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MULTIDISCIPLINARY DESIGN AND OPTIMIZATION OF GAS TURBINE ENGINE LOW PRESSURE TURBINE AT PRELIMINARY DESIGN STAGE

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Abstract

The gas turbine engine has evolved rapidly during past decades to provide a reliable and efficient business solution for global transportation. The engine design process is clearly a large contributor to this evolution. This process is highly iterative, multidisciplinary and complex in nature. The success of an engine depends on a carefully balanced design that best exploits the interactions between numerous traditional engineering disciplines such as aerodynamics and structures as well as lifecycle analysis of cost, manufacturability, serviceability and supportability. To take into account all of these disciplines and optimization should be used. Currently most of present state-of-art numerical modelling methods, which are used mainly at detailed design stage, are unsuitable for this task due to very high computational time. The solution to this problem can be found in multidisciplinary design and optimization at preliminary design stage with use of simple 1-2D models. This paper presents current aero engine design process and indicates possibilities of future improvements by utilization of proposed methodology, which take into account aerodynamic, thermodynamic and structures (blade, fixing and disc) calculations, connected in one multidisciplinary model, which is suited for optimization. All disciplinary models are presented and described in this paper as well as connection between them, with study over design variable, goal function and constrains that should be used. Moreover, a strategy of optimization is proposed as well as methods for acceleration of optimization process by use of surrogate. The presentation of methodology is followed by example optimization of low-pressure aero engine turbine.

Keywords: *design and optimization, turbo machinery, turbines*

1. Introduction

The aero engine design process is highly iterative, multidisciplinary and complex in nature. Usually this process is divided into subparts with milestones in between to provide suitable control and validation as it can be seen in Fig. 1.

During three past decades, a significant improvement in this process can be observed. Especially in detailed design phase. All new state-of-art computational methods like FEM, CFD, CAD and CAM together with more and more efficient computation platforms brought brand new possibilities in order to produce cheaper and better engines in shorter time. A multi-objective and multidisciplinary optimisation had a crucial influence to these improvements. It can be observed that great effort is placed on very detailed optimisation of aero engine geometry and is disproportionate to other phases of design, which seems to be much neglected. In turbines design a good example are articles [1-3] in which; blade, end-wall, tip clearance and cooling channels geometry are optimized in order to improve efficiency, reduce mass but as well to reduce life cycle cost, manufacturability, serviceability and supportability.

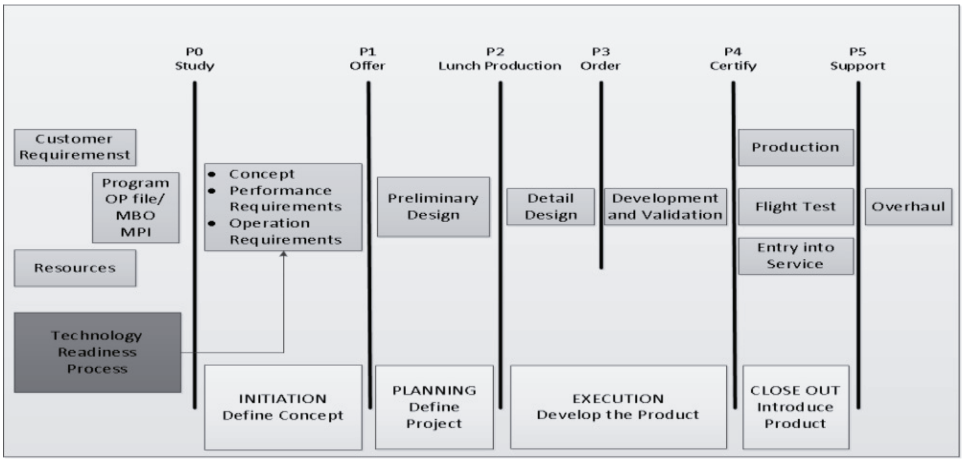

Fig. 1. Aero-engine design process

All of cited articles utilize very high fidelity 2D and 3D methods. These methods require high computational power and need a good deal of time. They are allowing improving performance by adjustments to geometry, so they play a key role at detailed design phase. But they can't be used for synthesis of a complete product or even a product component to evaluate its attributes over a range of alternative designs. An ability to do so can be obtained with use of PMDO (Preliminary Multi-Disciplinary Optimisation) in a hierarchical multi-level approach to design space presented in Fig. 2.

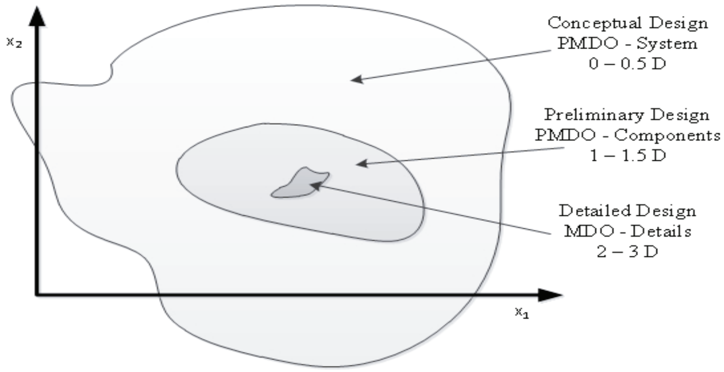

Fig. 2. Hierarchical multi-level approach to design space example – aerodynamic design

Hierarchical multi-level approach to design problem fits perfectly into whole aero-engine design process. It uses methods of different fidelity in order to reduce design space. This approach requires minimum three levels of fidelity. First level utilizes numerical model of low resolution to perform conceptual design. Low fidelity and high integration enable analyse of a whole engine as a system [4, 5]. This approach allow rapid synthesize of a complete product and evaluation of many alternate designs. Second level uses medium resolution models to carry out preliminary design of components. Medium fidelity and integration allow synthesise of a component and helps to explore alternate designs of this component. The constrains and objectives for this phase come from previous level and reduce the design space in which search are performed for a feasible solution. The last level uses highest resolution. High fidelity but low integration model allow to improve particular aspects of a component by small adjustments to its geometry [1-3] taking into account constrains from previous level.

Studying literature and publications on aero-engine and turbine design it is hard to find articles that presents methodology, which can be straight, used at second level of presented multi-level approach. Moreover, in most of companies, PMDO is used at conceptual phase and MDO is used during detailed design, but preliminary design methodology still stays very classical. On the other hand, if PMDO is used at this stage, the current methodology do not let for a high-speed assessment of many concurrent designs because of high fidelity methods. In order to give ability to study wider range of alternatives designs on preliminary design phase a multidisciplinary methodology is proposed.

2. Multi-disciplinary modelling of a aero-engine turbine

The work over developing multidisciplinary design and optimisation methodology for preliminary turbine design began with study over current design process. A key design phases and disciplines have been recognized. The selection of disciplines and design phases was conducted in a way to allow high-speed assessment of competitive designs and at the same time to provide as much definition of geometry as it is possible at preliminary design phase. The main design disciplines in aero-engine turbine design are shown in Fig. 3. The disciplines selected to come into presented methodology are chosen based on type of turbine (low-pressure turbine) that is picked to design. Disciplines marked by black rectangles in Fig. 3. where taken into account in presented model.

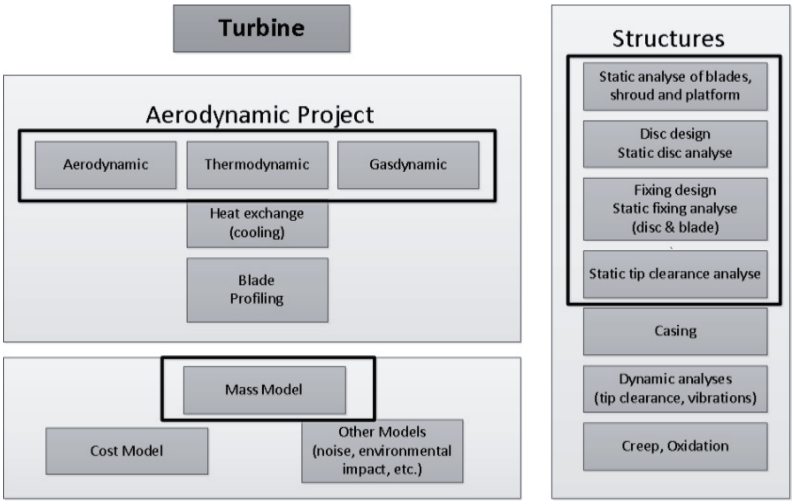

Fig. 3. Design disciplines in aero-engine turbine design

The design phases like blade profiling and dynamic analyse of structures, especially tip clearance, was omitted because they require higher fidelity methods. It seems more important to achieve closure over a wider range of alternatives with a fast procedure that has a lower resolution. Than to run out of time and fail to achieve closure or miss key strategic decision milestone by using a slower process that offers a theoretically higher resolution [4]. That analysis can be made as a post process during preliminary design. Alternatively, moved to detailed design where higher resolution methods on smaller design space can be used.

The key part of multi-disciplinary turbine design model is aerodynamic model. It must take into account aerodynamic, thermodynamic and gas-dynamic relations in order to give performance data based on given geometry and boundary conditions. The one-dimensional semi-empirical mathematical model was picked. The model uses mean-line analyse based on [6-12], with some corrections that takes into account change in radius at key stations.

The governing equation is based on one-dimensional continuity equation along a channel. Using isentropic and perfect gas relations, energy conservation relation, Mach number equation and losses term as presented in [12] a relation for purely axial machines can be obtained. In order to take into account change in mean radius along machine, for rotor analyse, isentropic relations for relative total temperature and pressure that takes into account blade speed should be used.

The key role, in presented model, plays loss and deviation correlations. The loss model is based on Ainley and Mathieson (AM) loss correlation presented in [13] with updates made by Dunham and Came (AMDC) [14], Kacker and Okapuu (AMDCKO) [15], Moustapha [16] and Dubitsky [17]. The transition between pressure loss coefficient and total pressure loss coefficient is based on isentropic relation as presented in [12] with correction for change in mean radius along the machine. The deviation angle is calculated based on assumed Mach number and profile geometry as presented in [13, 17].

Based on described governing equation and simple relation for velocity triangles and gas state parameters a multistage turbine can be solved with row-by-row method. The boundary conditions for this analyse are total pressure and temperature at inlet to turbine and static pressure at outlet from turbine. In this way, the turbine performance is calculated based on geometrical parameters in design-point and off-design conditions.

Most of turbine structures elements; shroud, blade, platform, and fixing, has been modelled with use of one-dimensional relationship presented in [18] with some modifications. For example the model for fixing calculation was adjusted for bigger lobes than original [18] in line with contemporary trends in fixing design. All the analyses are run in a way to take into account high temperature in which turbine elements works. The models of shroud, platform and fixing are constructed in the way to obtain minimum mass of these elements that will sustain actual centrifugal force on the machine. The blade is divided into sections in order to check tensile stresses and calculate total elongation of the blade. The disc is analysed with use of Finite Differential Method (FDM) presented in [18, 19]. The geometry of a disc is constructed on six points with two coordinates (R – radius, H – width) each as shown at Fig. 4. As a result from this analyse reduced stresses and disk elongation is obtained.

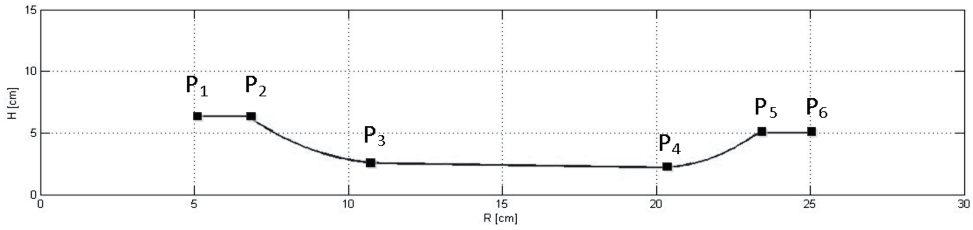

Fig. 4. Cross-section of disc geometry. R – radius, H – disc width

Another important part of structures model is a profile model. The blade geometry take into account parameters mentioned at Fig. 5.

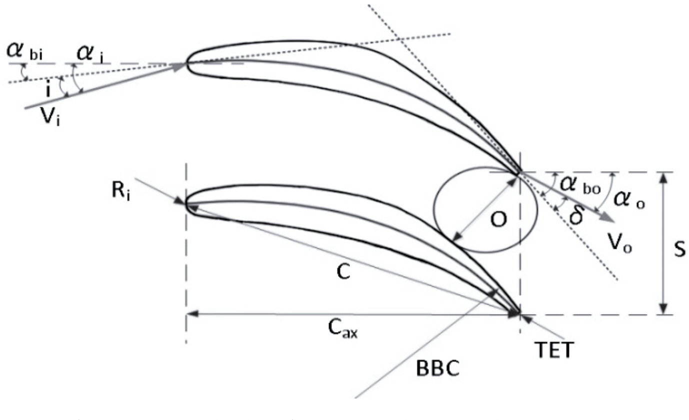

Fig. 5. Blade model: c – chord, c_{ax} – axial chord, s – pitch, o – throat, Vi – Inlet speed, Vo – outlet speed, Ri – leading edge radius, BBC – back blade curvature radius, TET – trailing edge thickness, α_{bi} – blade angle at inlet, α_i – gas angle at inlet, α_{bo} – blade angle at outlet, α_o –gas angle at outlet, i – incidence, δ – deviation

A real blade profiles has been constructed and parameterized in CAD system. The design of experiment (DoE) procedure has been run in order to get nominal point for interpolation. Based on blade design variables: chord, stagger metal angles and pitch to chord ratio, the blade model is interpolating; blade cross-section area, throat, pitch, trailing edge thickness, back blade curvature radius, leading edge radius and maximum blade thickness. Those parameters play a key role in deviation and loss models for performance calculation and in structures models for stress and elongation calculations.

The multidisciplinary model of aero-engine turbine has been implemented in MatLab environment. The input variable that are necessary to perform one stage calculations are: outlet static pressure, inlet total pressure, inlet total temperature, inlet total density, inlet gas angle, gas constant, inlet adiabatic ratio, inlet heat capacity at constant pressure, air-fuel ratio, stoichiometric air, angular velocity of rotor, mean radiuses at inlet, intermediate and outlet station, channel height at the same stations, blade staggers, metal angles at inlet and outlet, chords, tip clearance, blade numbers, type of blade tip (shrouded or unshrouded), profile, blade material, disc material, disc bore width, disc bore height, disc live rim radius and coordinates for points P3 and P4 from Fig. 4. As a output from multidisciplinary analyse the following parameters are obtained: performance of turbine (efficiencies, mass flow, work, power, flow and load coefficients and etc.), speed triangles and flow angles, total and static gas parameters in relative and absolute frame, loss coefficients, mass of turbine, corrected tip clearance height, information on safety factor (actual stress/max admissible stress) of blade and disc and dimensions of fixing, shroud and platform.

3. Multi-disciplinary design and optimization

The problem statement can be described as: “Maximize the efficiency and minimize the mass of a aero-engine low pressure turbine by changing blade, channel and turbine structures geometry while satisfying the given mass flow and power output requirements for given conditions at turbine inlet and outlet stations”. The general formulation of this design and optimization problem takes the following form:

$$\begin{gathered} \widetilde{F} = extr\Phi\left(f_1\left(x,p\right),\ \ldots,f_n\left(x,p\right)\right) \\ \text{for} \quad x_i \in X;\ p_i \in P, \end{gathered} \tag{1}$$

where:
x – vector of design variables,
p – vector of parametric variables,
ϕ – objective function.

The total mass of turbine and efficiency are objective functions. Turbine geometry data are design variables. The power output and mass flow are nonlinear constrains. The boundary conditions are introduced into model along with other constant geometrical variables as a parametric variables. Beside those variables linear constrains over design variables must be defined to ensure feasibility of geometry.

The schema of adopted optimization algorithm is presented on Fig. 6. The task requires using of global optimization methodology in order to find satisfying solution. A Monte-Carlo method was chosen for outer loop because of integer values of some design variables. Gradient and pattern search methods from MatLab optimization toolbox fail in this kind of cases. Only genetic algorithm is capable of solving problems with integer values but in this particular example this methods fails. The outer loop continues its search until it finds a good feasible point that might ensure success of inner loop gradient search. The local optimization is run for integer design variables: blade number, shrouded/unshrouded option, disc and blade material and profile type set during Monte Carlo optimization loop. In this way, solutions from local optimization for different turbine arrangement can be obtained. Those designs are evaluated in order to find satisfying solution. During evaluation, a further design space exploration is also performed. Approximations are made in order to find turbine arrangement that is worth to check. Moreover, all solutions are archived in order to prepare surrogate model for finding new interesting starting points.

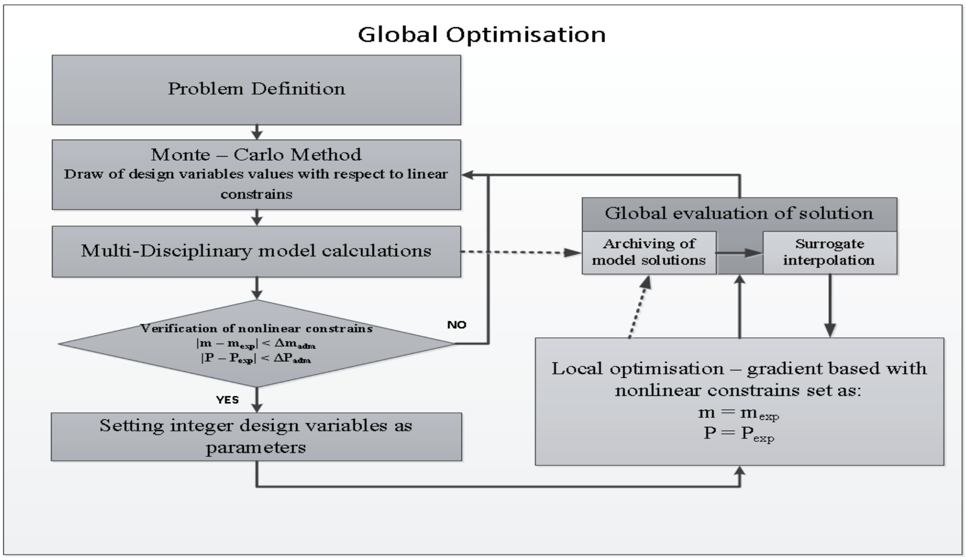

Fig. 6. Global optimisation schema .m – actual mass flow, m_{exp} – expected value of mass flow, Δm_{adm} – admissible value of difference between actual mass flow and expected mass flow, P –actual power output, P_{exp} -expected value of output power, ΔP_{amd} – admissible value of difference between actual output power and expected output power

The surrogate model uses neural network approximation based on all design points generated in the past. Having sufficient number of points and well-trained neural network gives the ability to explore design space even ten times faster. The main disadvantage of this solution can be quite big uncertainty of obtained values when neural network is not well-taught or constructed on not sufficient number of points. Anyway, it can give quite interesting starting points for local optimization and speed up the solution process.

4. Example optimization

In the example optimization presented in this paper the main boundary conditions was static pressure at outlet from turbine – 140000 [Pa], total temperature at inlet to turbine – 1100 [K], total pressure at inlet to turbine – 290000 [Pa], gas angle at inlet to turbine – 0 [deg], rotational speed – 17000 [RPM]. The calculation was conducted for one blade profile type and one material type (the same for blade and disc). Moreover, rotor blades were assumed shrouded. The constrains on geometry was: mean radius – <0.1429-0.2058> [m], stagger – <10-30> [deg], height of channel passage – <0.041-0.0864> [m], metal angle inlet – <0 – 50> [deg], metal angle outlet – <40-70> deg, blade aspect ratio – <0.7 2>. The nonlinear constrains was: power – $1.3*10^6$ [W] and mass flow – 10 [kg/s]. Moreover additionally constrains was introduced. The gas outlet angle should be between <-10 10> [deg] and choking conditions should occur in stator row. The goal function in local optimization was based on total-to-total isentropic efficiency. The goal of minimum mass is achieved on global optimization level during results analyse and by optimization of disc geometry inside structures mathematical model which gives minimum mas for maximum efficiency point.

After solving around 376000 points in optimization algorithm presented in Fig. 6. we can present some data in order to evaluate them and set direction for further search. Fig. 7. presents mass flow vs. power output from turbine. Based on the chart it can be quickly validated if the number of stages is sufficient for the desired power output or another stage is necessary. In presented example, the design point lies exactly in the middle of max and min black lines from the figure. Fig. 8a. presents how many points was calculated for different blade number arrangement and Fig. 8b. presents how many of this points was feasible. Those are very important information that tells about the progress of optimisation. It gives clues, which arrangement still needs to be checked, and where number of calculated points is sufficient to stop searches.

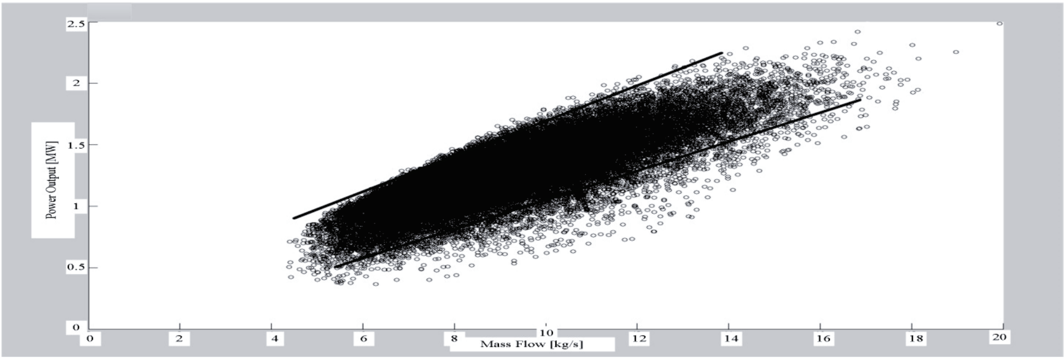

Fig. 7. Mass flow vs. Power output based on around 376000 points calculated

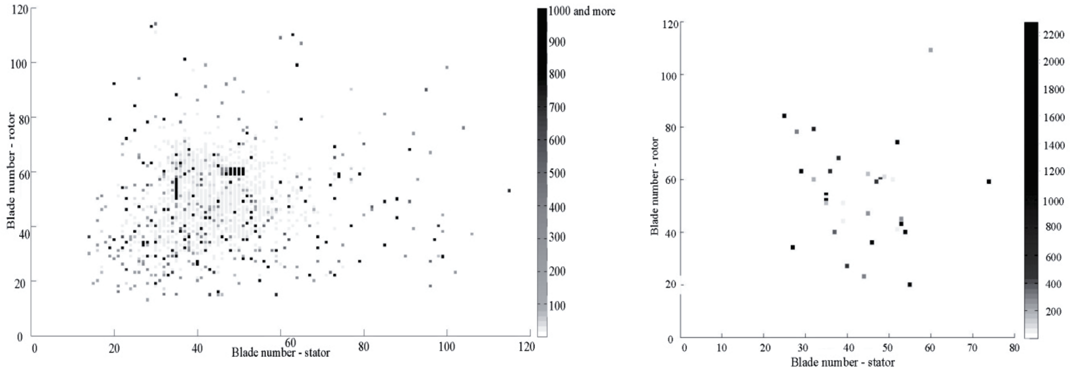

Fig. 8. a) Number of points calculated for different blade number arrangement. b) Number of feasible points calculated for different blade number arrangement

The Fig. 9. presents total-to-total isentropic efficiency vs. turbine weight for feasible highest efficiency points with different blade number arrangement. The points in lower left corner of chart are the most promising. To choose the proper one that will be used, additional tests with higher fidelity methods should be done.

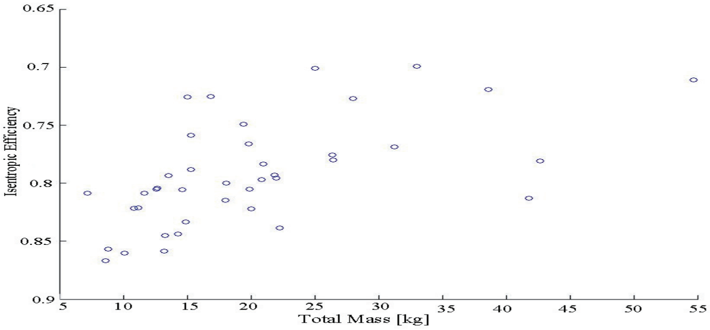

Fig. 9. Total turbine weight vs. total-to-total isentropic efficiency for different blade arrangement

5. Summary

The use of PMDO methodology at preliminary design phase allows evaluation of turbine attributes over a wide range of alternative designs. The crucial influence on success of PMDO system is a well-balanced and carefully chosen mathematical modelling of optimised structure, which must compromise demanded high speed of calculations with analyse resolution. Proposed low resolution and high speed methodology allows investigating tremendous amount of concurrent design in a small time. Which gives more insight and understanding of designed component, and might lead to better design.

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