-time according to the driver’s actions. A concept is presented that covers all classes of relevant sound components: background sounds, engine, tire and wind sound, sounds of other vehicles, pedestrians and warning signals. At the beginning of a virtual car project, normally the sound generation is based on recordings. In order to investigate the effect of vibroacoustic relevant car components on the overall interior sound the different sound components can also be generated by binaural transfer path analysis and synthesis (BTPA and BTPS). Simulation tools enabling interactive sound engineering as well as sound and vibration reproduction techniques are discussed.

2 - CONCEPT OF A SOUND SIMULATION SYSTEM

The virtual vehicle is doubtless one of the most interesting applications of virtual environment technologies. The ‘driver’ feels immersed into the virtual world if he/she receives a plausible feedback to his/her actions. The most important feedback components are inertial feedback, visual feedback and acoustical feedback including vibrations. Normally a ‘mixed reality’ scenario is implemented: A real passenger compartment with real control instruments is combined with a simulation of inertial, visual, acoustical and vibrational feedback. For the simulation of the driving situation the following sound components have to be taken into consideration [1]:

- Engine sound, dependent on engine type, speed and load.
- Tire sound, dependent on tire type, speed and road conditions.
- Wind noise, dependent on speed.
- Sounds produced by other dynamically moving objects, especially other vehicles. Those sounds depend on vehicle speed and orientation.
- Background sounds, including interior and exterior sources.
- Commands to the driver.
Dependent on the user requirements more or less simplifications can be made concerning the generation of the different sound components. If the system shall achieve an auditory impression very close to that perceived in a specific real vehicle, a lot of specific recordings of that vehicle have to be stored in a local database. If a ‘good impression’ is sufficient, more general sounds can be used instead. In both cases synthesized sounds can be included. For sound design applications, additional tools for the interactive manipulation of sound components are required.

Engine sound is the most complex sound dependent on the actual status of the engine described by engine speed (rpm) and load. Instead of waveform synthesis [1] playback of an engine sound consisting of subsequent short recordings representing a specific rpm/load situation is preferred. For a sufficient database representation sounds of about 200 rpm classes and 10 load conditions have to be stored for each engine type to be simulated. During simulation that recording which parameters are closest to the required ones is selected. For constant conditions a randomized playback of different sequences belonging to the same rpm/load class avoids the impression of periodic looping. Sounds generated by this approach are comparable to sounds recorded in the original conditions, deviations are below 3 dB.

Principles of binaural technology

In order to generate 3D sound the simulation concept presented in this paper uses binaural technology.

For stationary sound sources the interior car sounds are binaurally recorded using an artificial head or a binaural microphone worn by a subject and stored in a sound database. During simulation sound segments are recalled from the database according to the current driving conditions, defined by engine rpm, load and vehicle speed. Each selection of a new segment is optimized with regard to a smooth transition. For constant conditions random principles have to be included in order to avoid periodic sound patterns. Databases of binaural recordings can be used for virtual sound sources remaining in the same position with regard to the driver all the time. Thus, this principle can be applied to engine, wind, tire and background sounds.

All moving virtual sounds have to be generated by binaural synthesis from monophonic sources, i.e. by convolution of the monophonic input sound with head-related impulse responses (HRIR) that include all information about the direct sound path from a sound source at a certain position to both ears. HRIR sets consist of HRIR for several directions, normally all directions required for the simulation. They have to provide a sufficient spatial resolution in order to achieve smooth movements without audible steps. In order to be compatible to the binaural recordings described above the HRIR of an artificial head or of a subject will be used.

To move a sound pattern in the virtual space the signal has to be processed by following steps:

- Simulation of the directivity of the sound source.
- Simulation of Doppler shift.
- Convolution with left and right HRIR according to the direction of the direct sound, and in addition – if required – also for reflections at trees, houses, walls etc.
- If required, reverberation is added to the binaural signal.
- Binaural playback.

Since position and speed of the dynamic objects change permanently, the system parameters (sound direction, delay, Doppler shift, etc.) have to be adapted in real-time. For practical applications, 20 updates per second can be regarded as sufficient.
**Binaural transfer path analysis**

In addition to binaural recordings at the driver’s position also sounds generated by binaural transfer path analysis / synthesis [2] can be included into the sound database. For analysis, a set of microphones placed close to the main sound sources are used for recording, in parallel all relevant transfer paths from those source locations to the driver’s ear positions are measured. For synthesis, the binaural sound is re-synthesized summing up the contributions of all transfer paths. Such a model (see Fig. 1) introduces the possibility to modify the characteristics of a single car component (e.g. an engine mount) and listen immediately to the sound effect perceived by the driver.

The triaxial accelerations at all engine mounts on engine side are combined with mount transfer characteristics, car-body inertance and structure-borne transfer paths to receive the interior noise caused by structure-borne excitation.

In parallel, the measured acoustic data at the engine are combined with the airborne transfer paths considering the particularities of coherence.

In this context it has to be considered that – in the case of only one source location – the interior sound is independent of the number of measuring microphones. Therefore, the mixture of the single airborne noise signal to a summarized overall signal requires a correction factor dependent on coherence. This factor is applied to the binaural simulation (C4).

The method has been tested and refined in the last 8 years analyzing some dozens of cars with regard to the contribution of structure-borne and airborne sound to the sound quality of the interior car sound.

All needed transfer functions are determined in situ, without any deassembling of the engine or other components. The benefits of this approach are:

- Structural characteristics of the real system are considered.
- No influence on structural characteristics by removing and reinstalling the engine.
- Reduced measuring time.

A detailed description how to measure and calculate the different filtering functions of the above model can be found e.g. in [3].

Main applications of the BTPA/BTPS are:

- Trouble shooting: BTPA/BTPAS allow to detect and identify the relevant sources and transfer paths of an annoying noise share.
- Simultaneous engineering: Modification of source and transfer path characteristics can be simulated, without installing a new engine or an engine mount. This target oriented virtual design allows an acoustical optimization of the car without any hardware changes.
Fig. 1: Binaural transfer path synthesis model
3 - SOUND DESIGN TOOLS

For sound design applications, the following tools can be realized online during simulation:

- Changing the complete sound scenario intuitively by just driving virtually.
- A/B comparison between different engines measured inside passenger cabins.
- A/B comparison between wind and tire noises.
- Online filtering of those three sound components.
- Recalculation of a binaural transfer path synthesis model as described above. During simulation each transfer path shown in fig. 1 can be modified separately.
- Binaural Simulation of interior car sound for different engines measured on a test rig using data of binaural transfer path analysis. For this application a correction function has to be applied to the test rig data, which considers the structure borne coupling of the engine at the test rig and the room acoustics of the engine compartment.

The big difference to well-known laboratory sound design tools is that all sound perception effects are perceived within a quite realistic context, namely driving a virtual vehicle.

4 - REPRODUCTION OF SOUND AND VIBRATION IN A CAR CABIN

Introduction

As mentioned above, binaural technology is based on the idea of reproduction of the ear signals in order to reproduce the complete hearing sensation as described in [4, 5]. This idea implies the use of headphones since only headphone reproduction ensures that no cross talk between both channels of the binaural signal occurs by the reproduction system, i.e. the right ear receives only the signal recorded in the right ear and the left ear only that recorded in the left ear.

Sometimes, e.g. in driving simulation, headphone reproduction is not desirable in order to achieve a virtual situation in which all aspects are close to reality. In that case loudspeaker reproduction of all sounds is required.

During the development of the artificial head as described in [6], theoretical research and numerous experiments with loudspeaker reproduction have been performed. Since head-related interaural time differences are included in the HRTF, the spatial definition of auditory events in a loudspeaker playback situation based on artificial head signals often delivers better results than solutions using coincident or semi-coincident microphone techniques. The HRTF is still present in loudspeaker reproduction, but without coloration of timbre, due to normalizing equalization (e.g. free-field or diffuse field equalization). Head-related time and frequency domain information remains in the loudspeaker reproduction despite the non-binaural presentation mode, giving excellent imaging and transparency.

Two-loudspeaker arrangement

Arrangements for loudspeaker reproduction using crosstalk canceling techniques have been described in [7], [8], [9] and [10]. Under ideal conditions (anechoic chamber, exact positioning of the listener, correct equalization) it is possible to achieve the same (or even better) reproduction quality for binaural signals compared to headphones. The disadvantage of this method, however, is that these environmental conditions cannot be easily realized in car cabins.
Four-loudspeaker arrangement

As an alternative solution a 4 loudspeaker arrangement has been developed, first for rectangular listening studios [11], later it has been adapted to car cabins. The principle of this reproduction technique is very simple: The left hand speakers are fed by the left channel of the binaural signal, the right hand speakers are fed by the right channel of the signal, typically adjusting same levels for front and rear loudspeakers. Each loudspeaker is separately equalized in order to get a correct timbre of the overall sound, delays resulting from different distances to the listener are compensated. The big advantage of such type of reproduction is that small movements of the listener’s head do not disturb the acoustical image, the sound sources stay virtually stable in place, no discoloration of the sound is perceived. It is not necessary to adjust the arrangement for listeners with different body sizes or different seat positions. Localization tests [11] showed as a general tendency that similar localization accuracy can be achieved by a 4-loudspeaker arrangement in comparison with headphone reproduction. In addition it can be stated that the localization in reverberant rooms gets better compared to the anechoic situation. Additional experiments using the loudspeaker arrangement in a car cabin showed a reasonable spatialization capability [12]. Due to the problematic acoustics in a car cabin the localization accuracy is slightly reduced in comparison with headphone reproduction. Fig. 2 shows a typical application in a car cabin. For sound reproduction the implemented loudspeakers can be used. The four speaker levels have to be balanced carefully. In order to give a more realistic simulation low frequency airborne sound down to 20 Hz is generated by a high quality subwoofer system.

The Integration of Vibration Simulation

Realism of virtual environments can be significantly enhanced by the integration of feedback channels not addressing the ears, but the whole body: very low frequency airborne sound as well as structure vibration. For that purpose the binaural technology as described above has to be extended. For recording, multi-channel measurement systems have to be used that allow the recording of acoustical and vibrational data simultaneously. As a simplification for some applications (e.g. driving simulation for training purposes) it is sufficient to generate those vibration components directly from the binaural recording by lowpass filtering and equalization. For playback, suitable playback arrangements have to be found.

The vibrational situation in a passenger compartment can be divided into two main categories:

- Vibrational excitation through operational devices, i.e. engine, transmission system, wheels and suspension system. A typical example is the second order of a 4-cylinder engine.
- Vibrational impact by ‘comfort features’, such as power windows, electric sunroof, power seats and electrical mirrors. The electrical devices used here primarily cause low frequent noise shares (‘booming’) and vibrations.

At present, there is no detailed research yet on the dependencies between vibrational and acoustical perception. Examinations have shown a trade-off phenomena between sound and vibration when the vibration level is in the range of perception threshold: The loudness is judged higher when vibrations are present in this case [13]. The experience when dealing with complaints in vehicles have shown that normally it is sufficient to consider the vibrations at the passenger’s seat and the rotational vibrations at the steering wheel for a first approach. The mentioned vibrations represent the major part of relevant influences for the judgement. For particular devices - for example power windows - the excitation of other points at the car body may be considered. Introductory research tests within the European research project OBELICS (BRPR CT96-0242) have shown that the use of combined vibroacoustic playback systems leads to more reliable judgements of sound characteristics and sound quality. Based on this, a suitable vibro-acoustical playback system may
consist of airborne sound via head phone(s), low frequent sound (20 - 150 Hz) via subwoofer(s), and vibrations at steering wheel and seat via excitation devices [14]. The set-up of such a system is shown in fig. 2.

Fig. 2: Arrangement for sound and vibration reproduction in a car cabin

5 - REFERENCES


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