Foroozan Zare, Árpád Veress

PRELIMINARY INTRODUCTION TO VIRTUAL PROTOTYPING OF JET ENGINE COMPONENTS BY MEANS OF AERODYNAMIC DESIGN

The goal of the present paper is to provide a short introduction about the ongoing research project in conjunction with virtual prototyping of jet engine components. Several sampling phases can be omitted by computational technology and so significant amount of cost, time and capacity can be saved. Although the steps of the presented process are performed for the components belong to different applications, it can be extended and used for certain engine and its parts also. A concentrated parameter distribution-type method has been developed and implemented to analyse the thermodynamic characteristics of a jet engine by considering the expected specification. Mass and energy balance with realistic thermodynamic conditions are applied in the analytical approach. Mean line design of the compressor and turbine unit can be performed, by which the geometrical sizes of the compressor and turbine will be the output of the method following the 3D extension of the blading. Based on the available dimensions, including the other components, the 3D model of the gas turbine can be prepared in a CAD software.Following the verification of the design, CFD analyses can help to crosscheck the differences between the expected and the computed characteristics of the engine. The results of the simulations can be compared with the available measured and/or previously calculated data for validation and verification purposes and conclusions can be drawn about the accuracy and the efficiency of the used analytical and numerical methods.Inverse design method is a preferable tool to increase static pressure rise, the mass flow rate per unit length in the vanned diffuser of the compressor unit. The results of the inverse design method can be verified by a commercial CFD code via specific test case.

Keywords: *Low-sized jet engine, engine design, CAD modelling, CFD, validation*

INTRODUCTION

Many leading technologies are established in the aeronautical sector, wide spectrum of research and development are in progress in that areas [1][2], in which the propulsion systems of the aircrafts are also included.

Todays, the application of the gas turbine engines has increased significantly. This is especially true for the jet engines, which are the only relevant propelling systems of the high power commercial and military airplanes today. ВД-7Б single spool turbojet engine from Rybinsk Motors are shown in Figure 1. Additionally, the gas turbines are utilized also in the other sectors as oil and gas in energy production. In spite of the fact that those engines in comparison with piston ones don’t have similar level of thermal efficiency, they have substantial advantages in powerfulness, power density (power of the engine/mass of the engine), compactness, streamlining, simplicity and low maintenance cost demand.

These engines are less sensitive for the overloads; they produce less vibration due to the well balanceable and rather axisymmetric rotational components. The gas turbines have high availability (97%) and reliability (> 99%), they have low emission (there is no lubricant in the combustion chamber and no soot during transient loads) they contain less moving parts and represent less sensitivity for the quality of the fuel compared to the piston engines. Additionally, there is no need for liquid-based cooling system, but the maximum allowable temperature (~ 1500 °C) at the turbine inlet section must be limited due to the metallurgical reasons.

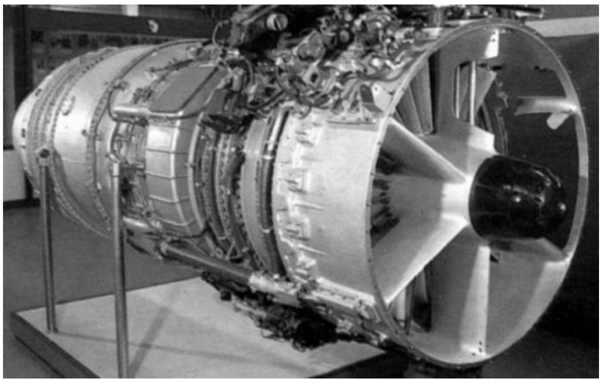

Figure 1. Photo of the ВД-7Б single spool turbojet engine from Rybinsk Motors, Russia [3]

Beside the technical characteristics of the gas turbines and its components today, certain amounts of potentials are available for improving their efficiencies, performances and emissions over the wider range of operational conditions [4][5]. Although the experiences and the know-how of the gas turbine manufacturers increasing continuously, the different mathematical models with using of optimum choice and form of the most dominant processes can significantly contribute to decrease the cost, time and capacity in the early phase of gas turbine design and developments. The main goal of the present ongoing research is to introduce a design procedure and analysis of a jet engine and its components by means of virtual prototyping.

DEVELOPMENTS OF A CONCENTRATED PARAMETER-DISTRIBUTION TYPE METHOD

A thermodynamic model has been developed and implemented in MATLAB environment for determining the main characteristics of single spool, dual spool turbofan, and triple spool turbojet engines w/wo afterburner at start position. The mass, energy balance and the real thermo dynamical processes are used in the concentrated parameter distributions type model. Ambient conditions, incoming air mass flow rate, pressure ratio of the compressor, turbine inlet total temperature, the length and diameter of the engine is used as available input parameters of the analyses. The material properties as specific heats and the ratio of the specific heats are depends on the temperature and component mass fraction and so they are determined by iteration cycles. Mechanical, isentropic and burning efficiencies, pressure losses, the bleed air ratio for technological reasons, air ratio for blade cooling, fan and intermediate compressor pressure ratios (if they are the cases), the afterburner temperature and power reduction rate of the auxiliary systems are involved as unknown parameters in the specifications. Hence, nonlinear constraint optimization is applied for determining the mentioned values by means of fitting the calculated thrust and thrust specific fuel consumption to the known parameters, which are available in the technical documents. The results of the optimization show that available and the resulted thrusts and thrust specific fuel consumptions are close to each other, the differences between them are below 5% as it is shown in the Table 1 for the engines ВД-7 and РД-9Б for example. The thermodynamic cycle of the specific engines can be plotted in T-s diagram (see Figure 2 for the ВД-7 engine). The processes between the engine-states denoted by numbers are plotted by black lines. This visualization effect is the reason of the constant pressure line goes below the process line in case of pressure decrement just after section “3”.

Type of turbojet engines	Available technical data for the verification (at start position)		Resulted parameters of the goal function by the optimization (at start position)		Relative errors	
	T [kN]	TSFC $[\text{kg.kN}^{-1}\text{h}^{-1}]$	T [kN]	TSFC $[\text{kg.kN}^{-1}\text{h}^{-1}]$	T [%]	TSFC [%]
single spool engine (ВД-7)	107.8	82	103.09	84.3	3.6	2.8
single spool engine (РД-9Б) with afterburner	32.4	163	33.5	166	3.3	1.84

Table 1. Comparisons of available data with the results of optimisation in case of single spool turbojet engines

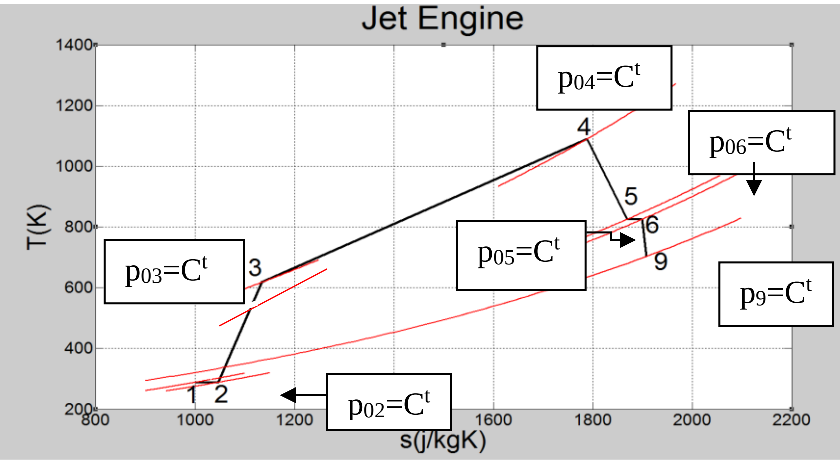

Figure 2. Thermodynamic cycle of the ВД-7 turbojet engine

MEAN LINE DESIGN OF JET ENGINE

Following the determination of the main geometrical sizes, the mean line design of the compressor and the turbine can be completed. The equations considered here are based on the common thermodynamic and aerodynamic principles in a mean stream path.

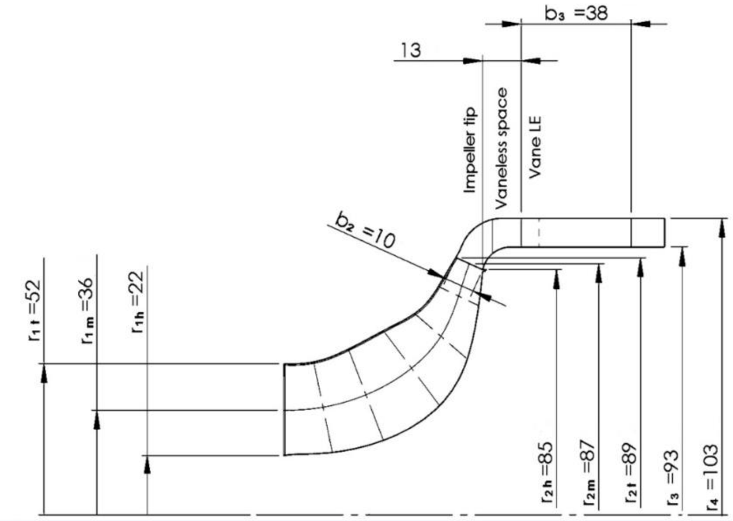

Figure 3. Meridional view of a compressor rotor

The output of the process is the type and the stages of the compressor and turbine units, if any, and the velocity triangles. The 3D model of the assembly can be prepared after the determination of the blade numbers and the design of the profiles with including the effect of real 3D flow conditions by means of blade twisting in case of need. Figure 3 shows a meridional view of a centrifugal compressor as one of the preliminary result of the design.

CFD MODELLING AND ANALYSES

CFD analysis can be applied to determine the correlation level between the expected and simulation provided parameters. ANSYS CFX program can be used for that purpose and the Reynolds averaged Navier-Stokes equation are considered to be solved numerically in the commercial software by finite volume method. The SST turbulence modelling can be applied following the Boussinesq approximation. A quarter model of a preliminary 3D jet engine flow field is found in Figure 4.

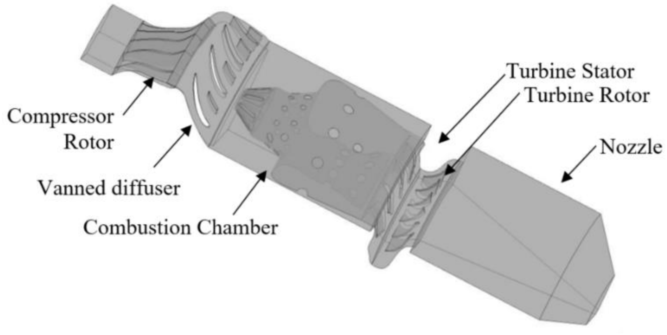

Figure 4. Assembly of a research jet engine

Although a full gas turbine section is presented in Figure 4, a preliminary CFD analysis of a centrifugal compressor has been completed within the framework of the present paper. The qualitative results are plotted at 80% RPM and 0.8 kg/s mass flow rate and they are shown in Figure 5. The output of the simulation is compared to the analytically calculated parameters in [6] for verification.

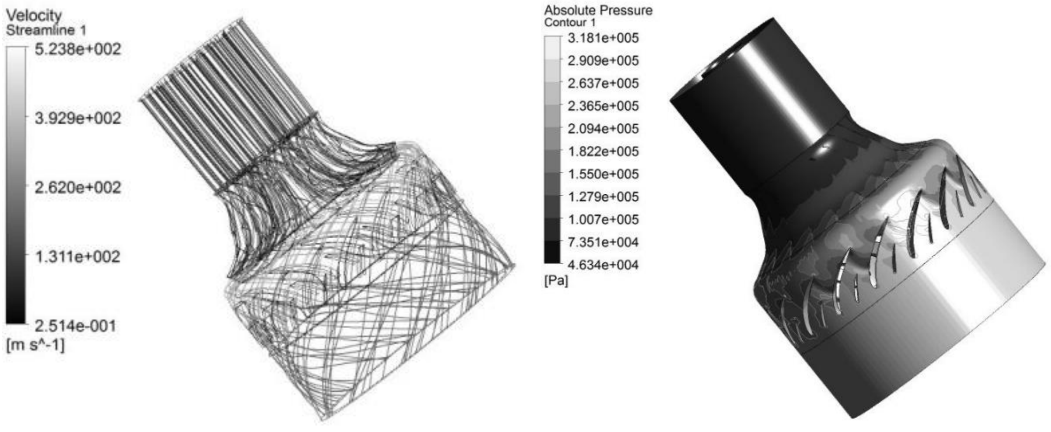

Figure 5. Streamlines (are coloured by the velocity magnitude) (left) and absolute static pressure distribution (right) in the centrifugal compressor unit at 80% rotational speed and at 0.8 kg/s mass flow rate

The compressor map is determined at three RPMs as 60%, 70% and 80% of design speed and at 3 mass flow rates. The quantitative simulation results together with the previously, analytically calculated ones in [6] are shown in Figure 6. The plausibility check of the simulation provides acceptable differences between the two approaches; the average deviation between the two results is less than 5%.

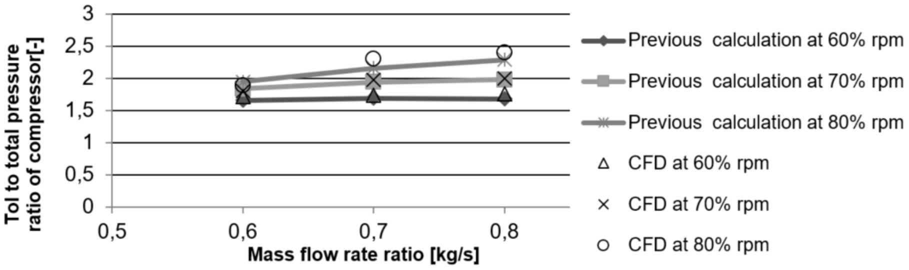

Figure 6. Comparison of CFD simulation and the analytical calculation results in the compressor map

The exact value of total pressure ratio in case of the previously calculated [6] and CFD results are also presented in Table 2.

	Mass flow rate [kg/s]			Results of the analytical calculation for the total pressure ratio [-]			CFD results for total pressure ratio [-]		
60%	0.6	0.7	0.8	1.66	1.69	1.69	1.72	1.74	1.76
70%	0.6	0.7	0.8	1.84	1.94	1.99	1.8	1.98	2
80%	0.6	0.7	0.8	1.96	2.16	2.29	1.89	2.3	2.4

Table 2. Compressor characteristics at the investigated range

APPLICATION OF THE INVERSE DESIGN METHOD

The inverse design method can be implemented and applied for increasing the static pressure ratio of the vanned diffuser. Compressible Euler equations are considered in the presently used inverse design code and a finite volume method has been applied to solve the system of the nonlinear partial differential equation numerically.

The basic operation principle of the inverse design process is the following. Initial geometry and expected (optimal) pressure or velocity distribution over the profile should be available. The iterative cycle starts with the direct solution of an inviscid CFD solver in the present case. Completing the convergence criteria, a new boundary condition is imposed at the solid boundary to be optimized, by which the wall become locally opening as inlet or outlet, depends upon the evolved pressure distribution between the boundary and computational domain. The outcome of this analysis is a velocity distribution along the wall, which is not necessarily parallel with it. The final step of the cycle is the wall modification. The wall becomes parallel with the local velocity vector corresponds to a new streamline of the flow field. The mentioned procedure is repeated until the target distribution is reached by the direct analysis and so the new geometry is available.

Before the application of the inverse design method, plausibility analyses were completed in order to verify the correct operation and the accuracy of the method. NACA 65-410 profile has been adopted for constructing a 2D cascade and for providing initial geometry. Stratford's separation prediction method with constrained Sequential Quadratic Programming was used to determine the optimum pressure distribution at given boundary conditions along the suction side. The optimum pressure distribution was imposed in the inverse design mode of the solver for evolution of the corresponding contour belongs to that required pressure distribution. Following the determination of the expected profile with the flow field, the results were compared with the outcomes of the ANSYS CFX in inviscid and viscous mode also at the same geometry, mesh, boundary conditions, material properties and physical settings. Figure 7 provides information about the results of the in-house program and the CFX software. The pressure distribution around the blade profile shows around 7% average deviation between the two results.

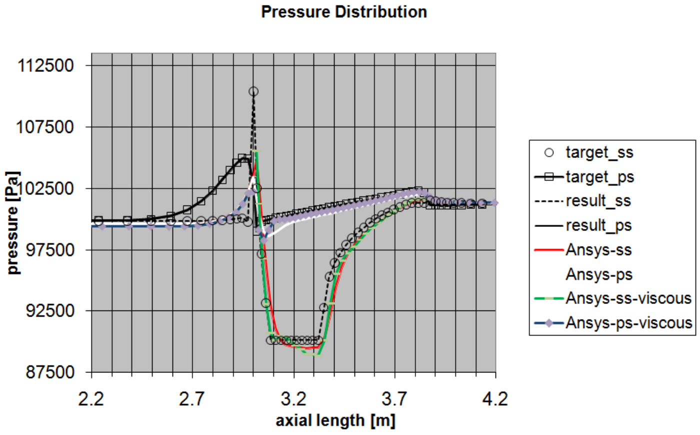

Figure 7: Pressure distribution of the redesigned blade configuration

CONCLUSIONS

An outline about the main steps of a design process of jet engine with analysis is briefly introduced in the present paper. Although the procedure can be used for the components belong to different applications, it can also be applied after specific adaption to certain engine and its parts.

The thermodynamic variables of the engine can be determined by a concentrated parameter distribution-type method based on the predefined design specification. Mass and energy balance with real thermodynamic processes were considered in the analytical model.

Mean line design of the jet engine can be completed with considering the available thermodynamic results. Following the consideration of the 3D realistic flow conditions, the outputs of the present design can be used to determine the dimensions of the engine.

Based on the available dimensions, the 3D model of the gas turbine can be prepared in CAD software. CFD analyses can be completed to verify the differences between the expected and the computed performances.

Inverse design method can implemented in order to increase pressure rise in the vanned diffuser of the compressor unit. The results of the inverse design method have been verified by a commercial CFD code via a specific test case.

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REFERENCES

[1] Gáti, B. - Drouin, A.: Open Source Autopilot for Academic Research – The Paparazzi System, Proceedings of the American Control Conference, Washington DC: AACC International, pp. 1-6. ISBN: 978-1-4799-0175-3, 2013

[2] Voskuilj, M. - Rohács, D. - Rohács, J. - Schousttra, R. J.: Preliminary Evaluation of the Environmental Impact related to Aircraft Take-off and Landings supported with Ground Based (MAGLEV) Power, Journal of Aerospace Operations, vol. 2, no. 3-4, pp. 161-180. DOI: 10.3233/AOP-140040

[3] Shustov, I. G.: Dvigateli, 1944-2000: Aviatsionnye, Raketnye, Morskie, Promyshlennye, pp.: 165, Moskva: AKS-Konversalt, ISBN: 5900954048 9785900954042, 2000.

[4] Beneda, K.: Preliminary Results of Active Centrifugal Compressor Surge Control Using Variable Inducer Shroud Bleed, Periodica Polytechnica Transportation Engineering, 39 (2), pp. 49-54. 2011, DOI: 10.3311/pp.tr.2011-2.01

[5] Beneda, K.: Numerical simulation of MEMS-Based Blade Load Distribution Control in Centrifugal Compressor Surge Suppression, AIP Conference Proceedings, 1493, pp. 116-123, 2012, DOI: 10.1063/1.4765479

[6] Beneda, K.: Épülő gázturbinás sugárhajtómű üzemi jellemzőinek vizsgálata matematikai modell segítségével, MSc thesis, BME, Department of Aeronautics, Naval Architecture and Railway Vehicles, (http://marert.fw.hu/tsz21/tkt-1.htm, 29.11.2015.), 2006.

SUGÁRHAJTÓMŰ-RÉSZEGYSÉGEK AERODINAMIKAI ALAPÚ TERVEZÉSÉNEK ÉS VIRTUÁLIS PROTOTÍPUS GYÁRTÁSÁNAK ELŐZETES BEMUTATÁSA

A jelen publikáció célja, hogy a virtuális prototípus gyártás kutatási témakör keretében betekintést nyújtson a sugárhajtóművek tervezésének és fejlesztésének főbb lépéseibe. A virtuális prototípus gyártás egyik legfontosabb előnye az, hogy alkalmazásával számos mintafázis elkészítése és valós körülmények közötti tesztelése váltható ki, melynek köszönhetően jelenős költség, kapacitás és idő takarítható meg. A bemutatott munka elsősorban az egyes lépések rövid ismertetésére koncentrálódik függetlenül az egymásra épülő számszerű adatoktól. A módszer kiterjeszthető és alkalmazható eltérő üzemállapotokkal és részegységekkel rendelkező gázturbinák esetén is. Koncentrált paramétereloszlású eljárást dolgozunk ki és implementáltunk MATLAB környezetben a sugárhajtóművek termodinamikai vizsgálatának és fejlesztésének érdekében. A módszer a tömeg- és az energia-megmaradás elvére épül a súrlódásos folyamatok, valamint az anyagtulajdonságok hőmérséklet-, és összetétel-függésének figyelembevétele mellett. Az elvárt tervezési specifikációk alapján kiszámított paramétereket a tervezés következő fázisaiban használhatók fel. A kompresszor és a turbina geometriai méreteinek meghatározása érdekében az áramlás középvonalán érvényes tervezési lépéseket kell végrehajtani. A 3D-s kiterjesztést követően a rendelkezésre álló dimenziók segítségével elkészíthetővé válik a hajtómű CAD modellje. A tervezés eredményeinek plauzibilitás-vizsgálata után CFD számítások segítségével ellenőrizhetők az elvárt és a kialakult tervezési specifikációk közötti különbségek. A validáció és verifikáció érdekében a CFD számítások eredményei összehasonlíthatók a rendelkezésre álló korábbi számítási, illetve mérési eredményekkel, melynek köszönhetően megállapítható az alkalmazott analitikus és numerikus módszer pontossága és hatékonysága. Inverz tervezési módszer implementálását követően lehetőség nyílik a kompresszor egység lapátos diffúzorában kialakult statikus nyomás, az egységnyi hosszon figyelembe vett tömegáram és az axiális irányú áramláseltérítés további növelésére. Az inverz tervezési módszer alkalmazásának verifikációját egy kereskedelmi CFD szoftver segítségével végeztük el egy adott teszt esetre vonatkozóan.

Kulcsszavak: *kis-gázturbina, sugárhajtómű, hajtóműtervezés, CAD modell-készítés, CFD, validáció*

Zare Foroozan	Zare Foroozan
PhD hallgató	PhD Student
Budapest Műszaki és Gazdaságtudományi Egyetem	Budapest University of Technology and Economics
Közlekedésmérnöki és Járműmérnöki Kar	Faculty of Transporting Engineering and Vehicle Engineering
Vasúti Járművek, Repülőgépek és Hajók Tanszék	Department of Aeronautical, Naval Architecture and Railway Vehicles
fzare@vrht.bme.hu	fzare@vrht.bme.hu
orcid.org/0000-0002-5486-5881	orcid.org/0000-0002-5486-5881
Dr. Veress Árpád	Dr. Veress Árpád
egyetemi docens	Associate Professor
Budapest Műszaki és Gazdaságtudományi Egyetem	Budapest University of Technology and Economics
Közlekedésmérnöki és Járműmérnöki Kar	Faculty of Transporting Engineering and Vehicle Engineering
Vasúti Járművek, Repülőgépek és Hajók Tanszék	Department of Aeronautical, Naval Architecture and Railway Vehicles
averess@vrht.bme.hu	averess@vrht.bme.hu
orcid.org/0000-0002-1983-2494	orcid.org/0000-0002-1983-2494

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