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LOW NOISE COMPRESSOR DESIGN WITH A LINEARIZED EULER METHOD

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Abstract. *Because of the growth in air traffic, aircraft noise becomes an increasing environmental problem. Hence, the reduction of aircraft noise emissions is an important goal for aircraft and aero engine manufacturers. MTU Aero Engines is using advanced CFD/CAA methods to find an optimum low noise design for its turbines and compressors. This paper presents the concept of the numerical procedure for noise generation and propagation calculations with a linearized Euler-Code, the results of the acoustic analysis of a compressor, including the identification of the main noise sources, the concept for the optimization and the results of this successful optimization.*

1 INTRODUCTION

Because of the growth in air traffic, aircraft noise becomes an increasing environmental problem. Hence, the reduction of aircraft noise emissions is an important goal for aircraft and aero engine manufacturers. MTU Aero Engines is using advanced CFD/CAA methods to find an optimum low noise design for its turbines and compressors.

Within the European 5th Framework research project *TurboNoiseCFD*, a methodology has been developed to calculate the tonal sound generation due to aerodynamic interaction as well as the propagation of tonal sound through multistage turbomachines. For each cascade, three rotor-stator interaction mechanisms are considered: interference with the wake of the upstream cascade and interference with the steady pressure fields fixed to the neighbouring cascades both upstream and downstream.

Objective of the here presented work is the optimization of an existing compressor under acoustic criteria. The methodology mentioned above, including steady and linearized Euler codes, is applied to find a low noise design for the *SILENCER* compressor rig analytically by means of parameter variations. This rig is a model for a compressor of a UHBR (ultra high bypass ratio) engine with a geared fan and high speed low pressure compressor / turbine. Such a compressor is assumed to be potentially noisy, which leads to this investigation.

Varying parameters are the blade/vane numbers and the stacking parameters lean and bow of the profiles. This work is part of the European 5th Framework research project *SILENCER*. For both designs, the original and the acoustic optimized one, noise measurements are performed in 2003 and 2004 respectively within *SILENCER*. The results of the measurements and the here published predictions will be compared afterwards.

2 THE SILENCER COMPRESSOR RIG

2.1 RIG 235

The original configuration is sketched in Figure 1. Profiles listed in downstream direction are 9 symmetrical struts, followed by 40 inlet guide vanes, and 3 rotor-stator pairs.

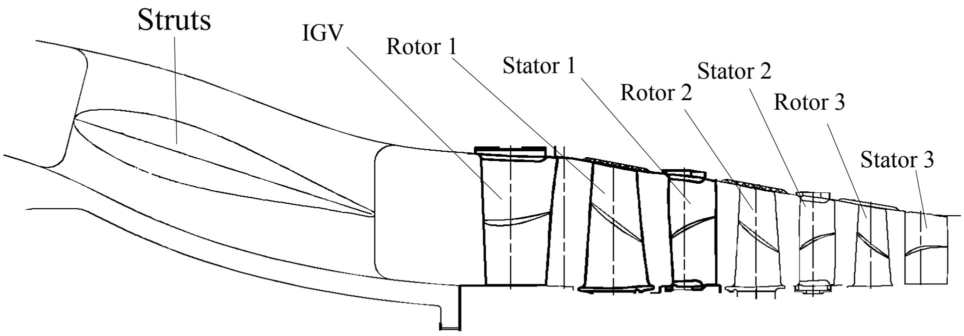


Figure 1. Compressor Rig 235 with 9 struts, 40 inlet guide vanes, and three successive blade vane pairs.

2.2 Operating Conditions

For acoustic certification of an aircraft, the noise at the performance points "Approach", "Cutback" and "Sideline" has to be below the requirements. "Approach" is the important operating condition of this study. The complete design geometry optimization is made for "Approach".

2 METHOD

2.1 Numerical Method of Sound Generation Calculation

The numerical methods used for the parametric study are described in several publications [1][2][3]. Starting points of the process are the blade/vane geometries. Eul3D creates a steady flow Euler solution on the defined mesh. WAKEPHASE calculates the wake disturbance using a semi-empirical model [4]. The time-linearized Euler code LIN3D calculates the unsteady flow field, which is viewed by a in-house tool or processed to get modal results.

A time-linearized Euler code calculates the unsteady flow while we assume small harmonic perturbations in the flow field. This allows to decouple the steady and unsteady flow. Furthermore the unsteady flow equations can be linearized in the unsteady flow variables. A wave approach transforms the Euler equations into the frequency domain. LIN3D uses a Finite-Volume scheme with a 3-step Runge-Kutta time integration method. A structured H-type mesh with centered variable arrangement is required to describe the geometry of the flow domain.

LIN3D uses the steady Euler solution and a disturbance on the entry or exit as an input. The calculations are on coarse, medium or fine mesh. However it starts always with a coarse mesh calculation. Results are radial distributions of the pressure and intensities (among other data) and integrated Sound Power Levels for each scattered mode. Input perturbations are velocity disturbances from a wake upstream or pressure disturbances from upstream or downstream generated by a neighbored row. Sound generation calculations use both types of calculations, sound propagation calculation use only pressure disturbances.

The CPU time depends on the calculated case. Fine mesh calculation with more than 1.5 million nodes can run between 2 days and 2 weeks. Compared with these coarse and medium mesh computation time can be neglected.

The MUTANT tool is used to modify the geometry. It contains several features to modify an existing profile. Two of them are used for this investigation.

1. Vane/blade number modification.
   Changing the number of blades/vanes means always a down- or upsizing in such a way that the ratio of spacing to chord length remains constant. In general, changing the chord length means changing the leading or trailing edge position. One of both edges or the center of gravity stays unchanged as a reference line.
2. Lean/bow/sweep modifications.

The radial stacking of the profiles on the stream tubes can be modified by these predefined geometry classes. While sweep works in axial direction and lean in azimuthal, bow has both degrees of freedom. Lean and sweep are defined by an angle, bow needs two parameters, first one is the position of the maximum bow, second is the shift of the profile at this position, while the positions at hub and tip are unchanged.

2.2 Numerical Method of Sound Propagation Calculation

Sound propagation calculations [3] close the gap between sound generation calculations for a particular stage and measurements upstream from the IGV.

Sound, e.g. generated on S1, has to travel upstream through IGV and R1, which means two successive propagation calculations ("beetle method"). Also downstream traveling waves should be considered because of reflections further downstream (down to S3). Sound waves can be scattered, reflected or dissipated, so usually the transmission coefficient is smaller 1 on every blade or vane row.

LIN3D is used for sound propagation calculations:

- While doing series of propagation calculations only those modes are of interest, which have a sufficient integrated sound power. Only scattered modes in the frequency range of interest are considered.
- The input is always an output pressure disturbance mode of an existing calculation.
- While the mode order stays constant through any kind of propagation calculation the frequency will not.
- Sound propagation depends on the azimuthal mode order, the frequency, and the radial distribution of the input pressure (amplitude and phase). So, waves with the same order and frequency have not necessarily the same transmission and reflection coefficients due to their different radial distributions.
- PWL of sound waves with same mode and frequency are added neglecting their phase differences.
- No multi-reflections are considered.

2.3 Optimization Strategy

A well-balanced strategy is needed to find a promising solution for this design problem which is characterized by a large set of parameters. Following a classical approach the complex process is divided into two steps. In a first step (Figure 2) the relevant cascades and interaction mechanisms are identified. For that task calculations are done on the original configuration. As will be shown later, the dominant noise is generated at Rotor 1 and Stator 1.

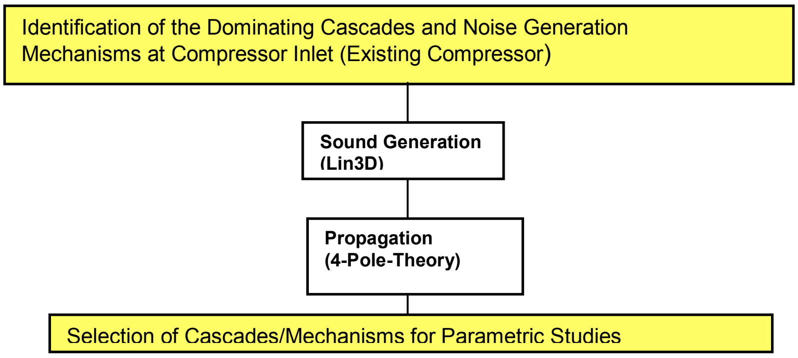


Figure 2: First step of the design process includes measurements and calculations.

In a second step the optimization is done (Figure 3), divided into several single tasks which are done successively without any branches and loops. The initial state of each step is a solution of a former step. Thus the original configuration is optimized from step to step until the last step is done and a solution is found (no loops).

The scope of possibilities is limited to the most promising candidates. The first step is to do noise generation calculations for blade/vane number variations of IGV and S1, explicitly sound generation on R1 in the wake of IGV and on S1 in the wake of R1:

1. IGV number varies – R1 blade number is constant.
2. R1 blade number is constant – S1 vane number varies.

Result of this study and approximate propagation calculations based on the 4-Pole-Theory are promising options for the blade/vane numbers. Propagation calculations with LIN3D then finally select the optimum blade/vane number configuration.

This configuration will not change for all following optimization steps. Because better solutions will be found it is called sub-optimum. Next step is the radial stacking variation with lean and bow modifications. For this, extensive investigations are made previously to clarify the noise reduction potential. Here again we find an optimum shape and verify its quality with a propagation calculation. At last profile variations are made to optimize the former solution.

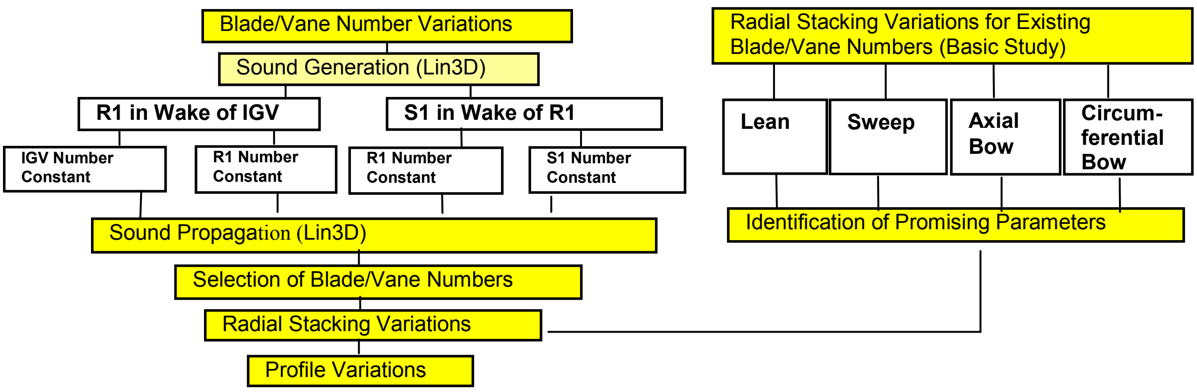
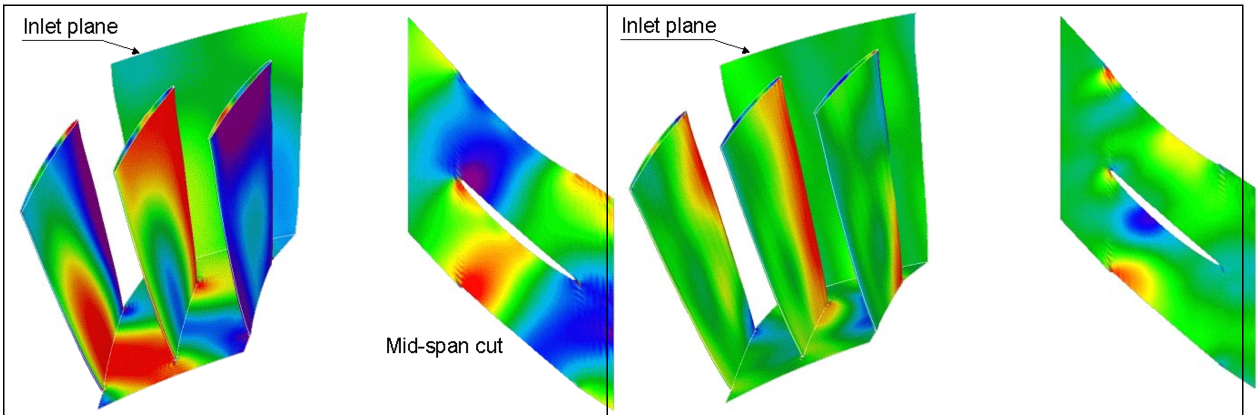


Figure 3. Second step: Optimization process with alternating calculation and selection steps. The order of the steps corresponds to their optimization potential.

3 IDENTIFICATION OF MAIN NOISE SOURCES OF BASELINE CONFIGURATION

3.1 Noise Generation of Baseline Configuration

Three different noise generation mechanisms are considered. These are the interaction of cascades with the wake of the upstream row and adjacent cascade's interactions by potential field disturbances. Computations for the seven rows for the three noise generating mechanisms are carried out for the first two harmonics of the perturbation. Pressure disturbances of first and second harmonics of Rotor 1 (R1) as a result of wake interference are shown in Figure 4. The same scale is used for both pictures. It clearly shows that the disturbances of the first harmonic is the dominating source of noise emission. Hence, only the results of first harmonic are presented in Figure 5.



First harmonic pressure disturbance	Second harmonic pressure disturbance

Figure 4. First and second harmonic pressure disturbances of Rotor 1 row, generated by interaction with the IGV wake.

The source noise of the three mechanisms for all rows of the LPC is presented in Figure 5. These results also readily indicate that the wake interference is the dominating source of the noise compared to the potential flow field interference of the inlet and outlet. It was therefore clearly concluded to continue with the further studies of first harmonic wake interference.

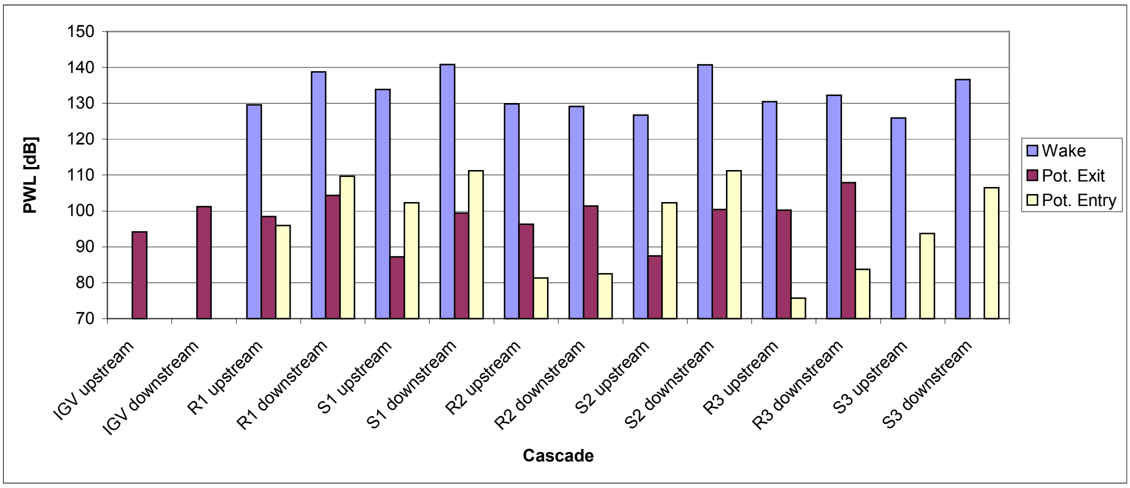


Figure 5. Total sound power generated by the first harmonic wake and potential flow field interference at the inlet and outlet interface planes of each row for medium mesh resolution.

3.2 Approximate Noise Propagation to IGV inlet of Baseline Configuration

All cascades show source noise levels in a similar order of magnitude at their generation origin. Relevant is the noise level at the entry of the IGV. With respect to this, some rough straight forward calculations, using the 4-pole-theory [5][6], show that the noise, generated at Rotor 1 and Stator 1, are the dominant sources (

Figure 6). As expected noise from further downstream looses importance due to transmission (and reflection) losses.

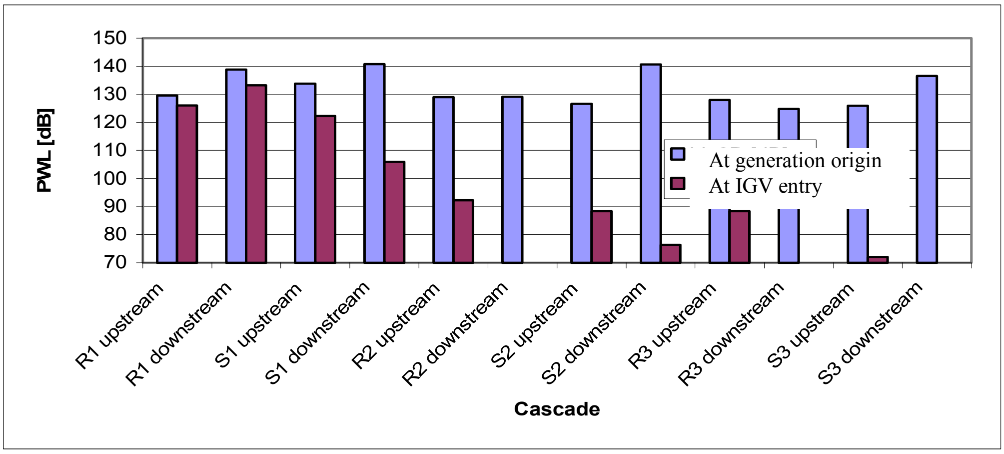


Figure 6. Source noise and the sound power arriving at the inlet of IGV as a result of first wake harmonic interaction

3.3 Considered Noise Generation Mechanisms for Optimization

As shown in chapters 3.1 and 3.2, the noise generation at Rotor 1 and Stator 1, due to the 1st wake harmonic, has been identified as the dominating mechanism. Hence only these interactions are considered for the optimization described in the following chapters.

4 NUMERICAL RESULTS OF ACOUSTIC OPTIMIZATION

4.1 IGV Number Variation

The influence of IGV number on the unsteady Rotor 1 flow field is studied. Disturbances are caused by the first wake harmonic of the IGV's. All calculations are done using LIN3D.

The IGV number is 40 in case of the baseline configuration. Within this study it is varied down to 32 and up to 156.

The Sound Power Level is plotted for 2 scattered modes upstream and downstream respectively more or less over the complete cut-on range in Figure 7. IGV number equal to 40 marks the origin of the mutation process.

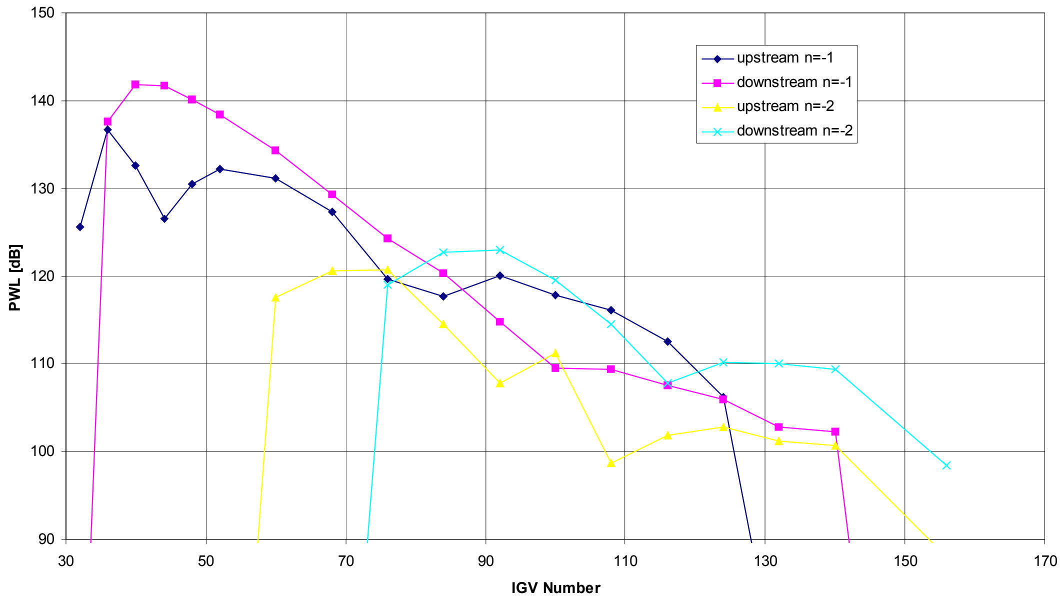


Figure 7 Sound Power Level upstream and downstream from Rotor 1 (medium mesh). The disturbances are first IGV wake harmonics. Different n reflect different scattered sound modes.

The most important results are:

- With higher inlet guide vane numbers decreases the noise generation in upstream and downstream direction both clearly.
- Highest PWLs are at 40 vanes (downstream) and 36 (upstream).

- The PWL distribution according to the downstream wave decreases monotonously. The upstream related PWL curve shows oscillations with relative minimums at 44 and 84 vane numbers.
- Downstream noise dominates over upstream noise for vane numbers less 90. In the high vane number range exists a reverse relation.

The negative slope of the curves is related to an increasing distance between the disturbance creating IGV and the Rotor 1 blade. Choosing “Center of Gravity” as the reference line, the distance grows with smaller vanes. The vane shift effect causes a decrease of 1.3 dB while changing the vane number from 40 to 124. 1.3 dB is small compared with the changes in the Sound Power Level due to IGV number variations, as can be seen in Figure 7. This is, the vane number effect dominates clearly compared to the distance effect.

4.1.3 Conclusion of IGV number variation

The power level decreases with increasing IGV number inside the cut-on range. In general higher vane numbers produce less noise. So the selection of a suitable vane number should be restricted of values higher 60. Our choice is 76 because of a small local valley there. A possible cut-off version should work with 30 vanes, but is not an option for further calculations. Second wake harmonics can be neglected for those high vane numbers.

4.2 Stator 1 vane number variation

Sound generation calculations are made for Stator 1 in the wake of R1, whereby the number of Stator 1 vanes varies between 62 and 116. The original vane number is at 92. Because of the variation of S1 vane number, each LIN3D calculation uses its own steady Euler solution.

Sound power levels versus vane numbers are presented in Figure 8. Without exception upstream travelling waves have a smaller PWL than the corresponding downstream waves. Both curves are separated by 4 dB at vane number 62 but 12.5 dB at vane number 110.

The Sound Power Level distribution of the upstream travelling wave shows a maximum at about 80 vanes, and a relative minimum at about 110 vanes. Based on this calculations a Stator 1 vane number of 110 is choosen.

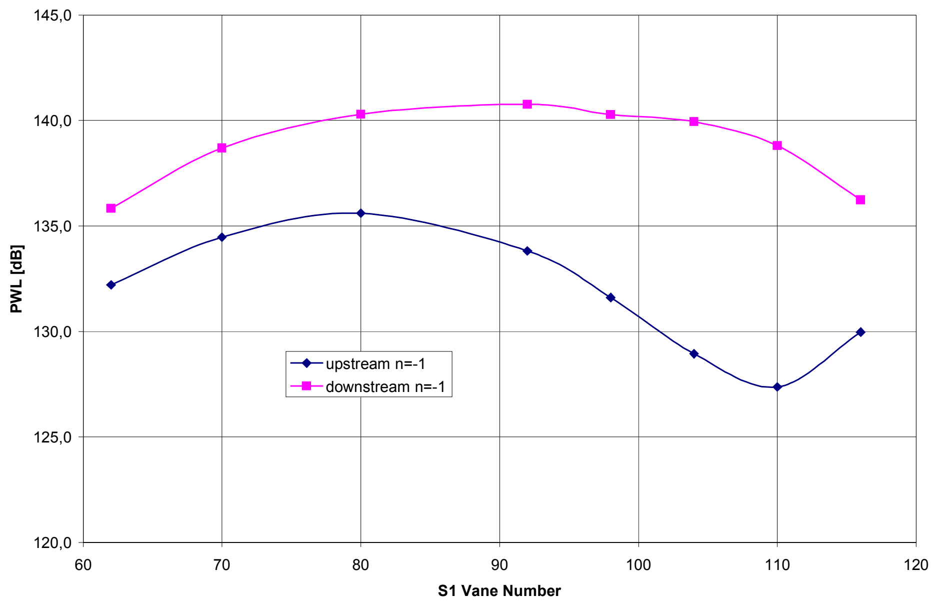


Figure 8. Sound Power Level upstream and downstream of Stator 1. The disturbances are first Rotor 1 wake harmonics.

4.3 Radial Stacking

4.3.1 Introduction

Lean, bow and sweep modifications are made on IGV and Stator 1 for noise generation calculations. In this chapter we focus on very small modifications of the optimized vane number option (76-67-110).

- In this study *Lean* means tangential lean that is in purely circumferential direction. Positive lean means the blade tip is bend against rotation direction, negative means the blade tip is bend in rotation direction. The lean is defined by an angle usually in degrees.
- *Bow* is defined by a shift value in meter and a relative position of the maximum shift. Only circumferential bow is used.

4.3.2 IGV Stacking - Lean

All modifications are defined against the original vane. The lean angle of the IGV varies from -7.5 degrees to 7.5 degrees.

Disturbances as a consequence of 3 lean angles are shown in Figure 9, where the inlet plane and parts of the of R1 blade is shown. A lean angle of -7.5 means that the radial phase distribution is nearly constant over the vane leading edge. Vanishing differences exist between the phase distributions in the inlet plane of the mesh and the plane of the leading edge of the blades.

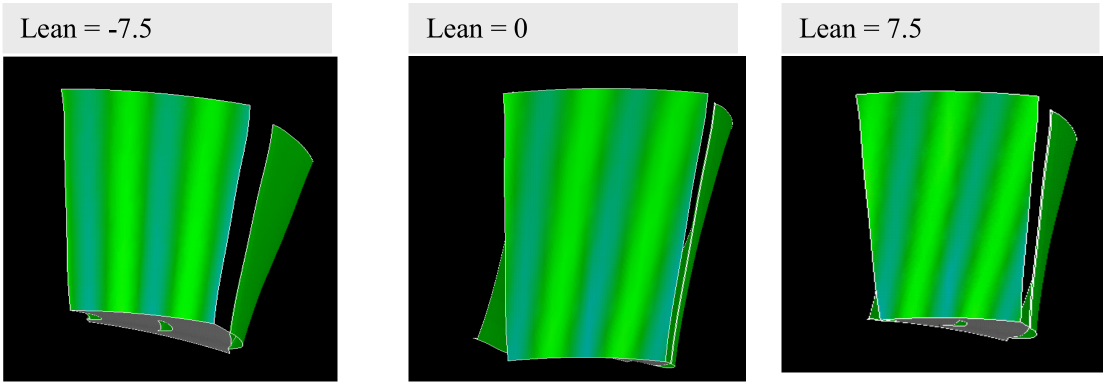


Figure 9. Visualization of the pressure fluctuation induced by the wake at the entrance of the grid of R1. The view is in downstream direction.

Results of the calculation are presented in Figure 10.

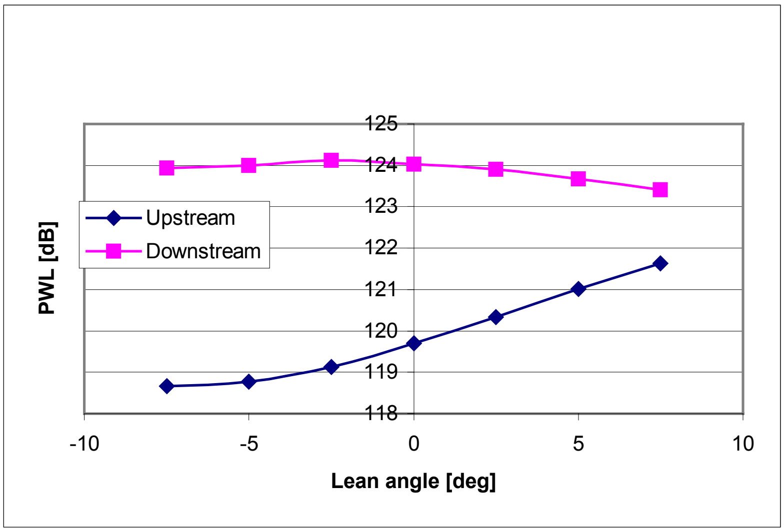


Figure 10. Sound power level for various IGV lean angles on the entrance and exit of R1.

Focusing on the upstream PWL, less lean means less noise. Positive lean means an increase of the PWL of the upstream wave and a decrease of the downstream wave PWL. Negative lean angles lead to a noise reduction on the upstream wave, for example 0.9 dB at -5 degrees, and a more or less constant Sound Power Level on the downstream wave. This result stands in opposition to the explanation that a phase change of the disturbance along the leading edge determines a noise reduction (please compare with Figure 9). A radial mode analysis is made to clarify this phenomenon (see Figure 11). The radial distribution of the wake (amplitude and phase) is used as an input. Output is the modal distribution for the first 6 modes. The disturbances at lean -7.5 has a dominating zero mode order while all mode orders for the 7.5 degrees case are of same order of magnitude.

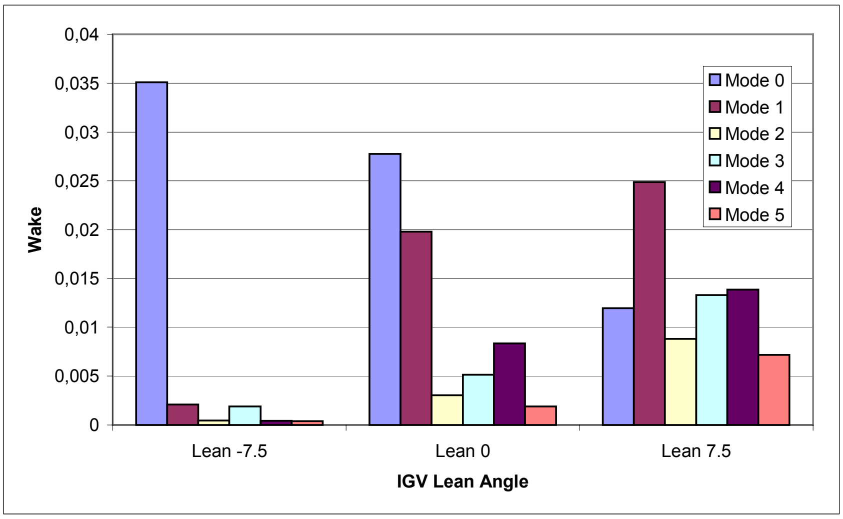


Figure 11. Results of the radial mode analyses of the pressure fluctuations for various lean angles, azimuthal mode order is -9.

4.3.3 IGV Stacking - Bow

Higher lean angles, which are not possible from the construction side, can be replaced by a degenerated bow. Degenerated means that the position of the maximum bow is either very near the hub or very near the tip. All calculations here are made with lean angles of -3 degrees, -3.7 degrees, 0 degrees. Calculations are made for various bow values up to 6.5 mm. The position of the maximum bow is an additional parameter to optimize the vane. A variation of the bow position is made from 0.01 up to 0.1 relative duct height with bow values 3 mm, 4 mm, and 5 mm for a lean angle of -3.7 degrees. Results of the calculation are shown in Figure 12 (upstream).

Maximum bow near the hub shows a similar result as maximum bow near the tip when using a bow in the opposite direction. Only the investigation with maximum bow near the hub is presented here. A minimum PWL exists at 3.8 mm bow for the relevant upstream case. The difference to the unbowed configuration is 0.3 dB

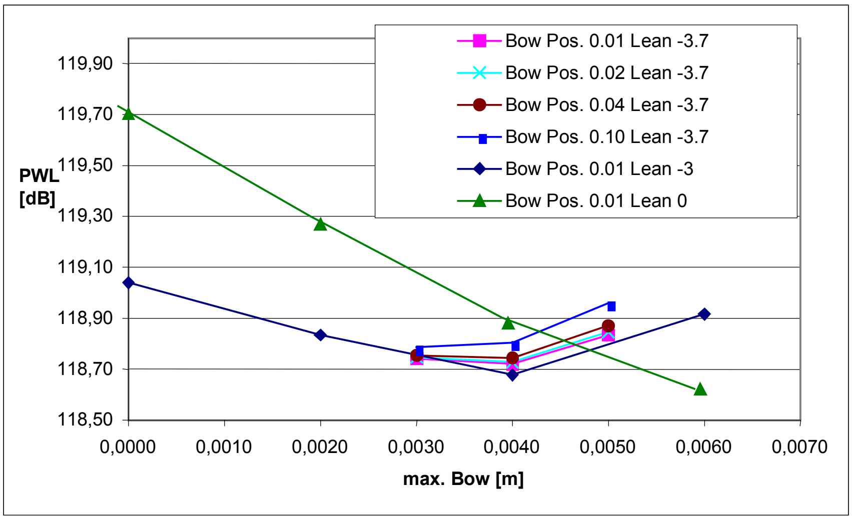


Figure 12. Sound power level upstream of R1 for various IGV bow values, max. bow positions, and lean values

4.3.4 *Conclusion IGV Stacking*

Downstream generated noise could be reduced by lean and bow. Here we focus on upstream noise because propagation calculations show this noise to be more relevant.

Using bow as a lean replacement, the maximum bow should be as near as possible at the hub. This could be concluded from the calculation results for max bow positions 0.01, 0.02, and 0.04.

Both lean and bow effects work in the same direction and one supports the other. With regards to limitations from mechanical design and aerodynamics our best (lowest PWL upstream) configuration would have:

4 mm bow at 1% duct height together with -3 degrees lean

In all cases effects of lean, bow, and sweep are small when compared to blade/vane number effects.

4.3.5 *Stator 1 Stacking – Lean*

Stacking modifications for Stator 1 are made with 110 vanes. There is of course no warranty that this chosen blade/vane number combination (76-67-110) is the best after the stacking modification. But as we know that the stacking influence is smaller on the acoustics than the blade/vane number influence, the optimum solution should not move too far away.

The original profile is already bowed, however referenced as zero bow and zero lean. The lean angle varies between -5 and 5 degrees. LIN3D calculation results are shown in Figure 13.

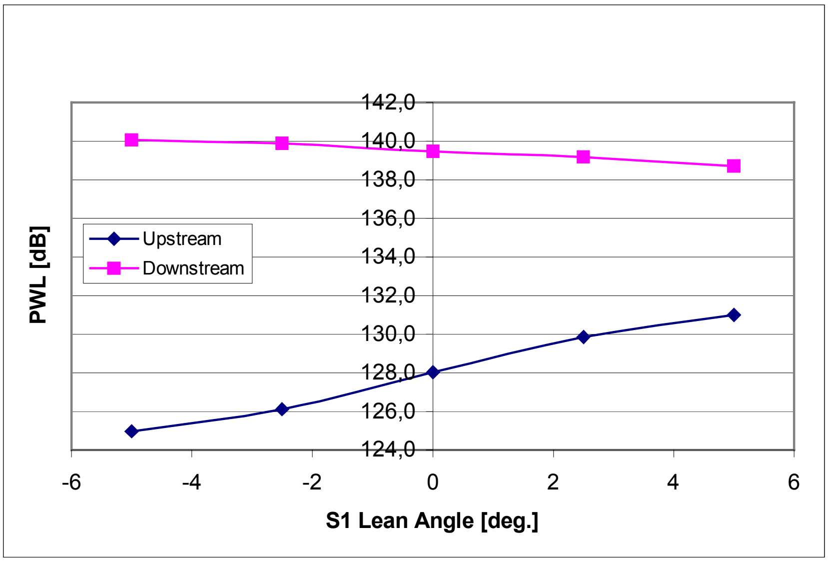


Figure 13. Stator 1 lean variation. Sound power levels of the upstream and downstream traveling wave

Positive lean reduces the Sound Power Level of the downstream traveling wave but increases the sound power of the upstream traveling wave and vice versa. The noise reduction upstream is 3 dB at a lean angle of -5 degrees.

4.3.6 Stator 1 Stacking – Bow

Bow studies are made for lean angles -6, -3, and 0 degrees systematically. Negative lean angles are chosen because of their noise reduction potential.

Upstream and downstream calculations show contrary results. Upstream minimum and downstream maximum exist for the same lean and bow. A Sound Power Level reduction of 3.5 dB could be found for the upstream wave at 3 mm bow and -3 degrees lean (Figure 14) where the downstream wave Sound Power Level is near its maximum.

When compared with the IGV lean/bow modifications, the influence of lean and bow on the PWL of S1 is much higher. A reason could be that the steady flow changed with every single S1 lean/bow modification. All the results presented here use a S1 vane with the position of the max bow at 0.01 duct height. Calculation with 0.04 duct height shows worse results.

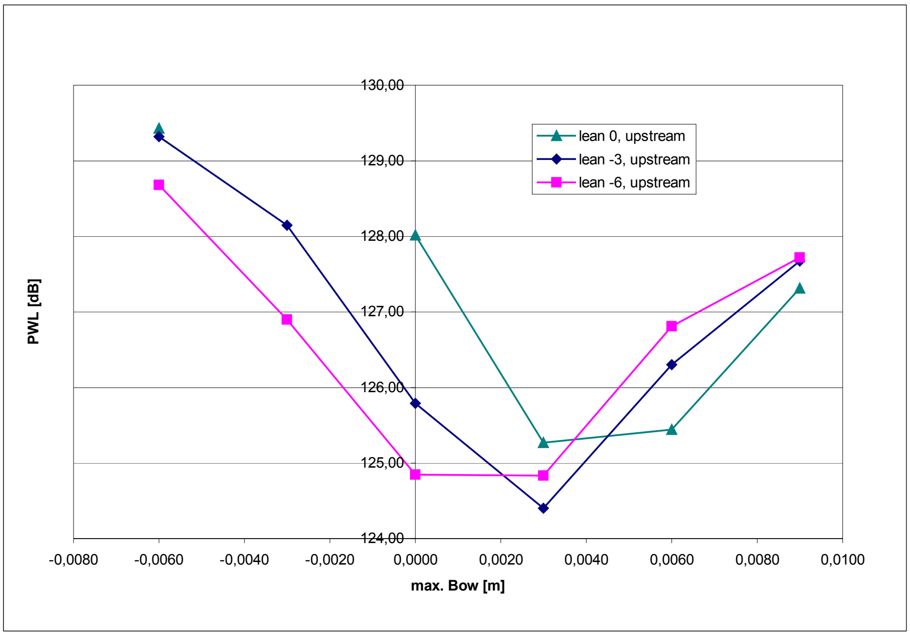


Figure 14. Stator 1 bow variation. Sound power level for the S1 upstream wave. Max. bow at 0.01 duct height

4.3.7 *Conclusion Stator 1 Stacking*

Lean and bow modifications have a total noise reduction potential of about 3.5 dB for the calculated S1 case. To achieve this, the parameters have to be selected as follows:

3 mm bow at 1% duct height together with -3 degrees lean.

4.4 Final Geometry Results

The parameters of the final IGV and Stator 1 are listed in Table 1. The lean and bow parameters are valid in MUTANT and relative to the original IGV profile.

	IGV	Stator 1
Vane number	76	110
Tangential lean	-3 degrees	-3 degrees
Tangential bow	0.004 m	0.003 m
Max. bow position	0.01	0.01
Sweep	-	-

Table 1. Final Geometry Parameters of IGV and Stator 1

Sound generation at R1 and S1 is compared in Figure 15. Differences between the results for the final and the original configuration are between 2.1 dB for the S1 downstream case and 15.4 dB for the most important R1 upstream case.

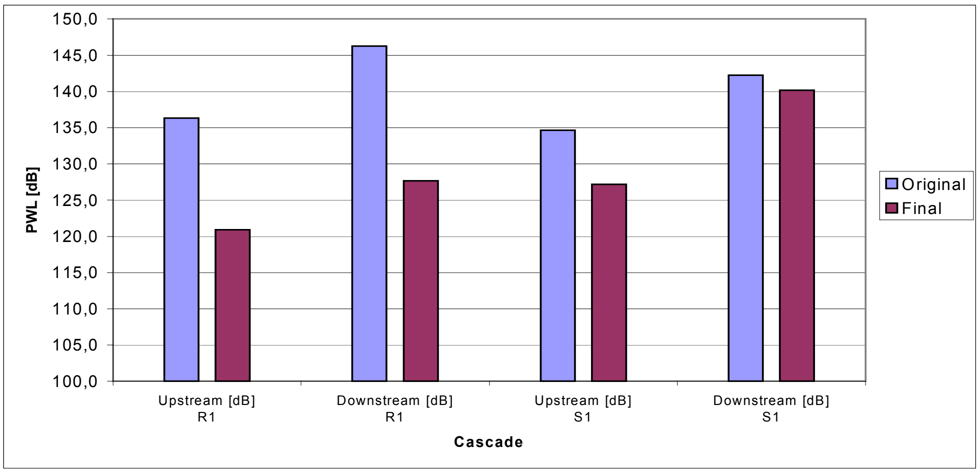


Figure 15. Comparison of Sound Power Levels generated at R1 and S1 for the original and the final configuration

Table 2 shows the results of the propagation calculation for the original and the final configuration respectively. Results are Sound Power Levels at the entrance of the IGV separated for different modes all with the same frequency. Blank positions indicate low values which have been neglected during the propagation calculation process.

		R1 PWL [dB]	R1 PWL [dB]	S1 PWL [dB]	S1 PWL [dB]	PWL [dB]
		Upstream	Downstream	Upstream	Downstream	Total
Original	Total	130,8	125,8	127,0	115,9	133,3
	Mode 1	129,2	124,2	126,9	115,8	
	Mode 2	125,7	120,7	107,9	96,8	
Final	Total	118,9	108,6	104,6	96,7	119,5
	Mode 1	118,9		103,9		
	Mode 2			96,5		

Table 2. Sound Power Levels as a result of the propagation calculation for both the original (40-67-92) and the final configuration (76-67-110).

The “Total” row contains the sum of the single modes while the “Total” column indicates the sum of power levels generated at R1 and S1. The total PWL of the original configuration is 133.3 dB, the PWL of the final configuration is 119.5 dB.

Totally for both cascades R1 and S1 and both wave directions upstream and downstream a noise reduction by 13.8 dB is calculated. The limiting part is the R1 upstream wave with 11.9 dB reduction, which is a consequence of the IGV vane number modification. Transmission losses for the R1 generated waves are more or less unchanged, thus noise reduction is at the sound generation process. In case of S1 generated noise, sound propagation is responsible for the noise reduction (22.4 dB), completed by a fraction due to the lean-bow modifications.

Figure 16 shows the portions which contribute to the total noise reduction. We differentiate between sound generation vane number effects on IGV and Rotor 1, lean+bow effects caused by stacking modifications on the IGV and Rotor 1, and effects from wave propagation through R1 and IGV. Summarizing these three portions to the value characterized by the final (optimized) configuration gives the original values.

The R1 noise reduction is based on a vane number effect at sound generation (13 dB). No reduction takes place because of lean-bow modifications or propagation effects. In contrary S1 sound is reduced because of sound propagation and, on a smaller scale, by S1 lean+bow for the more important upstream wave.

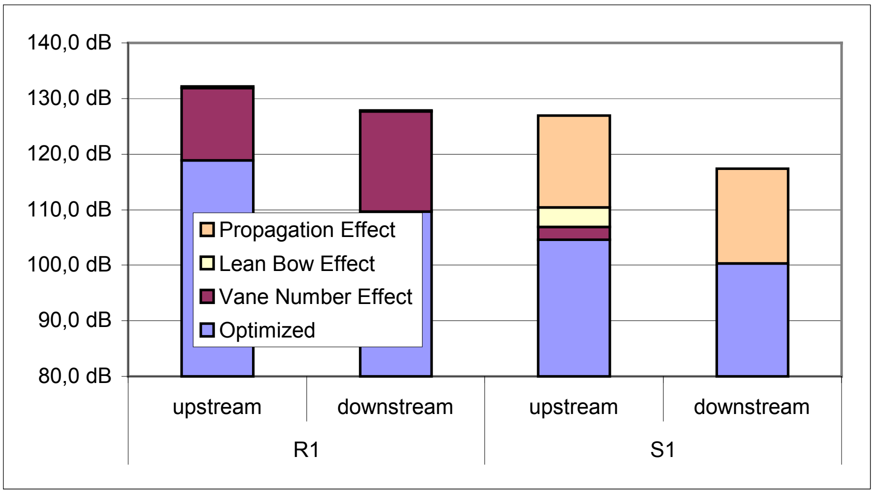


Figure 16. Reduction effects for the R1 and S1 generated noise.

5 CONCLUSION

Within the European 5th Framework research project *SILENCER*, a 3-stage compressor (model for a ultra high bypass ratio engine compressor) has been analyzed and successfully acoustically optimized with CFD/CAA methods.

This paper presents the concept of the numerical procedure for noise generation and propagation calculations with a linearized Euler-Code, the results of the acoustic analysis of the compressor, including the identification of the main noise sources, the concept for the optimization and the results of this optimization.

Noise generation and propagation within the compressor have been calculated using a unsteady linearized Euler code. The solution is based on steady Euler solution and unsteady disturbances. The interactions between neighbouring rows (wakes and pressure fields) are the considered noise generation mechanisms.

The noise generated at Rotor 1 and Stator 1, caused by the wake of the respective upstream grid, has been identified as the dominating source. Investigated parameters for potential noise reduction have been vane numbers, lean and bow of IGV and Stator 1. For the resulting configuration, the noise is reduced by 13.8 dB. In case of the noise generated at Rotor 1, the vane number is responsible for the reduction, in case of the noise generated at Stator 1, all measures participate in the reduction.

The noise of the optimized compressor will be measured within the SILENCER project and compared to the analytical predictions presented here. It is important to note, that this paper presents the prediction of noise reduction. It is not ment to predict absolute values.

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