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[Extended Abstract]

Numerical simulation of time domain response of an elastic surface subjected to turbulent boundary layer wall-pressure fluctuations

Sreevatsa Anantharamu, Department of Aerospace Engineering and Mechanics, University of Minnesota - Twin Cities, Minneapolis, USA

Krishnan Mahesh, Department of Aerospace Engineering and Mechanics, University of Minnesota - Twin Cities, Minneapolis, USA

Abstract

Understanding the influence of turbulent boundary layer wall-pressure fluctuations on elastic structures like propulsors and turbines is essential to reduce the acoustic radiation to far-field due to their vibration. In this paper, we will consider the coupling between turbulent boundary layer wall-pressure fluctuation and a elastic plate placed beneath it. The results of time domain response of a linear elastic plate excited by synthetically generated wall-pressure fluctuations will be presented. The technique used to generate space-time wall-pressure fluctuations given its cross-spectral density will be discussed. The plate response is obtained from an in-house developed parallel solver. The development, validation and capabilities of the developed parallel solver will also be discussed. A spatial domain technique based on Proper Orthogonal Decomposition (POD) of the cross-power spectral density of wall- pressure will be presented to analyze the coupling between wall-pressure fluctuations and the structural modes.

1. Introduction

The interaction of elastic surfaces with turbulent flows is prevalent in many applications. Two such applications are structural vibration of elastic surface due turbulent fluid loading and large structural loads during propeller crashback. Our in-house unstructured parallel flow solver MPCUGLES which uses Large Eddy Simulation (LES) technique [1] to model small scale turbulence has been shown to reasonably predict the unsteady fluid loading on propeller blades during crashback maneuver ([2, 3, 4]). A parallel structural solver is being developed which will be coupled with MPCUGLES to perform large scale fluid-structure interaction simulations. In this paper, we will discuss results of time domain response of a linear elastic plate excited by wall pressure fluctuations beneath a turbulent boundary layer. This can be seen as a first step towards understanding the coupling between flow turbulence and structures of different material properties and geometries.

Wall-pressure fluctuation beneath a boundary layer has been extensively studied theoretically, experimentally and more recently numerically. The wall-pressure fluctuations will be assumed to be stationary and homogeneous along the wall to simplify the analysis. Then, quantities like auto-spectral density (ASD) and cross-spectral density (CSD) can be used to characterize wall-pressure fluctuations. Several models for ASD [5] and CSD [6, 7] of a subsonic turbulent boundary layer have been proposed in the literature.

From Poisson-Kirchoff plate theory, the CSD of wall-pressure fluctuations can be related to CSD of plate displacements using normal-modes of vibration [8]. Such frequency domain calculations have been performed by Hambric et al. [9] and Ciappi et al. [10]. Time-domain simulations are essential as they provide a framework to perform strongly coupled fluid-structure interaction simulations which can predict the effects that structural vibrations can have on flow-turbulence for different material properties and geometries.

2. Simulation details and numerical method

Time domain response of a linear elastic plate excited by synthetically generated wall-pressure fluctuations representative of CSD at $Re_\tau = 2233$ will be numerically simulated. The dimension of the plate is 47 *cm* in streamwise and 37 *cm* in spanwise direction and plate thickness is 0.159 *cm*. The ASD of plate velocity at a point on the rectangular plate will be compared with experimental measurements of Han et al. [11].

Wall-pressure fluctuations will be generated by discrete Fourier transform with random phase angles. Let $p(x, z, t)$ denote wall pressure fluctuation at a point (x, z) on the plate at time instant t. The discrete Fourier transform $\hat{p}(k_1, k_3, \omega)$ can be related to the cross-spectral density $S_{pp}(k_1, k_3, \omega)$ by

$$\hat{p}(k_1, k_3, \omega) = \left(\sqrt{\frac{2\pi}{L_1}\frac{2\pi}{L_3}\frac{2\pi}{T}S_{pp}(k_1, k_3, \omega)}\right)e^{i\phi} \tag{1}$$

where ϕ is a uniformly distributed random number between 0 and 2π. The $\hat{p}(k_1, k_3, \omega)$ is then inverse Fourier transformed to obtain $p(x, z, t)$. The CSD and ASD of wall-pressure fluctuations is modeled by modified Corcos [12] and Smolyakov-Tkachenko [5] models respectively. The details will be discussed in the full length paper.

An in-house parallel solver is developed to solve the dynamic equations of linear elasticity using continuous Galerkin/finite element method. The parallel solver is unstructured and is developed in a generic way so as to extend later for non-linear computations and strongly coupled fluid structure interaction simulations. The validation of the solver for some canonical static and dynamic linear elasticity problems will be discussed.

The coupling between CSD of wall-pressure fluctuation and the structural modes has been theoretically discussed in literature mainly in wavenumber space. An alternative and equivalent analysis can be performed in physical space by POD of cross-spectral density. This analysis gives maximum possible values of joint acceptance of the CSD of input force by the structural modes for a given cross-spectral density and shape of elastic surface. The obtained results will be discussed with this analysis.

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