Pressure Fluctuations in the Vicinity of a Wall-Mounted Protuberance

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Objective and Background:

In order to accurately predict the structural response to a given flow field, the surface pressure distribution needs to be completely defined. This is a very difficult problem for even the simplest flat surfaces. Consider now the complexity of defining the surface pressure field on a curved surface with a surface mounted-protuberance. This is the problem facing many aerospace engineers. Examples of surface mounted protuberances are numerous; cameras, measurement probes and sensors just to name a few. One of the major problems arising from surface mounted protuberances is the treatment of the surrounding surfaces due to the high loading levels. Mathur et al. [1] studied experimentally the surface loads in the vicinity of a protuberance mounted on a large aircraft and found fluctuating pressure levels nearing the 140 dB. This magnitude of pressure levels can lead to sonic fatigue of the structures surrounding the protuberance and eventually failure. Therefore it is critical to include any surface mounted protuberances in preliminary studies and to perform shape optimization in order minimize the protuberance impact on the surrounding surfaces.

Surface pressure fluctuations are hard to measure due to the fact that so much information is needed to characterize them well; in addition transducer flushness is always an issue, Rizzi et al. [2]. This has led structural dynamics researchers and engineers to use semi-empirical models extensively to predict the structural response to a given pressure field. One of the most widely used models is the Corcos model [3]. This model is derived using experimental observations to determine the frequency and spatial dependence of the pressure field. Over the years, several improvements to the Corcos model have been proposed [4-5]. However, none of these models can address the problem of wall pressure fluctuations surrounding a protuberance. This is mainly due to the complexity of the flow field surrounding protuberances; adverse pressure gradients, flow separation and shock boundary layer interactions.

Fortunately, in the last three decades, the rapid increase in computational power has led researchers in computational fluid dynamics to attempt to understand the structure of the wall pressure fluctuations. Choi and Moin [6] studied the structure of the wall pressure fluctuations in a turbulent channel flow using a DNS database of Kim et al. [7]. Choi and Moin computed the wave number/frequency spectra and the convection velocities of the wall pressure fluctuations and found that small structures convected at a slower speed than large structures. Na and Moin [8] studied the effect of an adverse pressure gradient on the structure of the wall pressure fluctuations using DNS. They found that adverse pressure gradients lead to elongated two point correlation maps in the spanwise direction and decreased convection velocities. Viazzo et al. [9] studied the spectral features of the wall pressure fluctuations using a large eddy simulation database of a plane channel flow. They reported that a sinusoidal wall perturbation had a very weak effect in terms of time mean values. Wall pressure fluctuations and flow-induced noise from a turbulent boundary layer over a bump were investigated by Kim and Sung [10] using DNS. They found that wall pressure fluctuations increased near the trailing edge of the bump along with the presence of large structures that convected rapidly downstream.

Scope:

The previous summary showed the level of computational research effort undertaken to understand the critical problem of wall pressure fluctuations. However, the summary also shows the academic nature of this effort based on the use of simple geometry and low Reynolds numbers in addition to the use of DNS and LES in the modeling of turbulence. These modeling approaches are not yet suitable for engineering problems due to their prohibitive computational cost. In the last fifteen years, a new modeling approach has been gaining popularity and acceptance in the CFD community. This method, referred to by some specialist as a bridging method or by others as

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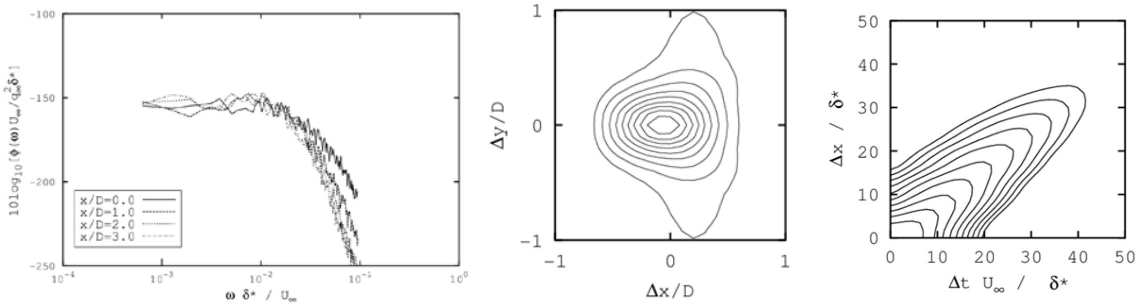
a hybrid method, combines the best attributes of the widely used Reynolds Averaged Navier-Stokes method with those of LES. One such method known as Detached Eddy Simulation [11] has been used extensively and will be used in our current study. The current study will address the problem of surface pressure fluctuations around a cylindrical, wall-mounted protuberance, in a supersonic turbulent boundary layer. Extensive comparisons of surface pressure coefficients and the fluctuating surface pressure coefficients to those measured by Robertson [12] show good agreement. In addition, and as shown on Figure 1(a), wall pressure spectra, two-point space correlations and two-point space-time correlations are also obtained and compared to previous work. Figure 1(a) shows that the wall pressure spectra at various distances downstream of the protuberance collapse well at low frequencies using the outer scaling but not so well at high frequencies. The ratio of protuberance height to boundary layer thickness in this case is 2.0. The two-point space correlation three diameters downstream of the protuberance shows the presence of large structures with stretching in the spanwise direction, Figure 1(b). The space-time correlation, Figure 1(c), shows a short lived coherence in both space and time. One can also deduce the convection velocity of the surface structures based on the slope of the curves, in this case it found to be between 0.6 and 0.77 of the freestream.



(a) (b) (c)

Figure 1: (a) Wall pressure spectra at various downstream locations from the protuberance, (b) two-point space correlation three diameters downstream of the protuberance (c) two-point space-time correlation three diameters downstream of the protuberance. The protuberance height to boundary layer thickness is 2.0 and for both the two-point and the space-time correlations the contours levels are between 0.1 and 0.9.

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