47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition
5 - 8 January 2009, Orlando, Florida

AIAA 2009-865

Numerical Researches on Aeroelastic Problem of a Rotor due to IGV/Fan Interaction

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The commercial code CFX-10 was used For NASA Rotor 67, the blades are most likely to flutter in the second bending mode with IBPA of 60°. It is widely known that the upstream wake is a major contributor to the rotor blade forced vibration. The present research shows that the wake will also change the flutter characteristics of the rotor blade significantly. If the natural frequency of the most dangerous flutter mode of the blade is close to the IGV passing frequency, flutter may happen even it is very stable analyzed without IGV. This vibration is more like a sympathetic vibration. For a mode whose natural frequency is far away from the IGV passing frequency, the wake may also drive the vibration to be unstable. Though the IGV doesn't influence the performance of the rotor much, it does add significant nonlinear effects to the flutter behavior of the rotor blades. Designers need to increase the gap distance between IGV and rotor to avoid the significant change of the flutter boundary to solve the unsteady flow field. The code was validated by the calculation of STCF4 and NASA Rotor 67. The aeroelastic characteristics of Rotor 67 without IGV are analyzed with energy method, and then the results are compared with that of the model with IGV. The results show that Rotor 67 most likely to flutter in the second mode with an IBPA of 60˚. The IGV excitation will add significant nonlinear effects to the flutter behavior of the rotor blades, and may lower the flutter boundary greatly. Unsteady calculations with a larger IGV-rotor gap show that this wake effects will not be weaken unless the IGV is far away enough.

I. Introduction

An important consideration in turbomachinery design is the aeroelastic behavior of the blades. Classical aeroelastic phenomena can be generally classified into two categories: forced response and flutter[1~3]. Flutter is a typical asynchronous self-excited vibration, generally occurs at a frequency corresponding to one of the lower blade or coupled blade-disk natural frequencies. Forced response of rotor blades, on the other hand, generally results from periodic aerodynamic forcing functions with frequencies of integer multiples of the resonant natural frequency of the system. Wakes from blades of a previous row is one main source of unsteadiness in a turbomachinery blade row. The associated frequency is determined by the blade counts and shaft rotating speed. Hence, the downstream blade rows experience a high frequency excitation due to the flow wakes.

Either flutter or forced response results in high-frequency vibration of the blades, which causes blade to fail prematurely due to high cycle fatigue (HCF). The failure of the blade will cause catastrophic disaster. This consideration is further underscored as designers strive to achieve performance improvement through higher rotational speed, higher operating temperature, higher pressure ratio, and more compact designs. Until now very limited experiment data are available due to the difficulty of the experiment and the related high cost. Therefore, the computational approach has become a most common because of its relatively low cost and short design cycle. With

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the development of computers, recently Navier-Stokes method has become the mainstream way in flow field simulations[1, 4~9]. At the same time, research is also being performed on the development and use of unsteady aerodynamic ROM (reduced order model) in order to reduce the time on aerodynamic computations[3, 10, 11].

Flutter and forced response have been studied usually separately. Zhou et al investigated IGV/Rotor interaction case considering fluid-structure interactions and found that even with high stiffness blade vibration of small displacement can introduce significant change in the blade surface unsteady pressure distribution[12, 13]. A question arises regarding whether forced response changes the flutter characteristics significantly? In this paper, the aeroelastic characteristics of a typical fan without IGV are analyzed with energy method, and then the results are compared with that of the model with IGV. Unsteady calculations with varied structural frequency and IGV/ Rotor gap distance are also performed to investigate their influences on flutter boundary.

II. Methodology

The commercial code CFX-10 is used to model the flow field by solving the three-dimensional, compressible, unsteady Reynolds-Averaged Navier-Stokes equations. Second-order upwind scheme is used for spatial discretization and formally second-order backward Euler scheme was used for temporal discretization. The SST K-ω turbulence model is used throughout the computations. It has been validated that different turbulence models perform almost the same in laminar flow but the SST K-ω model gives better predictions in slight stall conditions[14]. Lane's traveling wave model (1956)[15] and Carta's energy method (1967)[16] are used for the aeroelastic analysis. Neighboring blades are assumed to oscillate harmonically at a same IBPA (Inter-Blade Phase Angle) throughout the cascade. The work that the aerodynamic forces perform on the oscillating blade serves as the measure for instability. As a classic two-dimensional cascade aeroelastic experiment, the STCF4 (Standard Test Configuration 4) [17, 18] is first calculated as methodology validation. NASA Rotor 67[19], a typical transonic fan case, is chosen to be the research object. A simple straight IGV with NACA0012 airfoil is put in front of the fan. The performance map of the rotor under design condition with and without the IGV are calculated and compared with the experimental data to validate the code in three-dimensional conditions and to investigate the influence of the IGV.

We performed modal analysis for the blades on Rotor 67 with certain isotropy material. The movements of the No. n blade on the rotor are described as:

$$\boldsymbol{\delta} = \boldsymbol{\Phi} \cdot \xi_0 \cdot \sin(\omega t + n\varphi)\,,\ n = 0,1,2... \tag{1}$$

Where $\boldsymbol{\delta}$ is the vector of displacement, $\boldsymbol{\Phi}$ is the mode shape vector, ξ_0 is the amplitude of the generalized displacement, ω is the frequency of the vibration and φ is the IBPA. The aerodynamic damping is investigated for the first three modes (which are the first and second bending modes and the first torsional mode) of the blades at the design condition. The aerodynamic damping for the three modes are analyzed at corresponding frequencies to find the most dangerous mode and IBPA, then ω is tuned to find the zero damping condition (the critical value).

After that the IGV is added to explore the coupling effects on the flutter characteristics. The aerodynamic damping at two specific frequencies, the critical one without IGV and the forcing frequency of the IGV, are examined and compared. In order to reduce the computational requirement, the IGV/Rotor blade count ratio is set to 1:2 (11 vanes in IGV and 22 blades in the rotor). In addition, we studied a case with larger rotor/IGV gap distance to see the impact on flutter characteristics.

III. Results and Analysis

STCF4 is a standard transonic stator with detailed 2D steady and unsteady experimental data initially obtained at the Swiss Federal Institute of Technology. Case 552B is chose to be the test case, with the inlet total pressure of 1.691 atm, inflow angle of 11.65˚ to the chord and the outlet static pressure of 1 atm. In the unsteady cases, the blades vibrate at a frequency of 149Hz with the amplitude of 0.3mm. The steady and unsteady results of STCF4 are shown in Figs. 1 and 2. Figure 3 gives the distribution of the amplitude and phase angle of the unsteady pressure coefficient on the blade for IBPA=180˚. Both the steady and unsteady results match the experimental data well, indicating that the code CFX-10 provides accurate steady and unsteady CFD simulations.

A. Aeroelastic characteristics of Rotor 67 without IGV

Figure 4 gives the model views of the Rotor 67 with IGV. The chord length of the vanes of IGV is 100mm while

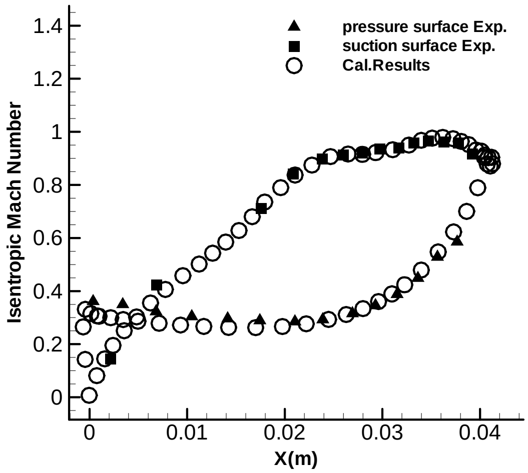


Figure 1 Steady results of STCF4 (Case 552B)

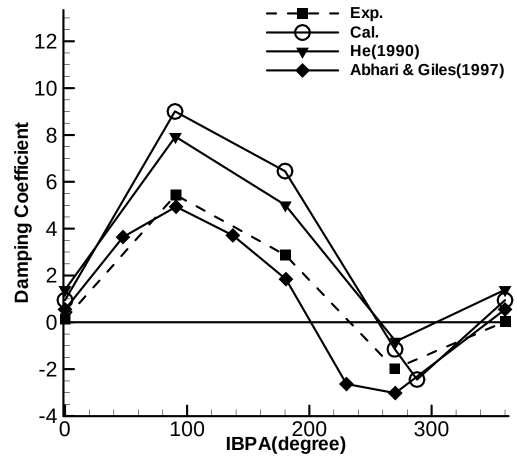


Figure 2 Unsteady results of STCF4: aerodynamic damping coefficient vs. IBPA (Case 552B)

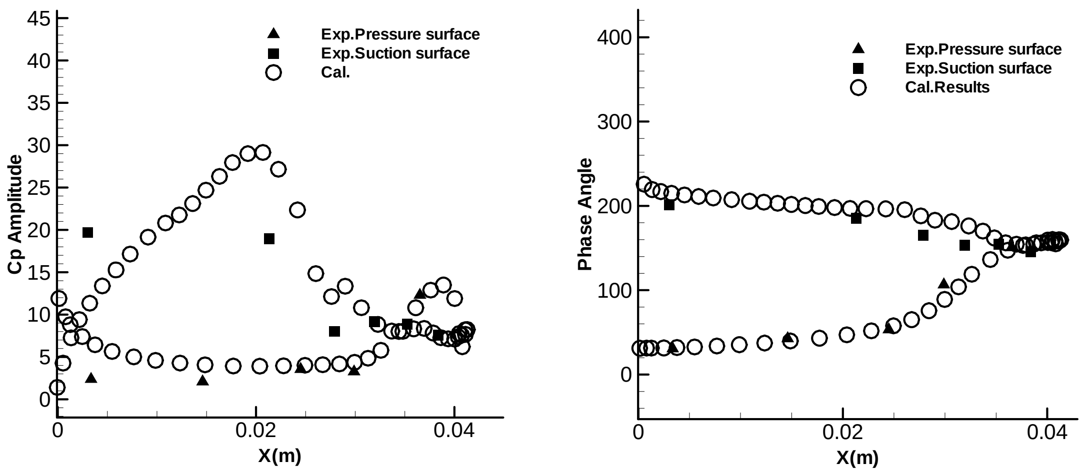


Figure 3 Unsteady results of STCF4 (Case 552B, IBPA=180°)

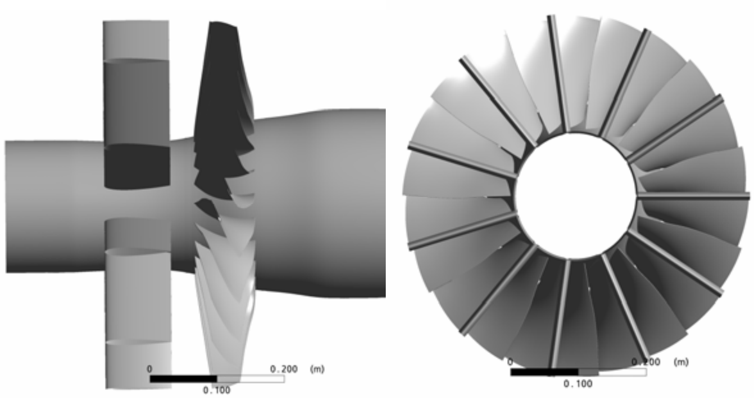


Figure 4 Different views of the IGV/Rotor model (Rotor 67)

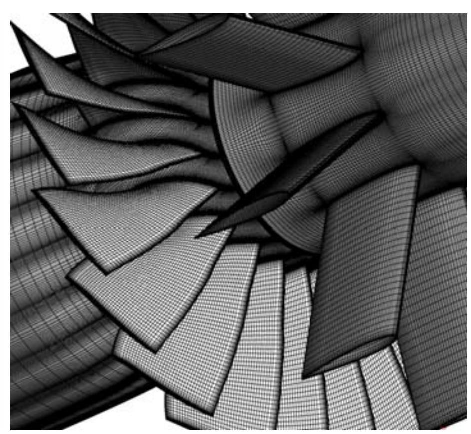


Figure 5 Grid of IGV/Rotor (Rotor 67)

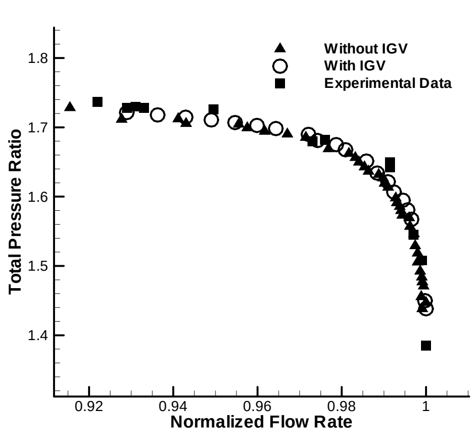
the least gap distance (at the hub) between IGV and rotor is 35.5mm and the max value (at the tip) is 60.3mm. This is a model without tip clearance. Figure 5 shows the surface grid of the IGV/Rotor. The grids of each rotor passage have 317,460 elements for the model without IGV. For the one with IGV, there are 339,660 elements in each rotor passage and 183,552 elements in the IGV passage. For the IGV grid, it has 49 grid points spanwise, and the rotor grid contains 75 grid points spanwise.

Rotor 67 is designed to run at a rotational speed of 16,043rpm. The steady results of NASA Rotor 67 with and without IGV are compared with the experimental data in Fig. 6. The computational results agree well with the experimental data. The adiabatic efficiency is higher than the experimental value because the computational model ignored the tip clearance. The results of the rotor with and without IGV are very close to each other, meaning that the influences of IGV on the performance of compressor are very small.

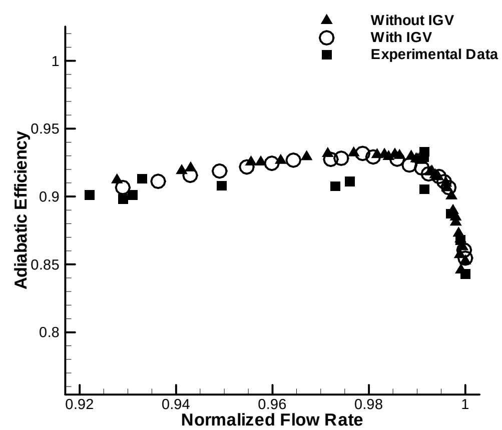
Unsteady calculations are performed at a near peak efficiency point with the outlet static pressure of 1.18atm and all the unsteady calculations using the same ξ_0. The aerodynamic damping here is defined as:

$$\Xi = -\frac{1}{\xi_0 c^2} \cdot \frac{1}{\overline{P}_{w2} - \overline{P}_2} \int_0^T \int_{blade} P ds \mathbf{n} \cdot d\mathbf{h} \tag{2}$$

where c=0.0921749m is the tip chord length of the rotor blade, $\overline{P}_{w2}$ and $\overline{P}_2$ are the outlet averaged total pressure and static pressure, respectively; P is the pressure on an element face ds; $\mathbf{n}$ is the normal unit vector of ds; $d\mathbf{h}$ is the displacement vector in a time step; and T is a period of vibration.

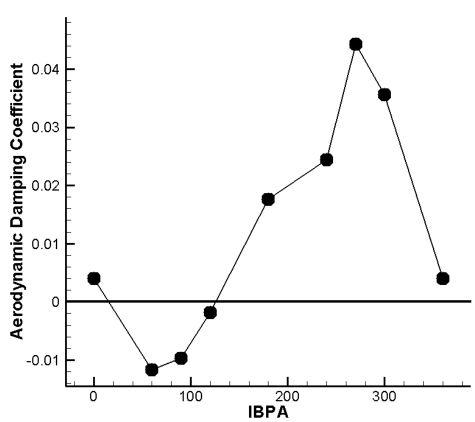


a. Total pressure ratio – Flow rate

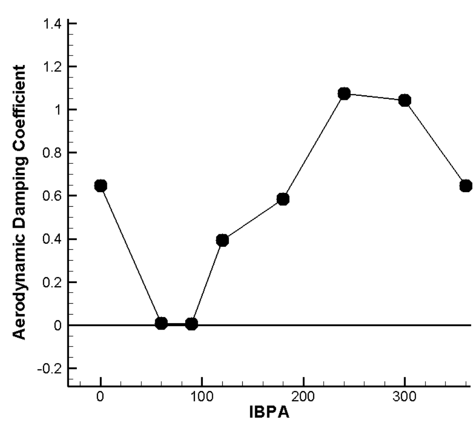


b. Adiabatic efficiency – Flow rate

Figure 6 Steady results of Rotor 67: performance map



a. Mode2 at 250 Hz



b. Mode3 at 429 Hz

Figure 7 Unsteady results of Rotor 67: aerodynamic damping coefficients - IBPA

The computed aerodynamic damping of the first mode remains positive even when the frequency is tuned down to a very low value， indicated that flutter does appear in this mode. Figure 7a plots the aerodynamic damping coefficients at different IBPA for mode 2 while ω=250Hz. We can see that the minimum damping appears around IBPA=60˚. Figure 7b plots the aerodynamic damping coefficients at different IBPA for mode 3 at ω=429Hz, which is the corresponding frequency of mode 3 when the frequency of mode 2 is 250Hz. The minimum damping appears at an IBPA between 60˚ and 90˚. However, all the damping values are positive. The results show that mode 2 is the most dangerous mode for flutter, and IBPA=60˚ is the most dangerous IBPA. Hence mode 2 with the IBPA of 60˚ is the condition of our interest.

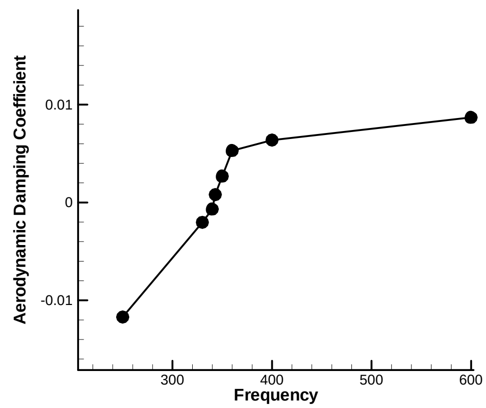


Figure 8 Aerodynamic damping coefficients – frequency: Mode 2, IBPA=60˚

Figure 8 shows the aerodynamic damping coefficient of mode 2 with IBPA=60˚ at different frequencies. The corresponding frequency of zero damping is found to be at 341.17Hz by interpolated from the nearby points. It means that without coupling effects, the blades of Rotor 67 would flutter in mode 2 at 341.17Hz with an IBPA=60˚.

Table 1 Comparison of aerodynamic damping coefficients of Rotor 67 with and without IGV

Mode3 IBPA=180°	f=2941.2Hz	1.0936
	f=2941.2Hz, with IGV	**0.4629**
	f=1986Hz	0.5020
Mode2 IBPA=60°	f=2941.2Hz	0.2375
	f=2941.2Hz, with IGV	**0.0329**
	f=341.17Hz	0
	f=341.17Hz, with IGV	**-0.0033876**

B. The coupling effects between IGV/fan

There are 11 vanes in IGV and the rotational speed of rotor is 16043rpm, thus the frequency of the IGV wake disturbance would be 2941.2Hz. Designers would always avoid having the natural structural frequency to be the same or around the wake forcing frequency of the upstream vanes, because it induces resonant vibration. In a linear system, forced response and flutter are two independent phenomena. We would like to investigate whether flutter of the blades are in any way affected by the wake forcing.

Table 2 Comparison of aerodynamic damping coefficients of Rotor 67 with different IGV/rotor gap distance

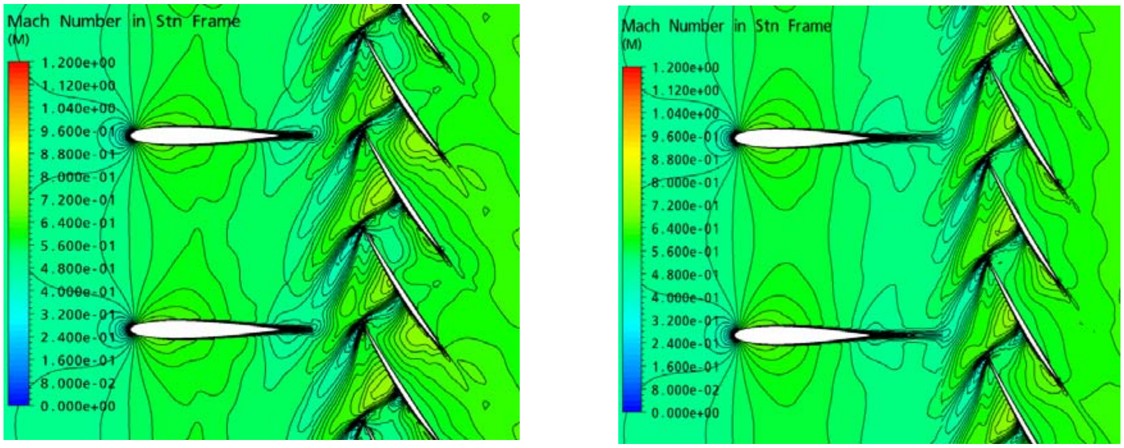
Mode2, IBPA=60°		
Gap distance at the tip / Frequency	60.3mm	90.3mm
2941.2Hz	0.0329	0.0340
341.17Hz	-0.0033876	-0.002855

Table 1 is a comparison of the results between the model with and without IGV. We can see that the upstream wake does have a significant effect on the flutter characteristics of the rotor blades. At the wake forcing frequency of 2941.2Hz, the aerodynamic damping coefficient is reduced to 0.0329 from 0.2375 for mode 2 and IBPA=60° , very close to the flutter boundary. For mode 3 and IBPA=180° , which is not the corresponding IBPA of minimum damping, the wake also makes the damping less than half of the original value, even lower than the damping of the model without IGV at f=1986Hz. At the critical flutter frequency of f=341.17Hz, which far away from the forcing frequency, the wakes of IGV push the damping into the negative range, indicating flutter.

In order to investigate the in influences of the gap distance between IGV and rotor, another model with a larger gap distance is calculated. Table 2 gives the comparison of the calculated damping with these two models. The results show that when the gap distance gets larger, the vibration becomes more stable. However, comparing with the significant reduction of damping due to the addition of IGV, the increment is very small. The answer can be found in Figs. 9 and10. The wake hit the leading edge of the rotor blades directly near the hub. The wake does not become weak enough when the gap between the IGV and the rotor is not significantly increased.

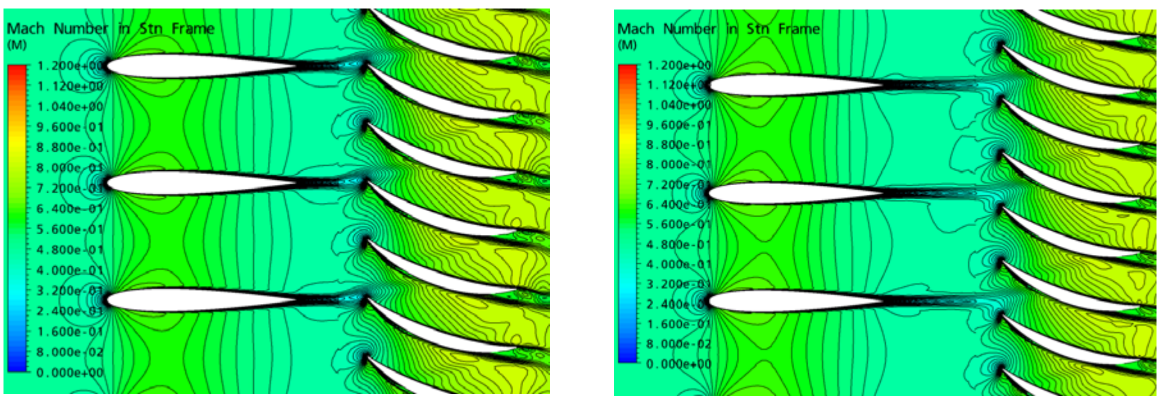
IV. Conclusions

It is widely known that the upstream wake is a major contributor to the rotor blade forced vibration. By adding an



a. 60.3mm gap **b. 90.3mm gap**

Figure 10 Mach number distributions on 80% span (with IGV)



a. 60.3mm gap **b. 90.3mm gap**

Figure 9 Mach number distributions on 10% span (with IGV)

IGV to rotor 67, the present research shows that the wake also changes the flutter characteristics of the rotor blade significantly. If the natural frequency of the most dangerous flutter mode of the blade is close to the IGV passing frequency, flutter may happen even when isolated-rotor computations show that it is very stable without the IGV. For a mode whose natural frequency is far away from the IGV passing frequency, the wake also results in reduced aerodynamic damping. Though the IGV doesn't influence the performance of the rotor much, it does add significant nonlinear effects to the flutter behavior of the rotor blades. This points to the need for the use of coupled multi-blade row models in flutter boundary predictions turbomachines.

V. Acknowledgement

This research is funded by Honeywell Corporation, their support is most gratefully acknowledged. The authors would like to thank Dr. Josef Panovsky at Honeywell E & S and Dr. Shi Ai-ming in NWPU for their helpful suggestions.

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