Cavitation Effects on the Structural Dynamics of Turbomachinery Components

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Extended Abstract

1 INTRODUCTION

The structural integrity of inducer and impeller blades in rocket engine turbomachinery must be evaluated in the face of complex excitation mechanisms including fluctuating pressures due to cavitation. Cavitation occurs when the local fluid pressure drops below the vapor pressure, causing the formation of vapor-filled bubbles. Cavitation can exist to various extents within the typical operating range of rocket engine turbopumps. Despite recent progress towards reducing uncertainties in structural dynamic models of turbomachinery components, the extent to which pump cavitation affects the structural dynamic properties (i.e., natural frequencies, damping, and mode shapes) of inducer and impeller blades remains largely unknown. To study the structural dynamic effects of cavitating flows, experiments are conducted in a high-speed water tunnel. The test article is a low aspect ratio cantilevered plate, thus mimicing a single inducer blade that is unwrapped from its hub. The test article is oriented at zero angle of attack and has a triangular trip at its leading edge to induce cavitation. To change the extent of cavitation, the static pressure of the water tunnel is controlled. A high-speed camera is used to quantify the coverage of the cavitation sheet.

2 PRIOR WORK

Over the last decade, a number of studies have focused on fluid-structure interaction (FSI) phenomena in rotating machinery [1]. A relatively small subset of this research has considered the FSI effects of cavitation (see Refs. [2–6]), with all of these studies involving hydrofoils as the structure of interest. In this study, two FSI effects are of particular interest: fluid-added mass and hydroelastic damping. Fluid-added mass refers to the fluid mass entrained by the vibration of the submerged structure. Because natural frequencies are related to the ratio of a structure's stiffness to its mass, decreasing fluid-added mass increases a structure's natural frequencies. Since cavitation involves vapor bubbles in the flow, fluid-added mass has been shown decrease with increasing levels of cavitation. This relationship has been quantified for cavitating hydrofoils [3], but never for structures resembling inducer or impeller blades.

Hydroelastic damping refers to the energy losses from interactions between a structure and flowing fluid. Hydroelastic damping can be predicted using analytical, numerical, or computational techniques, and is still an active area of research, even for non-cavitating flows. How cavitation affects hydroelastic damping of hydrofoils (let alone structures resembling inducer or impeller blades) remains an open question. Since hydroelastic damping can dominate the total damping, its prediction is essential to structural integrity assessments. In the absence of reliable damping inputs, analysts have no recourse but to assume damping values that are conservatively low. This can result in situations in which existing components fail structural integrity assessments. In the case of new designs, an overly conservative damping value results in components that are heavier than necessary. Reducing the weight of rotating components reduces power level requirements, which are one of the main drivers in turbopump design.

Understanding the effects of cavitation on fluid-added mass and hydroelastic damping is complicated by the fact that cavitation can have a destabilizing effect on structures. Not much research on the stability of structures in cavitating flows exists, but at least two theoretical studies suggest that cavitation has a destabilizing effect on structures, and can cause flutter to occur more readily than in corresponding non-cavitating flows [7, 8]

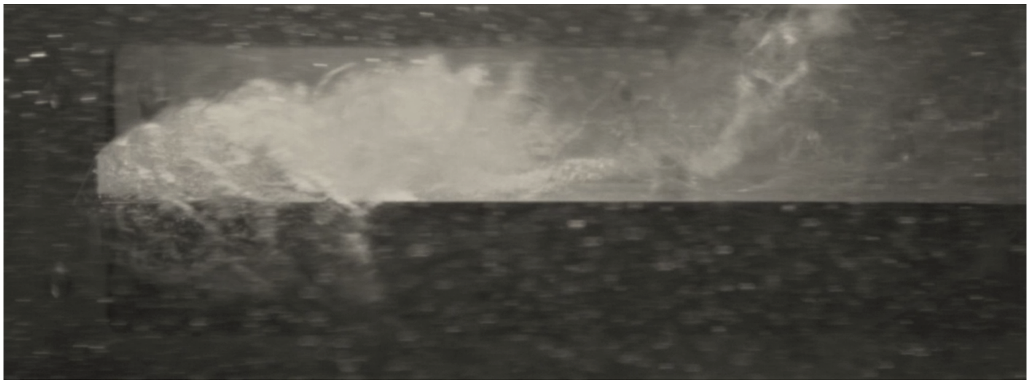


Figure 1: Cavitation on the test article at a cavitation number of 0.50 corresponding to 35.66 kPa absolute static pressure and 11.5 m/s flow speed.

3 TEST SETUP

Tests on cavitating plates are conducted in the high speed water tunnel at the University of Georgia. The water tunnel generates flow speeds up to 12.5 m/s in a 0.3 m x 0.3 m x 0.9 m rectangular test section. The water tunnel offers variable internal static pressurization from -20.68 to 48.26 kPa gauge (0.80 to 1.48 atm absolute) in the test section with no flow. Testing is performed on an AISI 304 stainless steel plate immersed in flow. The plate's span, chord and thickness are 12.07 cm, 30.49 cm, and 1.59 mm, respectively. A stainless steel fixture mounts the plate to a wall of the test section in a cantilever configuration at zero angle of attack. The leading edge of plate is fitted with a 3D printed triangular attachment. In high-speed flow with low static pressures, high-vapor-fraction cavitation forms at the plate's leading edge (Fig. 1). This sheet extends to approximately 43% of the plate's chord at a cavitation number of 0.188 corresponding to 14.98 kPa absolute static pressure and 11.5 m/s flow speed. The dynamic displacement of the test article is collected using a Micro-Epsilon optoNCDT 1420 triangulation laser. The laser has a sampling rate of 4 kHz and is mounted to the water tunnel test section. The cavitation sheet is recorded with a Chronos 2.1 HD monochrome high-speed camera.

For all tests presented here, the flow speed in the test section was set to 11.5 m/s. The absolute static pressure was held at 6.89 kPa increments decreasing from 90.82 kPa to 14.98 kPa, which produced cavitation numbers decreasing from 1.335 to 0.188. At each pressure set point, data were continuously collected for 2 minutes. The response measurement point was located at 82.60% of span and 98.69% of chord.

4 RESULTS

Fig. 2 shows the power spectral densities (PSD) of the plate response in the style of a spectrogram, with the horizontal axis denoting the cavitation number in the water tunnel. In this series of tests, leading edge cavitation first becomes visually pronounced at a cavitation number of 0.55, with the extent of cavitation increasing with decreasing cavitation number. The response of the plate is purely due to the fluctuating pressures of the flow, and since the frequency content of turbulent flow is known to roll-off dramatically with increasing frequency, only the first two natural frequencies (23.5 Hz and 48.0 Hz at the highest pressure) of the plate are clearly evident in the response. As cavitation number is reduced and cavitation begins to be present, both of the first two natural frequencies reduce considerably and appear to nearly merge, resulting in a high-amplitude response that is dominated by a single resonance. This behavior is reminiscent of two-mode flutter where the two component natural frequencies abruptly shift toward each other with increasing flow speed and coalesce at the flutter speed. In the present case, it is not clear whether the structure loses stability via flutter and has gone into a limit cycle oscillation (LCO), or whether the structure remains stable while merely approaching the stability boundary. The fact that higher-order harmonics of the plate's response are not evident suggest that the latter possibility is more likely.

To better observe the relevant trends from Fig. 2, the (a) natural frequencies and (b) damping ratios of the first two plate modes are plotted against cavitation number in Fig. 3. The natural frequencies are determined by dividing the resonance frequencies of the FFT by $\sqrt{(1-2\zeta^2)}$, and the damping ratios are determined by fitting the FRF of a damped SDOF oscillator to resonance peaks. The fitting algorithm uses least squares minimization over 7 Hz and 6 Hz bands for the first and second modes, respectively. Fig. 3 (a) indicates that, prior to cavitation, the natural frequencies are relatively flat, and both experience a dramatic reduction when the cavitation number is 0.35. The damping trends in Fig. 3 (b) are similar, though for cavitation numbers above 0.35 damping does appear to increase somewhat with decreasing pressure. There is a dramatic reduction in first-mode damping for cavitation numbers below 0.35.

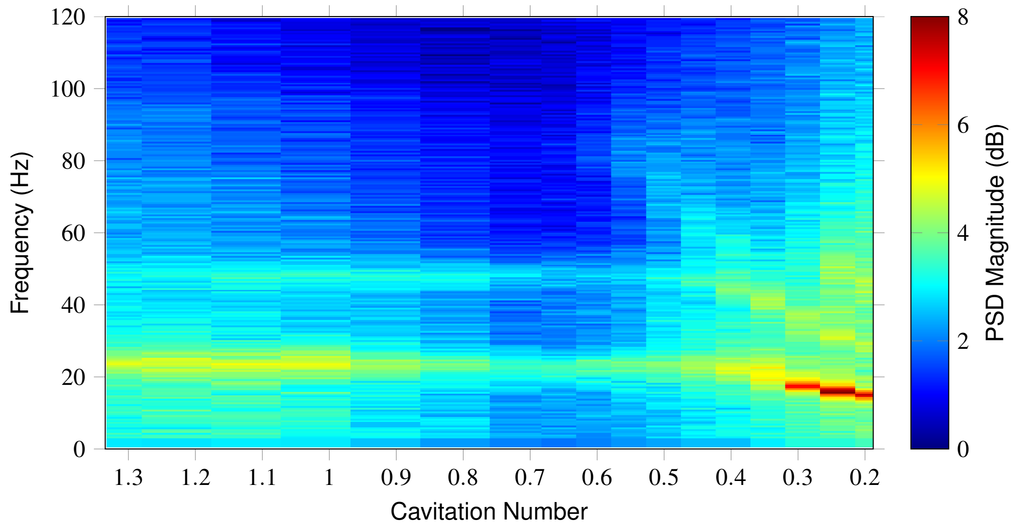
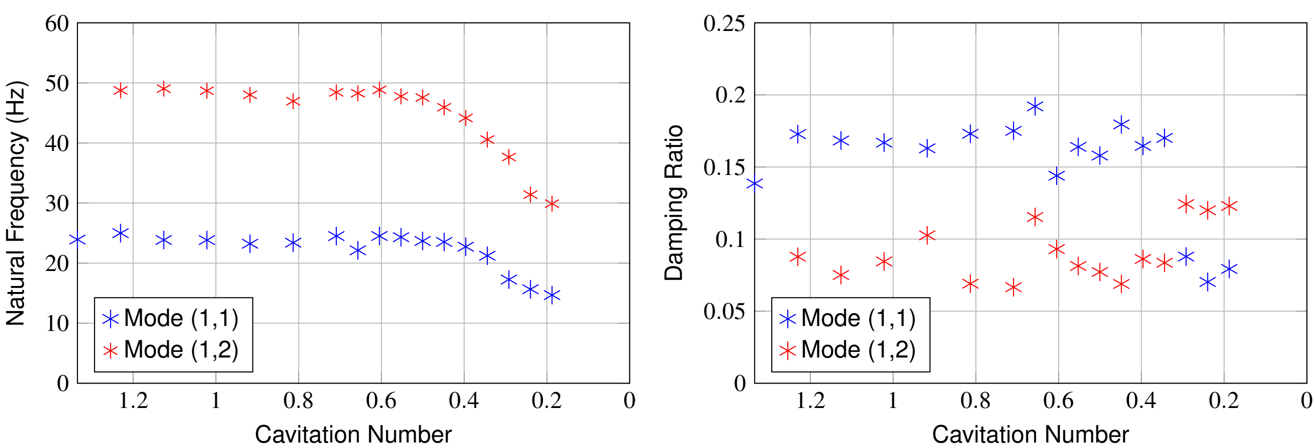


Figure 2: Effects of varying cavitation number on plate response frequency content. Here, 0 dB represents the lowest spectral power density in the domain shown (0.0944 mm^2/Hz).



(a) (b)

Figure 3: Effects of varying cavitation number on (a) natural frequencies and (b) critical damping ratios of the first two plate modes.

5 CONCLUSIONS AND FUTURE WORK

The preliminary results presented here indicate that cavitation-induced changes to the structural dynamic properties of submerged plates are more complicated than initially thought. At least for the present test article, cavitation appears to have a destabilizing effect that can dramatically reduce both natural frequency and damping. Corresponding behavior has not been observed in rocket engine inducer blades, suggesting that typical inducer blades occupy a region of parameter space that is more hydroelastically stable in the presence of cavitation. Future work will be aimed at improving our understanding the hydroelasric stability envelopes, and a two-way coupled CFD/FE model is under development to aid in this effort. Ultimately, we will use our improved understanding to redesign a test article that still cavitates, but is less susceptible to instability at the tested flow speed. Having such a test article allow us to isolate the structural dynamic effects of cavitation under hydroelastically stable conditions.

ACKNOWLEDGEMENTS

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