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PREDICTING THE VIBROACOUSTIC RESPONSE OF AN ELASTIC HYDROFOIL IN A TURBULENT FLOW

Paul Williams[1*] **Mahmoud Karimi**[1] **Jamie Kha**[1]
Kostas Tsigklifis[2] **Richard Howell**[2]
[1] Centre for Audio, Acoustics and Vibration, University of Technology Sydney, Australia
[2] Platforms Division, Defence Science and Technology Group, Australia

ABSTRACT

This work investigates the vibration of an elastic hydrofoil submerged in water and excited by a turbulent flow. The excitation of the hydrofoil due to incident turbulent flow (turbulence ingestion) and a turbulent boundary layer is considered. The hydrofoil and surrounding fluid are modelled numerically using the finite element method (FEM). Each excitation mechanism introduces a surface pressure fluctuation across the hydrofoil. The forces caused by these pressure fluctuations are applied to the FEM nodes at the hydrofoil's surface using the uncorrelated wall plane wave method to synthesise realizations of the stochastic wall pressure field. The incident turbulent flow is modelled using Amiet's theory while the turbulent boundary layer is modelled using semi-empirical methods. The contribution of each component is discussed and compared to experimental data from the literature.

Keywords: *flow generated noise, finite element method, turbulence ingestion, turbulent boundary layer*

1. INTRODUCTION

When turbulent flow passes across an elastic surface, the interaction between the pressure fluctuations and the elastic structure can give rise to vibration. These vibrations are then capable of radiating acoustic pressure back into the environment causing noise pollution. Such effects can be more noticeable in marine environments due to the strong acoustic-structure coupling between water and the hull of ships and other marine vehicles. Given the importance of reducing anthropogenic noise pollution due to its effects on nature, understanding the noise generation mechanisms and later reducing the emissions is an important topic.

The vibration response of elastic, simply supported, flat plates due to a turbulent boundary layer (TBL) has been investigated numerically using the uncorrelated wall plane wave (UWPW) method by Maxit [1] and Karimi et al. [2]. Meanwhile, the surface pressure fluctuations on the surface of a rigid plate caused by turbulence ingestion (TI) has been investigated by Karimi et al. [3] using the UWPW method and Amiet's method. During this investigation, the TI and TBL excitation mechanisms will be applied to a clamped, elastic hydrofoil to investigate its vibration response. The aim of this investigation is to understand the relative contribution of each excitation on the vibration response of a hydrofoil.

2. THEORY

The response of a hydrofoil excited by turbulent flow will be explored using the finite element method. The finite element domain is shown in Fig. 1. It consists of the elastic hydrofoil within a fluid filled duct. The hydrofoil and duct parameters used mirror those found in Lelong et al. [4]. The duct has a height and width equal to 192 mm. The NACA15 profile

[*]***Corresponding author***: paul.williams@uts.edu.au.

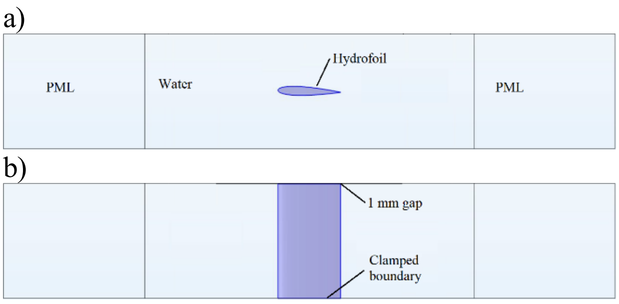

Figure 1. Diagram of the clamped hydrofoil in a water filled duct. a) Side view. b) Top view.

hydrofoil has a span of 191 mm, chord of 100 mm. The hydrofoil is clamped to the rigid duct wall on one side and left free on the other with a 1 mm gap between the tip and the duct wall. The fluid domain is bounded upstream and downstream by a perfectly matched layer (PML). The model is built in COMSOL Multiphysics.

The hydrofoil is modelled as a three-dimensional elastic body with a Young's modulus of 2.9 x 10^9 Pa, a Poisson's ratio of 0.35, and a density of 1420 kg m^{-3}. A structural loss factor of 0.5 % was applied, however a hydrodynamic loss factor was also required to demonstrate the damping observed by Lelong et al. [4]. The water was given a density of 1000 kg m^{-3} and a speed of sound equal to 1500 m s^{-1}.

The surface pressure excitation applied to the hydrofoil is calculated using the uncorrelated wall plane wave (UWPW) method [2,3]

$$\Delta p^{n}(x, y, f) = \sum_{i=1}^{M} A(x, \boldsymbol{k}^{i}, f) \exp\left(i\left(k_x^i x + k_y^i y + \phi_i^n\right)\right), \quad (1)$$

where $A(x, \boldsymbol{k}^i, f)$ are the amplitudes for each excitation type, $\boldsymbol{k}^i = [k_x^i, k_y^i]$ is the i^{th} wavenumber, ϕ_i^n is a phase that is randomised between wavenumbers and realizations, n denotes the realization, f is the frequency, and M is the number of wavenumbers used in the discretization. The superscript n denotes the realization number. The total number of realisations required to ensure a converged solution is typically between 30 and 60.

The source amplitudes for each wavenumber are calculated for each excitation type. Karimi et al. [3] presented a method by which the UWPW method can be applied to the TI using Amiet's method. The amplitudes are calculated as

$$A_{TI}(x, \boldsymbol{k}^i, f) = 4\pi\rho g_{TI}\left(x, K_x, k_y^i\right)\sqrt{\pi U_\infty \phi_{ww}\left(K_x, k_y^i\right)\delta k_y^i}, \quad (2)$$

where ρ is the fluid density, U_∞ is the mean flow velocity, $\phi_{ww}\left(K_x, k_y^i\right)$ is the power spectrum density calculated using the rapid distortion theory, and $g_{TI}\left(x, K_x, k_y^i\right)$ is the gust transfer function relating the response of the hydrofoil to the turbulence. The convected wavenumber is $K_x = 2\pi f / U_\infty$.

The TBL is applied using method of Karimi et al. [2]. The properties of the TBL are assumed to be homogeneous over the chord of the hydrofoil. The amplitude related to the wall pressure fluctuations due to a TBL excitation is

$$A_{TBL}(x, \boldsymbol{k}^i, f) = \sqrt{\frac{\phi_{pp}(k_x^i, k_y^i, f)\delta k_x^i \delta k_y^i}{4\pi^2}}, \quad (3)$$

where ϕ_{pp} is the cross-spectrum of the wall pressure fluctuations calculated using the Mellen model.

The surface pressure fluctuation for each realization is applied as a force to the finite element model. The surface displacement of the hydrofoil is determined by solving the finite element equations. The response due to turbulence can then be calculated by averaging over all realizations.

3. RESULTS AND DISCUSSION

In this section the surface pressure fluctuation due to each excitation type will be illustrated. This will allow for a comparison into the distribution of force across the hydrofoil caused by each excitation type.

Figs. 2 and 3 show a single realization of the surface pressure fluctuation at 235 Hz due to a TI and TBL excitation. The surface pressure level has been normalized against the maximum value for comparison. As expected, the TI excitation is concentrated at the leading edge with amplitude falling towards the trailing edge. The homogeneous TBL shows a significant variation across the surface due to the interaction of energy in each wavenumber.

Application of the TBL excitation to the hydrofoil as a normal force causes a vibration. The surface average of the autospectrum of velocity due to the TBL excitation is shown

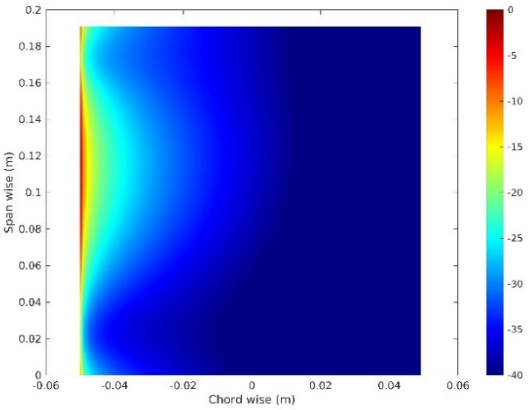

Figure 2. The surface pressure (dB) across the top surface of the hydrofoil for a single realization of the surface pressure fluctuation caused by TI at 235 Hz.

in Fig. 4. Comparison to the work of Lelong et al. [4] shows that the natural frequencies observed at 34 Hz and 180 Hz are consistent. Increasing the flow speed of fluid in the calculation for the turbulent amplitude results in an increase to the vibration velocity of the hydrofoil across the frequency range, as expected.

4. CONCLUSIONS

The vibration response of a hydrofoil due to flow was investigated for the case of excitation by turbulence ingestion and a turbulent boundary layer. A numerical approach was taken to investigate these phenomena using the UWPW method to simulate the turbulence. It can be shown that the UWPW method is a flexible approach that can be used to apply a variety of vibration sources caused by stochastic wall pressure fields.

5. REFERENCES

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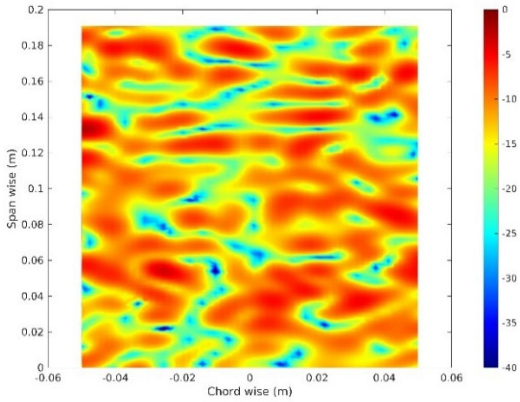

Figure 3. The surface pressure (dB) across the top surface of the hydrofoil for a single realization of the surface pressure fluctuation caused by a TBL at 235 Hz.

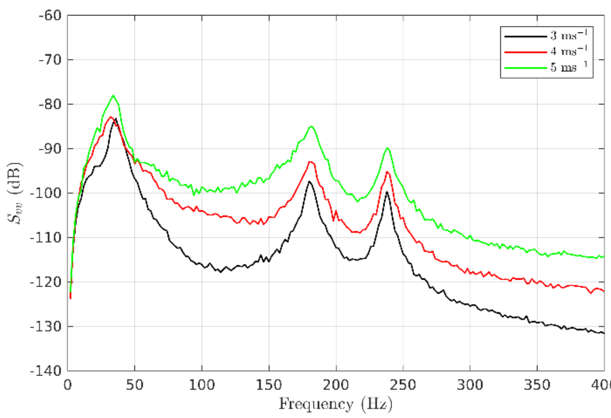

Figure 4. The surface average of the autospectrum of velocity (dB, ref. 1 m^2 s^{-2} Hz^{-1}) due to TBL excitation at various flow speeds.