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The Use of Equivalent Source Models for Reduced Order Simulation in Room Acoustics

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Motivation

□ Room Acoustics with Source of Finite Size

Available techniques are not suitable for a fast and accurate room acoustics simulations of finite-size sources

Sound prediction of a flat screen TV:

- Not point sources
- Arbitrary room shapes
- Fast

Traditional Methods:

- Ray Tracing
- Image Source Model (hybrid)
- BEM/FEM

□ The Use of Equivalent Source Models (ESM)

ESM in General:

ESM in Room Acoustics

□ Sound Field Components in Room Acoustics

□ Free-space ESM vs. Room Acoustics ESM

Boundary Conditions

□ BC of the Room Components in Room Acoustics

○ BC on source surface, Γ_1 , (admittance β_1):

Total: $\beta_1(x)p_t(x) + u_0(x) = u_{nt}(x)$

Free-space: $\beta_1(x)p_f(x) + u_0(x) = u_{nf}(x)$

In-vacuo driving velocity on the source surface. (source characteristics)

○ BC on room surface, Γ_2 , (admittance β_2):

Total: $\beta_2(x)p_t(x) = u_{nt}(x)$

Total sound field:

$$\begin{cases} p_t = p_f + p_r \\ \vec{u}_t = \vec{u}_f + \vec{u}_r \end{cases}$$

Boundary conditions used in the room acoustics ESM:

$$\begin{cases} \beta_1(x)p_r(x) - u_{nr}(x) = 0 & x \in \Gamma_1 \\ \beta_2(x)p_r(x) - u_{nr}(x) = u_{nf}(x) - \beta_2(x)p_f(x) & x \in \Gamma_2 \end{cases}$$

The problem of room acoustics:

Given: p_f, u_f ; Calculate: p_r, u_r

Construction of ESM in General

□ General Procedure of Constructing Room Acoustics ESM

After choose the type of equivalent sources:

$$\begin{cases} p(x) = \sum_{i=1}^N g_i(x, y_i) Q_i, \\ \vec{u}(x) = \frac{1}{j\omega\rho_0} \sum_{i=1}^N \vec{\nabla} g_i(x, y_i) Q_i, \end{cases}$$

- $g_i(x, y_i)$ – sound field of source with unit strength
- Q_i – the source strength

Location in the sound field

Location of each source

Matrix form used to estimate the ESM parameters:

$$\begin{bmatrix} B_1 A_p^{(1)} - A_{u_n}^{(1)} \\ B_2 A_p^{(2)} - A_{u_n}^{(2)} \end{bmatrix} \vec{Q} = \begin{bmatrix} 0 \\ \vec{u}_{nf} - B_2 \vec{p}_f \end{bmatrix}$$

→ Boundary condition on source surfaces

→ Boundary condition on room surfaces

Evaluate P and u_n at a number of sampling locations on both source and room surfaces

$$\begin{cases} B_1 = \text{diag}(\beta_1(x_1), \beta_1(x_2), \dots, \beta_1(x_{M_1})), \\ B_2 = \text{diag}(\beta_2(x_{M_1+1}), \beta_2(x_{M_1+2}), \dots, \beta_2(x_M)) \\ (A_p^{(1)})_{ij} = g_j(x_i, y_j), & (A_{u_n}^{(1)})_{ij} = \frac{1}{j\omega\rho_0} \partial_n g_j(x_i, y_j), \\ (A_p^{(2)})_{ij} = g_j(x_{M_1+i}, y_j), & (A_{u_n}^{(2)})_{ij} = \frac{1}{j\omega\rho_0} \partial_n g_j(x_{M_1+i}, y_j), \end{cases}$$

Construct a specific ESM
(find the sound field expression)

Two Types of ESMs

□ Room Acoustics ESM Using Monopole Distributions

- Monopoles are distributed inside the source surface (outgoing wave) and outside the room surface (incoming wave)
- Sound field expression (2D):

$$g(x, y) = \frac{j}{4} H_0^{(1)}(kr)$$

□ Room Acoustics ESM Using Monopole Distributions

- Multipoles of monopole, dipole, quadrupole, ... n th order, ... (both incoming and outgoing)
- Sound field expression (2D):

$$n = 0: \quad P_0^{out}(x, y) = \frac{j}{4} H_0^{(1)}(kr), \quad P_0^{in}(x, y) = \frac{j}{4} H_0^{(2)}(kr)$$

$$n \text{ th order: } \begin{cases} P_{Sn}^{out} = S_n P_n^{out} = S_n R_n(P_0^{out}) \cdot \vec{v}_1 \cdot \vec{v}_2 \dots \vec{v}_n \\ P_{Sn}^{in} = S_n P_n^{in} = S_n R_n(P_0^{in}) \cdot \vec{v}_1 \cdot \vec{v}_2 \dots \vec{v}_n \end{cases},$$

$$R_n = \nabla^{\otimes n}$$

⊗ – tensor outer product
· – tensor inner product

Details on next slide

Sound field of Multipole Sources

□ Sound field expression for multipole sources (2D):

Sound field of order $n + 1$ source and order n source can be related by directional derivative:

$$P_{Sn+1}(\vec{X}|\vec{X}_0, \omega) = d \langle \nabla P_{Sn}(\vec{X}|\vec{X}_0, \omega), \vec{v}_{n+1} \rangle$$

$$= d \left\langle \left[\frac{\partial P_{Sn}(\vec{X}|\vec{X}_0, \omega)}{\partial x_0}, \frac{\partial P_{Sn}(\vec{X}|\vec{X}_0, \omega)}{\partial y_0} \right]^T, \vec{v}_{n+1} \right\rangle$$

Dipole: $P_{S1} = S d_1 \langle \nabla P_0, \vec{v}_1 \rangle,$

Dipole strength: $S d_1$

Quadrupole: $P_{S2} = S d_1 d_2 \vec{v}_2^T R_2 \vec{v}_1,$

Quadrupole strength: $S d_1 d_2$

$$\begin{bmatrix} \frac{\partial^2 P_0}{\partial x^2} & \frac{\partial^2 P_0}{\partial x \partial y} \\ \frac{\partial^2 P_0}{\partial y \partial x} & \frac{\partial^2 P_0}{\partial y^2} \end{bmatrix}$$

Order n:

$$P_{Sn} = Q_n g_n$$

Source strength:

$$Q_n = S d_1 d_2 \dots d_n$$

$$g_n = R_n(P_0) \cdot \vec{v}_1 \cdot \vec{v}_2 \dots \vec{v}_n,$$

$$R_n = \nabla^{\otimes n}$$

⊗ - tensor outer product

• - tensor inner product

Decomposition of the Multipoles

- For a source of order n ($n > 1$), there could be infinitely many types because of the orientation vectors.

- How many independent elements?

n th order source, in r -D space :

$$N(n, r) = \begin{cases} 1 & , \quad n = 0 \\ C_{n+r-1}^n & , \quad n > 0 \end{cases}$$

- Can be numerically enumerated for an arbitrary n .

Simulation Setup

□ Simulation in a 2 dimensional room (circular geometry)

Geometry of the room

- $R_1 = 0.5$ m (source surface),
- $R_2 = 2$ m (room surface),
- $r_1 = 1$ m (100 microphones) ,
- $r_2 = 1.5$ m (100 microphones).

Normal impedance on different surfaces

Non-uniform

In-vacuo Driving velocity on the source surface

Models Used in Simulations

□ Different models used in the simulation

Type of ESM	Number of Parameters
Multipole ESM (order up to 3)	10
Multipole ESM (order up to 6)	28
Monopole ESM (outside: 100; inside: 30)	130
Monopole ESM (outside: 150; inside: 45)	195
Monopole ESM (outside: 200; inside: 60)	260
Monopole ESM (outside: 1000; inside: 300)	1300

- Result from a Boundary Element Model was used as the true sound field.

□ Choice of regularization techniques

Use TSVD for
multipole ESM

Use GCV for
monopole ESM

Singular value distribution in monopole ESMs

Singular value distribution in multipole ESMs

Analysis of Results

□ Results from monopole distribution ESMs

Spatially averaged prediction from monopole ESMs

Spatially averaged prediction from monopole ESMs

-
- Accurate (up to 5000 Hz) if there are a large number of monopoles and with regularization.
 - Regularization may cause instabilities.

Analysis of Results

□ Results from monopole distribution ESMs

Prediction from monopole ESMs at 2000 Hz

Prediction from monopole ESMs at 4000 Hz

-
- A monopole ESM requires at least 260 model parameters to achieve accurate predictions.

Analysis of Results

□ Results from multipole ESMs

- Regularization does not cause instabilities (more robust).
- The spatially averaged predictions are similar with different multipole orders (accurate up to 5000 Hz).
- Multipole ESM requires much fewer number of model parameters than monopole ESM

Spatially averaged prediction from multipole ESMs

Analysis of Results

Results from multipole ESMs

Prediction from multipole ESMs at 2000 Hz

Prediction from multipole ESMs at 4000 Hz

-
- Increase of multipole order improves the prediction oscillation in space.
 - It is flexible to balance the computational effort and the prediction accuracy. (choose an appropriate truncation order)

Conclusions

- ❑ Equivalent source models are constructed for room acoustics simulations with finite-size source, arbitrary geometry and non-uniform surface normal impedances.
- ❑ In room acoustics ESMs, both outgoing and incoming waves should be included, and the impedance boundary conditions for the room component sound field are used for parameter estimation.
- ❑ Both monopole ESMs and multipole ESMs can achieve accurate performance up to 5000 Hz, but the multipole ESM requires fewer model parameters and is more robust.
- ❑ When using multipole ESM, there is a flexible balance between the computational effort and the prediction accuracy, controlled by choosing an appropriate truncation order.

Thank You!