Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-46335

DETERMINATION OF THE WAKE FREQUENCY CONTENTS FOR A TWIN SHAFT GAS TURBINE VARIABLE NOZZLE GUIDED VANE

Antonio Maria Grimaldi
GE Oil & Gas
Florence, Italy

Simone Colantoni
GE Oil & Gas
Florence, Italy

Antonio Melani
GE Oil & Gas
Florence, Italy

Pierre Manenc
Consultant*
Paris, France

ABSTRACT

This paper focuses on improving maintenance techniques for GE twin shaft gas turbines equipped with variable Nozzle Guided Vanes (NGVs) by enhancing the ability to predict potentially harmful stimuli due to NGV misalignment. NGV, by varying the geometry, controls the energy split between the high-pressure turbine and power turbine, allowing higher operational flexibility and higher efficiency at partial load/speed. This flexibility is a requirement for GT mechanical drive applications.

The alignment of the NGV according to specification is part of the GE procedure to guarantee reliable operation of the turbine. The orientation of the vanes is checked and guaranteed via the measurement of the S/T ratio (throat opening/pitch). The S/T distribution potentially affects the downstream buckets in terms of harmonic stimuli for natural frequencies that could result in bucket HCF failures.

The scope of this work is to develop a Fourier series-based tool that, for any statistically possible distribution of S/T ratios, automatically computes the Fourier Coefficients of the corresponding wake pattern and scales each harmonic magnitude with respect to the maximum harmonic magnitude of the symmetric wake pattern.

This tool has been specifically developed to drive field operations when some of the NGVs in the row must be replaced. It allows the detection of harmonic stimuli that could potentially increase downstream bucket resonance without making S/T measurements, reducing the forced outage cycle time and saving maintenance costs.

NOMENCLATURE

a_n	n^th Cosine Coefficient of Fourier Series
b_n	n^th Sine Coefficient of Fourier Series
CCW	Counter Clock Wise
CFD	Computational Fluid Dynamics
CL	Center Line
CSYS	Coordinate System
CTQ	Critical To Quality
$f(x)$	x-dependent S2N Wake Function
GTDP	Gas Turbine Design Practice
HCF	High Cycle Fatigue
HPT	High Pressure Turbine
ID	Inner Diameter
LE	Leading Edge
LPT	Low Pressure Turbine
n	Harmonic index
NGV	Nozzle Guide Vane
NUNS	Non Uniform Nozzle Spacing
OD	Outer Diameter
P_{defect}	Probability of Defect
PDF	Probability Density Function
PS	Pressure Side
P_∞	S2N Wake Free Stream Pressure, Pa
S	Throat Opening [mm]
SS	Suction Side
S/T	Throat/Pitch
S2B	Stage 2 Bucket
S2N	Stage 2 Nozzle
T	Section Pitch [mm]
TA	Throat Area
TE	Trailing Edge
TO	Throat Opening
Z	Process Capability

* Pierre Manenc worked as GE Oil & Gas employee till December 2010

1. INTRODUCTION

The MS5002D [1] is a heavy duty 2-shaft gas turbine for mechanical drive applications. Variable guided nozzles (also called Stage 2 Nozzle, S2N), by varying the geometry, control the distribution of energy between the High Pressure Turbine (HPT) and the Low Pressure Turbine (LPT) (see Figures 1 and 2). A twin shaft gas turbine equipped with NGVs allows higher operation flexibility and a higher efficiency at partial load/speed.

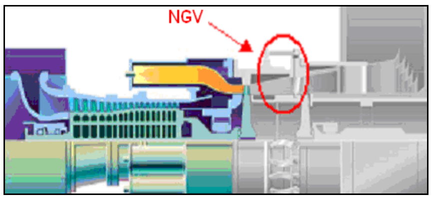

FIGURE 1. MS5002D 2-shaft gas turbine

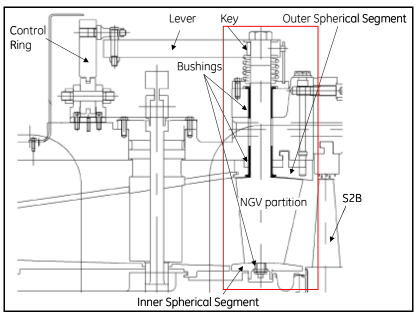

FIGURE 2. MS5002D Low Pressure Section

2. PROBLEM STATEMENT

During an MS5002D maintenance program, some partitions of the 32 variable S2N may need to be replaced because of excessive damage. After replacement, measurements of all the S/T ratios are made. The pitch dimensions are more generally referred to as T, and the throat dimensions as S (see Figure 3). This S/T ratio governs static pressures downstream of the nozzle, with each producing different impulses acting on the downstream buckets. These ratios represent the impulse for each passage, and are generally defined by limits on the arrangement drawing.

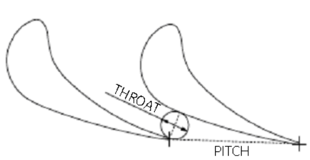

FIGURE 3. Pitch and throat definition

If misalignment is found, then the partitions are adjusted to keep the S/T ratio within the specification limits. This procedure ensures that the downstream buckets (S2B) are only excited by multiples of 32/rev stimuli and that other excitations are negligible noise. As a consequence, no harmonic analysis of the S2N wake pattern is needed. However, to perform these measurements at the customer's site, it is necessary to dismantle the low-pressure turbine rotor and downstream components. The time spent on dismantling and reassembling the rotor is at least seven working days. The CTQs, which need to be met, are the total throat area (performance) and the S/T ratio for each flow passage [2]. The single throat area (TA) CTQ is not considered while performing measurements in the shop or in the field. It is a second order CTQ. The design Specification Limits of CTQs are defined according to GE Turbine Nozzle Design GTDP.

3. DELIVERABLES AND ASSUMPTIONS

3.1 Deliverables

- Determination of the S/T statistics before shop alignment
- Determination of the S/T statistics for site vane replacement
- Process capabilities for performance CTQ: Total TA
- Investigation of S/T effects on S2N wakes
- Wake parameter regressions as a function of S/T
- Update of a dedicated tool for MS5002D applications

3.2 Assumptions

1. The creep strain is negligible so that after machine shutdown all the vanes return to their out-of-factory states
2. Unless stated otherwise, all process capabilities are assumed to be 2σ
3. For each partition, the upper and lower stems share the same axis
4. For each partition, the stems are perfectly cylindrical. There is no shape tolerance on the stems
5. Partition orientation is given by the stem alignment in its bushings
6. Only the two casing bushings contribute to the stem alignment; the inner spherical segment bushing has loose enough tolerances to accommodate any misalignment due to the upper bushings
7. For the machining process, the airfoil high points defining datum planes are assumed to be those for the nominal shape
8. First order effects of S/T on the wake parameters are found for S2N rows with uniform S/T ratios
9. The S/T ratio only affects the wake parameters of the vane whose pressure side bounds the flow passage
10. The influence of the S/T ratio on the wake parameters of the vane whose suction side bounds the flow passage are second order effects and are negligible
11. The wake parameters depend only on the S/T ratio
12. The wake interactions are considered negligible
13. The S2B bow wave is neglected (bucket not included in the CFD)
14. Only the stagnation pressure distribution at the LE of S2B has an effect on vibrations
15. Stagnation pressure distributions at the inner/outer sidewall median plane are good indicators of the actual pressure distributions, i.e., no radial variations of stagnation pressure are assumed
16. Tolerances on the inter-segment spacing are not considered

4. ANALYSIS

4.1 Stack-up analysis

The throat openings correspond to the minimum distance between a cross section PS and the adjacent vane SS surface. They are measured at different radial locations. The throat area is the product of an “average” throat opening and the flow path height. The “average” throat opening is calculated from a weighted average of different radial throat openings. The throat openings and pitches are defined as segments. Only nominal length is taken into account.

Models of the Second Stage Nozzle Tolerances

For each vane, the local coordinate system (CSYS) is Cartesian with:

- x-axis = radial, pointing outward;
- y-axis = tangential, CCW from aft looking forward;
- z-axis =axial, pointing downstream (machine CL).

When performing throat opening and pitch measurements, all vane coordinates are converted to a global CSYS, which is identical to the local CSYS of the first vane. Thus, all distances are computed with the same vector space base.

To perform a stack-up analysis on the S2N, manufacturing, casting and assembly tolerances must be accounted for. The chronological order of the tolerances is the following:

a) Casting tolerances on airfoil shape
b) Manufacturing tolerances on stem axis
c) Manufacturing tolerances in shear pin groove
d) Assembly of NGV in its bushings
e) Shop alignment (when applicable)

a) Airfoil Shape Tolerance Models

As the throat openings and pitches are measured at different cross sections of the airfoil, only airfoil shape tolerances need to be accounted for. The shape tolerances for the throat opening measurements include tolerances for both the airfoil PS and SS, whereas for pitch measurements only TE tolerances must be taken into account. To model the shape tolerance, it is assumed that the actual points can be located within a circular area whose diameter is the tolerance range and which is centered on the nominal location of the point (Figure 4).

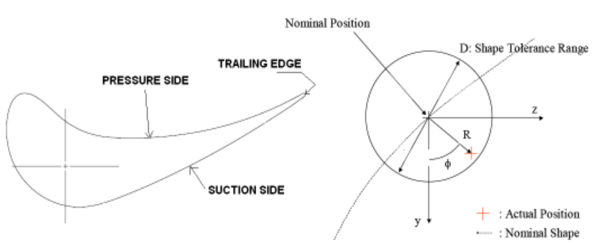

FIGURE 4. Airfoil Shape Tolerance Model

All coordinates refer to the local CSYS. Following this model, two random variables R and Φ are defined for each measuring point.

- Φ: Angular position of the point with respect to the Y-axis (marginal distribution)
- R: Distance of the actual point from its nominal position (marginal distribution).

The PDF’s of these random variables are shown in Table 1.

TABLE 1. Generic Airfoil Shape Tolerance Random Variables

Random Variable	Distribution	Mean	Standard Deviation	Min	Max
Φ	Uniform	0	$\sqrt{\frac{1}{3}\pi^2}$	-π	+π
R	Normal	0	$D/2\sigma_{process}$	0	+infinity

Where D and $\sigma_{process}$ are respectively the shape tolerance range and the process capability of the airfoil casting. The actual location of a point in the vane local CSYS is:

$$X_{actual} = X_{nom}$$
$$Y_{actual} = Y_{nom} + R\cos(\phi)$$
$$Z_{actaual} = Z_{nom} + R\sin(\phi)$$

The X value does not change as all measurements are made at a given radius.

b) Stem Machining

In the partition machining process, the stem machining is performed after that of the airfoil casting. The tolerances on this process are accounted for and result in the determination of the statistical distribution of the angles $\theta_{machining}$ and $\Phi_{machining}$ that the stem axis makes with the airfoil casting x-axis (radial direction) as shown in Figure 5.

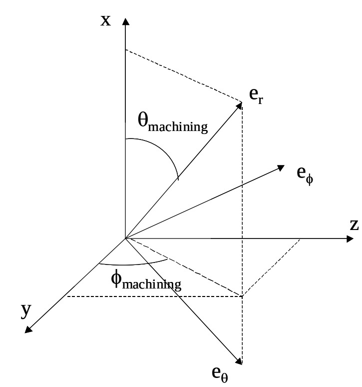

FIGURE 5. Shape Tolerance

A Monte Carlo analysis was performed to determine the distribution of $\theta_{machining}$ (see Figure 6) and $\Phi_{machining}$. The random variables follow the marginal distributions of the machining-induced stem misalignment joint probability. The results are shown in Table 2.

At this point, the stem misalignment with respect to its airfoil casting x-axis is statistically determined. The stem gives its orientation to the whole partition; therefore it is necessary to determine the airfoil measuring point coordinates in a CSYS whose x-axis coincides with the radial direction and matches the stem axis.

To better understand, consider that the airfoil casting has its nominal shape and is in place (its x-axis matches the radial direction). Now suppose that the machining of the stem introduces a stem misalignment measured by $\theta_{machining}$ and $\Phi_{machining}$. If there were no other tolerances in the manufacturing process, assembly of the partition would ultimately align the partition stem axis with the radial direction leading to the misalignment of the airfoil casting. The measuring point coordinates (those that define the throat opening and pitch) must therefore be recalculated.

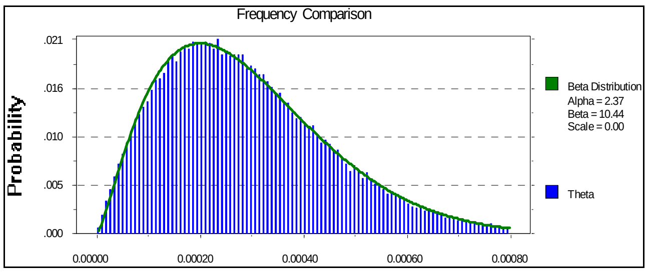

FIGURE 6. Monte Carlo Results for $\theta_{machining}$

TABLE 2. Stem Machining Misalignment Marginal Distributions

Random Variable	Distribution	
$\Phi_{machining}$	Uniform	U (-π, π)
$\theta_{machining}$	Beta	β (2.37; 10.44; 0.001571)

c) Shear Pin Groove Tolerance

From the machining drawing, the shear pin groove median plane is defined with respect to the reference planes A and B (Figure 7).

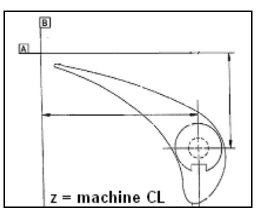

FIGURE 7. Shear Pin Groove

In the worst machining case, the shear pin grove median plane can make an angle α with respect to the NGV outer stem axis. The random variable, which models this angle, is shown in Table 3.

TABLE 3. Shear Pin Groove random variable

Random Variable	Distribution	Mean	Standard Deviation
α	Normal	0	$2\Lambda / 2\sigma_{process}$

Λ and $\sigma_{process}$ are respectively the machining misalignment specified in drawings and the process capability of the groove machining process.

d) Stem Axis Misalignment Due to Assembly in Bushings

So far, all the machining/casting tolerances have been described. Other tolerances due to external parts (bushings, casing) and assembly in the shop add up in the whole stack-up analysis. In the manufacturing shop, the outer and inner spherical segments are bored for the S2N bushings. For the assembly, the stem seats in three bushings, two of which are located on the casing (Figure 2). The tightest tolerances are set for the two casing bushings whereas the inner bushing tolerances are made loose enough to accommodate all potential stem-axis misalignment. Though the two casing bushings are assembled in the same casing bore (the assumption is made that the bore is perfectly cylindrical w/ axis being radial), their axis of symmetry may not coincide due to tolerances. Taking into account the clearances between the bushing OD and casing and between the stem OD and bushing ID permits computing the statistical stem misalignment once assembled. A Monte Carlo stack-up analysis is performed to derive the resulting position tolerance of the stem axis (θ_{stem} and Φ_{stem}) once in the bushing. As mentioned previously, the casing bores for the bushings are assumed to be perfectly cylindrical and radial. However, according to the drawing, there is a position tolerance for the bore axis. For the stack-up analysis, this tolerance translates into Y and Z shifts of the origin of the CSYS attached to the vane. Again, two random variables (R_{casing_bore} & ϕ_{casing_bore}) model the position tolerance (Table 4).

Table 4. Position Tolerance Model for Casing Bore Marginal Distributions

Random Variable	Distribution	Mean	Standard Deviation	Min	Max
ϕ_{casing_bore}	Uniform	0	$\sqrt{\frac{1}{3}\pi^2}$	-π	+π
R_{casing_bore}	Normal	0	$T / 2\sigma_{process}$	0	+infinity

The CSYS shifts are then computed as:

$$Y_{shift\_casing} = R_{casing\_bore} \cos(\Phi_{casing\_bore})$$
$$Z_{shift\_casing} = R_{casing\_bore} \sin(\Phi_{casing\_bore})$$

The two angles θ_{stem} and Φ_{stem} (Figure 8) describe the precession of the stem-axis about the radial direction. The coordinates of all points of interest (those defining the pitch and TO) are then computed taking into account the stem precession about the radial direction due to the above assembly tolerances.

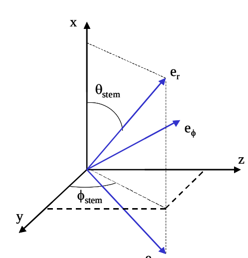

FIGURE 8. Local CSYS(black) and stem-defined CSYS (blue)

e) Shop Alignment of Partitions

Before shipping the gas turbine to the customer's site, all the NGV's orientations are fine tuned so that the S/T ratio ranges are within the specification limits (+/- 1% of the nominal value). The tuning is performed by rotating every vane about its stem axis. The angle of rotation is composed of two angles:

- α: Angle of misalignment due to the shear pin groove tolerances
- β: Vane rotation needed to meet the constraint on the S/T ratio measured between the machine CL and the vane nominal position.

The rotation component, α, is added to β because the shear pin groove machining process may induce a misalignment between the vane nominal position and the groove median plane. Hence, the effective rotation of the vane is $\alpha + \beta$. As previously mentioned, shop alignment is performed to ensure that before shipping to the customer's site, all S/T ratios fall within the specification limits. The purpose of this alignment is to compensate for all manufacturing, assembly and casting tolerances that cause the S/T ratios to be outside of the specification limits. A stack-up analysis was performed to determine the process capability of the S/T ratio before shop alignment. This was carried out by including all the tolerances so far described and setting $\beta = 0$ in the rotation matrix. The Monte Carlo analysis showed that the S/T ratio followed a normal distribution (Figure 9).

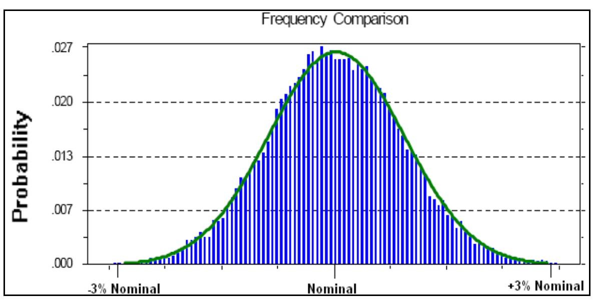

FIGURE 9. S/T Distribution before Shop Alignment

From these results, the $\pm 3\sigma$ ranges for S, T and S/T were computed. These ranges represent the 99.73% probability intervals for these parameters before shop alignment is performed. For S/T, the range is +/- 3% of the nominal value.

To statistically determine the necessary alignment angle for each vane, regressions of S, T and S/T were computed. The vital X's of the regressions were the relative angles θ_0 and θ_1 that two adjacent vanes make with respect to their nominal orientation (see Figure 10). Regression data points would be obtained by rotating the vanes about their stem-axis and recording the corresponding S, T and S/T values. From these regressions, it is possible to identify vane configurations that yield a given value of S, T or S/T. For example, for an S/T ratio of –3% of the nominal value physically measured before shop alignment, there correspond many equivalent combinations of θ_0 and θ_1 for the nominal vanes.

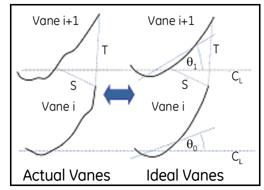

FIGURE 10. Equivalence between Actual Vanes and UG Ideal Vanes θ_0, θ_1

A filtered Monte Carlo analysis was then performed to determine the equivalent "Space of Possible" when θ_0 and θ_1 range between –1° and +1° about their nominal value. The constraints for the filtering were such that S, T and S/T must fall within their $\pm 3\sigma$ respective ranges (before shop alignment). Figure 11 shows the resulting equivalent space when the three constraints are applied. When only the $\pm 3\sigma$ range for the S/T ratio is used for filtering, the corresponding equivalent space is as shown in Figure 12.

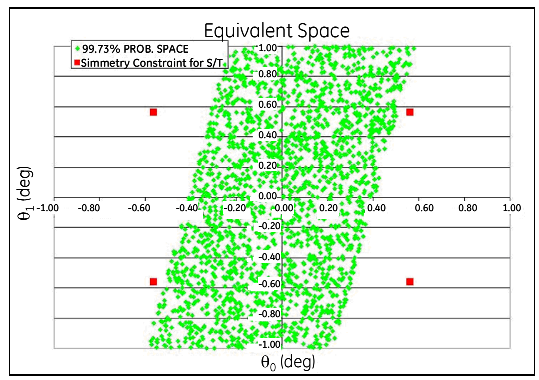

FIGURE 11. Space of Possible (θ_0, θ_1) with constraints on θ_0, θ_1, S/T

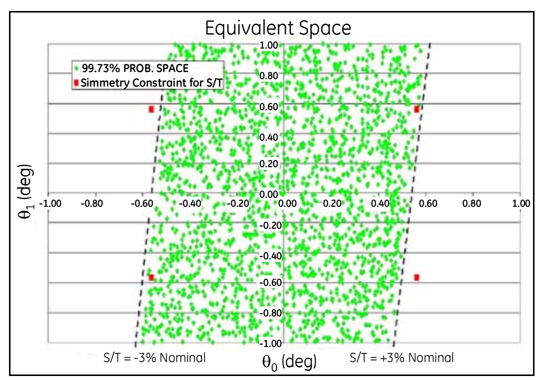

FIGURE 12. Space of Possible (θ_0, θ_1) with constraint on S/T only

From the above figures it appears that θ_0 and θ_1 do not have the same influence on the S/T ratios; θ_0 has the greater influence of the two angles. Since shop alignment is based on correcting vane passages with S/T ratios falling outside the specification limits, only the equivalent space depicted in Figure 12 was used to determine the shop alignment distribution. So far, the analysis has been performed for two adjacent vanes. However, once in the context of a S2N row, every vane is at the same time a “PS” vane or “SS” vane. A vane would be labelled as “PS” or an “SS” if any of the two end points of the throat opening S being measured lies either on the vane PS or its SS.

In view of the above remark, it is clear that θ_0 and θ_1 must have the same range for a vane to be “PS” or “SS”. This translates into defining a square (of feasible combinations) centered at the origin in the equivalent space. This square encloses the range $\pm 3\sigma$ for S/T only; its corner points are indicated as red squares in Figure 12. From the specification limits for the S/T ratio (+/-1% nominal value), the target space can be found. It has to meet the following constraints:

- S, T must be within the $\pm 3\sigma$ range (before shop alignment) to reflect reality
- S/T must be within specification limits
- It must be square (θ_0 and θ_1 have the same ranges)

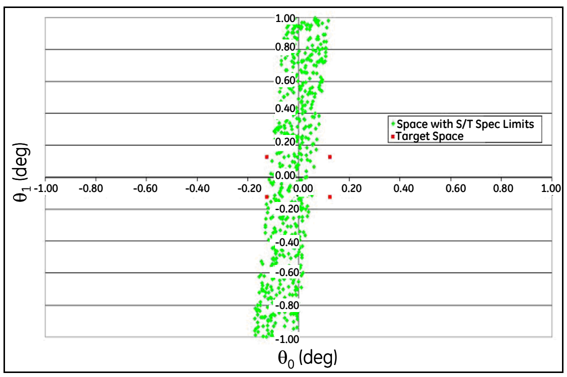

FIGURE 13. Target Space for θ_0 and θ_1

The target design space (Figure 13) is the space for which any vane in the S2N row is “PS” and “SS” simultaneously and any measured S/T ratio is within the specification limits. As a consequence, the shop alignment procedure aims at setting every vane θ_0 in the target space. The purpose of alignment is to drive all the vanes into the target space. For example, if for a given S/T value, the equivalent θ_0 and θ_1 settings are outside the target space, the shop operator will rotate the vanes to set θ_0 and θ_1 toward the target space center. Due to axi-symmetry, only θ_0 needs to be driven to the origin for each flow passage as θ_1 becomes θ_0 for the adjacent flow path and will eventually be driven to the target space center as well. Therefore, for S/T=+3σ, θ_0 must be rotated by +0.5° to reach the target center whereas it needs to be rotated by –0.5° if S/T=-3σ. Only worst-case alignment is taken into account to add more conservatism.

To compute the statistics of the S/T ratio after vane replacement in the field, the following procedure has to be executed:

1. Determine coordinates of nominal S and T points in local CSYS
2. Apply the airfoil shape tolerances to get the actual airfoil points in local CSYS
3. Account for stem axis machining tolerances
4. Compute stem axis misalignment and in-plane shifts due to bushings
5. Assemble the stem-axis in the bushing and compute its coordinates
6. Account for shear pin groove misalignment
7. Add up the former shop alignment settings
8. Run a Monte Carlo Analysis on the S/T for the desired number of replaced vanes

The $\pm 3\sigma$ range for the S/T ratio, after vane replacement in the field, is within +/-5% of the nominal value.

4.2 TACOMA Wake analysis

Tacoma simulations were run to determine the effect of S/T on the S2N wake pattern. The Program TACOMA (Turbine And COMpressor Analysis) is a GE proprietary code [3]. It is a 3D multiblock, multi-grid, structured non-linear and linear Euler/Navier-Stokes solver for turbomachinery blade rows [4]. The equations, in Cartesian form, solved in TACOMA are the 3D Euler equations (inviscid flows), the 3D Navier-Stokes equations (laminar flows), or the 3D Reynolds-Averaged Navier-Stokes (RANS) with a turbulence model. TACOMA uses the k-ω turbulence model as developed by Wilcox [5, 6]. The only significant departure from the standard k-ω model is that TACOMA uses the production modification of Launder and Kato [7].

a) Determination of a Conservative Flow Domain

The wake was determined from the stagnation pressure pattern downstream the S2N. Indeed, the rationale was that inside the wake, the total pressure drops with respect to the free stream stagnation pressure, therefore making it easier to define the wake for vibration purposes.

A radial surface (surface at constant radial location) at the mid-span of the S2N (see Figure 15) was used to determine the stagnation pressure distribution downstream of the S2N. At mid-span, it was assumed that perturbations due to the outer and inner sidewalls and vortices were negligible. Even if the impulse acting at the tip of the bucket is more severe (in terms of bucket dynamic response) than that acting in the middle of the bucket, the scope of the model is to address the downstream pressure evaluating the S/T variation (due to possible misalignment in the stator row) without taking into account its radial distribution. Hence, the mid-span stagnation pressure distributions were assumed to be a good representation of the pressure pattern downstream of the S2N.

The S2B effects were not considered, as the buckets are not present in the simulations. To be more conservative, the flow domain extends beyond the actual S2B. To confirm the above statement, a comparison of stagnation pressure distributions was carried out for two Tacoma simulations. The simulations were perfectly identical except for the location of the mixing end plane (static pressure outlet) and its corresponding boundary conditions.

The end plane locations (see Figure 14) were:

• Simulation 1: half way between S2N TE and S2B LE

• Simulation 2: 4 inches downstream of the Simulation 1 end-plane

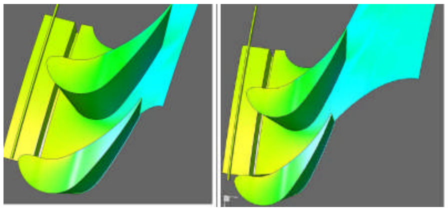

FIGURE 14. Flow Domains: Simulation 1 (left); Simulation 2 (right)

The stagnation pressure distributions of both simulations were recorded on ten meridional cuts (see Figure 15, right side) spanning the flow domain extending behind the S2N TE. The cuts were located at the same meridional positions for both simulations so that the tenth cut coincides with the Simulation 1 end plane.

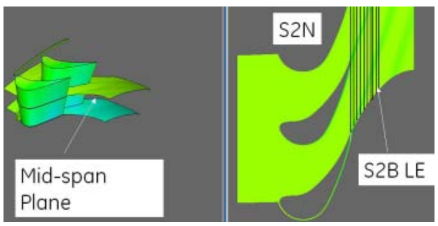

FIGURE 15. Mid-plane and meridional cuts for wake defintion

It is clear from the distributions shown in Figure 16 that the extended flow domain returns more important stagnation pressure drops in the wake; the further downstream, the more significant the pressure drop.

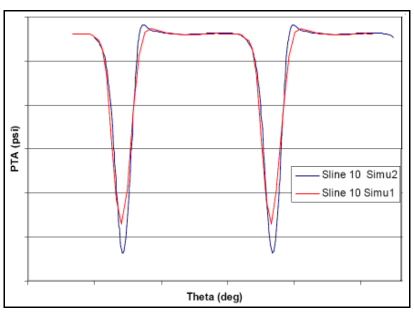

FIGURE 16. Comparison of Stagnation Pressure Distributions for Simulation 1 and 2 for the 10th cut

This is attributed to the fact that the end plane boundary conditions are tangentially averaged.

At the S2B LE there is a stagnation point. Therefore the total pressure increases in the vicinity of the S2B LE (bow wave). As a result, the pressure drop in the wake is reduced and is accounted for in the boundary conditions of the simulation whose end-plane is halfway the axial gap between S2N TE and S2B LE (Simulation 1). Since, the pressure drop is lower, the average pressure increases with respect to that obtained when the S2B is not considered (simulation with end plane beyond S2B LE). To conclude, it was shown that an increased pressure drop is obtained when the flow domain extends beyond the S2B. Thus, all the Tacoma simulations have an extended flow domain. No changes in the wake pattern itself are taken into account as explicitly specified in the assumptions paragraph.

b) Determination of the Stagnation Pressure Distribution

It was assumed that the S2B will only sense the pressure distribution at its LE and that its vibratory behavior depends only on this distribution. As a consequence, the total pressure distribution is analyzed at the intersection of the mid-span plane and the meridional plane just upstream of the S2B LE.

c) TACOMA Simulations

The stack-up analysis discussed previously returned the ± 3σ for the S/T ratio once partitions are replaced in the field. It means that the actual S/T has 99.73% probability of falling within this range. It should be recalled that the ± 3σ range is computed by assuming that all the vanes are replaced at the same time without changing any settings. This results in the most conservative range.Though the S/T ratio from one flow passage to another may differ, the Tacoma simulations are run assuming equal S/T ratios for the entire S2N row. This is a limitation of Tacoma as only axisymmetric simulations can be run. In order to address the effects of different vane settings an annulus CFD simulation should be run. This will be a scope of work of future model development.

To investigate the effects of S/T on the wake parameters, all vanes at hot conditions are rotated by the same angle about their stems in order to drive S/T towards the desired value. For the CFD simulations, the vanes are in their nominal geometries, meaning that no tolerance is accounted for. In total, five Tacoma simulations were run as shown in Table 5.

TABLE 5. TACOMA Simulations

Run Number	S/T	Equivalent rotation Needed About Nominal position
1	100% Nominal	0.0°
2	103% Nominal	-0.5°
3	97% Nominal	+0.5°
4	105% Nominal	-0.8°
5	95% Nominal	0.8°

The first run is a simulation at nominal conditions to determine the baseline wake pattern when the gas turbine is operated at ISO conditions. The other four runs are simulations at off-design conditions. They serve to investigate the effects of S/T on the wake parameters when outside the specification limits. Runs 2 and 3 simulate the ± 3σ value of S/T before shop alignment is performed. Runs 4 and 5 set all the S/T ratios to the ± 3σ value of S/T when all the vanes are replaced at the customer's site.

It is important to remember that for each run, all the flow passage S/T's are equal to the S/Ts value being considered.

Finally, all the Tacoma simulations have the following features:

- Single stage
- Steady state conditions are assumed

- S2B are not present
- The flow domain extends well beyond the actual TE of S2B
- Axisymmetry of vanes

d) Determination of Wake Parameters

- Wake Pressure Drop ΔP
- Free Stream Total Pressure
- Wake Angular Offset θ (relative to nominal position)
- Half Wake Width on Pressure Side W_{PS}
- Half Wake Width on Suction Side W_{SS}

They are represented in Figure 17.

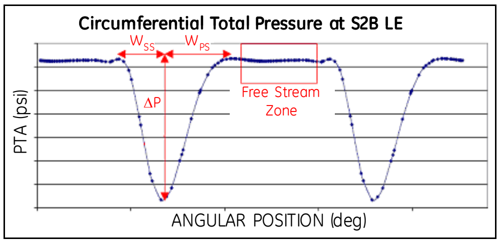

FIGURE 17. Wake Parameters

The free stream stagnation pressure is determined as the average value of the total pressure outside the zone of significant pressure drops.

ΔP corresponds to the maximum total pressure drop in the wake with respect to the free stream pressure level.

The wake angular offset with respect to the nominal position is computed from the value of S/T assuming that it is only the "PS" vane orientation θ_0 that governs the S/T value.

The computation is made by considering a regression for S/T with θ_0 as the sole X. A quadratic fit is obtained; its coefficients are shown in Table 6.

TABLE 6. Angular offset regression coefficient

Quadratic Fit Coefficients		
Term	Name	Value
Constant	c	= S/T nominal value
Theta0	b	-0.01602
Theta0^2	a	-5.4886E-05

For a given value of S/T (say x), the following Equation (2) is solved and only the meaningful solution is retained.

e) Wake Parameters Regressions

For each of the five Tacoma simulations, the wake parameters described above were determined. Regressions of ΔP and relative wake widths as functions of S/T were performed using a proprietary tool. Linear regressions were found for the relative wake widths $\%W_{PS}$ and $\% W_{SS}$. Two quadratic fits were determined for the wake stagnation pressure drop -- the percentage pressure drop in the wake with respect to the free stream total pressure and the ratio of the actual pressure drop to pressure drop for the symmetric nominal S2N.

The wake pattern produced by the S2N is 2π-periodic. Therefore, it can be written as a Fourier Series.

f) Wake Pattern Model

Obviously, the wake pattern is perfectly 2π-periodic. It is modeled using sine functions and four parameters, which are:

- Wake Percentage Pressure Drop %ΔP
- Wake Angular Position θ
- Half Wake Width on Pressure Side W_{PS}
- Half Wake Width on Suction Side W_{SS}

The detailed model equation can be cast in the following form:

$$Wake(x) = P_\infty - f(x) \quad (1)$$

This model of the wake patterns meets all requirements to have a uniform convergence of the Fourier Series towards: x→Wake(x) (Uniform Convergence implies local convergence). However, only the Fourier coefficients of f need to be calculated. Finally, the wake function can be written as:

$$Wake(x) = P_\infty \left(1 - \frac{a_0}{2} - \sum_{n=1}^{\infty} a_n \cos(nx) + b_n \cos(nx) \right) \quad (2)$$

g) NUNS Tool update

The initial inputs for NUNS (Non Uniform Nozzle Spacing) were the number of segments, vanes and their respective wake parameters.

For the purpose of investigating the feasibility of NGV replacement without measurements, the tool was tuned to the MS5002D GT. Namely, the number of vanes was fixed at 32.

The input is now greatly simplified, as only the S/T ratio for each flow path is required. The wake parameters such as pressure drops, widths and offsets are automatically computed from the regressions previously discussed.

The offset angle corresponds to the equivalent vane misalignment θ_0.

As it is resource expensive with Tacoma simulations to determine the effects of non-uniform S/T ratios on the wake, in this analysis (see assumption 11) the S/T ratio of any flow passage is the only driver considered for the wake imparted to the downstream bucket pressure side vane. The present work doesn't address effects on the wake thickness due to flow separation.

For example, consider two consecutive flow passages of respective S/T = 97% nominal and S/T = 102% nominal made from three vanes, V1, V2 and V3. With the above assumption, the wake parameters for V1 will be found by plugging in an S/T value of 97% nominal, whereas those parameters for V2 will be computed by plugging in S/T = 102% nominal. The S/T value of the subsequent flow passage (V3-V4) will dictate the V3 wake parameter.

Three main reasons justify this simplifying assumption:

- The S/T ratio depends mostly on the pressure side vane
- The equivalent misalignment angles are sufficiently small
- The Tacoma simulation results have shown only small variations on the wake parameters as S/T varies

In the end, the wakes are considered independent and the wake interactions are deemed to be negligible higher order terms.

h) Fourier Analysis [8]

Given all flow passage S/T ratios, NUNS automatically computes the Fourier Coefficients of the corresponding wake pattern and scales each harmonic magnitude with respect to the maximum harmonic magnitude of the symmetric wake pattern (all flow passage S/Ts set to the nominal value). The normalized magnitudes are then plotted in a histogram-type chart along with the symmetric S2N wake harmonic magnitudes. Thus, it is possible to graphically visualize the effects of non-uniform S/T ratios on the frequency contents of the wake distribution with respect to the ideal case.

5. RESULTS

The stack-up analysis permits computing throat openings and pitch values when the vanes deviate from nominal conditions and nominal orientation due to tolerances.

Process Capabilities Before Shop Alignment

Before shop alignment, the stack-up analysis performed on the S2N row of 32 vanes returned the process capabilities shown in Table 7.

TABLE 7. Process Capabilities before Shop-Alignment

Process Capability Data			
CTQ	**Distribution**	**P_{defect}**	**Z**
A_{TOTAL}	Normal	0.0%	> 8.00
A_{SINGLE}	Normal	26.3%	1.63
S	Normal	49.0%	1.02
T	Normal	0.6%	3.49
S/T	Normal	62.3%	0.69

The results are compiled while taking into account the following tolerances for the stack-up analysis:
- Airfoil shape tolerances
- Stem machining tolerances
- Casing bore and bushing tolerances
- Shear pin tolerances

The analysis clearly shows that the performance CTQ -total throat area- is met at 100%. It also confirms that a rough adjustment of the S/T ratios by rotating the control ring is not sufficient to drive all the S/T ratios to the spec limits. There is a 62.3% probability of being outside the specification limits. Therefore, it shows the need to fine tune in the shop the alignment of the partitions to compensate for all tolerances and to ensure that the S/T ratios are within the specification limits. There is no need to compute the statistics of the S2N row after the shop alignment is performed as all the S/T ratios are within the specification limits and the total throat area CTQ is still satisfied.

Process Capabilities During NGV Replacement

NGV replacement takes place at the customer's site when the MS5002D is shutdown and the turbine section upper casing is removed. To replace an NGV, only the partition is changed, meaning that all settings of the upstream components (such as the lever arm orientation, control ring reference angle, etc.) are kept unchanged. With this process, variations in CTQs may arise from two sources:
- Tolerances from the new partitions;
- Incorrect settings of upstream components.

Indeed, for the second source of variation, since the new partition is statistically different from the one it replaces, the shop alignment settings are highly likely to be inappropriate and may not compensate for the new vane tolerances. In some instances, the wrong settings may further drive the S/T ratio away from the specification limits. In the stack-up analysis performed to determine the process capabilities for the CTQs during vane replacement, the following tolerances are considered:
- Airfoil shape tolerances
- Stem machining tolerances
- Casing bores and bushings tolerances
- Shear pin tolerances
- Shop alignment settings not correct for the new hardware

Furthermore, the capabilities are computed by assuming that all 32 vanes are replaced at the same time without performing adjustments. Therefore, the results are extremely conservative as only a few vanes are actually replaced during a replacement campaign. The results are summarized in Table 8.

TABLE 8. Process Capabilities for 32 NGV Replaced without Measurements

Process Capability Data			
CTQ	**Distribution**	**Pdefect**	**Z**
A_{TOTAL}	Normal	0.0%	5.04
A_{SINGLE}	Normal	50.1%	1.00
S	Normal	69.1%	0.50
T	Normal	2.0%	3.05
S/T	Normal	63.6%	0.37

From the above results, it is confirmed that inadequate settings for upstream components worsen the capabilities of the S/T ratio and the single throat area. However, the total throat area CTQ is still very good. Of particular interest is the $\pm 3\sigma$ range for S/T after vane replacement. There is a 99.73% probability that any S/T will be within +/-5% after vane replacement. The normality test for the S/T ratio is shown in Figure 18.

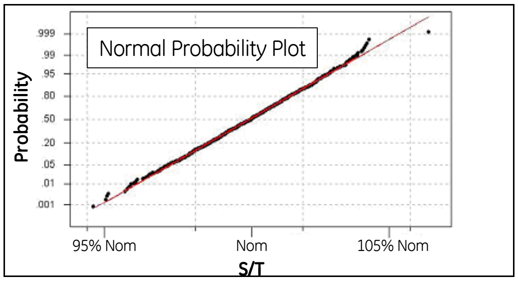

FIGURE 18. S/T Normality Test After Field Replacement

Effects of S/T on Wakes

Tacoma simulations were run for different values of S/T to assess the effects of this ratio on the wake parameters. In total, five runs were conducted and the corresponding wake distributions at the leading edge (LE) of the S2B were analyzed. Figure 19 shows the evolution of the wakes as S/T varies within +/- 5% Nominal S/T value. In addition to an obvious space shift of the wake, it can be noted that as S/T increases (vanes open) the maximum total pressure drop in the wake increases (the converse is also true). However, the magnitude of the variations of the pressure drop as S/T varies is small compared to the free stream value. Indeed, these variations represent 0.5/45.6 ≈ 0.1% of the free stream pressure.

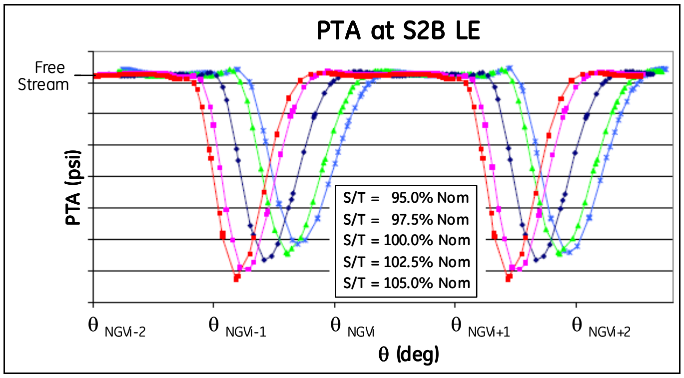

FIGURE 19. Wake Evolution with S/T

Harmonic Analysis for S/T within Specification Limits

According to internal design specifications, if all the S/T ratios are within the specification limits, there is no need for harmonic analysis of the wake pattern to determine potential excitations for the downstream S2B [9]. However, a harmonic analysis was conducted in the case for which all S/T ratios are within the specification limits. The S/T ratios were randomly generated using Monte Carlo and considering a uniform distribution for the S/T ratio within the specification limits. The Fourier Series Coefficients of a randomly generated S/T distribution are displayed on Figure 20.

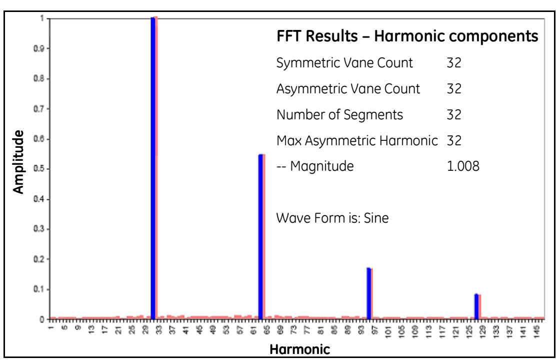

FIGURE 20. Wake Frequency Contents for all S/T within Spec Limits

The blue bars are the harmonics for nominal ideal conditions (all S/T ratios equal to the nominal value) and the red bars are the harmonics for the case where the S/T ratios are uniformly distributed within the specification limits (+/- 3% nominal value). All the harmonics are scaled with respect to the maximum amplitude harmonic of the nominal case, namely, harmonic 32. For the nominal case, only harmonic multiples of 32 are present whereas for the other case, other harmonics are visible though their amplitude is negligible (below 3% of the 32/rev excitation amplitude). Therefore, it is concluded and confirmed that there is no need to perform a harmonic analysis when all the S/T ratios are within the specification limits.

Harmonic Analysis after Vane Replacement in the Field

After vane replacement, it was shown that all the S/T ratios might fall within +/- 5% of the nominal value with 99.73% probability with a normal distribution. A harmonic analysis was performed assuming all vanes are replaced and S/T is uniformly distributed within this range. The wakes were changed according to the S/T values. An example of the Fourier Series Coefficients for a random S/T distribution are depicted in Figure 21. It is clear that not performing S/T measurements will result in increasing the excitation spectrum for the S2B. However, the magnitudes of all non-32/rev-multiple harmonics remain low. It remains to be determined if these harmonics can cause the S2B HCF failure.

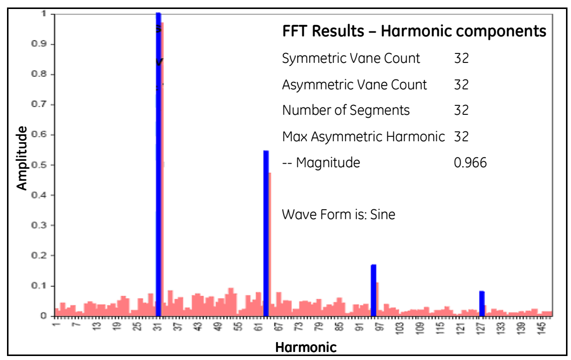

FIGURE 21. Wake Frequency Contents when all S/T are within +/- 5% Nominal

Statistical Analysis of Frequency Contents

Using a Monte Carlo approach, the statistics of all harmonics composing the S2N wake pattern can be derived by randomly varying the S/T distribution. This analysis was conducted for the limit case where all the vanes are replaced. This scenario can be thought of as the limiting result of multiple MS50052D NGV replacement campaigns if no planned maintenance is implemented. Indeed, after a certain number of outages, all vanes would have been changed. For this scenario, all flow passage S/Ts range within +/- 5% of the nominal value with a normal distribution. A 7500-run Monte Carlo analysis was performed by varying all the S/T ratios and by computing the statistics of all harmonics below the 90th. It showed that the maximum harmonic is below 13% of the 32/rev harmonic of the ideal case (all S/Ts set at the nominal value). A sensitivity analysis of the wake harmonics with wake parameters was also conducted. Figure 22 shows the influence of each parameter and the interactions on the maximum amplitude value (% of fundamental amplitude) for all harmonics not a multiple of 32/rev.

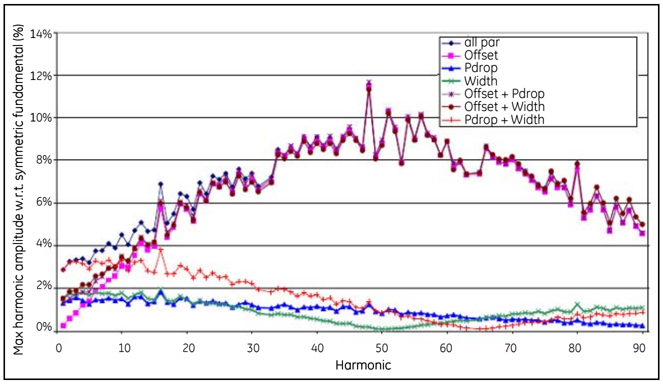

FIGURE 22. Contributions of Wake Parameters to Harmonic Amplitudes (scaled amplitudes)

It is clear from the above figure that the angular offset is the main contributor to the harmonic amplitudes. It is worth noting that while each parameter contributes to the frequency contents, their contributions do not necessarily add up in the case where all wake parameters are considered.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

A stack-up analysis was performed on the S2N row. It returns the process capabilities of the S/T ratio and Total Throat areas when the NGVs are replaced without measurements. It was found that in the worst case scenario (all the NGVs replaced without measurements), the total throat area of the S2N is within the specification limits, and hence, the performances parameters are guaranteed. Furthermore, the S/T ratio follows a normal distribution centered on the nominal value.

The Tacoma simulations based on possible S/T ratios returned wake parameters evolution as a function of the S/T ratios. The Fourier series for the wake for the design conditions (all S/T ratios within the specification limits) showed that the maximum harmonic amplitude (for frequencies not equal to a multiple of 32/rev) is below 3% of the fundamental harmonic amplitude of the nominal case (all S/T=nominal value). This was obtained with a Monte Carlo type analysis by varying all the S/T ratios uniformly within the specification limits. The same procedure applied to the case where all the vanes are replaced without measurements (hence S/T has 70% probability of being outside the spec limits) showed that the maximum amplitude does not exceed 13% of the fundamental amplitude. However, no acceptance permitted to assess if replacement without measurement could be carried out.

The analysis was the first step in an overall project to reduce the NGV replacement cycle time. The Fourier series analysis of wakes returns the frequency contents and potential S2B natural frequency crossings for the MS5002D. The wake frequency contents were obtained from a very conservative approach in the stack-up analysis phase. A second project needs to be conducted to derive acceptance criteria to assess if NGV replacement without S/T measurements is applicable. For this purpose, a ping test of the actual S2B row should be performed and the actual amplification factor computed. With the amplification factor (transfer function), the response of the S2B to any excitation can be determined. A modal cyclic analysis of the S2B should be performed to obtain the modal stresses. The relative stresses between the nominal case (all S/Ts set to the nominal value) and any wake distribution (hence any frequency contents) should be reported on a Goodman Diagram to determine the sensitivity of the S2B to wake harmonic contents. In this way, an HCF risk assessment can be conducted to verify the acceptance or to refute NGV field replacement without measurements.

REFERENCES

[1] Cocca, M. A., and Marcucci, N., “Performance and Reliability Improvements for MS5002 Gas Turbines”, GER-4171, GE Power Generation.

[2] Norek, R. S., 1972, “Nozzle Area and Harmonic Approval”, 72-GTD-23, Oct. 17, 1972, G.E. Class II.

[3] Felten, F. N., Kapetanovic, S., Ostrowski, M., and Holmes, D. G., 2008, “Gas turbine temperature prediction using unsteady CFD and realistic non-uniform 2D combustor exit properties”, GT2008-50275, ASME Turbo expo 2008, Berlin, Germany.

[4] Holmes, D. G, Mitchell, B. E, and Lorence, C. B, 1997, “Three Dimensional Linearized Navier-Stokes Calculation For Flutter and Forced Response”, ISUAAT Symposium, Sweden.

[5] Wilcox, D. C, 1988, “Reassessment of the scaledetermining equation for advance turbulence models”, AIAA J., 28, pp. 1299-1310.

[6] Wilcox, D. C, 1993, “Turbulence Modeling for CFD”, DCW Industries, La Canada, California.

[7] Launder, B. E, and Kato, M, 1993, “Modeling flowinduced oscillations in turbulent flow around a square cylinder”, ASME FED, 57, pp 189-199.

[8] Gasquet, C., and Witomski, P., 2000, “Analyse de Fourier et Applications, Filtrage, Calcul Numérique et Ondelettes”, First ed., Dunod, 2000.

[9] Kemp, R. H., Hirschberg, M. H., and Morgan, W. C., 1958, “Theoretical and Experimental Analysis of the Reduction of Rotor Blade Vibration in Turbomachinery through the Use of Modified Stator Vane Spacing”, NACA TN 4373, September 1958, Washington.