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Aeroelastic Investigation of a Transonic Compressor Rotor with Multi-Row Effects

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Abstract

According to the modern turbomachinery design trend, blades are getting more and more flexible and loaded, and therefore prone to vibration issues due to forced response and flutter phenomena. For this reason, the flutter stability assessment has become a key aspect to avoid high cycle fatigue (HCF) blade failures. The aim of this paper is to numerically evaluate the influence of unsteady aerodynamic effects, due to upstream and downstream rows, on flutter predictions using an uncoupled method. Both CFD aeroelastic and modal analyses have been carried out for a one and half compressor stage in transonic conditions. Flutter results are reported for the classic single-row approach and then for the multi-row model which includes rotor/stator unsteady interactions: a good agreement with measured data is shown for both cases and also a no negligible impact of adjacent rows can be observed.

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Keywords: aeroelasticity; flutter; axial compressor; FEM; CFD

1. Introduction

The main purpose in modern turbomachinery design for propulsion and power production is to develop system more powerful, economic, environmental friendly allowing a reduction in fuel burn, community noise and NO_x emissions. This design trend has led to machines with a lower number of stages, lower blade count and with thinner

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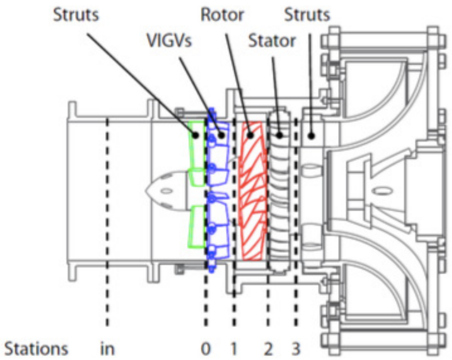
and lighter profiles which are thus more affected to structural integrity issues. Indeed, blades are now more highly loaded, with a higher possibility to flow induced blade vibrations caused by aeroelastic phenomena, as flutter and forced response. Especially flutter occurrence represents one of the major concern in the nowadays turbomachinery design, as this phenomenon is a self-excited and self-sustained instability, that may cause failures in fan, compressors and turbine blade-rows. For this reason, in the last few decades, numerical methods for flutter assessment have been developed and used in the turbomachinery design loop. Flutter prediction methods have been firstly validated in low pressure gas turbine environment for the aeronautical industry [1] [2], whereas for the compressor rows flutter methods [3] [4] need a more accurate validation, especially in the transonic conditions. In these cases, flutter stability assessment is not trivial as the blade behavior mostly depends on the shock wave interaction with the moving blade surfaces [5].

The purpose of this paper is to numerically evaluate flutter stability of a rotor blisk, in a one and a half compressor stage of TUD test rig, installed at the Technishe Universitat von Darmstadt. Extensive studies have been carried out about aeroelastic stability turbomachinery blades, but usually the effects of adjacent rows are not taken into account. This is due to the fact that flutter onset and rotor/stator interaction frequencies are usually well separated and the two phenomena can be considered uncoupled. However, the extension of flutter analyses to multi-row environment allows the inclusion of physical phenomena as acoustic wave propagation in the model in order to achieve more accurate results. The flutter results presented herein allow the identification of multi row environment effects (acoustic waves, wakes and potential effect) on flutter stability. Unsteady flutter uncoupled analyses have been carried out with κ-ω turbulence model, using an in-house URANS code (Traf) [6] with moving blades [1].

a



b

TUD test rig	
Operative condition	Transonic
Number of stages	1.5
Maximum Shaft Speed	21000 [rpm]
Design Shaft Speed	18000 [rpm]
Maximum Mass Flow	16.0 [kg/s]
Design Mass Flow	13.8 [kg/s]

c

Mass flow	**Ptot inlet**	**Pstat outlet**	**Rotation speed**
12.4 Kg/s	101325 Pa	120540 Pa	16000 rpm

Fig. 1. (a) TUD test rig layout; (b) TUD test rig operative conditions; (c) Operative point tested conditions

A cross sectional view of compressor layout (Fig.1 (a)) shows the one and a half stage layout composed by 15 VIGVs (Variable Inlet Guide Vane), 21 rotors, and 29 stator blades.

To evaluate the energy exchange between flow and a vibrating row an uncoupled method is used: following this approach, it is assumed that the unsteady flow does not modify the mode shapes and frequencies computed by a free response analysis with a FEM solver and so structural and aerodynamic phenomena can be solved individually. The energy exchange has been evaluated by integrating the unsteady pressure caused by blade oscillation over the entire blade surface for a cycle of oscillation. The experimental flutter results of this test rig have been provided in the context of EU FUTURE project and have been used for comparison and method validation.

Nomenclature

E	Young modulus
W_{aero}	Aerodynamic work
m	Modal mass

a	Modal amplitude
n	Surface normal unit vector
p	Static Pressure
c	Blade velocity
E_{kin}	Kinetic energy
T	Vibration period

Greek Letters

θ	Portion of blade surface
ν	Poisson ratio
ξ	Critical damping ratio
ρ_ξ	Energetic damping coefficient surface density
ω	Angular frequency

Acronyms

HCF	High Cycle Fatigue
TUD	Technishe Universitat von Darmstadt
PS	Pressure Side
SS	Suction Side
ND	Nodal Diameter

2. Modal analysis

As a first step of the flutter evaluation method, a modal analysis has been carried out in order to compute eigenfrequencies and linked mode shapes for the rotor blisk (Fig.2 (a)). Such mode shapes will be transferred to the blade surfaces in the fluid domain mesh and used for the instantaneous re-meshing strategy during the non linear flutter computations with vibrating blades. Firstly, the structural interactions between different rows of the test rig have to be considered. The disk root is bounded in axial direction, both in front and back region with blocking elements, and in radial direction thanks to a spacer: these aspects are reproduced through an interlock constraint. Also the presence of screws has to be taken into account as they make the blisk to be rigidly coupled to the compressor shaft. Even if screw holes are not included in CAD model, their presence is shaped through an axial-tangential constraint. Assuming the blade with same elastic, inertial and damping properties, the so called "*tuned configuration*", the entire structure can be studied applying cyclic symmetry boundary condition, which is imposed on right and left periodic surface of the disk. This choice leads to a substantial simplification as it allows to compute just one sector (Fig.2 (b)) instead of the entire row. Hence, the number of degrees of freedom of the FEM model is reduced by a factor equal to the number of identical sectors and the computational costs result significantly decreased.

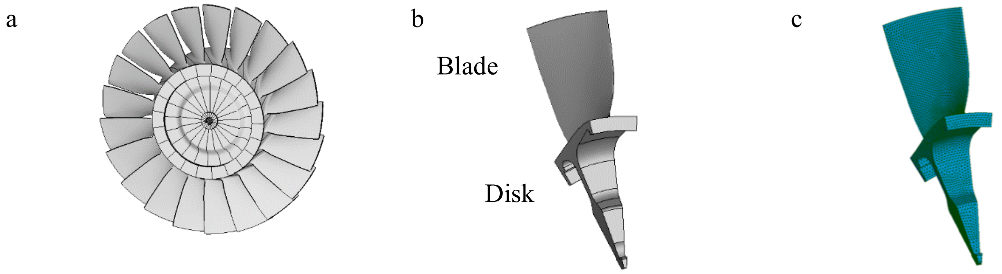


Fig. 2. (a) Rotor blisk; (b) Blisk sector; (c) Blisk sector mesh

The Open Source software *Salome* has been used for the solid mesh generation of the blisk sector using about 50000 quadratic tethraedron elements (Fig.2 (c)). Modal analysis has been performed with the Open Source *Calculix* solver, considering mechanical properties of a titanium alloy ($E=1.165\cdot10^{11}$ [Pa], $\nu=3.225\cdot10^{1}$ [-], density=$4.43\cdot10^{3}$ [kg/m^{3}]). Eigenfrequencies values plotted against nodal diameters, are reported in Fig.3 for the three lower frequencies mode families. Since the first bending family usually results as the most critical one from flutter stability point of view, only this one will be under investigation. Looking at the 1st mode curve in Fig.3 (a) it can be appreciated a frequency saturated trend around 570 Hz, caused by the lack of disk participation to the mode shape for this 1st mode family. For 2nd and 3rd mode families at the low nodal diameters (up to ND=0 and with a small phase shifting between two adjacent blades), the disk deformation is not negligible and a major participation to system vibration is confirmed. This globally results in lower stiffness value. On the other hand, for high nodal diameters, the disk again does not participate to the sector deformation, the mode shape become real and the frequency remains almost constant.

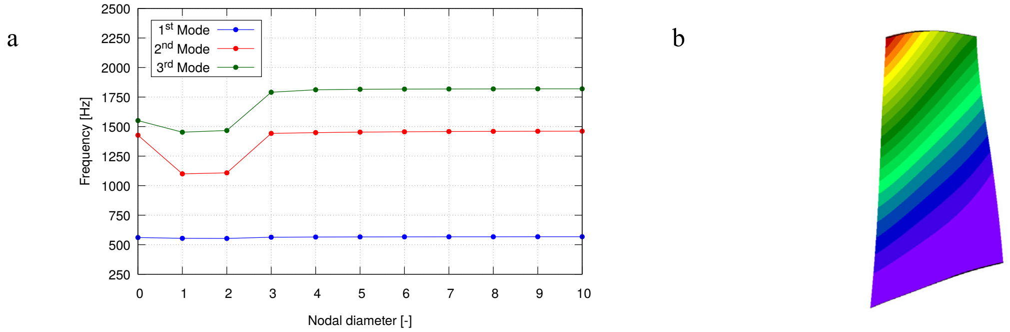


Fig. 3. (a) Eigenfrequencies vs. Nodal Diameter; (b) First Bending mode shape

3. Flutter results

Unsteady flutter results are presented for single and multi-row environment. The unsteady pressure response due to vibrating blade has been evaluated by computing the critical damping ratio (Eq. (1)), over a period of blade oscillation on the whole surface. It mainly depends on the phase shift between local blade displacements and pressure response. Stability or flutter onset is assessed by checking the sign: a positive sign indicates a stable condition in which blade dissipates energy to the fluid (therefore if the system starts vibrating, it results damped by fluid), whereas a negative value denotes an unstable condition characterized by an extraction of energy from the fluid to the blade, enhancing vibration amplitude. The amplitude of these effects is determined by the magnitude of the aerodynamic work (Eq. (2)). The evaluations of the critical damping ratio have performed for all the possible nodal diameters (from -10 to 10), even if the experimental values are acquired only for ND=-2,0, +1, +2, +3. The experimental values show a significant uncertainty associated to the measurement chain and reported with an error bar in Fig.6.

$$\xi = \frac{-W_{aero}}{2\pi m\omega^2 a^2} \qquad 1$$

$$W_{aero} = \int_t^{t+T} \oiint (-p)\vec{n}\cdot\vec{c}\,dt \qquad 2$$

These above-mentioned parameters give a global evaluation of the flutter stability assessment, yet no local information on stable and unstable blade surface areas are provided. To have a better insight on the blade flutter response, a local quantity, the energetic damping coefficient surface density ρ_ξ, is introduced (see Eq. (3)). Blade surface maps of this quantity provide a very detailed description of stabilizing and destabilizing regions on the blade surface, correlating these areas to fluid flow structure as shock waves, flow separations, etc.. As for the critical damping ratio, a positive value corresponds to stable areas and vice versa.

$$\rho_\xi = \frac{-dW_{aero}}{8\pi E_{kin}\frac{-d\theta}{\theta}} \qquad 3$$

3.1. Single row unsteady analysis

Before computing the flutter response of the 1st mode shape a steady state CFD analysis was carried out in order to verify the average working conditions of the rotor. As can be seen comparing the pressure contours at the rotor tip (see Fig.4 (b) and Fig.4 (c)) the agreement between numerical and experimental results is satisfactory. This steady state flow field is used as initialization for the following flutter computations with a phase-lagged approach to assess the flutter stability of the rotor row in a single-passage approach. The main hypothesis of this approach is that all the blades composing the row are identical and follow a travelling wave deformation, and instantaneous flow quantities at the single sector periodic boundaries can be imposed with a time shift. As usual, all the analyses have been carried out assuming the same pitch-wise uniform flow conditions. For each nodal diameter, 15 periods of blade oscillations have been computed in order to obtain a converged and periodic flutter simulations. The simulation periodicity is checked by comparing the critical damping ratio of the different periods: when the value remains constant the simulation can be considered converged.

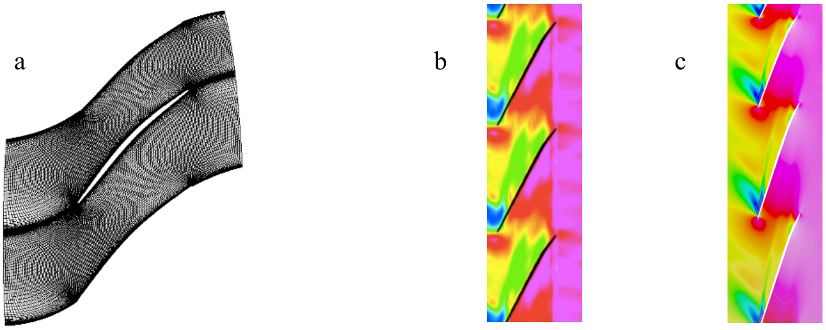


Fig. 4. (a) 2D Single-row midspan mesh; Rotor tip pressure contours: experimental (b) and computed (c)

The main approximation of this classical approach for flutter assessment is that the effect of adjacent row cannot be taken into account and only the single vibrating rotor with constant inlet condition is simulated. Exploiting the phase-lagged approach each computation can be reduced to a single vane with an important saving of computational requirements. Results for single row environment are reported in Fig.6 (Blisk κ-ω): the critical damping ratio curve presents a sinusoidal trend with maximum value at higher nodal diameters as expected. Finally, when comparing numerical values with experimental date a slight underestimation of the critical damping ratio is observed. This can be due to an underestimation of blade frequencies from modal analysis and to small discrepancies in the mean flow field. Anyway, as it will be shown in the following paragraph, the inclusion of multi-rows effects enhances the result accuracy.

3.2. Multi row unsteady analysis

The main objective of this work is to evaluate the effects of adjacent rows in the flutter assessment. The test-case under investigation gives the opportunity to widen the simulation domain by including an upstream VIGV and a downstream stator, thus simulating the entire 1.5 stage with the vibrating rotor.

The blade count of 1.5 stages has no a common factor, so it is not possible to reduce the computational domain to a single sector and a full annulus approach with the whole wheel must be applied. Since it is necessary to model the whole annulus, and the frequencies of interest (mode-shape frequency and blade passing frequencies) are quite distant, a high computational cost is required and some slight approximations must be introduced to make the analysis affordable.

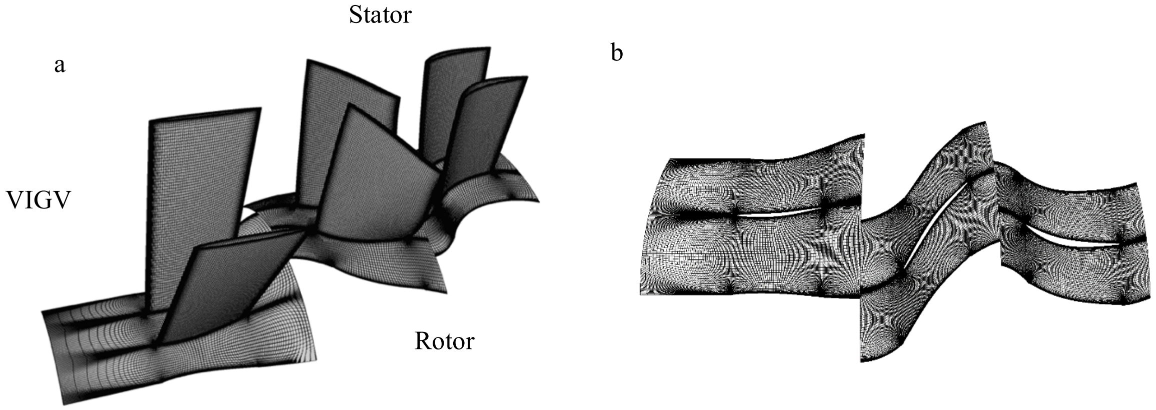


Fig. 5. (a) 3D multi row environment view; (b) 2D multi row midspan environment mesh

As already stated, the physical domain cannot be reduced; yet slightly modifying the blade vibration frequency, the overall time period to be simulated can be drastically reduced. The basic idea is to compute the minimum time interval that ensures the periodicity of all the fluctuations under investigation (blade vibration and blade passing frequencies). To shorten the time interval, the blade frequency was slightly modified (533.16 Hz) so that it is twice of the rotational frequency (266.58 Hz). With this setup, during a single rotor rotation, two complete blade oscillations occur and the overall time interval is limited to one rotor revolution.

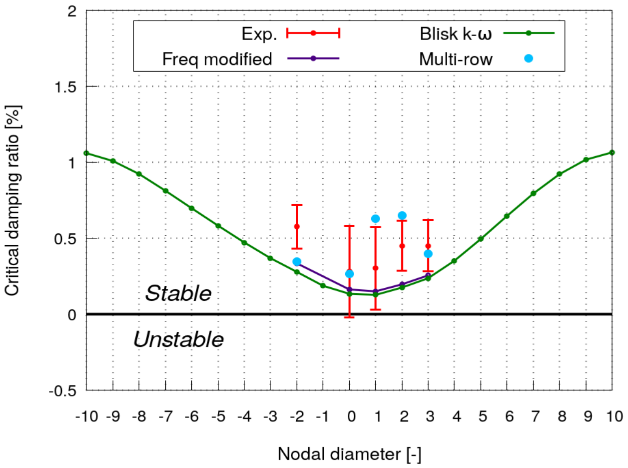


Fig. 6. Critical damping ratio vs. Nodal diameter

The required time discretization to compute the single rotor revolution, with the dual-time stepping method, is strictly connected to the highest BPF to be solved. The highest BPF is related to the row with the highest blade count (29 blade of the stator), and so 25 [time step] x 29 [blade] = 725 [total time step] were used to analyze a single period. Finally, five periods, was simulated to reach solution periodicity and this happens when rotor aerodamping and blade loads stay very close between consecutive periods. Therefore, before performing multi-row flutter computations the effect of the slight modification in rotor 1st mode frequency was evaluated with a single row approach. The results with modified frequency are reported in term of critical damping ratio in Fig.6 (Freq modified). As expected, no significant discrepancies can be appreciated between these two cases, and thus these results are used as basis to evaluate multi-row effects.

From the multi-row flutter analyses, the results for low nodal diameters show different values of critical damping ratio as shown in Fig.6. The aerodamping value is obtained by averaging this quantity computed on each of the 21 rotor blades. A significant increase in critical damping ratio can be appreciated for almost all computed nodal diameters, showing a stabilizing effects of adjacent rows. The multi-row results have a better agreement with experimental data and also the aerodamping curve trend is better captured. This less regular trend of the critical damping ratio, also confirmed by the experimental measures, can be due to the multi row effects now included in the simulations which are related to wake passage and acoustic wave reflections form adjacent rows. Indeed, a vibrating rotor generates up/downstream running acoustic waves which can be reflected back by adjacent rows (VIGV and stator) and modify the pressure fluctuation on the rotor, thus influencing the aerodamping.

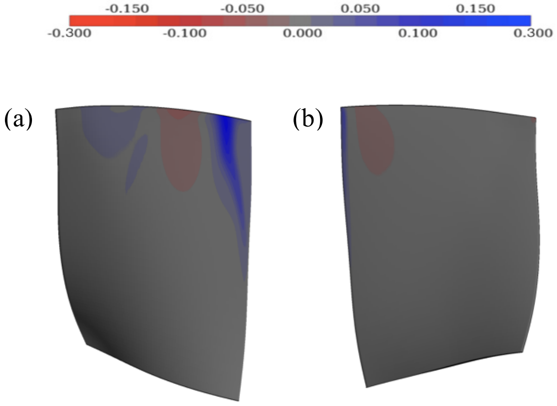


Fig. 7. ρ_ξ distribution in single-row environment (a) Suction Side; (b) Pressure Side

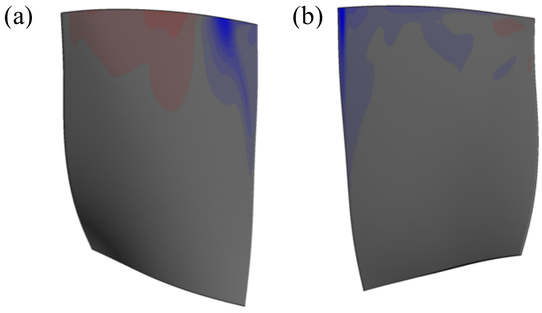


Fig. 8. ρ_ξ distribution in multi row environment (a) Suction Side; (b) Pressure Side

Acoustic fluctuations generated by a vibrating row have a number of circumferential lobes equal to the nodal diameters. The number of lobes changes the axial propagation of acoustic wave coming from the vibrating row and, in turn its reflection, leading to a less regular aerodamping curve. A further difference with respect to the single row environment analysis can be ascribed to the inclusion of VIGV wakes and stator potential effect in the computation with vibrating rotor, thus considering a fully unsteady environment, where instantaneous flow quantities change due to rotor/stator interactions. The multi-row effects can be investigated more in detail considering the *energetic damping coefficient surface density* over the rotor surface. The single row results clearly show the area where shock impinges on the blade SS. This zone has a stabilizing effects (Fig.7 (a)), whereas on the blade PS a small unstable area can be observed (Fig.7 (b)). When looking at the multi-row results (Fig.8) for the same nodal diameter (ND=+3), it is clearly visible an increase of areas where ρ_ξ is positive (stabilizing effect) and also an increase of the positive value magnitude. These differences in the energetic damping coefficient surface density leads to the increase of the overall aerodamping value. The better agreement with the experimental data confirms that the inclusion of multi-row effects in flutter computations can improve the accuracy of the flutter results.

4. Conclusion

The numerical evaluation of flutter stability in transonic compressor stages is not a trivial task, so it is important to exploit high quality aeroelastic measurements to calibrate and validate flutter prediction methods.

In the paper two different flutter analysis approaches have been used to assess the flutter stability of a rotor blisk included in a 1.5 stage of a transonic compressor, installed at the Technishe Universitat von Darmstadt. Classic single-row flutter analysis and multi-row computation with vibrating blades to include rotor/stator unsteady interaction effect (acoustic waves propagation, wakes) are used fot the damping evaluation. The aim of this paper is to validate the numerical methods against experimental data and evaluate the impact of adjacent rows on flutter stability prediction. The numerical procedure is based on an uncoupled method, hence structural and aerodynamic problems are solved separately. Firstly, a free response analysis has been carried out with an Open Source FEM solver to find out blisk frequencies and related mode shapes that have been transferred to the blade surface on the fluid mesh for the non linear flutter computations with vibrating rows. Unsteady flutter results for the single-row configuration, obtained with a phase-lag approach, show a good agreement with experimental data acquired in the context of the European research project FUTURE.

Multi-row configuration results also confirm the experimental evidences: the overall stability of the blisk (a positive damping for all the nodal diameters) is correctly predicted as in the single-row analysis and the damping curve trend obtained from experimental is better captured by the multi-row approach. Also *energetic damping coefficient surface density* maps on the blade are provided, so that is possible to appreciate where positive/negative local damping contributions are located, highlighting the differences between these two numerical solutions. In conclusion, both the approaches (single and multi-row) are suitable to assess the flutter stability of a transonic compressor rotors as both computations show an overall flutter stability confirmed by experimental data. Yet, when a more accurate aerodamping evaluation is required, this work suggest to include multi-row effects despite the increase of the computational cost.

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