Next Generation Acoustical Simulations: Listen to Your Digital Prototypes

A. J. Svobodnik, M. Levasseur
MVOID Group, Germany
C. Faller
Illusonic GmbH, Switzerland
Introduction

• Success story of digitalization based on engineering analysis (e.g. FEA) since the 1950’s
• Recently resulting in a development paradigm change towards simulation driven approach
• Move CAE more and more upfront in the design process
  – Frontloaded virtual product development
  – Virtual assessment of products in early development stages
    • Product planning phase
    • Virtual concept models
Introduction

• Successful introduction of multiphysical engineering analysis in the audio industry in the last decade
  – Loudspeakers (transducers)
    • Electromagnetics, structural dynamics, acoustics
  – Enclosures
    • Consumer applications
    • Automotive applications
      – Complex geometry
      – Integration into car structure
Introduction

• Successful introduction of multiphysical engineering analysis in the audio industry in the last decade
  – Listening spaces
    • Most challenging application in automotive industry
    • Realistic simulation model for a car cabin has been developed
    • Virtual prototyping is used on a daily basis
      – Virtual measurement
Introduction

• Definition and assessment of audio quality is very challenging
  – No closed form definition of sound quality (no metric)
  – Assessment of sound quality is based on subjective methods
    • Listening tests

• Prof. M. Vorländer
  – Any sound, noise, music, or in general any signal generated, transmitted, radiated and perceived can more precisely be interpreted and compared by people if it is made audible instead of discussing “levels in frequency bands”, “single number quantities” or “dB(A)”. 
Introduction

- Virtual listening tests are required to completely assess the product quality of audio systems already in the concept phase, where no physical prototype exists.
- Auralization needs to be added to the multiphysical simulation model.
- Prof. em. M. Kleiner
  - *Auralization is the process of rendering audible, by physical or mathematical modeling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modeled space.*
Multidisciplinary Environment

- Multiphysical Engineering Analysis
- Industrial Design
- Binaural Audio
- Psychoacoustics & Subjective Evaluation
- Digital Signal Processing
- Sound Tuning
Multidisciplinary Environment

• Challenges of modeling automotive audio systems
  – Multiphysics of loudspeakers, enclosures and listening spaces
    • Material properties, boundary conditions, coupling effects, …
  – Whole audible frequency range from 20 Hz to 20 kHz requires combination of numerical procedures
    • Finite elements in the frequency domain
      – Covers modal region of room acoustics (car cabin: f < ~1 kHz)
        » Covers also transition region (1 – 2 kHz)
    • Raytracing in the time domain
      – Covers statistical region of room acoustics (car cabin: f > ~1 kHz)
Multidisciplinary Environment

• Auralizations require an impulse response (IR)
  – IR is the time domain response to an idealized infinitely short impulse (Dirac function)
  – IR defines the response of a linear time-invariant system for all frequencies

• FEA results in the frequency domain (frequency response FR) needs to be transformed into the time domain (IR) and combined with RT results
  – Advanced signal processing (inverse FFT, etc.)
Multidisciplinary Environment

- Final IR is also transformed into the frequency domain
- Both, FR and IR, are useful for assessment of sound quality
  - Spectral and spatial attributes
- IR that includes the listening room is called room impulse response (RIR)
- Multiphysical engineering analysis is used to simulate the RIR of every loudspeaker in a car
  - Vibro-electroacoustic sound path from the speaker terminals, where voltage is applied, to specific measurement points in the passenger compartment, including also the location of the listener’s ears
Multidisciplinary Environment

- Because of severe limitations in automotive applications the “raw” response of a loudspeaker is very poor
- Each amplifier channel enhances loudspeaker response by means of digital signal processing
  - Sound tuning
- Sound tuning in the virtual domain needs to be applied as well before performing an assessment of sound quality
  - Virtual tuning
  - Application of signal processing to the simulated RIR
Virtual Tuning

• Major factors of perceived sound quality
  – Frequency response smoothness on and off-axis
  – Perceived bass extension
  – Naturalness ("feeling of space", correct sense of ambience)

• Spectral attributes
  – Virtual "visual" tuning based on frequency response

• Spatial attributes
  – Virtual "audible" tuning based on listening by means of auralizations
    • Virtual playback via headphones
Virtual Tuning

• Poor listening experience in a car because of
  – Modal effects (usually for frequencies < 500 Hz)
    • Huge variation of SPL
      – Spectrally and spatially (seat-to-seat variation)
  – Boundary effects (reflections)
    • Leading to comb-filtering effects
  – Misalignment of loudspeakers
    • Leading to level and time differences
  – Packaging and integration constraints

• It is mandatory to tune automotive audio systems to significantly improve perceived sound quality
Virtual Tuning

1. Mode at 45 Hz
2. Mode at 85 Hz

Point Graph: Sound pressure level (dB)
Virtual Tuning

• Virtual tuning is based on a similar process as executed in reality
• Perception of sound in small spaces is related to sound power
  – Localized sound power method (E. Geddes and H. Blind, 1986)
• Array of six microphones for approximation of sound power based on spatial average of sound pressure
• “Local” means proximity of listener
  – Location of mics covers the “99% ear ellipsoid”
    • Zone where 99% of the listener’s ears are located
• Multiphysical simulation of room impulse response is used as a virtual measurement for sound power
Virtual Tuning

- Virtual tuning means real-time tuning based on virtual measurements
  - For each channel individually
    - Filters (equalization)
    - Changes in channel gain
    - Channel delays
  - Summation of all channels
    - At specific seating location
- Virtual tuning delivers a basis for a decision if hardware changes to a design (packaging/integration) need to be applied or software (tuning) can be used
Auralization

• The virtual measurement is enriched by major psychoacoustic features for a realistic listening experience in the virtual domain
  – Spatial effects and localization of sound is based on binaural hearing
  – Binaural cues, because of diffraction of incident sound waves on head and torso, are added to the virtual measurement
    • Head-related-transfer-Function HRTF
Auralization

- Generalized HRTF’s
  - Analytical model with simplified geometry
- Rigid sphere is used as head model
  - Closed form solution for an efficient approximation of left and right HRTF due to time and level differences
- 3D model
  - Varies horizontally (azimuth) and vertically (elevation)
- Applied to simulated room impulse response at ear locations
  - Time difference between left and right ear is based on 3D multiphysical simulation leading to more natural listening experience
• Finally, a VR-like audio environment for real-time virtual sound tunings and listening tests of audio systems is realized
• Opens the possibility for assessing the sound quality in the early concept phase, long before any hardware exists
Multidisciplinary Virtual Environment

- Industrial Design
- Binaural Audio
- Multiphysical Engineering Analysis
- Psychoacoustics & Subjective Evaluation
- Digital Signal Processing
- Sound Tuning