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Comparison of Models to Predict Low Engine Order Excitation in a High Pressure Turbine Stage

Markus Jöcker, Alexandros Kessar, Torsten H. Fransson
Kungliga Tekniska Högskolan (KTH)
S-10044 Stockholm, Sweden
email: markus@egi.kth.se
Tel: +46 8 790 7471
Fax: +46 8 20 41 61

Gerhard Kahl
MTU Aero Engines
D-80995 Munich
email: Gerhard.Kahl@muc.mtu.de

Hans-Jürgen Rehder
German Aerospace Center
D-37073 Göttingen, Germany
e-mail: hans-juergen.rehder@dlr.de

Abstract

The paper compares three numerical strategies to predict the aerodynamic rotor excitation sources of "Low Engine Order" (LEO) in a high-pressure turbine stage. Main focus is laid on methods to compute the stator exit flow. The aim is to evaluate computationally cheap approaches to avoid modelling the whole circumference of the stator. A single passage viscous strategy, a single passage inviscid linear blade movement strategy and a viscous multi passage sector strategy are compared and evaluated. The assessment of the prediction quality is made by comparison of the computed stator exit flow to experimental data. The main result is that only the global behaviour of the stator exit flow is estimated right, both level and amplitude of Mach number and pressure are computed with poor agreement to experiments. Future evaluations of the resulting rotor excitation pressure are needed to estimate the level of necessary agreement to give acceptable predictions of the low engine order forced response.

Nomenclature

A	Area
h/H	Relative blade height
m	Passage number
p	Pressure
N	Number of stator passages

Indices:

1	stator inlet
2	stator exit
t	throat
t	total

Abbreviations

EO	Excitation order

L2F	Laser Two Focus Anemometry
LEO	Low Engine Order
DLR	German Aerospace Centre
SP	Single passage model
MP	Multi passage model

Introduction

Forced vibrations are characterised by aerodynamic excitation sources, which are flow disturbances acting periodically on the blades and originate from upstream and/or downstream obstacles. The time-periodic excitation is in all cases caused by the relative rotational motion of excitation source and the excited structure, which leads to excitation frequencies multiples of the rotation frequency. A common way to identify forced response regions of a blade row is the “Campbell Diagram”, an example shown in Figure 1, which is a key plot in the unsteady design process. The diagram shows crossings of excitation frequencies due to upstream and downstream vanes as well as burner cans with the eigenfrequencies of the blades. At these crossings the risk of resonant excitation of the structure exists. Practically, in high-pressure turbines vane passing does not excite the 1st flex mode because of its low eigenfrequency (typical frequencies correspond to 8 to 10 excitations per revolution in the operating range, compare also Figure 1). To the original figure by [Jay et al. 1988] an additional line was added indicating another excitation of low frequency, named “Low Engine Order” (LEO) excitation. Such can be caused by non-uniformities on the stator blade row due to manufacturing variations and wear (for example vane erosion or burnout). The excitations can induce vibrations in fundamental blade modes as the first bending or torsion mode, characterised by low frequency and possibly high vibration amplitudes. The severity is increased due to occurrence at high load operating conditions.

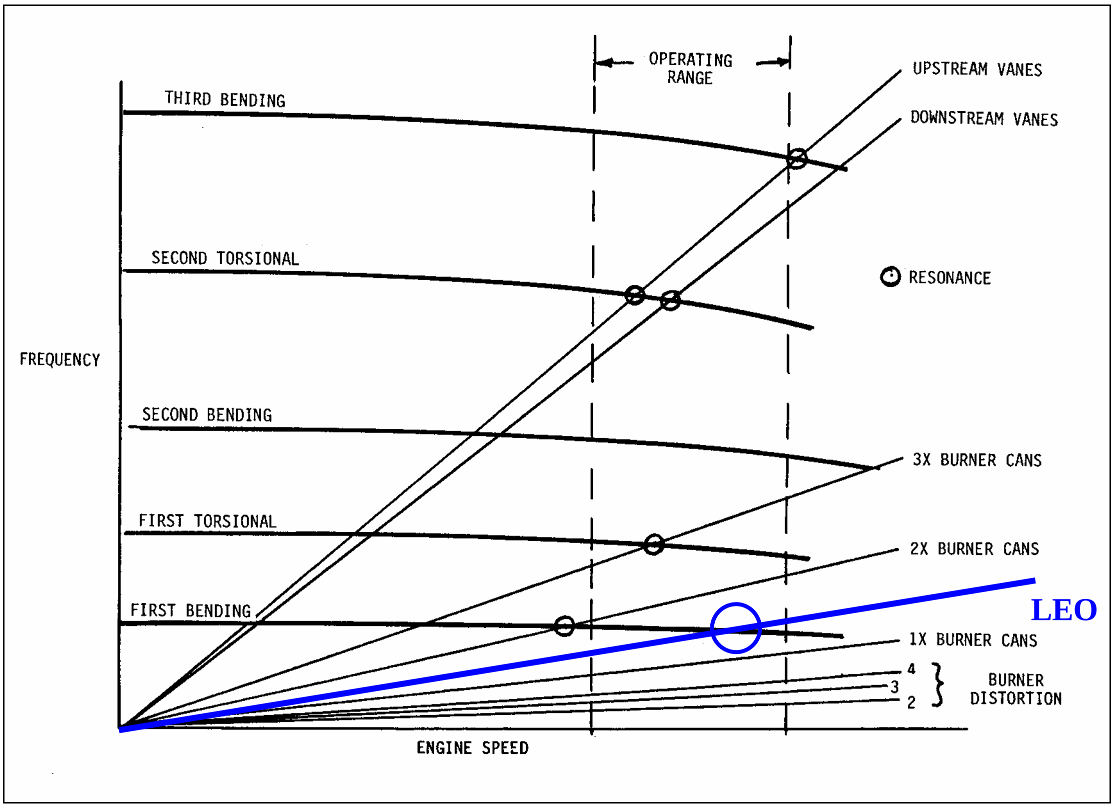

Figure 1: *Example of a Campbell diagram indicating Low Engine Order resonance [Jay et al. 1988]*

During the last decade intensive research and development activities have focused on the computation of wake passing frequency excitation in turbomachinery stages. The goal was to benchmark the capabilities of computational tools for further application during engine design. Furthermore, the investigation of unsteady flow physics was addressed aiming at widening the understanding of the mechanisms of aerodynamic blade vibration excitation (for example [Jöcker et al. 2000]).

Only little work has been published on the computation and understanding of low engine order excitations. These are more difficult to predict than vane passing excitations due to the following reasons:

1. The frequency of the low engine order excitation is not known a priori, because it is caused by unknown variations in the vane geometry due to manufacturing tolerances or wear on the vanes during operation.
2. The periodicity of the excitation is often not known a priori. The spatial periodicity of the stator exit flow must be assumed to be over the whole circumference.

Manwaring and Kirkening [1997] investigated in a low-pressure turbine rotor the 2nd engine order temperature variations, which emanated from the combustor. The excitation was modelled with help of measured data. A full annulus analysis was presented by Vahtati et al. [1998] indicating LEO excitations due to throat width variations in the stator. Bréard et al. [2000] showed a systematic study of low engine order forced response considering the effects of throat width variation in the stator and temperature distortion. A typical sector of the stage was modelled to compute the aerodynamic excitation. In [Marshall et al. 2000] linear inviscid flow and non-linear viscous flow models for the unsteady flow in the ADLARF fan rotor are compared, LEO boundary conditions were derived from experiments. All these investigations derived the unsteady boundary conditions either from full annulus or sector vane computations or calculated them from measured data.

This paper investigates the LEO excitation in a high-pressure turbine with transonic flow, where a companion experimental program prescribes the type of excitation. Instead of modelling the coupled stator-rotor domain the computationally cheaper but more modelling intensive approach of de-coupling the stator and rotor computation is chosen. The goal is to find approaches suitable for design. The objective of the present work is to assess different modelling options to compute the unsteady inlet boundary conditions due to a given distortion in the stator. This is the first critical step in the de-coupled approach. Unsteady pressure response on the rotor can presently not be evaluated due to the lack of experimental data.

The stator configuration is given by a sinusoidal variation of stator throat area, both a 5th engine order variation and a 7th engine order variation is available with two amplitudes of throat area variation each (2% and 4%). To limit the study on the modelling evaluation the 5th engine order case with 4 % variation was chosen (see also Figure 2). Three modelling strategies are evaluated and compared.

Experimental data and boundary conditions

Experiments:

High quality experiments were set up and performed at the cold flow wind tunnel for rotating cascades (RGG) at DLR in Goettingen, Germany. The aim of the experiments was to simulate the effects of Low Engine Order excitation in a high pressure turbine stage. Therefore, the stator was modified to provide well defined configurations of distorted stators. One modification comprised a 5th engine order variation of the stator pitch, which is shown in Figure 2. In a similar way a 7th engine order variation was established. A more detailed description of the RGG and the design of different stator configurations for Low Engine Order experiments is given in Rehder [2001].

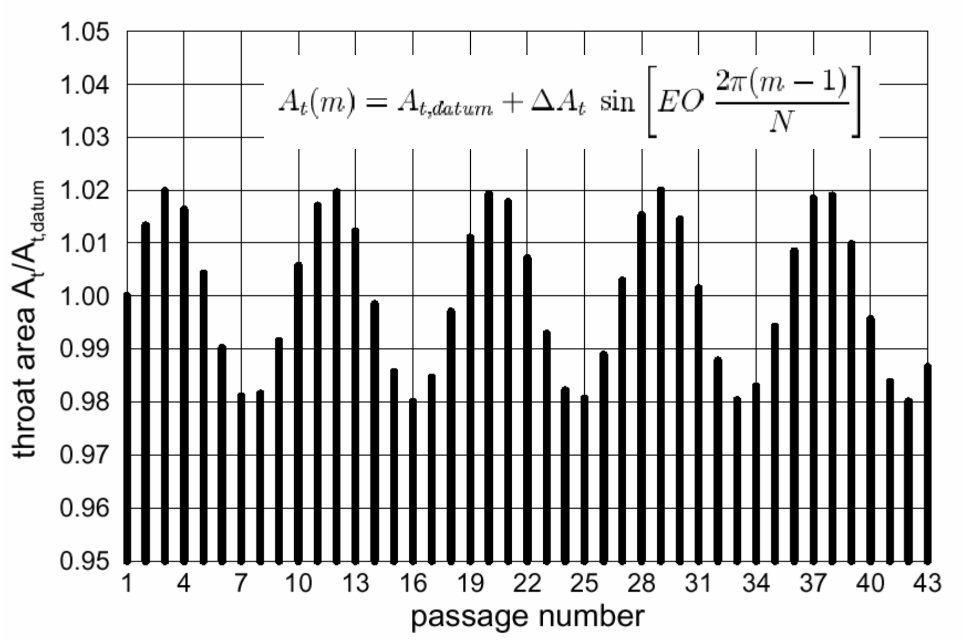

***Figure 2**: 5th engine order throat area variation realised in experiments at DLR*

The stator exit flow was measured first without and then with the rotor behind the stator. The following data was measured to provide and evaluate boundary conditions for CFD simulations:

Technique	**Stator only**	**Stage**
Probe	Stator exit: Total pressure	Stator exit: - Rotor exit: Total pressure
L2F	Stator exit: -2D velocity vectors -2D turbulence level	Stator exit: -2D velocity vectors -2D turbulence level Rotor exit: -2D velocity vectors

		-2D turbulence level

Table 1: *Overview of available measured data*

Additionally, stator inlet flow measurements were available including an assessment of the hub and tip end wall boundary layer status in front of the stator, see Freudenreich et al. [1999]. The operating point studied in this paper leads to transonic flow both in the stator and in the rotor, a stator trailing edge shock contributes significantly to the stator exit flow. The effective exit Mach number is averaged to slightly above 1, which makes the analyses relative sensitive regarding the resulting rotor excitation. The averaged rotor exit flow is well below 1, but inside the passage local transonic regions are expected. The rotational speed is adjusted such that a resonance condition as computed in a structural analysis of the rotor is met. A detailed evaluation of the experimental data is available in the companion paper by Kessar et al [2003]. Planned experiments will assess the unsteady pressure and the vibration characteristics of the rotor blades under these forded response conditions. However, such data is not available for the present evaluation of the numerical results.

Boundary conditions:

Experimental stator only results of the exit flow are different to the stage results due to not completely matching conditions of experimental conditions in the two test runs. In the stator only tests the average exit Mach number at 128 % $c_{ax,stator}$ was 1.00, in the stage experiments the corresponding number was 1.05. These small differences can be significant for the aerodynamic rotor excitation in the studied transonic flow. In all computations beside one (TRACE) the stage results have been used for setting up the computations, because it is assumed that the boundary conditions from the stage experiments will lead to better agreement to the unsteady flow in the stage than the stator only computations. A Fourier analysis of the stator exit harmonics at midspan indicates that the low engine order harmonic content is only little influenced by the stator exit flow difference of the single passages. Closer to the end walls (at 20 % and 90 % of blade height) the differences between stator only and stage experiments are however remarkable. This can be seen in Figure 5 and Figure 5 when comparing the relative differences between stator only and stage result of the vane passing frequency (and multiples) to the ones in the low engine order frequency.

The mixed out flow parameters behind each passage of the stator are different, which is most probably caused by the geometric variation of the stator. To define a boundary condition for the computation an arithmetic average of the mixed out flow parameters of each passage was specified.

Modelling approaches

For the low engine analysis it is necessary to compute the aerodynamic excitation due to a spatial stator exit flow variation, which has a larger period than the vane pitch. In the present case of 5th EO this variation has a spatial period of exactly 43/5 of the vane pitch, were 43 is the number of vane passages of the stator. If the unsteady computation is chosen to follow a linearized approach, the rotor inlet boundary condition needs to consist of an amplitude and a phase shift of this spatial flow distribution at the stator exit. The form is by definition of the linearized approach assumed to be sinusoidal. Therefore, the following modelling approaches will focus on the estimation of the LEO harmonic of the excitation, but where available other harmonics will be included in the discussion.

Strategy 1: Viscous single passage flow assembly

The simplest method would compute just one single passage and "shift" the resulting stator wakes according to the positions of the stator trailing edges. In a pre-study it has been found that this method is not suitable to reproduce the variations behind the real stator. The next approximation is to only compute the minimum and maximum spacing vane passage with single passage computations and use these to calculate the amplitude of the low engine order excitation. This approach assumes that the relation between throat area and stator exit flow in terms of 1st harmonic spatial distribution is linear. For simplicity, the passages are computed with the same average exit boundary conditions. The evaluation is done by computing the absolute difference between the 1st harmonic amplitudes of the minimum and maximum spacing result. A closer look at the differences between the two exit flows confirmed that they are mainly in the 1st harmonic. But it should be remarked that at 90 % blade height the difference in mean value was largest, which indicates that other physical effects are probably involved (see further results discussion). The computational tool VolSol, provided by Volvo Aero Corporation, Sweden, is used for the computations. For the present investigation the standard k-e. turbulence model with an extension by Kato Launder [Kato and launder, 1993] and standard wall functions was applied. The numerical method [Eriksson, 1990, 1995] is an explict three stage Runge Kutta, time marching finite volume approach. The convective fluxes are calculated with a third order upwind biased scheme, the viscous fluxes are computed with a second order centred scheme. The code applies structured multiblock H-type and O-type meshes and can be used for 2D and 3D computations. Farfield boundary conditions are partly non-reflecting.

Strategy 2: Inviscid quasi steady linear flutter computation

The 3D linearized method SliQ [Giles, 1992], [Marshall and Giles, 1997] allows the computation of the unsteady flow due to a blade movement flow perturbation. The method is foreseen for blade cascade flutter analyses and hence allows the specification of an inter blade phase angle between the motions of adjacent blades. The present strategy sets this inter blade phase angle between the modelled vanes of the stator to a value corresponding to the throat variation in the stator, which must be sinusoidal to allow this approach. The frequency of the blade movement is however set to 0, which is the major difference to a usual flutter computation. The computation leads to a quasi-steady result of the unsteady flow to be evaluated at "a time" corresponding to the investigated stator configuration. A disadvantage of the method is that viscous effects cannot be regarded correctly. However, the huge advantage is that in very quick and simple computations stator exit flows may be computed due to different orders of distortion, which makes it suitable for design approaches. The evaluation in here will give some insight on the applicability of this approach.

Strategy 3: Viscous computation of a sector of several vane passages

The number of NGVs (43) is not an integer multiple of the engine order under consideration. For a CFD analysis of this configuration, the whole annulus would have to be modelled. To reduce the computational effort, a sector of the stator is modelled. Two approaches are presented:

1. A modified configuration with a scaled stator is modelled, where the throat width pattern repeats after an integer number of vanes. The NGVs are scaled so that the pitch/chord ratio and hence the vane loading remains identical to the original configuration. In the present case this implies that the stator is scaled from 43 to 45 vanes on the circumference, each vane reduced in size by a factor 43/45. A sector of 9 passages is modelled to represent a periodic domain for the 5th engine order excitation, resulting in a mesh of approximately 1.9 million points. The inlet total pressure, total temperature and flow angle distribution was taken from traverse measurements taken previously in the ADTurB program, these were scaled to the correct mean total pressure and total temperature levels. The exit boundary condition used here sets the mid span circumferentially averaged pressure, thus allowing radial variations according to the radial equilibrium condition and circumferential variations due to the re-distribution of the flow according to the varying stator spacing. The computations are performed with the TRACE code, developed in co-operation between the DLR Institute of Propulsion Technology and MTU Aero Engines [Fritsch et al, 1997]. The block-structured code uses a cell-centred explicit finite-volume to solve the Reynolds-averaged Navier-Stokes equations formulated in relative Cartesian co-ordinates It employs a time-marching Runge-Kutta scheme along with matrix dissipation to minimise corruption of solutions by numerical smoothing. For the current analysis, a k-w turbulence model was employed in combination with wall functions on the blade, hub and tip surfaces.
2. The stator is not scaled but the nearest number of passages representing a periodic sector are modelled. In the present case 9 passages are modelled, which results in a domain which is slightly larger than the 5th engine order domain of 43/5 passages. Without scaling of the vanes this represents the exact geometry of the 9 passages measured in the experimental programme, the modelling error is introduced by assuming a periodic continuation of the domain, i.e. that passages 10 to 18 are identical to the modelled passages 1 to 9. The computations are performed with VolSol with similar computational parameters as for in the single passage approach described above (Strategy 1).

Results

Space resolved data

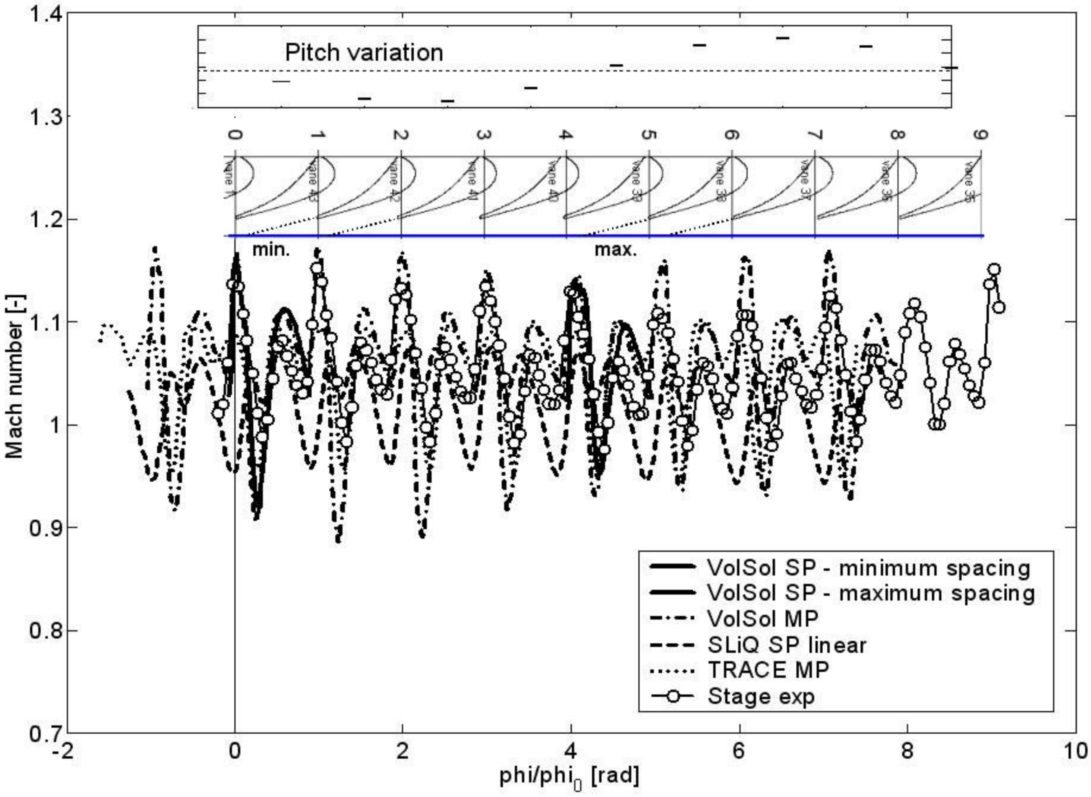

Figure 3: *Space resolved stator exit pressure at midspan at 128 % of* $c_{ax, strator}$

Figure 3 shows the space resolved stator exit flow behind nine passages. The Mach number has been chosen to represent the data because it is a direct measured result whereas the pressure is a derived result with more uncertainty. Also illustrated is the variation of the corresponding vane pitches. It is obvious that a comparison of the data sets in this form is difficult. Measured and computed domain are not exactly the same so that the 9 passage period is only partly overlapping. The single passage approach with VolSol is of course only represented in one passage each, the result of minimum and maximum spacing shown at the corresponding locations. Each passage exit flow goes through two Mach number deficits, which have been described and discussed in detail in earlier work for example by [Freudenreich et al. 1999] and (from left to right) identified as a wake and a shock deficit. This pattern is found in all of the curves. The global behavior found by all methods and in the experiments is that Mach number level and deficit amplitude decrease with increasing spacing. Obviously, the larger pitch leads to less acceleration of the flow and hence reduced deficits due to the wake and shock. The VolSol single and multi passage results fit well but small differences indicate that the exit flow variation is not purely controlled by the single passage aerodynamics. Compared to experiments the Mach number deficits by VolSol are too large. The TRACE computation is performed with slightly different boundary conditions (stator only boundary conditions, see above) and hence the Mach number result is at a lower level and also the wake and shock deficits are less than computed with VolSol and hence fall better into the range of the experiments. The inviscid linear code SliQ overestimates the shock deficit and gives a too small wake deficit. The code was neither expected to predict the correct viscous flow behavior.

So, beside the global behavior none of the methods give a good representation of the measured data.

Harmonic decomposition

The important results from the stator computations with regard to the intended unsteady linearized rotor computations are the 5th harmonic Fourier coefficients of the stator exit flow. These are compared below for the Mach number (Figure 4) and for the pressure (Figure 5). As all the results are available behind 9 passages only the Fourier coefficients for the whole circumference were computed from an assembled result built from 5 times the 9 passages. Therefore, the vane passing frequency appears as the 45th EO (see also Strategy 3 description above). An evaluation of the error introduced by this will be possible when also full annulus computations are available.

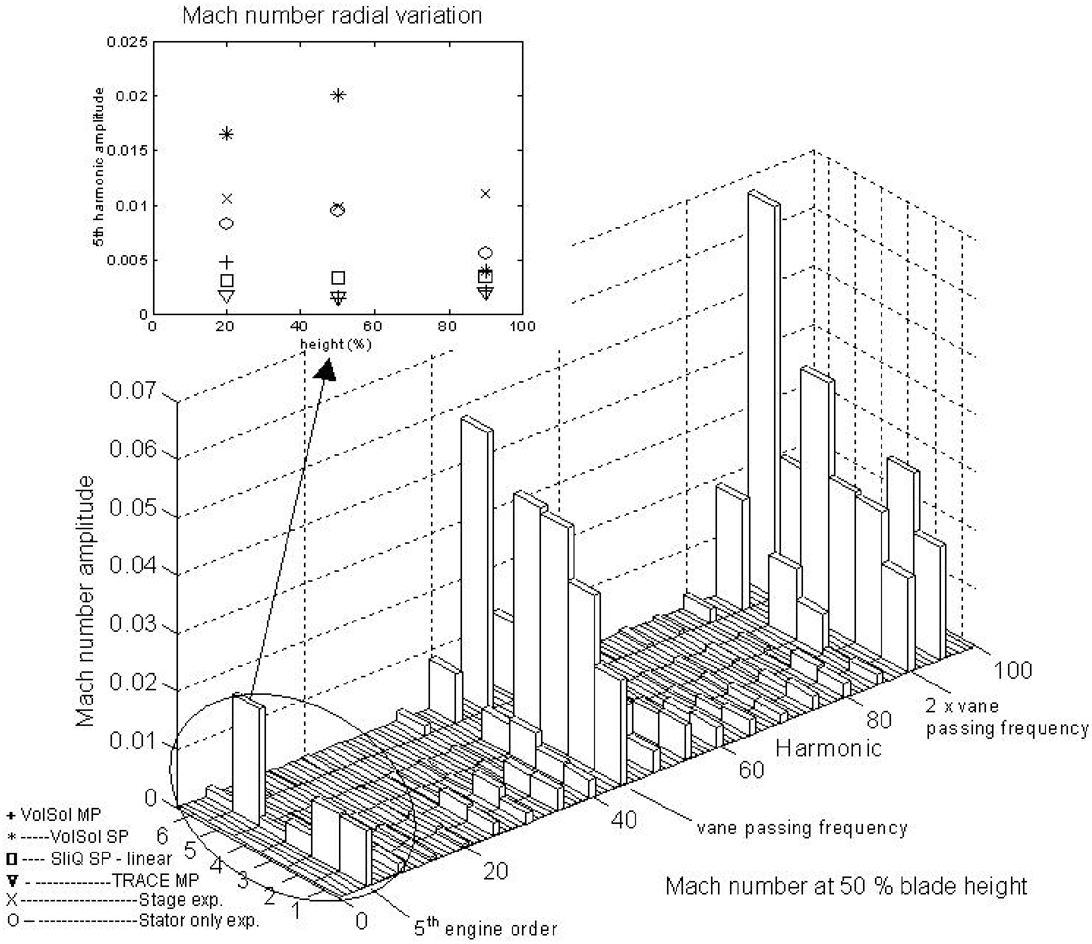

Figure 4: Mach number harmonics at 128 % of $c_{ax,stator}$

The largest coefficients are at vane passing frequency for the pressure and at two times vane passing frequency for the Mach number. The latter one is due to the Mach number double deficit (wake and shock) as described above. Differences in these harmonics are related to the passage computation differences described in the space resolved data above. For, example the over prediction of Mach number deficits with VolSol gives too large amplitudes of one and two times vane passing frequency. The multi passage computations by VolSol and TRACE give remarkably similar results in the 5th harmonic both at midspan and close to the endwalls despite the observed differences in the global result. Both give much too small 5th EO amplitudes. For the single passage method result only the 5th EO is included in the figures, which indicate a large over prediction both in Mach number and in pressure at 20% blade height and at midspan, at 90 % blade height this result falls in the same range as the other viscous results. Some error can be introduced as only the 1st harmonic variation is considered (see Strategy 1 description.

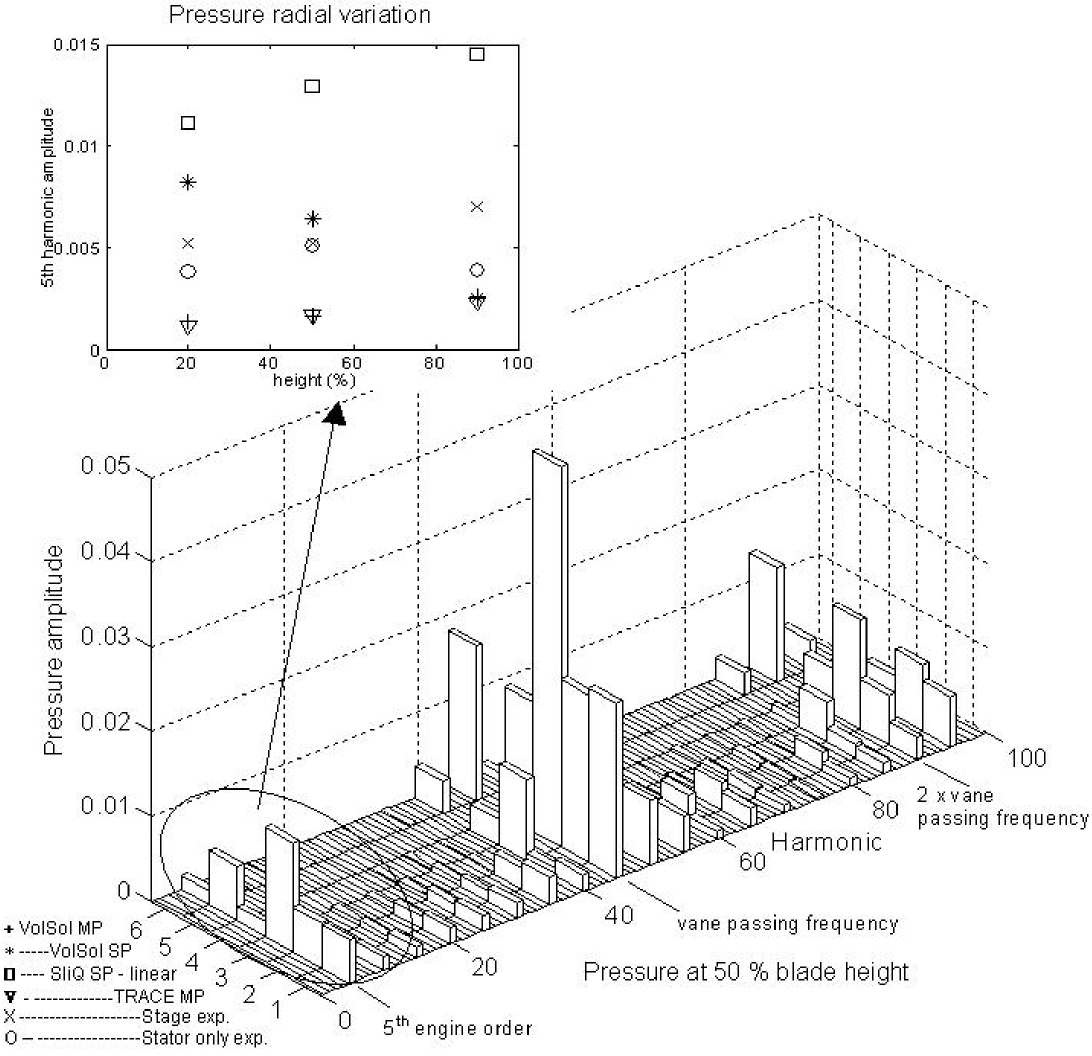

Figure 5: Pressure harmonics at 128 % of $c_{ax,stator}$

The inviscid linearized method SliQ gives a reasonable result for the Mach number compared to the other computations but over predicts strongly the 5th EO pressure variation. However, the good Mach number result is not regarded a reliable result because the code is not capable to compute the viscous effects. It is planned to extend the study and base the linarized SliQ computation on a steady viscous base flow.

At 90 % blade height large variations in the stator exit flow are observed in the experiments, which are not computed by any of the methods. The analysis of the experiments shows that in this region high secondary flow field effects occur (arising from a horse shoe vortex due to the inlet tip boundary layer and a passage vortex due to the high flow deflection through the stator), causing large variations in the 5th engine order exit flow harmonic. As pointed out in the description of Strategy 1 the single passage analysis indicates that 5th EO type of variation seems to change close to the tip, as the 1st harmonic variation decreases and instead the mean value variation increases. This is however not included in the harmonic analysis in Figures 3 and 4.

Conclusions and Future Work

1. At midspan the differences in the stator exit flow boundary conditions between stage and stator only experiments are more significant for the vane passing frequency than in the Low Engine Order frequency. Closer to the endwalls the differences become remarkable.
2. None of the modelling approaches match the measured low engine order exit flow, only the global behaviour is represented by the computations.
3. The single passage models of minimum and maximum spacing overestimate the exit flow variation at 20% and 50 % of blade height. At 90 % of blade height the shift of significance from 1st harmonic to the spatial average indicate the different physical effect causing the low engine order.
4. The linearized method overestimates the variation of stator exit flow. The correct prediction of viscous effects as the wake deficit can not be expected and a reasonable applicability is only granted when viscous effects are negligible for the rotor blade excitation. Future investigations will clarify this.
5. Both multi passage viscous methods give similar results even though the codes and the modelling approaches have been different. This gives confidence in the results of this type. Nevertheless, the calculated amplitudes are significantly smaller over the whole span than those of the experimental data. The reason for this discrepancy is not yet clear – since different scaling approaches, different meshes and different solvers were used and still very similar results were achieved, these parameters do not seem to have a large influence on the results. Possible reasons could be connected to the large differences observed in the predicted and measured secondary flows described below. For now, it must be stated that the current sector model obviously yields inadequate results.
6. Largest differences between the models and the experiments have been detected at 90 % span. Future modelling refinements will investigate if and how these flow variations can be computed and which influence they have on the low engine order excitation of the rotor.
7. From the present analysis it is concluded that the physical effect causing the low engine order variation is probably the higher flow acceleration in a smaller pitch passage. At 90 % span the tip secondary flow seems to be effected by the pitch variation causing large changes in the stator exit flow field. Future analyses of the flow field will clarify this.

8. The computed harmonics will be used for unsteady rotor computations to estimate the unsteady rotor blade pressure, which will be compared to measured data as soon as available. The importance of different physical effects on the low engine order excitation will be estimated.

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