Postprint: Counter-Rotating Pump-Jet Propulsor Design for High Cavitation Performance

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Abstract

The propulsor converts mechanical energy from the power equipment into thrust to propel the vehicle forward, serving as a critical power device that determines vehicle performance. As vehicle speed increases, propulsors are prone to issues including cavitation, noise, and reduced propulsion efficiency. Addressing the demands of high-speed propulsion and leveraging the performance advantages of contra-rotating pumps, this paper proposes a contra-rotating pump-jet propulsor configuration. Through a series arrangement of front and rear rotors rotating in opposite directions, this design replaces conventional modes with a higher-density energy conversion model, achieving relatively lower rotor speeds and blade loads under identical design parameters, thereby enhancing the anti-cavitation performance and associated acoustic characteristics of the vehicle propulsor. Based on the performance parameters of a specific vehicle, an experimental model pump-jet and its test system are designed via similarity scaling, with propulsor performance investigated through numerical simulation. The results indicate that the Euler energy distribution and load model of contra-rotating pump-jet propulsor blades are markedly superior to those of single-rotor propulsor blades, with significant improvements in anti-cavitation performance.

Full Text

Design of Contra-Rotating Waterjet Pump Based on High Cavitation Performance

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Abstract: The propulsor converts mechanical energy from the power plant into thrust to drive an underwater vehicle forward, making it a critical component that determines vehicle performance. As vehicle speed increases, propulsors commonly encounter cavitation, noise, and declining propulsion efficiency. Addressing the need for high-speed propulsion and leveraging the performance advantages of contra-rotating pumps, this paper proposes a contra-rotating waterjet pump configuration. Through the series connection and counter-rotation of front and rear rotors, this design replaces the traditional model with a higher energy conversion density, achieving relatively lower rotor speeds and blade loading under identical design parameters, thereby enhancing cavitation resistance and acoustic performance. Based on the performance parameters of a specific underwater vehicle, an experimental model waterjet pump and test system were designed through similarity conversion, and the propulsor performance was investigated via numerical simulation. Results demonstrate that the contra-rotating waterjet pump exhibits significantly improved Euler energy distribution and loading models compared to single-rotor propulsors, with markedly enhanced cavitation performance.

Key words: Waterjet pump; Underwater vehicle; Contra-rotating pump; Cavitation-resistant design; Blade loading distribution

0 Introduction

The required thrust and operating depth directly determine the configuration of the propulsion system. Mainstream propulsor types for current underwater vehicles include single-rotor propellers, contra-rotating propellers, waterjet pumps, and ducted propellers. From a technical standpoint, both propellers and waterjet pumps face a series of challenges associated with increased rotational speed as vehicle velocity and propulsion power rise, with the most critical issues being cavitation, noise, and propulsion efficiency degradation [1,2,3].

Traditional propulsors typically rely on increasing rotational speed to enhance thrust. However, as rotational speed increases, the relative fluid velocity rises substantially, making cavitation difficult to avoid in high-speed propulsors. Cavitation bubble growth and shedding generate intense broadband noise, severely compromising acoustic performance [4]. The continuous evolution of cavitation bubbles also alters blade surface pressure distribution, leading to increased unsteady blade loading. Since cavitation development varies among blades during high-speed rotation, propulsors experience severe vibration. Furthermore, propulsors with weak cavitation resistance may encounter sudden cavitation growth, causing large-scale flow blockage, rapid deterioration of power capacity, and sharp declines in propulsion efficiency. Therefore, maintaining lower rotational speed while ensuring equivalent propulsion capability represents an important design philosophy for advancing high-speed propulsion systems.

A contra-rotating pump consists of two counter-rotating rotors arranged in series. Its core concept involves utilizing the residual energy from the front rotor' s outflow, which is captured by the rear rotor and converted into pressure head, achieving swirl-free discharge at the pump outlet and significantly increasing energy density. The rear rotor' s contribution to head rise far exceeds that of conventional stators, and the distribution of head and torque between the two rotors can be adjusted through speed regulation. By fully exploiting the front rotor' s outflow energy, such pumps have been demonstrated in theoretical and experimental studies to achieve lower rotational speeds, higher hydraulic efficiency, more compact structures, more stable performance curves, and superior cavitation performance compared to conventional pumps under identical design specifications (flow rate, head, specific speed, etc.) [5-8].

These advantages of contra-rotating pumps align well with the requirements of high-speed underwater vehicle propulsion systems. Although similar in appearance and internal flow mechanisms to ducted contra-rotating propellers, contra-rotating waterjet pumps fundamentally belong to the pump category, utilizing rotor blades to pressurize water and channel geometry to generate high-velocity jets for thrust production. This paper proposes introducing the contra-rotating pump concept into waterjet propulsion systems, establishing a contra-rotating waterjet pump concept for small underwater vehicles. Based on the performance parameters of a specific underwater vehicle, an experimental model waterjet pump and test system were designed through similarity conversion, and preliminary investigations were conducted using numerical techniques.

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1 Contra-Rotating Waterjet Pump Design

1.1 Propulsor Parameters

This paper designs a first-generation experimental model waterjet pump based on the performance parameters of an underwater vehicle through similarity conversion. During the initial design verification phase, the first-generation experimental model was configured as an axial-flow rotor type, comprising three components: a front rotor, rear rotor, and nozzle. The computational model is shown in [Figure 1: see original paper].

The flow direction in the figure is from right to left. Viewed from inlet to outlet, the front rotor rotates counterclockwise while the rear rotor rotates clockwise. The computational domain inlet is positioned approximately two diameters upstream of the front rotor leading edge, and the outlet is located about three diameters downstream of the guide cone trailing edge—a configuration validated through grid independence studies. ANSYS TurboGrid 16.0 was employed for rotor grid generation. To facilitate structured grid creation, an extremely thin virtual hub was added downstream of the guide cone, with negligible impact on hydraulic performance calculations.

Key design parameters for the waterjet pump are presented in and .

1.2 Rotor Design Methodology

High cavitation performance design approaches the problem from two perspectives: first, employing a contra-rotating configuration to reduce blade loading on individual rotors and decrease rotational linear speed; second, optimizing blade profile loading based on this contra-rotating structure.

The contra-rotating rotors utilize an equal-speed differential design. To simplify implementation, equal-speed drive is prioritized, thereby simplifying the reversing mechanism. Given the different positions relative to the incoming flow, the front rotor emphasizes cavitation-resistant design while the rear rotor focuses on propulsion performance. Additionally, from a system matching perspective, drive system stability is crucial. To eliminate residual torque in the drive mechanism, torque balance must be satisfied between the front and rear rotors.

The principle of airfoil design lies in optimizing blade loading. Addressing the deterioration of cavitation performance at blade tips, the design utilizes variations in airfoil angle of attack to achieve slight unloading at the tip, simultaneously weakening tip leakage flow. All five design sections employ NACA 4-digit series airfoils. By specifying a linear increase in the relative position of the maximum camber (xf/l) from hub to tip—effectively shifting the loading point rearward—further tip unloading is achieved to improve cavitation performance. The final airfoil design parameters are listed in .

1.3 Nozzle Design Methodology

Nozzle design controls flow area variation to obtain a uniform, stable flow field, avoid flow separation, and minimize losses. Based on a contraction ratio of 1.77 and referencing empirical values for water tunnel contraction section design [9,10], the initial length-to-diameter ratio was set at L/D=1. Using curve data from literature [11], a fifth-order polynomial curve was selected and transformed into area variation. The inner guide cone follows a parabolic curve with a length-to-diameter ratio of 1. The outer curve equation was then calculated from the area variation and inner curve equation, with smooth transition processing at boundary points. The final nozzle geometry is shown in [Figure 2: see original paper]. Numerical calculations of the designed nozzle revealed a uniform, stable flow field without separation, confirming the design' s validity.

1.4 Numerical Calculation Method

Numerical computations were performed using the commercial CFD software ANSYS CFX 16.0. Full-channel unsteady calculations were employed for hydraulic performance and internal flow characteristic evaluation, while single-passage steady two-phase flow calculations were used for cavitation performance assessment. ANSYS TurboGrid 16.0 generated the computational grids, with grid independence analysis determining final grid counts of approximately

520,000 cells for the front rotor single passage, 350,000 cells for the rear rotor single passage, and 870,000 total cells for the entire pump single passage.

Boundary conditions were specified as follows: mass flow rate inlet, opening outlet, rotating wall for blades and hub, and counter-rotating wall for the shroud. For cavitation calculations, the medium consisted of two phases—water and water vapor at 25°C—with initial volume fractions of 0 for vapor and 1 for liquid. The SST turbulence model and Rayleigh-Plesset cavitation model were employed. High-resolution discretization schemes were used with RMS residual convergence criteria set to 1×10 .

2 Performance Analysis

2.1 Hydraulic Performance

Unsteady hydraulic performance numerical calculations for the contra-rotating waterjet pump are presented in [Figure 3: see original paper]. At design conditions, the pump head is approximately H = 15.28 m, pump efficiency = 90%, and thrust T = 1.48 kN. The H-Q curve for the contra-rotating waterjet pump is relatively steep, with the efficiency curve remaining relatively flat near the design condition—consistent with performance studies of contra-rotating axial-flow pumps [5].

2.2 Cavitation Performance

To obtain the cavitation characteristic curve, numerical calculations were conducted by varying the outlet pressure from 150 kPa down to 50 kPa, corresponding to NPSHa values decreasing from 14.1 m to 7.7 m. Each calculation used the previous result as the initial condition to improve computational efficiency. The resulting cavitation characteristic curve for the contra-rotating waterjet pump rotor is shown in [Figure 4: see original paper].

The critical cavitation condition is defined as the NPSHa at which head drops by 3%. From the cavitation characteristic curve, the critical net positive suction head is NPSHcr = 8.44 m. The traditional cavitation specific speed is calculated using Eq.(1), where n (min ¹) represents rotor speed and NPSHr (m) represents required net positive suction head.

Using Eq.(1) with n = 2000 rpm and substituting NPSHcr for NPSHr, the cavitation specific speed is calculated as C = 1045. However, since the contra-rotating pump employs two counter-rotating rotors, the traditional definition cannot fully represent its cavitation performance. Furukawa A et al. from Kyushu University' s Fluid Control Research Laboratory derived the relationship between contra-rotating and single-rotor axial-flow pumps under identical design conditions as shown in Eq.(2), where subscripts RR and RS denote contra-rotating pump and single-rotor pump, respectively.

Based on Eq.(2), converting the contra-rotating pump to an equivalent single-rotor pump yields an equivalent cavitation specific speed of C = 1810. For further comparison, a single-rotor pump with identical design conditions was selected. At its design condition (Q = 0.212 m^3/s, H = 13.15 m, = 89%), its critical cavitation head was NPSHcr = 12.6 m, corresponding to C = 1160. This demonstrates that the contra-rotating pump' s cavitation performance is significantly improved.

2.3 Local Euler Energy Distribution

Five design sections along the blade span were selected to investigate local Euler energy distribution along the axial direction. Local Euler energy distribution characterizes the energy growth process from rotor inlet to outlet on the studied stream surface, defined by Eq.(3), where m represents the meridional coordinate, s the spanwise coordinate, U the circumferential velocity, V the circumferential component of absolute velocity, and Vm the meridional component of absolute velocity.

The local Euler energy distribution curves for both the contra-rotating waterjet pump and the single-rotor pump under identical design conditions are shown in [Figure 5: see original paper]. The results indicate that the two rotors of the contra-rotating pump share the loading, whereas the single-rotor pump bears the entire load on a single impeller. The front rotor exhibits a gentler slope, indicating gradual blade loading, while the rear rotor shows a steeper slope, reflecting higher energy density—consistent with the equal-speed differential design philosophy. In contrast, the single-rotor pump displays a significantly steeper slope, indicating larger energy gradients and greater susceptibility to cavitation and secondary flow phenomena.

2.4 Blade Loading Distribution

Blade loading distribution curves for the contra-rotating waterjet pump and the single-rotor pump are presented in [Figure 6: see original paper]. The single-rotor pump blade exhibits significantly lower minimum pressure and highly non-uniform loading, characteristic of front-loaded design. In contrast, each blade of the contra-rotating pump shows minimum pressure approximately half that of the single-rotor pump, with relatively uniform loading distributed over the middle and rear sections. This demonstrates that the contra-rotating pump' s loading distribution is substantially superior, resulting in improved cavitation resistance.

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3 Conclusions

This paper proposes the concept of a contra-rotating waterjet pump and designs a first-generation experimental model and test system based on the performance parameters of an underwater vehicle through similarity conversion. The design methodology for the contra-rotating pump rotors and nozzle is described, and numerical techniques are employed to investigate hydraulic and cavitation characteristics, with comparisons made to a single-rotor pump under identical design conditions. The main conclusions are:

1) At design conditions, the experimental model contra-rotating waterjet pump achieves a head of approximately H = 15.28 m, pump efficiency = 90%, and thrust T = 1.48 kN. The H-Q curve is relatively steep, while the efficiency curve remains relatively flat near the design condition.

2) The experimental model' s critical net positive suction head is NPSHcr = 8.44 m, yielding a cavitation specific speed of C = 1045 using the traditional calculation formula. When converted to an equivalent single-rotor pump, the equivalent cavitation specific speed becomes C = 1810, significantly higher than that of the comparable single-rotor pump. Analysis of local Euler energy distribution and blade loading distribution confirms that the contra-rotating waterjet pump' s cavitation performance is substantially improved.

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