ABSTRACT

“*If you want to find the secrets of the universe, think in terms of energy, frequency, and vibration*” – Nicola Tesla

The present thesis started in the quest to understand the energy, frequency, and vibration behaviour of the structural panels when subjected to turbulent boundary layer (TBL) excitation, one of the major noise sources. Structural vibration and noise (vibroacoustic) problem is a serious issue encountered by the transportation industry in terms of human health, environmental noise pollution, structural stress, fatigue, etc. Therefore, it is very important to understand the TBL-excited vibroacoustic behaviour of the vehicular panel and the enclosed cabin. Usage of stiffened, tensioned, double wall panels and panels made of orthotropic laminated composites also necessitates a comprehensive TBL-excited vibroacoustic study with a fully coupled system development.

Over the years, the vibroacoustic response of plate structures subjected to a turbulent boundary layer flow has been the subject of numerous studies. This is because the interaction between the flow and the plate can lead to significant changes in the acoustic and vibration characteristics of the panel. The understanding of this interaction is essential in various engineering domains such as aerospace, automobile, marine, high-speed railway, and civil engineering where plate structures are commonly used.

This thesis work focuses on investigating the vibroacoustic response of a plate structure due to the fully developed turbulent boundary layer over it. Besides the analytical and semi-analytical models, the study combines computational fluid dynamics (CFD), Reynolds-averaged Navier-Stokes (RANS) simulations, and large eddy simulations (LES) to investigate/predict the turbulent pressure fluctuations over a plate structure. The aim is to understand vibration, sound radiation, and sound transmission characteristics of several different panel configurations that include single, double, tensioned, and stiffened panels. Different orthotropic laminated panels are also extensively studied in this context. The study also evaluates the influence of the turbulent boundary layer on the panel's overall vibroacoustic response. In-house finite element (FE) codes are developed to couple the TBL loading with the flexible structure and the flexible structure with the adjacent acoustic medium. All the coupling models are developed in the FE environment using in-house MATLAB (ver. R2013b) or cloud-based Python scripts.

Different semi-analytical single-point wall-pressure spectrum models are used to estimate the pressure fluctuations, with prior studies of their prediction accuracy with the wind tunnel experiments and the in-flight test results. All these spectrum models essentially work based on the TBL wall parameters, like boundary layer thickness, displacement thickness, momentum thickness, shear velocity, etc. Therefore, one has to depend upon the experimental feed, which is quite a labour and cost intensive. In order to predict various wall parameters, the computational

fluid dynamics (CFD) simulations are carried out using both commercial and open-source flow solvers, ANSYS Fluent (V14.5) and OpenFOAM (v-2012 in Ubuntu 20.04 LTS), respectively. A detailed sensitivity study is performed to identify the change in wall-pressure fluctuations due to the choice of RANS turbulence model parameters, like turbulence model, solver, normalized wall distance, flow velocity, etc. The best predicting configuration is thus identified and used in further vibroacoustic computations in the energy (power spectral density; PSD) domain.

The wall pressure fluctuations are estimated in the normal frequency domain also. In order to achieve this, two methods are adopted in the present study. A) The wall-pressure spectrum is decomposed using Cholesky's technique. This resulted in the pressure fluctuations magnitude in the frequency domain. B) The large eddy simulation (LES) is employed to simulate the real-time pressure fluctuations over single or multiple points over the plate. The Smagorinsky-Lilly model is used as the sub-grid scale model. Typical LES models have a near-wall eddy-damping issue which is resolved using the artificial inflow turbulence generated using the superposition of the Fourier modes. This continuously perturbs the flow and desired near-wall pressure fluctuations are obtained.

In the present study, the single-point pressure fluctuation is obtained considering the wall beneath the TBL to be rigid. Considering the TBL wall pressure to be random, stationary, and ergodic, the cross-spectrum of the pressure fluctuations over the plate is calculated using Corcos and Mellen's spatial coherence function. This pressure cross-spectrum is further used to estimate the plate vibration.

Once the wall-pressure fluctuation is obtained over the panel, in the next step the TBL-excited plate vibration is estimated using a one-way coupled fluid-structure interaction model. A two-way coupling model is used to couple the excited plate and the adjacent acoustic domain to estimate the radiated sound power in the free field or the sound transmission into the enclosed cavity. The required panel transfer function or the frequency response function (FRF) is developed using the mode shape and frequency data obtained from the FE modal analysis using MATLAB or ANSYS APDL (V14.5). The FE discretization of the panel is performed with the TBL-induced plate bending wave consideration. The coupling between the TBL cross-spectra and the panel transfer function resulted in panel response in terms of displacement and velocity PSD.

In order to simulate the real-life sound radiation and transmission phenomena *four* types of TBL-structure-acoustic coupling models are developed to account for single panel, panel-enclosure, panel-cavity-panel (double wall), and panel-cavity-panel-enclosure (double wall backed by an enclosure) systems. Panels are modelled using 4-node isoparametric plate elements, and the acoustic domain is modelled using 8-noded 3D brick elements. Once the transfer functions of the panel(s) and the acoustic domain(s) are estimated in a fully coupled condition, they are used to calculate the panel-radiated sound power into the free field using the radiation resistance matrix (RRM) technique, where each finite element behaves as an elemental radiator. The TBL-excited panel velocity PSD is coupled with the RRM and the radiated sound power is estimated. In the case of sound transmission into an enclosure, the system transfer functions of each part are directly coupled with the TBL cross PSD, and the panel velocity PSD and the enclosure pressure PSD are obtained.

As observed from the two-fold sensitivity study, $k - \omega$ family of turbulence models are found to be best predicting the TBL wall pressure over a flat plate. Large eddy simulation (LES) powered by the in-house developed user defined functions (UDFs) for artificial inflow turbulence manifests excellent wall pressure fluctuation prediction. Wall pressure fluctuations using Cholesky decomposition coupled with boundary element (BE) technique estimates panel vibration and sound radiation in frequency domain, providing with similar trend to the results obtained in the PSD domain. Orthotropic laminated composite panels with $(45/-45)_n$ sequence, when excited by TBL force, exhibits counter-intuitive vibroacoustic results. The results obtained using FE-RRM technique for free field sound radiation, and fully coupled FE-FE technique for sound transmission in panel-gap-panel-enclosure system are in excellent agreement with the reported analytical results.

In real-life transport vehicles, different type of structural variations is observed, in terms of geometry, material properties and support conditions. In order to capture these variations, the present study uses FE modelling of the orthotropic laminated composite panels, stiffened and tensioned panels with generic boundary conditions and scope of different geometry. This study can thus be useful for any structural or aerodynamic modification of the transport vehicle in the very early design stage.