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

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Abstract

Propellers convert mechanical energy from power equipment into thrust to drive the vehicle forward, and constitute key power devices that determine vehicle performance. As speed increases, propellers are prone to encountering problems such as cavitation, noise, and decreased propulsion efficiency. Combining the requirements for high-speed propulsion with the performance advantages of contra-rotating pumps, this paper proposes a contra-rotating pump-jet propulsor structure. Through the configuration of front and rear rotors in series rotating in opposite directions, this design replaces the traditional mode with a higher-density energy conversion model, achieving relatively lower rotor speeds and blade loads under equivalent design parameters, thereby improving the anti-cavitation performance and related acoustic performance of the vehicle propulsor. Based on the performance parameters of a specific vehicle, an experimental model pump-jet and its experimental system are designed through similarity scaling, and the propulsor performance is investigated via numerical simulation. The results demonstrate that the Euler energy distribution and load model of contra-rotating pump-jet propulsor blades are significantly superior to those of single-rotor propulsor blades, with substantially improved anti-cavitation performance.

Full Text

Preamble

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 power device that determines vehicle performance. As navigation speed increases, propulsors commonly encounter problems such as cavitation, noise, and declining propulsion efficiency. Combining the demand for high-speed propulsion with the performance advantages of contra-rotating pumps, this paper proposes a contra-rotating waterjet pump propulsor. Through a series arrangement of front and rear rotors rotating in opposite directions, this design replaces the traditional model with a higher-density energy conversion mechanism, achieving relatively lower rotor speeds and blade loading under equivalent design parameters, thereby enhancing the cavitation resistance and acoustic performance of the vehicle propulsor. Based on the performance parameters of a specific vehicle, an experimental model waterjet pump and its test system were designed through similarity conversion, and the propulsor performance was investigated via numerical simulation. Results demonstrate that the Euler energy distribution and loading model of the contra-rotating waterjet pump blades are significantly superior to those of single-rotor propulsors, with substantially improved cavitation performance.

Keywords: Waterjet pump; Underwater vehicle; Contra-rotating pump; Anti-cavitation design; Blade loading distribution

0 Introduction

The propulsor converts mechanical energy from the power plant into thrust to drive an underwater vehicle forward. Therefore, the vehicle' s navigation speed, required thrust, and operating depth directly determine the configuration of the propulsion system. Currently, mainstream propulsor types for underwater vehicles include single-rotor propellers, contra-rotating propellers, waterjet pumps, and ducted propellers. From a technical perspective, both propellers and waterjet pumps face a series of problems associated with high rotational speeds as vehicle speed and propulsion power increase, 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. As propulsor speed increases, the relative fluid velocity rises significantly, making cavitation difficult to avoid in high-speed propulsors. Regarding cavitation bubbles themselves, their growth and collapse are accompanied by intense broadband rupture noise, severely degrading propulsor acoustic performance [4]. The growth and shedding of bubbles continuously alter the blade surface pressure distribution, leading to increased unsteady blade loading. Moreover, the varying degrees of cavitation development on each blade during high-speed rotation cause severe propulsor vibration. Propulsors with weaker cavitation resistance may even experience sudden increases in cavitation scale, resulting in large-scale flow blockage, and a sharp decline in power capacity and propulsion efficiency.

Therefore, maintaining lower rotational speed while ensuring equivalent propulsion capability represents an important design philosophy for propulsors developing toward high-speed applications. A contra-rotating pump is a type of water pump consisting of two rotors rotating in opposite directions in series. Its core concept involves the rear rotor fully utilizing the residual energy from the front rotor' s outflow, converting it into pressure head to achieve swirl-free outflow for the entire pump and significantly increasing its energy density. The rear rotor' s contribution to head far exceeds that of traditional rear stators, and the distribution of head and torque between the two rotors can be adjusted through speed regulation. By fully utilizing the outflow energy from the front rotor, such pumps have been proven in theoretical and experimental studies to achieve lower rotational speed, higher hydraulic efficiency, more compact structure, more stable performance curves, and superior cavitation performance compared to traditional pumps under equivalent design parameters (flow rate, head, specific speed, etc.) [5-8].

The aforementioned advantages of contra-rotating pumps align well with the requirements of high-speed underwater vehicle propulsion systems. Although this contra-rotating pump shares many similarities with ducted contra-rotating propellers in appearance and internal flow mechanisms, its thrust generation mechanism still belongs to the pump category, utilizing rotor blades to pressurize water and channel geometry variations to achieve high-speed water jet propulsion.

This paper proposes introducing the contra-rotating pump concept into waterjet propulsion systems, forming a contra-rotating waterjet propulsor concept for small underwater vehicles. Based on the performance parameters of a specific underwater vehicle, an experimental model waterjet pump and its test system were designed through similarity conversion, and preliminary studies were conducted using numerical calculation techniques.

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1 Contra-Rotating Waterjet Pump Design

1.1 Propulsor Parameters

Based on the performance parameters of an underwater vehicle, a first-generation experimental model waterjet propulsor was designed through similarity conversion. In this initial design verification stage, the first-generation experimental model was configured as an axial-flow rotor type, consisting of three components: a front rotor, rear rotor, and nozzle. The computational model is shown in [Figure 1: see original paper].

The water 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 located approximately two diameters upstream of the front rotor leading edge, and the outlet is about three diameters downstream of the guide cone tail—this configuration has been verified through grid independence studies. ANSYS TurboGrid 16.0 was used for grid generation of the rotating components. To facilitate structured grid generation, an extremely thin virtual hub was added downstream of the guide cone, whose influence on hydraulic performance calculations is negligible.

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

TABLE:1 Performance design parameters of contra-rotating waterjet pump
TABLE:2 Geometrical parameters of contra-rotating waterjet pump

1.2 Rotor Design Methodology

High cavitation performance design of the waterjet propulsor approaches from two aspects: first, employing a contra-rotating structure to reduce blade loading on individual rotors and decrease the linear velocity of rotor rotation; second, further optimizing blade airfoil loading distribution based on the contra-rotating structure.

The contra-rotating rotors adopt a constant-speed differential design. To simplify the reversing mechanism, equal-speed drive is preferred. Considering that the front and rear rotors face different incoming flow positions, the front rotor emphasizes cavitation performance design while the rear rotor focuses on propulsion performance design. Additionally, from the perspective of matching performance with the vehicle, the stability of the drive system itself is crucial. To eliminate residual torque in the drive mechanism, torque balance constraints must be satisfied between the front and rear rotors.

The principle of airfoil design lies in optimizing airfoil loading. Addressing the degradation of cavitation performance at rotor blade tips, the design utilizes variations in airfoil attack angle to achieve slight unloading at the tip, simultaneously weakening tip leakage flow. All five design sections employ NACA 4-digit series airfoils. By specifying that the relative position of the airfoil camber line' s maximum height (x_f/l) increases linearly from hub to tip—meaning the loading point gradually moves rearward—further tip unloading is achieved to improve cavitation performance. presents the finalized airfoil design parameters.

TABLE:3 Design parameters of profile

1.3 Nozzle Design Methodology

Nozzle design controls the variation of flow passage area 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 as $L/D = 1$. Using curve data from reference [11], a fifth-order polynomial curve was selected and transformed into area variation. The inner guide cone curve is parabolic with a length-to-diameter ratio of 1, yielding its curve equation. The fifth-order outer curve equation was then calculated from the area variation and inner curve equation, with smooth transition processing applied at boundary points. The final nozzle curve is shown in [Figure 2: see original paper]. Numerical calculations of the designed nozzle revealed a uniform, stable flow field without flow separation, confirming the nozzle design' s validity.

1.4 Numerical Calculation Method

Numerical calculations in this study were performed using commercial CFD software ANSYS CFX 16.0. Hydraulic performance and internal flow characteristics were evaluated using full-passage unsteady calculations, while cavitation performance assessment employed single-passage steady two-phase flow calculations. ANSYS TurboGrid 16.0 was used for computational model grid generation. Following grid independence analysis, the final single-passage grid contained approximately 520,000 cells for the front rotor, 350,000 cells for the rear rotor, and 870,000 cells total for the single-passage pump model.

Boundary conditions were set as follows: inlet used mass flow rate boundary condition, outlet used opening boundary condition, blades and hub employed rotating wall boundary condition, and shroud used counter-rotating wall boundary condition.

For cavitation calculations, the medium selected was water and water vapor at 25°C. Initial gas volume fraction was 0 and initial liquid volume fraction was 1. The SST turbulence model and Rayleigh-Plesset cavitation model were employed. The solution scheme used high-resolution differencing scheme with RMS residual set to 1×10^{-4}.

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2 Results and Analysis

2.1 Hydraulic Performance

Unsteady hydraulic performance numerical calculations for the contra-rotating waterjet propulsor are shown in [Figure 3: see original paper]. At design conditions, the pump head is approximately $H = 15.28$ m, pump efficiency $\eta = 90\%$, and thrust $T = 1.48$ kN. As seen in [Figure 3: see original paper], the H-Q curve of the contra-rotating waterjet pump is relatively steep, while the efficiency curve remains 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 of the research object, numerical calculations were performed by varying the outlet pressure value to obtain a series of relationships between available net positive suction head (NPSHa) and total head H. Outlet pressure was reduced from 150 kPa 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 NPSHa at 3% head drop was taken as the critical cavitation margin for the contra-rotating pump. From the cavitation characteristic curve, the critical net positive suction head is NPSHcr = 8.44 m. The traditional cavitation specific speed formula is given by Equation (1):

$$C = \frac{n \cdot Q^{0.5}}{(NPSHr)^{0.75}}$$

where n (min^{-1}) is rotor speed and NPSHr (m) is required net positive suction head.

Using Equation (1) to calculate the cavitation specific speed of the contra-rotating pump with $n = 2000$ rpm and substituting NPSHcr for NPSHr yields $C = 1045$.

However, since the contra-rotating pump employs two counter-rotating rotors, the traditional cavitation specific speed definition cannot fully reflect its specific cavitation performance. Furukawa A et al. from Kyushu University' s Fluid Control Research Laboratory derived the relationship between contra-rotating axial-flow pumps and conventional axial-flow pumps under identical design conditions as shown in Equation (2):

$$\frac{C_{RR}}{C_{RS}} = \left(\frac{n_{RR}}{n_{RS}}\right)^{0.5} \cdot \left(\frac{NPSHr_{RS}}{NPSHr_{RR}}\right)^{0.75}$$

where subscripts RR and RS represent contra-rotating pump and single-rotor pump, respectively.

According to Equation (2), converting the contra-rotating pump to an equivalent single-rotor pump yields an equivalent cavitation specific speed $C = 1810$.

For further comparison, a single-rotor pump with identical design conditions was selected. At its design condition, flow rate $Q = 0.212$ m^3/s, head $H = 13.15$ m, and pump efficiency $\eta = 89\%$. Its critical net positive suction head was calculated as NPSHcr = 12.6 m, giving a cavitation specific speed $C = 1160$. 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 study the local Euler energy distribution along the axial direction. Local Euler energy distribution characterizes the energy growth process from rotor inlet to rotor outlet on the studied flow surface, defined by Equation (3):

$$LEH(m,s) = U(m,s) \cdot V_\theta(m,s) - U_{in}(s) \cdot V_{\theta,in}(s)$$

where m represents the meridional coordinate, s represents the spanwise coordinate, U is circumferential velocity, V_θ is the circumferential component of absolute velocity, and V_m is the meridional component of absolute velocity.

The local Euler energy distribution curves for the contra-rotating waterjet pump and a single-rotor pump with identical design conditions are shown in [Figure 5: see original paper]. The results show that the two rotors of the contra-rotating pump each bear part of the load, whereas the single-rotor pump relies on a single impeller to carry the entire load. Additionally, the front rotor curve has a smaller slope, indicating gradual blade loading, while the rear rotor has a steeper slope, indicating higher energy density—consistent with our constant-speed differential design philosophy. For the single-rotor pump, its slope is significantly steeper, indicating larger energy gradients on the blade and greater susceptibility to cavitation and secondary flow phenomena.

2.4 Blade Loading Distribution

The blade loading distribution curves for the contra-rotating waterjet pump and the single-rotor pump with identical design conditions are shown in [Figure 6: see original paper]. The results indicate that the minimum pressure on the single-rotor pump blades is significantly lower than that on the contra-rotating pump, with highly non-uniform loading distribution typical of front-loaded blades. In contrast, each blade of the contra-rotating pump exhibits minimum pressure approximately half that of the single-rotor pump, with essentially uniform blade loading distributed in the middle-to-rear region. Therefore, the loading distribution of the contra-rotating pump is clearly superior to that of the single-rotor pump, resulting in improved cavitation resistance.

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3 Conclusions

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

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

2) The critical net positive suction head of the experimental model contra-rotating waterjet pump is approximately NPSHcr = 8.44 m. Using the traditional cavitation specific speed formula yields $C = 1045$. When converted to an equivalent single-rotor pump, the equivalent cavitation specific speed becomes $C = 1810$, which is greater than that of the single-rotor pump under equivalent design conditions. Furthermore, analysis of local Euler energy distribution and blade loading distribution confirms that the contra-rotating waterjet pump' s cavitation resistance is significantly improved.

References

[1] Amsler R C, Thurston S. Review of marine propellers and ducted propeller propulsive devices [J]. Journal of Aircraft, 2012, 3(3):255-261.

[2] Wang Jinhua, Yan Weisheng, Liu Xulin. Development of Testing and Verification Techniques for Autonomous Underwater Vehicles[J]. Torpedo Technology, 2010, 18(3):202-208.

[3] Guo Qing. The Design and Development of the Torpedoes[J]. National Defense Science and Technology, 2011, 32(2):8-13.

[4] Van Oossanen P. Theoretical Prediction of Cavitation on Propellers[J]. Marine Technology Society Journal, 1977, 14(4):391-409.

[5] Furukawa A, Shigemitsu T, Watanabe S. Performance test and flow measurement of contra-rotating axial flow pump[J]. Journal of Thermal Science, 2007, 16(1):7-13.

[6] Momosaki S, Usami S, Okuma K, et al. Experimental Study on Rotational Speed Control of Contra-Rotating Axial Flow Pump[C]. Proceedings of 3rd Asian Joint Workshop on Thermophysics and Fluid Science, 2010.

[7] Momosaki S, Usami S, Watanabe S, et al. Numerical simulation of internal flow in a contra-rotating axial flow pump[J]. IOP Conference Series: Earth and

Environmental Science, 2010, 12:12046.

[8] Cao L, Watanabe S, Momosaki S, et al. Low Speed Design of Rear Rotor in Contra-Rotating Axial Flow Pump[J]. International Journal of Fluid Machinery and Systems, 2013, 6:105-112.

[9] Morel T. Comprehensive Design of Axisymmetric Wind Tunnel Contractions[J]. Journal of Fluids Engineering Transactions of the ASME, 1975, 97:225-233.

[10] Morel T. Design of Two-Dimensional Wind Tunnel Contractions[J]. Journal of Fluids Engineering Transactions of the ASME, 1977, 99:371-377.

[11] Zhou Gang, Wang Jiadao, Chen Haosheng, et al. Optimized design of the contraction in a minitype high-speed water-tunnel[J]. Journal of Ship Mechanics, 2009, 04:513-521.