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ITM-Based FSI-Models for Rooms with Absorptive Boundaries

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Abstract

Models for Fluid Structure Interaction (FSI) in room acoustical calculations are used in many different fields of engineering like automotive industry or civil engineering. For simulations of the spatial resolution of the sound field within acoustic cavities very often techniques based on Finite Element formulations are used.

In order to reduce the number of degrees of freedom and therefore the numerical effort, a model reduction method, based on a Component Mode Synthesis (CMS), is applied in this thesis. Macrostructures are assembled out of single substructures applying shape functions at the interfaces. These substructures contain acoustic components like absorbers or resonators. They are calculated separately in the frame of the CMS approach. The acoustic fluid is modeled with the Spectral Finite Element Method (SFEM) and coupled with plate-like compound absorbers at the interfaces via wavenumber- and frequency-dependent impedances using *Hamilton*'s Principle and a *Ritz* approach, where phase correct coupling conditions are ensured. The porous foam in the absorber is modeled with the Theory of Porous Media (TPM) and the impedances are calculated with the help of the Integral Transform Method (ITM).

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To my family I would like to thank for their patience with me during the final stages of writing this thesis.

dedicated to
Sabine and Maximilian

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Table of Symbols

General

λ	[m]	wavelength
ω	[rad/s]	natural circular frequency
Ω	[rad/s]	circular frequency of excitation
k_x, k_y	[rad/m]	wavenumbers in x- and y-direction
$Z(k_x, k_y, \Omega)$	[Ns/(m^3)]	wave impedance
U	[Nm]	potential energy
T	[Nm]	kinetic energy
L	[Nm]	Lagrangian
c	[Nm/s]	damping coefficient
D^{Lehr}	[$-$]	damping ratio
η^D	[$-$]	damping loss factor
A - E	[$-$]	coefficients in the formulation of the absorber
$\mathscr{A}$ - $\mathscr{D}$	[$-$]	abbreviations in the formulation of the absorber
$\mathcal{A}$ - $\mathcal{C}$	[$-$]	coefficients in the FSI-formulation

Technical Acoustics/FSI

ρ_A	[kg/m^3]	density of the air	$\left(\rho_A = 1.204\,\frac{kg}{m^3}\text{ at }20°\text{C}\right)$
c_A	[m/s]	speed of sound of the air	$\left(c_A = 343.4\,\frac{m}{s}\text{ at }20°\text{C}\right)$
k_A	[rad/m]	wavenumber in the air	
Z_0	[Ns/(m^3)]	plane wave impedance	$\left(Z_0 = 413.5\,\frac{Ns}{m^3}\text{ at }20°\text{C}\right)$
r	[$-$]	reflection factor	
α	[$-$]	absorption coefficient	
ϱ	[$-$]	reflection coefficient	
δ	[$-$]	dissipation coefficient	

$\boldsymbol{\lambda}$		vector of *Lagrange* multipliers
Φ_A	[m^2/s]	velocity potential in the acoustic fluid
$\mathbf{v}_A$	[m/s]	velocity in the acoustic fluid
$\mathbf{u}_A$	[m]	displacement in the acoustic fluid
p_A	[N/m^2]	pressure in the acoustic fluid
$\hat{\Phi}_A$	[m^2/s]	velocity potential in the *Fourier*-domain
$\hat{\mathbf{v}}_A$	[m/s]	velocity in the *Fourier*-domain
$\hat{\mathbf{u}}_A$	[m]	displacement in the *Fourier*-domain
$\hat{p}_A$	[N/m^2]	pressure in the *Fourier*-domain
$\psi_n(y,z)$		trial function for the absorber
$\hat{\psi}_n(y,z)$		*Fourier* approximation of $\psi_n(y,z)$

Theory of Porous Media

ϕ_α		denotes the constituent α ($\alpha = S$ for the solid- and $\alpha = G$ for the gas-phase)
dv_α	[m^3]	partial volume element of the constituent α
dv	[m^3]	total volume element
B_α		domain of the constituent α
n_α	[−]	volume fraction of the constituent α
$\rho_{\alpha R}$	[kg/m^3]	macroscopic real density
ρ_α	[kg/m^3]	macroscopic partial density
$\mathbf{x}$	[m]	position vector in the actual configuration
$\mathbf{X}$	[m]	position vector in the reference configuration
$\boldsymbol{\chi}_\alpha$		function of placements
$(\dots)'$		material time derivative
$\mathbf{u}_\alpha$	[m]	displacement of the constituent α
$\mathbf{v}_\alpha$	[m/s]	velocity of the constituent α
$\mathbf{a}_\alpha$	[m/s^2]	acceleration of the constituent α
$\mathbf{w}$	[m/s]	seepage velocity between the phases
$\mathbf{w}_F$	[m/s]	filter velocity
$\hat{\mathbf{u}}_\alpha$	[m]	displacements in the *Fourier*-domain
$\hat{\mathbf{v}}_\alpha$	[m/s]	velocities in the *Fourier*-domain
g	[m/s^2]	gravitational acceleration
Φ_α	[m^2]	scalar potential for the displacement field
$\boldsymbol{\Psi}_\alpha$	[m^2]	vector potential for the displacement field

$\hat{\Phi}_\alpha$	$[m^2]$	scalar potential in the *Fourier*-domain
$\hat{\mathbf{\Psi}}_\alpha$	$[m^2]$	vector potential in the *Fourier*-domain
k_x, k_y	[rad/m]	wavenumbers
k_{11}, k_{12}	[rad/m]	wavenumbers of the compressional waves
k_2	[rad/m]	wavenumber of the shear wave
$\mathbf{F}_\alpha$	[−]	deformation gradient
$\mathbf{H}_\alpha$	[−]	displacement gradient
$\mathbf{C}_\alpha$	[m]	right *Cauchy-Green* deformation tensor
$\mathbf{B}_\alpha$	[m]	left *Cauchy-Green* deformation tensor
$\mathbf{E}_\alpha$	[−]	*Green* strain tensor
$\mathbf{A}_\alpha$	[−]	*Almansi* strain tensor
e_S	[−]	volumetric strain of the solid component
e_{SR}	[−]	part of e_S belonging to the real material
e_{SN}	[−]	part of e_S belonging to the change of pores
$\mathbf{T}_\alpha$	$[N/m^2]$	*Piola-Kirchhoff* stress tensor of the constituent α
$\mathbf{T}_\alpha^E$	$[N/m^2]$	tensor of effective stresses of the constituent α
$\mathbf{T}_S^D$	$[N/m^2]$	deviatoric part of the stress tensor
$\hat{\mathbf{T}}_\alpha$	$[N/m^2]$	*Piola-Kirchhoff* stress tensor in the *Fourier*-domain
σ_α, τ_α	$[N/m^2]$	physical normal and shear stresses
$\hat{\sigma}_\alpha$, $\hat{\tau}_\alpha$	$[N/m^2]$	physical stresses in the *Fourier*-domain
$\tilde{\lambda}_S$	$[N/m^2]$	1^{st} macroscopic *Lamé* constant
μ_S	$[N/m^2]$	2^{nd} macroscopic *Lamé* constant
$\tilde{\lambda}_S^c$, μ_S^c	$[N/m^2]$	complex macroscopic *Lamé* constants
p	$[N/m^2]$	pore pressure
$\hat{p}$	$[N/m^2]$	pore pressure in the *Fourier*-domain
p_α^E	$[N/m^2]$	effective stresses of the constituent α
p_α	$[N/m^2]$	partial hydrostatic stresses of the constituent α
K_{SR}	$[N/m^2]$	compression modulus of the real solid material
K_{SN}	$[N/m^2]$	compression modulus of the solid skeleton
$\widehat{p}_\alpha^E$	$[N/m^3]$	interaction forces between the constituents
$\mathbf{S}_G$	$[Ns/m^4]$	permeability tensor
γ_{GR}	$[N/m^3]$	effective fluid weight
k^G	[m/s]	*Darcy* flow coefficient
K^G	$[m^4/(Ns)]$	specific permeability/conventional saturated permeability

K^S	$[\mathrm{m}^2]$	intrinsic permeability
η_G	$[\mathrm{Ns/m}^2]$	partial dynamic fluid viscosity
η_{GR}	$[\mathrm{Ns/m}^2]$	effective dynamic fluid viscosity
Ξ	$[\mathrm{Ns/m}^4]$	specific flow resistance $\left(1\,\frac{Rayl}{cm} = 10^3\,\frac{Ns}{m^4}\right)$
θ	[K]	temperature
R	$[\mathrm{J/(kg\,K)}]$	specific gas constant ($R = 287.058$ for dry air)

Theory of Elasticity

ρ_H	$[\mathrm{kg/m}^3]$	density of the elastic material
$\mathbf{u}_H$	[m]	displacement vector for the elastic material
$\mathbf{v}_H$	[m/s]	velocity
$\mathbf{a}_H$	$[\mathrm{m/s}^2]$	acceleration
$\hat{\mathbf{u}}_H$	[m]	displacements in the *Fourier*-domain
$\hat{\mathbf{v}}_H$	[m/s]	velocities in the *Fourier*-domain
Φ_H	$[\mathrm{m}^2]$	scalar potential for the displacement field
$\mathbf{\Psi}_H$	$[\mathrm{m}^2]$	vector potential for the displacement field
$\hat{\Phi}_H$	$[\mathrm{m}^2]$	scalar potential in the *Fourier*-domain
$\hat{\mathbf{\Psi}}_H$	$[\mathrm{m}^2]$	vector potential in the *Fourier*-domain
k_x, k_y	[rad/m]	wavenumbers
k_3, k_4	[rad/m]	wavenumbers of the compressional and the shear wave
k_r	[rad/m]	circular wavenumber
$\mathbf{E}_H$	[−]	*Green* strain tensor
$\mathbf{T}_H$	$[\mathrm{N/m}^2]$	*Piola-Kirchhoff* stress tensor for the elastic material
$\hat{\mathbf{T}}_H$	$[\mathrm{N/m}^2]$	*Piola-Kirchhoff* stress tensor in the *Fourier*-domain
σ_H, τ_H	$[\mathrm{N/m}^2]$	physical normal and shear stresses
$\hat{\sigma}_H$, $\hat{\tau}_H$	$[\mathrm{N/m}^2]$	physical stresses in the *Fourier*-domain
λ_H	$[\mathrm{N/m}^2]$	1^{st} *Lamé* constant of the elastic material
μ_H	$[\mathrm{N/m}^2]$	2^{nd} *Lamé* constant of the elastic material

Acronyms

BEM	Boundary Element Method
BT	Biot's Theory
CMS	Component Mode Synthesis
EFEM	Energy Finite Element Method
FEM	Finite Element Method
FSI	Fluid-Structure Interaction
FRF	Frequency Response Function
HBEM	Hybrid Boundary Element Method
IRF	Impulse Response Function
ITM	Integral Transform Method
SFEM	Spectral Finite Element Method
SM	Spectral Method
TPM	Theory of Porous Media