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Review of parameters influencing the structural response of a submerged body under cavitation conditions

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Abstract. Submerged structures that operate under extreme flows are prone to suffer large scale cavitation attached to their surfaces. Under such conditions the added mass effects differ from the expected ones in pure liquids. Moreover, the existence of small gaps between the structure and surrounding bodies filled with fluid also influence the dynamic response. A series of experiments and numerical simulations have been carried out with a truncated NACA0009 hydrofoil mounted as a cantilever beam at the LMH-EPFL cavitation tunnel. The three first modes of vibration have been determined and analysed under various hydrodynamic conditions ranging from air and still water to partial cavitation and supercavitation. A remote non-intrusive excitation system with piezoelectric patches has been used for the experiments. The effects of the cavity properties and the lateral gap size on the natural frequencies and mode shapes have been determined. As a result, the significance of several parameters in the design of such structures is discussed.

1. Introduction

The current interest among structural designers lies in seeking the limits of new materials or new structural configurations that offer improved and suitable qualities to create thinner, lighter and more flexible structures. At the same time, the concentration of power and the off-design operation of fluid machinery results in an increase of the unsteady hydrodynamic loads and the appearance of fluid instabilities. This general trend leads to more frequent material fatigue or resonance failures due to undesirable flow induced vibrations.

In this sense, a deep understanding of the fluid-structure interaction (FSI) of submerged bodies is fundamental for the design of a large variety of systems. This problem, although not new, has undergone a recent growth in popularity due to the large number of applications for fluids. In brief, the structural response of a submerged body depends significantly on its boundary conditions. However, the actual hydrodynamic conditions are often uncertain and it is difficult to determine them because the in-situ environment is not accessible for observation or measurement.

As a first approach, it is well known that a body in a dense and still fluid exhibits a different dynamic behavior than when surrounded by air due to the so-called "added mass effect" that is mainly translated to a reduction of the natural frequencies [1-4]. If the fluid flows around the body, additional uncertainties appear with a possible influence on the total damping and stiffness [5-6]. For example, the proximity of solid boundaries create small gaps filled with fluid that affect significantly the dynamic response [7-8]. And certainly, the presence of a two-phase flow due to hydrodynamic cavitation will add new boundary conditions that are not fully understood yet.

From a structural point of view, the interest in cavitation stems from the fact that many submerged bodies suffer from this phenomenon or they are prone to suffer it. The mixture of liquid and vapor water phases that forms the macroscopic hydrodynamic cavities can create averaged properties that vary from the expected effects of a pure liquid. Moreover, the complex structure and morphology of the two-phase flow enhances its scientific interest and opens new challenges to the design of submerged structures [9]. Consequently, evidence obtained from experiments and numerical simulations is summarized in the current paper to illustrate the significant parameters to take into account in such cases.

2. Experimental set-up

A series of experimental modal analysis were performed on an aluminum NACA0009 hydrofoil at the High Speed Cavitation Tunnel of the Laboratory for Hydraulic Machines (LMH-EPFL). A couple of Plumbum (lead) Zirconate Titanate (PZT) patches made of piezoelectric ceramic material were used as excitation and measuring systems perfectly embedded on the surface to avoid affecting the flow around the profile. The patch closer to the leading edge was used as exciter and the other one closer to the leading edge was used as sensor.

To measure structural vibration velocities, a single point Laser Doppler Vibrometer was used which is based on the “Doppler effect”. Additional transducers consisted of two IEPE accelerometers, a force transducer and an instrumented hammer with a steel tip. For signal acquisition, recording and analyzing a sweep signal function generator, an analog to digital (A/D) converter with simultaneous channel sampling and a Fourier analyzer system were used.

The dynamic response of profile was studied under different flow conditions including leading edge attached sheet cavitation and supercavitation. Before filling the tunnel, a modal analysis was performed to obtain the reference natural frequencies (“Air” condition). Then, with the tunnel full of still water, the “Still water” conditions were also obtained. Finally, the “Cavitation” conditions were selected to ensure a series of stable attached cavities as shown on the left of Figure 1. The cavity lengths were varied from 2 to 75 % of the chord at 14 m/s free stream velocity and for two incidence angles of 1° and 2°.

3. Numerical model

A NACA0009 hydrofoil mounted inside the tunnel test section submerged with water was modelled with a FEM solver. A coupled Structural – Acoustic analysis was used to simulate the dynamic behaviour of the system. A sensibility analysis of the solid domain mesh was performed to determine its optimal size. Regarding the fluid domain, the dimensions were also selected to ensure that the lateral walls considered as fully reflective did not influence the numerical solution. Moreover, special attention was given to the small lateral gap between the hydrofoil tip section and the tunnel wall that has a size of approximately 0.12 mm as drawn in the centre of Figure 1. The final model can be seen on the right of Figure 1.

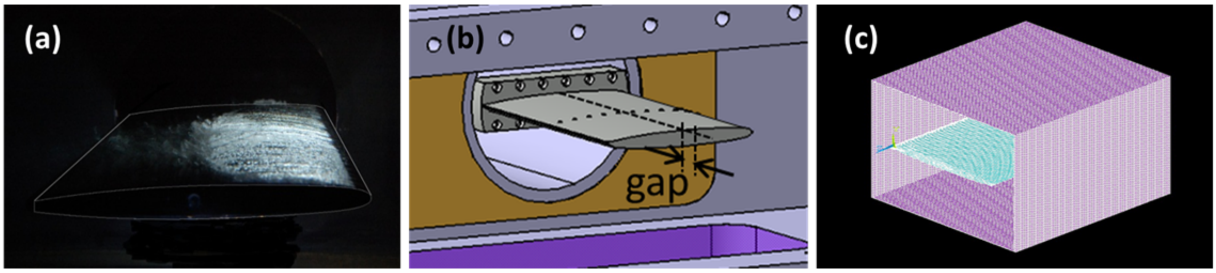

Figure 1. Photograph of partial cavitation (a), hydrofoil in the test section with lateral gap (b) and solid-fluid computational domain (c).

4. Results and discussion

To quantify the effects of various parameters on the modal behaviour of the hydrofoil, both the added mass coefficient, C_M, and the mode shapes have been determined and analysed. The C_M is defined by Equation (1) where f_{vacuum} and f_{fluid} correspond to the natural frequencies for the hydrofoil surrounded by air and by water or cavitation, respectively.

$$C_M = \left(\frac{f_{vacuum_i}}{f_{fluid_i}}\right)^2 - 1 \tag{1}$$

To characterize the attached cavity dimensions the CSR defined by Equation (2) has been used where l is the cavity length and c is the hydrofoil chord.

$$CSR = \frac{l}{2c} \tag{2}$$

In particular, the three first modes of vibration named f_1, f_2 and f_3 corresponding to the first bending, the first torsion and the second bending ones, respectively, have been identified and considered for the studies.

4.1. Cavity properties

As observed on Figure 2, the added mass effects depend on the particular mode shape. They are maximum for f_1 and minimum for f_2. The CSR obviously determines the effect but no linear relationship is found with C_M because other factors also influence the result. On the contrary, for the two angles of attack similar results are obtained.

A detailed analysis of the cavity morphology and dimensions [9] has demonstrated that a linear correlation can be found between C_M and the so-called entrained mass which accounts for the average density of the cavity, the hydrofoil surface covered by the cavity and its relative displacement induced by the mode of vibration. Therefore, for an accurate prediction of the added mass effects under cavitation conditions, these variables must be taken into account which is not an easy task. In particular, it is necessity to improve the experimental and numerical tools to quantify the void ratio of the cavities.

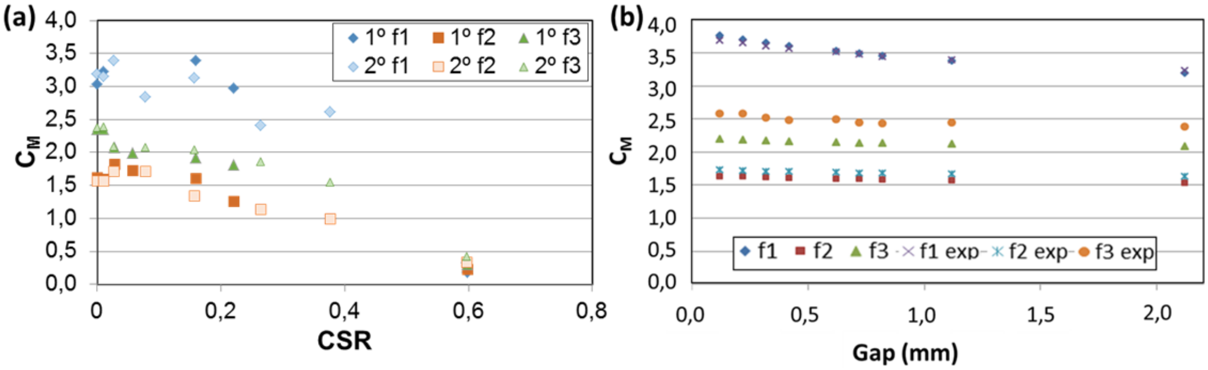

Figure 2. Added mass coefficient as a function of cavity surface ratio (a) and of lateral gap dimension without cavitation (b).

4.2. Lateral gap

A significant effect has been identified that is provoked by the narrow gap between the structure and the solid boundary. In our case, the experimental and numerical results plotted on the right of Figure 2 clearly show how the added mass effects increase following a quadratic law when the gap distance is reduced. This behaviour is observed in all the modes and the effect increases with mode order.

4.3. Mode shapes

Finally, a relevant mode shape alteration has been clearly measured regarding mainly the second bending mode, f_3, under cavitation conditions in comparison with the reference mode shape in air as shown in Figure 3. As observed, under partial cavitation the new mode loses the symmetry and it resembles a more complex bending-torsion coupled mode. The different properties of the fluids surrounding the hydrofoil -water and vapor-, their location and their size appear as the main factors determining the mode shape alteration.

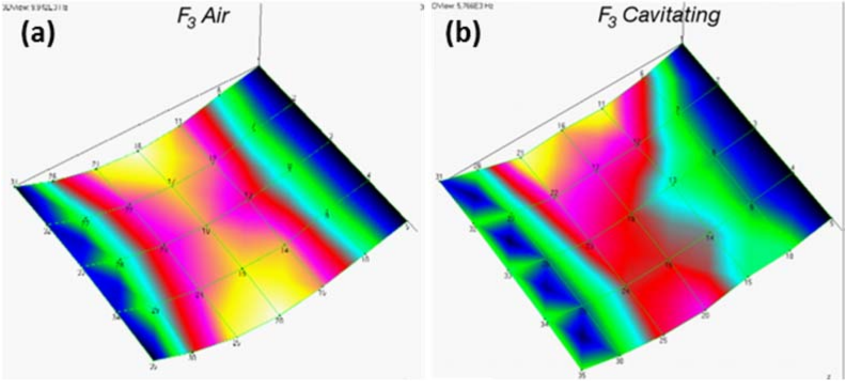

Figure 3. Mode shape of second bending mode of vibration obtained experimentally in air (a) and with attached partial cavitation (b).

5. Conclusions

The design of submerged structures that are prone to suffer macroscopic cavities attached to their surfaces requires the consideration of several parameters that have a significant effect on their dynamic response. The experimental and numerical studies demonstrate that the average properties of the cavity, the cavity size and the cavity location have a relevant effect on the added mass coefficients depending on the particular mode shape under consideration. Moreover, the existence of narrow gaps between the structure and the solid boundaries also has a significant influence on the overall behaviour. And finally, it must be noted that the new mode shapes might differ from the predicted ones in air conditions.

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