Paper ID: ETC2017-305 Proceedings of 12th European Conference on Turbomachinery Fluid dynamics & Thermodynamics
ETC12, April 3-7, 2017; Stockholm, Sweden

# A COMPARATIVE STUDY OF TRANSIENT BLADE ROW AND BLADE COUNT SCALING APPROACHES FOR NUMERICAL FORCED RESPONSE ANALYSIS IN A TRANSONIC TURBINE

*Aravin Dass Naidu*
ABB Turbocharging
Baden, Switzerland
aravin.dass.naidu@gmail.com

*Klemens Vogel*
ABB Turbocharging
Baden, Switzerland
klemens.vogel@ch.abb.com

*Magnus Fischer*
ABB Turbocharging
Baden, Switzerland
magnus.fischer@ch.abb.com

## ABSTRACT

**Traditional forced response calculations for adjacent blade rows without a common divisor demand full annular transient simulations. This typically results in large and often impractical computational costs during development. The present article discusses an approach to reduce this cost using a signal-patching routine on a transonic axial turbine. Additionally, the potential for further reduction of computational cost by means of time domain flow transformation methods is investigated. The methods assessed are profile transformation, time inclination and Fourier methods, all within ANSYS CFX. Comparisons are made for the vector components of blade force harmonics, generalised force and computational costs. The computational cost can be reduced to 40% and 5% of the full annular simulation with signal patching or time domain flow transformation methods respectively. The signal-patching and transformation methods applied result in an error of 10% and 15% of generalised force respectively.**

## KEYWORDS

**PROFILE TRANSFORMATION, TIME INCLINATION, FOURIER METHOD, BLADE COUNT SCALING**

## NOMENCLATURE

U arbitrary flowfield variable
P pitch
$P_S$ stator pitch
$P_R$ rotor pitch
$\Omega$ rotational speed
a axial coordinate
r radial coordinate
$\theta$ circumferential coordinate
t time coordinate
$\Delta t$ time coordinate variation

## INTRODUCTION

In turbomachinery applications, unsteady aerodynamic forcing is attributed to inherent unsteadiness in the surrounding flowfield. Such unsteadiness is often a result of blade row interactions. This includes wake impingements from upstream blade rows, interactions due to unsteady vortex shedding and potential flow effects from downstream blade rows. Blades subject to unsteady forcing show a vibrational response that may lead to conditions of high cycle fatigue (HCF) and as a result, potential failure. Accordingly, an accurate prediction of blade row interactions should constitute an integral part of forced response analysis. The prerequisite for this is an accurate capturing of transient flow field effects across stage interfaces without a common integer divisor. Traditionally, this is achieved by full annular simulations. Unfortunately, this often results in exceedingly large computational cost which usually renders the approach impractical in industrial settings. Hence, a pertinent need exists for strategies to reduce computational time without significantly affecting the quality of unsteady aerodynamic forcing predictions.

One approach used to alleviate the large computational domain problem is a blade count scaling strategy from Rai (1987). It involves altering the blade count in blade rows which permits a common integer reduction of blades for simulation in a stage while retaining a direct spatial periodicity along the circumferential direction. Mayorca et al. (2011) determined that an error of 10% can be expected for the excitations at the first harmonic with a stage scaling factor below 5% and a harmonic amplitude and frequency correction. Further investigations into the implication of blade count scaling on aerodynamic disturbance forces were carried out by Fruth et al. (2010, 2011). In addition, methods which take advantage of the flowfield spatial and temporal variations have been developed. A detailed insight into the flowfield dynamics is provided by Erdos and Alzner (1977). He (2010) presents an overview of available time domain and frequency domain approaches which enable simulated flow passage reductions by accounting for temporal and spatial lags along passage interfaces. Time domain flow transformation include a time inclination approach by Giles (1988) and a time shifted Fourier approach presented by He (1990) and further developed by Gerolymos et al. (2002).

The present work investigates the possibility of changing the stator blade count and applying signal patching to  reconstruct the results of the actual full annular configuration. This is done by splitting the stator blade row into two sections before expanding each section circumferentially thereby resulting in two possible stator-rotor configurations. A detailed explanation of the geometry and process is presented in the numerical method section. The procedure forms part of a numerical forced response analysis of a rotor blade row subjected to unsteady forcing due to rotor-stator interactions. The goal is to reconstruct the unsteady forcing in the actual turbine configuration by using the results of numerical simulations of altered geometries. Furthermore, each of the two configurations are examined against a time inclination approach, a time shifted Fourier approach and a profile transformation approach.

## MATHEMATICAL MODEL

In this section, the mathematical representation of the unsteady flow field and different time domain flow transformation approaches are described. To mathematically represent the unsteady flow field, two particular configurations are introduced. One with identical and the other with unidentical number of blades in adjacent blade rows.

For identical number of blades in adjacent rows, identical flow channels lead to circumferential periodicity of flow variables (U) at every instant in time, i.e. equation (1)

$$U(a, r, \theta, t) = U(a, r, \theta + P, t) \tag{1}$$

where a, is the axial coordinate, r is the radial coordinate, θ is the circumferential coordinate, t is time and P is pitch.

In latter configuration, Erdos and Alzner (1977) demonstrated that the projected wave pattern along the meridional direction at circumferentially periodic points are identical at phase lagged conditions. This means that the disturbances across a blade at any instant in time are determined by the relative position to its neighbouring blades in the same row. Hence, the entire flowfield across neighbouring flow passages can be reconstructed by imposing the solution from a previous timestep at a corresponding point. This amounts to a spatial temporal periodicity with the phase shift being a function of adjacent blade row pitch. The relation can be expressed as in equation (2) and (3):

$$U(a, r, \theta, t) = U(a, r, \theta + P, t + \Delta t) \qquad (2)$$

$$\Delta t = \pm \frac{P_S - P_R}{\Omega} \qquad (3)$$

where $P_S$ and $P_R$ are the stator and rotor pitch, respectively, and $\Omega$ is the rotational speed.

The application of spatial temporal periodicity between adjacent blade rows follows an analogous technique. It must be highlighted that across the adjacent blade rows, the same periodic signal is recovered but with a different base frequency. Such a frequency shift is a function of rotation speed and blade count in adjacent rows. A detailed mathematical development of the periodicity in flow fields is presented by Erdos and Alzner (1977).

**Time Inclination Method**

The time inclination method introduced by Giles (1988) involves tilting the computational time domain. Effectively a coordinate transformation is introduced to represent a node at time (t) and its corresponding periodic node at time (t+Δt). Simple spatial periodicity can thereby be enforced. Three independent time coordinates are introduced to account for the circumferential phase shift in a blade row, the interaction of adjacent blade rows and the differences in timestep size across adjacent blade rows. In addition, the number of timesteps must be identical in both blade rows for simultaneous time marching which amounts to varying timestep sizes. An inherent limitation with this method is that the computational plane inclined in time cannot be inclined more than a physical parameter as this amounts to time reversal Giles (1988). This translates to a functional range for pitch ratios between 0.6-1.5 for most turbomachinery configurations, which can be met by altering the number of simulated passages.

**Fourier Method**

The Fourier Method assumes that the flow field is periodic. A Fourier series then approximates the flow variables at the circumferentially periodic boundaries and the phase shift is applied to the temporally summed Fourier coefficients to retrieve the equivalent flow. Along the rotor stator interface, double periodicity occurs both temporally and spatially and is accounted for with a double Fourier decomposition of the flow field with respect to time and space. He (1990) and Gerolymos et al. (2002) describe the mathematical formulation of the Fourier method.

**Profile Transformation Method**

In this approach, the flow profile is circumferentially stretched or compressed across the domain interfaces to account for any variation in pitch. A direct periodicity is enforced at circumferential periodic points and at the rotor stator interfaces. Hence, this approach might not accurately capture variations of the flow variables at the blade passing frequency and its harmonics [see Witteck et al. (2014)].

## NUMERICAL METHOD

The investigation is based on a single-stage transonic axial turbine at ABB Turbocharging. The turbine is constructed with 33 rotor blades (R) and a stator blade count of 23 (S). In particular, the stator is constructed from two halves with 11 and 12 equally spaced stator blades each shown in figure (1). The approach used for the signal-patching routine, is to extend the 11 or 12 stator blade haves to a 22 or 24 evenly distributed blade stator. As a result, a common integer across the rotor and stator of 11 and 3 can be deduced for the blade count configurations of 22S/33R and 24S/33R, respectively. This enables a significant blade count reduction while retaining a pitch ratio of 1.

The characteristics of the computational domains for the various transient methods are highlighted in table (1). Particular emphasis is given to the need to have pitch ratios between 0.6-1.5 for the time inclination approach. In addition, the Fourier method implemented in ANSYS CFX requires two blade passages.

**Table 1: Computational domain of the different transient blade row methods**

| Test Cases | Method | 360° Blade Count (Stator / Rotor) | Reduced Blade Count (Stator / Rotor) | Pitch Ratio |
|---|---|---|---|---|
| 1 | Full annular | 23 / 33 | 23 / 33 | 1 |
| 2 | Altered blade count | 22 / 33 | 2 / 3 | 1 |
| 3 | Profile transformation | | 1 / 2 | 0.75 |
| 4 | Time inclination | | 1 / 2 | 0.75 |
| 5 | Fourier method | | 2 / 2 | 1.5 |
| 6 | Altered blade count | 24 / 33 | 8 / 11 | 1 |
| 7 | Time inclination | | 2 / 3 | 0.92 |
| 8 | Fourier method | | 2 / 2 | 1.38 |

In all cases, a structured grid is used for both the stator and rotor rows. A grid independence study was performed with steady state simulations to obtain an accurate mesh strategy resulting in approximately 350k and 400k elements for the stator and rotor passages respectively. The final mesh is shown in figure (1).

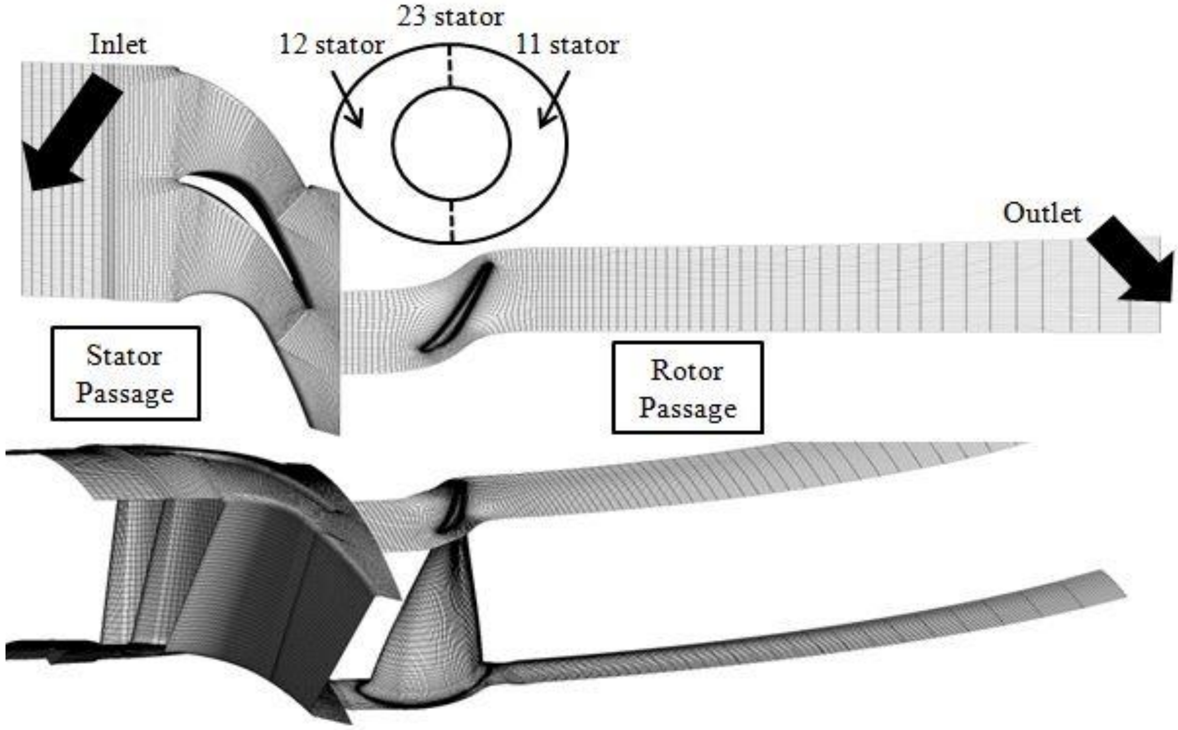


**Figure 1: Final mesh with stator passage (left) and rotor passage (right)**

Particular attention was placed on the rotor boundary layer mesh refinement since the analysis of rotor blade surface unsteady pressure harmonics formed a crucial part of the study. To correctly capture near wall physics, the boundary layer is discretised with 10 nodes and automatic near-wall treatment/mixed formulation used. The non-dimensional near wall cell size (Y+) is approximately unity throughout the domain. In addition, to capture the highly turbulent tip leakage phenomenon, the tip gap is modelled with 10 elements in the spanwise direction.

The commercial CFD solver ANSYS CFX 17.0 is used and steady state simulations are carried out. For steady simulations, the Reynolds Averaged Navier Stokes Equations (RANS) are solved with a mixing plane interface between the stators and rotors, Denton et al. (1979). For transient simulations, the Unsteady Reynolds Averaged Navier Stokes Equations (URANS) are solved by means of an implicit second order backward numerical solver algorithm and a transient rotor stator interface is applied. In fully transient simulations, a pitch ratio of one ensures no scaling of the interface flowfield. In the time domain transformation approaches, this requirement is alleviated by accounting for necessary phase lagged conditions as described above. The SST turbulence model from Menter (1994) was applied for all steady and transient simulations. The inlet boundary is defined by circumferentially averaged total pressure, total temperature and flow direction from a previous simulation including the inlet and outlet casings. The outlet boundary is prescribed with a circumferentially averaged static pressure profile. The highly loaded turbine operational condition corresponds to a known resonance condition. The inlet and outlet boundary conditions were obtained from a previous experimental test campaign.

To determine if the mesh is sufficient to capture relevant global flow physics, plots of Mach number and entropy are extracted at a spanwise position of 50% for steady state simulations. The results for the 22S /33R configuration are shown in figure (2). Here the Mach (left) and entropy (right) contour plots have been normalised by the maximum local Mach and the entropy data respectively.

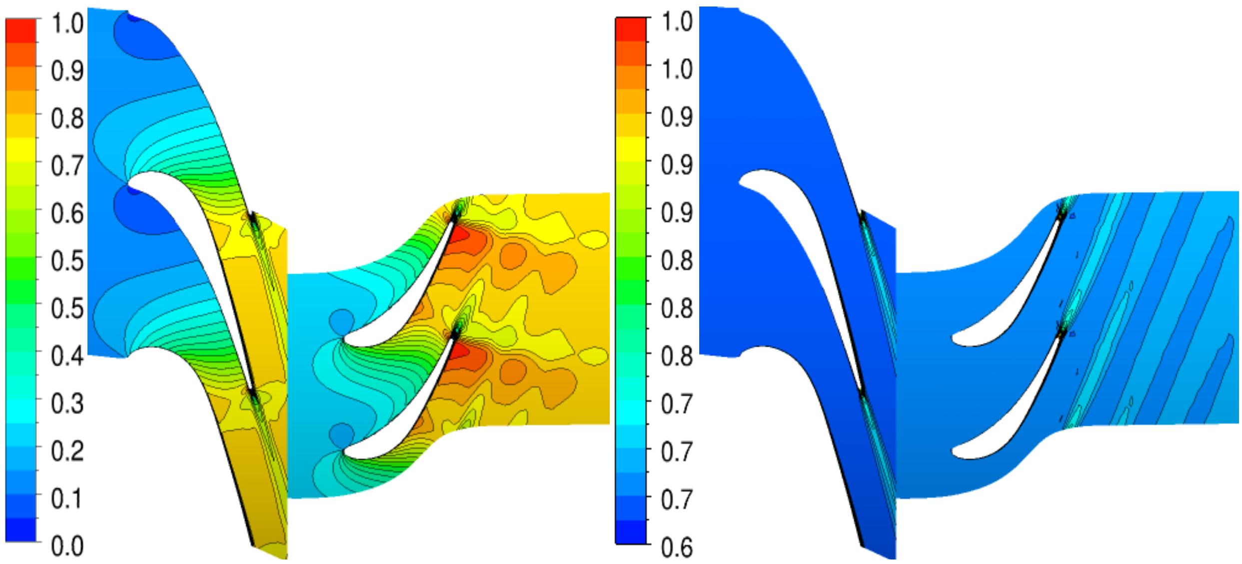


**Figure 2: Normalized Mach number (left) and entropy (right) contours on 50% span.**

Regions of high losses can be detected in the wake region along the trailing edge of both stator and rotor blade row. The wake does not transit across the stator rotor interface due to the averaging of flow field in the mixing plane approach. Close inspection also reveals a growing boundary layer along the rotor blade surface from leading to trailing edge. Furthermore, the transonic nature of the flow as it is expanded through the turbine can be seen from the Mach contour plots. A high Mach number contour along the throat of the stator and rotor passages can be seen observed, which stretches from the pressure side to suction sides. In addition, an attached shock is recorded close to the trailing edge along the suction side. The shock interfere with the passing wake from neighbouring blades thus, dissecting the high Mach number contour.

## TRANSIENT AND FLOW FIELD TRANSFORMATION SIMULATION RESULTS

In the following, the results of the fully transient run are compared with those from the time inclination method, the Fourier method and the profile transformation method. For this purpose, total rotor blade force components in the (a, r, θ) system from above, generalised force and computational demands are analysed. The unsteady results were evaluated after a periodic solution was reached. To gauge convergence, the time-averaged and first harmonic of the total blade force and seven local monitor point pressure values along the blade pressure and suction sides at 50% span and 90% span were plotted for each simulation and compared to the preceding periods. In addition, a timestep independence study was carried out for each of the above mentioned transient approaches. An analogous criterion to periodic convergence is adopted to justify timestep independence.

The unsteady harmonic component of blade force represents the stimulus or aerodynamic disturbance excitation acting on the blade. In practice, knowledge of resonant crossings on a Campbell diagram allow for identification of specific harmonic components of interest. This study focuses on the zeroth and first harmonic components (actual resonance frequency). The zeroth and first harmonic blade forces are normalised by the amplitudes of the altered simulation configuration. The zeroth harmonic component of blade forces in radial, meridional and axial directions have a variation below 0.5% for all configurations and have been excluded from table (2) for clarity. The first harmonic components for all cases are presented in table (2)

**Table 2: Blade force components for 22S/33R and 24S/33R cases**

| Blade Force | | $F_r$ | $F_\theta$ | $F_a$ |
|---|---|---|---|---|
| Harmonic Count | | 1st Harmonic | 1st Harmonic | 1st Harmonic |
| 22S/33R | Altered 2S / 3R | 1.000 | 1.000 | 1.000 |
| | Time inclination | 1.013 | 1.007 | 0.982 |
| | Fourier method | 0.875 | 1.038 | 1.034 |
| | Profile transformation | 3.456 | 2.590 | 2.057 |
| 24S/33R | Altered 8S / 11R | 1.000 | 1.000 | 1.000 |
| | Time inclination | 0.968 | 1.024 | 0.949 |
| | Fourier method | 0.934 | 1.010 | 0.987 |

The time inclination strategy is shown to have a difference to the reference solution of less than 5% for the first harmonic component. The error using the Fourier method for the first and the zeroth harmonic components is less than 15% and 0.5%, respectively. With the Fourier method, the full unsteady flow field can be more accurately resolved in theory using more Fourier coefficients at the cost of solver runtime. It must be noted that altering the Fourier coefficients require experimentation with software features which are not recommended by ANSYS. From steady simulations in figure (2), the presence of non-linear oblique and standing shock features are evident. As recorded by Srivastava at al. (1999), the linear superposition of a limited number of Fourier coefficients is unable to capture them accurately. Using a profile transformation strategy, a distinct frequency shift of 25% is recorded for the first harmonic force components. An amplitude error of approximately 250% is also recorded in the first harmonic force component at the shifted frequency. The zeroth harmonic or time-averaged component is unaffected. The absence of any time/phase lag implementations at the interface and periodic boundaries lead to incorrect flow interactions at these locations. Hence, the direct stretching of the flow profile across the rotor stator interface to compensate for a non-unity pitch during blade passage reduction does not adequately represent the temporal variations across interfaces. Profile transformation will not be regarded in the subsequent analyses due to its insufficient accuracy.

The generalised force is an appropriate parameter to compare the above-mentioned approaches as it approximates the forcing behaviour at a specific Eigenmode under unsteady loading through a superposition of blade surface harmonic forces with mode shape deflection. The results for two different mode shapes are illustrated in figure (3). The mode shapes are chosen based on known resonance potential in the relevant operating range. The generalized forces are normalised by the amplitudes of the 22S/33R and 24S/33R transient simulation.

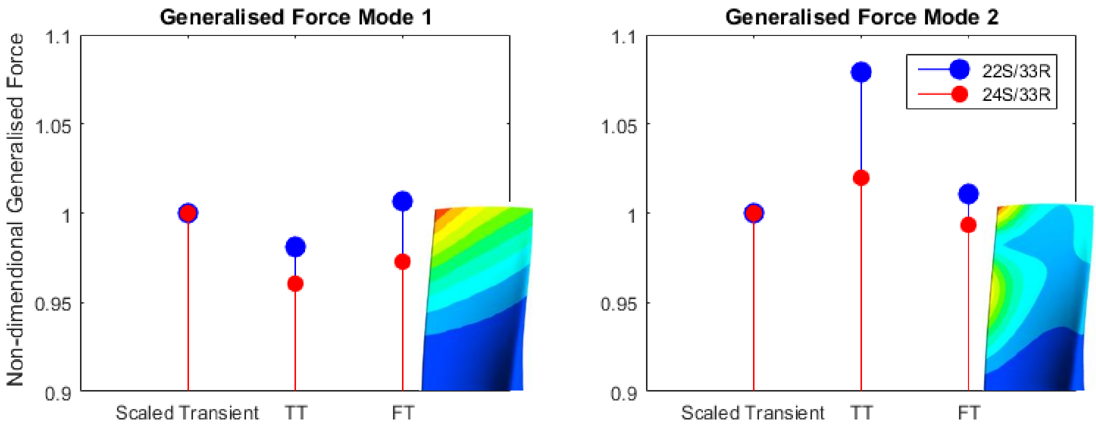


**Figure 3: Total generalised blade force with respective mode shape deflections for altered transient, time inclination (TT) and Fourier Transformation (FT) Method.**

The maximum deviations with respect to the reference transient simulation for the time inclination and Fourier methods are 8% and 5%, respectively. The interaction of local blade unsteady forces and deformation is well represented with the two approaches. It is apparent that both approaches represent reasonable strategies to model forcing due to rotor-stator interactions.

The computational demand for all simulations are listed in table (3). The runtimes are again normalized by the transient simulation results. Different number of CPUs are linearly corrected. All simulations were initialised from steady state simulation results. Significant computational runtime savings are recorded with the implementation of both time inclination and Fourier methods. This is largely attributed to the reduced number of simulated passages and the time required to reach convergence. With the blade count 22S/33R permitting a reduction to 2S/3R, the time inclination and Fourier methods have runtimes of approximately 10% and 20%, respectively, of the altered/scaled configuration. With the altered configuration permitting a reduction to 8S/11R, the computational runtime reduction for the time inclination and Fourier methods is 9% and 10%, respectively. It is also important to note that with the Fourier method the blade passage counts are fixed at 2S/2R. In the time inclination method the blade passage counts are limited by a pitch ratio 0.6-1.5. The data indicates that the CPU time for a Fourier method falls below that of the time inclination method when 5 blade passages are necessary for the latter.

## BLADE COUNT VARIATION RESULTS

In the second part of this study, we discuss the results for the signal-patching method by comparing the simulation results for various stator blade counts. For this purpose, total rotor blade forces, generalised forces and computational costs will be considered.

To reconstruct the reference unsteady force (23S/33R) for the signal-patching method, the force signal from both, the 22S/33R and 24S/33R case, are patched together by using each case for 0.5 revolutions.. No attempt is made to model the transition between the two stator parts with 11 and 12 equally spaced blades. The time domain and frequency domain plots of original and patched signals are illustrated in figure (4) and figure (5), respectively.

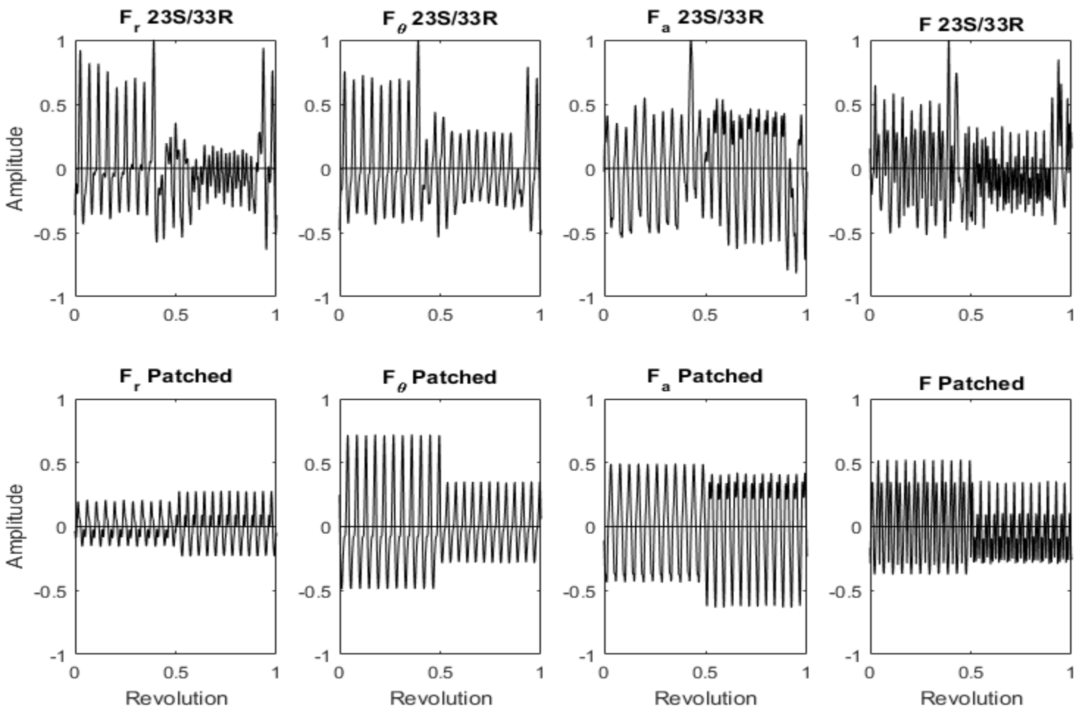


**Figure 4: Time domain total blade force for 23S/33R (top), and patched (bottom) cases**

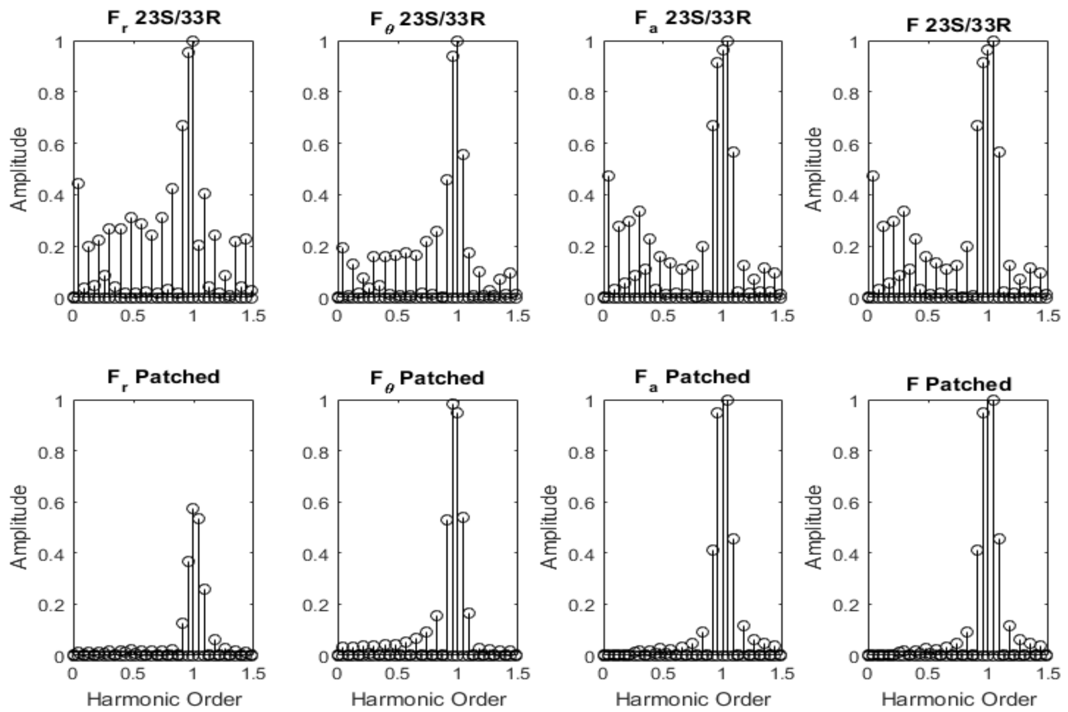


**Figure 5: Frequency domain total blade force for 23S/33R (top), and patched (bottom) cases**

The two stator blade row halves with 11 and 12 blades can be identified as two sections with distinct forcing patterns in the original data, see upper part of figure (4). This is likewise modelled with the patched data in the lower part of figure (4). The transition region between both halves, which can be observed in the original data is not captured in the patched data. The unequal stator distribution in the original configuration transmits a circumferentially varying forcing to the rotor domain. This results in a large frequency spectrum forcing when being decomposed. This is the reason why the differences in amplitude are large on the engine orders (EO) outside of 22, 23 and 24, see figure (5). This is the expected behaviour as the patched data is obtained from two configurations with 22 and 24 equally spaced stators For the EOs 22 - 24. a maximum difference of 9% for total blade force is obtained, when comparing patched and original data. For the force components this difference amounts to about 5%. With the signal-patching method, the EO23 signal is rather well modelled despite the absence of such an EO forcing from either one of the two 22S/33R and 24S/33R signals patched together. A larger error was recorded on the radial force component. Due to the low radial force absolute amplitude, its effect on the total blade force harmonic component is negligible. In summary, the dominant amplitude signals can be rather well reconstructed with the signal-patching approach.

In figure (6), the generalised force for EO 22 - 24 are depicted, for the two investigated modes using the reference force pattern and the patched force signal. The values are normalised by the components from the reference configuration.

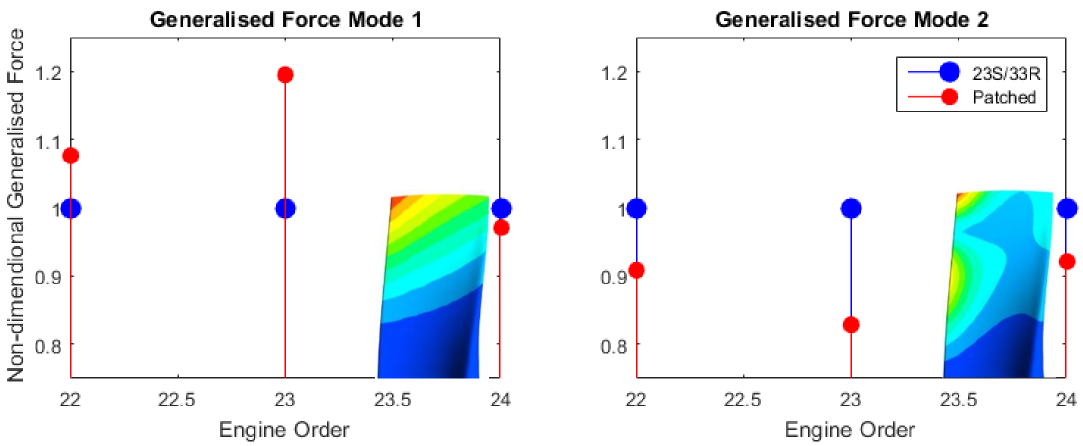


**Figure 6: Total blade generalised force for mode 1 (left) and mode 2 (right) EO**

It is evident from figure (6) that the use of eigenvectors in computing blade response amplifies the variation from reference. The variations are particularly large on EO23 with a maximum global force variation of around 18%. The maximum global force variation for EO22 and EO24 are lower at around 9% and 8% respectively. It can also be seen from figure (7) that a difference exist on the local distribution of generalised force across the blade surface. The local generalised force distributions for mode 2 have been normalised by the maximum value. While the general force pattern distribution is very similar for original and patched data, specific variation are visible. A possible cause of such variations is the neglected modelling of the transition from 11 to 12 stators.

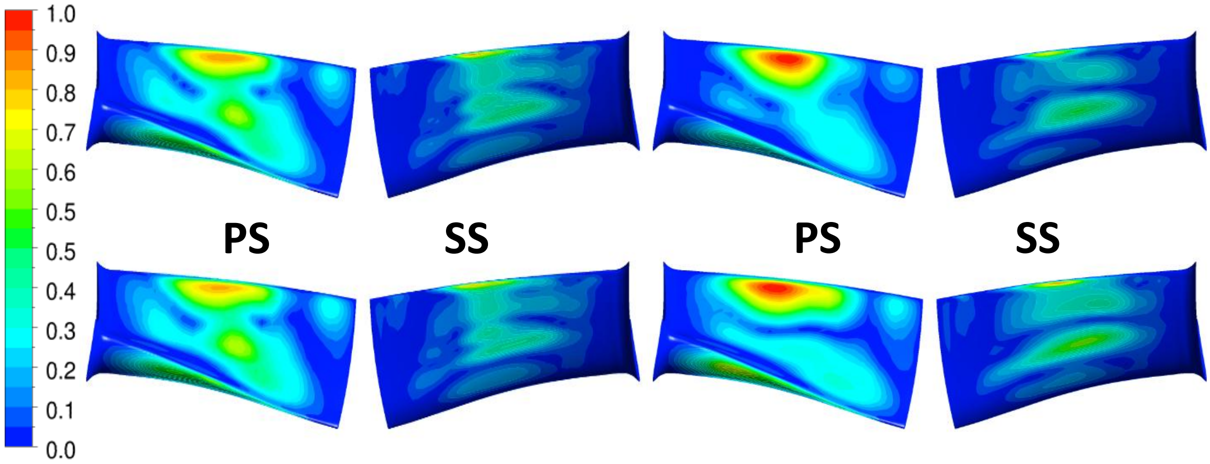


**Figure 7: Total local generalised force distribution with original (top) and patched signal (bottom) for EO22 mode 2 (left) and EO23 mode 2 (right)**

It can be inferred from table (3) that running two separate simulations with a reduced blade count due to scaling amount to 41.9% of a full annular simulation's computational demand. In addition, the data shows that when used in conjunction with a time inclination or Fourier method, the computational cost drops to between 3.7% and 5.3% of the full runtime.

**Table 3: Computational demands**

| Method | 360° Blade Count (S / R) | Reduced Blade Count (S / R) | CPU |
|---|---|---|---|
| Original blade count | 23 / 33 | 23 / 33 | 1 |
| Altered blade count | 22 / 33 | 2 / 3 | 0.095 |
| Time inclination | | 1 / 2 | 0.0086 |
| Fourier method | | 2 / 2 | 0.022 |
| Altered blade count | 24 / 33 | 8 / 11 | 0.324 |
| Time inclination | | 2 / 3 | 0.028 |
| Fourier method | | 2 / 2 | 0.031 |

## CONCLUSIONS

In the present paper, an axial turbine was numerically investigated to evaluate unsteady forcing behaviour. The investigation focused on a method to alter the blade count of a turbine in order to allow for a reduction of the number of modelled blade passages. Furthermore, two time domain flowfield transformation methods and profile transformation were investigated to further reduce computational cost. The methods considered were time inclination and Fourier transformation. The results indicate that the profile transformation method does not correctly capture unsteady force components both in amplitude and frequency, as has also been shown in previous investigations. On the other hand, both the time inclination and the Fourier method perform reasonably well while also showing significant computational savings. In addition, reasonable accuracy was obtained with a simple reconstruction approach of the original force components and the generalised force of the annular configuration. Moreover, the computational cost was significantly reduced for two altered configurations when compared to the respective original reference configuration. In conclusion, the combined application of blade count variation and time domain transformation methods can be used to obtain unsteady forcing components with large computational cost savings. These methods, therefore, represent practical alternatives to full domain simulations for forced response predictions.

**REFERENCES**


Erdos, J., Alzner, E., (1977). *Computation of Unsteady Transonic Flows Through Rotating and Stationary Cascades I - Method of Analysis*. NASA CR-2900, Washington, USA

Denton, JD., Singh, UK. (1979) *Time-marching Methods for Turbomachinery Flow Calculations*. VKI LS, Brussels, Belgium

Rai, M., (1987). *Navier-Stokes simulations of rotor/stator interaction using patched and overlaid grids*. AIAA Journal, 3, 387 396

Giles, M., (1988). *Calculation of Unsteady Wake/Rotor Interaction*. Journal of Propulsion and Power, 4, 356-362

He, L., (1990). *An Euler Solution for Unsteady Flows around Oscillating Blades*. ASME Journal of Turbomachinery, 12, 714-722

Menter, F., (1994). *Two-equation Eddy-viscosity Turbulence Models for Engineering Applications*. AIAA Journal, 32, 1598-1605

Srivastava, R., Bakhle, M., Keith, T., Stefko, G., (1999). *Phase-Lagged Boundary Condition Methods for Aeroelastic Analysis of Turbomachines - A Comparitive Study*. Proceedings of the International Gas Turbine & Aeroengine Congress & Exhibition, Indianapolis, Indiana

Gerolymos, G., Michon, G., Neubauer, J. (2002). *Analysis and Application of Chorochronic Periodicity in Turbomachinery Rotor/Stator Interaction Computations*. Journal of Propulsion and Power, 18, 1139-1152

He, L., (2010). *Fourier Methods for Turbomachinery Applications*. Progress in Aerospace Sciences, 46, 329-341

Fruth, F., Vogt, D., Martensson, H., Mayorca, M., Fransson, T., (2010). *Influence of the Blade Count Ratio on Aerodynamic Forcing - Part I: Highly Loaded Transonic Compressor*. Proceedings of the ASME Turbo Expo 2010, Glasgow, UK

Fruth, F., Vogt, D., Fransson, T., (2011). *Influence of the Blade Count Ratio on Aerodynamic Forcing - Part II: Highly Pressured Transonic Turbine*. Proceedings of the ASME Turbo Expo 2011, Vancouver, Canada

Mayorca, M., DeAndrade, J., Vogt, D., Martensson, H., Fransson, T., (2011). *Effect of Scaling of Blade Row Sectors on the Prediction of Aerodynamic Forcing in a Highly-Loaded Transonic Compressor*. ASME Journal of Turbomachinery, 133, 10

Witteck, D., Micallef, D., Mailach, R., (2014). *Comparison of Transient Blade Row Methods for CFD Analysis of a High Pressure Turbine.* Proceedings of the ASME Turbo Expo 2014, Düsseldorf, Germany