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Vortex Induced Vibration Analysis of a Cantilevered Hydrofoil by Laser Vibrometry and TR-PIV

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Abstract

The structural response of a steel cantilevered hydrofoil is analyzed through an experiment carried out in a hydrodynamic tunnel for Reynolds numbers ranging from 2×10^5 to 8.25×10^5 . The hydrofoil is set at a 17° angle to the flow direction, in order to maximize the hydrodynamic forcing issued from the vortex shedding, thus enhancing fluid structure interactions. The structural response is measured through the vibration velocity using a laser Doppler vibrometer. The flow dynamics are analyzed through Time Resolved-Particle Image Velocimetry (TR-PIV) and Proper Orthogonal Decomposition. An interaction between the vortex shedding phenomenon and the modal response of the structure is observed. A decrease of the modal frequencies occurs for Reynolds numbers above 4×10^5 . The modal frequencies are found to decrease towards the vortex shedding frequency as the velocity increases resulting in resonance flow velocities much lower than the ones predicted in a non coupling hypothesis. The experimental results presented in this paper will help to develop fluid-structure interaction models and simulations in naval applications.

Keyword: Vortex Induced Vibration, Hydrodynamics, vibrometry, hydrofoil

1 Introduction

Due to the large density of water and very small Mach numbers compared to air, Fluid Structure Interactions are much different for naval applications than for aerodynamic ones. The knowledge of the vibratory response of lifting bodies to hydrodynamic excitation is fundamental for the designing and sizing of naval systems such as marine propellers (Young, 2008), active control surfaces like rudders (Turnock and Wright, 2000) or innovative tidal turbine blades (Nicholls-Lee et al. 2009). Moreover flow induced vibrations are a major issue for naval ship discretion or passenger comfort. Indeed, marine propellers for instance are mainly designed considering the hydrodynamic aspect and less attention is paid to the deformations and vibrations of the structure interacting with the flow. In some extreme cases, the flow excitation can tune in with the structural response and cause major noise or dramatic deteriorations of the structure. Research have already enlightened interactions between viscous flow and the modal response of a hydrofoil in various flow conditions at the Naval Academy (Ducoin et al. 2012, Lelong et al. 2018).

One topic of great interest for naval applications is the coupling between vortex shedding and structural response (Blevins, 1984) and the understanding of Fluid Structure Interaction on

elastic structures immersed in a high density fluid still requires experimental studies. The present paper deals with the study of a cantilevered rectangular NACA0015 hydrofoil modal response through an original experiment carried out in the French Naval Academy hydrodynamic tunnel for Reynolds number ranging progressively from 2×10^5 to 8.25×10^5 . The hydrofoil is set at a 17° angle to the flow direction, in order to maximize the hydrodynamic loading issued from the vortex shedding phenomenon, thus enhancing fluid structure interactions. The experimental set-up is presented in Section 2 where the vibration velocity measurement and time-resolved Particle Image Velocimetry are presented. Results are presented and discussed in Section 3 and concluding remarks are given in Section 4.

2 Experimental set-up

2.1 Hydrodynamic Tunnel

The experiments were carried out at the hydrodynamic tunnel of the Research Institute of the French Naval Academy. The test section is $0.192 \times 0.192 \text{ m}^2$ and 1 m long, as shown in figure 1. At the entrance of the test section, the upstream velocity and pressure are regulated with an accuracy of $\pm 2\%$ and $\pm 2.5\%$ respectively. In the test section, the upstream flow velocity ranges from 0.5 m.s^{-1} to 15 m.s^{-1} and the pressure ranges from 300 mbar to 3 bar to control cavitation inception and development.

For the present study, the upstream flow velocity U ranges from 2 m.s^{-1} to 8.25 m.s^{-1} by steps of 0.5 m.s^{-1} and a last step of 0.25 m.s^{-1} . The pressure in the test section is set to avoid the development of cavitation on the surface of the hydrofoil. The free stream turbulence intensity in the middle of the test section is 2%.

A stainless steel hydrofoil is mounted with an angle of incidence of $\alpha = 17^\circ$ at mid height of the test section (figure 2). The hydrofoil is clamped at the end of the rotation axis. The hydrofoil has a span-symmetrical NACA0015 section with a relative thickness of 15%, the chord is $c = 0.1 \text{ m}$ and the span is 0.191 m .

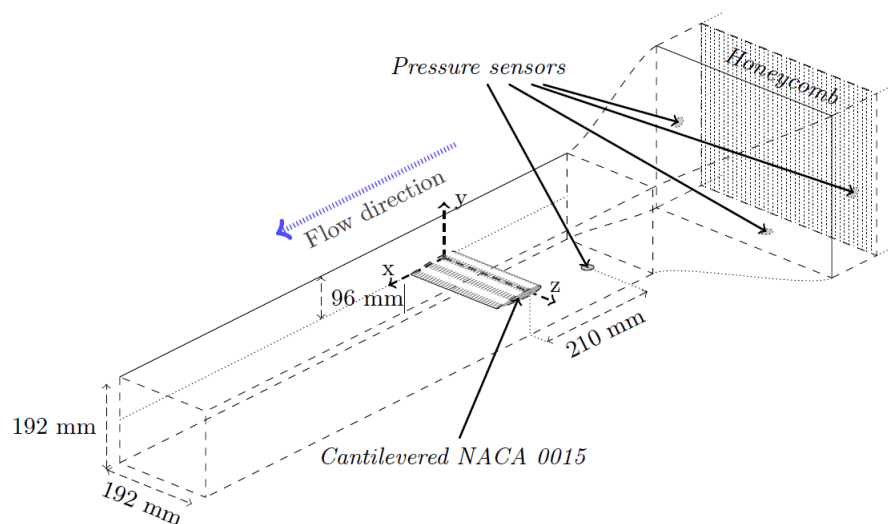


Figure 1: Test section of the hydrodynamic tunnel at the french naval academy

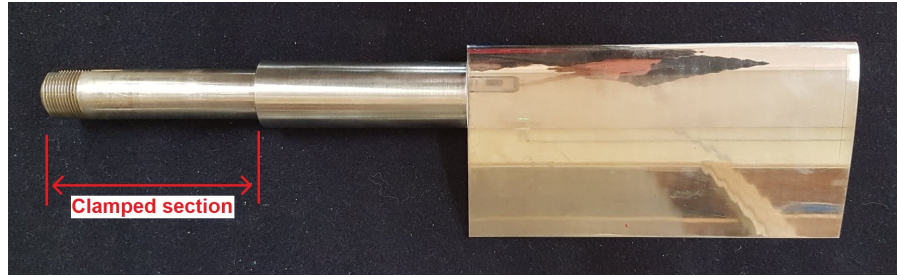


Figure 2: Cantilevered NACA0015 hydrofoil

2.2 Vibration measurements

The vibration measurements and modal analyses were performed with a Polytec® PSV-400 scanning laser vibrometer. The vibrometer measured the vibration of a single reference point situated near the trailing edge at the free tip of the structure. The laser vibrometer can detect vibration velocities from $0.01 \text{ m}\cdot\text{s}^{-1}$ to $10 \text{ m}\cdot\text{s}^{-1}$ using a HeNe laser ($\lambda = 633 \text{ nm}$) based on the Doppler effect. It is equipped with two analog velocity decoders VD-04 and VD-06. Time evolution of the vibration velocity is measured and is then post processed using a Fast Fourier Transform Algorithm to obtain the spectrum of the signal with a frequency resolution of 0.3125 Hz . Each spectrum used in this study comes from the mean of 64 individual measurements. The spectra amplitude can be presented in two ways: $\text{m}\cdot\text{s}^{-1}$ or dB. Conversion from $S=\text{m}\cdot\text{s}^{-1}$ to $\text{dB}=20\log(S/S_{\text{ref}})$, with $S_{\text{ref}} = 1 \text{ m}\cdot\text{s}^{-1}$. This allows us to detect the modal structure frequencies as well as hydrodynamic frequencies as the vortex shedding in the present study.

2.3 TR-PIV measurements

2D Time Resolved -Particle Image Velocimetry (PIV) technology was also used for the experimental characterization of the flow. The PIV measurement plane is located at mid-span. The PIV device consists of two pulsed YAG laser used to lighten the flow. A high precision CCD camera with a high resolution and a sampling frequency of 1KHz has been used. The Proper Orthogonal Decomposition was applied on the PIV measurements in order to analyze flow dynamics. Figure 3 shows the two first modes showing clearly the vortex shedding structure and dynamics. The analysis of the time series of the mode coefficients allows us to extract the frequency contents and particularly the vortex shedding frequency f_0 . This allows to clearly identify this frequency in the structural vibration spectra

3 Results and discussion

3.1 Modal response of the structure

Figure 4 shows the individual measured spectrum of the vibration for various stream velocities. Figure 5 shows the same results in a plane view representing the amplitude of vibration versus the frequency and the Reynolds number. Several peaks can be observed corresponding to the natural modes of the structure. Only the first 3 modes will be studied, due to their greater

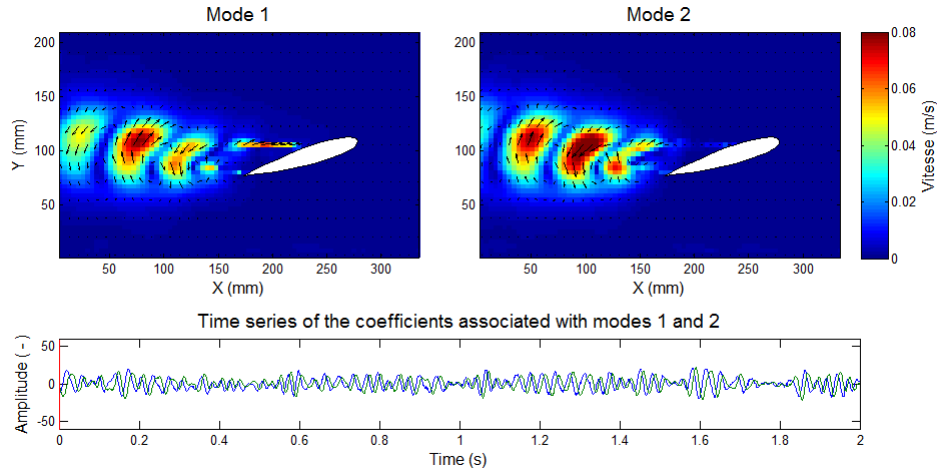


Figure 3: POD analysis, Innox hydrofoil, $\alpha = 17^\circ$, $U = 4\text{m.s}^{-1}$

amplitude compared to the others. The main peak frequency ranges from 105 up to 116 Hz, depending on the stream velocity and corresponds to the first mode (f_1). Then, a second peak from 194 Hz to 204 Hz corresponds to the second mode (f_2). Finally, a third peak ranges from 509 Hz to 552 Hz and corresponds to the third mode (f_3). According to the works of Lelong et al.(2018) on the same geometry, the nature of the first, second and third modes are respectively the first bending mode, the first twisting mode and the second bending mode.

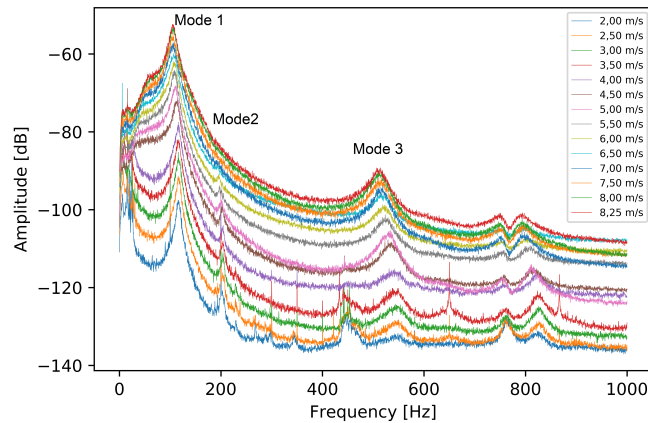


Figure 4: Vibration velocity spectra for various free stream velocities.

In order to correctly detect the local maxima corresponding to the 3 modes the spectra are smoothed using the moving average over 3Hz, avoiding small parasitic fluctuations. Then, the frequency of the 3 modes are extracted from each vibration spectrum by selecting the corresponding local maximum. They are reported on Figure 6 as a function of the flow velocity. For a clearer view on the same plot the evolution of these frequencies, f_1 has been multiplied by a factor of 4 and f_2 by a 2.5 factor.

Two distinct behaviors can be distinguished in figure 6. First, for flow velocities lower than 4 m.s^{-1} the modal frequencies remain constant. Then, for higher flow velocities the modal frequencies tend to decrease with the stream velocity. This enlightens an interaction between

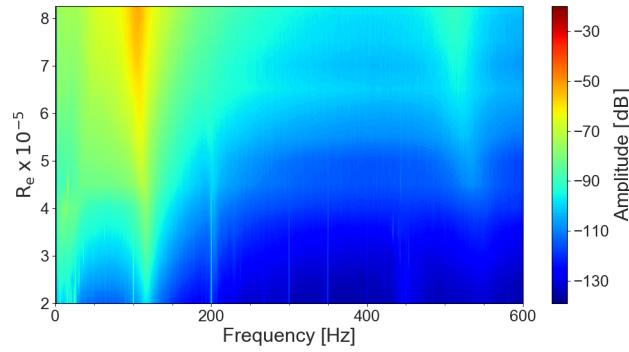


Figure 5: Power spectral density of the structure response versus frequency and Reynolds number.

the flow and the vibration of the hydrofoil. In taking a closer look around the first mode peak on figure 4, the start of the modal frequency decreasing is accompanied by a net increase of the vibration amplitude for flow velocities larger than $4 \text{ m}\cdot\text{s}^{-1}$. The matching of this increase with the vortex shedding phenomenon will be addressed in the next section.

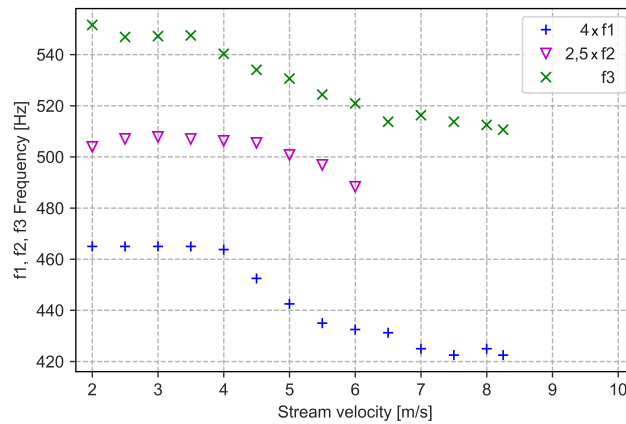


Figure 6: Modal frequencies versus free stream velocity.

3.2 Vortex shedding

A focused view on the low frequencies of the spectra can be seen in figure 7. The two different behaviors discussed in the previous section can thus be depicted further. The vibration spectra for flow velocities lower than $4 \text{ m}\cdot\text{s}^{-1}$ show a more or less well defined frequency peak. Increasing the flow velocity beyond $4 \text{ m}\cdot\text{s}^{-1}$ shows that the peak turns clearly into a change of slope inducing an inflexion zone into the vibration spectra with a global increase of the vibration level up to the bending mode.

In order to determine whether the peak or the inflexion point stands for the vortex shedding frequency (f_0), a Strouhal number is defined by :

$$St = \frac{f_0 \times c \times \sin(\alpha)}{U}$$

By setting $St=0.2$ it is clearly shown in figure 7, that the so calculated f_0 frequency corresponds to the noisy peak at low flow velocities and to the inflexion point for larger velocities. The present phenomenon can be described as the shedding of vortices inducing fluctuations of the pressure distribution along the surface of the hydrofoil, thus leading to a periodic variation of the lift force (Williamson and Govardhan, 2004). The structure vibrates under such a load so that the vortex shedding frequency is printed on the vibration spectra.

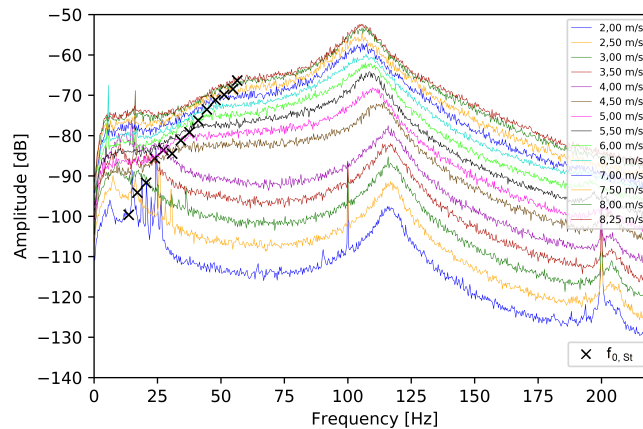


Figure 7: Vortex shedding frequency given by $St=0.2$, plotted (black symbols) on the vibration velocity spectra.

The experimental f_0 values can now be extracted from the vibration spectra on figure 8. The local maximum corresponding to the noisy peak is selected for spectra under $4\text{m}\cdot\text{s}^{-1}$. An interpolation on the interval $[25\text{Hz}, 75\text{Hz}]$, using the least square method, with a two piecewise line function is used for each spectrum above $4\text{m}\cdot\text{s}^{-1}$, the f_0 value corresponding to the intersection point. These experimental values are reported in figure 9 showing a fairly linear evolution. It can be pointed that the f_0 frequency extracted from the vibration spectra was found to be in very good agreement with the one issued from the POD analysis of the flow field. Finally the experimental Strouhal numbers extracted from the vibration spectra are plotted versus the stream velocity (figure 10), confirming that $St=0.2$ is fairly good especially at velocities larger than $4\text{m}\cdot\text{s}^{-1}$.

The extreme case of shedding frequency excitation occurs when the shedding frequency aligns with a natural frequency of the structure. This lock-in condition increases strongly the vibration magnitudes until other loss mechanisms dissipate the energy or catastrophic failure occurs. In the present case, for a stream velocity lower than $4\text{m}\cdot\text{s}^{-1}$ the vortex shedding excites the structure around one particular frequency f_0 . Then above $4\text{m}\cdot\text{s}^{-1}$ the vortex shedding phenomenon excites the structure evenly on a range of frequencies, from f_0 to f_1 .

In order to bring to light the start of a lock-in effect during this experiment, the RMS value of the vibration signals is calculated from the integration of the vibration spectra.

It is plotted versus the flow velocity on Figure 11. As shown, a net rise of the vibration intensity is clearly noticeable from $4\text{m}\cdot\text{s}^{-1}$ velocity. A power law interpolation shows that the RMS value evolves as the flow velocity to the power 2.7.

Therefore, when the range of frequencies from f_0 to f_1 are excited, the vortex shedding

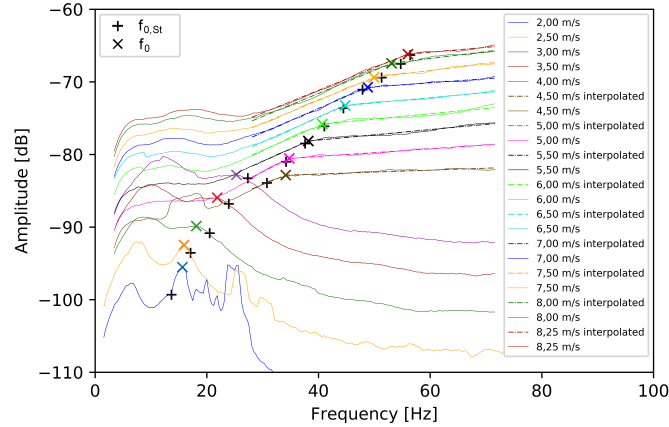


Figure 8: Vortex shedding frequency f_0 extraction on the vibration velocity spectra based on the inflexion point determination. Comparison with f_0 deduced from $St=0.2$ (black symbols)

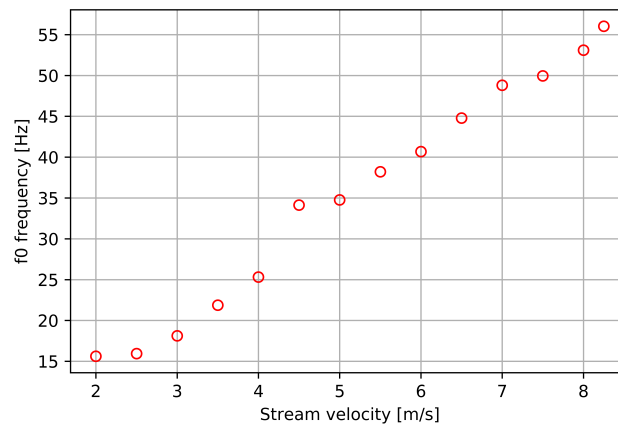


Figure 9: Experimental vortex shedding deduced from vibration spectra versus the flow velocity.

starts to tune in with the first mode of vibration. That lock-in seems to be the cause for the modal frequencies to decrease. This phenomenon is all the more interesting as it influences not only the first mode, but at least the first three modes.

Furthermore, the flow velocities for which the natural modes of the structure coincide to the vortex shedding phenomenon can be extrapolated from figure 12 considering a linear decreasing of the modal frequencies from a $4\text{m}\cdot\text{s}^{-1}$ along with the linear extrapolation of the vortex shedding frequency f_0 .

As shown in table 1 the resonance velocities are found to be much lower when considering the linear decreasing of modal frequencies versus the flow velocity due to flow structure coupling.

4 Conclusions

The experimental vibration response of a cantilevered NACA0015 hydrofoil has been analyzed using a laser Doppler vibrometer at 17° angle of incidence. The first three modes frequencies as well as the vortex shedding frequency could be extracted from the vibration spectra of the

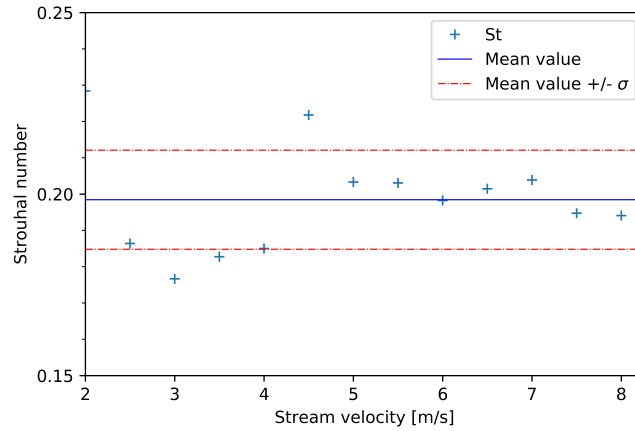


Figure 10: Experimental Strouhal number versus the flow velocity.

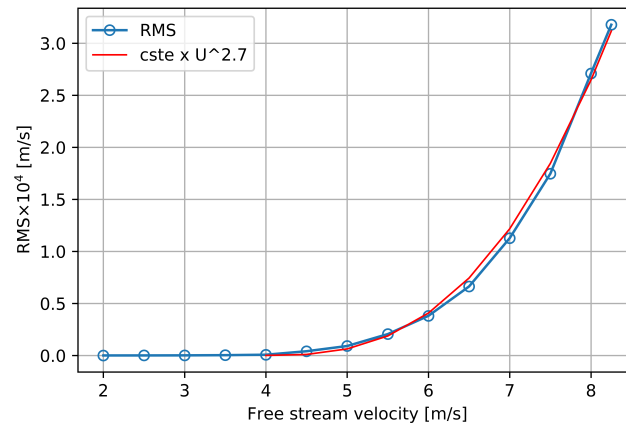


Figure 11: Vibration rms value versus flow velocity.

 Table 1: Extrapolated resonance velocities with constant modal frequencies or linear decreasing (unit $\text{m}\cdot\text{s}^{-1}$)

Extrapolation	Mode 1	Mode 2	Mode 3
constant	17,1	29,7	80,4
linear	13,3	21,9	35,1

hydrofoil.

Two behaviors have been identified. The first one at stream velocity lower than $4\text{m}\cdot\text{s}^{-1}$, the vortex shedding phenomenon excites the structure solely at the vortex shedding frequency. In that case the modal frequencies of the foil remain unaffected. The second one at higher stream velocity, the vortex shedding phenomenon excites the structure evenly on a range of frequencies from the vortex shedding frequency to the first mode frequency. In that case the modal frequencies are observed to decrease linearly with the stream velocity.

Furthermore, this decreasing of the modal frequencies causes the resonance phenomenon, be-

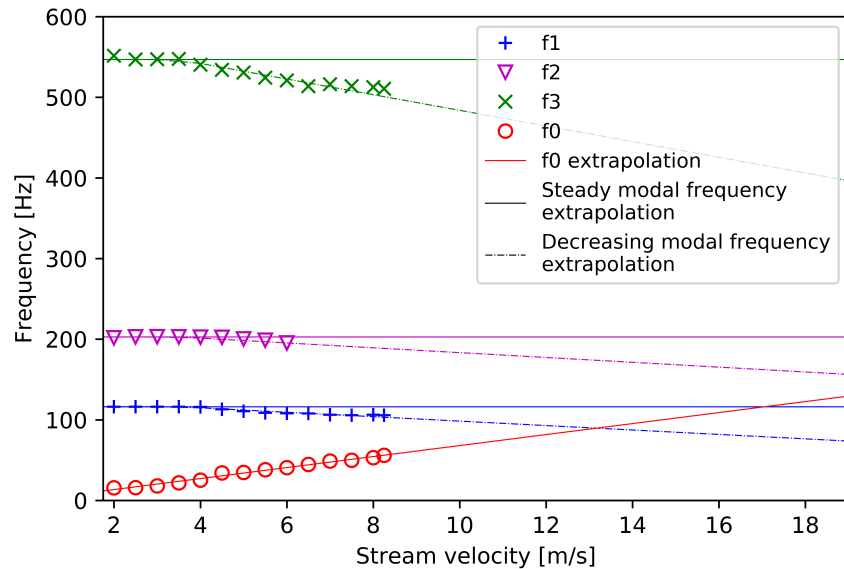


Figure 12: Modal and vortex shedding frequencies versus the flow velocity.

tween the natural modes of the structure and the vortex shedding, to occur at lower stream velocities than expected, when initially considering constant modal frequencies.

The shift of the modal frequencies towards the vortex shedding frequency of the structure enlightened in this paper is of primary importance when designing marine lifting surfaces. This study paves the way for further investigations in understanding fluid structure interactions for naval applications. These results would benefit from additional measurements at higher Reynolds numbers, which were not feasible without inducing cavitation in the hydrodynamic tunnel.

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