Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

High blade lift generation through short rotor–stator axial spacing in a tiny pump

Han Xu, Donghai Jin *, Mengyu Wang, Lin Du, Dakun Sun, Xingmin Gui, Xiaofeng Sun

School of Energy and Power Engineering, Beihang University, Beijing 100083, China

ARTICLE INFO

Article history:
Received 19 May 2017
Received in revised form 27 March 2018
Accepted 25 May 2018
Available online xxxx

ABSTRACT

Short rotor–stator axial spacing has been demonstrated to be beneficial to the aerodynamic performance of subsonic compressors. In this paper, it is further verified that this benefit partly originates from the improvement of the rotor blade lift. A tiny axial pump is investigated both numerically and experimentally with three different rotor–stator axial spacings. The time-accurate simulation indicates that both the peak and average rotor blade lifts are enhanced as the axial spacing decreases. The potential field of the downstream stator has significant effects on the pressure distribution in the rotor when the blade rows get close. The two-dimensional (2D) PIV measurement demonstrated that short axial spacing generates high circulation around the rotor blade due to the flow tube compression, which contributes to the blade lift improvement. Besides, close blade-rows axial spacing generates enhanced unsteadiness for the inlet flows of the downstream stator, which should be taken into consideration in the design process.

1. Introduction

The effect of the rotor–stator axial spacing on the aerodynamic performance of turbomachinery has been investigated both numerically and experimentally by many researchers. It is convinced that the axial spacing is closely bound up with the blade interaction, noise generation and wake propagation. However, the mechanism seems to be different for subsonic and transonic flows, so there is no general agreement that the axial spacing should be decreased or increased to improve the aerodynamic performance.

Smith [1] proposed that short rotor–stator axial spacing leads to higher total pressure efficiency from a series of experimental results on a low-speed four-stage compressor. This mechanism could be explained by the theory proposed by Smith [2,3] which is named as "wake recovery". Smith considered the wake propagation through the downstream blade rows as a reversible process in compressor. Based on this theory, Van Zante [4] suggested that it is the inviscid stretching rather than the viscous dissipation that dominates the wake decay process. He indicated that short axial spacing makes more wakes decay in the downstream passage in a reversible way, thus the mixing losses from viscous dissipation are minimized. However, Gorrell [5,6] discovered a 1.3 point efficiency reduction in a transonic compressor rig when the axial spacing between the blade rows was decreased. Further studies indicated that the rotor bow shock interacts with the trailing edge (TE) of the upstream blade and generates additional losses as the blade rows are drawn near to each other.

Besides the total efficiency, the stage loading is also observed to be significantly affected by the blade-rows axial spacing. Koch [7] published the experimental data from a four-stage compressor and indicated that the stalling pressure rise capability of the compressor is improved by the reduction of the blade-rows axial spacing. In the experiment conducted by Furber and Ffowcs Williams [8] on a small closed-cycle water rig, an increase in pressure rise was found with decreasing rotor–stator axial spacing both above and below the stalling point. They attributed this pressure rise benefit to the Weis-Fogh mechanism, which was originally formulated by Weis-Fogh [9] from the "clap-and-fling" motion of the small Encarsia Formosa. This mechanism generates high lift arising from the large circulation around the wing during the "fling" process. Based on this discovery, Lighthill [10] presented the analytical solution of the "fling" motion and proposed a preliminary analysis of this lift generation mechanism. The basic conclusions of Weis-Fogh and Lighthill were verified by the experiment conducted by Maxworthy [11,12], in which a lift coefficient with the peak value up to 8 was observed. Then both numerical and experimental researches were carried out on this new mechanism of lift generation and its application on the design of aircraft [13–19].

So can the Weis-Fogh mechanism be exploited in turbomachinery? Furber and Ffowcs Williams [8] think the answer is yes. Based on their computational results, the stage performance is improved in a wide range of flow coefficient under the Weis-Fogh condi-

---

* Corresponding author.
E-mail address: jdh@buaa.edu.cn (D. Jin).

https://doi.org/10.1016/j.ast.2018.05.047
1270-9638/

Please cite this article in press as: H. Xu et al., High blade lift generation through short rotor–stator axial spacing in a tiny pump, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.047

Nomenclature

C_L	normalized rotor blade lift
D	tip diameter at the rotor outlet
F_u	circumferential rotor blade lift
N	number of the instantaneous images
Re	Reynolds number
u_i	instantaneous axial velocity component
$\bar{u}$	phase-averaged axial velocity component
v_i	instantaneous circumferential velocity component
$\bar{v}$	phase-averaged circumferential velocity component
V	absolute velocity
W	relative velocity
x	axial coordinate
y	lateral coordinate
ρ	density
ν	kinematic viscosity
ϕ	phase angle
LE	leading edge
NAS	normalized axial spacing
TE	trailing edge

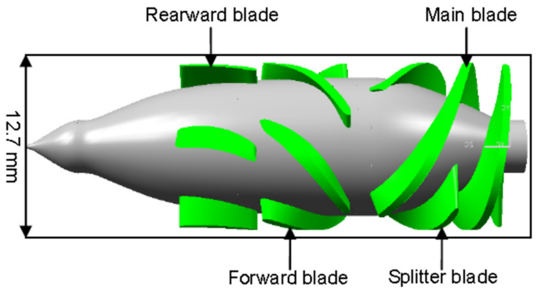

Fig. 1. Structure map of the research pump.

tion compared with that under the Kutta condition. However, Du [20] pointed out that the effect of unsteady vortex was not taken into account in the study of Furber and Ffowcs Williams [8]. Du investigated the relationship between the shedding vortices and stage loading numerically by means of the immersed boundary method in a compressor stage. Results indicated that close rotor–stator axial spacing generates stronger shedding vortices at the TE and enhances the average lift of the rotor blade. The author concluded that the unsteady vortex produced by the blade interaction increases the rotor blade lift and then improves the total performance. However, this conclusion based on quasi three-dimensional (3D) computation is lack of experimental verification.

Based on the prior studies, it can be summarized that close rotor–stator axial spacing is always beneficial for the stage performance of subsonic compressors. Question worth discussing is whether this benefit comes from the rotor or the stator. In other words, will the close axial spacing generate high blade lift in the rotor as suggested by Du [20]? In this paper, a tiny axial pump with water as the working fluid is chosen as the research model to explore this topic. 3D unsteady computation was conducted and 2D PIV measurement was implemented. Both the numerical and experimental results are presented and discussed.

2. Computational method

2.1. Research model

The tiny axial pump, designed as a left ventricular assist device (LVAD) [21,22], is composed of a rotor and a stator, as shown in Fig. 1. In order to control flow separations, two splitters are employed in the latter half of the rotor, which have the same profile with the main blades. In the stator row, tandem cascade is adopted with five upstream vanes and five downstream vanes to improve the pressure-rise capability. The detailed design parameters are listed in Table 1. Three different axial spacings were chosen in this study with the values of 0.03, 0.12 and 0.30 normalized by the rotor chord in the hub. The "normalized axial spacing" is abbreviated in "NAS" in this paper for convenience.

Table 1
Design parameters of the axial pump.

Design parameters	Rotor	Upstream vane	Downstream vane
Number of blades	2	5	5
Number of splitters	2	0	0
Inlet hub/tip ratio	0.32	0.83	0.80
LE tip diameter	12.7 mm	12.7 mm	12.7 mm

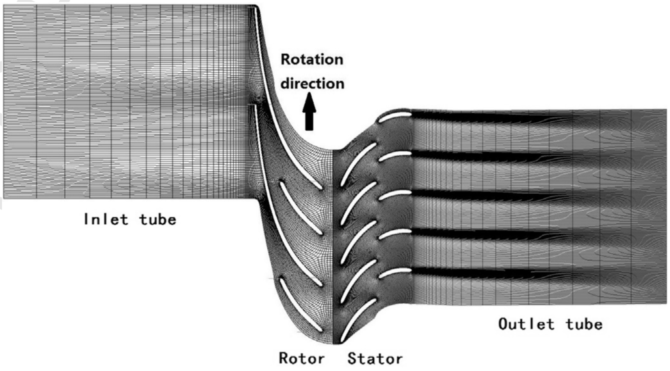

Fig. 2. The blade–blade view of the computational domains.

2.2. CFD method

Both the steady-state and time-resolved flow fields were simulated using the 3-D RANS solver ANSYS 17.1. The Reynolds number is computed using:

$$\mathrm{Re} = \frac{V_\infty D}{\upsilon} \tag{1}$$

in which V_∞ (m/s) is the inlet free-stream velocity, D (m) the tip diameter at the rotor outlet, ν (m^2/s) the kinematic viscosity. The Reynolds number was computed to be around 1×10^4 in the simulation. The turbulent Reynolds stress is treated employing the Shear Stress Transport (SST) model to have a good prediction both inside and outside the boundary layer. The computational domain includes the inlet tube, rotor, stator and the outlet tube, as shown in Fig. 2. The whole passage meshes are used. O-grid topology was applied around the blade surface for good orthogonality and grid refinement was carried out near walls. The average number of the mesh nodes is 1660000 in the rotor and 3250000 in the stator. The computation was first run in steady mode using the mixing-plane model to transfer flow quantities between the rotor and stator rows. The total pressure was given at the inlet and the mass flow rate at the outlet. The iterations proceeded until the average residual error dropped to 10^{-6}. The steady computational hydraulic head performance was compared with the experimental values to validate the CFD results in Fig. 3. The steady result at the volume flow rate of 4 Lpm was used as the initial condition for the

Please cite this article in press as: H. Xu et al., High blade lift generation through short rotor–stator axial spacing in a tiny pump, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.047