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Vibro-Acoustics of Plates and Shells — A Review

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Abstract: This is a review of the state-art in vibro-acoustics of plates and shells that include theoretical background, analytical and numerical modelling methods, experimental methods, material and structural development (composites, sandwich, functionally graded and metamaterials), fluid-structure interaction, and aerospace, marine, automotive and architectural acoustics. The critical issues and research opportunities are given such as multi-scale modelling, uncertainty quantification, inverse problems, and new metamaterial-based sound control. The review refers to the classic literature and to the latest studies as to give a consistent roadmap to people who work or want to work in this area.

Keywords: vibro-acoustics, plates, shells, fluid-structure interaction, acoustic radiation, composite panels, metamaterials

1. Introduction: Plates and shells represent common structural components found in the engineering systems - aircraft fuselages and ship hulls, cars and car bodies, and architectural facades. Noise control, structural health monitoring, and design of aeroacoustics and underwater acoustics are concerned with their vibrational behavior and the resulting acoustic radiation (vibro-acoustics). The analytical theory, computational modeling, and experimental methods have been developed over the recent decades. The review is intended to combine classical theory and current advances (composite materials, metamaterials, new numerical methods) as a concise referenced source of information to graduate students and researchers.

Organization of the review: Section 2 summarizes equations governing and classical plate and shell theories; Section 3 summarizes modelling (analytical, semi-analytical, numerical); Section 4 summarizes fluid-structure coupling and acoustic radiation; Section 5 summarizes material and structural innovations; Section 6 summarizes experimental methods and validation; Section 7 summarizes applications and Section 8 identifies challenges and future directions; Section 9 concludes.

2. Theoretical foundations

2.1 Classical plate and shell theories

The Kirchhoff-Love (classical plate theory) (describing the behaviour of thin non-shear-deformable plates) and Reissner-Mindlin (first-order shear deformation) (describing the behaviour of moderately thick plates in which transverse shear is important) are commonly used to describe the behaviour of thin plates. Shells introduce both curvature and coupling between bending and membrane, and some higher-order shell theories of shear deformation have been presented: shallow shells (Donnelly-Mushtari-Vlasov), and thick shells or composite shells (higher-order shear deformation). They give the equations of motion of transverse (and certain formulations in-plane) displacements; canonical (simply supported, clamped, free) boundary conditions have their modal solutions, which give the natural frequencies and modes shapes used in the vibro-acoustic analysis.

2.2 Governing equations for coupled vibro-acoustic problems

The vibro-acoustic problem is the coupling of the elastodynamic structural equations with that of the acoustic wave equation in the surrounding fluid (typically linear, homogeneous, inviscid compressible fluid). Coupled boundary conditions are obtained at the fluid-structure interface as a result of the application of kinematic and dynamic continuity conditions (pressure traction balance and normal velocity continuity). The coupled systems are solved by analytical techniques (modal expansions, Rayleigh integrals) and by numerical techniques (FEM, BEM, FEMBEM coupling).

2.3 Key physical phenomena

Acoustic radiation efficiency: the efficiency with which structural modes radiate sound to the fluid; depends on the modal wavelength compared to acoustic wavelengths as well as on radiation ratios.

Flanking and transmission: when buildings are a part of a complex assembly sound transmission and flanking paths are important.

Fluid loading: when adding mass and damping in water or heavy fluids, the modal frequencies and response are very sensitive to the added mass and damping.

3. Modelling approaches

3.1 Analytical and semi-analytical methods

In canonical geometries and boundary conditions, insight and rapid calculations can be gained by using analytical solutions (e.g. modal expansions, orthogonal function series, spectral methods). The integral proposed by Rayleigh is used to relate plate surface velocity fields to the radiated sound; this is very useful in computing the far-field radiations of measured or calculated velocity fields.

Semi-analytical procedures (e.g. Chebyshev spectral methods, Galerkin methods) generalize analytical methods to higher complexity in terms of boundary conditions and orthotropic materials and still maintain computational efficiency.

3.2 Finite element and boundary element methods

The Finite Element Method (FEM) is the workhorse for structural vibration analysis of complex plates and shells, while the Boundary Element Method (BEM) (or acoustic BEM) is efficient for unbounded acoustic domains. Coupled FEM–BEM formulations allow solving the fluid-structure interaction with good accuracy: FEM discretizes the structure (and sometimes a near-field fluid volume) and BEM models the exterior acoustic radiation. Recent publications illustrate robust FEM–BEM coupling for plates and shells with complex boundary conditions and loading.

High-order spectral elements, isogeometric analysis, and reduced-order models are increasingly used to improve accuracy and reduce computational cost for large-scale vibro-acoustic systems.

3.3 Computational challenges and remedies

Some of the important computational challenges are dense BEM matrices with large problems, ill-conditioning around resonances, and multi-scale character (thin structural shells surrounded by thick supports or stiffeners). Standard remedies include fast multipole methods (to BEM), iterative solvers with preconditioning, domain decomposition and hybrid methods (e.g. statistical energy analysis (SEA) at high-frequency with deterministic FEM at low-frequency).

4. Fluid-structure coupling and acoustic radiation

4.1 Radiation from plates and shells

The vibrating plate acoustic radiation is dependent on the shape of structural modes and on the coincidence phenomenon - when the bending wave phase velocity is equal to acoustic wave speed - to increased radiation. In case of shells, the curvature will alter the dispersion relations, and often will lead to so-called denser modal spectra. In higher density fluids (water) modal frequencies, radiation efficiency, and added mass, radiation damping change.

4.2 Cavities and enclosure coupling

In the situation where plates/shells enclosed an enclosure (e.g., aircraft cabin, vehicle interior) then internal acoustic modes are strongly coupled to structural modes. The mode formulations and the reduced-order models (modal truncation, cavity FEM) are applied to predict the loss of insertion, transmission loss and reverberant fields.

4.3 Transmission loss and sound transmission class (STC)

Assessment of transmission loss through panels and sandwich assemblies is also the main focus of acoustic design. Simple single panels have analytical formulas; more complex systems that are based on waves and numerical calculate transmission loss with damping, poroelastic layers, and constrained-layer treatments.

5. Material and structural innovations

5.1 Composite and sandwich structures

The use of composite laminates and sandwich panels (foam or honeycomb cores) offers weight-saving and stiffness benefits, as well as vibro-acoustic tuning. Ply orientation and damping layers, as well as the core properties, have a big influence on modal behavior as well as acoustic radiation. There are a few, recent studies investigating radiation efficiency of laminated plates and techniques to minimize noise by optimization of layups.

5.2 Functionally graded materials and porous media

The porous materials and functionally graded materials bring about spatially different stiffness and mass, which allow customized dispersion and damping. These materials are especially appealing to vibro-acoustic design in which spatial grading muffles radiations or coincidence frequencies.

5.3 Metamaterials and phononic structures

Acoustic metamaterials (periodic resonant inclusions, locally resonant structures) and phononic crystals can create bandgaps can be formed by inclusions, locally resonant structure) and phononic crystals to prevent the propagation of waves and attenuate the transmission of vibrations. The recent studies have used concepts of metamaterials to plates and shells in order to come up with the low-frequency noise mitigation that is challenging to obtain with traditional materials.

5.4 Additive manufacturing and complex architectures

Architected materials and graded structures with custom dynamic behavior can be made available using 3D printing. The manufacturing variability and scale effects present additional modeling and experimental validation problems, but have positive prospects in combined vibro-acoustic control..

6. Experimental techniques and validation

6.1 Modal testing and operational modal analysis

Mode shapes and modal parameters are extracted using classical modal testing (impact hammer,shaker, laser vibrometry). Full-field maps of vibration can be monitored with non-contact laser Doppler vibrometers as well as scanning systems to drive Rayleigh-integral-based acoustic predictions.

Operational modal analysis (ambient excitation) can be used to determine modes in realistic loading conditions, without controlled excitation, and can be used to vibro-acoustically characterize an in situ object.

6.2 Acoustic measurements and beamforming

Radiating sound is measured on ana echoic and reverberant facilities and microphone arrays and beamforming and used to locate acoustic sources on complex panels and shells. Nearfield acoustical holography (NAH) can be used to reconstruct the surface velocity using the measured pressure fields and the opposite.

6.3 Coupled experiments and fluid-loading tests

Fluid-loaded response and radiation measurement is done by experiments in water tanks or aeroacoustic wind tunnels. The tests confirm fluid-structure models and nonlinearities and noise mechanisms induced by the flow.

7. Applications

7.1 Aerospace

The typical vibro-acoustic issues of aircraft fuselage and interior panels include cabin noise, panel flutter, and excitations by the fan/engine. Composite objects with light weight and sandwich constructions are popular; in vibro-acoustic optimization, the task is to reduce the noise of the cabin and satisfy the requirements of the structure.

7.2 Marine and underwater acoustics

The underwater radiation and scattering of ship hulls and submerged shells has to be examined. The effects of fluid-loading prevail and stealth (low radiated noise) is an ideal goal. Shell stiffness, additional mass and damping, and hull treatments (coatings, damping layers) are all designed to minimize far-field radiation.

7.3 Automotive and architectural acoustics

Interior noise is determined by the interaction of automotive panels, floor assemblies and glazing. Shell-like facades and roofs require environmental excitation transmitted and radiated noise to be controlled in buildings.

7.4 Musical instruments and specialized devices

Vibro-acoustic principles are the design of plates (soundboards) and shells (mandolins, guitars). In this case, tonal qualities are exploited using radiation efficiency and modal shaping.

8. Challenges and future directions

Multi-scale modelling: Intermediating between micro scale material architecture (metamaterials) and macro scale structural behaviour.

Uncertainty quantification & robust design: Modeling variability in manufacturing processes and material uncertainties and operational environment.

Inverse vibro-acoustics Source identification and control with limited measurements.

Active and Hybrid control: Combined active vibration control and passive metamaterial approaches to broadband noise suppression.

Computational efficiency: Coupled FEMBEM as well as time-domain solvers at high frequency that are scalable.

Sustainability & manufacturing integration: Adopting noise-low manufacturing designs that can be recycled.

9. Conclusion:

Vibro-acoustics of plates and shells is a well-developed but dynamically developing practice. The classical theories are still more fundamental in understanding physics and the progress in computation and experimental research allows addressing more realistic and complex systems. The current research focuses on material innovations (composites, functional-graded materials, metamaterials), and computational techniques (FEM -BEM coupling, spectral methods, reduced-order models). The future work will be based on the multi-scale integration, the uncertainty-aware design as well as the hybrid passive/active control approach.

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