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Overview

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1.1 Introduction

Structural vibrations couple with interior and exterior acoustic fields to produce sound. A vibrating structure generates sound waves in an acoustic field, and conversely, the acoustic pressure affects the structural vibration, along with stresses that may degrade structural integrity. Computational methods for solving vibration and sound problems have been an ongoing development since the early 1960s when digital computers became available. Using computers, complicated analytical formulas that were available to represent structural and acoustic solutions were then able to be solved numerically.

For complicated geometrical systems, the finite element (FE) method was developed, where any shape, source, or boundary condition could be discretized. Structural and acoustic regions may be assembled to capture waveforms and their interactions, while various boundary conditions and forcing functions are generally applied. While the FE method is commonly used to solve interior structural-acoustic problems, the boundary element (BE) method was subsequently developed, which is more suitable for solving exterior structural-acoustic problems, although it is also often used for interior acoustics.

While the FE and BE methods are generally applicable in the low-frequency range, other methods were developed that depend on the frequency range of interest and the level of uncertainty of the structural-acoustic system. These methods include statistical energy analysis (SEA), which was the first such method that was developed for application in the high-frequency range to obtain approximate and statistically relevant solutions. Subsequently, transfer path analysis (TPA), energy FE analysis (EFEA), wave-based structural modeling, among others, have been developed to solve a wide range of structural-acoustic problems [1–3].

This book describes the vibroacoustic methods that are commonly used for predicting the structural and acoustic response in sound–structure interaction applications in transportation

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vehicles and other mechanical systems. Section 1.2 gives an overview of the traditional FE, BE, and SEA vibroacoustic methods. Section 1.3 gives an overview of the alternative newer methods, hybrid FE/SEA, hybrid TPA, EFEA, and wave-based structural modeling, that have been developed. The modeling, computational, and application considerations for choosing the different methods are then described in Section 1.4, followed by an outline of the book organization in Section 1.5.

1.2 Traditional Vibroacoustic Methods

1.2.1 Finite Element Method

The FE method has been and remains the most popular numerical modeling approach. While the FE method was originally developed to simulate static deformation and stress, it was subsequently extended to model structural vibration by including mass and damping effects. The FE modeling approach was then extended to model sound waves in acoustic enclosures and the structural-acoustic interaction with vibrating structures. It is thereby applicable to solve for the structural and acoustic responses in coupled structural-acoustic systems.

The FE method has also been developed for heavy fluid–structure interaction problems in the nuclear industry and nonlinear structural-acoustic interactions in unbounded acoustic domains such as in underwater acoustics applications. Besides sound pressure response prediction in air, structural-acoustic interaction has been analyzed for acoustic pressure loading effects on structures. This interaction is especially evident in aircraft fuselage designs that sustain intense pressure pulsations during launch or repetitive turbulence pressure loading on the fuselage surface. Similarly, structural-acoustic interaction effects have been assessed for nuclear reactor designs to ensure fatigue design criteria over long lifetimes (30–50 years). More recently, structural-acoustic interactions on medical devices have drawn increased interest.

The FE method was initially implemented in the later 1970s for structural-acoustic analysis of transportation vehicle interiors, such as automobiles, aircrafts, heavy trucks, and so on. With advanced software development for modeling and solving complicated structural systems, the FE method is now commonly used in transportation vehicle interior noise analysis and design. In these applications, the FE solution is generally obtained using the normal-mode synthesis method to predict the coupled structural-acoustic response. This modal approach involves significantly fewer degrees of freedom as compared with the direct solution method and is, therefore, more computationally efficient.

In acoustic noise control, impedance boundary conditions or acoustic interior absorption materials can be modeled using the FE method. Measured material behavior or a model representation of the material is required to represent these in the FE model. Recently, the structural-acoustic wave interaction in multimedia has drawn significant interest in geoacoustics, metamaterials, electroacoustics, and medical acoustics. To solve the highly nonlinear nature of some problems, the FE method is deemed a necessary tool. Finally, developing efficient solution methods to solve large complex problems continues to be a challenging and ongoing research area.

This book mainly covers linear structural-acoustic applications in transportation vehicles and mechanical systems, although as indicated earlier there are a wide range of other structural-acoustic applications using the FE method.

1.2.2 Boundary Element Method

Instead of discretizing a mesh throughout a volume as in the FE method, the BE method decomposes the solution in the integral form only at the boundary of an acoustic region. For exterior acoustics, the traditional FE method is not usually suitable to solve radiation and scattering problems involving an unbounded region. Instead, boundary integral approaches are more direct and straightforward for such problems.

For an unbounded acoustic region in exterior acoustics, the basic solution to the acoustic wave equation that satisfies the Sommerfeld radiation boundary condition of an infinite region is the free-space acoustic Green's function. By applying the divergence theorem to the acoustic wave equation, the solution can be obtained in the form of the Helmholtz boundary integral equation or the Rayleigh boundary integral equation, which are then discretized using the BE formulation.

The acoustic BE method is also commonly applied to interior acoustics for predicting the sound pressure response resulting from structural vibrations, when the structural-acoustic interaction effect on the response can be neglected. Compared to the use of an FE model of an acoustic region, as in large interior enclosures or unbounded acoustic media, a BE model involves a much smaller mesh as only the boundary is discretized with elements. However, a computational penalty is required to solve the resulting complex fully populated matrices.

1.2.3 Statistical Energy Analysis

While many problems may be solved using simple modal summations computed by the FE method, others may be impractical due to significant number of elements or modes required. For very large structures, like aircraft or ships, it may not be possible to generate very finely meshed FE or BE models unless some form of component reduction method is employed. Even for smaller problems, FE and BE models are also impractical at high frequencies when dense meshes are needed. This is because traditional discretization techniques like FE and BE must subdivide models to the point that all structural and acoustic wavelengths are captured properly over all frequencies of interest. The most commonly cited criterion for this is to ensure at least six to eight subdivisions, or elements, represent each wavelength.

Based on the physics of high-frequency response, approximate methods have been developed which are not based on subdividing structures into small elements, but instead generalize groups of energy or waves that subdivide structural or acoustic regions into subsets. Instead of solving for the sound pressure and vibration response everywhere in a subset, a mean value of the energy response is obtained, from which spatially averaged pressure or vibration responses are calculated. The prevailing method that emerged from these developments is SEA. Instead of modeling vibration or sound directly, SEA tracks the flow of energy between groups of interconnected subsystem modes.

Here, the modal density (number of modes/frequency band) is the important parameter, with subsystems that are modally rich enjoying most of the vibroacoustic energy. Also, more modes in a subsystem result in less variation in the subsystem response. In this case, a mean energy estimate is quite accurate over the full region of the structure or acoustic subsystem, with only minor variations about that mean. As modal density increases with frequency, therefore SEA is most useful at high frequencies. At lower frequencies, however, variability about the mean response is much greater, and SEA is not as useful, particularly when an analyst is most interested in extreme response values at a particular location of interest or from a particular resonant mode.

1.3 New Vibroacoustic Methods

1.3.1 Hybrid FE/SEA Method

In the 1990s, numerical modeling experts began pointing out the so-called mid-frequency gap, where modal density is not very high, so that SEA is not as useful, but where using full FE and/or BE models is still computationally intractable. New investigations suggested various mid-frequency methods, some of which are highlighted in this book. A hybridization of the FEA and SEA methods is one where large-scale vibration is captured with FE models, and coupled to smaller-scale vibrations in connected structures. In this case, the modal response of the large-scale vibration is captured using the FE method, while only the approximated mean value of the smaller-scale vibration is predicted using the SEA method. Framed panels are a typical application to demonstrate the methodology.

1.3.2 Hybrid FE/TPA Method

Transfer path analysis (TPA) is a frequency-based transfer function analysis approach in terms of frequency-response functions (FRFs) computed from an FE model or measured experimentally. The TPA method has been used particularly in the automotive industry for the analysis of different contributions of noise and/or vibration at a particular receiver position. The classical TPA method employs the measured FRFs of the various source-receiver paths by using laboratory-controlled excitation devices. The hybrid TPA (HTPA) method combines the measured FRFs of some substructures with the predicted FRFs of the substructures that are obtained from their FE models. This method is most useful to solve problems in the mid-frequency range where validated FE, BE, or other analytical models of the substructures are not available, so that test-based methods can be used to compensate for analytical limitations and assumptions.

1.3.3 Energy FE Analysis

Energy FE analysis (EFEA) is similar to SEA in that the solution is obtained for the energy distribution in the structural or acoustic system, from which the vibration or sound pressure responses can be calculated. However, while SEA is based on the total energy within subsystems, the EFEA method is based on the derivation of the governing equation of motion in terms of the spatial distribution of energy in structural or acoustic subsystems. The result is a partial differential equation of motion similar to that of heat conduction, from which the energy solution can be obtained from an FE formulation. This provides a more detailed spatial distribution of the energy response and, thereby, more fidelity than SEA in terms of the spatial response in the structural and acoustic systems. This allows the method to be adaptable to a lower frequency range than SEA. Conventional FE models can be used for structural and acoustic analysis, which are readily adaptable to predict the energy distribution in the system. Similar to hybrid FE/SEA, the hybrid EFEA method also combines the FE and EFEA methods for application in the mid-frequency range.

1.3.4 Wave-Based Structural Analysis

Other investigators have recognized that finite elements can represent waveforms in a piecewise fashion, and the so-called spectral element formulation approach has emerged. Spectral elements are ideal for rod and beam structures, where only a few elements may be used to generate exact response throughout a model. Current research is focused on extending the method to two- and three-dimensional problems, where enforcing continuity between elements is more difficult.

1.3.5 Future Developments

There are other emerging vibroacoustic methods that continue to be developed, but none has enjoyed widespread acceptance yet. A conference devoted to noise and vibration emerging methods (NOVEM) tracks these developments, and is a recommended supplementary resource to this book. Details can be found in the NOVEM proceedings on the INCE-USA (Institute for Noise Control Engineering) electronic publications website (see www.inceusa.org).

1.4 Choosing Numerical Methods

There are three main considerations for choosing numerical methods to model structural-acoustic systems: geometrical discretization, solution frequency ranges, and the type of application.

1.4.1 Geometrical Discretization

In present-day applications, the FE method is mainly used for interior structural-acoustics, and the BE method is mainly used for exterior structural-acoustics, as well as for interior acoustics where the coupling effect of the air on the structure can be neglected. Both methods are heavily used today in practical applications, and both require detailed meshing of the structural and acoustic systems. However, with advanced computer pre-processing software, engineers can digitize complicated geometry and generate FE and BE meshes within days (or even hours). By applying boundary conditions and loads, vibration and sound anywhere in a structure or fluid are then computed. Many computer software systems can post-process enormous amounts of data output to assist engineers in examining and interpreting the results. The process is so streamlined that FE and BE are often routinely implemented as requirements in any product design cycle and will be continuously enhanced for the foreseeable future. To be consistent with the same geometry as well as to implement the same preprocessing software, SEA software has also evolved to accept FE-like meshes as inputs, while the EFEA method adapts conventional FE meshes with modified properties.

Table 1.1 Approximate frequency range, computational requirements, and model and response resolution of vibroacoustic analysis methods

Frequency range	Estimated range	Methodology	Computational requirements	Model and response resolution
Low Frequency	$0<ka<\sim 20\pi$	FE and BE	High	High
Mid Frequency	$\sim 10\pi<ka<\sim 40\pi$	Hybrid FE/SEA Hybrid FE/EFEA Hybrid FE/TPA	Mid	Mid
High Frequency	$\sim 20\pi<ka$	SEA, EFEA	Low	Low

1.4.2 Solution Frequency Ranges

Table 1.1 categorizes the various analysis methods that are applicable in the low-frequency (LF), mid-frequency (MF), and high-frequency (HF) ranges. In general, one really should not classify analysis methods purely by frequency, but instead by how many waves span a given dimension. This is done by multiplying a wavenumber k (inverse of wavelength) by a characteristic length to get a non-dimensional parameter as ka. Thus, "$ka = 2\pi$" means one full wavelength over the dimension a, "$ka = 4\pi$" means two waves and "$ka = 6\pi$" means three waves, and so on. By knowing the ka range of a specific problem, one can quickly determine appropriate numerical methods. A high ka value means a large number of waves, so that higher frequency methods like SEA and EFEA are more likely to be applicable.

Of course, for complicated structural or acoustic systems, it may be difficult to identify the appropriate wavenumber k and characteristic length a, and only rough estimates of the ka ranges can be made. In addition, there may be considerable overlap between the ranges of applicability of the methods as well as the distribution of various wave numbers in multi-coupled subsystems. This means that two or even three methods may be applicable to solve the problem, so that the results overlay in the overlapping frequency range(s). Note that Table 1.1 is only approximate, and other factors like structural damping affect the valid frequency ranges of statistical and hybrid methods.

There is also an increased development of methods that are applicable in the mid-frequency range. In particular, as supercomputing capability continues to grow, the low-frequency computational methods are being extended to the mid-frequency ranges, while the high-frequency computational methods are being enhanced to be better applicable to the mid-frequency ranges. Other newly developed methods also claim their capabilities in the mid-frequency ranges. Despite the computational capabilities or modeling details, the fundamental physics of mid-frequency problem should be fully understood before implementing an appropriate computational method.

Example 1.1

Figure 1.1 is a diagram of the sound pressure response in a vehicle travelling over a rough road. An acoustic mode of the cavity exists at approximately 50 Hz. Determine the LF, MF, and HF ranges of the cavity.

Solution

The acoustic mode of the cavity can be approximated as the first mode of a tube for which $f_1 = c/2L$. One can then evaluate ka as $ka = \omega L/c = \omega/2f_1 = 2\pi f/100$. Therefore, from

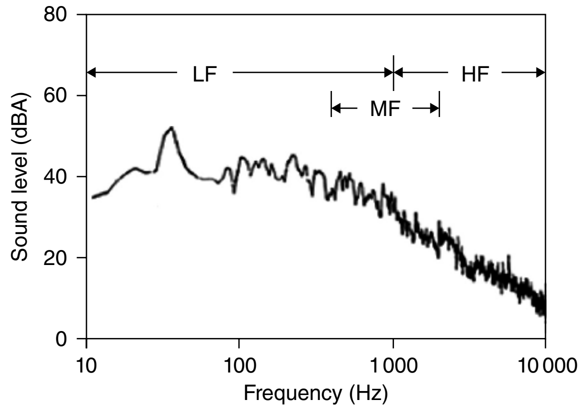

Figure 1.1 Low-frequency (LF), mid-frequency (MF), and high-frequency (HF) approximate ranges in sound-pressure-level response in an automotive vehicle passenger compartment

Table 1.1, the frequency ranges in Hertz are $20 \leq LF \leq 1000$, $500 \leq MF \leq 2000$, and $1000 \leq HF$. The FE and BE methods would apply to the acoustic cavity in the low-frequency range, and the SEA or EFEA methods would apply in the high-frequency range. In the mid-frequency range, the hybrid FE/SEA, hybrid FE/EFEA, and hybrid FE/TPA methods are applicable. The LF, MF, and HF frequency ranges are depicted in Figure 1.1. In the low-frequency range, the characteristic modal peak responses are due to a small number of modes (low-modal density). In the high-frequency range, due to the damping of the many modes (high modal density), major modal peak responses are not evident and the response decays due to the damping. In the mid-frequency range, there exists a combination of modal peak responses in the low-frequency range and the damped response in the high-frequency range. ■

1.4.3 Type of Application

The choice of modeling method also depends on the application and the response resolution that the analyst expects to obtain from the structural and acoustic solutions. The FE and BE methods require detailed modeling of the structural and acoustic systems, and they provide vibration and sound pressure-response solution information in a narrow-band form at all of the grid locations. On the other hand, the SEA and EFEA methods require much less modeling detail of the structural and acoustic systems, and they provide broadband (typically one-third octave) solutions of the spatially averaged energy response, from which the frequency averaged and spatially averaged vibration and sound pressure response of the subsystems are obtained.

Therefore, in applications, the FE and BE methods are most useful for diagnosis of particular modal peak response problems that occur at discrete frequencies in the low-frequency and mid-frequency ranges. On the other hand, the SEA and EFEA methods are most useful for identifying and minimizing the frequency-averaged and spatial-averaged vibration and sound pressure responses. The mid-frequency methods (hybrid FE/SEA, hybrid FE/EFEA) provide a combination of the detailed modal information and averaged response information. The hybrid TPA method provides narrow-band response, but it requires measured FRFs to be obtained.

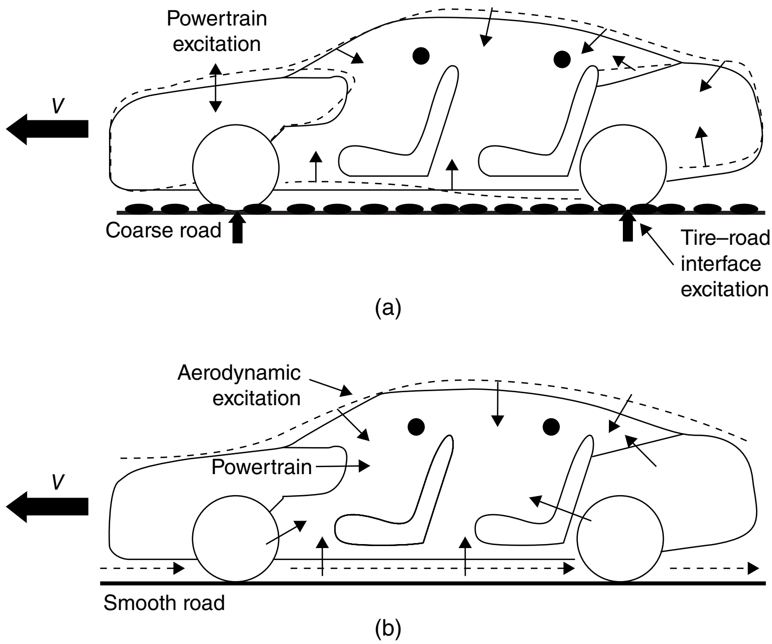

Figure 1.2 Road noise sources in vehicle traveling at speed *V*: (a) Structure-borne noise in vehicle traveling on coarse road and (b) airborne noise in vehicle travelling on smooth road

Example 1.2

Figure 1.2 shows the interior road noise in a vehicle traveling at constant speed (a) on a coarse road and (b) on a smooth road. The interior noise in the vehicle results from a combination of structure-borne noise and airborne noise. The structure-borne noise results from body panel vibrations that are excited by dynamic loads either from road excitation or from powertrain excitation, as in Figure 1.2a. For these types of noise sources, harmonic response in the low-frequency range is of interest where modal density is low and modal-phase interaction is important. The design changes may involve detailed structural architecture modification that would require FE models to optimize the design.

The airborne noise results from body panel vibrations that are excited by pressure loads acting on the panels from either the airflow excitations around the vehicle or from the radiated pressures from the powertrain and tires, as in Figure 1.2b. For these types of noise sources, broadband response in the high frequency is of interest where modal density is high and modal-phase interaction is no longer relevant. The design changes may only involve add-on treatments, such as damping layers or mass backings on the panels so that SEA or EFEA would be more efficient to analyze the trade-off designs.

Before choosing an appropriate numerical method, one needs to understand the physics of the problem and the expectation of the solution for vibration and noise reduction.

1.5 Chapter Organization

The chapter organization starts by providing the basics of vibration and sound in Chapters 2 and 3, followed by the fundamentals of sound–structure interaction in Chapter 4. A firm understanding of this background is required before studying vibroacoustic methods and applications in the remaining chapters of the book.

Chapter 5 introduces the modal synthesis method of structural-acoustic system to analyze structural-acoustic modal interaction that couples vibrational and acoustic systems. Modes are coupled in multi-structural systems by connections of the substructures, as well as in multiple-acoustic systems by the presence of absorption materials on the boundaries or within the acoustic regions. The subsystem coupling depends on the similarity of the mode shapes at the junction and mating surfaces.

The detailed modeling methods, FE and BE, are described in Chapters 6 and 7. Extensions to FE/BE modeling to assess vibration and sound reductions due to added noise control materials such as elastomers and rubber are provided in Chapter 8. Automated methods for modifying structural designs to optimize noise and vibration reduction are outlined in Chapter 9.

Chapter 10 introduces an important concept, namely nearly all structures vary slightly due to material and/or manufacturing differences and uncertainties. Therefore, a numerical model should be considered as only a single instance of a statistical ensemble of realizations. The methods in Chapter 10 enable evaluating uncertainty bounds in numerical model simulations.

The SEA method is introduced in Chapter 11, and it has much in common with uncertainty analysis, as it assumes averaged coupling between groups of modes. Randomness in this coupling is assumed in the formulation, and SEA solutions are mainly to provide the averaged response over space and time (or frequency band).

The remainder of the book is devoted to advanced and emerging methods, many of which address the mid-frequency analysis range. The hybrid FE/SEA methods in Chapter 12 combines the SEA and FE methods, where FE models represent global modal response, and the SEA models represent a superimposed local statistical response on the global behavior.

In Chapter 13, the HTPA is presented which combines FE-based or test-based frequency-response functions with FE-based or test-based operating powertrain loads.

In Chapter 14, the EFEA method is described where an FE model is used to represent localized designs in more detail than SEA and to capture local distributions and interactions. Conventional FE models are then used to obtain the predicted vibration and acoustic response.

Finally, Chapter 15 presents the basics of wave-based structural modeling, using exact spectral elements to represent the wave forms of simple structure such as beams and rods.

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