RESEARCH NOTE

STALL VORTEX SHEDDING OVER A COMPRESSOR CASCADE

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Abstract The unstable flow with rotating-stall-like (RS) effects in a rotor-cascade of an axial compressor was numerically investigated. The RS was captured with the reduction in mass flow rate and increasing of exit static pressure with respect to design operating condition of the single rotor. The oscillatory velocity traces during the stall propagation showed that the RS vortices repeat periodically, and the mass flow rate was highly affected by the blockage areas made by stall vortices. The results also showed that large scale vortices highly affects on the generation and growth of the new vortices. An unsteady two-dimensional finite-volume solver was employed for the numerical study which was developed based on Van Leer's flux splitting algorithm in conjunction with TVD limiters and the κ-ε turbulence model was also employed. The good agreement of the computed mass flow rate with the experimental results validates the numerical study.

Key Words Stall, Single Rotor, Axial Compressor

چکیده جریان ناپایدار درون یک زنجیره رتور پنج پره ای از یک کمپرسور محوری مورد ارزیابی عددی قرار گرفته است. ناپایداری جریان از نوع گردابه های دوار یا همان سکته دورانی است. با کاهش دبی جرمی و افزایش فشار خروجی محدودهٌ محاسباتی در مقایسه با شرایط عملکرد پایدار، شرایط ناپایدار مهیا گردیده است. رفتار نوسانی دنباله های سرعت حاکی از تکراری بودن گردابه ها در این شرایط است و به دلیل تاثیر قابل توجه گردابه ها روی مسیر جریان محوری ، دبی جرمی دچار نوسانات قابل توجه ای میگردد. نتایج همچنین نشاندهنده تاثیر بسزای گردابه های بزرگ در تشکیل گردابه های کوچکتر است. برای این بررسی عددی نرم افزار حجم محدودی نوشته و مورد استفاده قرار گرفته که در آن از روش تفکیک شار ″ون لیر″ به همراه محدود کننده های TVD برای جملات جابجائی استفاده شده است. همچنین مدل توربولانس "Baldwin-Lomax"برای برآورد آشفتگی بکار کرفته شده است. تطبیق نتایج عددی با نتایج آزمایشگاهی دیگران حاکی از صحت نسبی بررسی های عددی است.

1. INTRODUCTION

Recent issues on rotating stall have been focused on mechanisms associated with short length scale disturbances [1] growing to fully developed rotating stall. Inception of this type of stall is significantly influenced by end-wall phenomena, and modal wave analysis is not always applicable. Hoying et al [2] suggested through a 3-D computation that a tip clearance vortex induces an upstream directing velocity composing a blade passage blockage. Such active behavior of the tip vortex is also suggested by precise hot-wire measurements [3]. A better understanding about processes to a fully developed rotating stall would be provided by unsteady 3-dimensional computations over multiple blade passages. Hah et al [4] first indicated that a system of radially directed vortices is established ahead of the rotor by a full passage analysis. This result implies that the rotating stall takes a form of circumferentially aligned vortices in a two-dimensional sense outside of the end-wall region. The author has developed a 2-D Navier-Stokes (N-S) analysis to study deep rotating stall behavior [5-8], which may consume an extraordinarily long CPU time if 3-D analysis is conducted. A similar attempt was made using an Euler analysis [9]. Another similar attempt was also made using 2-D, N-S equation system without using turbulence model on compressor stage with 18 rotor blade and 30 stator-vanes, and the Newton-Raphson iteration was also employed [10]. A further numerical study on a stage of an axial compressor was made [11]. The Navier-Stokes equations were discretized in space by finite-volume method and integrated in time by the using a four stage Rung-Kutta scheme and the second- and fourth-order blended smoothing was adopted in both the stream wise and circumferential directions for numerical damping, and Baldwin-Lomax turbulence model was also adopted. In case of the 2-D analysis, rotating stall under uniform an inlet flow condition is triggered off by an incidental coupling of a rotor light stall with stator stall blockages. When there exists an inlet flow distortion, rapid circumferential changes of the flow incidence will also excite an onset of rotating stall, as observed in high speed compressor experiments [12].

In the present work, the history of rotor-cascade flow in rotating stall operation is discussed based on the 2-D analysis, indicating (1) a multiple vortices system ahead of the rotor, (2) temporal change in the system composed of evolution, merging and recession of vortices, which is a source of fluctuation in the performance, (3) structure causing the well known large scale hysteresis between rotating stall and recovered stable flows.

2. NUMERICAL PROCEDURE

The governing equations in conservative form are transformed to a computaional space for a structured grid finite-volume solution. Hence, they are as following:

$$\frac{\partial \overline{\mathbf{Q}}}{\partial \tau} + \frac{\partial \overline{\mathbf{E}_E}}{\partial \xi} + \frac{\partial \overline{\mathbf{F}_E}}{\partial \eta} = \frac{\partial \overline{\mathbf{E}_v}}{\partial \xi} + \frac{\partial \overline{\mathbf{F}_v}}{\partial \eta} \quad (1)$$

$\overline{\mathbf{Q}}$ is the premitive variables matrix, $\overline{\mathbf{E}}_E$ and $\overline{\mathbf{F}}_E$ are the transformed convective flux matricies in ζ and η directions respectively, and $\overline{\mathbf{E}}_v$ and $\overline{\mathbf{F}}_v$ are the transformed viscous matrices in ζ and η directions respectively. τ is the dimensionless time variable.

The equation (1) is rearranged to its discrete form, the time derivative is approximated by a first-order backward differencing quotient and the remaining terms are evaluated at time level n+1. Thus:

$$\frac{\overline{\mathbf{Q}}^{n+1} - \overline{\mathbf{Q}}^{n}}{\Delta \tau} + \left(\frac{\partial \overline{\mathbf{E}}}{\partial \xi}\right)^{n+1} + \left(\frac{\partial \overline{\mathbf{F}}}{\partial \eta}\right)^{n+1} = \left(\frac{\partial \overline{\mathbf{E}_v}}{\partial \xi}\right)^{n+1} + \left(\frac{\partial \overline{\mathbf{F}_v}}{\partial \eta}\right)^{n+1} \quad (2)$$

The inviscid flux vectors on cell faces were evaluated by Van-Leer's Flux splitting scheme. To prevent the oscillatory behavior of the numerical results and to increase the accuracy, the Van-Leer's limiter was added to the flux splitting algorithm [13].

The second-order derivatives are evaluated by central difference approximation.

The standard κ-ε turbulence model was also employed in turbulent boundary layer over the blades. This model was compared with the Baldwin-Lomax (BL) model and experimental results by Bohn et al [14], over a cascade and the comparing results gives the required assurance of using the κ-ε and BL models in cascade problems. Additionally, using BL model by Farhanieh et al [15-16] for flow instability calculations over a cascade, gives the more assurance of using κ-ε.

The grid system is composed of O-type grids structured grids around the blades, Unstructured near the cascade, and H-type at the inlet and the outlet zones. The grid resolution is chosen upon grid dependency studies (Figure. 1a and 1b).

3. EXPERIMENTAL RESULTS

The geometrical characteristics of the blades in the stage are given in table 1 and the flow characteristics in the normal and unstable operating point are given in tables 2nd 3respectively.

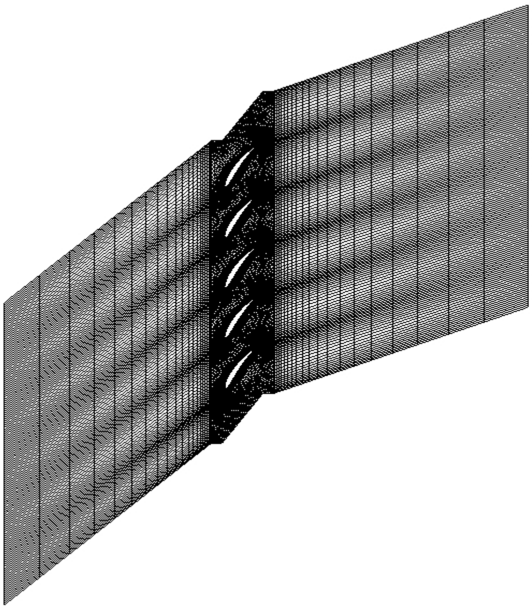


Figure 1a. Grid system for the rotor cascade

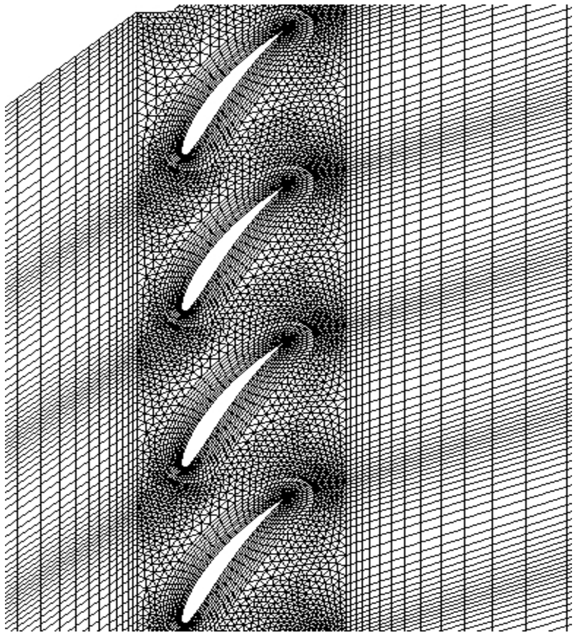


Figure 1b. The Enlarged Grid system for the rotor

Table 1. Geometrical characteristics of the cascade

Stagger angle of rotor blades	55°
Stagger angle of stator blades	35°
Rotor blade profile	NACA65-(A_{10})
Stator blade profile	NACA65-(A_{10})
Solidity	1.35

Table 2. The stable condition

r_h / r_t	0.6
R	0.56
P_{in}	100000 Pa
T_{in}	300 K°
P_{exit}/ P_{in}	1.02589
β_1	62°
ψ	0.28
ϕ	0.4
V_{xin}	36 m/s
M_{in}	0.223
U_r	90 m/s
RPM	1240

Table 3. The unstable condition

P_{exit}/Pin	1.02989
β_1	72°
Vx_{in}	22 m/s
ϕ	0.24
RPM	1240

Figure 2. indicates the schematic process to trigger the stall condition. The numerical solution is started at the conditions given in table 2. After about 3 rotor revolutions, the solution reaches to the normal operating condition (Figure3). At the normal operating point, the counter was set to zero and the unstable conditions were imposed to the computational area. The inlet flow angle, the axial velocity and the exit pressure were changed to the values given in table 3, and the rotating speed remained unchanged.

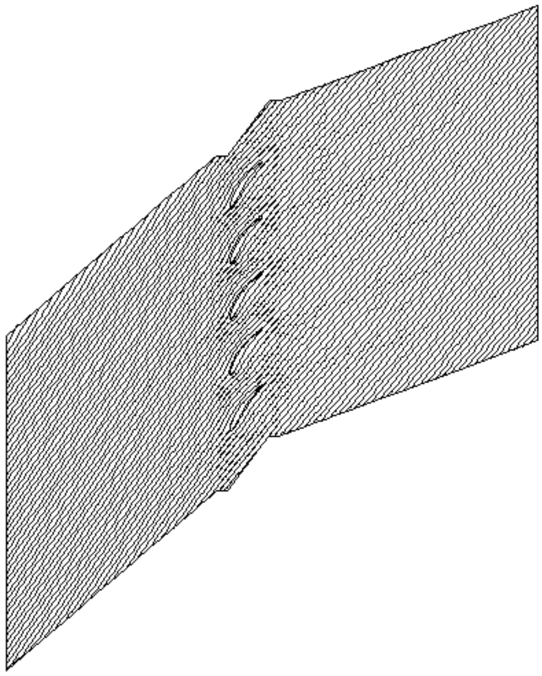


Figure 3. Normal operating streamlines for the cascade.

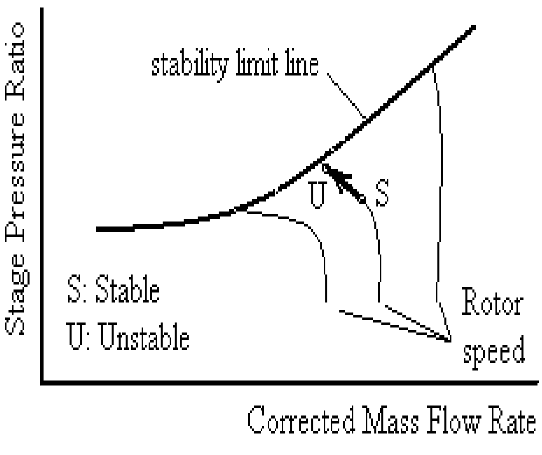


Figure 2. Schematic instability process for a compressor.

A stall vortex comes to exist near the leading edge of lower blades, and through the cascade passages (Figure.4). After some rotor revolutions the stall vortices move and propagate in circumferential direction, and a deep cell vortex comes into existance in front of the cascade (Figure.5). The deep cell spreads over the cascade and diffuses within the passages of the cascade (Figure.6). This is the final step of the formation of the maximum blockage against normal flow direction. In this condition, the overall mass flow rates through the cascade decreases to its minimum value. Then, the complete blockage is partially removed and again the deep cell generation initiates (Figure.7). The recycling of the deep cell generation and the growth of the large scale vortices indicates the hysteresis character of the rotating stall phenomena. The histeresis character of deep cell generation which is shown during the figures 5 to 9 highlights the reality of energy consumption of the fully developed rotating stall and the complete reduction of the rotor performance.

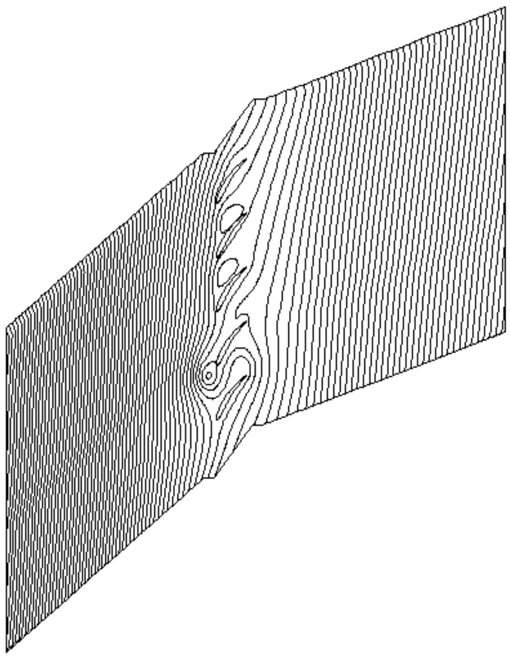


Figure 4. Stall initiation over the cascade

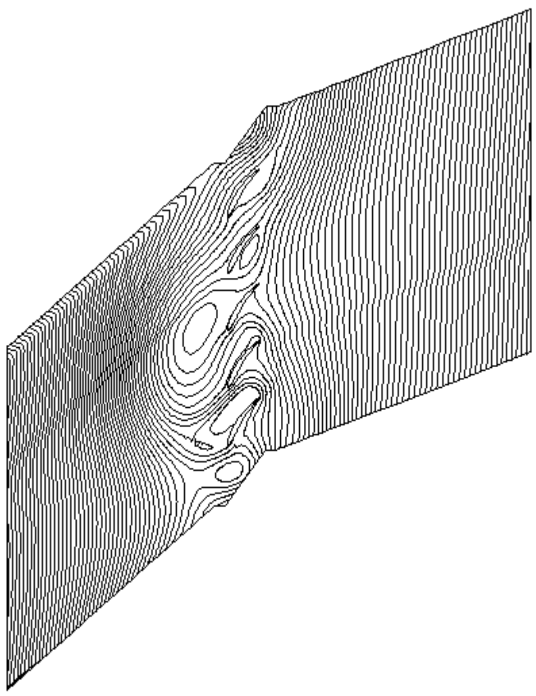


Figure 5. stall progress and large vortex generation.

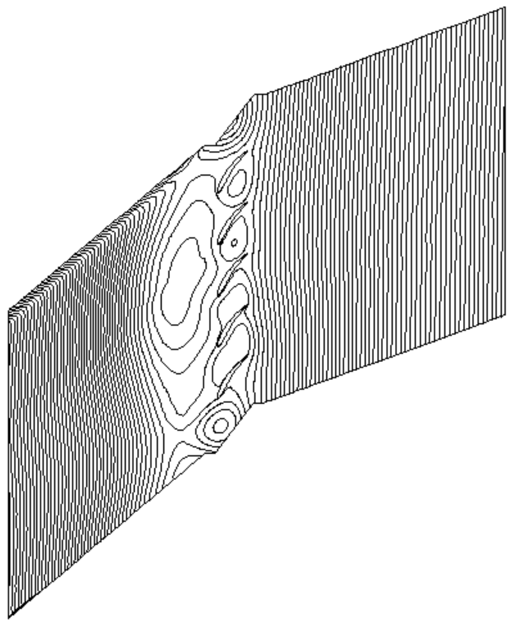


Figure 6. Grown vortex and blockage initiation.

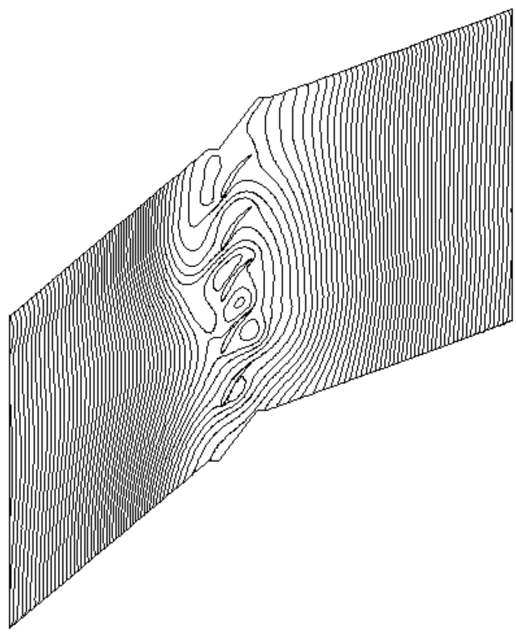


Figure 8. Recycling and the hysteresis of the stall propagation and large vortex diffusion.

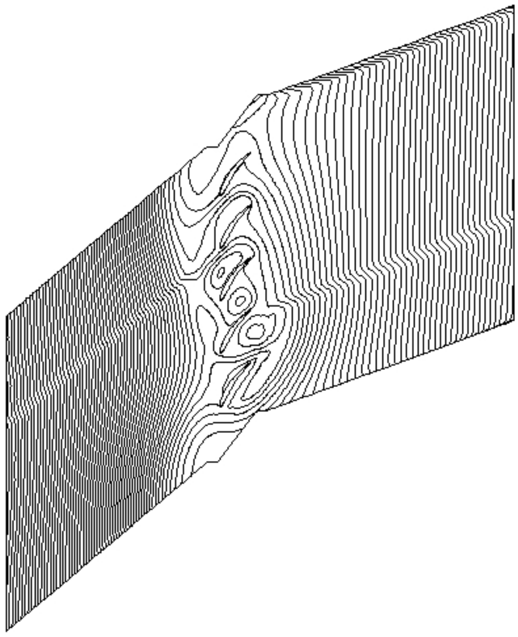
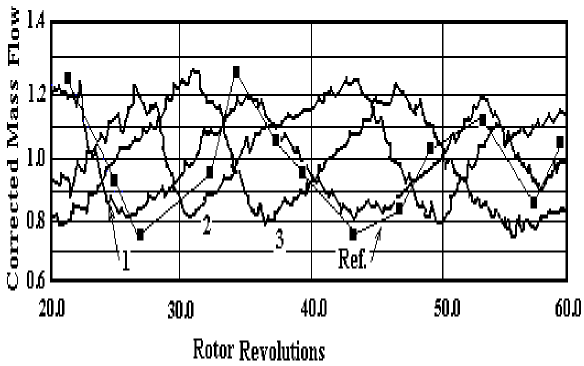


Figure 9. Diffusion and spreading of the vortices at the blockage area of the cascade



This is probably the main reason of sudden reduction of the exit pressure for an axial compressor during the stall condition. Additionally, the histeresis character fortifies the remaining of the exit pressure reduction of the compressor. The corrected mass flow rates of the first, third and the fifth passages (in y direction) are sketched and named in fig. 10 as the 1, 2, and 3 curves respectively. The curve 1 is compared with similar numerical study [17] with geometric and thermodynamic conditions, but with different blade number, different numerical procedure, and without any turbulence model. The qualitatively, good agreement of the compared results gives the required assurance of the numerical study and the employed computer code. The periodic behavior of the passage mass flow rates interprets the histeresis and recycling of the deep cell generation and the rotating stall. Besides, the average frequency of the waves shown in fig. 10 is lower than the rotation frequency of the rotor. Further, the phase difference among the curves explains the movement of the deep cells and the minor blockage area.

Figure 10. Corrected mass flow for three selected passages and comparison of the reference data with the first passage curve.
1. first passage from the bottom of the cascade,
2. second passage from the bottom of the cascade
3. third passage from the bottom of the cascade
Ref.: computed results from [17]

4. CONCLUSION

The results and the discussions give the following conclusion remarks:

1. In rotating-stall propagation in a 2-D stage, the velocity traces showed a periodic behavior.
2. The rotating stall and large-Scale vortex generation have a recycling character.
3. The mass flow rate and consequently the rotor performance reduce to very low levels and remain decreased and oscillate around the low levels.
4. The rotating stall effects can be numerically observed with much shorter cascades with respect to previous long cascade studies. This may save a lot of CPU times and memory usage.
5. Comparing the current results and the previous related works [15-17] we conclude

that the turbulence models seem to have minor effects on captured results.

NOMENCLATURE	
τ	time in transformed coordinatetime step
ξ	horizontal axis of transformed coordinate
ρ	density
β_1	inlet angle of relative velocity
ψ	load coefficient
ϕ	flow coefficient
η	vertical axis of transformed coordinate
$\overline{\mathbf{E}}_F$	inviscid transformed flux vector
$\overline{\mathbf{E}}_v$	viscous transformed flux vector
r_t	tip radius
T	time in physical coordinate
T_s	static temperature
Tin	inlet temperature
V_x	Axial velocity in stage
subscript	
ξ	partial derivative with respect to ξ
η	partial derivative with respect to η
b	index of bottom face flux
h	hub for blade radius
in	inlet condition
l	index of left face flux
r	index of right face flux
t	index of top face flux
t	total state for thermodynamic properties
superscript	
n	previous time level
n+1	current time level

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