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A coupled smoothed finite element method (S-FEM) for structural-acoustic analysis of shells

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ABSTRACT

In this paper, a coupled smoothed finite element method (S-FEM) is developed to deal with the structural-acoustic problems consisting of a shell configuration interacting with the fluid medium. Three-node triangular elements and four-node tetrahedral elements that can be generated automatically for any complicated geometries are adopted to discretize the problem domain. A gradient smoothing technique (GST) is introduced to perform the strain smoothing operation. The discretized system equations are obtained using the smoothed Galerkin weakform, and the numerical integration is applied over the further formed edge-based and face-based smoothing domains, respectively. To extend the edge-based smoothing operation from plate structure to shell structure, an edge coordinate system is defined local on the edges of the triangular element. Numerical examples of a cylinder cavity attached to a flexible shell and an automobile passenger compartment have been conducted to illustrate the effectiveness and accuracy of the coupled S-FEM for structural-acoustic problems.

1. Introduction

With the increasing demands on the sound quality, such as the vehicle passenger compartments and the aircraft cabins, noise in enclosures induced by the vibration of the bounding structure has becoming an important issue encountered by many engineers and acousticians. As is known to all, the noise in most cases is caused by a coupled vibrating effect between the structure and its ambient medium; therefore, the structural-acoustic interaction problems must be given full considerations in investigating the mechanism of noise emission [1,2]. Because the analytical solution is only available for problems with very simple geometry configurations [3], thus effective numerical methods have been devised to simulate the behaviors of structural-acoustic problems during the past several decades.

Generally speaking, numerical analysis of fluid–structure interaction problems involves the modeling of structure domain, acoustic fluid domain and the coupling between these two configurations. Currently, the standard finite element method (FEM) is still the most reliable and widely-used numerical tool in simulating acoustic scatting with many meaningful investigations can be found in literature reviews [4–6]. However, the FEM model suffers from the low calculating accuracy deficiency in computational acoustics due to its "overly-stiff" property. In order to overcome this drawback, researchers [7–9] then proposed the concept of equivalent mass source and analyzed the free vibration problems of a structural-acoustic coupled system. Further, a so-called energy finite element method (EFEM) was formulated by Bernhard et al. [10] to extend the standard FEM for higher frequency problems. As time went on, the nonlinear effect [11] and interface damping effect [12] were also considered by scholars when constructing the coupled system equations, which promoted the development and improvement of the finite element method in structural-acoustic studies. Based on the fundamental researches given above, abundant works on structural optimization design [13–16] have been carried out by acoustic finite element users in recent years. All these works are very meaningful and facilitated the development of structural-acoustic coupling analysis.

Another commonly used numerical approach in structural-acoustic analysis is the boundary element method (BEM). For exterior acoustic problems, the BEM shows great advantages than the standard FEM, since it allows the simulation of fields in unbounded domains and automatically satisfies the radiation condition at infinity [17–19]. By modeling the structure and fluid domains with the FEM and BEM respectively, the coupled FEM/BEM method has long been used for structural-acoustic coupling

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analysis [20,21]. In this case, the fluid domain requires only meshing on the boundary; thus the coupled FEM/BEM model uses fewer elements than the corresponding FEM/FEM model in simulating the fluid–structure interaction problems. However, it is regrettable that the coupled FEM/BEM model suffers from the lower computational efficiency due to the fully populated discretization matrix derived using global approximation [22]. To circumvent this deficiency, Schneider [23] presented a finite element (FE)/fast multipole boundary element (FMBE)-coupling method. Moreover, surface meshing in a three-dimensional (3D) domain is still a nontrivial task when employing BEM for acoustic analysis. Without a need of harassing mesh generation in the traditional FEM and BEM, a variety of boundary-type meshless methods, such as the method of fundamental solutions (MFS) [24,25], boundary collocation method (BCM) [26], boundary knot method (BKM) [27,28], boundary particle method (BPM) [29–31] and singular boundary method (SBM) [32–34], have been proposed by researchers over the past decade. These meaningful works have no requirement of domain or boundary discretization compared with the grid-based numerical methods, thus greatly expands the applicable scope of the boundary element method.

Although the above mentioned numerical approaches perform well in simulating the fluid–structure interaction problems, there still exist some ailments that need to be conquered when extending these methodologies to practical engineering applications. One is the loss of accuracy and reliability due to the pollution error caused by numerical dispersion. He et al. [35–37] proved that the "compounded" effects of differences in "stiffness" between the exact continuous system and the discretized model are the main cause for dispersion error. As is known to all, the traditional FEM model based on the standard Galerkin weakform exhibits "overly-stiff" property, which makes the numerical speed of sound propagates faster than its real value. This also means that the wave number in the FEM model is smaller than the actual one. Indeed, it is for these reasons, making the dispersion error increases dramatically for high wave number problems. So producing a proper "softened" stiffness is more effective to remove the pollution error. For this reason, a stabilized conforming nodal integration (SCNI) approach was first proposed by Chen and his co-workers [38,39], in which a constant strain smoothing operation was introduced to smooth the compatible strain field. Later, a group of smoothed finite element method (SFEM) was proposed by Liu et al. [40,41] by combining the advantages of both the finite element method and meshfree method. In their studies, the authors revealed that the SFEM can provide an ideal stiffness to the discretized model, and thus significantly improves the numerical accuracy. Driven by this meaningful property, researcher then extended the SFEM to dynamic analysis [42], plate and shell analysis [43] and acoustic analysis [44]. A general framework of the gradient smoothing technique (GST) used in SFEM can be found in [45,46]. Based on the features of the smoothing domain, different smoothed finite element methods, such as the node-based smoothed finite element method (NS-FEM) [47,48], edge-based smoothed finite element method (ES-FEM) [49,50] and face-based smoothed finite element method (FS-FEM) [51], have already been presented by scholars in recent years. Among these different numerical improvements, the ES-FEM and FS-FEM are still so far the two most reliable numerical tools, as they can provide much more accurate solutions compared with the other methodologies. Studies [52–55] have found that these two numerical algorithms possess the "close-to-exact" stiffness, which is much softer than the "overly-stiff" FEM and much stiffer than the "overly-soft" NS-FEM. Thus, it is expected that the coupled ES-FEM/FS-FEM model will work well for structural-acoustic problems.

In this work, we further formulate a coupled ES/FS-FEM formulation for the modeling and simulation of structural-acoustic problems consisting of a 2D flexible shell interacting with the 3D acoustic fluid. The structure is modeled using the ES-FEM based on the first order shear deformation theory, and the discrete shear gap method (DSG) [56] is used to eliminate the shear locking phenomenon. A set of three-node triangular elements are adopted to discretize the problem domain and linear shape functions are used to interpolate the displacement fields. The smoothed strains are reconstructed within the further formed edge-based smoothing domains along the edges of the triangular meshes and an edge coordinate system is defined local on the edges of the triangular cell for the strain smoothing operation. For the acoustic fluid, the problem domain is first discretized into a set of tetrahedral elements. Based on the faces of the tetrahedral meshes, the face-based smoothing domains are further formed, where the gradient smoothing operation and the numerical integration are performed to obtain the smoothed acoustic stiffness matrix. The generalized smoothed Galerkin weakform is then used to create the discretized system equations. Because the present formulation possesses an ideal stiffness to the coupled system, thus it can significantly improve the numerical accuracy for fluid–structure interaction problems.

This paper is organized as follows. After a short introduction to the subject of structural-acoustic coupling problem, the ES-FEM formulation for the shell structure and FS-FEM formulation for the acoustic fluid are presented in Section 2. The coupling procedures between the structure and the fluid are outlined in Section 3. In Section 4, we assess the performance of the ES/FS-FEM through two numerical cases. Some concluding remarks are made in Section 5.

2. Formulations of the S-FEM

The illustration of a typical structural-acoustic system is shown in Fig. 1, where the acoustic fluid is enclosed by a flexible shell Ω_s together with a rigid wall Γ_f, the structure domain is bounded by the essential boundary condition Γ_u and the natural boundary condition Γ_t. In order to simulate the dynamic response of the coupled system, the edge-based smoothed finite element method (ES-FEM) and face-based smoothed finite element method (FS-FEM) are employed here to model the shell and fluid domains, respectively. The detailed formulations are given as below.

2.1. Formulations of the shell structure

2.1.1. Basic formulations for a triangular shell element

Let us consider a flexible shell subjected to both membrane forces and bending moments. The middle surface of the shell is chosen as the reference plane that occupies a domain $\Omega \in R^3$ as shown in Fig. 2. Discretize the problem domain with a set of flat shell elements. The five field variables defined in the local

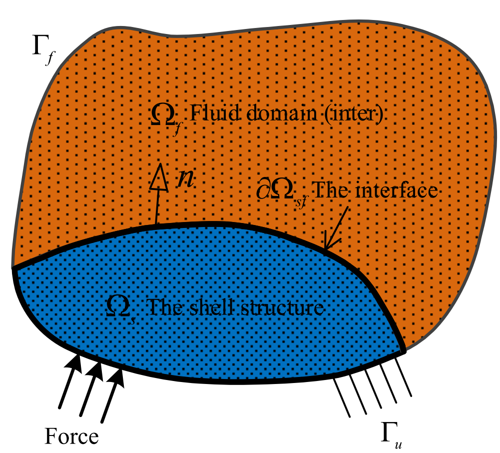

Fig. 1. Shell structure domain Ω_s coupled with acoustic fluid domain Ω_f.