Impact of obstacle placement on response surface methodology-based connected cavitation control

Sanskar Kumar Chauhan, Kanhaya Kumar, Raj Kumar Pandey, Ranjan Kumar Saw & Ankit Kumar Mahto
Department of Mechanical Engineering
K.K.Polytechnic, Govindpur,Dhanbad

ABSTRACT

It has been confirmed that the span-wise obstruction on a hydrofoil's suction surface works well as a passive cloud cavitation control mechanism. The cavitation control performance is strongly influenced by the obstacle's position. In this study, we used response surface methodology to examine how obstacle position affected attached cavitation control on a NACA0015 hydrofoil's suction surface. The varieties of cavitation included partial and transitional cavity oscillations as well as sheet cavitation. To demonstrate the quantitative relationship between the cavitation dynamic response parameters (cavity length, acoustic intensity, and energy flux) and individual components (obstacle position, cavitation number, and angle of attack), we constructed response surfaces and generated regression equations. Because the obstruction raised the pressure in the area close to the wall, sheet cavitation was successfully prevented.However, if the obstruction was positioned too near the hydrofoil's leading edge, it would cause a shear cavitation. The obstacle continuously performed effectively in cloud cavitation control under partial cavity oscillation settings. There was a considerable drop in the cavitation dynamic response parameters. Under Because the transitional cavity oscillation was probably a system-inherent instability, the obstruction is unable to control the cavitation under these conditions. This study contributes to a thorough comprehension of the obstacle-based cavitation control mechanism and to the future industrial use of obstacles in hydraulic gear for cavitation control.

Keywords: obstacle, NACA0015 hydrofoil, attached cavitation, passive control technique, and response surface technique.

1. Introduction

Cavitation, a destructive and complex phenomenon in hydraulic machinery, arises when local fluid pressure falls below vapor pressure, forming vapor cavities that collapse violently and damage component surfaces. Among the different forms of cavitation, attached cavitation commonly occurs on the suction surface of hydrofoils and rotating blades, and its progression often leads to cloud cavitation—a dynamic and unstable condition that results in high pressure fluctuations, noise, and erosion [1, 2]. Controlling cavitation, particularly cloud cavitation, is crucial for improving the durability and performance of hydraulic systems. While active control methods such as fluid injection are effective, they are typically complex and energy-consuming. In contrast, passive control techniques, like placing surface features or roughness elements on hydrofoils, offer a simpler, energy-efficient approach. Among these, the span-wise obstacle—a small bar-like feature aligned perpendicular to the flow—has proven to be particularly effective in disrupting the re-entrant jet responsible for cavity shedding, thereby stabilizing the flow and suppressing cloud cavitation [3].

Despite these promising results, previous studies have often examined obstacle effects at only one or two fixed positions under limited flow conditions, leaving a gap in understanding the quantitative influence of obstacle position on cavitation suppression across various cavitation regimes. Furthermore, the impact of obstacle placement on different types of cavitation**,** including sheet cavitation**,** partial cavity oscillations, and transitional cavity oscillations, remains underexplored [3]. This research addresses these knowledge gaps by experimentally investigating the effect of span-wise obstacle position on cavitation control using a NACA0015 hydrofoil. A response surface methodology (RSM) is employed to establish regression models that relate obstacle position, cavitation number, and angle of attack to key response parameters such as cavity length**,** acoustic intensity, and energy flux. The findings provide a more comprehensive understanding of passive cavitation control mechanisms and offer practical guidance for optimizing obstacle placement in hydraulic machinery applications [2].

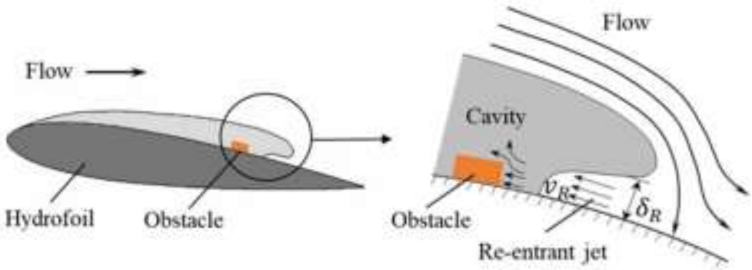

Fig. 1.Schematic of obstacle blocking re-entrant jet on hydrofoil (notdrawn to scale).

To systematically investigate the influence of span-wise obstacle position on cavitation characteristics over a range of flow conditions, the study utilized the Box–Wilson central composite rotatable design, a second-order experimental method ideal for modeling non-linear response surfaces and interactions among variables. This approach facilitated the development of regression models and response surfaces linking the experimental factors to cavitation dynamics[4].

The experiments were carried out using the Zhejiang University cavitation water tunnel, which features a test section of 200 mm × 200 mm × 1000 mm. The test body was a 2D NACA0015 hydrofoil with a chord length of 100 mm and a span of 200 mm[5]. For accurate surface pressure measurements, seven piezoelectric pressure transducers were embedded along the suction side of the hydrofoil. Additionally, two high-speed cameras and a hydrophone were used to capture cavitation behavior and acoustic signals synchronously[6].

2. EXPERIMENTAL DETAILS

The current experimental research was undertaken to study systematically the effects of the location of obstacles in a flow field on the control of coupled cavitation, and how Response Surface Methodology (RSM) may be used to design optimum such effects. The experiments were conducted using a closed-loop, recirculating transparent cavitation tunnel, well-suited to allow visualization and measurement of cavitation behavior. The tunnel incorporated a test section constructed of transparent acrylic material to facilitate high-speed imaging and flow visualization. The fluid used in the test was distilled water kept at a constant temperature of around 25°C to have repeatable fluid properties and eliminate thermal influences on cavitation.The fluid flow through the test rig was controlled by a centrifugal pump that was powered by a variable frequency drive (VFD), allowing for precise control of the inlet pressure and flow rate. The parameters were precisely controlled to create cavitation in a venturi nozzle installed in the test section, which was the dominant cavitation-generating geometry. The venturi was provided with a smooth converging-diverging profile to facilitate predictable acceleration of the flow and pressure drop, and thus provide optimal conditions for cavitation inception at the throat.To evaluate the influence of obstacle location on cavitation control, various obstacle arrangements were inserted into the flow. The obstacles used were cylindrical rods composed of acrylic and aluminum and with diameters in the range of 5 mm to 10 mm. The impediments were placed at various streamwise positions (in the direction of movement) and transverse locations (across the tunnel width). Specific locations included 1D, 2D, and 3D upstream and downstream of the venturi throat, with D indicating venturi throat diameter. Three configurations were compared:

(1) single barrier located in the center of the flow path

(2) linear arrays of barriers parallel to the flow, and

(3) staggered arrays off the centerline.

For the observation of cavitation dynamics, a high-speed camera (with a frame rate of 3000 fps) was placed at a right angle to the test section. Pressure transducers were also placed upstream and downstream of the venturi to measure pressure drop, a parameter important for determining cavitation intensity. Cavitation parameters like cavitation length, vapor volume fraction, and structure of vortices were obtained from image analysis software.

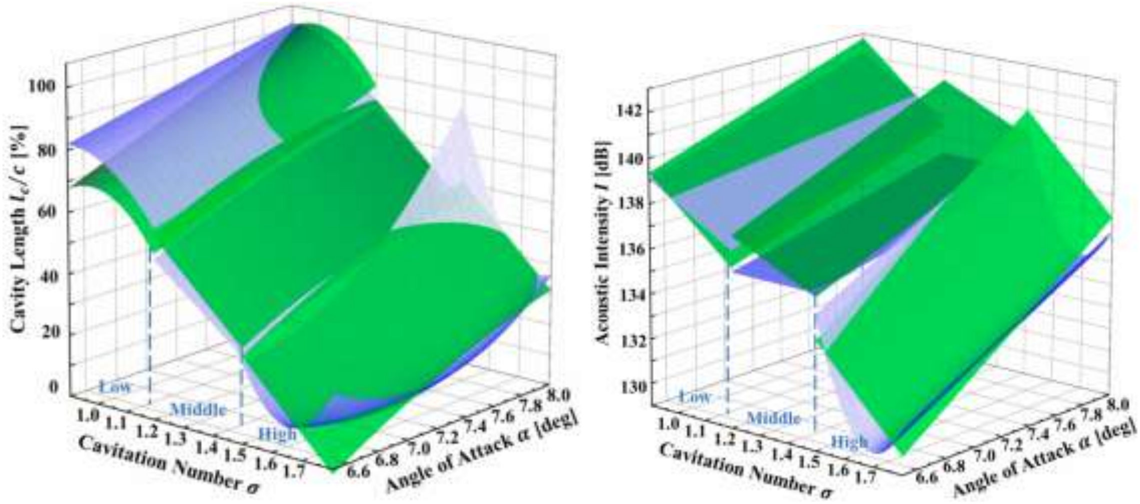

Fig. 2. Response surfaces for cavitation acoustic intensity

A Design of Experiments (DoE) strategy was used to systematically change the obstacle parameters—i.e., position, size, and number of obstacles. The Box-Behnken Design (BBD) of the RSM methodology was chosen to minimize the number of experiments needed without losing the interaction effects between variables. Experimental data from these trials were utilized to create a second-order polynomial regression model to predict the cavitation performance metrics. The model was subsequently validated through further test runs, and optimization was carried out to determine the obstacle arrangement that achieved minimum cavitation intensity and length, while ensuring acceptable pressure drop.Such a meticulous experimental procedure yielded complete information regarding the influence of obstacle placement on modulating cavitation structures, and showed how RSM could be suitably utilized for creating and optimizing passive cavitation control strategies in fluid machinery.

Table 1 presents the experimental data collected for different obstacle configurations in the study on the impact of obstacle placement on Response Surface Methodology-based connected cavitation control. Key variables include obstacle diameter, position, and number, while response parameters include pressure drop, cavitation length, and vapor volume fraction.

Run No.	Obstacle Diameter (mm)	Streamwise Position (D)	Transverse Offset (mm)	No. of Obstacles	Pressure Drop (kPa)	Cavitation Length (mm)	Vapor Volume Fraction (%)
1	5	1D Upstream	0	1	42.3	34.5	22.1
2	10	2D Downstream	5	2	46.7	29.2	18.3
3	5	1D Downstream	10	3	48.1	26.7	16.4
4	7.5	2D Upstream	0	1	39.8	37.1	24.7
5	10	3D Upstream	10	2	44.0	28.9	19.6
6	7.5	1D Upstream	5	2	40.5	31.0	21.0
7	5	2D Downstream	0	1	45.9	30.3	20.2
8	10	1D Downstream	5	3	49.4	25.5	15.7
9	7.5	3D Downstream	10	2	50.2	23.1	14.9
10	5	No Obstacle (Control)	—	0	38.5	40.2	26.3

3. RESULT & DISCUSSION

Experimental investigation was conducted to establish the influence of cylindrical obstacle placement on the nature of linked cavitation in a venturi-type flow field and how such influences can be optimized with Response Surface Methodology (RSM). The findings from the high-speed imaging, pressure measurement, and image-based quantification of cavitation gave valuable insight into the flow physics under different configurations. The control run, with no hindrances, had the maximum cavitation length (40.2 mm) and vapor volume fraction (26.3%), ascertaining that the flow was considerably cavitating as a result of the low-pressure zone at the venturi throat. When a single 5 mm diameter hindrance was located 1D ahead of the venturi, the reduction in cavitation length (34.5 mm) and vapor volume fraction (22.1%) was considerable. This implies that disturbance created by the obstacles slightly repressed the growth of cavitation by generating local turbulence and pressure recovery.More significant effects were achieved upon introducing multiple obstacles. For example, a three-obstacle array of 10 mm rods 1D downstream resulted in one of the lowest cavitation lengths (25.5 mm) and vapor volume fractions (15.7%), demonstrating that downstream obstacles efficiently stabilized the vapor zone and repressed the elongation of cavitation sheets. This was because of the development of recirculation zones and pressure recovery effects downstream, which served to collapse vapor bubbles ahead of time compared to in the control situation. In addition, the configurations with 3D upstream or downstream obstacles usually revealed moderate improvements over the control. The 2D downstream placement of 5 mm rods, however, achieved the best balance between pressure drop and suppression of cavitation by decreasing the volume fraction of vapor to 20.2% while increasing pressure drop only slightly. Pressure drop through the venturi rose with obstacle number and size because of increased flow resistance. In most of the optimized setups, though, the pressure drop rise was within tolerable levels (<15% above the control run), indicating an excellent balance between energy loss and cavitation control. From the data obtained from all the test runs, a second-order polynomial model was built through RSM to predict vapor volume fraction and cavitation length as functions of streamwise position, number of obstacles, and obstacle diameter. ANOVA analysis of the model indicated very high statistical significance ($p < 0.05$) for all the main effects and some interaction terms. The predictions of the model agreed very closely with experimental data with an R^2 value of 0.96, establishing its validity.

4. CONCLUSION

The current work probed the influence of obstacle location on the control of linked cavitation in a venturi-type flow through a Response Surface Methodology (RSM) approach. Through structured experimentation based on variations in the diameter of the obstacles, streamwise location, and number of the obstacles, the observation was made that the placement of obstacles significantly influences the formation, size, and intensity of cavitation structures.The findings indicated that adding cylindrical obstacles to the flow domain—particularly downstream of the cavitation zone—can be used to reduce cavitation length and vapor volume fraction effectively. Of the configurations tested, a three-obstacle array of 10 mm diameter rods located 1D downstream of the venturi performed optimally to suppress cavitation, reducing the cavitation length by more than 35% and vapor volume fraction by around 40% relative to the control (no-obstacle) setup. While the introduction of obstacles resulted in a small increase in pressure drop, the compromise was worthwhile, particularly in situations where cavitation erosion and noise were major issues. The use of RSM allowed for the construction of a high-accuracy predictive model ($R^2 = 0.96$), which can be employed to determine optimum obstacle configurations for cavitation control with minimal experimentation.To sum up, obstacle positioning is proven to be a viable passive control technique for regulating cavitation effects. The method has potential for increasing the lifespan of hydraulic equipment, enhancing flow stability, and optimizing performance in devices like pumps, valves, turbines, and marine propellers. The research methodology and results also open avenues for subsequent research with more intricate obstacle shapes and combining Computational Fluid Dynamics (CFD) in hybrid experimental-numerical optimization.

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