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Far-field Aeroacoustic Noise Prediction of a Tall Standard Building Model by Measuring Unsteady Surface Pressures

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ABSTRACT: In the present study, far-field aeroacoustic noise emitted due to the air flow over a standard tall building model at different angles of attack is investigated. The purpose of this study is to estimate the far-field aeroacoustic noise emitted by measuring the unsteady surface pressures. The surface pressure data are used as input of a numerical algorithm which is written to solve the Ffowcs Williams and Hawkings equation. The aerodynamic and aeroacoustic characteristics of flow over a two-dimensional square cyliner (for algorithm validation) and the main model are presented. The results revealed that the peak of vortex shedding frequency could be observed in the spectrum of surface pressure signals of sensors located on the side surfaces of the model. Its frequency is in an excellent agreement with the signals captured by hot wire measurement. The Strouhal number changes in the range of 0.08-0.1 depending on the angle of attack. Dipole pattern for sound radiation was also observed for three-dimensional model which is related to the vortex shedding phenomenon. The sound pressure level increases with increasing upstream velocity and decreases with distance from the model. The effect of angle of attack is also dependent on the reciever's location.

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1. INTRODUCTION

The aerodynamic sound is one of the most important parts of the noise produced by modern vehicles like airplanes, cars, and trains. The sound generated due to the interaction of turbulent wind and cylindrical structures is of basic importance due to their wide range of application in the airplane landing gear, pantographs, high rise buildings, chimneys, pipelines, etc.

Aerodynamic noise propagation from cylindrical shaped objects received considerable attention from the researchers in the last decades. Most of the studies on flow-induced noise from the cylinders have focused on the noise generation from two-dimensional cylinders. However, most applications of cylindrical geometries in the real-world applications such as electronic boards, low-rise buildings, cooling towers, etc. use finite-length cylinders with different cross-sections. To the best of our knowledge, few investigations have been conducted on the sound generation by wall mounted finite-length cylinders. Movahedi et al. [1] experimentally investigated aeroacoustic characteristics of the flow over a finite height wall mounted square cylinder at incidence. They analyzed the influence of upstream flow velocity and its incident angle on the overall sound pressure level. Porteous et al. [2] experimentally studied the relationship between the flow structures in the wake of a wall-mounted square cylinder and the radiated noise. Based on the aspect ratio of the cylinders, four shedding regimes were identified. Each one was characterized by a progressively higher number of tonal components in the acoustic spectrum.

In addition to studying the flow structure and its related phenomena, the results of experiments on simple and standard models (like Commonwealth Advisory Aeronautical Council (CAARC) tall building) are required for the validation of numerical methods as well as calibration of the experimental equipment. CAARC standard building has a rectangular prismatic shape characterized by the full-scale dimensions of 100×150×600 ft. The results of primary studies on the CAARC building model are summarized by Melbourn [3].

From an extensive literature survey, it is revealed that the information about the aerodynamic noise radiated from free end Three-Dimensional (3D) cylinders, especially one with the rectangular cross-section, is very limited. The present study investigates the semi-empirical prediction of aerodynamic noise radiated from a 3D cylinder with a rectangular cross-section (model of CAARC tall building) by measuring unsteady surface pressures. The great advantage of this method is that it allows acoustic studies to be carried out in a cost-effective way in aerodynamic wind tunnels.

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2. METHODOLOGY

In the 1950s, Lightheil [4] combined the Navier-Stokes and continuity equations into a completely inhomogeneous wave equation. One of the limitations of Lighthill's theory is that it only estimates sound waves in interfaces without boundaries. In 1955, Curle [5] extended the theory of Lighthill for the presence of solid boundaries. He related the sound radiated from the objects with fluctuating surface pressures. Then Ffowcs Williams and Hawkings (FW-H) [6] modified Lighthill analogy by considering the effect of the arbitrary surface motion. In the present paper, the FW-H analogy has been employed to predict the sound pressure level in the far-field of a CAARC model.

When the flow around the bluff bodies is investigated, dipole sources of sound are dominant in comparison with monopole and quadrupole ones. In this case, the FW-H equation can be simplified as follows [7]:

$$p'(\vec{x},t)=\frac{1}{4\pi c_0}\int_S \frac{(x_i-y_i)n_i}{r^2}\frac{\partial p(\vec{y},\tau)}{\partial t}dS(\vec{y}) + \frac{1}{4\pi}\int_S \frac{(x_i-y_i)n_i p(\vec{y},\tau)}{r^3}dS(\vec{y}) \tag{1}$$

where p' is far-field pressure fluctuation, p is surface pressure recorded at the location of each sensor, $\vec{x}$ and $\vec{y}$ are receiver and source locations respectively, r is the distance between the source and the receiver and $\tau = t - r/c_0$ is the emission time. The sound pressure level is defined as:

$$SPL = 20\log\left(p'_{\mathrm{rms}} / P_{\mathrm{ref}}\right) \tag{2}$$

where p'_{rms} is the Root-Mean-Square (RMS) of pressure fluctuations and p_{ref} $=2\times10^{-5}$ Pa. The model used in this study is schematically shown in Fig. 1.

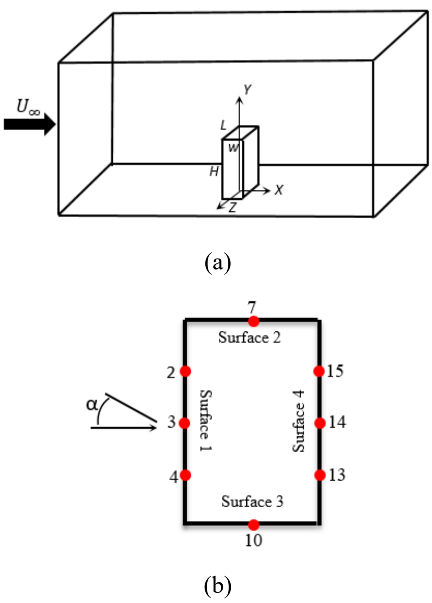

Fig. 1. (a) Schematic drawing of the model; (b) surface pressure measuring points on the middle height belt.

All measurements are performed in the acoustically improved aerodynamic wind tunnel of the Yazd University. Twenty one pressure taps are imbedded on the five faces of the model.

3. DISCUSSION AND RESULTS

Surface pressure spectrum of the side faces and velocity signals in the wake region show nearly the same values for vortex shedding frequencies. This frequency increases with upstream velocity and has a higher value for the angle of attack α=90 in comparison with α=0. The results are in good agreement with previous studies. It should be noticed that surface pressure taps which are located on the side surfaces of the model can show a sharp and clear peak of shedding frequencies in the pressure spectra.

After validating the analogy used in this paper for the far-field aeroacoustic noise prediction from a 2D square cylinder, noise radiation from the CAARC model is investigated. Directivity pattern of noise level from a *XZ* plane at different distances and for two angles of attack is summarized and plotted in Fig. 2. The directivity patterns at this plane show the dipole characteristic of the sound pattern. The effect of the upstream velocity on the predicted far-field noise in *YZ* plane is shown in Fig. 3. It can be observed that the higher noise amplitudes are

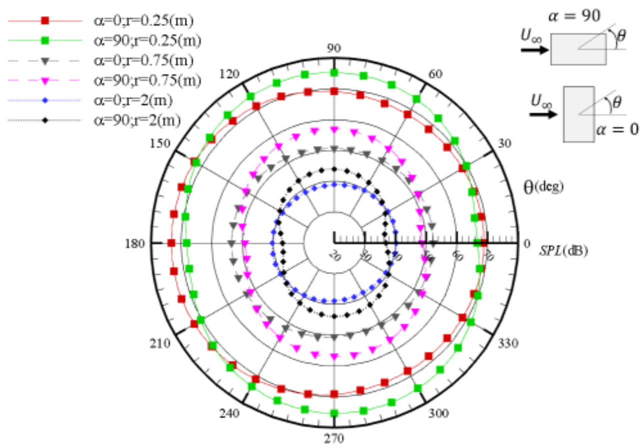

Fig. 2. Directivity noise patterns for CAARC model for U_∞=17.5 m/s on the *XY* plane (*Z*=0).

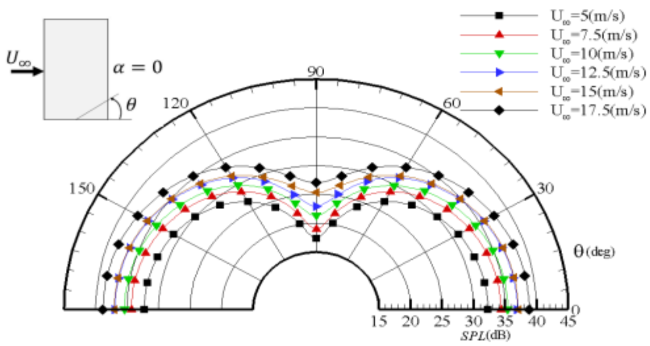

Fig. 3. Directivity noise patterns for CAARC model on the *YZ* (*X*=0) plane (*r*=2m) and α=0.

located at the opposite points near the bottom plane and the lower one right above the cylinder. On the other hand, the directivity plot on the *YZ* plane presents much lower sound pressure levels in comparison with the *XY* plane. Also, the noise radiated increases with upstream velocity, as expected.

4. CONCLUSIONS

Flow-induced noise from CAARC building model was predicted semi-empirically. For this purpose, the unsteady surface pressures were measured and then the far-field noise was estimated by using FW-H equation. The results showed that there is a sharp peak in the surface pressure spectra obtained for sensors located on the side faces of the model. The Strouhal number obtained from both unsteady surface pressure signals and hot-wire measurements were equal to 0.08 and 0.1 for 0° and 90° angles of attack, respectively. For the CAARC building model, dipole pattern for sound radiation was observed. Also, the Sound Pressure Level (SPL) increases with upstream velocity and decreases with distance from the cylinder. Due to the asymmetry of the cross-section of the model, the angle of attack has a complex effect on radiated noise level. By changing the angle of attack the predicted sound level can be decreased or increased, depending on the listener's location.

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