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# ENHANCED EFFICIENCY STEAM TURBINE BLADING

## For Cleaner Coal Plant

PROJECT SUMMARY 317

CLEANER FOSSIL FUELS PROGRAMME
– CLEANER COAL R&D PROGRAMME

## OBJECTIVES

The aim of this project was to increase the efficiency of the short height stages typically found in high pressure steam turbine cylinders. For coal-fired power plant, this would directly lead to a reduction in the amount of fuel required to produce electrical power, resulting in lower power station emissions. The continual drive towards higher cycle efficiencies demands increased inlet steam temperatures and pressures, which necessarily leads to shorter blade heights. The specific objectives were as follows:

- To increase the accuracy and execution speed of in-house Computational Fluid Dynamic modelling (CFD) codes.
- Develop new Computer Numerical Control (CNC) techniques to efficiently produce model turbine blade rows with highly curved 3D blades.
- Optimise existing 3D fixed blade designs to improve performance and gain better understanding of how to deal with very short height blading.
- Produce a novel design for very short height fixed blades.
- Perform a model air turbine test on the new design of fixed blade to assess the performance benefit gained from it.

## SUMMARY

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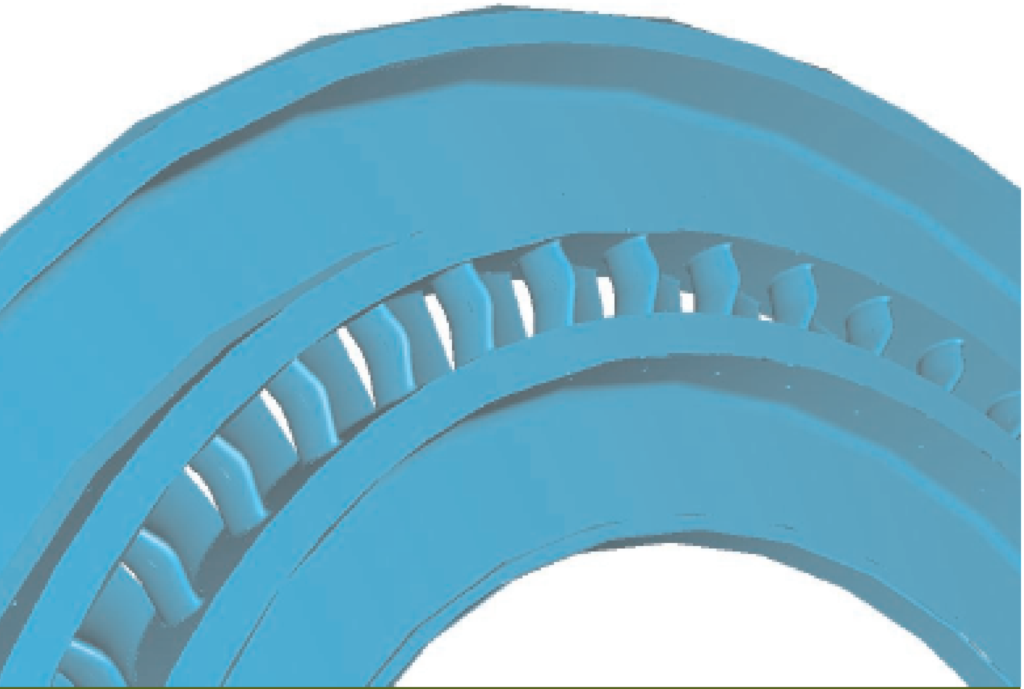

*Figure 1. Very short height fixed blades*

A 3D flow solver code supplied by ALSTOM Power has been analysed and successfully restructured to run on parallel processors by CCLRC.

ALSTOM Power has developed an improved grid generation package for CFD calculations. The use of 'templates' means that different design ideas can be calculated with as similar grids as possible to minimise the effects of grid dependency.

The development of CNC techniques at Cranfield University has led to one of their existing CNC machines being converted into a 6-axis machining centre capable of manufacturing a wide range of complex 3D blade profiles for testing in model turbines.

Optimisation of ALSTOM's existing, patented 'controlled flow' design philosophy led to the development of an 'evaluation matrix' for comparing different design concepts. The evaluation matrix was used to analyse a number of different concepts for a novel very short height fixed blade for use in the early stages of a high pressure turbine. The design that evaluated the best has been manufactured and tested in the model air turbine at ALSTOM Rugby.

The model turbine test of the very short height fixed blade design produced a disappointing result, with the performance of the new blade being worse than a prismatically stacked blade.

Whilst the reasons for this are still not understood, the result has led to changes in the way that such blades will be designed in the future. It also provides a challenging test case for future CFD code validation.

## BACKGROUND

The efficiency of the steam turbine is a key factor in both the economics and environmental impact of any coal-fired power station. For example, increasing the efficiency of a typical 600MW turbine by 1% reduces emissions of $CO_2$ from the station by approximately 50,000 tonnes per year, with corresponding reductions in $SO_x$ and $NO_x$. Typically, efficiency uprates are economically evaluated at about £700 per kilowatt, so the 1% increase of a 600MW machine is worth about £4.2 million. Hence performance is frequently the single most important buying criterion for customers of retrofit coal-fired power plant. The market is potentially world-wide.

ALSTOM is a world leader in the design and manufacture of large steam turbines for coal-fired power plant. In recent years ALSTOM has made major advances in steam turbine aerodynamics leading to significant increases in the efficiency of coal-fired power stations.

The programme of work undertaken in this project aimed to further improve the efficiency of ALSTOM's short height steam turbine blading.

In order to perform the large number of calculations required to optimise a modern 3D blade design, upgrades were required to both the software and hardware available at ALSTOM. Therefore The Council for the Central Laboratory of Research Councils (CCLRC) at Rutherford Appleton Laboratory were partners in this project, bringing their experience of parallel and large-scale scientific and engineering computing. In particular, the networking of many relatively cheap PC processors to form a powerful 'Beowulf Cluster' is a cost effective way of increasing computer power. CCLRC undertook to port ALSTOM software to the Linux operating system and to create parallel versions of the software currently used and under development at ALSTOM. CCLRC then assessed the optimum hardware to run these codes on a cost per calculation basis.

Model turbine tests were performed to demonstrate the increase in performance achieved by the designs produced in this project. Cranfield University School of Mechanical Engineering developed new CNC techniques to efficiently produce model turbine bladed rings ('blings') with highly curved 3-D blades typical of ALSTOM designs. This established a state of the art CNC machining facility in the UK for this type of work.

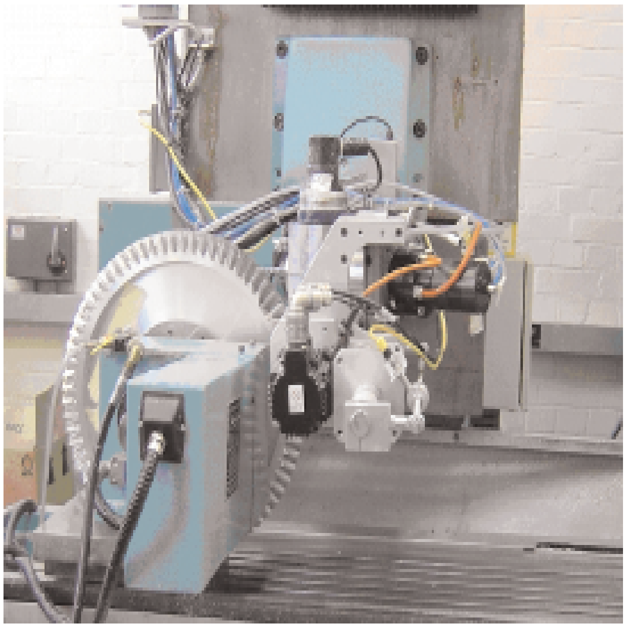

*Figure 2. Six-axis milling head and blisk*

## OVERVIEW OF THE PROJECT

The following activities were undertaken during the course of the project:

1. Increase the execution speed of in-house CFD codes by improving the structure of the code and by running the programme on multiple processors. This activity was performed by CCLRC.
2. Develop new CNC techniques to efficiently produce model turbine blade rows with highly curved 3D blades. This activity was performed by Cranfield University.
3. Increase the quality of 3D blading efficiency calculations by improving the structure of the computational grid.
4. Optimise existing controlled flow fixed blade designs to improve performance and gain better understanding of the flow structure in very short height blading.
5. Produce a novel design for a very short height fixed blade.
6. Perform a model air turbine test on the new design of fixed blade to assess the performance benefit gained from it. These activities were performed by ALSTOM Power Limited.

The work that CCLRC undertook on the ALSTOM CFD code was very successful. The 3D flow solver code supplied by ALSTOM was analysed and two methods of parallisation implemented. The OpenMP method of parallisation is only suitable for use on 'shared memory' multi-processor computers. The message passing (MPI) method of parallisation is suitable for use on 'distributed memory' computers, sometimes know as 'Beowulf Clusters', which tend to be significantly cheaper to buy than large shared memory computers of similar processing power. As a result of this work, ALSTOM Power have purchased a Beowulf Cluster, and it has become the main workhorse of the Aerodynamics Group.

The development of CNC techniques at Cranfield University has lead to one of their existing CNC machines being converted into a six-axis machining centre capable of manufacturing a wide range of complex 3D blade profiles for testing in model turbines. A six-axis milling head has been made and fitted to a BostoMatic milling machine for the purpose of making complex integrally bladed turbomachinery components. The approach has been shown to be successful in the machining of a blisk embodying sweep and lean. However, the width of the head makes the machine unsuitable for making blings in which large cutter inclinations are necessary to obtain access to the passage. An alternative separately bladed approach for nozzles has been investigated in which the maching of individual blades is done using five of the machines axes. These blades would engage in slots cut in carrier rings which could also be machined on the six-axis machine.

ALSTOM Power developed an improved grid generation package for CFD calculations. The generation of high quality structured grids for CFD analysis of blade flows in impulse, high pressure, steam turbine cylinders presents a significant challenge, due to the characteristics of the fixed blade sections and the typical layout of a stage. These challenges have been addressed by making available a choice of grid types; simple-H, curvilinear-H and H-O-H; which allow superior quality computational grids to be generated. The use of templates simplifies the grid generation process, and enables 'similar' grids to be easily applied to different geometries. This minimises the effect of grid dependency on the solution. The use of algebraic grid smoothing techniques further improves the quality of the computational grids. Grid quality metrics are available to the user to monitor the quality of the grids produced.

The ALSTOM in-house CFD code was used to calculate a number of blading geometries that have been tested in the company's model turbine. Analysis of the results of the calculations showed that the programme was not able to automatically calculate the relative performance of the different designs, despite the previous efforts put into improving the grid generation for the calculations. Therefore it was necessary to define a number of important flow parameters against which the various designs could be evaluated. An evaluation matrix was therefore developed, which was calibrated using available model turbine data. The evaluation matrix provides a mechanism by which existing controlled flow designs can be optimised. The evaluation matrix developed during this project gives a method to determine the relative performance of the similar designs. It takes account of flow field features and parameters that are not captured, or only partly captured, in the 3D calculations. Pressure fluctuations before the stator hub and rotor tip are one such flow parameter. Furthermore, the evaluation value can be related to efficiency, although it must be calibrated with experimental data and a degree of engineering knowledge. This method will be used in future design activities.

A number of different 3D blade stacking configurations were conceived, designed, calculated and analysed. The evaluation matrix was used to evaluate the relative performance of the various designs and to indicate how further improvements could be made. Using this method, the concept of enhanced controlled flow was developed. The evaluation of enhanced controlled flow indicated it has a significant performance benefit compared to the types of fixed blades currently being used by ALSTOM. Therefore this design of fixed blade was selected for testing in the final activity of this project.

The model turbine test of the very short height fixed blade design produced a disappointing result, with the performance of the new blade being worse than a prismatically stacked blade. Whilst the reasons for this are still not understood, the result has led to changes in the way that such blades will be designed in the future. It also provides a challenging test case for future CFD code validation.

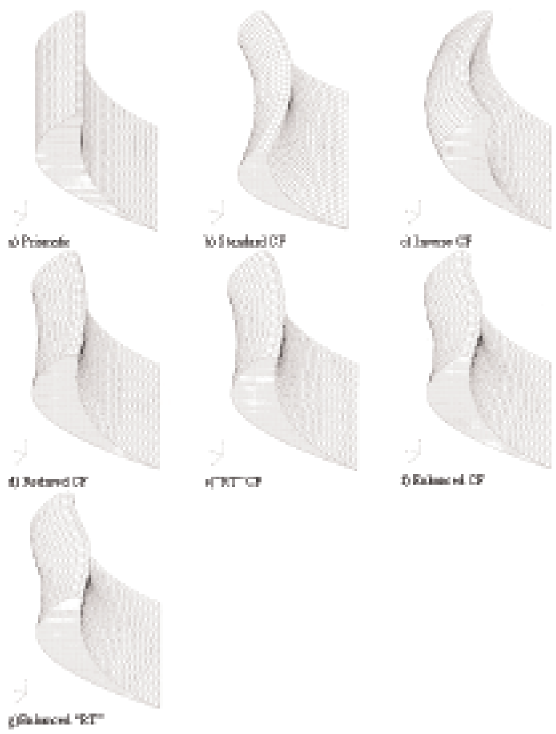

*Figure 3. Fixed blade designs evaluated during the project*

## CONCLUSIONS

- Message passing and OpenMP parallel versions of in-house CFD software have been developed. Tests of the combined OpenMP and message passing version of the code show this to be practical and to offer better performance than either method on its own for some computer architectures.
- A six-axis milling head has been made and fitted to a BostoMatic milling machine for the purpose of making complex integrally bladed turbomachinery components. The approach has been shown to be successful in the machining of a blisk embodying sweep and lean.
- An improved grid generation package for CFD calculations makes available a choice of grid types, which allow superior quality computational grids to be generated. The use of templates simplifies the grid generation process, and enables similar grids to be easily applied to different geometries. The use of algebraic grid smoothing techniques further improves the quality of the computational grids.
- An evaluation matrix has been developed, which was calibrated using available model turbine data.
- The concept of enhanced controlled flow was developed. The evaluation of enhanced controlled flow indicated it would have a performance benefit compared to the types of fixed blades currently being used.
- The model turbine test of the very short height fixed blade design produced a disappointing result, with the performance of the new blade being worse than a prismatically stacked blade.

## POTENTIAL FOR FUTURE DEVELOPMENT

The performance benefits of controlled flow for fixed blades of larger aspect ratio has been proven in the model turbine. The methods and techniques developed during this Cleaner Coal project are already being applied to other ALSTOM blade development projects. In particular, the use of a calibrated evaluation matrix has been extended and continues to be refined.

The use of controlled flow technology to control secondary losses produced in the fixed blades might also be applicable to moving blades. Similarly the same principals can also be applied to reaction type steam turbines produced by ALSTOM elsewhere in Europe. Investigation of such extensions to the application of controlled flow are currently being planned by ALSTOM.

The development of improved manufacturing techniques for model turbine components at Cranfield University has led to a change in the way the model air turbine at ALSTOM Rugby is constructed. Having been reassured by the quality and accuracy of the 'bling' manufactured for the short height fixed blade tests, subsequent tests in the model turbine are being constructed with 'blings' and 'blisks'.

## COST

The total cost of this project is £472,233, with the Department of Trade and Industry (DTI) contributing £217,575. The balance of funding was provided by the participants.

## DURATION

30 months – October 2001 to March 2004

## CONTRACTOR

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## COLLABORATORS

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## FURTHER INFORMATION

For further information about this project see contractor report Enhanced Efficiency Steam Turbine Blading For Cleaner Coal Plant, R283 URN 05/658 available from the helpline.

**Further information on the Cleaner Fossil Fuels Programme, and copies of publications, can be obtained from:**
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