UNSTEADY AERODYNAMICS, AEROACOUSTICS
AND AEROELASTICITY OF TURBOMACHINES
Unsteady Aerodynamics, Aeroacoustics and Aeroelasticity of Turbomachines

Edited by

KENNETH C. HALL
Duke University, Durham, North Carolina, U.S.A.

ROBERT E. KIELB
Duke University, Durham, North Carolina, U.S.A.

and

JEFFREY P. THOMAS
Duke University, Durham, North Carolina, U.S.A.
Contents

Preface xi

Part I Flutter

Flutter Boundaries for Pairs of Low Pressure Turbine Blades 3
Roque Corral, Nélida Cerezal, and Cárlos Vasco

Influence of a Vibration Amplitude Distribution on the Aerodynamic Stability of a Low-Pressure Turbine Sectored Vane 17
Olga V. Chernysheva, Torsten H. Fransson, Robert E. Kielb, and John Barter

A Method to Assess Flutter Stability of Complex Modes 31
Andrea Arnone, Francesco Poli, and Claudia Schipani

Flutter Design of Low Pressure Turbine Blades with Cyclic Symmetric Modes 41
Robert Kielb, John Barter, Olga Chernysheva and Torsten Fransson

Experimental and Numerical Investigation of 2D Palisade Flutter for the Harmonic Oscillations 53
Vladymir Tsimbalyuk, Anatoly Zinkovskii, Vitaly Gnesin’ Romuald Rzadkowski, Jacek Sokolowski

Possibility of Active Cascade Flutter Control with Smart Structure in Transonic Flow Condition 65
Junichi Kazawa, and Toshinori Watanabe
Experimental Flutter Investigations of an Annular Compressor Cascade: Influence of Reduced Frequency on Stability
Joachim Belz and Holger Hennings

Part II  Forced Response
Unsteady Gust Response in the Frequency Domain
A. Filippone

Axial Turbine Blade Vibrations Induced by the Stator Flow
M. B. Schmitz, O. Schäfer, J. Szwedowicz, T. Secall-Wimmel, T. P. Sommer

Mistuning and Coupling Effects in Turbomachinery Bladings
Gerhard Kahl

Evaluation of the Principle of Aerodynamic Superposition in Forced Response Calculations
Stefan Schmitt, Dirk Nürnberger, Volker Carstens

Comparison of Models to Predict Low Engine Order Excitation in a High Pressure Turbine Stage
Markus Jöcker, Alexandros Kessar, Torsten H. Fransson, Gerhard Kahl
Hans-Jürgen Rehder

Experimental Reduction of Transonic Fan Forced Response by IGV Flow Control
S. Todd Bailie, Wing F. Ng, William W. Copenhaver

Part III  Multistage Effects
Unsteady Aerodynamic Work on Oscillating Annular Cascades in Counter Rotation
M. Namba, K. Nanba

Structure of Unsteady Vortical Wakes behind Blades of Mutual-Moving Rows of an Axial Turbomachine
V.E. Saren, S.A. Smirnov
## Contents

The Effect of Mach Number on LP Turbine Wake-Blade Interaction  
*M. Vera, H. P. Hodson, R. Vazquez*  
203

Multistage Coupling for Unsteady Flows in Turbomachinery  
*Kenneth C. Hall, Kivanc Ekici and Dmytro M. Voytovych*  
217

### Part IV Aeroacoustics

Passive Noise Control by Vane Lean and Sweep  
*B. Elhadidi*  
233

Interaction of Acoustic and Vortical Disturbances with an Annular Cascade  
in a Swirling Flow  
*H. M. Atassi, A. A. Ali, O. V. Atassi*  
247

Influence of Mutual Circumferential Shift of Stators on the Noise Generated  
by System of Rows Stator-Rotor-Stator of the Axial Compressor  
*D. V. Kovalev, V. E. Saren and R. A. Shipov*  
261

A Frequency-domain Solver for the Non-linear Propagation and Radiation  
of Fan Noise  
*Cyrille Breard*  
275

### Part V Flow Instabilities

Analysis of Unsteady Casing Pressure Measurements During  
Surge and Rotating Stall  
*S. J. Anderson (CEng), Dr. N. H. S. Smith (CEng)*  
293

Core-Compressor Rotating Stall Simulation with a Multi-Bladerow Model  
*M. Vahdati, A I Sayma, M Imregun, G. Simpson*  
313

Parametric Study of Surface Roughness and Wake Unsteadiness on a Flat Plate  
with Large Pressure Gradient  
*X. F. Zhang, H. P. Hodson*  
331
Bypass Flow Pattern Changes at Turbo-Ram Transient Operation of a Combined Cycle Engine
Shinichi Takata, Toshio Nagashima, Susumu Teramoto, Hidekazu Kodama 345

Experimental Investigation of Wake-Induced Transition in a Highly Loaded Linear Compressor Cascade
Lothar Hilgenfeld and Michael Pfitzner 357

Experimental Off-Design Investigation of Unsteady Secondary Flow Phenomena in a Three-Stage Axial Compressor at 100% Nominal Speed
Andreas Bohne, Reinhard Niehuis 369

Analyses of URANS and LES Capabilities to Predict Vortex Shedding for Rods and Turbines
P. Ferrand, J. Boudet, J. Caro, S. Aubert, C. Rambeau 381

Part VI Computational Techniques

Frequency and Time Domain Fluid-Structure Coupling Methods for Turbomachineries
Duc-Minh Tran and Cédric Liauzun 397

Study of Shock Movement and Unsteady Pressure on 2D Generic Model
Davy Allegret-Bourdon, Torsten H. Fransson 409

Numerical Unsteady Aerodynamics for Turbomachinery Aeroelasticity
Anne-Sophie Rougeault-Sens and Alain Dugeai 423

Development of an Efficient and Robust Linearised Navier-Stokes Flow Solver
Paul Petrie-Repar 437

Optimized Dual-Time Stepping Technique for Time-Accurate Navier-Stokes Calculations
Mikhail Nyukhtikov, Natalia V. Smelova, Brian E. Mitchell, D. Graham Holmes 449
Contents

Part VII  Experimental Unsteady Aerodynamics

Experimental and Numerical Study of Nonlinear Interactions in Two-Dimensional Transonic Nozzle Flow
Olivier Bron, Pascal Ferrand, and Torsten H. Fransson

Interaction Between Shock Waves and Cascaded Blades
Shojiro Kaji, Takahiro Suzuki, Toshinori Watanabe

Measured and Calculated Unsteady Pressure Field in a Vaneless Diffuser of a Centrifugal Compressor
Teemu Turunen-Saaresti, Jaakko Larjola

DPIV Measurements of the Flow Field between a Transonic Rotor and an Upstream Stator
Steven E. Gorrell, William W. Copenhaver, Jordi Estevadeordal

Unsteady Pressure Measurement with Correction on Tubing Distortion
H. Yang, D. B. Sims-Williams, and L. He

Part VIII  Aerothermodynamics

Unsteady 3D Navier-Stokes Calculation of a Film-Cooled Turbine Stage with Discrete Cooling Hole

Analysis of Unsteady Aerothermodynamic Effects in a Turbine-Combustor
Horia C. Flitan and Paul G. A. Cizmas, Thomas Lippert and Dennis Bachovchin, Dave Little

Part IX  Rotor Stator Interaction

Stator-Rotor Aeroelastic Interaction for the Turbine Last Stage in 3D Transonic Flow
Romuald Rzadkowski, Vitaly Gnesin, Luba Kolodyazhnaya
Effects of Stator Clocking in System of Rows Stator-Rotor-Stator of the Subsonic Axial Compressor

N.M. Savin, V.E. Saren

581

Rotor-Stator Interaction in a Highly-Loaded, Single-Stage, Low-Speed Axial Compressor: Unsteady Measurements in the Rotor Relative Frame

O. Burkhardt, W. Nitsche, M. Goller, M. Swoboda, V. Guemmer, H. Rohkamm, and G. Kosyna

603

Two-Stage Turbine Experimental Investigations of Unsteady Stator-to-Stator Interaction

Jan Krysinski, Robert Blaszczyk Jaroslaw, Antoni Smolny

615
Preface

Over the past 30 years, leading experts in turbomachinery unsteady aerodynamics, aeroacoustics, and aeroelasticity from around the world have gathered to present and discuss recent advancements in the field. The first International Symposium on Unsteady Aerodynamics, Aeroacoustics, and Aeroelasticity of Turbomachines (ISUAAAT) was held in Paris, France in 1976. Since then, the symposium has been held in Lausanne, Switzerland (1980), Cambridge, England (1984), Aachen, Germany (1987), Beijing, China (1989), Notre Dame, Indiana (1991), Fukuoka, Japan (1994), Stockholm, Sweden (1997), and Lyon, France (2000). The Tenth ISUAAAT was held September 7-11, 2003 at Duke University in Durham, North Carolina. This volume contains an archival record of the papers presented at that meeting.

The ISUAAAT, held roughly every three years, is the premier meeting of specialists in turbomachinery aeroelasticity and unsteady aerodynamics. The Tenth ISUAAAT, like its predecessors, provided a forum for the presentation of leading-edge work in turbomachinery aeromechanics and aeroacoustics of turbomachinery. Not surprisingly, with the continued development of both computer algorithms and computer hardware, the meeting featured a number of papers detailing computational methods for predicting unsteady flows and the resulting aerodynamics loads. In addition, a number of papers describing interesting and very useful experimental studies were presented. In all, 44 papers from the meeting are published in this volume.

The Tenth ISUAAAT would not have been possible without the generous financial support of a number of organizations including GE Aircraft Engines, Rolls-Royce, Pratt and Whitney, Siemens-Westinghouse, Honeywell, the U.S. Air Forces Research Laboratory, the Lord Foundation of North Carolina, and the Pratt School of Engineering at Duke University. The organizers offer their sincere thanks for the financial support provided by these institutions. We would also like to thank the International Scientific Committee of the ISUAAAT for selecting Duke University to host the symposium, and for their assistance in its organization. Finally, the organizers thank Loraine Ashley of the Department of Mechanical Engineering and Materials Science for her Herculean efforts organizing the logistics, communications, and finances required to host the conference.

The Eleventh ISUAAAT will be held in Moscow, Russia, September 4–8, 2006, and will be hosted by the Central Institute of Aviation Motors. Dr. Viktor Saren, the hosting member of the International Scientific Committee, will serve as deputy chair of the symposium; Dr. Vladimir Skibin, the General Director of CIAM, will serve as chair.

Kenneth C. Hall
Robert E. Kielb
Jeffrey P. Thomas

Department of Mechanical Engineering and Materials Science
Pratt School of Engineering
FLUTTER BOUNDARIES FOR PAIRS OF LOW PRESSURE TURBINE BLADES

Roque Corral, 1,2 Nélida Cerezal, 2 and Cárlos Vasco 1

1 Industria de Turbopropulsores SA
Parque Empresarial San Fernando, 28830 Madrid
Spain
roque.corral@itp.es

2 School of Aeronautics, UPM
Plaza Cardenal Cisneros 3, 28040 Madrid
Spain

Abstract

The aerodynamic damping of a modern LPT airfoil is compared to the one obtained when pairs of blades are forced to vibrate as a rigid body to mimic the dynamics of welded-pair assemblies. The stabilizing effect of this configuration is shown by means of two-dimensional simulations.

The modal characteristics of three bladed-disk models that differ just in the boundary conditions of the shroud are compared. These models are representative of cantilever, interlock and welded-pair designs of rotating parts. The differences in terms of frequency and mode-shape of the three models are sketched. Finally their relative merits from a flutter point of view are discussed using the 2D aerodynamic damping characteristics.

Keywords: Flutter, Low Pressure Turbine, Stability Map

Introduction

Flutter has been a problem traditionally associated to compressor and fan blades. However the steady trend during the last decades to design high-lift, highly-loaded low pressure turbines (LPTs), with the final aim of reducing their cost and weight, while keeping the same efficiency, has lead to a reduction of the blade and disk thickness and an increase of the blade aspect ratio. Both factors tend to lower the stiffness of the bladed-disk assembly and therefore its natural frequencies.

As a result of the afore mentioned evolution vanes and rotor blades of the latter stages of modern LPTs of large commercial turbofan engines, which may

K. C. Hall et al. (eds.),
Unsteady Aerodynamics, Aeroacoustics and Aeroelasticity of Turbomachines, 3–16.
be designed with aspect ratios of up to six, may potentially flutter and undergo alternate stresses similar to the ones encountered in fans and compressors.

Vibration control of shrouded LPT blades may be accomplished using either cantilever, inter-lock or welded-pair configurations. Flat sided shrouds may vibrate freely even for very small clearances specially for low inter-blade phase angles (IBFA) and provide little control over the vibration characteristics of the bladed-disk. To remedy this deficiency z-shaped shrouds (interlocks) were designed with the aim of remaining tight during the whole flight envelope. This type of designs significantly modify the vibration characteristics of cantilever blades, however, the mode-shapes of a given family may significantly vary with the nodal diameter and induce bending-torsion coupling. Finally, pairs of blades welded in the tip-shroud, were devised as a practical alternative to control the vibration characteristics of LPT bladed-disks and may be seen in some turbofan engines. This latter configuration substantially modifies as well the mode-shapes and frequencies of the baseline (cantilever) and interlock solutions.

It is well known that flutter boundaries are very sensitive to blade mode-shapes and that the reduced frequency plays a secondary role. A comprehensive numerical study of the influence of both parameters for LPT airfoils was performed by Kielb & Panowski (2000) and supported by experimental work (Nowinski and Panovski, 2000). The aim of this work is to investigate the influence of pairing the blades in the aerodynamic damping of a typical LPT section and apply the results to a realistic configuration to elucidate the potential benefits of such configurations in the modal behaviour of bladed-disk assemblies.

Numerical Formulation

Linearized Euler Equations

A two-dimensional cascade of blades vibrating sinusoidally with a small amplitude, common angular frequency, \( \omega \), and common inter-blade phase-angle, \( \sigma \), may be modeled within engineering accuracy by the linearized Euler equations if the fbw remains attached along the airfoil.

The two-dimensional Euler equations in conservative form for an arbitrary control volume may be written as:

\[
\frac{d}{dt} \int_{\Omega} U d\Omega + \int_{\Sigma} \{ (f, g) - UV \cdot dA \} = 0
\]

where \( U \) is the vector of conservative variables, \( f \) and \( g \) the inviscid fluxes, \( \Omega \) the fbw domain, \( \Sigma \) its boundary, \( dA \) the differential area pointing outward to the boundary and \( V \) the velocity of the boundary. Now we may decomposed the fbw into two parts: a steady or mean background fbw, plus a small but
periodic unsteady perturbation, which in turn may be expressed as a Fourier series in time. If we retain just the first harmonic any variable may be expressed as:

$$U(x, t) = U_0(x) + Re(\tilde{u}(x)e^{i\omega t})$$

where $U_0$ represents the background flow and $\tilde{u}$ is the complex perturbation. The Euler equations may then be linearized about the mean flow to obtain:

$$\left(\frac{d}{d\tau} + i\omega\right) \int_{\Omega} \tilde{u} d\Omega + \int_{\Sigma} \left( \frac{\partial g}{\partial U} \tilde{u}, \frac{\partial g}{\partial U} \tilde{u} \right) dA = i\omega \int_{\Sigma} U_0 x' dA$$

$$i\omega \int_{\Omega} U_0 d\Omega' + \int_{\Sigma} (\ell_0, g_0) dA'$$

which is a linear equation of complex coefficients and where the first term is an additional time-derivative added to solve the equations marching in the pseudo-time $\tau$.

**Spatial Discretization**

The code known as $Mu^2s^2T - L$ solves the two-dimensional linearized Euler equations (3) in conservative form. The spatial discretization is obtained linearizing the discretized equations of the non-linear version of the code $Mu^2s^2T$ (Corral and Gisbert, 2002), from which the background solution is obtained. The spatial domain is discretized using hybrid unstructured grids that may contain cells with an arbitrary number of faces and the solution vector is stored at the vertexes of the cells. The code uses an edge-based data structure, a typical grid is discretized by connecting the median dual of the cells surrounding an internal node (Figure 1). For the node $i$ the semi-discrete form of Eq 3, can be written as
\[ \frac{d\Omega_i}{d\tau} \hat{u}_{ij} + \sum_{j=1}^{n_{edges}} \frac{1}{2} S_{ij}(\hat{F}_i + \hat{F}_j) - \hat{D}_{ij} = \hat{S}(\hat{u}_i) \]  

where \( S_{ij} \) is the area associated to the edge \( ij \), and \( n_{edges} \) the number of edges that surround node \( j \). The resulting numerical scheme is cell-centered in the dual mesh and second-order accurate. It may be shown that for triangular grids the scheme is equivalent to a cell vertex finite volume scheme. A blend of second and fourth order artificial dissipation terms, \( \hat{D}_{ij} \), is added to capture shock waves and prevent the appearance of high frequency modes in smooth flow regions respectively. The second order terms are activated in the vicinity of shock waves by means of a pressure-based sensor and locally the scheme reverts to first order in these regions. The artificial dissipation terms can be written as

\[ \hat{D}_{ij} = |A_{ij}| S_{ij} \left[ \mu_{ij}^{(2)} (\hat{u}_j - \hat{u}_i) - \mu_{ij}^{(4)} (L_j - L_i) \right] \]  

where \( \mu_{ij}^{(2)} \) and \( \mu_{ij}^{(4)} \) are the average of the artificial viscosity coefficients in the nodes \( i \) and \( j \), \( L \) is a pseudo-Laplacian operator:

\[ L(\hat{u}_i) = \sum_{j=1}^{n_{edges}} (\hat{u}_j - \hat{u}_i) \simeq \frac{n_{edges}}{4} (\Delta x^2 \hat{u}_{xx} + \Delta y^2 \hat{u}_{yy})_i \]  

where the last approximation is only valid in regular grids and \(|A_{ij}|\) is a \( 4 \times 4 \) matrix that plays the role of a scaling factor. If \(|A_{ij}| = (|u| + c)_{ij} I\), where \( I \) is the identity matrix, the standard scalar formulation of the numerical dissipation terms (Jameson et al., 1981) is recovered. When \(|A_{ij}|\) is chosen as the Roe matrix (1981) the matricial form of the artificial viscosity (Swanson and Turkel, 1992) is obtained. The scalar version of the numerical diffusion terms has been used in this work since for the Mach numbers of interest in this work the differences between both approaches are negligible (Corral et al. 2000).

The exact, 2D, unsteady, non-reflecting boundary conditions (Giles, 1990) have been used at the inlet and outlet while the phase-shifted boundary conditions at the periodic boundaries are written in Fourier space as \( \hat{u}(x, y + \text{pitch}) = \hat{u}(x, y)e^{i\alpha} \).

A more detailed description of the code as well as some validation examples may be found in Corral et al. (2003)

**Analysis Methodology**

Since one of the aims of this work was to study the influence of the torsion centre for different reduced frequencies and configurations it was decided to follow a simplified design approach (Panovski and Kielb, 2000). The basic
idea is to assume that the main contribution to the aerodynamic damping is due to the actual blade and the two neighbouring blades. In this case the aerodynamic damping varies sinusoidally with the inter-blade phase angle and it may be computed with as few as three linear computations. The validity of such approach has been shown both experimentally (Nowinski and Panovski, 2000) and numerically (Panovski and Kielb, 2000).

Following the approach of Panovski and Kielb (2000) just the unsteady pressure field associated to the bending in the $x$ and $y$ direction and the torsion about a given point, $P$, for a reference displacement are computed. The unsteady pressure associated to the motion of the airfoil as a rigid body about an arbitrary torsion axis, $O$, is computed as a linear combination of three reference solutions. The velocity of an arbitrary point, $V_Q$, of the airfoil is of the form:

$$V_Q(t) = V_P(t) + \Omega(t)k \times PQ$$

where $\Omega$ is the angular velocity of the airfoil, $k$ is the unit vector perpendicular to the $xy$ plane. Choosing $V_P$ and $\Omega$ properly it is possible to make an arbitrary point $O$ the torsion axis, this condition is

$$V_O(t) = V_P(t) + \Omega(t)k \times PO = 0$$

and hence is enough to satisfy $V_P = -\Omega k \times PO$ for an arbitrary $\Omega$. We may write $V_P = v_xi + v_yj$ where

$$v_x = \epsilon_x \omega \text{Re}(i\hat{h}_{x,ref} e^{i\omega t}) \quad \text{and} \quad v_y = \epsilon_y \omega \text{Re}(i\hat{h}_{y,ref} e^{i\omega t})$$

and $\epsilon_x$ and $\epsilon_y$ are scaling factors of the actual displacements with respect the ones of reference $\hat{h}_{x,ref}$ and $\hat{h}_{y,ref}$. Analogously

$$\alpha = \epsilon_\alpha \omega \text{Re}(i\hat{\alpha}_{ref} e^{i\omega t}) \quad \text{and} \quad \Omega = \epsilon_\Omega \omega \text{Re}(i\hat{\alpha}_{ref} e^{i\omega t}).$$
The unsteady pressure perturbation, \( p' \), due to the motion of the airfoil as a rigid body is assumed to behave linearly and therefore it may be expressed as the sum of the unsteady pressure fields associated to bending in the \( x \) direction, \( p'_{x} \), bending in the \( y \) direction, \( p'_{y} \), and torsion about the point \( P \), \( p'_{\Omega} \), i.e.:

\[
p' = p'_{x} + p'_{y} + p'_{\Omega} = \epsilon_{x}p'_{x,ref} + \epsilon_{y}p'_{y,ref} + \epsilon_{\Omega}p'_{\Omega,ref}.
\] (11)

The work per cycle over the airfoil, \( W \), is

\[
W = \int_{0}^{2\pi/\omega} \int_{\Sigma_{c}} p'V_{q}dA dt
\] (12)

where \( V_{q} \) is the velocity of the blade surface. \( W > 0 \) means that the blade motion is damped by the aerodynamics. Substituting equations 7 and 11 in 12 it is possible to obtain the following expression for \( W \) in non-dimensional form:

\[
\Theta = \frac{W}{\rho_{c}U_{c}d_{max}^{2}\omega cH} = \left\{ \begin{array}{ccc}
\epsilon_{x} & \epsilon_{y} & \epsilon_{\Omega} \\
\bar{w}_{x,x} & \bar{w}_{x,y} & \bar{w}_{x,\Omega} \\
\bar{w}_{y,x} & \bar{w}_{y,y} & \bar{w}_{y,\Omega} \\
\bar{w}_{\Omega,x} & \bar{w}_{\Omega,y} & \bar{w}_{\Omega,\Omega} \end{array} \right\} \left\{ \begin{array}{c}
\epsilon_{x} \\
\epsilon_{y} \\
\epsilon_{\Omega} \end{array} \right\}
\]

where each element of work coefficient matrix represents the non-dimensional work obtained combining each unsteady pressure field with on the displacements of each mode (e.g., \( \bar{w}_{x,\Omega} \) is the work perform by the unsteady pressure associated to the airfoil bending in \( x \) on the displacements due to the torsion about point \( P \)). \( \rho_{c} \) and \( U_{c} \) are, respectively, the density and velocity at the cascade exit, \( d_{max} \) is the maximum airfoil displacement in the reference cases and \( cH \) is an estimate for the airfoil surface.

The work coefficient matrix \([w]\) is calculated once for each IBFA of the fundamental modes. The general procedure is then to run the unsteady code in the three fundamental modes with a reference amplitude through the range of inter-blade phase angles. As few as three inter-blade phase angles per fundamental mode need to be used. The rest of IBFA are obtained assuming that \( w = a + b \sin \sigma + c \cos \sigma \). The critical IBFA is computed then as the minimum of the previous expression.

In this work we have obtained the values of the damping coefficients for \( \sigma = 0^\circ \) and \( \sigma = \pm 90^\circ \) to estimate the whole range of inter-blade phase angles. The errors associated to this approximation may be seen in figure 3 where the damping coefficients for the edgewise, flap and torsion modes for different reduced frequencies are displayed. It may be appreciated that the damping coefficient curves of the edgewise and flap modes have a sinusoidal form. This is specially true for \( k = 0.1 \) while for \( k = 0.4 \) two spikes, corresponding to resonant conditions, are superimposed to the sine-like shape. This behaviour
is as could be expected since it is well known that the relative influence of the adjacent blades to the reference one decreases when the reduced frequency is increased (see Corral & Gisbert (2002) for example). The deviations from the sinusoidal form of the torsion mode are larger, but in all the cases the critical interblade phase angle is still well predicted.

Flutter Stability Maps

Panovski and Kielb (2000) showed, using flutter stability maps, how the modeshape and the reduced frequency were the basic parameters that controlled the stability of a two-dimensional LPT section. In practice only the mode-shape is relevant from a design perspective since the possible range of variation of the reduced frequency is very limited. We have extended such analysis to pairs of airfoils moving as a rigid body. The aim is to mimic the mode shapes obtained when pairs of blades are welded to increase the aerodynamic damping of the bladed-disk assembly. The edgewise and flap modes are defined as bending modes along and perpendicular to the line that joins the leading and trailing edges, respectively. The center of torsion of the third fundamental mode is located at the l.e. of the airfoil, when pairs of blades are considered the pair is formed adding a new airfoil adjacent to the pressure side of the reference airfoil and the center of torsion of the fundamental node is kept at the l.e. of the reference section. The airfoil used in all the simulations
corresponds to the mid-section of a representative rotor blade \( \alpha_{inlet} = 37^\circ, \alpha_{exit} = 64^\circ, M_{is} = 0.76 \).

Figure 3 displays the damping coefficient as a function of the IBFA for the different fundamental modes previously described. For both configurations it may be seen the stabilizing effect of the reduced frequency although for the single blade configuration there always exists a region of unstable IBPA for the computed range of reduced frequencies. The stabilizing effect of the welded-pair configuration may be clearly seen at the bottom of the same figure. In this case all the fundamental modes are stable for \( k = 0.4 \) being the flap mode the most critical one. The torsion mode is highly stabilised for the welded-pair configuration and becomes neutrally stable for \( k = 0.1 \).

The damping curves of the fundamental modes have been fitted to a sine curve and the methodology described in the previous section used to construct the stability maps for both configurations to conduct a complete study of mode shape in a practical and systematic manner.

Figure 4 shows the flutter stability maps for the single blade configuration, the middle section represents the reference section and the shadow regions the locus of the stable torsion centres. It may be appreciated firstly how the airfoil is intrinsically unstable in torsion and secondly how increasing the reduced
Flutter stability maps for the welded-pair configuration. The shadow regions represent the locus of the stable torsion centres.

Figure 5. Flutter stability maps for the welded-pair configuration. The shadow regions represent the locus of the stable torsion centres.

frequency the stable region is enlarged. It is worth noting as well that while the axial mode (bending in the $x$ direction) is stable the flex mode (bending in the $y$ direction) is unstable, this may inferred by realizing that a torsion axis at infinity ($y \to \infty$ for instance, which is a stable region) generates a pure axial bending stable mode.

Figure 5 shows the equivalent map for a pair of airfoils moving as a rigid body. The upper airfoil of the pair corresponds to the upper section of the figure. The increase of the aerodynamic damping with respect the single blade configuration is clearly seen and for $k = 0.4$ the airfoil is stable in torsion modes whose centre of torsion is in the vicinity of the blade and in a wide range of bending directions, the only unstable mode is the flex mode.

Only qualitative comparisons are possible with the results obtained by the research efforts of Panovski & Kielb (2000) since neither the geometry nor all the aerodynamic conditions are available, still it may be concluded that the basic steady aerodynamic conditions are comparable in first approximation and the stability map of both cases is similar as well confirming the idea that the sensitivity to the geometry and aerodynamic conditions is low.
Figure 6. Global view of the bladed-disk assembly configurations
Modal Characteristics of Bladed-Disks

The aim of this section is to elucidate in a qualitative manner how the previous results influence the stability of realistic bladed-disk configurations and in particular to discuss the relative merit of using cantilever, interlock or welded-pair configurations. Although there exists a big leap in moving from pure 2D to fully 3D mode shapes the simplicity of the approach makes the exercise still attractive.

The bladed-disk assembly considered in this study is representative of the first stages of modern LPTs. A global view of the whole assembly may be seen in figure 6. The vibration characteristics of the cantilever, interlock and welded-pair configurations has been obtained with the same grid. The boundary condition in the contact nodes between sliding parts, namely, between the disk and the blade in the attachment, and between the shroud contacts in the interlock configuration enforces that the displacements of these in both sides are identical. This simplifying hypothesis is made to avoid the generation of non-linear models where the concepts of natural frequency and mode-shape need to be re-interpreted.

Since only the first two families are usually relevant for flutter studies we have restricted ourselves to the lowest range of the frequency - nodal-diameter diagram. Two analysis were carried out, firstly at rest and ambient temperature and secondly at the operating speed with the associated temperatures. Only slight differences were seen in this particular case because the increase in stiffening due to the centrifugal force was compensated by the decrease in the Young’s module due to the increase in the inlet temperature of the turbine at the operating conditions. Since both results were very similar and to avoid further complications, the results presented correspond to the ones obtained at rest. The figure 7 shows the frequency characteristics of the first families for the cantilever (top), welded-pair (middle) and interlock (bottom) configurations. Several conclusions may be drawn upon inspection of this figure and the mode-shapes, not shown here for the sake of brevity,

1 The disk is very stiff compared to the blades. This may be seen in the mode-shapes, that show very small displacements of the disk, and in the frequency nodal diameter diagram that displays a high number of modes with nearly the same frequency within the same family.

2 The welded-pair configuration has slightly higher frequencies than the cantilever one with the exception of the third family that corresponds to the first torsion (1F) mode whose frequency drops.

3 The interlock provides and effective means to raise the frequencies of the assembly. The lower nodal diameters of the first family correspond to shroud dominated modes.
The baseline (cantilever) configuration is likely to be unstable since the reduced frequency of the first flap mode is too low, the first torsion mode is probably unstable as well. The welded-pair configuration is better from a flutter point of view than the cantilever one, the torsion mode will be stable in spite of having a lower reduced frequency, however, although the frequency of the 1st flap mode is slightly higher than before, according with the 2D inviscid results the mode is still unstable although the damping coefficient for the most unstable inter-blade phase angle has been reduced to one third of the original baseline configuration. This means that to predict absolute flutter boundaries three-dimensional and mistuning effects need to be retained.

The interlock configuration raises significantly the natural frequencies of the bladed-disk and hence is an effective mechanism as well to prevent flutter. A very similar interlock configuration was analyzed by Sayma et al. (1998), they found that the 6-12 nodal diameters, which corresponds in figure 7 (bottom) to 20% of the maximum nodal diameter, were unstable confirming previous engine testing. A plausible explanation may be found by noting that the modes corresponding to the low diameter nodes of the interlock configuration are edgewise modes, which are stable, while the modes corresponding to the high diameter nodes are torsion modes, whose stability depends on the reduced frequency but that figure 3 (right) shows that is stable. The instability is concentrated in the region where the edgewise modes become torsion modes and the reduced frequency is not high enough to ensure their stability.

**Concluding Remarks**

LPT blades are sometimes welded in pairs to increase their flutter characteristics. It has been shown by means of two-dimensional simulations that the aerodynamic damping welded-pairs is larger than the one of single blades. This specially true for torsion modes and bending modes whose flapping direction is aligned with the tangential direction of the cascade. A more in depth dis-
The discussion of the theoretical benefits of using such configurations requires taking into account the frequency and three-dimensional mode shape modification.

The frequency characteristics of three bladed-disk configurations have been presented. The three assemblies differ just in the boundary conditions of the tip-shroud. It has been observed that the frequency characteristics of the welded-pair configuration are essentially the same that the cantilever configuration while the interlock changes dramatically the overall behaviour of the assembly. The prediction of the stability or not of the welded-pair configuration requires to account for three-dimensional and mistuning effects. The stability of the interlock is compromised by the transition between edgewise and torsion modes with the nodal diameter of the first family. It is believed that the torsion modes with low reduced frequency, that the 2D simulations show are unstable, are responsible of the instability, this is consistent with the results of other researchers.

Acknowledgments

The authors wish to thank ITP for the permission to publish this paper and for its support during the project. This work has been partially funded by the Spanish Minister of Science and Technology under the PROFIT grant FIT-100300-2002-4 to the School of Aeronautics of the UPM.

References

INFLUENCE OF A VIBRATION AMPLITUDE DISTRIBUTION ON THE AERODYNAMIC STABILITY OF A LOW-PRESSURE TURBINE SECTORED VANE

Olga V. Chernysheva,1 Torsten H. Fransson,1 Robert E. Kielb,2 and John Barter3

1Royal Institute of Technology
S-100 44 Stockholm, Sweden
olga@egi.kth.se
fransson@egi.kth.se

2Duke University
Durham, NC 27708-0300, USA
rkielb@duke.edu

3GE Aircraft Engines,
Cincinnati, OH 45215-1988, USA
john.Barter@ae.ge.com

Abstract A parametrical analysis summarizing the effect of the reduced frequency and sector mode shape is carried out for a low-pressure sectored vane cascade for different vibration amplitude distributions between the airfoils in sector as well as the numbers of the airfoils in sector. Critical reduced frequency maps are provided for torsion- and bending-dominated sector mode shapes.

Despite the different absolute values of the average aerodynamic work between four-, five- and six-airfoil sectors a high risk for instability still exists in the neighborhood of realistic reduced frequencies of modern low-pressure turbine. Based on the cases studied it is observed that a sectored vane mode shape with the edge airfoils in the sector dominant provides the most unstable critical reduced frequency map.

Keywords: Flutter, sectored vane, sector mode shape, vibration amplitude distribution, critical reduced frequency.
Nomenclature

- $c$: chord length [m]
- $k$: reduced frequency based on half-chord and outlet inflow velocity $\omega/(2V_2)$ [-]
- $M$: Mach number [-]
- $V$: inflow velocity [m/s]
- $X$: cascade axial co-ordinate [-]
- $Y$: cascade tangential co-ordinate [-]
- $\beta$: absolute inflow angle [deg]
- $\omega$: circular frequency [rad/s]

Subscripts

- IS: isentropic
- 1: inlet
- 2: outlet

1. Introduction

In order to eliminate or reduce blade vibration problems in turbomachines, the adjacent airfoils around the wheel are often mechanically connected together with either facing wires, tip shrouds or part-span shrouds in a number of identical sectors. Such mechanical connections make the vibratory mode shapes much more complex. At the same time it allows a significant improvement in the stability margin of the design.

Numerical (see, for example, [1-3]) and experimental aerodynamic analysis has demonstrated the stabilizing effect. The numerical studies for sectored vanes presented in [1-2] were conducted with all blades in the sector vibrating with the same frequency and amplitude and at different real mode shapes. The method used in [1] utilized the possibility of superposition for a linear system, the approach in [2] required calculations on a domain that covered as many passages as airfoils belonging to one sector. The findings were illustrated for selected sets of sectored vane modes for five- and six-airfoil low-pressure steam turbine sectored vanes in [1] and for three-airfoil low-pressure turbine sectored vane in [2]. Nevertheless, even though the sectored vanes benefited by the mechanical connection between vanes, flutter was still predicted for certain ranges of inter-sector phase angles.

According to structural analysis of a sectored vane displacement the blades in the sector might have different amplitudes, mode shapes and vibration frequencies which obviously affect the aerodynamic stability of the sectored vane. An important contribution of the blade mode shape into the aerodynamic stability of the cascade has been already demonstrated in [4] for a freestanding low-pressure turbine blade with a real rigid-body mode shape. During the aeroelastic design phase, it was recommended to also study mode shape rather than only the reduced frequency of a blade. Further investigation, conducted in
Vibration Amplitude Distribution Influence

[5] for a wide range of physical and aerodynamic blade parameters confirmed the findings and made it more general.

The approach presented in [3] employed, similarly to [1], the superposition assumption and, unlike [1], allowed a complex rigid-body mode shape with non-uniform amplitude distribution between the blades in a sector. The effect of real rigid-body sector mode shape variation on the aerodynamic stability of a low-pressure six-airfoil sectored vane was shown when all blades in sector were vibrating with identical amplitude. Although it was confirmed that tying blades together in a sector drastically improved the stability of the cascade, for some mode shapes sectored vane still remained unstable at relevant reduced frequencies.

2. Objectives

The present paper aims to investigate further the sensitivity of the critical (flutter) reduced frequency versus mode shape maps for the sectored vane, namely towards an non-uniform distribution in the amplitudes between the blades in the sector. The influence of the number of the airfoils in the sectored vane will be demonstrated.

3. Method of attack

The method for investigation of flutter appearance in a cascade, where blades are connected together in a number of identical sectors is presented in [3] and can be shortly described as follows:

- The aerodynamic response of a sectored vane is calculated based on the aerodynamic work influence coefficient representation of a freestanding bladed cascade.

- There is a possibility to consider different vibration amplitudes and any inter-blade phase angles for the blades in the sector, while the inter-sector phase angles follow the Lane’s criteria [6] and all blades have the same vibration frequency.

- Assuming a rigid-body motion allows to define the blade mode shape entirely by its pitching axis position. Thus, at a selected reduced frequency and given pitching axis positions for the blades in sector the aerodynamic work for the sector is calculated as a function of the inter-sector phase angle as well as amplitude and phase angle distributions between the airfoils in the sector. The absolute maximum of the work is then calculated and the algorithm is continued for another pitching axis position until the whole range of the mode shapes is covered.
Afterwards, the results for a number of reduced frequencies are overlaid to produce a plot of critical reduced frequency versus pitching axis position for the reference sectored vane. This determines the value of reduced frequency for which each torsion axis locations of the blades in the sector becomes unstable.

For the practical applications shown in this paper the following restrictions are applied in the algorithm:

- Mode shape of the sectored vane is considered to be real, i.e. the blades in sector can only have 0 and/or 180 degree inter-blade phase angle between each other.
- All the blades in the sector have the same relative pitching axis location.

In the present paper the method is applied for a number of different vibration amplitude distributions for the airfoils belonging to the same sector as well as for different numbers of airfoils in the sector.

4. Sectored vane geometry and calculations in traveling wave domain

The stability analysis is performed for a sectored low-pressure gas-turbine vane cascade (Fig. 1) consisting of 15 sectors.

![Sectored vane geometry](image.png)

**Figure 1.** Sectored vane geometry and parameters for the profile

Steady and unsteady calculations are performed with the linearized inviscid fbw solver NOVAK [7]. An overview of physical and aerodynamic parame-
ters for the aeroengine profile used for the calculations in the traveling wave domain is presented in Fig. 1. The basic calculations in the traveling wave domain are performed at 10 different inter-blade phase angles for the three fundamental modes, bending in two orthogonal directions and torsion.

5. **Results and discussion**

The vibration amplitude distributions between the airfoils in sector are chosen as for the following three cases:

1. Uniform: all blades in sector vibrating with the same amplitude.
2. Edge blades dominated: vibration amplitude of the edge blades is 1 while the amplitude of the inner blades is 0.5.
3. Internal blades dominated: vibration amplitude of the edge blades is 0.5 while the amplitude of the inner blades is 1.

The number of airfoils in a sector has been selected as four, five or six. While varying the real sector mode shape it is assumed that the mode shapes of the airfoils belonging to the same sector are changing in an identical manner.

The maps in Figures 2 to 8 show the values of the critical reduced frequencies. Each contour line in the critical reduced frequency map corresponds to the value of reduced frequency for which the reference vane is neutrally stable. The reference vane is in the center of the diagram and identified with a thicker line.

The discussion of the results is divided into two parts, for the torsion axis location varied in the near field of the reference vane (torsion dominated modes) and for torsion axis location approaching infinity (bending dominated modes).

A comparison of the aerodynamic behavior of the multiple airfoils sectored vanes is made against a freestanding blade cascade. In the freestanding blade cascade the blades vibrate with identical mode shapes as well as amplitudes and have a constant inter-blade phase angle between each other. The critical reduced frequency maps for the freestanding blade cascade are shown in Fig. 2a (torsion-dominated mode shapes) and in Fig. 2b (bending-dominated mode shapes) as a reference towards the four-, five- and six-airfoil sectored vanes to be shown later.

**Near field domain**

Comparing the present investigation with the findings for the freestanding blade (Fig. 2a), it is concluded from Figures 3 to 5 that the overall stability behavior of a sectored vane cascade of four, five or six blades, as well as the main directions, for the most stable and unstable regions, remains the same. These directions are also not affected by the different amplitude distributions.