Institution: University College London

Unit of Assessment: 12 – Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Increased efficiency in turbomachinery design, manufacturing and performance using 3D inverse design software

1. Summary of the impact

The development of a novel 3D inverse design method for turbomachinery aerodynamic design at UCL has led to important design breakthroughs for pump and compressor applications. The resulting IP and software has been commercialised by a UCL spinout company Advanced Design Technology Ltd (ADT), which is now considered a global leader in advanced turbomachinery design software. Since 2008, the 3D inverse design codes embedded within ADT's TURBOdesign™ suite of software have been adopted by many of the leading turbomachinery equipment manufacturers in Europe, Japan and the US. These companies are using the TURBOdesign suite to achieve significant improvements in the time taken to design their turbomachinery components. It has also helped them unlock major efficiency gains and hence achieve a reduction in CO_2 emissions. [text removed for publication]

2. Underpinning research

There are two different approaches to aerodynamic design of turbomachinery components such as turbines, compressors, fans, pumps and torque converters. The direct design approach is based on trial and error iteration of the blade or vane geometry by the designer, using feedback from a Computational Fluid Dynamics (CFD) code. This approach inherently results in a reduction of the design space as designers tend to operate within their comfort zone. Using this approach makes it more difficult to achieve designs beyond the designer's previous experience and is also time-consuming. The result is significant constraints on the ability of companies to achieve further improvements in the performance of their turbomachinery. By contrast, in the inverse design approach, the blade or vane geometry is designed for a given specified distribution of pressure or blade loading. The 3D pressure distribution controls the viscous behaviour of the flow; by controlling the 3D pressure field it is possible to directly use the detailed information provided by CFD solutions to arrive at a choice of optimum loading to control particular sources of loss in turbomachines. By removing the need for empiricism in the design process, the inverse design approach allows designers to directly use their knowledge of detailed fluid dynamics, as provided by CFD and detailed measurements, to arrive at a breakthrough solutions that solve particular adverse flow phenomena.

The inverse design approach had previously been used extensively in two dimensions by the aeroengine industry but no robust design methods existed in three dimensions. To address this gap, the research group headed by Professor Mehrdad Zangeneh (Professor of Thermofluids, at UCL since 1989) in UCL's Department of Mechanical Engineering started working on the development of novel 3D inverse design methods in the early 1990s. One of the key aspects of previous inverse design methods was that they mainly relied on the specification of blade surface pressure on suction and pressure surfaces. This removed the designer's control of blade thickness, which is a very important parameter for high-speed applications. Furthermore, the compatibility conditions in three dimensions make it difficult to know the correct feasible spanwise static pressure distribution on the blade *a priori*, as spanwise variations in pressure are influenced by the streamwise flow distribution. This meant that development or extension of any inverse method in 3D had limited success. A key innovation arising from the UCL research was the use of blade loading within the design methodology. When coupled with pressure jump across the blade and blade thickness, it was possible to achieve a significantly more robust 3D inverse design method and this allowed some of the important outstanding problems in turbomachinery aerodynamics to be solved [1][2]. The design code was subsequently extended to marine ducted propulsors as a result of a $700k research grant from the US Office of Naval Research [3] and extended to include coupling with automatic optimisation for multi-point/multi-objective design [4]. UCL's application of 3D inverse design methods to various applications, especially in radial turbomachinery, resulted in important breakthroughs in design and led to the university filing a number of international patents [8].

One of the first applications of the 3D inverse design method was in centrifugal compressors and pumps. The main aim was to reduce or eliminate secondary flows in the impeller, which result in significant flow non-uniformity (jet/wake flow) and hence are a major cause of loss in impellers. The nature of secondary flows and what causes them was quite well understood, but with conventional (or direct) design based on iterative changes to geometry it was rather difficult to arrive at a design that helped to reduce or minimise secondary flows. By using the 3D inverse design method, UCL researchers could establish a systematic approach for minimising secondary flows in centrifugal impellers. The control of secondary flows actually led to significant improvements to compressor/pump stage efficiency [5 and patents i and iii]. Other breakthroughs were related to control of 3D corner separation in pump diffusers [6 and patents iv, v and vi]. Further important breakthroughs were obtained in cavitation in pumps [7] and shockwave losses in transonic axial fans [2].

The research was subsequently commercialised through the formation of a UCL spinout company, Advanced Design Technology (ADT), which was established as a joint venture with the major Japanese turbomachinery manufacturer, Ebara Corporation, in 1998.

3. References to the research

[1] M. Zangeneh, “Invisicid-viscous interaction method for three-dimensional inverse design of centrifugal impellers”, *Journal of Turbomachinery*, vol. 116, pp. 280–290, 1994. DOI: doi.org/bgcp5h

[2] W. T. Tiow and M. Zangeneh, “Application of a three-dimensional viscous transonic inverse method to NASA rotor 67”, *J of Power and Energy, Proc of IMeche*, vol. 216, pp. 243–255, 2002. DOI: doi.org/bq7z94

[3] K. Yiu and M. Zangeneh, “On the simultaneous design of blade and duct geometry of marine ducted propulsors”, *Journal of Ship Research*, vol. 42, pp. 274–296, 1998. Available on request.

[4] D. Bonaiuti and M. Zangeneh, “On the Coupling of Inverse Design and Optimization Techniques for the Multiobjective, Multipoint Design of Turbomachinery Blades”, *Journal of Turbomachinery*, 2009. DOI: doi.org/fvzncz

[5] M. Zangeneh, A. Goto, and H. Harada, “On the design criteria for suppression of secondary flows in centrifugal and mixed flow impellers”, *ASME J of Turbomachinery*, vol. 120, pp. 1–15, 1998. DOI: doi.org/dmr3xr

[6] A. Goto and M. Zangeneh, “Hydrodynamic Design of Pump Diffuser Using Inverse Design Method and CFD”, *Journal of Fluids Engineering*, vol. 124, pp. 319–328, May 2002. DOI: doi.org/bnds24

[7] D. Bonaiuti, M. Zangeneh, R. Aartojarvi, and J. Eriksson, “Parametric Design of a Waterjet Pump by Means of Inverse Design, CFD Calculations and Experimental Analyses”, *Journal of Fluids Engineering*, vol. 132, pp. 1–15, Apr. 2010. DOI: doi.org/ckh5ds

[8] Selected related patents: i) US5685696 A – (1997-11-11), ii) EP0775248 B1 – (1999-09-15), iii) JP3693121B2 B2 – (2005-09-07), iv) US6595746 B1 - (2003-07-22), v) DE69812722T T2 (2004-01- 29), vi) JP2002513117T T – (2002-05-05), vii) US6062819 A (16-05-2000), viii) EP 1082545 B1 (03-03-2004), ix) US6508626 B1, x) DE69915283D D, xi) JP4405966 (B2) (2010-01-27). Available on request.

Patent xi won the commendation of the Japan Institute of Invention and Innovation in November 2010. References [1], [4] and [5] best demonstrate the quality of the research.

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4. Details of the impact

Since 2008, major turbomachinery manufacturers have adopted ADT's TURBOdesign^{TM} software suite in ever increasing numbers, as they sought to achieve improvements in their design processes and manufacturing methods, and thus unlock benefits such as increased efficiency of their turbo-machinery and reductions in CO_2 emissions. Some of the key impacts arising from the UCL research are summarised below.

Delivering more efficient design methods for the turbomachinery industry: A number of the leading turbomachinery manufacturers have changed their design systems to access the benefits that arise from the use of ADT's 3D inverse design approach. For example, in pumps manufacturing, four of the top ten global manufacturers, including Ebara Corporation, use TURBOdesign^{TM} in their design workflow [a]. Also the world's leading fan manufacturer, ebm-papst, uses TURBOdesign^{TM} in most of its divisions; one of the company's engineers noted: "*Our experience shows that TURBOdesign^{TM} can reduce development / design time, improve efficiency and reduce noise of fan blades*" [b]. Other leading companies in turbomachinery application areas such as aeroengines, automotive cooling, Central Processing Unit (CPU) cooling, cryogenic and air-conditioning applications and power generation have switched to using TURBOdesign^{TM} in their design systems [c].

Many of these manufacturers are finding that using the code reduces the development and design time for their new designs and improves performance. For example, the Director of R&D at Andritz Group said in a March 2013 article in Pumps and Systems magazine that the "*the [ADT] software considerably supported the pump manufacturers to accelerate the hydraulic design process*" [d]. In another article in Machine Design, Mr Toru Iwata of Daikin Industries said: "*The software helped us reduce development time and slash material use, as well as develop new models of high-efficiency fans*" [e].

Enabling improvements in manufacturing methods in the turbomachinery industry: In the turbomachinery industry various methods are used for manufacturing the vanes and blades. For low volume vane and blade manufacture within aerospace applications, it is usual that CNC machines are utilised. For high-volume applications, such as turbochargers, it is customary to use casting or in some cases a flank milling process for blades with straight filaments, as these approaches result in lower manufacturing costs.

In 2011, Cummins Turbo Technology, one of the leading manufacturers of heavy-duty diesel turbochargers globally, decided to take into high-volume production a turbocharger compressor with 3D blades. This was designed using the 3D inverse design method TURBOdesign^{TM} and machined by using a 5-axis point milling process. The point milling process can add between 15-20 per cent to manufacturing costs compared to flank milling or casting. The main impetus for the company to make such a substantial change in its manufacturing process was the fact that for 10 years they had not been able to make any improvement in the performance of a baseline turbocharger compressor, which had straight filaments, with direct design methods. By using the inverse design approach an impeller could be designed that was up to 3 points more efficient through most of the compressor map. However, this impeller had a 3D geometry and required a significant change in manufacturing process. The significant improvement in performance of the new compressor, in the eyes of Cummins Turbo and its major engine manufacturers, more than justified the additional costs associated with the changes to manufacturing method [f].

The TURBODesign^{TM} software makes it easier to design 3D blade and vane geometries with high efficiency, and with the current rate of reduction in the cost of the point milling process it can create important possibilities for further improvement in turbomachinery component efficiencies.

Increased turbomachinery efficiency and reduction of CO_2 emissions: One of the major impacts of industry's adoption of ADT's inverse design method is a significant improvement in the efficiency of turbomachinery. Earlier research had shown that breakthrough designs made possible by this approach can lead to significant improvements in pump stage efficiency of up to 6 points (see outputs [5] and [6], above). Similar levels of performance improvement are being achieved by industrial use of the inverse design method. For example, in 2013, Daikin Industries confirmed that they had improved the efficiency of an air-conditioning fan by 10% by using the inverse design method [e].

Likewise, performance improvements have been achieved in other industries such as pumps, automotive and power generation through the adoption of this technology. For example in 2008, RR Marine, a major manufacturer of large-scale marine waterjets, was able to improve the propulsive efficiency of their marine waterjets by 3-5% by using ADT's software TURBOdesign™ [g]. Furthermore, they obtained a significant reduction in manufacturing cost of their waterjets, which came on the market in 2013 [g].

These efficiency savings have consequent environmental benefits by reducing CO_2 emissions. ebm papst has been using the inverse design method since 2006, and claimed in a 2008 advert in The Economist magazine that "*If for ventilation, refrigeration and airconditioning, European industry switches to the latest generation of fans (designed by ebm-papst), 16 Million tons of CO_2 emission will be cut and 4 coal fired power stations will be made redundant"* [h].

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5. Sources to corroborate the impact

[a] Case study on Ebara (http://www.adtechnology.co.uk/case-studies/ebara-manufacturing-system-hydraulic-parts) corroborates the company's use of the software. Available on request.

[b] ADT case studies on epm pabst confirm that TURBODesign™ is the standard design tool in use at the company and the quote from the engineer. Available on request.

[c] For a range of ADT's customers, see:
http://www.adtechnology.co.uk/adtsearch/node/_/cas_/_/cas_/_

[d] Quote from Andritz Group in "Design Software Increases Hydraulic Efficiency", Pumps & Systems, March 2013, p 44, http://pump-zone.imirus.com/Mpowered/book/vps13/i3/p44

[e] Quote from Daikin Industries, in "Inverse design code boosts HVAC fan efficiencies", Machine Design, January 2013, http://machinedesign.com/news/inverse-design-code-boosts-hvac-fan-efficiencies

[f] Pages 9 and 10 of Cummins Turbo Technologies' HTi magazine confirms Cummins' use of ADT software and the 3 percentage points efficiency improvements. http://bit.ly/15W2vnK

[g] A letter from the Senior Hydrodynamicist at Rolls Royce Marine confirms the 3-5% improvement in propulsive efficiency of the company's next generation of marine waterjet pumps using the ADT system. Available on request.

[h] The epm-pabst advert is in The Economist, 10 October 2008. Available on request.

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