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Investigation on Unsteady Flow of a Turbine Stage with Negative Bowed Stator

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***Abstract*—**Complicated unsteady flow in axial turbines produces high-frequency unsteady aerodynamic exciting force, which threatens the safe operation of turbines. This paper illustrates how negative-bowed stator reduces the rotor unsteady aerodynamic exciting force by unsteady flow field. With the support of three-dimensional viscous compressible Navier-Stokes equation, the single axial turbines with 0, -10 and -20 degree bowed stator are comparably investigated, aiming to identify the flow field structure difference caused by various negative-bowed degrees. The results show that negative-bowed stator strengthens the turbulence kinetic energy, which is further strengthened with the increase of negative-bowed degree. Meanwhile, the flow phenomenon including stator wakes and passage vortex is shown. In addition, the interaction of upstream negative-bowed wakes contributes to the reduction of unsteady blade load fluctuation. Furthermore, the aerodynamic exciting force decreases with the increasing negative bowed degree, while the efficiency is correspondingly reduced. This paper provides the reference for the alleviation of the harmful impact caused by unsteady interaction with the method of wake control.

***Keywords*—**Unsteady flow, axial turbine, wake, aerodynamic force, loss.

I. Introduction

SAFETY and high efficiency are the most important problems in turbine operation. Turbine safe operations are affected by blade fatigue damage to a great extent, and blade fatigue damage results from the blade vibration due to dynamic stress. Further, the unsteady aerodynamic exciting force mostly influences the dynamic stress. Therefore, the investigations on unsteady aerodynamic exciting force are necessary to guarantee the safe operation. The unsteady flow field in passages induces unsteady aerodynamic exciting force; hence the key point of reducing exciting force is the understanding and improvement of unsteady flow. In addition, from the perspective of high efficiency operation, the unsteadiness in turbine passages is also a key consideration. For these reasons, domestic and foreign scholars have carried out a very wide range of unsteady flow studies in recent years, revealing the mechanism of unsteady flow field development and rotor- stator interaction. Experiments have been performed by Smith [1] in a three-stage axial compressor to investigate unsteady stator boundary-layer transition. The effects of upstream rotor interactions on the stator suction surface boundary layer have been investigated. Payne et al. [2] have performed the investigation into unsteady losses based on experimental method. The effects of blade row interaction on the stage performance are presented. The vibration and noise induced by the unsteady flow in the compressor as has been investigated by Zhou [3] based on numerical method. The pressure fluctuation and vibration has been presented. The unsteady interaction between blade rows has been illustrated by Bellucci [4] with the variation of axial gap. And the stage efficiency has been explained based on the unsteady flow field. The mixing losses and secondary flow development have been described by Pullan [5], Chaluvadi [6]. Marconcini [7] has performed the investigation of turbine performance under steady and periodic unsteady inflow boundary condition during off-design operation. The casing endwall unsteady flow interaction has been investigated by Gao [8]. Rai [9] has presented a finite-difference, unsteady method to obtain the flow in the axial turbine. The numerical method includes tip leakage and endwall effects. Osipov [10] has given a mathematical model for the turbomachinery tonal noise which considers the unsteady aerodynamic interaction. These studies are important for understanding the unsteady flow inside the cascade.

It comes to the question that is it possible to improve the aerodynamic efficiency and to reduce the air excitation force by improving the unsteady flow field? Turbine design has begun to consider the unsteady problems in recent years, including wake recovery effects [11], [12], clocking effects [13] and calming effects [14], in order to improve unsteady flow field to some degree. As an effective structure to improve the flow field, the curved blade has been widely used in compressors and fans. The major objects of camber or lean blade application are efficiency improvement [15]-[17] and the reduction of noise [18]-[20].

The curved blade has a significant effect on the flow control of the compressor and fan. However, there are few researches on the turbine unsteady interaction of the bowed blade, and it is not clear yet how the bowed blade affects the unsteady flow field. Based on this, a three-dimensional compressible N-S equation is used to study the effect of the negative-bowed blade on the unsteady flow of an axial flow turbine. In this paper, we found that the structure of the negative-bowed blade can improve the turbulent kinetic energy, which is further strengthened with the increase of the bending angle. The wake interaction of upstream negative-bowed stator blade is helpful to reduce the fluctuation of the unsteady rotor blade load, and it is further found that the unsteady aerodynamic force decreases with the increase of the bending angle, at the expense of efficiency instead.

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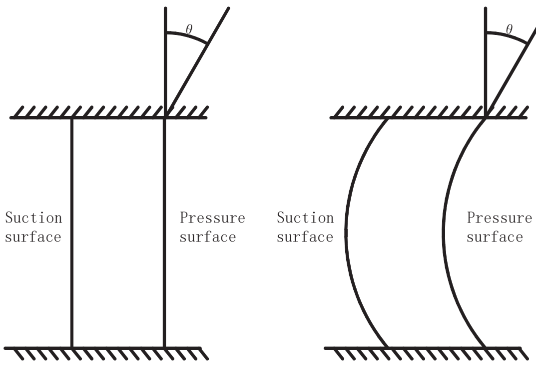
II. Numerical Method

A. Numerical Method

To reveal the unsteady flow of a turbine stage with negative bowed stator, three dimensional unsteady numerical computations have been conducted using CFX software. The RNG k-ε turbulence model with non-equilibrium near-wall modeling is adopted, which is validated to have a good agreement with experiment by Hushmandi [21]. Moreover, the interface between rotor and stator is treated with transient rotor stator method. Furthermore, the grid independence verification has been done in previous articles to utilize the computational resources effectively [22] and 6 million grids are used. The single axial turbines with 0, -10 and -20 degree bowed stator are comparably investigated, the schematic diagram is presented in Fig. 1. Thermodynamics parameters including inlet total pressure (130kPa), inlet total temperature (323K), outlet static pressure (97kPa) and rotational speed of 5000 rpm are given to perform detail simulations.



(a) Straight blade (b) Negative-bowed stator

Fig. 1 The schematic diagram of stator model

B. Validation

The validation of the numerical method is completed through the comparison of numerical simulation results and experimental data of Matsunuma [23]. The numerical simulation is based on the experimental condition. The inlet axial velocity is 4.4m/s, and the turbulence intensity is 0.5%. The rotor blade outlet Reynolds number, which is based on rotor chord and outlet velocity, is $3.5*10^4$. In addition, the rotating speed is set as 402rpm. Takayuki Matsunuma's test rig with a single axial flow stage is presented in Fig 2 (a). The numerical method with 5 turbulence models is applied to simulate the flow field, and the RNG k-ε turbulence model is verified to satisfy the experimental results better as shown in Fig 2 (b). Hence, the numerical method with RNG k-ε turbulence model is validated to be reliable.

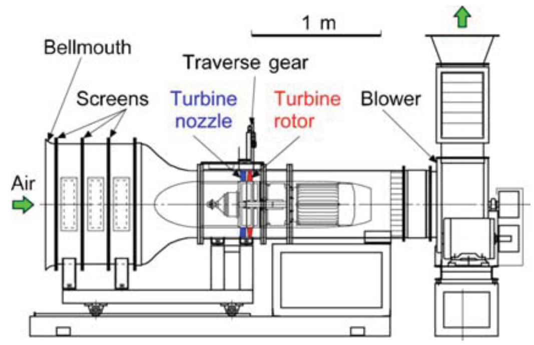
III. Results and Discussion

A. Loss Distributions

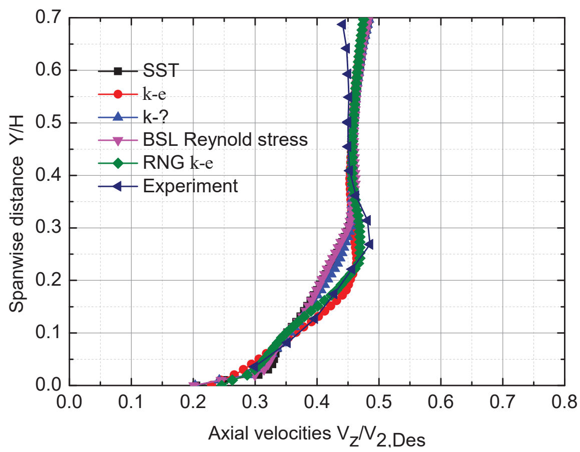
Total to static efficiency is the key parameter which can directly reflect whether the turbine can run efficiently. The total to static efficiency is shown below:

$$\eta_{ts} = \frac{h_{s2} - H_{01}}{h_{s2'} - H_{01}} \tag{1}$$

where, h_{s2} means actual static enthalpy at stage outlet, $h_{s2'}$ means isentropic static enthalpy at stage outlet and H_{01} means total enthalpy at stage inlet.



(a) Test rig



(b) Validation with axial velocities

Fig. 2 Numerical validation through annular turbine wind tunnel

Fig. 3 shows the comparison of the total static efficiency under different stator structures. It can be seen from the figure that the efficiencies of turbine stages with the three statormodelsare very close. However, the negative-bowed stator reduces the turbine stage efficiency to some degree, and the efficiency decreases obviously with the increase of negative-bowed angle. In detail, the turbine stage efficiency with stator bowed angle of 20 degrees is 1.3% lower than that with stator straight blade.

In order to explain the reason why the turbine stage efficiency is reduced, the turbulent kinetic energy distribution of the rotor inlet is given in Fig. 4. At the inlet of the rotor blade, there are obvious up and down passage vortexes near the end walls, as shown by the red dashed line. Meanwhile a high turbulence zone can be found caused by the stator wake, as represented by the red line area. It can be seen that with the increase of negative-bowed angle, the fluid moves to the endwall due to the "reverse C" type pressure distribution in the stator passage. As a result, the endwall boundary layer increases, and the vortexes in the up and down passages are enhanced obviously. In addition, the stator wakes at the end walls skewed due to the impact of the passage vortex. The stator wakes are more and more obviously bent with the increase of the bending angle, and the circumferential turbulence intensity of the stator wakes is enhanced relatively. In summary, the turbine stage efficiency decreases with the increase of stator negative-bowed angle.

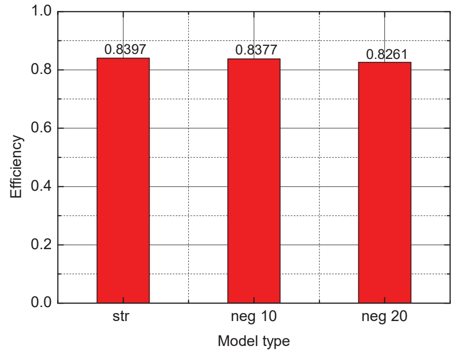


Fig. 3 The comparison of the efficiency under different stator structures

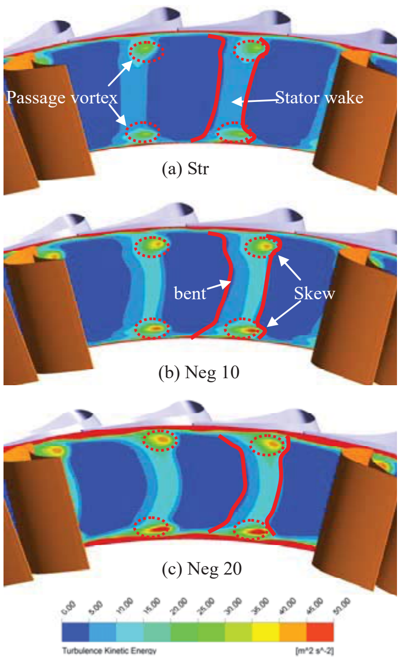


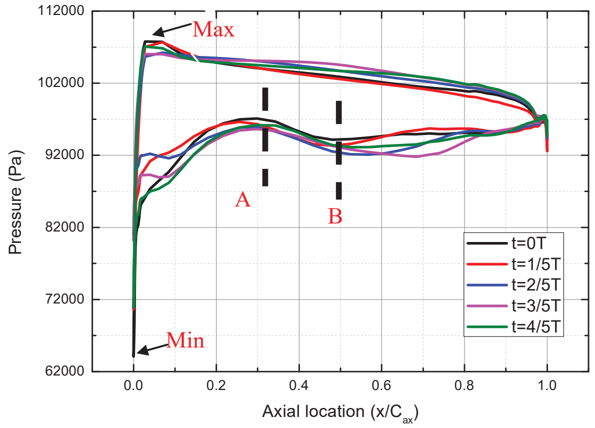
Fig. 4 Turbulence kinetic energy distributions at rotor inlet

B. Unsteady Blade Load

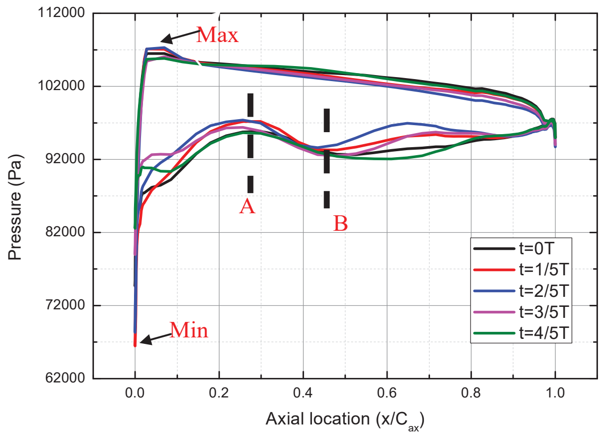
The pressure distribution on the rotor surface is an important parameter to reflect the work capacity of the turbine stage, and unsteady surface pressure fluctuations can reflect the unsteadiness in flow field. Fig. 5 shows the unsteady rotor load distribution at the 10% blade height. The maximum pressure on the rotor blade surface is on the pressure surface at the leading edge of the blade, and the minimum pressure on the rotor blade surface is on the suction surface at the leading edge of the blade. With the increase of the bowed angle, the maximum pressure value is relatively stable, while the minimum pressure value increases obviously. Therefore, it can be seen that the negative-bowed stator blade can improve the inlet pressure of the rotor blade, which has a certain relationship with the fact that the negative-bowed stator resistance reduces the flow velocity at the rotor inlet. Meanwhile, it is found that for the unsteady blade pressure distribution, there are two adverse pressure gradient regions. They are respectively from the leading edge of rotor to point A and from point B to the trailing edge of rotor. Aerodynamic separation occurs easily in these regions. The adverse pressure gradient region from the leading edge of rotor to point A is caused by the positive attack angle of rotor, and another region is caused by the pressure diffusing effect near the trailing edge. It can be seen from Fig. 5 that with the increase of the stator negative-bowed angle, point A and B obviously moves towards the leading edge, increasing the amplitude of the pressure gradient ahead of point A and the distance of the pressure gradient after point B. In addition, since the negative-bowed blade increases the pressure on the suction surface, the work capacity is reduced. And, it is found that the pressure fluctuations on the rotor surface can be reduced effectively by the negative-bowed stator, and the effect is more obvious with the increase of the bowed angle.

Fig. 6 shows the unsteady rotor load distribution at the 50% blade height. The maximum pressure point and minimum pressure point both increase compared with that at the 10% blade height. With the increase of the bowed angle, the pressure of the leading edge is obviously increased compared with the straight blade. Compared with the load distribution of 10% blade height, the adverse pressure region at the trailing edge of 50% blade height is effectively shorten due to the pressure increase at the rotor inlet, and point B moves to the vicinity of the 70% axial rotor chord length. The influence of the negative-bowed stator on the axial position of A and B is small. However, it can be seen from the 50% blade height pressure distribution that the fluctuation of the pressure surface and the suction surface is reduced effectively.

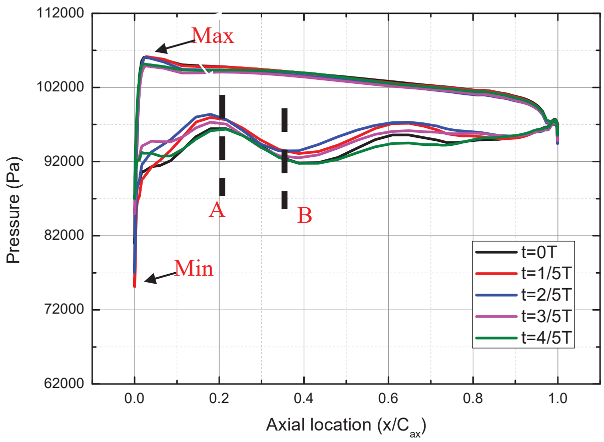
Fig. 7 shows the unsteady rotor load distribution at the 90% blade height. The maximum pressure point and minimum pressure point both further increase compared with that at the 50% blade height. The increase of pressure at rotor inlet effectively reduces the amplitude of the adverse pressure gradient from the leading edge of rotor to point A, compared with that at the 10% and 50% blade height. However, the amplitude of the adverse pressure gradient from point B to the trailing edge of rotor increases to a certain extent with the increase of negative-bowed angle. Therefore, the aerodynamic separation is more serious in this area, and it also explains the phenomenon that the efficiency of the stator reduces. It can be found with a further comparison of the pressure fluctuation on the rotor surface at the 90% blade height that, the unsteady pressure fluctuation on the pressure surface and the suction surface is inhibited to some degree with the increase of negative-bowed angle.



(a) Straight blade

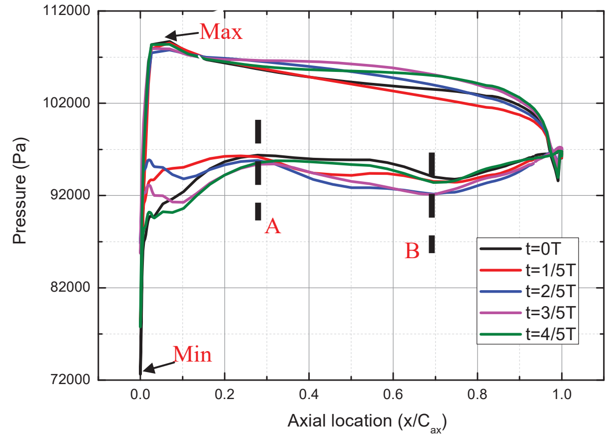


(b) Negative-bowed stator of 10 degree

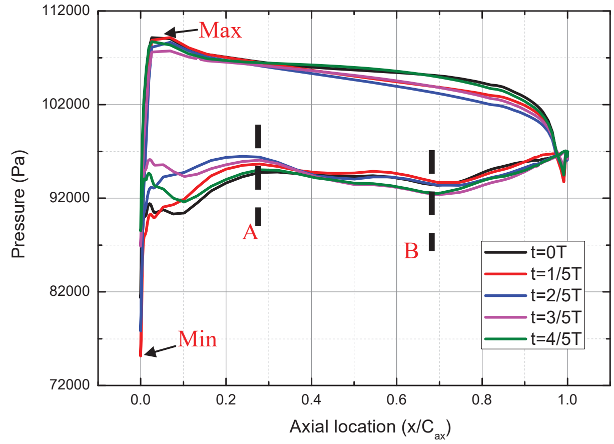


(c) Negative-bowed stator of 20 degree

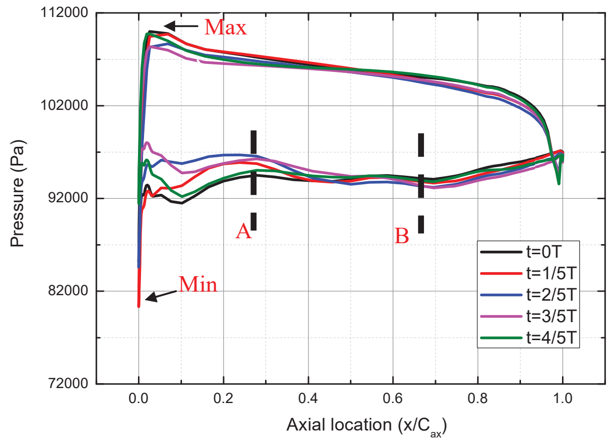
Fig. 5 Unsteady blade load at 10% rotor height



(a) Straight blade

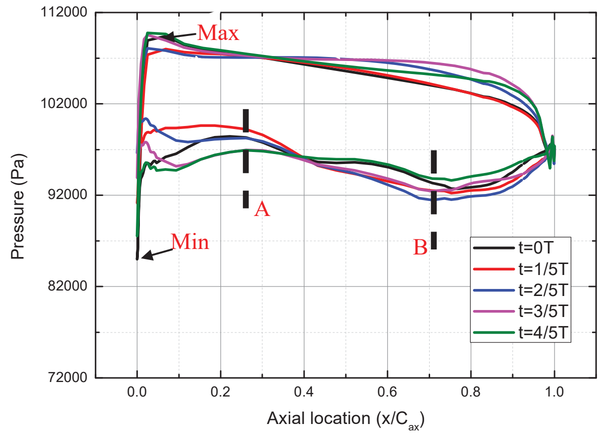


(b) Negative-bowed stator of 10 degree

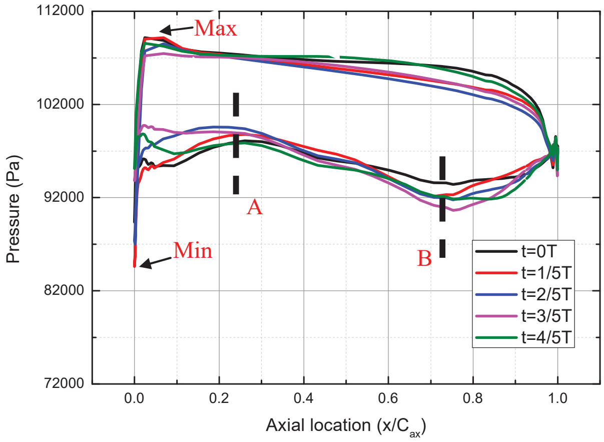


(c) Negative-bowed stator of 20 degree

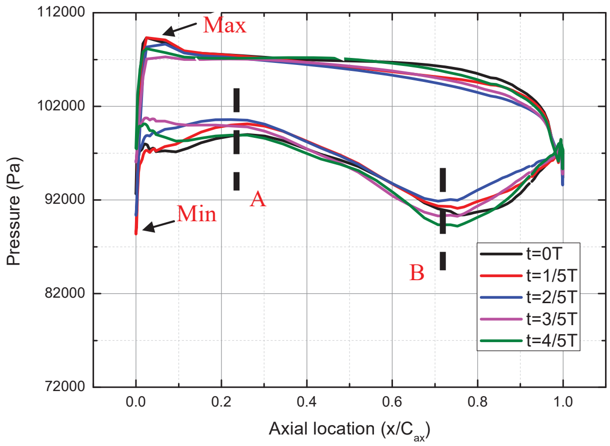
Fig. 6 Unsteady blade load at 50% rotor height



(a) Straight blade



(b) Negative-bowed stator of 10 degree



(c) Negative-bowed stator of 20 degree

Fig. 7 Unsteady blade load at 90% rotor height

C. Aerodynamic Exiting Force

Fig. 8 shows the time domain distribution of the unsteady flow force of a single rotor. It can be found that the axial force and tangential force of rotor fluctuate with sinusoidal periodic over time step. Compared with straight blade, negative-bowed blade has a pulsation amplitude reduction and the pulsation amplitudes of axial force and tangential force decrease gradually with the increase of bowed angle. Meanwhile, it can be found that when the turbine stage is given, for a single rotor, the maximum values of axial force and tangential force do not occur at the same time. For a stator straight blade, the distance of the maximum of axial force and tangential force is approximately 1/6T, and the distance is more obvious when the bowed angle increases. For a stator with a negative-bowed angle of 20 degrees, the distance of the maximum of axial force and tangential force is about 1/4T.

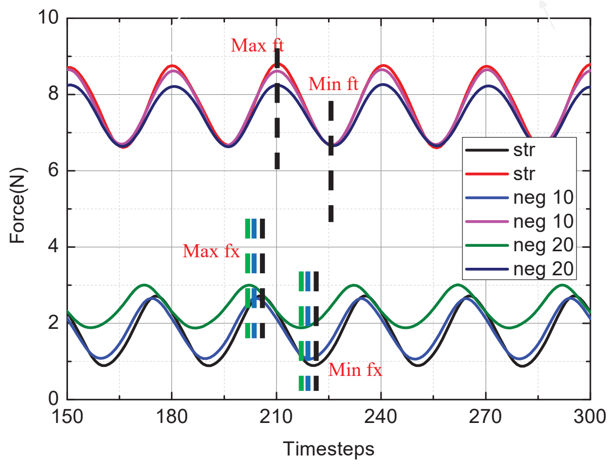
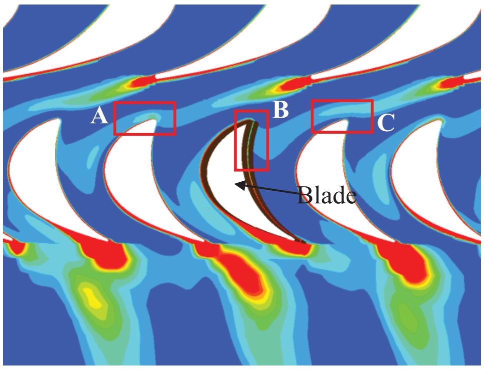
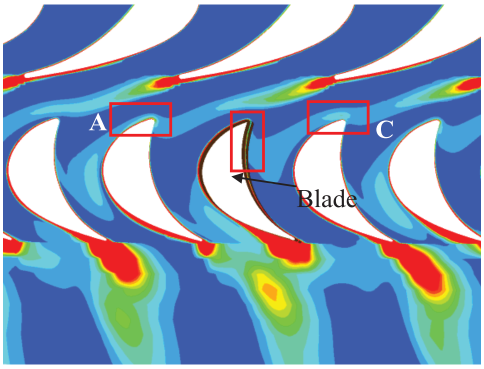


Fig. 8 Unsteady aerodynamic force of a single rotor

In order to explain the phenomenon of aerodynamic staggering peak, shows the position of the maximum values of axial force and tangential force of a single rotor is shown in Fig. 9 when the stator is straight. The rotor that the arrow refers to in the figure is the analysis blade, and three key positions are given such as A, B, C. As is shown in Fig. 9 (a), when the axial force is at the maximum value, the leading edge of the rotor that is on the left side of the analysis blade is just impacted by the upstream wake as A shows. While the leading edge of the rotor that is on the right side of the analysis blade just avoids the upstream wake as C shows. At the same time, the wake impacts on the pressure surface of the analysis rotor as B shows. As is shown in Fig. 9 (b),when the tangential force is at the maximum value, the leading edge of the rotor that is on the left side of the analysis blade is impacted by the upstream wake, and the impact point is slightly inclined to the pressure surface as A shows. And the leading edge of the rotor that is on the right side of the analysis blade is just impacted by the upstream wake as C shows. The wake impacts on the pressure surface of the analysis blade after sliding over the leading edge of rotor at C position, as B shows. Compared with the wake impacted position of axial force maximum, it is shown that the wake impacted position in B region moves slightly along axial direction when tangential force is at the maximum.



(a) The position of fx Max



(b) The position of ft Max

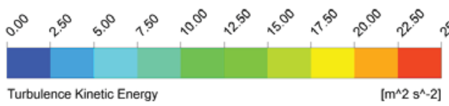
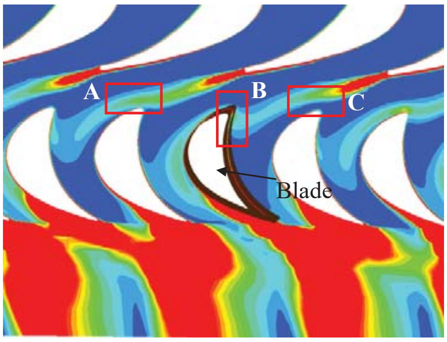


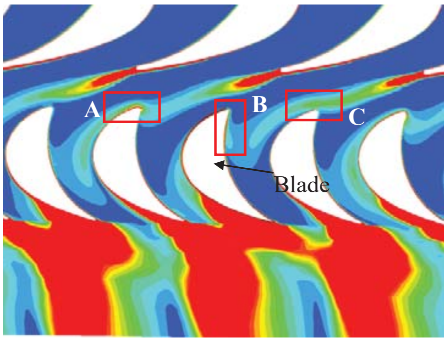
Fig. 9 The position of the maximum of axial and tangential forces of a single rotor when stator is straight

Fig. 10 shows the position of the maximum values of axial and tangential aerodynamic force of a single rotor when the stator is negative-bowed of 20 degrees. It can be found that the negative-bowed stator of 20 degrees not only enhances the stator wake turbulence, but also the turbulence inside the rotor passage is significantly enhanced. From the three-key points A, B and C, we can find that when the negative-bowed stator is of 20 degrees, at the position of maximum values of rotor axial and tangential force, the rotor- stator wake interaction phenomenon is the same with that of straight stator. However, it is also noteworthy that since the negative-bowed structure has changed the stator wake intensity, the relative position of stator and rotor blade is different from that of straight stator, and the rotor position corresponding to the negative-bowed stator is closer to the trailing edge of upstream stator than that corresponding to the straight stator.

In this paper, the aerodynamic exciting force factor under the maximum amplitude order is obtained by means of the Fast Fourier transform. Fig. 11 shows the comparison of the rotor axial and tangential aerodynamic exciting force factors. It can be found that for the turbine stage with negative-bowed stator, the rotor aerodynamic exciting force is obviously reduced and the decrease amplitude of axial aerodynamic exciting force is more apparent than that of tangential aerodynamic exciting force. For the stator with a negative-bowed angle of 20 degrees, the axial aerodynamic exciting force factor decreases by 55% and the tangential aerodynamic exciting force factor decreases by 22%. This is because in the negative-bowed stator structure, the stator wake bends relatively, therefore the rotor can cut the stator wake partly, reducing the impact of the stator wake on the rotor. In addition, the increase of turbulent kinetic energy of bowed wake contributes to the uniformity of the pressure potential flow field at the rotor inlet and in the passages.



(a) The position of fx Max



(b) The position of ft Max

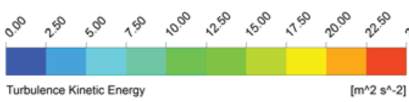
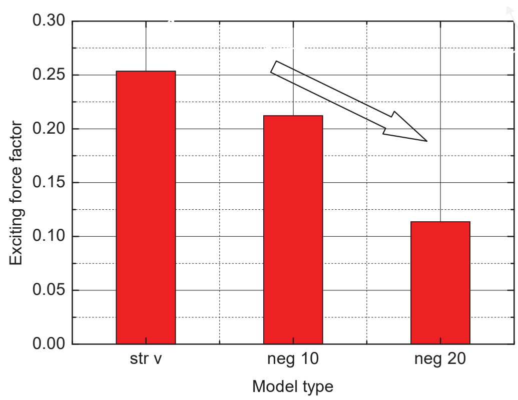
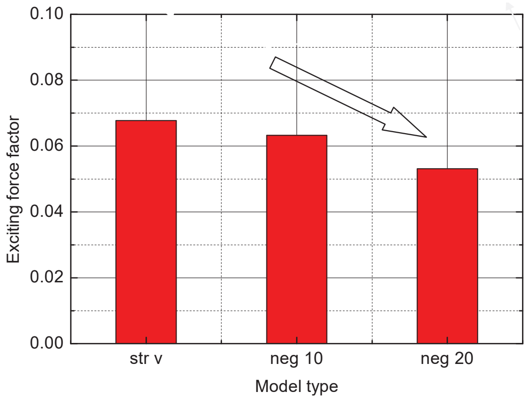


Fig. 10 The position of the maximum of axial and tangential forces of a single rotor when stator is negative-bowed of 20 degrees



(a)



(b)

Fig. 11 Axial (a) and tangential (b) aerodynamic exciting force factors

IV. Conclusions

Three dimensional unsteady flows in turbine stage with straight blade, negative-bowed of 10 degrees and negative-bowed of 20 degrees have been investigated based on viscous compressible N-S equation. The major conclusions are shown as follow:

- The stator wakes are bent with negative camber, resulting in the enhanced turbulence intensity. The pressure distribution of "reverse C" type strengthens the passage vortex and endwall boundary layer; hence the stage efficiency decreases with the increase of negative-bowed degree. The efficiency of turbine stage with negative-bowed stator of 20 degrees is 1.3% lower than that with straight stator.
- Two regions of adverse pressure gradient exist on the suction surface of rotor near leading edge and trailing edge. The adverse gradient near rotor leading edge is caused by the positive attack angle and the adverse gradient near rotor trailing edge is induced by diffusing action. The adverse pressure gradient near leading edge increases with negative-bowed degree for 10% blade height, and the adverse pressure gradient increase comes to the region near trailing edge for 90% blade height, which may induce flow separations. In addition, it is worthy to point out the pressure fluctuation of rotor surface decreases with negative-bowed degree.
- The aerodynamic force fluctuations decrease with negative-bowed degree. It is pointed that there is a certain distance between the maximum of axial force and tangential force. Compared with the wake impacted position of axial force maximum, it is shown that the wake impacted position in B region moves slightly along axial direction when tangential force is at the maximum. Moreover, the distance increases with negative-bowed degree. The rotor- stator wake interaction phenomenon remains the same both turbine stages with straight stator or negative-bowed stator, while the relative position of rotor and stator changes. Compared to the rotor of straight blade model, the rotor of negative-bowed stator model is closer to the trailing edge of upstream stator. Notably, the negative-bowed stator contributes to the reduction of aerodynamic exciting force. The axial and tangential exciting force factors of 20 degrees negative-bowed stator model are 55% and 22% lower than that of straight stator model, respectively.

Nomenclature

h_{s2}	actual static enthalpy at stage outlet
$h_{s2'}$	isentropic static enthalpy at stage outlet
H_{01}	total enthalpy at stage inlet
str	straight blade
neg 10	negative-bowed blade of 10 degree
neg 20	negative-bowed blade of 20 degree
T	Periodic time
x	axial distance
C_{ax}	blade axial chord length
fx	axial force
ft	tangential force

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