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MULTICRITERIA OPTIMIZATION OF CONCEPTUAL COMPRESSOR AERODYNAMIC DESIGN

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Abstract

A design method is introduced that incorporates a mean-line design code and a throughflow code with an optimization environment. The scheme makes it possible to use *design of experiments* for rapid exploration of the design space and also multiobjective optimization. The method is then demonstrated by defining a conceptual compressor optimization problem, typical for an open rotor engine compressor. The optimizer environment is used to establish a pareto front interrelating the compressor part load surge margin and the polytropic design point efficiency.

Nomenclature

SM surge margin
W corrected mass flow
Π overall total pressure ratio
V flow velocity
r radial direction

Subscripts

op conditions at the operating line
s conditions at the surge line
θ swirl component
Z axial component

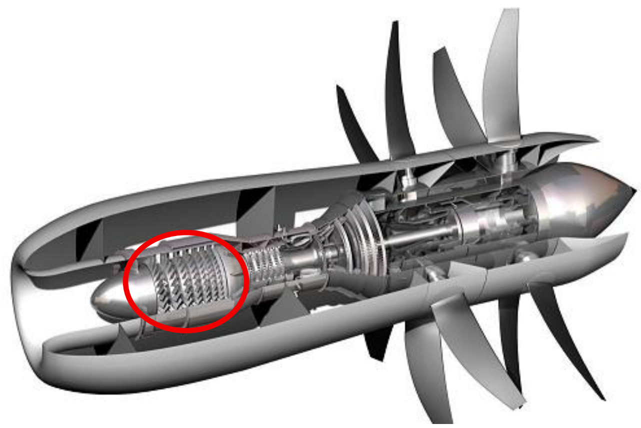

Figure 1: Conceptual drawing of an open rotor engine [14]. The circle shows where the low pressure compressor is located.

Introduction

There is a high demand on air traffic to reduce CO_2 emissions and decrease associated fuel consumption. An innovative concept to achieve a radical reduction in fuel burn is the open rotor engine. A drawing of a conceptual design of the open rotor engine is shown in Fig. 1. The open rotor, or the PROPFAN, received significant amount of research attention in the 1980's after the 1973 oil crisis. The interest in the engine declined as the fuel prices also declined. The engine has started to gain interest again both because of the increase in fuel prices and the global concern on the emissions of greenhouse gases into the atmosphere. Two concepts of the open rotor engine are being investigated in the FP7 project DREAM, "valiDation of Radical Engine Architecture systeMs" [1]. A comparative study of the open rotor engine, and the geared turbofan can be found in [9].

To be able to evaluate the open rotor engine in more details and compared to current technology, the components need to be designed. Establishing competitive multistage axial compressor designs requires that a number of design choices are made and that large parameter spaces are explored systematically. Over the years computer modeling of axial machines have evolved from using basic mean line stage by stage design analysis to the application of 3D Navier Stokes solvers. As computer resources gradually have allowed it, methods to automate the design process and analyze a large number of axial compressor concepts by means of optimization has evolved.

Although present computer performance may allow the direct application of three dimensional Navier Stokes solvers, there are a large number of complexities that have to be overcome if no prior use of simplified methods is incorporated in the design system. The engineer needs an advanced *design of experiments* tool allowing systematic variation of, for instance:

- the number of compressor stages
- annulus area distribution
- blade profiling
- aerodynamic loading distribution between stages
- radial variation of blade design parameters
- evaluation of off-design operating points

The flow in a compressor is a complex three dimensional flow field. The mean-line code incorporates very simple one dimensional methods to approximate the flow. The next step in level of details is to use throughflow calculation to solve the flow field using two dimensional methods. The results from the mean-line calculations is used as input parameters from the throughflow calculations. For the conceptual compressor design the paper uses a commercial meridional streamline curvature program [2] that allows interfacing the text based file input system with the built in optimizers in the iSIGHT tool [3].

A multipoint optimization formulation is studied where part load surge margin can be traded against design point efficiency. Pareto fronts for the multi-objective design space are established.

Mean-line code

The mean-line design is one of the crucial steps in the compressor design process. In this step the fundamental parameters are chosen and computed, such as number of stages, stage loading, length and annulus geometry. A poor choice in these parameters are hard, or even impossible to fix later in the design process. It should be noted that the greatest risk for designing a compressor that delivers a substantial short-fall in performance, is likely to be associated with poor one dimensional design rather than aspects associated with 2 and 3 dimensional design choices [5].

A one dimensional mean-line code was developed for transonic compressors. The loss model used is based on the prediction model developed by Wright and Miller [17]. The code includes also a shock loss model that was developed by Schwenk [15].

One to two dimensional mapping

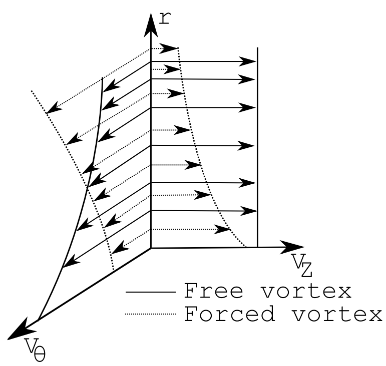

Figure 2: Free and forced vortex velocity distribution [8].

To go from the the mean-line method to the streamline curvature method some sort of mapping of the velocities is needed. Two approaches can be used within the optimization environment, either empirical/experienced based methods or analytical solutions of simplified governing equations. Two analytical solutions are shown in Fig. 2 that are called the free and forced vortex velocity distribution. In this paper the forced vortex is used to demonstrate the automated multicriteria optimization approach.

Streamline curvature method

The streamline curvature approach solves the governing equations in the meridional plane. The streamline curvature method is based on iteration of the locations of the streamlines based on the solutions of the radial equilibrium and continuity equation. The assumptions made when using the streamline curvature approach are that the flow is steady, adiabatic axisymmetric, inviscid, and with negligible body forces. A detailed description of the approach can be found in e.g. [4].

The approach in this paper was to use a commercial available code, SC90C, from PCA Engineers, that implements the streamline curvature method [2]. The code uses the loss model and calculation for annulus wall boundary layer developed by Wright and Miller [17]. The code also incorporates the spanwise mixing scheme from Howard and Gallimore [6].

Optimization algorithm

The evolutionary algorithms mimics the natural selection found in nature. The process starts from a randomly selected first generation; the parameters in the model. Then the algorithm selects the next generation based on the fitness, which is selected according to the objective function values. The selection process uses some of the same mechanism that natural selection uses, i.e. inheritance, mutation, selection, and crossover. The evolutionary algorithms are also robust and efficient and there are multiple studies that have used evolutionary algorithms in compressor design [7, 12, 13, 16].

Design method

The purpose of the mean-line calculation is to find model parameters that will result in a good flow field in the compressor and reasonable loading conditions. The main input parameters into the mean-line design code are:

- the inlet conditions (i.e. temperature and pressure)
- mass flow
- number of stages
- axial aspect ratio of the blades
- hub to rip radius ratio at the inlet
- relative Mach number at the tip of the first rotor

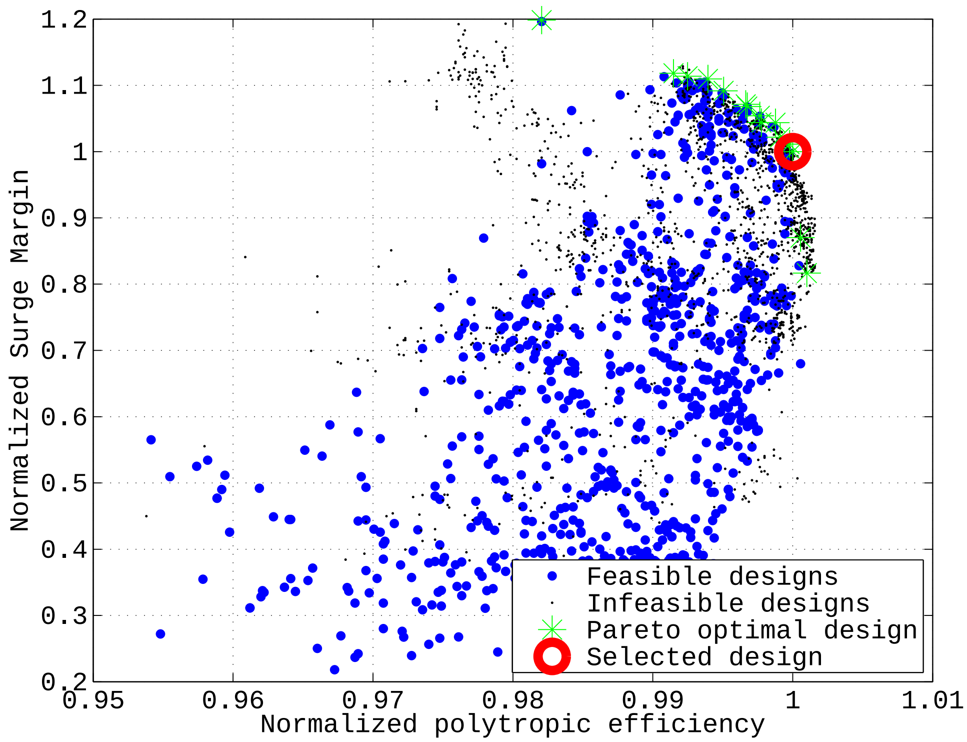

Figure 3: Results from the optimization showing the pareto optimial design points.

- maximum thickness over chord ratio
- leading edge radius over chord
- stage loading
- absolute angles into each stage
- exit angle after the last stage

The main output parameters are:

- rotational speed
- velocity triangles
- stagger angle
- number of blades in each blade row
- chord
- annulus geometry

The output data from the mean-line calculations serve as the input data for the streamline curvature code using the mapping to get the radial distribution. The streamline code is used in design mode, and therefore the main input parameters are the annulus geometry, number of blades and the exit flow angles from each blade row.

One of the most important objectives for a compressor is to have as high efficiency as possible. But only having the efficiency as an optimization variable may lead to stability problems when running the compressor at different conditions than stated at design point. By introducing another parameter, the surge margin

$$SM = 100\frac{W_{op}\left(\Pi_s - 1\right)}{W_s\left(\Pi_{op} - 1\right)}$$

it is possible to evaluate the stability of the compressor design. A model is incorporated into the design process to locate the compressor

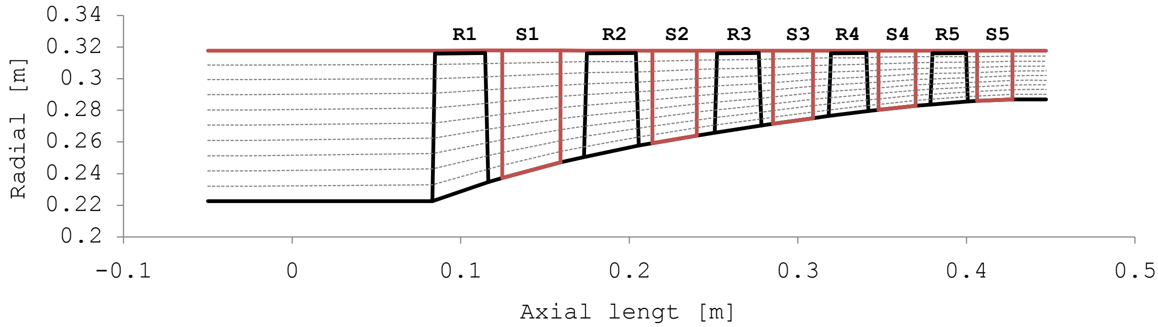

Figure 4: Annulus geometry for a 5 stage compressor. R - rotor, S - stator and 1-5 is the number of the stage, the IGV is not shown.

surge points. The method is based on locating the highest density ratio possible at a given speed line identifying these points as the surge line of the compressor [10, 11].

The optimization process will use the absolute angles and the stage loading as design variables and the polytropic efficiency at design point and the surge margin at off design point as objective functions.

Results

One of the major constraints currently being incorporated is to have a constant radius for the shroud of the compressor annulus. Another major high level design decisions is the relative Mach number at the tip of the rotor in the first stage.

The results from the optimization is shown in Fig. 3. A clear Pareto-optimal front can be seen and it is clear that the two variables are a competing objectives, getting higher efficiency means that the surge margin will be decreased and vice versa. A point located on the pureto front with a high surge margin and high efficiency was chosen arbitrarily. The results are normalized using the values from the selected design. The annulus of the design is shown in Fig. 4. The compressor map with the total overall pressure ratio and polytropic efficiency is shown in Fig. 5.

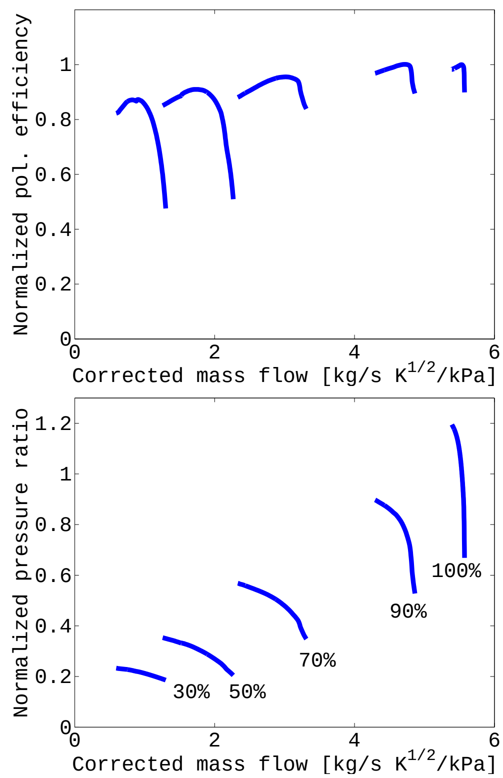

Figure 5: Compressor map for the compressor with running lines at 30%, 50%, 70%, 90% and 100% of the rotational speed at the design point.

Conclusion and future work

A design method has been developed that uses one dimensional and two dimensional calculations in connection. A multi objective evolutionary algorithm was used to construct a pareto front for the polytropic efficiency and surge margin of a multistage compressor. The method was then used to design the low pressure compressor in the open rotor engine. The method obtained multiple designs that had reasonable polytropic efficiency and surge margin.

The future work will focus on exploring a further range of degrees of freedom e.g. annulus geometry. It will include flow angles into the optimization process, rather than to apply empirical or analytical methods for designing the flow angles radial distribution.

Another interesting aspect is multilevel multiobjective optimization where the degrees of freedom being used varies hierarchically within the optimization process. For instance a large number of optimization variables may be used to optimize a stage or a blade row keeping other potential optimization parameters fixed. A reduced number of optimization parameters may then be used for that particular stage when the entire compressor is being optimized.

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References

[1] Dream project website. http://www.dream-project.eu/. Accessed April 2011.

[2] SC90C - A streamline curvature program for axial compressors, Userguide, 2008. PCA Engineers Ltd, Nettleham, Lincoln, UK.

[3] Isight User's Guide, Version 5.0, 2010. Engineous Software, Inc., Cary, NC, USA.

[4] N. A. Cumpsty. *Compressor Aerodynamics*. Longman Scientific & Technical, Longman Group UK, Limited Essex CM20 2JE, England, co-published in the United States with John Wiley & Sons, Inc, 1989.

[5] N. A. Cumpsty. Some Lessons Learned. *Journal of Turbomachinery*, 132:041018, 2010.

[6] M. A. Howard and S. J. Gallimore. Viscous throughflow modeling for multistage compressor design. *Journal of turbomachinery*, 115:296, 1993.

[7] A. Keskin and D. Bestle. Application of multi-objective optimization to axial compressor preliminary design. *Aerospace science and technology*, 10(7):581--589, 2006.

[8] B. Lakshminarayana. *Fluid dynamics and heat transfer of turbomachinery*. Wiley-Interscience. John Wiley & Sons, Inc, 1996.

[9] L. Larsson, T. Grönstedt, and K. G. Kyprianidis. Conceptual design and mission analysis for a geared turbofan and an open rotor configuration. In *Proceedings of ASME Turbo Expo*, June 2011. Paper No. GT2011-46451.

[10] A. B. McKenzie. *Axial Flow Fans and Compressors: Aerodynamic Design and Performance*. Cranfield Series on Turbomachinery Technology, 1997 (Ashgate Publishing Limited).

[11] DC Miller and DL Wasdell. Off-design prediction of

compressor blade losses. *Proc. Instn Mech. Engrs, Part C: J. Mechanical Engineering Science*, pages 249--260, 1987.

[12] S. Obayashi, D. Sasaki, and A. Oyama. Finding tradeoffs by using multiobjective optimization algorithms. *Transactions of the Japan Society for Aeronautical and Space Sciences*, 47(155):51--58, 2004.

[13] A. Oyama and M.S. Liou. Multiobjective optimization of a multi-stage compressor using evolutionary algorithm. *AIAA Paper*, 3545, 2002.

[14] Lewis Page. Nasa working on 'open rotor' green (but loud) jets. http://www.theregister.co.uk/2009/06/12/nasa_open_rotor_trials/. Accessed April 2011.

[15] F. C. Schwenk, G. W. Lewis, M. J. Hartmann, and NACA. Glenn Research Center. *A preliminary analysis of the magnitude of shock losses in transonic compressors*. National Advisory Committee for Aeronautics, 1957.

[16] M. Swoboda, A. Huppertz, A. Keskin, D. Otto, and D. Bestle. Multidisciplinary compressor blading design process using automation and multi-objective optimization. In *Congress of International Council of the Aeronautical Sciences*, September 2006. Paper ICAS2006-5.6S.

[17] P. Wright and D. Miller. An Improved Compressor Performance Prediction Model. *Proc. Inst. Mech. Eng.*, pages 69--82, 1991. Paper No. C423/028.