



Inverse design in subsonic and transonic external flow regimes using Elastic Surface Algorithm



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ABSTRACT

In this study, a novel inverse design method, called Elastic Surface Algorithm (ESA), is proposed for airfoil shape design in subsonic and transonic flow regimes. ESA is a physically based iterative inverse design method that uses a flow solver to estimate the pressure distribution on the solid structure, i.e. airfoil, and a 2D solid beam finite element code to calculate the deflections due to the difference between the calculated and target pressure distribution. The proposed method is validated through the inverse design of five different airfoils. In addition, three design examples in subsonic and transonic regimes are presented to prove the effectiveness and robustness of the method. Finally, the convergence rate of the method is compared with MGM and BSA methods. The results of this study showed that not only the ESA method is an effective method for inverse design of airfoils, but also it can considerably increase the convergence rate in transonic flow regimes.

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1. Introduction

Inverse design methods are powerful tools for aerodynamic shape design. The purpose of inverse design is to achieve a particular shape such that either the pressure or velocity distribution on the boundaries reaches to a particular target. Inverse design methods are classified into two main categories: (a) coupled (direct) and (b) decoupled (iterative) techniques.

In coupled methods, a formulation is used in which the surface coordinates appear (implicitly) as dependent variables. Indirect transpiration technique, stream-function-as-coordinate approaches are among the coupled methods [1,2].

Transpiration model is a physical based algorithm in which one can assume that the wall is porous and hence the mass can be fictitiously injected through the wall in such a way that the new wall satisfies the slip boundary condition. Hence, the normal velocity vanishes and the tangential velocity on the final body surface satisfies the target velocity distribution.

In the stream-function-as-coordinate approach, an alternative formulation for steady ideal flows can be formulated in a transformed computational space in which the surface coordinates appear as dependent variables [3].

In iterative design approach, a series of sequential problems are solved while geometry is modified at each step. In these methods, flow equations and geometry modification equations are solved, independently. Flow equation can be solved using any commercial flow analysis software.

Garabedian–McFadden [4,5] presented an iterative inverse design method based on a mathematical approach called flexible membrane method (GM design). This method was later modified by Malone et al. [6–8] presently known as MGM (modified Garabedian–McFadden or Malone–Garabedian–McFadden) technique. In this mathematical approach the surface of an aerodynamic body is modeled as a membrane that deforms under aerodynamic loads. MGM governing equation is an ordinary differential equation with constant coefficients (these constant coefficients are related to the surface coordinate, its first and second derivatives) and a forcing function; therefore, it is easy to implement. Furthermore, the coefficient related to the second derivative of the surface coordinate is chosen less than the two other coefficients [9]. Also, MGM works in three-dimensions (for wings, rotors, nacelle surface, etc.) [10]. Dulikravich [2,11] presented an inverse design method based on an analytical Fourier series solution for MGM equation. Thus, the method was successfully tested at subsonic and transonic flow regimes for both airfoils and wings.

Nili et al. presented a physical algorithm for internal flows in which the duct wall is considered as a flexible string that deforms under the difference between target and current pressure

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Nomenclature

AOA	angle of attack	u_x	node displacement in X direction
AUSM	advection upstream splitting method	u_y	node displacement in Y direction
BSA	Ball-Spine Algorithm	u'_x	X derivative of node displacement in X direction
CPD	current pressure distribution	u'_y	X derivative of node displacement in Y direction
DOF	degree of freedom	V^0	transverse shear force in the reference configuration
E	modulus of elasticity	v	transverse shear force in the current configuration
e	axial strain	w	internal displacement vector
Error P	pressure error parameter	X	X coordinate in the reference configuration
ESA	Elastic Surface Algorithm	$\mathbf{z}$	resultant stress vector
$\mathbf{f}$	force vector	Δ	difference
FSA	flexible string algorithm	θ	cross section rotation from the reference to the current configuration
FSI	fluid–solid interaction	θ'	X derivative of nodal rotation (beam curvature)
G	shear modulus	γ	shear strain
$\mathbf{h}$	generalized strain vector	κ	curvature of the beam
I_0	second moment of inertia in the reference configuration	ζ	dimensionless parameter coordinate
$\mathbf{K}$	stiffness matrix	ρ	density of fluid (kg m^{-3})
M	Mach number		
m	bending moment in the current configuration		
M^0	bending moment in the reference configuration		
$\mathbf{N}$	element shape function matrix		
n	axial force in the current configuration		
N^0	axial forces in the reference configuration		
P	static pressure (Pa)		
$\mathbf{p}$	internal force vector		
Q	such as ρ , ρu , ρv , and ρe in the Euler equations		
SSD	surface shape design		
TPD	target pressure distribution		
$\mathbf{u}$	nodal displacement vector		
U	strain energy		

Subscripts

Low	related to the lower wall of airfoil
Up	related to the upper wall of airfoil
I.G.	initial guess
Target	target shape

Superscripts

n	related to current displacement
$n + 1$	related to updated displacement

distribution until the target shape satisfies the prescribed wall's pressure distribution. In FSA method, string mass control the solution stability. They developed this method for non-viscous compressible [1,12] and viscous incompressible internal flow regimes [13].

Recently, Nili-Ahmadabadi et al. [14] developed a novel inverse design method called Ball-Spine Algorithm (BSA) for quasi-3D design of centrifugal compressor meridional plane. In BSA, the walls of passage are composed of a set of virtual balls that freely move along specified directions called spines. The difference between target and current pressure distribution at each modification step is applied to each ball as an actual force deforming the wall frequently. They developed this method for inverse design of airfoils in subsonic and transonic external flow regimes [15].

In this research, a novel inverse design algorithm called Elastic Surface Algorithm (ESA) is developed for inverse design of airfoils in subsonic and transonic regimes. ESA is an iterative inverse design method and can be used in conjunction with any flow field analysis code. The proposed method is quite general and is not limited to the use of any particular flow analysis code. In this study, the Euler equations are solved using the advection upstream splitting method (AUSM [16]) in inviscid flow regime and RANS flow solver is used for viscous flow regime. The novel idea behind ESA is to model the airfoil surface as an elastic beam that can be deformed due to the difference between current and target pressure distribution. The internal stresses are then set equal to zero in the modified shape and the process is repeated until the calculated pressure distribution converges to the target pressure distribution on the solid structure. The ESA turns the inverse design problem into a fluid–solid interaction (FSI) scheme that uses the pressure concept to deform the flexible wall. Setting internal stress equal to zero at each shape modification step is the main difference between ESA and fluid–solid interaction.

Despite mathematical based methods such as MGM that require arbitrary choice of parameters, the beam characteristics such as thickness, elastic modulus, and shear modulus, control the solution stability in ESA. Therefore, the proper choice of them increases the convergence rate of the design process. Finally, the performance of the proposed method is evaluated with eight different case studies, i.e. NACA0011, FX63-137, 727 BOEING, and ONERA M6, E61. Moreover, three new airfoils were designed using the modified pressure distributions to show the application of the method.

2. ESA design procedure

A 2-D airfoil whose wall is composed of a flexible beam is shown in Fig. 1. Passing fluid flow around the airfoil causes a pressure distribution to be applied to the outer side of its walls. If a target pressure distribution is applied to the inner side of each wall, it is logical that the flexible beam deforms to reach to a stationary shape in which internal stresses counteract the differences between the target and current pressure distribution. If the internal stresses are virtually set to zero through the deformation process, the flexible beam finally reaches to a shape in which the difference between the target and current pressure distribution approaches to zero. In other words, the final airfoil shape corresponds to the target pressure distribution along its walls.

There are two approaches for airfoil inverse design by ESA. In the first one, two 2D curved beams hinged at both ends, as shown in Fig. 1a, are used to model the airfoil boundaries. In the second one, these two curved beams are substituted with one continuous curved beam, as shown in Fig. 1b.

The finite element method is used to compute the nodal displacement of the airfoil wall. In shape modification process, the chord length of airfoil is fixed. In other words, the beam moves

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