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The implementation of a knowledge-based framework for the aerodynamic optimization of a morphing wing device

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ABSTRACT

In the field of aerospace engineering currently a lot of research effort is directed towards the reduction of cruise drag of civil transport aircraft in order to reduce fuel burn, and hence environmental impact and costs. In order to reduce cruise drag, a promising method is under consideration by adjusting, or rather morphing the rear part of the aircraft's wing during cruise flight. Given the premature state of knowledge of such a design implementation, a knowledge-based computational framework is developed. The purpose of this framework is to allow for an aerodynamic optimization of a section of the wing. The framework is set up in such a way that all relevant design knowledge generated in the process can be captured and used in a subsequent mechanical design process. In this fashion, the complex design process of a novel morphing wing device can be automated to a certain degree. This automation can be used to construct a large number of different feasible and optimized designs with varying boundary conditions of a complex experimental device.

This article describes the initial 2-dimensional aerodynamic design step of the morphing device under consideration and how it is implemented in a knowledge-based optimization framework. It describes the initial stage of the development of this tool, as it will be expanded by a number of design steps that each adds more detail to the design in all relevant aspect fields (aerodynamic, structural, actuation, etc.). Ultimately, this tool will be used to obtain a thorough evaluation of a number of different proposed structural solutions and allow for a comparison between them.

1. Introduction

In the field of preliminary aircraft design much effort is spend on the optimization of the aerodynamic shape. In particular the cross section of the wing at various spanwise positions is subject to careful design, analysis and eventual validation by means of a wind-tunnel or actual prototype.

The design of an airfoil typically results as a compromise between low high-speed cruise drag, favorable low-speed characteristics, thickness requirements for the internal structure and volume requirements for cruise fuel. These criteria are typical for a modern civil airliner cruising around a Mach-number of 0.8 (80% of the ambient speed of sound), which is the focus of this paper.

Because of the careful compromise between the various design requirements that are stated above, the performance of the airfoil under consideration is usually only optimized for 1 or 2 flight conditions (typically the cruise-flight and climb-out phases of flight). In order to improve the off-design performance of a given airfoil, wing-structures are under investigation that can adjust its cross-sectional shape in flight to maximize performance at the current flight condition. In particular, so-called morphing devices that can adjust the wing's shape in a smooth, seamless fashion are receiving a lot of attention from the research community.

In order to facilitate the optimization of a morphing airfoil for various cruise-conditions, a design framework has been developed, implementing a Knowledge-based Engineering platform with built-in geometrical modeling engine, as well as dedicated aerodynamic analysis tools. The focus of this design framework is to allow a large number of parametric studies to a given morphing wing implementation in order to discover not only specific optimized results, but also general trends and design behavior. This design "knowledge" (in the KBE sense) is subsequently captured and implemented in the same design framework in order to improve and speed-up the aerodynamic optimization of the morphing device. This will, in its turn, allow the current design framework to be integrated in a larger, more complex wing design framework. This article will describe the initial set-up of such a tool, address difficulties that were encountered in obtaining an optimized

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morphing TE device and finally present the results that were obtained in this research.

1.1. Aerodynamics and flight performance

The purpose of the aerodynamic optimization framework that is elaborated in this paper is to find suitable shapes for an aircraft that is equipped with a morphing trailing-edge. The aerodynamic-surface variation is characterized by the parameterization method, which is described in section 2.4.

When considering the flight performance of a civil airliner during cruise-flight, there is potential for the morphing device that is described here to improve the fuel efficiency, by adjusting the wing's trailing edge as aircraft weight is reduced by fuel burn. As an aircraft performs a cruise-flight, its total momentary weight is carried in full by its wing. For this process a common performance indicator is used, being the aircraft's Lift to Drag ratio or L/D-ratio. Since weight is a factor that is not directly influenced through aerodynamics, reducing the drag that the wing generates, improves the aircraft's fuel efficiency. The value of this L/D-ratio, however, is strongly influenced by the amount of lift that the wing is required to carry at a given moment during its cruise phase. At some point during the cruise-flight, the maximum-efficiency condition will be achieved for an instant, the rest of the cruise flight experiencing a penalty for off-design performance. Ruijgrok [1] provides a very accessible text on these aircraft performance indicators.

When considering the wing's lift, it is common to filter out the effects of variation in airspeed, wing area and air-density. This allows for a comparison based purely on the wing's aerodynamic merits for different aircraft and at different flight conditions. The number that is derived in the above-described process is termed the lift-coefficient C_L. In an analogue fashion, a drag-coefficient C_D can be arrived at. Often the L/D-ratio is equated to the ratio of these two coefficients.

Now, when a wing is required to deliver a lower lift, this can be achieved by reducing the C_L at which it operates, which is closely dependent on the angle of attack, or rather the angle at which the oncoming airflow meets the airfoil. As mentioned, this requirement to deliver a lower lift could impose a penalty on L/D because of the off-design condition. The relation between L/D and C_L is, however, strongly influenced by the wing's cross-sectional shape. By adjusting this cross-section, the point of optimum L/D performance can be adjusted to fit the momentary C_L requirements, thereby allowing the wing to operate at optimum efficiency at every point during the cruise-flight. [2] provides a study into the optimization of exactly such a device that is located at the airfoil's leading edge, while [3] investigates both leading and trailing edge devices. The work in this paper will focus on a device that is mounted on the airfoil's trailing edge.

Fig. 1 illustrates the trailing edge device as applied to an airfoil and several of its possible deflection-states.

2. Methods

2.1. Geometric modeling

For the morphing application at hand, it was decided to investigate the merits of such a device. As airliners currently and in the foreseeable future are equipped with a flap at the trailing edge with at least one slot (a so-called single slotted flap), as illustrated in Fig. 2, the implementation of a morphing device for cruise flight has some restrictions. The function of this flap is to increase the lift-generating capabilities of the wing at low airspeeds, typically during take-off and landing. Omission of such a flap would result in an uneconomically large wing, reduced cruise performance and impractically high take-off and approach speeds. Therefore the slotted flap is considered to be a sine qua non for an airliner's wing in this article.

To still be able to implement a morphing device in the trailing edge of a flapped wing, this device will be placed within the flap itself, the aft part of which forms the trailing edge of the wing in cruise flight.

To develop a structured representation of an airfoil, which allows easy adjustments to its shape, use is made of the KBE package GDL, or "General-purpose Declarative Language", which is developed by [4]. GDL is an object-oriented programming language, which forms a superset to ANSI Common Lisp [11]. In addition, it includes the SMlib geometric kernel by Solid Modeling Solutions, which is used to create and perform operations on geometrical entities in a fashion native to most CAD-packages. This geometrical kernel provides a large number of useful features and tools to the user, which facilitate the geometrical design and optimization of a given product.

Because of the object-oriented nature of GDL, full advantage can be taken of the benefits of this programming paradigm, while adding a geometrical component to it. [4] provides a brochure for GDL, while [5] give a more indepth description of the principles and application of this programming language. More details on the SMLib-kernel are found in [6].

The exact shape of the individual airfoil elements can be introduced into the current airfoil product-tree in two fashions. The first method is to read in a cloud of points (x-y coordinates) from a plaintext file for each element. A geometric curve-fitting routine from the SMlib kernel will then fit a NURBS curve through these coordinate-points. From this point onward, the airfoil element will be represented in this NURBS format, which is common in CAD-packages and for which a large number of manipulative tools exist in the SMlib kernel. More details on NURBS and their application to CAD-geometry modeling can be found in [7,8]. This method was implemented because the cloud of points is one of the most common ways of describing the shape of an airfoil and most airfoils that have been developed over the years have such a representation.

An issue that comes into play at this point is the distinction between single-element and multi-element airfoils. From a geometric modeling point of view, a single-element airfoil is just a special instance of a generic class of multi-element airfoils. From an aerodynamic analysis point of view, there is quite a difference in analysis complexity between the two airfoil types. It turns out that the analysis of a multi-element airfoil is more complex in terms of analysis routines and computational time.

While this difference in analysis complexity is taken for granted when the airfoil under consideration alters from a cruise configuration to a fully deployed state, it is possible and even desirable to treat a collapsed multi-element airfoil as a single airfoil. In this situation, all elements are placed closely together, which eliminates any slots and minimizes the gaps and seams between the

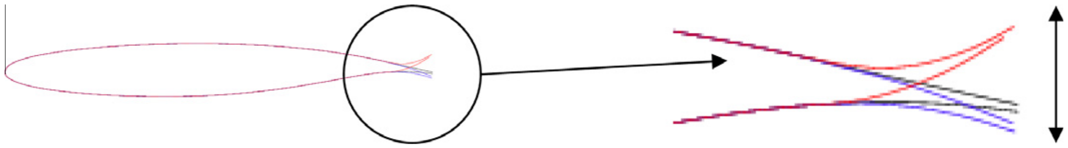

Fig. 1. Working principle of the proposed morphing trailing-edge device.