Numerical Study on the Effect of Stepped Casing on Cavitation Flow Characteristics in an Inducer Postprint

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Abstract

The reusability and wide-range thrust variation capabilities of liquid rocket engines impose extremely high demands on the power capacity of turbopumps, which serve as critical components. The inducer is a key component that determines the cavitation resistance of the turbopump. Cavitation flow characteristics are highly sensitive to inlet flow conditions, and modifying the structural features of the inducer inlet casing may prove beneficial for enhancing the inducer's cavitation performance. This study employs advanced adaptive cavitation models to conduct numerical simulations of cavitation flow characteristics within a typical three-blade inducer. The numerical simulation method is first thoroughly validated against visualization experimental results, demonstrating that the employed numerical approach can satisfactorily predict both the cavitation patterns and performance within the inducer. Based on these numerical simulations, an in-depth analysis is performed on the cavitation flow characteristics within inducers matched with different stepped casings. The results indicate that the stepped casing with an expansion angle of 30° delivers optimal performance. The stepped expansion increases the upstream clearance of the inducer, thereby weakening flow-induced vibration effects. At the initiation location of leakage vortex cavitation, the stepped casing forms a recirculation vortex-like structure that exerts a guiding effect on the vortex core of the leakage vortex cavitation, causing the cavitation zone to develop upstream. Simultaneously, the step splits the cavitation zone apart, suppressing cavitation bubbles from developing downstream, which reduces blockage of the flow passage by the cavitation zone and minimizes interference with the inlet incidence angles of adjacent blades. Consequently, this improves the inducer's cavitation performance and stabilizes the flow regime within the passage.

Full Text

Numerical Study on the Influence of Stepped Casing on Cavitation Flow Characteristics in an Inducer

Introduction

The inducer is a critical component determining the cavitation resistance of turbopumps in liquid rocket engines, featuring high-solidity cascades, low loading, and small flow turning angle with low pressure drop characteristics. It can operate under certain cavitation conditions without head breakdown, making cavitation-related hazards generally concentrated in the inducer or transmitted through it to the turbopump and entire engine. During development of a certain Chinese LOX/kerosene engine, cavitation-induced problems were encountered multiple times. Cavitation instability phenomena represented by rotating cavitation have long been one of the main vibration sources in the engine, posing an important safety hazard for turbopump operation.

Internationally, the Japanese H-II rocket [**?**], American Space Shuttle [**?**], and European Ariane rocket have all experienced cavitation-induced vibrations at frequencies 2-3 times the rotational speed, identified as being caused by rotating cavitation. To date, cavitation-induced flow instability remains a key factor limiting turbopump performance. Chen et al. \cite{88%} first identified cavitation instability phenomena in test data from a Chinese engine. OH, J et al. \cite{88"} effectively suppressed cavitation instability through casing modification, though the mechanism was not thoroughly revealed.

After the failure of the H-II rocket's 8th launch, researchers investigated the relationship between the inducer casing and rotating cavitation, finding that stepped casing could almost completely suppress rotating cavitation in three-bladed inducers. hJDG^2 et al. [**?**] used LES technology to study the relationship between inducer inlet stepped casing geometry and the backflow region and vortex structure, concluding that the step significantly affected flow patterns. When flow rate increased, the backflow region was suppressed but tip leakage vortex continued to develop; when flow rate decreased, backflow developed and backflow vortices appeared while tip leakage vortex weakened. hJDG^2 et al. [**?**] studied the vortex structure in non-cavitating flow fields of stepped casing inducers, finding that tip leakage vortex development depended on inlet casing and flow rate, and noting a strong correlation between tip leakage vortex and rotating cavitation.

During development of a new engine type, this phenomenon of vibration at 2-3 times rotational frequency caused by cavitation was encountered. In studying suppression measures, it was found that modifying inlet casing geometric parameters could eliminate rotating cavitation. H2SHJD, W, et al. [**?**] investigated the relationship between inducer casing and rotating cavitation, with results showing that stepped casing could almost completely suppress rotating cavitation in three-bladed inducers.

Considering experimental research costs and cycle times, rapidly developing CFD technology has become the choice for many researchers. Zhao Yu \cite{"“} proposed a cavitation vortex model to study the effects of attack angle and tip clearance size on leakage vortex cavitation. IJG et al. \cite{"!} proposed the Ω vortex identification method, which can effectively identify vortex structures in complex flow fields, and verified its applicability in high-speed turbopumps. Zhao Yu et al. \cite{"1} modified the standard k-ϵ model considering local vortex characteristics, accurately predicting the unsteady shedding process of hydrofoil suction-side cavitation bubbles.

This study, based on the adaptive cavitation model proposed in literature \cite{"B}, employs numerical simulation methods to comparatively investigate inducer cavitation flow characteristics under different casing schemes, aiming to provide reference data for further improving inducer cavitation flow characteristics.

Adaptive Cavitation Model

According to literature [**?**], multiple complex cavitation types exist within inducers, including leakage vortex cavitation, backflow vortex cavitation, attached cavitation, and shear layer cavitation, each with different formation mechanisms. Traditional cavitation models use a fixed set of empirical coefficients to predict all cavitation types, resulting in limited prediction accuracy.

In the equation, ρ_v, ρ_l, and ρ_m are vapor density, liquid density, and mixture density, respectively. The momentum equation source term is: Since the working fluid in this study is room-temperature water where thermodynamic effects can be neglected, the energy equation is not considered here. Flow within the inducer features high curvature and strong shear characteristics, thus the curvature-corrected SST turbulence model is adopted, with its specific formulation given in literature \cite{“B’}. The adaptive cavitation model is based on three-dimensional hydrofoil test results from literature \cite{"B}, which thoroughly validated the model and confirmed its ability to accurately predict leakage vortex cavitation morphology.

In addition to traditional mass conservation and momentum conservation equations, an additional transport equation for vapor volume fraction α_v is added, as shown in Equation (10). The blade wrap angle is γ, the inlet edge rounding angle is δ, and the inlet tip pitch is t_1 and outlet tip pitch is t_2.

Numerical Setup and Validation

To analyze the influence of inducer outlet pipe shape on simulation results, straight pipe and curved pipe computational models were established, where the curved pipe outlet matches the domain in experimental apparatus \cite{"A/0%’}.

Combined with Figure 0 and Table 1, the total mesh count reaches 1.8×10^6.

After verification, under $0.8Q_n$ flow rate, the inducer head coefficient variation is less than 1%. Considering both computational speed and accuracy requirements, and to more precisely calculate the cavitation region on blade surfaces, Mesh 0 is selected as the computational mesh. The mesh is divided into 3 computational domains: inlet domain, impeller domain, and outlet domain, where the inlet and outlet are stationary domains and the impeller domain is a rotating domain with rotational speed matching actual conditions $n = 6000$ rpm, with node count 1.5×10^6. The maximum y^+ on impeller blade surfaces is calculated to be approximately 30-50, meeting model computational requirements. Stationary and rotating domains are connected via rotor-stator interfaces.

The working fluid is water and water vapor at 25°C conditions, with saturation vapor pressure of 3169 Pa. The volume fractions of water and water vapor at the inlet are 1 and 0 respectively. The cavitating flow field calculation uses a single-phase water flow field as the initial condition. Tetrahedral and prismatic unstructured meshes are used, with boundary layer grids set on both impeller and casing surfaces to capture boundary layer flow characteristics. Mesh details are shown in Figure 2. A total of 4 mesh sets were generated, with mesh counts and independence verification shown in Table 1.

Flow rate is set as Q, with rated operating flow rate Q_n. The curved pipe inducer outlet uses unstructured mesh, while the impeller section uses structured mesh. The outlet domain for the curved pipe configuration yields a head coefficient of 0.21 under $0.8Q_n$ flow rate. The simulation and experimental curves show consistent trends (Figure 3). The head coefficient maintains a stable value, with simulated head coefficient $\psi = 0.21$ and experimental value of 0.215 under non-cavitating conditions, showing a deviation of about 2.3% and good agreement with experimental data.

To further analyze cavitation instability phenomena in the inducer, time-domain signals of inlet pressure fluctuations under $0.8Q_n$ flow condition were decomposed using Short-Time Fourier Transform (STFT) for time-frequency conversion, as shown in Figure 4.

The simulated cavitation performance curve under $0.8Q_n$ flow condition compared with experimental results is shown in Figure 5, where experimental data were obtained from the system described in literature \cite{"A'}. When cavitation number σ suddenly increases and continues decreasing to 0.02 and then suddenly decreases again, while simultaneously showing f_s with $0.8f_n$ and $1.2f_n$, this indicates super-synchronous rotating cavitation occurring in the inducer—cavitation region propagating at rotational frequency in one blade passage. This phenomenon was encountered during development of a new engine type.

Geometric Parameters of Stepped Casing

Three key geometric parameters of stepped casing were extracted, as shown in Figure 6: axial distance S, expansion angle θ, and radial height h. S values were taken as 10.5, 12.5, and 14.5 mm, where the red dashed line indicates the starting position where the leakage vortex detaches from the blade and develops upstream. Under $0.8Q_n$ flow condition and rotational speed 6000 rpm, using pressure inlet/mass flow outlet boundary conditions, the non-cavitating head coefficient calculation results are shown in Figure 7. The head coefficients differ among schemes. Scheme a yields the highest head coefficient among the three values at 0.205, approximately 1.2% higher than scheme b, and about 0.5% higher than scheme c, but still 0.5% lower than scheme 1.25, indicating that there exists a local optimal axial distance near the leakage vortex that changes the flow state while having low impact on performance, lower than conventional casing. Scheme a is selected for further study.

Influence of Expansion Angle on Cavitation Flow Characteristics

Expansion angle θ values were taken as 15°, 30°, and 45° in ascending order, as shown in Figure 8. As expansion angle increases, the slope increases, equivalent to simultaneous increase of S and radial height. When θ increases to 90°, the casing becomes fully stepped, forming corner vortices that affect both backflow region and leakage flow.

In Figure 9, head coefficients are normalized by conventional casing steady-state head coefficient 0.212 as baseline. This figure shows that the cavitation performance of inducers with stepped casing all slightly decreases. Compared with conventional casing, the steady-state head coefficient for 15° expansion angle stepped casing decreases by approximately 1.5%, 30° decreases by about 0.2%, and 45° decreases by about 3.1%. The predicted critical cavitation numbers for the three schemes are 0.021, 0.02, and 0.02, respectively, compared to conventional casing breakdown cavitation number 0.025, all showing delayed breakdown points, indicating that stepped casing improves cavitation performance but generates disturbances. Therefore, when S and radial height are fixed, changing only the expansion angle improves cavitation performance at the cost of partial head loss.

The 30° expansion angle scheme shows minimal steady-state cavitation performance degradation, while 45° shows maximum degradation. The performance curve for 45° shows a significant dip before breakdown with large fluctuations, making the 30° expansion angle scheme optimal among the three.

Cavitation zone morphology for the three expansion angles at different cavitation numbers is shown in Figure 10. To better explain Figure 9 and Figure 10, at $\sigma = 0.05$, cavitation inception occurs. Leakage vortex initiation positions are identical in 15° and 30° casings with essentially the same initial structure. As expansion angle increases, the vortex core first develops upstream then gradually approaches the suction surface, with stepped casings showing significantly longer vortex cores than conventional casing. The 15° case shows maximum upstream development, 45° minimum, and 30° similar to conventional casing.

At $\sigma = 0.04$, leakage vortex cavitation forms typical streak-like vortex bands with varying lengths and radii. The 45° case shows the most slender leakage vortex cavitation. As expansion angle decreases, leakage vortices become shorter with thicker tails, but the upstream development angle remains essentially the same.

At $\sigma = 0.03$, cavitation regions further expand with essentially no difference among the three schemes. Notably, attached cavitation appears on blade suction surface earlier in the 45° case. At $\sigma = 0.02$, the 15° scheme performance has already broken down, while the other two approach critical values, with 30° showing the shortest cavitation zone extending least downstream along the passage. At $\sigma = 0.01$, all schemes have completely broken down, with cavitation regions extending to passage trailing edge and the inducer essentially losing its pumping capability.

To analyze differences among expansion angle schemes, pressure distribution and axial velocity vectors on axial sections perpendicular to the Z plane are examined (Figure 11). The yellow planes in the figure represent sections arranged parallel to the positive Z-axis direction, covering the leakage vortex cavitation region on blades before complete performance breakdown.

As expansion angle increases, low-pressure regions at G and I sections gradually decrease because blade leading edges are rounded and tip clearance increases with expansion angle, resulting in decreased leakage flow velocity and reduced transverse fluid motion. The formed low-pressure region radius gradually decreases.

Section J shows the most significant low-pressure region for the 30° expansion angle because leakage flow from pressure to suction surface forms a leakage vortex exactly at the step end, where mainstream, backflow, and gap leakage vortex form G-shaped flow along the casing with minimal interference.

Conclusions

The optimized stepped casing reasonably increases tip clearance upstream of blades, forming a buffer zone at leakage vortex formation that reduces fluid excitation and enhances inducer operational reliability. It effectively intercepts downstream-propagating cavitation bubbles, thereby reducing flow passage blockage and interference with adjacent blades, and improving inducer cavitation performance while stabilizing internal flow state.

Simulation shows that under $0.8Q_n$ flow condition, stepped casing improves inducer cavitation performance at the cost of partial head loss—0.2%, but performance is superior to 15° and 45° expansion angles. The interaction between flow passage blockage and adjacent blades is reduced, thereby improving inducer cavitation performance and stabilizing internal flow state.

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Note: Figure translations are in progress. See original paper for figures.