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Mohamed Bouhaj

Experimental identification of SEA parameters for complex aircraft structures

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Institut für Modellierung und Berechnung

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Prof. Dr.-Ing. Otto von Estorff

Technische Universität Hamburg
Institut für Modellierung und Berechnung
Denickestraße 17
21073 Hamburg

Telefon: 040/42878-3032
Fax: 040/42878-4353
E-Mail: estorff@tuhh.de
Internet: http://www.tuhh.de/mub

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Hamburg, February 2020 Mohamed Bouhaj

Abstract

The **S**tatistical **E**nergy **A**nalysis (SEA) is a widely used tool for the vibro-acoustic analysis of dynamical systems in the high frequency regime. In the application of SEA to complex assembled structures, a purely predictive model often exhibits errors, which are mainly due to a lack of accurate modelling of the power transmitted between subsystems and the power dissipated by each of them. The description of the power terms and the SEA equations depend essentially on two key parameters: The coupling loss factor (CLF) and the damping loss factor (DLF).
This thesis is included in the framework of Experimental SEA (ESEA) and aims at providing reliable input parameters to an SEA representation of complex systems, as well as procedures that allow a statistical description of these parameters.
A new stochastic energy model (SEM) is adopted to enhance the estimation of structural loss factors and assess their sensitivity to subsystems energy variance. For this purpose, expressions are obtained to randomly perturb the energy matrix elements and generate individual samples for the Monte Carlo (MC) technique applied to derive the ensemble averaged CLF. The method is firstly applied to an academic example of two rigid coupled plates, then to a more complex aircraft fuselage section. The results indicate that the SEM approach has the potential to significantly enhance the CLF estimate compared to classical matrix inversion methods. Moreover, the new derived sensitivity criterion gives the opportunity to guide the selection of SEA subsystems.
A complementary topic of this dissertation concerns the experimental determination of the damping loss factor of single isotropic plates, built-up aircraft structures and trim panels using the power injection method and the decay rate technique. The significance of the radiation loss and its impact on the derived DLF of the cabin components is addressed. The installation effect on estimated damping is elaborated by comparing measured levels in the semi-anechoic room with freely suspended cabin panels and in the aircraft with fully installed components. Finally, some conclusions are drawn about the frequency ranges, in which the respective procedures can be used.

keywords: Statistical Energy Analysis (SEA), experimental SEA, noise, vibro-acoustics, coupling loss factor, damping loss factor, power injection method, uncertainty, Monte Carlo (MC) method

Zusammenfassung

Die statistische Energieanalyse (SEA) ist eine weit verbreitete Methode für die Vorhersage von Lärm- und Vibrationspegeln im mittleren und hohen Frequenzbereich. Bei der SEA wird die Gesamtstruktur in schwach gekoppelte Substrukturen unterteilt. Die Beschreibung des Energietransfers zwischen den Subsystemen ist abhängig von den jeweiligen Kopplungsverlustfaktoren. Der Grad der Dissipationsenergie der Subsysteme wird durch Dämpfungsverlustfaktoren angegeben. Diese Faktoren bilden zusammen mit der modalen Dichte die wichtigsten SEA Parameter.
Validierte SEA Modelle von komplexen Systemen erfordern sowohl eine genaue Modellierung der Energietransmission zwischen den gekoppelten Subsystemen, als auch der dissipierten Leistungen. Daher liegt die größte Herausforderung der SEA in der Bestimmung der zuvor erwähnten Verlustfaktoren und der damit verbundenen Parameterunsicherheiten.
Die vorliegende Arbeit gibt einen Überblick über die vorhandenen Ansätze zur experimentellen Bestimmung der SEA Parameter und untersucht die Verfahrensgrenzen insbesondere bei der Anwendung in komplexen Flugzeugstrukturen. Basis dafür bildet die Power Injection Method (PIM), die es ermöglicht den Energiefluss zwischen gekoppelten Subsystemen abzuleiten und die SEA Parameter durch Invertieren der gemessenen Energiematrix zu identifizieren.
Eine weitere Herausforderung betrifft die Unsicherheit der in der experimentellen SEA involvierten Parameter. Mit dem neuen stochastischem Energiemodell (SEM) sind Prozeduren aufgezeigt, die eine stochastische Analyse der gemessenen Eingangsgrößen (wie Eingangsleistung und Vibrationsenergien) und der abgeschätzten Ausgangsgrößen (wie Verlustfaktoren) erlauben. Experimentelle Untersuchungen an akademischen und Flugzeugstrukturen zeigen zudem die Anwendbarkeit des entwickelten Ansatzes mit realen Testdaten. Die Ergebnisse zeigen, dass das neue Modell zu einer robusten Abschätzung der SEA Parameter führt, und gibt dem Anwender die Möglichkeit geeignete SEA-Subsysteme zu definieren.
Ein weiteres Augenmerk dieser Arbeit ist auf die Bestimmung der Dämpfungsverlustfaktoren von isotropen Platten und Flugzeugstrukturen durch den Einsatz verschiedener experimentelle Verfahren gerichtet. Dabei gibt die Analyse Rückschlüsse auf das Dämpfungsverhalten der Kabinenbauteile, und ermöglicht sowohl den Einfluss der Einbaubedingungen zu untersuchen als auch Frequenzbereiche zu identifizieren, in welchen die jeweiligen Verfahren angewendet werden können.

Contents

Nomenclature

Latin nomenclature

$[a, b]$	Interval with lower and upper bounds a, b
$\mathbf{A}$	Matrix/vector (bold type)
c_0	Speed of sound
$\mathbf{D}^i_{dir}$	Direct field dynamic stiffness of the statistical subsystems
$\mathbf{D}_d$	Dynamic stiffness of the deterministic subsystems
$\mathbf{D}_{tot}$	Total dynamic stiffness of the system
$\langle E_i \rangle$	Spatial averaged vibration energy of subsystem i
$\widehat{E}$	Energy of single sensors
$E[X]$	Expected value
E_{ij}	Energy level of subsystem i when exciting subsystem j
E^n_{ij}	Normalized energy levels
E	Vector of energy levels
$\mathbf{f}^i_{rev}$	Vector of blocked forces on the deterministic interfaces due to the reverberant field
$f(x)$	Probability density function
f_c	Coincidence frequency
H_{af}	Frequency response function acceleration/force
h_{ij}	Hybrid CLF
$\mathbf{I}$	Identity matrix
$[\mathbf{K}]$	Stiffness Matrix
$\mathbf{L}$	SEA loss factor matrix
$[\mathbf{M}]$	Mass Matrix
M	Mass
n	Sample size
N	Number of subsystems
n_i	Modal density
$\widehat{P_{in}}$	Power input at single locations

$P_{i,diss}$	Dissipated power in subsystem i
$P_{i,in}$	Power input of subsystem i
P_{ij}	Net energy flow from subsystem i to subsystem j
P_{rad}	Radiated sound power
$\mathbf{S}_{ff}^{ext}$	Cross-spectral density matrix of the external forces
s	Sample variance
S_{af}	Cross spectral density of the force and acceleration
$S_{i,aa}$	Auto spectral density of the acceleration
T_R	Reverberation time
TL	Transmission loss
u_i	MC output variables
Var[X]	Variance of a random variable X
v	Vibration velocity
$\overline{x}$	Arithmetic mean of x
$\overline{x}$	Arithmetic mean of x
X	Random variable
Y_{ii}	Input mobility
Y_{ii}	Transfer mobility
Z_i	Semi-infinite input impedance

Greek nomenclature

η	Damping loss factor
η_b	Loss factor expressing damping at the boundaries of a subsystem
η_{ij}	Coupling loss factor between subsystem i and subsystem j
$\eta_i = \eta_{ii}$	Internal loss factor
η_{rad}	Acoustic radiation loss factor
η_s	Structural loss factor
$[\eta^t]$	Total loss factor matrix
σ	Radiation efficiency of the structure
Δf	Frequency bandwidth
ω	Center frequency
φ	Incidence angle
ρ_0	Air density

μ	Expected mean value, or population mean
ν	Degree of freedom parameter
$\sigma(X)$	Standard deviation
τ_{ij}	Transmission coefficient
ξ_i	MC input variables, random numbers

List of indices

$\langle ... \rangle$	Operator expressing spatial averaging
i	Index refering to the considered subsystem
j	Index refering to the excited subsystem
k	Index refering to an individual sensor
l	Index refering to an excitation location
Im(...)	Imaginary part operator
Re(...)	Real part operator

General abbreviations

A/C	Aircraft
BC	Boundary condition
BEM	Boundary Element Method
CB	Crossbeam
CI	Confidence Interval
CLF	Coupling Loss Factor
DLF	Damping Loss Factor
DRM	Decay Rate Method
ESEA	Experimental Statistic Energy Analysis
FEM	Finite Element Method
FP	Floor panel
FRF	Frequency response function
HPB	Half-Power Bandwidth
LSQI	Least Squares Minimization
MC	Monte Carlo
OHSC	Overhead stowage compartment
PDF	probability density function

PIM	Power Injection Method
RT	Reverberation time
SEA	Statistic Energy Analysis
SEM	Stochastic Energy Model
SNR	Signal Noise Ratio
SR	Seat rail
SS	Subsystem
SVD	Singular value decomposition
SWP	Sidewall panel
VSEA	Virtual SEA