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www.elsevier.com/locate/aescte

A novel concept for non-linear multidisciplinary aerodynamic design optimization

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ARTICLE INFO

Article history:
Received 30 August 2016
Received in revised form 4 June 2017
Accepted 28 August 2017
Available online xxxx

Keywords:
Entropy generation
Aerodynamic shape optimization
Wing box
Evolutionary algorithm
Entropy based design

ABSTRACT

A fundamental approach is presented here in order to define a comprehensive property that overwhelms the limitations of existing aerodynamic design/optimization practice. A novel parameter is derived extending the loss model accounted by the second law of thermodynamics. The given approach attempts to quantitatively relate the finite-time thermodynamic irreversibilities associated with a particular shape class of a body across a flow field. It is then studied analytically by applications in external and internal aerodynamics. Further, the physical behavior of the function is explored using a case study for aero-structural optimization along with other physical quantities with established behavior (Multi-Disciplinary-Optimization). A baseline model of aerodynamically twisted wing profile entailing NACA 1412 and NACA 621112 airfoils is optimized using Elite member selection based Multi-Objective Genetic Algorithm (MOGA). The proposed function is proven to be more computationally economical and comprehensive for optimization.

1. Introduction

The multi-disciplinary nature and complexity of aerospace systems make them uniquely challenging. Their numerical modeling/analysis and optimization are computationally expensive and exclusively selective to the area of investigation. Real-world aerospace systems encounter majorly two problems: Multiverse objectives and highly complex and diverse design space. Over past few decades various direct and inverse optimization techniques have particularly found utility in development of optimized aerodynamic shapes like wing/blade geometry. The flagship practices for optimization of aerospace systems are based on multiple-shape/topology optimization, exclusively modified/hybrid algorithms or a combination of both. Apart from numerical parameterization, selection of objective or cost function is a defining step for the accuracy and efficacy of the analysis. However, the major concerns over the selection of the objective function are: specificity in representation of domain, computational cost against the comprehensively and primordially its dependence on the knowledge and experience of the researcher.

The choice of parameterization is dependent upon the nature/complexity and scope of the design/analysis. The simplest parameterization schemes include utilizing point cloud method, which is confined to lower order complexity resulted by increase in number of parameters in design space proportional to the complexity of formulation. A report published by Melin [1] projects a detailed discussion on comparison of parameterized airfoil based point cloud airfoils. A 'super element' based wing aero-structural optimization was conducted by Kuntjoro et al. [2]. Their analysis included a leading edge circular approximation and generation of separate pressure & suction surfaces using a polynomial representation in terms of meridian and tangential coordinates. To effectively reduce the computational time, Davari et al. [3] proposed to build a simple model from free form polynomials by controlling the camber and thickness of wind turbine blade sections only. One of the most popular parameterization scheme used in analysis was proposed by Sobieczky [4,5], known as PARSEC method which utilized 11 geometric characteristics of airfoil as control parameters. The upper and lower surface of the airfoil can be separately generated by using this method. Since, PARSEC method was particularly developed for airfoil shape generation, it limits the possibility of different airfoil shapes at the leading edge and does not guarantee a physically acceptable trailing edge, as discussed by Castonguay and Nadarajah [6].

The use of Bezier curves for parameterization has also been widely studied [8–10]. A notable multi-disciplinary and multi-objective study was conducted by Toivanen et al. [11] for aero-electromagnetic optimization which used Bezier curves to represent upper and lower surface with 9 control points each. Subsequently, Dersken and Rogalsky [12], proposed a PARSEC-Bezier interaction based parameterization scheme. It was particularly de-

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http://dx.doi.org/10.1016/j.ast.2017.08.043

signed to reduce the non-linear interactions of parameters and create a direct link to objective function and reduce the computational time. Gardner and Selig [7], found the optimal airfoil shapes through manipulation of velocity distribution using normal/hybrid genetic algorithm. Based on preset criteria, the airfoil geometry was generated using an inverse method from velocity distribution parameters for candidate airfoils. They showed that using design variables defining velocity distribution in inverse method can profoundly enhance the performance of the airfoil shape optimization genetic algorithm. A detailed analysis of present evolutionary algorithms was conducted by Zitzler [13]. The main focus of the study was to study the sensitivity of the Pareto-front on the shape of the objective function & use of weight function in the domain. He also indicated that the use of 'weighing function' cannot generate all Pareto solution to the non-convex surfaces.

A multi-point shape optimization technique was utilized by Montanelli [14], for design of turbomachinery blades. He used a discrete adjoint method using Non Uniform Relational B-Splines (NURBS) parameterization to generate the coordinate control space. His study includes the use of 'weights' as per their importance to the analysis and then combine them to define a single objective function for analysis. Straathof [15] also discussed some recent parameterization techniques in his proposal of a novel method using B-splines. It is to notice that though NURBS provide a compact and intuitive geometric representation, it's the complexity in their definition and resolution to which a geometry can be replicated in different computational environment. A more efficient and utilitarian concept was proposed by Kulfan [16] for Computational Fluid Dynamics (CFD) analysis. She compiled a list of desirable features for geometric representations and introduced Class-Shape-Transformation (CST technique). The technique uses a combination of specific shape and class functions resulting in different surface design space. The method will be further discussed in current analysis in subsequent sections. A detailed survey of shape parameterization techniques was published by Samareh [17] from NASA which acts a very helpful source for elements of topology optimization.

Since last two decades, the concept of exergy based design optimization analysis has been widely used for multi-level and multi-disciplinary aerospace system and component designs. The main advantage for the popularity of exergy based analysis is their ability of application in geometrically complex systems. One of the early work for using exergy method in aerospace systems is derived from Paulus and Gaggioli [18]. They used 'exergy of lift' for calculations, based on the idea of the energy delivered *to and by* the wing. The objective of the study was to successfully use exergy and plot the 'Exergy flow diagram' of the aircraft for all modes of flight (i.e., take-off, cruise, landing) based on various aircraft components. Alabi and Ladeinde [19,20], utilized the CFD based exergy calculations for the design of a complete aircraft systems (Boeing B747-200 aircraft). They carried out physical decomposition of the overall system was done for multi-level identification of airframe subsystems. Similarly, Li et al. [21] used exergy method for aerodynamic designs using a 2D and 3D wing geometry under turbulent flow conditions. They used 3rd order NURBS parameterization scheme for increasing Cl/Cd ratio and reduce volumetric entropy production rate using Genetic algorithm.

It can be evidently understood that a particular shape of a devise (wing/blade) affects its aerodynamic characteristics and other features like its weight, modal response etc. Thus, the irreversibilities like viscous and thermal dissipation produced in the domain of interest by the specific body (shape) is a very effective signature of the devise for analysis. Exergetic losses associated with a flow field is directly proportionate to the losses and the useful work lost by the fluid. Thermal dissipative forces play a significant part in aero-turbomechanic analysis, where a combination of thermal and viscous dissipative forces is considered to include the stagnation losses and losses incurred to the pressure gradients in flow field.

Bejan calculated the effects of wing shape on viscous dissipation (first term) and thermal dissipation (second term) produced in a system (eqn. (1)). For external flows over a typical wing, placed in a laminar flow field velocity of U, temperature T, W is the wing span length, body temperature T_w, q'' as heat transfer rate from body and surface area A, the local entropy production rate (irreversibilities) can be estimated as [22]

$$S_g \frac{kT^2}{q'^2 W} = 1.456\,\mathrm{Pr}^{-\frac{1}{3}}\, Re_L^{-\frac{1}{2}} + 0.664 \frac{U^2 \mu k T}{q'^2} Re_L^{\frac{1}{2}} \tag{1}$$

Though, the local entropy production is considerably effective tool in representing the physical system and account for losses, but it lacks on account of representing the multi-disciplinary nature of the system. As in, for aero-structural or aero-electromagnetic optimization, it will treat the wing shape as a black body, hence the other relevant factors like internal structure etc. cannot be accounted for. Therefore, in order to include all the physical aspects new optimization function needs to be defined, to make the analysis comprehensive & computationally economical. Also, as per designer prospective the shape should be conveniently parameterized and controlled in optimization process. Hence the new function should also extend this ability to approximate various classes of geometrical shapes.

2. Derivation and study of parameter (π_s)

Let us assume a generic aerodynamic body moving across a flow regime. The entropic losses (irreversibilities) incurred in the flow are influenced by the thermo-physical state of the medium and the specific shape of the body. As we know that every system is associated with some specific form of energy, we can use the intrinsic energy form (Q') for an analysis. The choice of the energy form is of prime importance here, which is further illustrated. Also, the rate of work losses associated in such an aerodynamic system can be calculated using Guoy–Stodola theorem [23]

$$\dot{W}_{lost} = T\dot{S}_g = T\left(\dot{S}_g = \frac{k}{T^2}(\nabla^2 T) + \frac{\mu}{T}(\emptyset)\right) \tag{2}$$

such that $\frac{k}{T^2}(\nabla^2 T)$, represents the conductive effects for thermal interaction across the flow field and $\frac{\mu}{T}(\emptyset)$ is equivalent to the viscous forces acting on the body placed in a temperature field (T). It can be noted here that S_g is always positive whenever there are velocity and thermal gradients present in any fluid flow domain. Thus, for any aerodynamic system we can identify

$$\dot{W}_{lost} \propto Q', A, \mu$$

and Q' is the intrinsic form of associated energy, A is area associated with the loss generation and μ is the thermo-physical property of the medium. Using Buckingham-π theorem [24,25], let us consider

$$\dot{W} = \emptyset(Q', A, \mu) = \emptyset(Q')^a (A)^b (\mu)^c$$

$$[ML^{-1}T^{-2}] = \emptyset[L^2T^{-2}]^a [ML^{-1}T^{-1}]^b [L^2]^c$$

Comparing, we get $a = 1$, $b = 1$, $c = -1$. Thus we can define

$$T\dot{S} = \emptyset \frac{Q'\mu}{A}$$

For simplicity, let $\emptyset = 1/\pi_s$, rearranging we get

$$\pi_s = \left(\frac{Q'}{\dot{W}}\right)\left(\frac{\mu}{A}\right) \tag{3}$$