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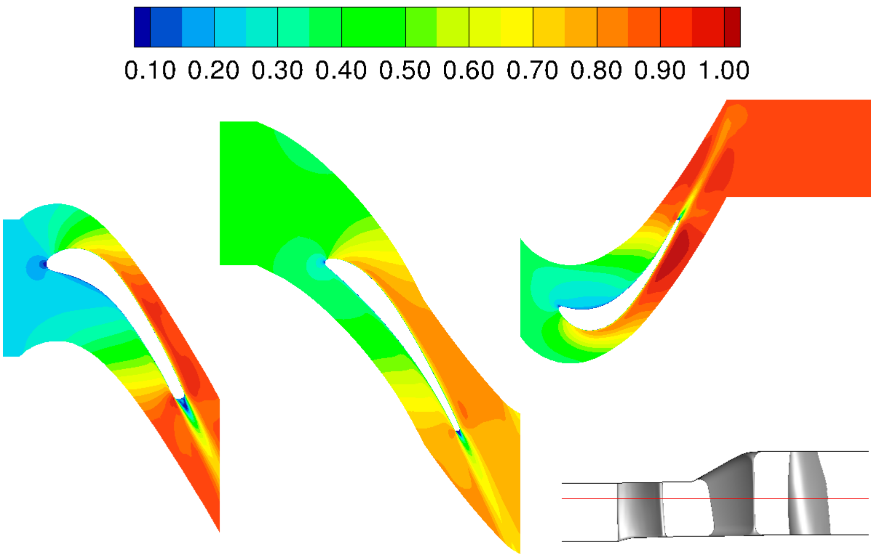
Executive summary

Engine performance prediction for varied low pressure turbine vane geometry utilizing test rig data and combined computational fluid dynamic and cycle models



Problem area
Engine performance is a result of the interaction between individual components. Any deviation from the design geometry does not only affect the flow locally, but can also lead to significantly altered whole engine performance. Specifically for Low Pressure Turbine (LPT) vanes, erosion and subsequent refurbishment can lead to considerable changes in geometry. Following vane refurbishment, the part's effective flow area may be measured and adjusted to meet turbine nozzle matching requirements for the engine build. Other parameters such as pressure loss and outlet flow angle are not evaluated, but rather assumed equivalent to a new part. Consequently, a large portion of vanes is rejected only after engine test, making it an expensive process.

Description of work
A new methodology is presented here that promises to reduce the cost of acceptance tests by predicting the performance of an engine with a refurbished vane. It follows a multi-fidelity approach involving experimental testing, zero-dimensional cycle modelling and three-dimensional

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Author(s)
M.P.C. van Rooij
O. Kogenhop
E.R. Rademaker
R. Woodason
B.I. Soemarwoto

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Knowledge area(s)
Computational Physics en theoretische aërodynamica
Gasturbinetechnologie
Computational Mechanics and Simulation Technology

Descriptor(s)
Gas Turbines
Turbine Vane
CFD (Computational Fluid Dynamics)
GSP (Gas turbine Simulation Program)

This report is based on a presentation held at the ASME Turbo Expo, Copenhagen (Denmark), June 15-18, 2012.

Computational Fluid Dynamics (CFD). Baseline performance maps of the LPT stage with varied vane geometries are generated using CFD. The obtained performance maps are incorporated into an engine cycle model. A multiple map feature for the cycle model was developed for this purpose. It enables accessing a plurality of stored maps representing a single LPT. Using performance parameters derived from test data of the isolated vane, a performance map is generated through interpolation of the baseline maps. The expected engine performance can now be readily predicted, and a well-founded decision on acceptance of the refurbished vane made.

Results and conclusions
The developed method makes it possible to readily predict the expected engine performance, allowing a well-founded decision on acceptance of the refurbished vane made.

Applicability
Once validated and extended, the method can be used for any manufactured or repaired blade of a gas turbine.

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

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Engine performance prediction for varied low pressure turbine vane geometry utilizing test rig data and combined computational fluid dynamic and cycle models

M.P.C. van Rooij, O. Kogenhop, E.R. Rademaker, R. Woodason[1] and B.I. Soemarwoto

[1] Standard Aero

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Date: 22/10/2012	Date: 22/10/2012	Date: 24/10/2012

Summary

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A new methodology is presented here that promises to reduce the cost of acceptance tests by predicting the performance of an engine with a refurbished vane. It follows a multi-fidelity approach involving experimental testing, zero-dimensional cycle modelling and three-dimensional Computational Fluid Dynamics (CFD).

Baseline performance maps of the LPT stage with varied vane geometries are generated using CFD. The obtained performance maps are incorporated into an engine cycle model. A multiple map feature for the cycle model was developed for this purpose. It enables accessing a plurality of stored maps representing a single LPT. Using performance parameters derived from test data of the isolated vane, a performance map is generated through interpolation of the baseline maps. The expected engine performance can now be readily predicted, and a well-founded decision on acceptance of the refurbished vane made.

Contents

Abbreviations

CFD	Computational Fluid Dynamics
EFA	Effective Flow Area
GSP	Gas turbine Simulation Program
HPT	High Pressure Turbine
LPT	Low Pressure Turbine
NV	New Vane
SFC	Specific Fuel Consumption
TW	Tweaked/modified vane

Symbols

P_0	absolute total pressure
α_θ	absolute circumferential flow angle
η_{ad}	adiabatic efficiency

1 Introduction

The performance of the turbine section in a gas turbine engine plays a major role in the overall efficiency of the engine. The turbine performance strongly depends on the profile losses, secondary losses and clearance (or leakage) losses of the nozzle guide vanes and rotor blades. Turbine blading suffer considerable erosion, cracking and distortion during engine operation. For un-cooled Low Pressure Turbine (LPT) vanes, refurbishment is a cost-effective means to restore mechanical integrity. However, depending on extent and specific location of damage as well as the refurbishment process, significant differences may remain between a refurbished and a new geometry. These may include changes in e.g. leading edge bluntness, stagger and profile thickness. Such geometric differences can lead to altered aero-performance of the vane and also affect engine performance.

Commonly, refurbished LPT vanes undergo acceptance tests before given clearance for engine operation. These consist of preliminary and full engine tests. Preliminary tests include geometric inspection, but also aerodynamic performance tests. In the latter, usually only flow capacity or effective flow area (EFA) is measured with an air-flow rig. After passing these preliminary tests, the vanes are built into an engine and a full engine test is performed. If engine test targets are not met, turbine vanes may be rejected or reworked, and the engine returned for test. The process is schematically shown in Figure 1.

Colantuoni et al. [1] presented an example of practical problems encountered while vane matching a turboshaft engine after overhaul. He reported engine test reject rates as high as 60 percent. Furthermore, it was observed that the status (new or used) of turbine components had an important effect on the engine test outcome. Whereas Colantuoni treated this effect using a qualitative variable in statistical models, the present work aims to develop more objective links. Because of the high cost of full engine tests, a substantial reduction in cost of the acceptance procedure can be obtained through improved discrimination between the repaired geometries in the preliminary test phase. This would involve a tool that can reliably predict engine performance based on preliminary acceptance tests. However, this should be achieved without much increase in complexity of preliminary testing, as this would decrease savings that are achieved through the reduced number of engine tests.

A new methodology is presented here that has been developed to predict changes in engine performance due to geometrical deviations in refurbished geometries. It follows a multi-fidelity approach involving experimental engine testing, zero-dimensional cycle modelling and three-dimensional Computational Fluid Dynamics (CFD). The ability of CFD to predict the effects of geometric variations of turbine vanes on aerodynamic performance, was demonstrated by Woodason [2], Woodason et al. [3] and Edwards et al. [4]. The objectives of these studies were to investigate experimentally the effect on pressure loss of the modification of a transonic turbine blade profile due to refurbishment, and assess the ability to quantitatively predict these effects using CFD. It was found that both the flow field and the trend of total pressure loss could be predicted accurately.

A schematic of the developed methodology is presented in Figure 2. The preliminary vane test will establish the aerodynamic performance of the refurbished vane, expressed in terms of one or more performance parameters. Besides the currently measured Effective Flow Area (EFA), these include e.g exit flow angle and total pressure loss at various spanwise positions. The precise definitions of the performance parameters defined during this research remain proprietary. Based on the parameter values, a set of baseline LPT performance maps is selected and interpolated to obtain a representative performance map. The baseline performance maps are established through CFD calculations. Thus, the performance parameters should capture the overall effect of a geometric variation on aerodynamic performance, allowing for the correct performance map for the cycle model to be selected. The purpose is not to identify a specific geometric variation based on the parameter values. Also, only the overall performance is of importance, not specific features in the flow field or geometry that lead to the measured performance.

With the obtained performance map, the expected engine performance is calculated using an engine cycle model in the gas turbine simulation software GSP [8]. A multiple map feature for GSP was developed for this purpose. Based on performance indicators such as fuel consumption, combustor exit temperature and/or turbine speeds, a decision is made to accept or reject the refurbished vane. Note that the baseline performance maps need to be generated only once, and that (time consuming) CFD calculations therefore are not part of the acceptance procedure in daily practice.

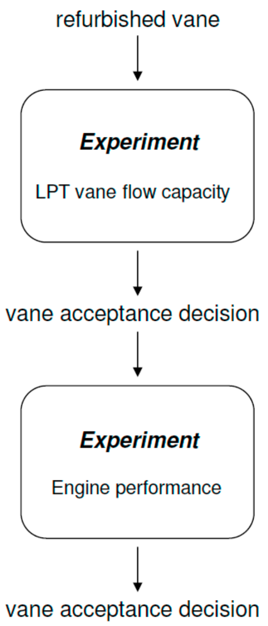

Figure 1 Schematic of current acceptance test procedure

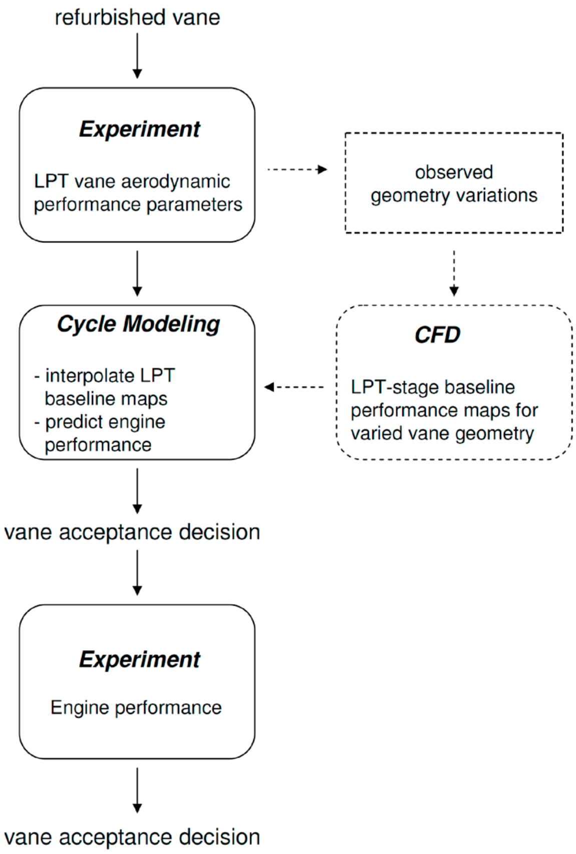

Figure 2 Schematic for newly developed acceptance test procedure involving enhanced preliminary testing and cycle modelling using performance maps created with CFD

The developed methodology is demonstrated here for a specific trailing edge modification to the geometry of an LPT vane. The LPT vane under consideration is part of an in-service turboshaft engine. A three-dimensional view of the LPT-stage together with the HPT-rotor is shown in Figure 3. The airfoil profiles selected for the present work represent the result of adjusting the part's flow capacity as is done in the current acceptance test procedure (Figure 1). One possible method is to mechanically rotate or tweak the aft end of the airfoil to increase or decrease the passage throat width, which is defined in Figure 4. The profile variation applied here is defined as a smooth departure from the nominal (new) geometry starting at approximately 70% chord, resulting in a deviation in metal angle of 3^{o} at the trailing edge as shown in Figure 5. The tweak is applied from 20% to 80% span, with gradual transition to zero tweak at the end walls. Hereafter, the nominal geometry will be referred to as "NV", the geometry with a reduction in trailing edge metal angle (increased throat) by "TW1", and the geometry with an increase in trailing edge metal angle (reduced throat) by "TW2".

Figure 7 shows the mass-averaged circumferential outflow angle of the three vane geometries. These results are from calculations performed for an isolated vane using the same inlet and exit conditions as exist in the EFA air flow rig. Values at mid span are -65.9^{o}, -64.1^{o} and -67.6^{o} for the NV, TW1 and TW2 geometries, respectively. The change in flow angle is in accordance with the change in metal angle. Near the hub, the change in flow angle is opposite to that in the core. This is partly a result of the end bends near the hub resulting from the trailing edge tweak (Figure 6). As stated above, a suitable performance parameter captures relevant overall effects of a geometric variation on aerodynamic performance. In reality, a combination of performance parameters would be used to describe the effect of the vane's geometric variation on its aerodynamic performance, involving values at several span locations. For the purpose of this demonstration, a simplified approach is followed and only the value of the outflow angle at midspan is used.

Although the methodology is demonstrated here for trailing edge modification only, it is applicable to arbitrary geometric variations such as changes in leading edge bluntness, stagger and profile thickness modifications, provided that appropriate performance parameters are defined. It can also be applied to blades other than the LPT vane, such as HPT and compressor blading.

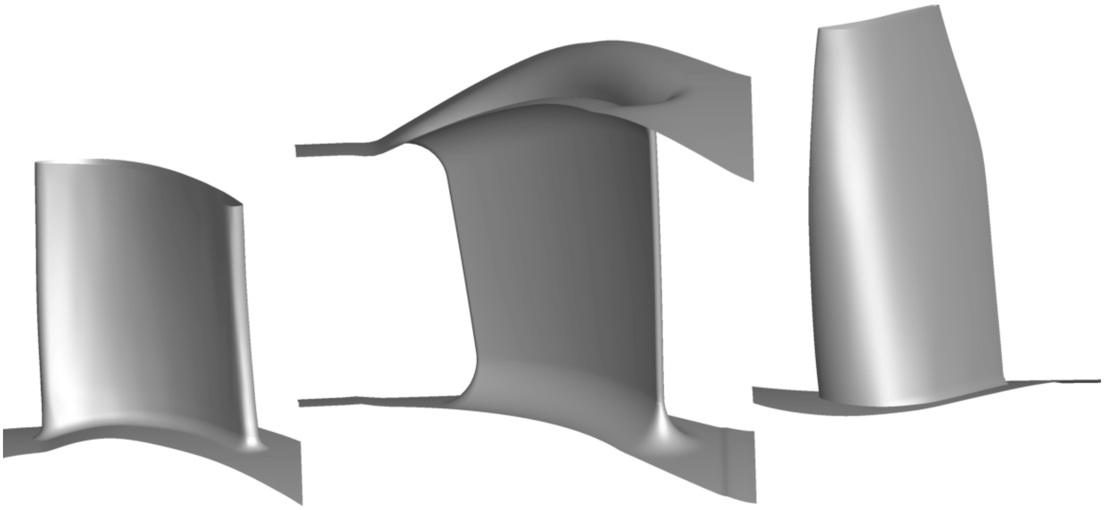

Figure 3 Three-dimensional view of HPT rotor blade, LPT vane and LPT rotor blade

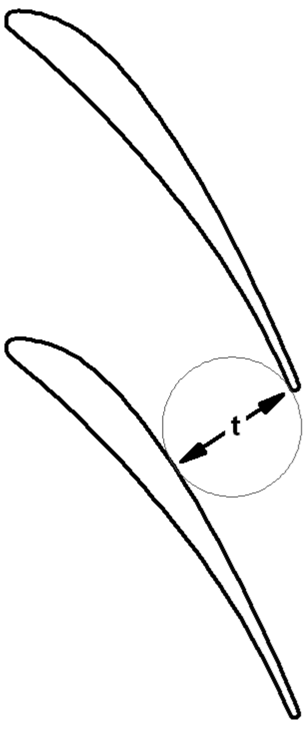

Figure 4 Vane passage throat width t may be adjusted by mechanically rotating aft end of airfoil

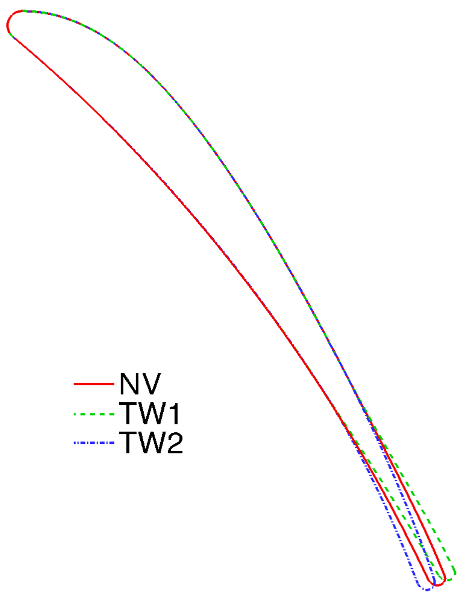

Figure 5 LPT vane midspan section. Original or new geometry (NV), trailing edge bending of +3^o^ (TW1) and trailing edge bending of -3^o^ (TW2)

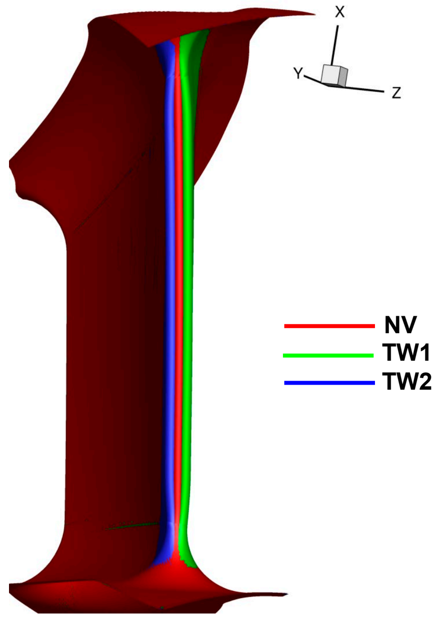

Figure 6 Trailing edge view of vane geometries NV, TW1 and TW2

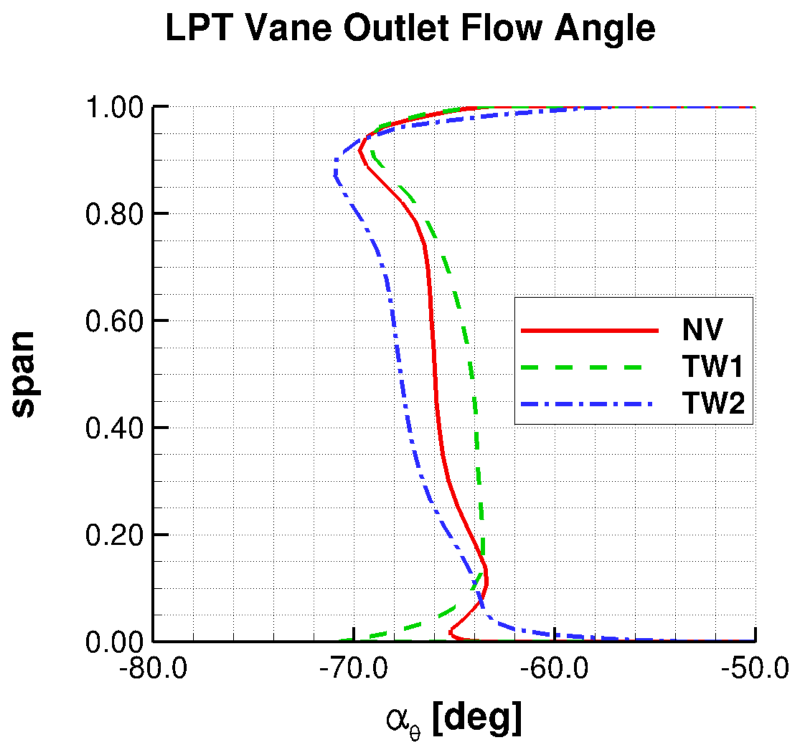

Figure 7 Vane outlet circumferential flow angle distribution for the vane geometries shown in figures 5 and 6

2 Description of methodology

2.1 Engine cycle modelling

NLR's primary tool for gas turbine engine performance analysis is the 'Gas turbine Simulation Program' (GSP[1]), a component based modelling environment. GSP's flexible object-oriented architecture allows steady-state and transient simulation of virtually any gas turbine configuration using a user-friendly 'drag and drop' interface with on-line help running under the Microsoft® Windows operating system.

GSP has been used for a variety of applications such as various types of off-design performance analysis, emission calculations, control system design and diagnostics of both aircraft and industrial gas turbines. More advanced applications include analysis of recuperated turboshaft engine performance, lift-fan STOVL propulsion systems, control logic validation and analysis of thermal load calculation for hot section life consumption modelling. Visser et al. [8] describe GSP's object-oriented architecture, which consists of a structured class hierarchy corresponding to a certain component modelling approach. The class structure allows for rapid development of new components. During off-design analyses, the performance of the gas turbine is calculated by solving a set of non-linear differential equations using off-design characteristic maps for compressors and turbines.

In this research a 'multi-map' turbine component is derived from the generic turbine component (or class). The difference between the multi-map turbine component and the generic turbine component can be explained by obtaining the component's off-design map values for the turbine; i.e. instead of a single map, multiple maps are available. Selecting the correct turbine map, or interpolation between two maps, is controlled by an extra 'effect' parameter that describes the turbine 'defect' or change with respect to the original design. Here, this is the LPT vane outlet flow angle at midspan.

A reference cycle model of the turboshaft engine is constructed from basic gas turbine components. The performance of each component is estimated from engine test measurements; and off-design analysis is accomplished using scaled map data. This reference model excludes the low pressure turbine, which is the subject of interest. Using the structured engine model data

[1] Download a free evaluation copy from www.gspteam.com

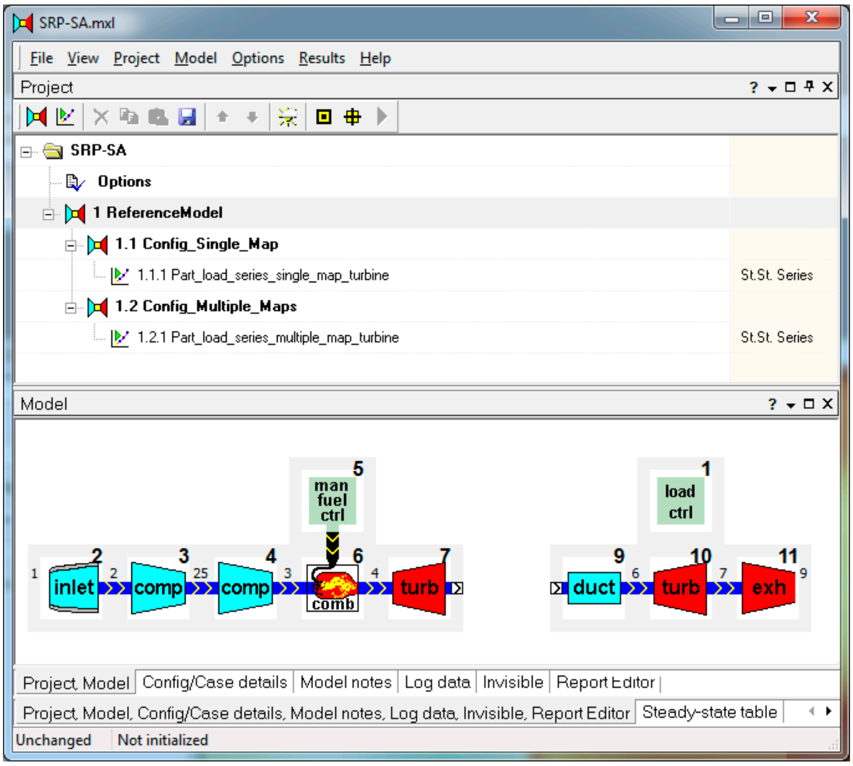

Figure 8 Screenshot of the engine simulation project showing the reference model

management features of GSP, the single map (standard) turbine component and the new multiple map turbine components are added in separate model configurations inheriting the parent reference model. Figure 8 gives a depiction of the simulation project with active reference model configuration.

2.2 CFD

CFD calculations are performed to calculate baseline performance maps of the LPT-stage. This is done for three LPT stator vane variations, and three different rotor speeds. The vane geometries are shown in Figures 5 and 6. The rotational speeds of the HPT and LPT rotors were derived from a total of 161 full engine tests at full power and with both new and refurbished LPT vanes with various geometric variations. The HPT speed was found to vary between 98.2% and 102.5% nominal speed, and the LPT between 98.3% and 101.3%.

The GSP cycle model provides the total and static conditions and mass flow at various stations throughout the engine. However, for CFD boundary conditions the flow angles are also required. These were obtained from a separate CFD calculation that included the HPT rotor. For this calculation, the HPT inlet values for total pressure and total temperature, as predicted by GSP, were prescribed at the inlet of the HPT rotor. The inlet circumferential flow angle was deduced from geometric investigation of the HPT stator blade, defining the blade angle. These inflow boundary conditions thus neglect total pressure losses and deviation in the HPT stator row. However, these errors are believed to be small and allowable for the purpose of this calculation, which is to establish averaged inlet conditions for the LPT stage. Moreover, the LPT calculations themselves will be used to establish relative changes to the LPT performance resulting from varied stator geometry.

The computational grids were generated using ENGRID [5] , an in-house mesh generator of NLR. In order to reduce the computational effort, the hub and shroud contours have been adjusted slightly in order to cover the end wall gaps between the rows with a smooth transition curve. The size of grid cells near solid walls resulted in an average Y^+-value in near-wall cells of 0.93. A meridional view of the computational domain is shown in Figure 9. The interface location between the HPT rotor and the LPT stator is also indicated.

Calculations were performed with NUMECA FINE/Turbo v8.73 [6] . The second order central difference scheme was used, with the Spalart-Allmaras model [7] for turbulence closure. Real gas effects in terms of temperature-dependent heat coefficients C_p and C_v were incorporated in the numerical model.

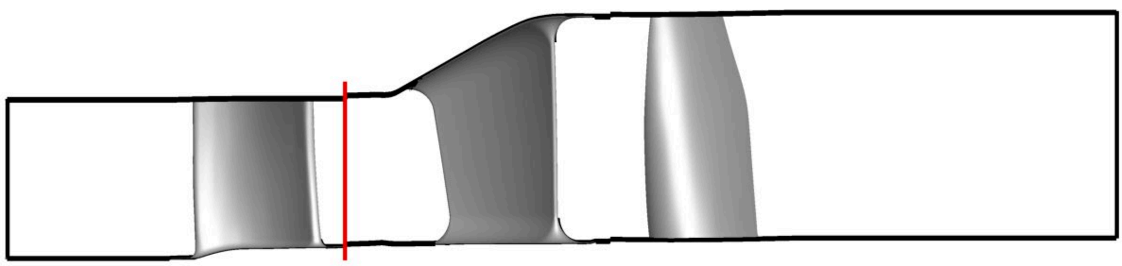

Figure 9 Meridional view of the computational domain. The interface location between HPT rotor blade and LPT vane is indicated by the red line

3 Results

3.1 CFD

The calculation of the combined HPT-rotor/LPT-stage was performed with the nominal HPT and LPT rotor speeds. The resulting flow field is shown in Figure 10, in terms of contours of relative Mach number at approximately 50% span of the LPT stator. It can be seen that the maximum Mach number around the stator is approximately 0.80. The highest Mach numbers exist in the LPT rotor, which is nearly completely choked at this operating point.

The total pressure and temperature, as well as the radial and circumferential flow angles were mass-averaged at the HPT-rotor/LPT-stator interface (Figure 9). The resulting values were prescribed as inlet conditions for the following LPT-stage calculations. These were performed with the nominal rotor speed, as well as the maximum and minimum values observed during engine tests (98.3% and 101.3% nominal speed). The back pressure was varied to cover a large portion of the speed line from choke, past the maximum efficiency point until approximately 80% choke flow. The obtained performance maps are shown in Figure 11. The vane trailing edge modification results in a different outflow angle and thus a different (relative) inflow angle into the rotor. As can be expected, this leads to a shift in mass flow. The observed difference in mass flow is 4%, comparing the new vane (NV) to either modified vane geometry (TW1 and TW2). A slight reduction in maximum efficiency is also observed. The rotational speed has a negligible effect on the mass flow, and only a small effect on the efficiency except at low mass flow.

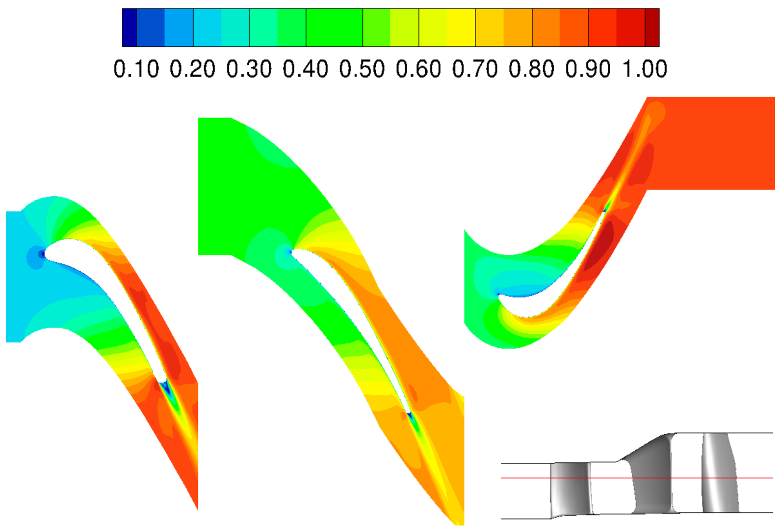

Figure 10 Computed flow field in terms of relative Mach number of HPT rotor and LPT stage with NV vane. The radial position of the blade-to-blade slice is indicated in the lower right corner. Parts of inlet and exit region not shown

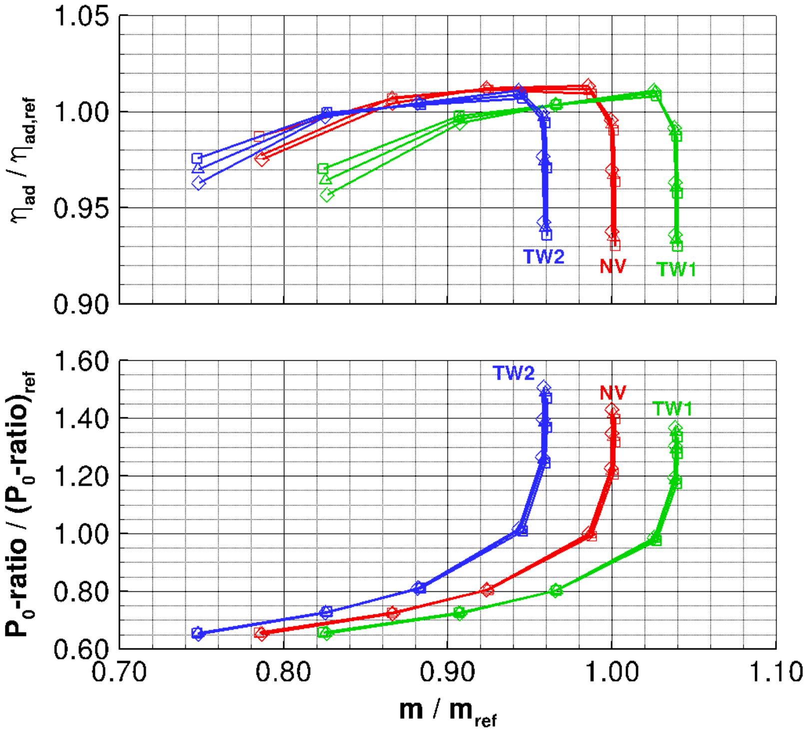

Figure 11 Computed performance maps for the LPT-stage with varied stator geometry (Figure 5, 6) and rotor rotational speed. Top: adiabatic efficiency; bottom: total pressure ratio. Rotor speeds: □ 98.3%, △ 100%, ◊ 101.3%

3.2 Engine cycle modelling

The LPT performance data obtained from CFD is converted into a turbine map with the commercially available program SmoothT [9] for both the modified vane geometries. When these maps are inserted into the turbine multiple-map component, the GSP model is ready for simulation. Figure 12 shows a screenshot of the map data input window. The simulation itself consists of a couple of steady state operating point series calculations for a decreasing shaft load demand. First, the model with a single (nominal) LPT map is run to set a baseline for the NV case. Second, a series of steady state operating points is calculated for the configuration containing the multiple map component for the NV geometry. The results of these simulations are plotted in Figure 13, where the solid (black) line denotes the single map NV configuration and the dashed (red) line denotes the multiple map NV configuration. The results clearly show the two lines coinciding, confirming that the new multiple map component works properly.

Next, the series of steady state operating points for the TW1 and TW2 geometries are calculated. The results of these calculations are also depicted in Figure 13; the single dotted and dashed (green) line denotes the TW1 geometry and the long-dashed (blue) line denotes the TW2 geometry. The results for the geometry with a reduction in trailing edge metal angle (TW1) show that the specific fuel consumption (SFC) and combustor exit temperature increase, while the geometry with an increase in trailing edge metal angle (TW2) leads to a decrease in SFC and combustor exit temperature with respect to the nominal geometry (NV).

A comparison of theoretical (based on correlations given in the engine hand book) and predicted engine performance change due to replacement of the NV with the TW2 vane geometry is given in Table 1. The performance change is provided in terms of LPT speed and fuel flow. The change in performance is accurately predicted.

The cycle model and the multiple map tool are now ready to be used in the new acceptance procedure (Figure 2), which in case of this demonstration would be as follows: during vane assessment on the EFA airflow rig, the exit flow angle is measured. This value is put into the cycle model in GSP, with which the proper LPT turbine map is created through interpolation of the available maps. The engine performance at full power is then calculated. As an example, simulations were run for a reduced flow angle of –65.0°. The cycle performance is calculated by interpolation of the TW1 and NV maps. The results are plotted in Figure 13 as the double dotted and dashed (orange) line.

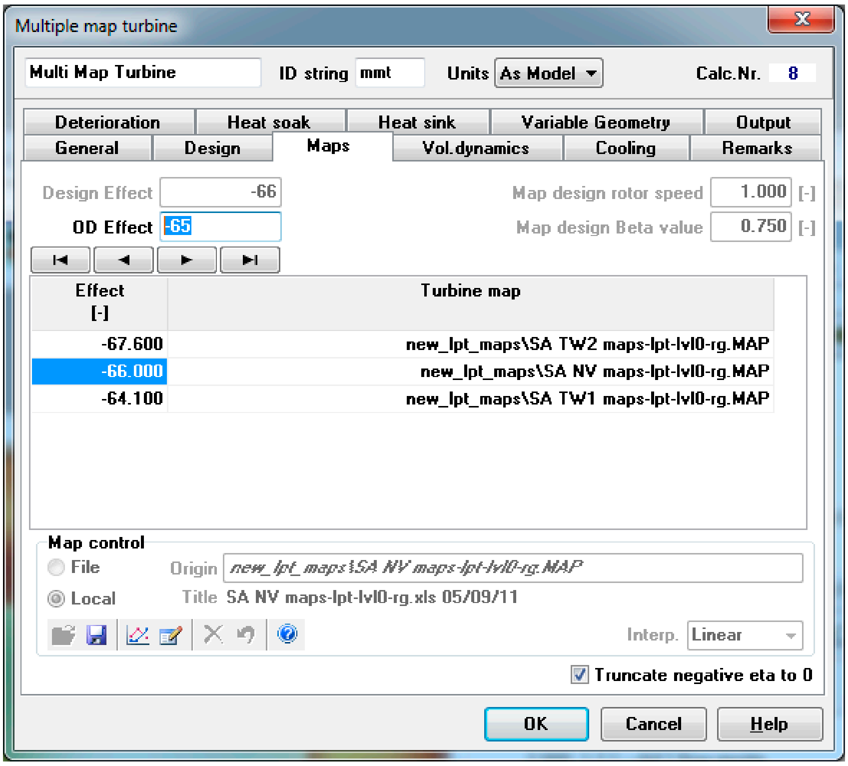

Figure 12   Screenshot of the maps input data window of the multiple map component

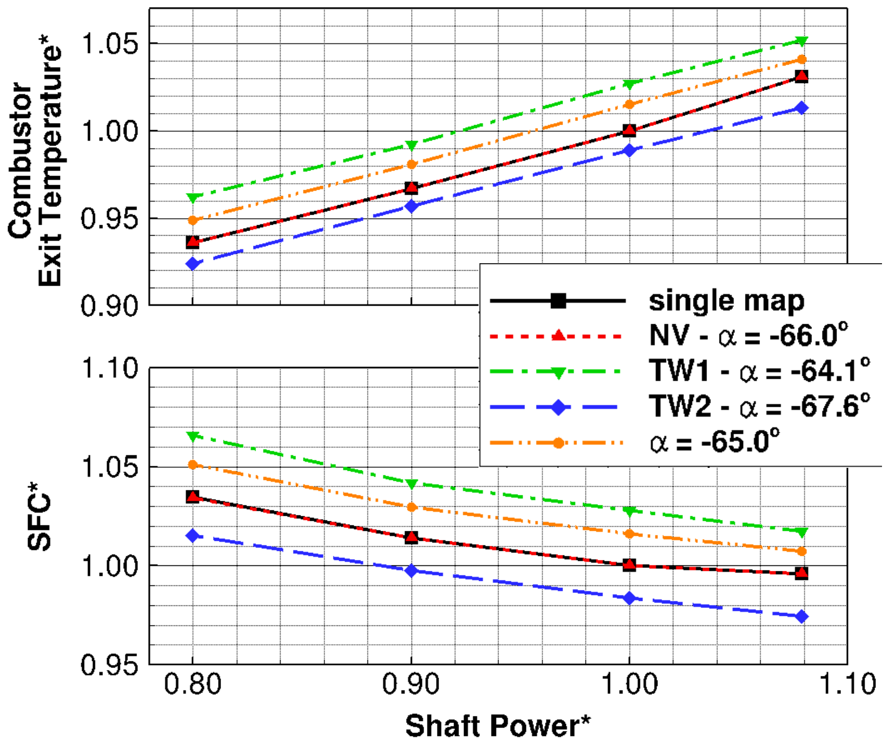

Figure 13 Combustor exit temperature and specific fuel consumption as function of delivered shaft power (normalized values).

Table 1 Predicted (cycle model) and theoretical changes in performance resulting from LPT vane geometry change NV to TW2.

	Theory	GSP Prediction
LPT speed	+2.7 %	+2.6 %
Fuel flow	-1.9 %	-2.2 %

4 Conclusions

A new methodology is presented here that has been developed to improve the acceptance test procedure of refurbished LPT vanes by predicting engine performance. It follows a multi-fidelity approach involving experimental engine testing, zero-dimensional cycle modelling and three-dimensional CFD. Using this methodology, it is expected that acceptance test costs of refurbished engine parts can be reduced substantially.

The developed methodology was demonstrated for modified trailing edge geometries of an LPT vane. Baseline performance maps of the LPT stage are generated using CFD calculations. The obtained performance maps are incorporated into an engine cycle model in the gas turbine simulation software GSP. A multiple map feature for GSP was developed for this purpose. Using the cycle model and parameters derived from test data, expected engine performance can readily be predicted. Based on calculated performance parameters such as fuel consumption, combustor exit temperature and/or turbine speeds, a well-founded decision can be made to accept or reject the refurbished vane.

Although demonstrated here for vane trailing edge modification, the methodology can be applied to arbitrary geometric variations such as changes in leading edge bluntness, stagger and profile thickness modifications, and combinations thereof. This requires definition of appropriate performance parameters that describe the effect of a geometric variation on aerodynamic performance, and allow selection of the correct performance map for the cycle model based aerodynamic test data of the isolated vane. It can also be applied to blades other than the LPT vane, such as HPT and compressor blading.

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