International Journal of Rotating Machinery
2001, Vol. 7, No. 5, pp. 365–374
Reprints available directly from the publisher
Photocopying permitted by license only

Recontouring of Jet Engine Compressor Blades by Flow Simulation

HERWART HÖNEN[a,*] and MATTHIAS PANTEN[b]

[a]*Aachen University of Technology, Aachen, Germany;* [b]*Lufthansa Technik AG, Hamburg, Germany*

(Received 30 May 2000; In final form 31 May 2000)

In modern jet propulsion systems the core engine has an essential influence on the total engine performance. Especially the high pressure compressor plays an important role in this scheme. Substantial factors here are losses due to tip clearance effects and aerodynamic airfoil quality. During flight operation the airfoils are subject to wear and tear on the leading edge. These effects cause a shortening of the chord length and the leading edge profiles become deformed. This results in a deterioration of the engine efficiency performance level and a reduced stall margin.

The paper deals with the re-contouring of the leading edges of compressor airfoils by application of a new developed method for the profile definition. The common procedure of smoothing out the leading edges manually on a wheel grinding machine can not provide a defined contour nor a reproducible result of the overhaul process. In order to achieve optimized flow conditions in the compressor blade rows, suitable leading edge contours have to be defined for the worn airfoils. In an iterative process the flow behavior of these redesigned profiles is checked by numerical flow simulations and the shape of the profiles is improved. The following machining of the new defined leading edge contours is achieved on a grinding station handled by an appropriately programmed robot.

Keywords: Blade re-contouring; Airfoil wear; Engine overhaul; Leading edge erosion; Flow simulation

INTRODUCTION

Due to erosion effects the compressor blades of jet engines become shortened and the leading edges are deformed. These deformations influence the flow behavior in the rotor blade passages. The operating range becomes smaller and the aerodynamic losses are increased. For a JT8D jet engine detailed investigations have been performed by Roberts (1984). With increasing wear of the compressor blades the usable angle range decreases. The suction side separation occurs at lower incidence angles. Thus, the operating range of the whole compressor becomes limited. In

---

[*] Corresponding author. Tel.: +49(0)241 80 5522, Fax: +49(0)241 8888-229, e-mail: honen@1st.rwth-aachen.de

addition, the aerodynamic losses are increased due to separation bubbles at the leading edge.

By a suitable refurbishment procedure worn blades could be made available for additional running cycles. The aim of this process is to produce a high profile quality in order to provide optimal flow conditions. By the today's state of the art method of rounding the worn leading edges manually either defined contours nor reproducible results are obtainable. This results in a wide spread of overhaul quality and partly to increased losses compared with the original blade. Especially for the application of manually smoothed blades with significantly reduced chord length considerable performance losses in the compressor have been observed. In order to keep the compressor performance in a tolerable range in many cases a minimum chord length has been defined by the user. So, even if the structure limit, defined by the jet engine manufacturer, is not yet reached these blades have to be rejected. This causes additional costs for new parts.

This demonstrates that a defined machining of the leading edges for optimal flow conditions in the bladings is required. Therefore, a new method for the refurbishment of compressor blades, the "Advanced Recontouring Process" (ARP), has been developed. This process is based on detailed studies of blade wear and the resulting flow behavior in the rotor blade rows of the high pressure compressor of a CF6-50 turbofan engine. The aim is the definition of an optimized leading edge geometry for worn compressor blades with respect to a high aerodynamic quality and a reproducible machining of the profiles.

DEFINITION OF REFERENCE DATA

The aim of the ARP is the production of recontoured blades with an aerodynamic behavior similar to the original design conditions of the compressor. The justification of the quality of the refurbished airfoils had to be based on the design data of the jet engine manufacturer. In order to provide a suitable information about the flow conditions at each step of the ARP, a Navier–Stokes code was applied. A description of program structure and its application is given by Benetschik (1993). In a first step the flow calculations with this code were performed using the original profile coordinates and the design flow data provided by the jet engine manufacturer. With these data a parameter study has been carried out to verify and to optimize the numerical results.

For the planned flow calculations a good resolution of the profile leading edges was required. Therefore, an *O*-grid configuration with 33 × 101 grid points has been chosen (Fig. 1). With this grid type contour fitted elements especially in regions with small curve radii can be achieved so that numerical failures caused by influences of the grid can be minimized. In order to achieve a high resolution in the boundary layer region the grid density was increased close to the profile.

Figure 2 shows a calculation result for the design conditions of a 5th stage rotor blade. The flow calculations for this case were performed with the target to reproduce the design flow data of the jet engine manufacturer (flow angles, pressure rise, Mach No.'s) in order to calibrate the numerical code. These simulations have been performed for each rotor blade row. The final results of these were stored in a data base as a reference case for the later justification of the later ARP results. In the following the optimized program parameters found for each blade row were applied to the calculations of the corresponding worn and redesigned blades.

CONTOURS AND CLASSIFICATION OF WORN AIRFOILS

For the rotor blades of the high pressure compressor of a CF6-50 jet engine numerous worn blades of the rotors of the stages 2 to 14 have been inspected. The measurements demonstrated different types of leading edge contours. Figure 3 shows

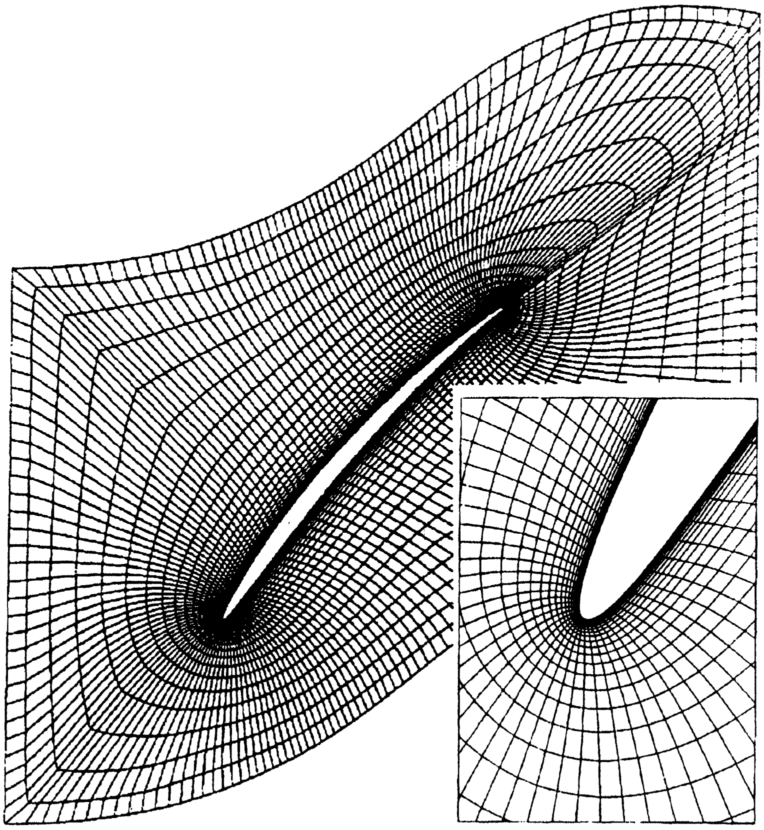


FIGURE 1 Numerical grid for the flow calculations (small picture: zoomed leading edge region).

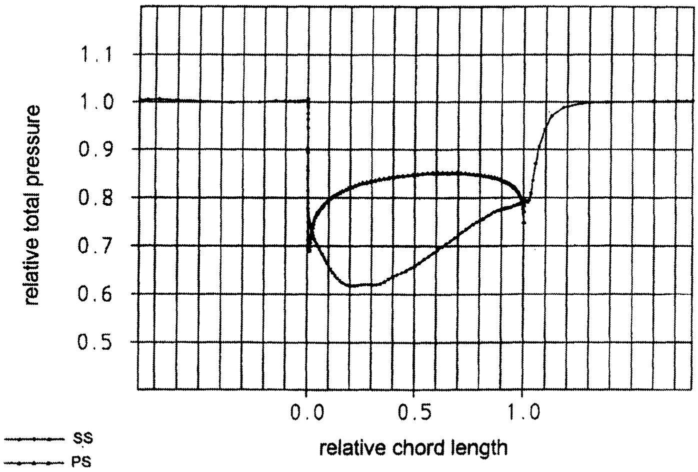


FIGURE 2 Pressure distribution of a new part profile (5th stage).

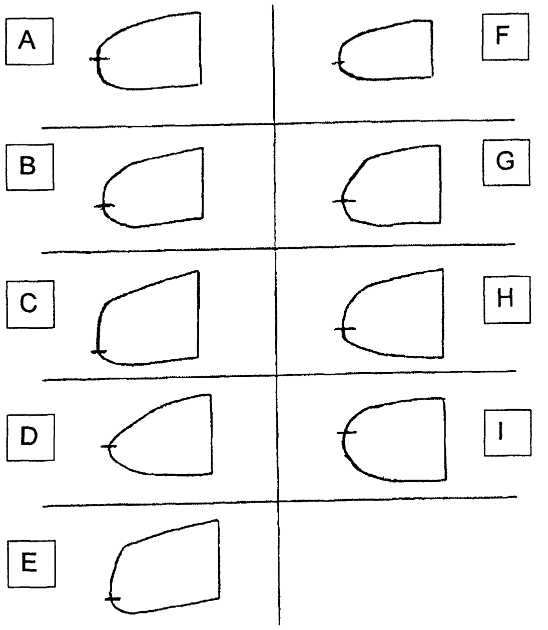


FIGURE 3 Variety of leading edge contours of worn airfoils (5th stage).

the variety of abrasion profiles for the 5th stage caused by different operating and flow conditions. The leading edges of the worn airfoils in some cases look nearly cut away or are unsymmetrically deformed. The point of maximum extension at the leading edge is marked in the drawings. In all cases the stagnation point is shifted from its original location. From these investigations 9 different classes for the leading edge profiles could be defined (see Fig. 3).

A comparison of the calculated vector plots of a 10th stage new part profile and a profile with deformed leading edge demonstrates the significant change in the flow distribution around the leading edge (Fig. 4). In this case the stagnation point of the worn blade (right plot) can be classified with form "A" (see Fig. 3). The flattened leading edge causes a large stagnation zone. A strong acceleration to both sides of the profile follows. This leads to a separation bubble on the pressure side.

In addition, the investigation of the rotor blades of all stages showed that the thickness differs in a wide range. Due to deviations of the new part blades and the erosion during operation differences of up to ± 0.3 mm in comparison with the design value could be detected.

One main reason for the different types of erosion was found in the profile quality of the original airfoil. Recycled blades with manually

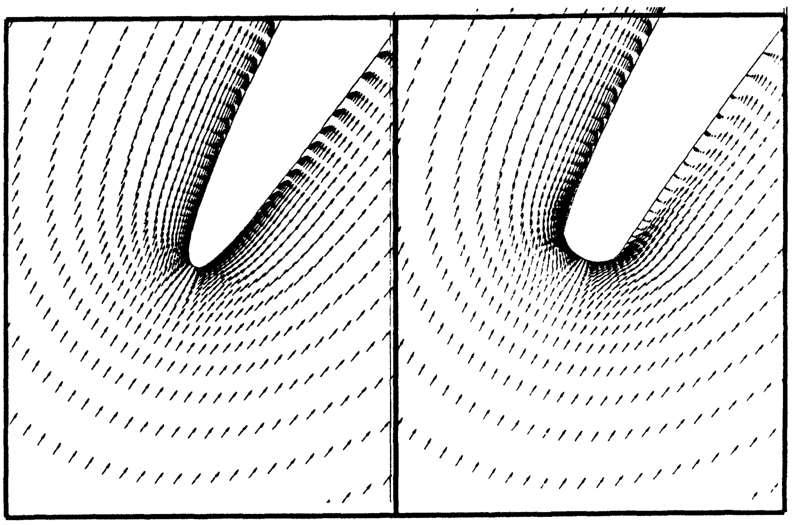


FIGURE 4 Comparison of the vector plots for a new part (left) and a worn (right) rotor blade.

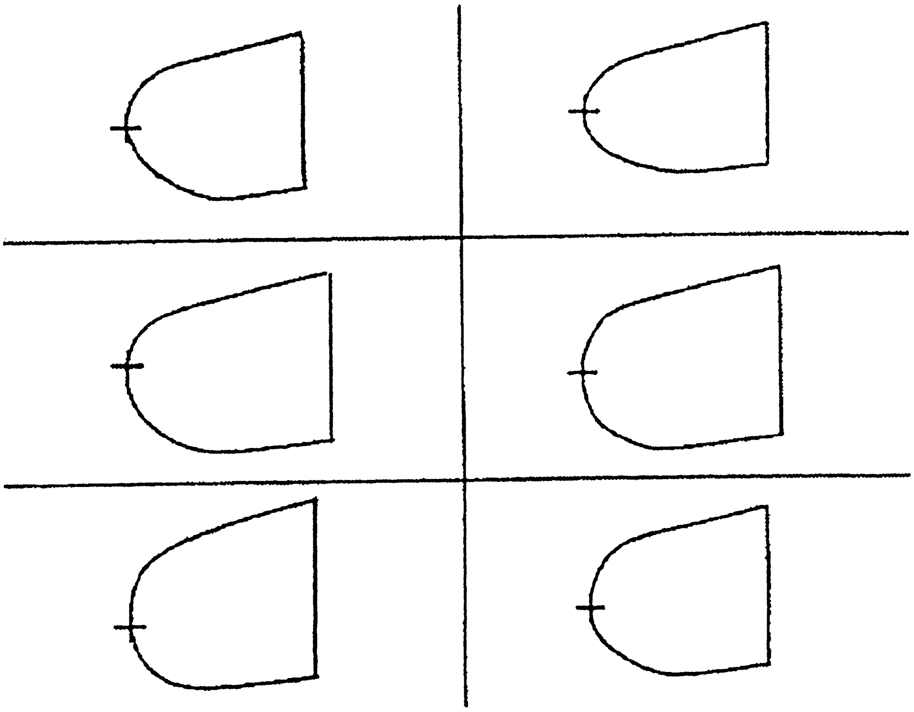


FIGURE 5 Different leading edge shapes of manually smoothed blades.

smoothed contours show a large variation range regarding the geometry (Fig. 5). This partly results in unsatisfactory flow behavior in the leading edge region due to the position of the stagnation point and the following acceleration towards the suction side and pressure side surfaces. In these regions the erosion increases due to the high impulses of the dust particles (see Fig. 4). Therefore, an optimized re-contouring quality not only provides low aerodynamic losses but also longer life times of the profiles.

In order to obtain the highest quality in re-contouring results the redesigning process for the leading edges would have to be performed individually for each blade. This would require an enormous effort regarding the numerical flow simulations, the programming of the robot grinding station, and the handling of the blades. Therefore, numerical parameter studies have been carried out to investigate the influence of the deviations of the blade thickness on the flow behavior. The aim of these studies was to define only a few geometry classes for each blade row which can be characterized by one typical profile each. It was found that for most of the stages two classes are sufficient for reliable re-contouring results.

DEFINITION OF NEW LEADING EDGE CONTOURS

The most significant part of leading edge erosion has been detected at radii above mid-span with increasing deformation with approach to the blade tip. Since the effects of blade erosion are primarily seen on the outer one-third of the span (near the tip), a characteristic radius for the robot was chosen at 90% blade height. This also greatly reduced the redesign programming effort.

The definition of new leading edge contours for the worn airfoils is based on the design flow data provided by the engine manufacturer. In order to produce re-contoured blades with a flow behavior similar to the new part blades the following parameters have been defined for comparison with the design conditions:

- pressure rise of the blade row
- turning angle
- Mach No. Distribution
- lift

Additionally, the loss production of the blade row is an important parameter. The efficiency and performance of the redesigned airfoils should be kept close to the new part profiles.

These parameters can be checked applying the design flow conditions of the different stages to the redesigned airfoils. Under optimum conditions the above mentioned results meet the reference stored in the data base of the new part profiles exactly. In order to validate the off design behavior (*i.e.*, take off conditions), the usable incidence angle range of the re-designed profiles also had to be proved.

In a parameter study the applicability of different geometric shapes for the replacement of the deformed leading edges were investigated. Suitable geometry shapes are circles, ellipses, parabola, and hyperbolas. In order to provide contours with smooth transition from the new leading edges to the remaining profile also combinations of these curves together with straight sections were tested. The new leading edge contour has to fit into the remaining material of the worn airfoils and from an economical view its definition has to consider the following conditions:

- machining of the leading edge contour only up to 10% chord length
- minimized abrasion of material during machining process

The easiest solution to meet these conditions is a leading edge shape based on a circular construction. It could be fitted into the remaining profile without supporting lines or other curves. From the part of calculation results however it becomes visible, that the flow patterns in the region of a circular leading edge are not sufficient. A comparison of the manually smoothed blades (see Fig. 5) shows also a nearly circular shape for all the various machining results. It becomes clear that the geometry has to be optimized and that there is a rather high potential of improvement.

Figure 6 shows an example of a redesigned leading edge using a hyperbola construction. The markers indicate the different parts of this construction. On the pressure side (upper side) the hyperbola fits directly to the contour of the original airfoil. On the suction side (lower side) a straight line and a circular part are necessary to provide a smooth transition from the hyperbola to the remaining profile. The connection point is located at about 30% of the chord length. This causes large region of machining with high abrasion of material. Nevertheless, the aerodynamic quality of the redesigned profile

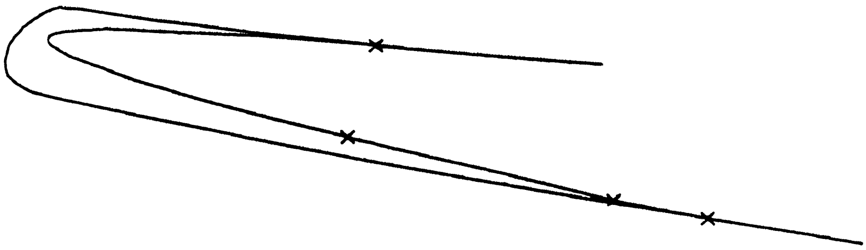


FIGURE 6 Redesign of the leading edge contour based on a hyperbola.

was found to be nearly as good as the new part profile.

This example demonstrates that a suitable compromise between aerodynamic and economical aspects had to be found. Therefore, a parameter study has been performed to achieve a sufficient solution for the construction of the leading edge contours. A shape based on an ellipsis provided the best results. By variation of the geometry parameters the optimum flow behavior is obtainable. With this method the necessary machining range could be reduced to about 10% chord length.

Detailed experimental investigations on blades with elliptical leading edges performed by Walraevens and Cumpsty (1993) demonstrated the origin of leading edge separation bubbles and loss production. By a suitable design of the leading edge an optimization of the performance could be obtained. Therefore, different leading edge designs shape based on ellipsis constructions were tested.

Figure 7 shows the calculated profile pressure distributions for a redesigned profile with elliptical leading edge. The corresponding flow vector plot for the leading edge section show flow conditions similar to a new part profile. Detailed studies have been performed for the 5th stage rotor in order to optimize the re-designing method and to evaluated the influence of the different geometry parameters.

In the following the method was applied to the rotor blades of all stages and all profile classes. For each case satisfactory results were obtained. Based on the experience an algorithm for the definition of the new leading edge contours was developed. This program allows an automated check of the remaining profile, the definition of new leading edge contours, and the check of the boundary conditions. Thus, a computerized parameter variation for the optimization of the leading edge contours becomes possible. The scheme of the designing process for the re-contoured blades is shown in Figure 8.

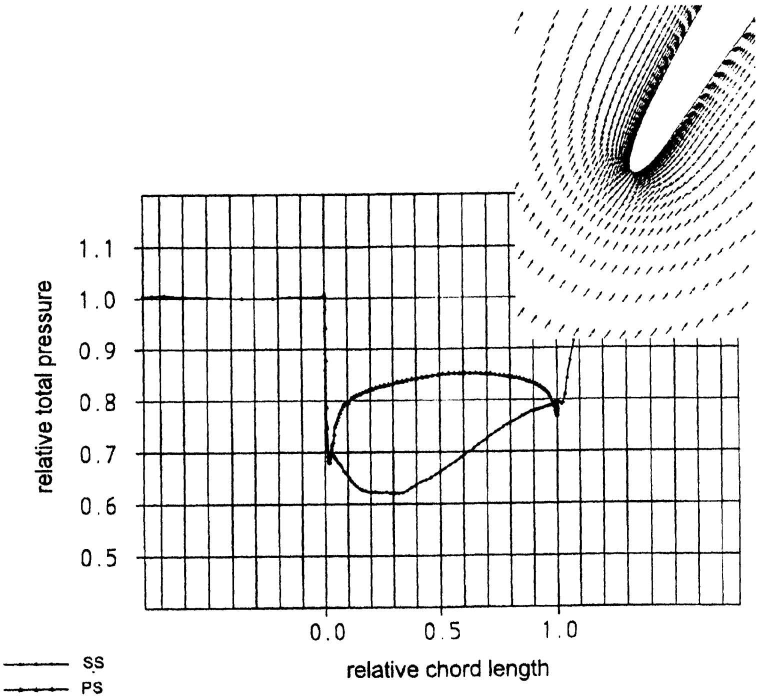


FIGURE 7 Profile pressure distribution and vector plot of a redesigned 10th stage rotor blade.

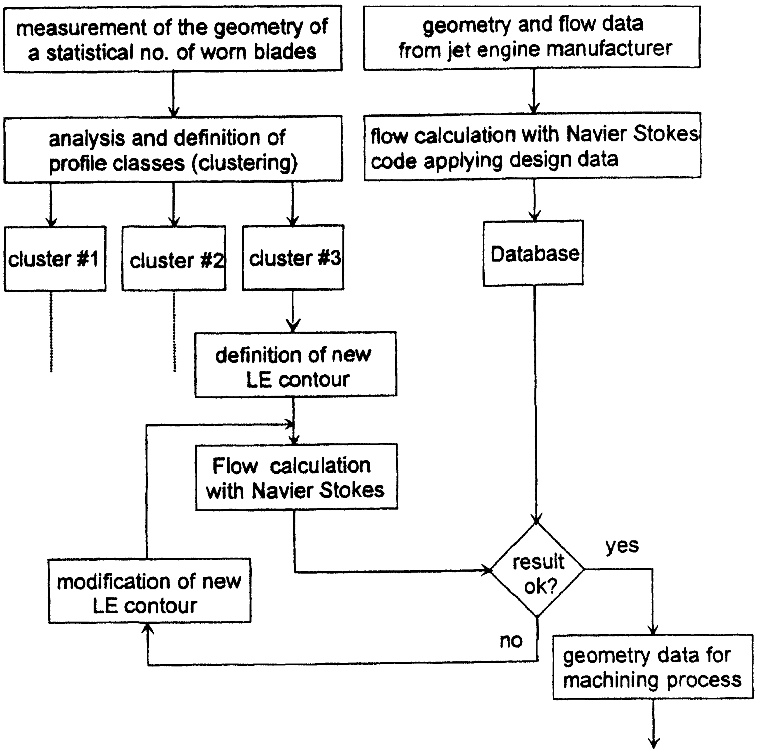


FIGURE 8 Scheme of the redesigning process.

MACHINING OF THE LEADING EDGE CONTOURS

In order to produce the leading edge contours as defined by the above mentioned method the airfoils are machined on a robot handled grinding station with a smooth grinding wheel. A more detailed description of the procedure and an economical discussion is given by Panten and Hönen (1998). By this method it becomes possible to machine the different profiles of each class using only one definition of the target contour. Due to the above mentioned geometry deviations of the worn airfoils the correlation between target and re-contoured profiles is not 100% exact but the method of defining a characteristic target contour for each cluster in combination with using a smooth grinding wheel is a very good approximation. Investigations of a statistical number of re-contoured blades have shown that approx. 95% of all blades treated with the ARP are nearly identical to the defined target contour. The quality of the remaining 5% was similar to that of the conventionally smoothed blades. Figure 9 shows the results of a Navier–Stokes calculation for a worn and a machined blade.

The sharp drop of the pressure-side pressure distribution is caused by a separation bubble in this region (see Fig. 4). The performance is significantly decreased and the operating conditions defined by the design case can not be reproduced in the calculations. The lower pressure distribution in Figure 9 belongs to a machined profile which was based on redesign data provided by the above mentioned method. The comparison with the calculation result of the target contour profile (Fig. 7) demonstrates the good agreement between redesigned and hardware

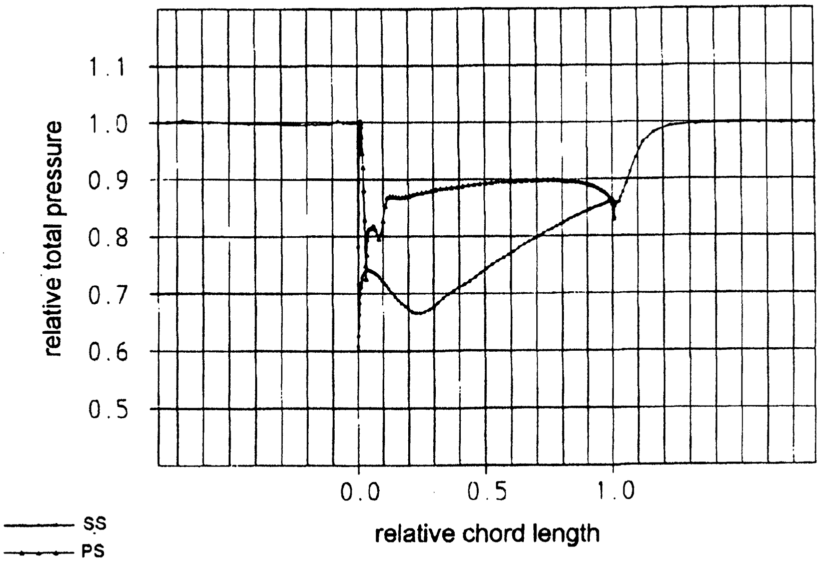


FIGURE 9a Calculated profile pressure distribution for a worn rotor blade.

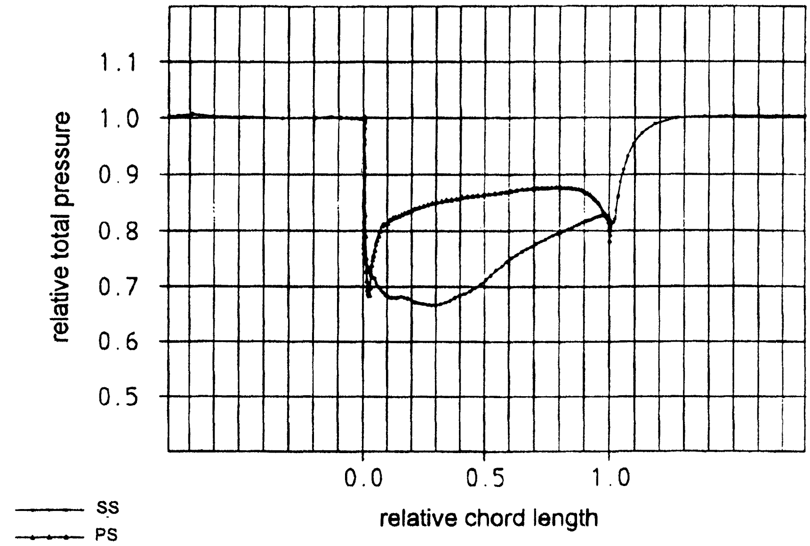


FIGURE 9b Calculated profile pressure distribution for a machined rotor blade.

contour. By a large number of inspected machining results during the production process the reliable quality of the ARP profiles could be proved.

Figure 10 shows a comparison of the blade element performance in different stages. The diagram shows the calculated relative loss coefficients for a new part, a worn, and a recontoured blade based on the loss coefficient of the design case. For the worn blades a strong increase (50%–95%) of the losses can be observed. The redesigning process improves the performance significantly. The losses could be reduced to the level of the new part blades. Only in stage 8 the

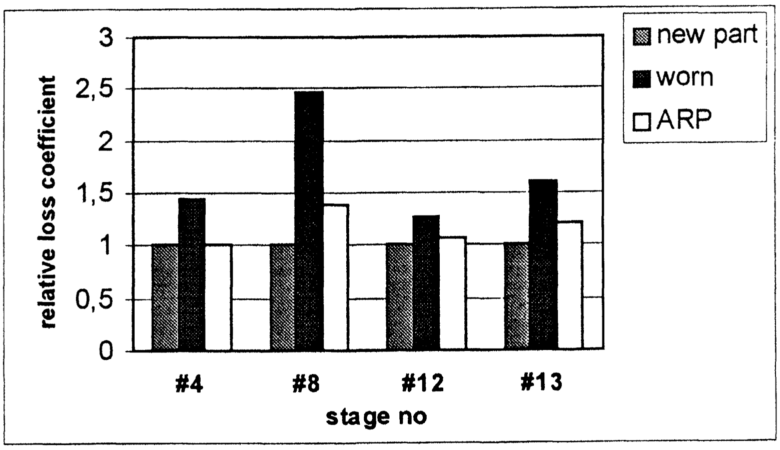


FIGURE 10 Comparison of the losses of different blade conditions in various compressor stages.

increase of losses remains quite high. These results indicate a good improvement of compressor performance by applying the ARP. This loss behavior of a blade row however can only be judged in combination with the other flow parameters. As mentioned before some main parameters have been defined which have to be kept in the range of the design profile. This master condition fôr the redesign of the blades guarantees an operating behavior of the blade rows similar to the originally designed profiles.

CONCLUSIONS

By means of a new developed method the overhaul process for compressor blades could be improved. Measurements of the geometry of a statistical number of blades demonstrated remarkable deviations of the chord length and blade thickness. Classification parameters have been defined for a clustering and definition of characteristical blade shapes for each cluster. These master profiles were subject to a re-contouring of the leading edges in order to improve the aerodynamic quality in comparison with the conventional smoothing by hand.

The redesign procedure based on CFD calculations defines master profiles with new leading edge contours. In the following machining process these data are used to re-contour the worn compressor blades on a robot controlled grinding station. Based on detailed numerical investigations a satisfactory compromise between an optimized aerodynamic quality of the redesigned blades and an economical machining could be provided.

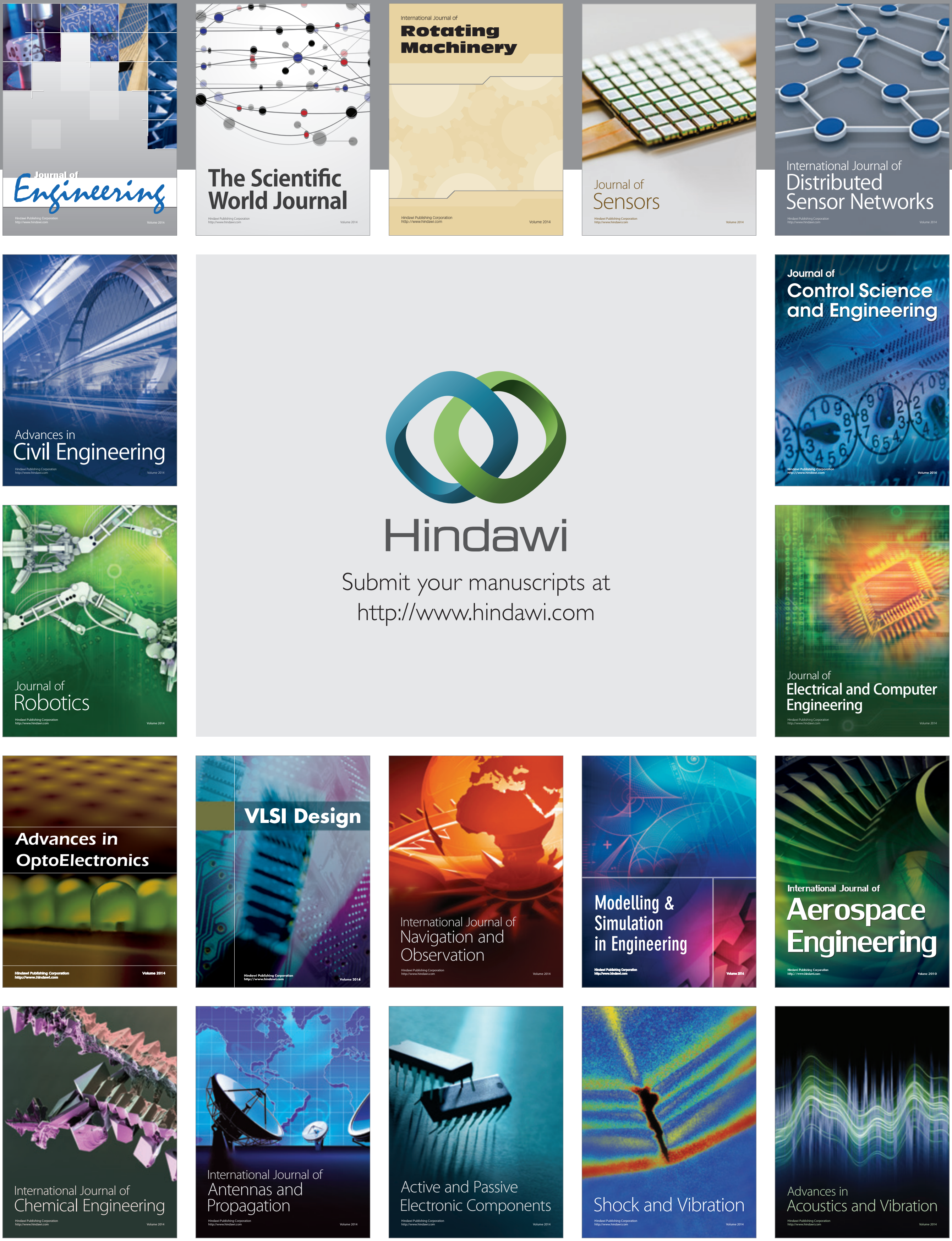
References

Benetschik, H. and Gallus, H. E. (1990) Inviscid and Viscous Flows in Transonic and Supersonic Cascades Using an Implicit Upwind Relaxation Algorithm, *AIAA-Paper No. 90-2128.*

Panten, M. and Hönen, H. (1998) Advanced Recontouring Process for Compressor Blades, *RTO Meeting Proceedings 17*, Qualification of Life Extension Schemes for Engine Components, RTO-MP-17.

Roberts, W. B. (1984) Axial Compressor Restoration by Blade Profile Control, *ASME Paper No. 84-GT-232.*

Walraevens, R. E. and Cumpsty, N. A. (1993) Leading Edge Separation Bubbles on Turbo-machine Blades, *ASME-Paper No. 93-GT-91.*


Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
International Journal of Distributed Sensor Networks
Advances in Civil Engineering
Journal of Control Science and Engineering
Journal of Robotics
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration