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Analysis of the Boeing 747-100 using CEASIOM

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ABSTRACT

One of the requirements for the SimSAC project was to use existing aircraft to act as benchmarks for comparison with CEASIOM generated models. Within this paper, results are given for one of these examples, the Boeing 747-100. This aircraft was selected because a complete dataset exists in the open domain, which can be used to validate SimSAC generated data. The purpose of this paper is to both give confidence in, and to demonstrate the capabilities of, the CEASIOM environment when used for preliminary aircraft and control system design. CEASIOM is the result of the integration of a set of sophisticated tools by the European Union funded, Framework 6 SimSAC program. The first part of this paper presents a comparison of the aerodynamic results for each of the solvers available within CEASIOM together with data from the 747-100 model published by NASA. The resulting nonlinear model is then trimmed and analysed using the Flight Control System Designer Toolkit (FCSDT) module. In the final section of the paper a state-feedback controller is designed within CEASIOM in order to modify the longitudinal dynamics of the aircraft. The open and closed loop models are subsequently evaluated with selected failed aerodynamic surfaces and for the case of a single failed engine. Through these results, the CEASIOM software suite is shown to be able to generate excellent quality adaptive-fidelity aerodynamic data. This data is contained within a full nonlinear aircraft model to which linear analysis and control system design can be easily applied.

Contents

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1. Introduction

Development and integration of a robust Flight Control System (FCS), either manual or fly-by-wire, is required for any successful aircraft design project. Classically, this begins with definition of the aircraft configuration, which in turn enables generation of the aerodynamic and structural parameters. Following the configuration definition, selection of trade-off studies and development of other subsystems, such as the FCS, begin. The purpose of SimSAC, through the creation of CEASIOM, was to allow the full preliminary design process to take place within a single software environment. This in turn would allow control system design to take place at an earlier stage, thereby offering potential performance improvements, rapid design development and the opportunity to consider novel configurations.

Chudoba [1] outlines the characteristics of idealised 'Class 5' design tools, which are in essence the basis of the work within SimSAC. CEASIOM itself is a first implementation of these tools within a software suite and provides the user with a wide range of aerodynamic, mass estimation, flight dynamic analysis and control system design modules. These 'Class 5' design techniques involve the implementation of a multi-disciplinary framework, modelling the coupled dependencies between subspaces, using sophisticated analysis tools to enable multi-objective optimisation of a multivariate design space [2,3]. Furthermore, the framework is independent of the design configuration, which allows development of generic design concepts. Ideally this provides an environment for fair comparison and evaluation of the design space and trade-off studies using unbiased decisions to modify the design concepts under investigation. This is said to move toward "capacitating true inverse design capability [1]".

1.1. SimSAC

The purpose of SimSAC was to enhance the conceptual design and early preliminary design processes by developing an integrated digital design and decision making environment. It was suggested that the introduction of FCS design in the concept definition phase would enable improvements in aircraft performance. This is supported in part by work presented by Perez et al. [4], which demonstrates the impact of implementing a Stability Augmentation System (SAS) on a conventional aircraft design. The additional control parameters within the optimisation process resulted in performance improvements, and the control configured design was shown to satisfy all of the requirements and constraints, even in some cases where the baseline design failed to meet them.

Whilst Perez et al. [4] introduced an SAS design early in the initial aircraft design process, Bauer et al. [5] sought to optimise the physical command-actuation system hardware. Bauer selected a discrete, branch-and-bound optimisation method to develop a system that satisfied the performance-reliability requirements for a given set of components and control effector parameters. In his work, Bauer et al. [5] demonstrates that these discrete optimisation methods find the required optimum within the target system design space. Furthermore, the systems design weight is implemented as a cost, and therefore minimised, leading to a reduction in the overall system weight.

As has been demonstrated by both the work of Perez and Bauer, the aircraft design parameters, FBW control system gains and command-actuation systems are intrinsically linked. The approach proposed by Beaverstock [6] is to unify these two conceptual approaches, whereby the control-system, command-actuation system and the control effectors are designed concurrently to capture the coupling between these design streams.

The Flight Control System Designer Toolkit (FCSDT), a component within CEASIOM allows the user to consider the system hardware, control surface sizing and control system design all within one integrated software environment. The version of CEASIOM currently available can be considered to be a multi-disciplinary tool, which provides analytical data in order to aid decision making within the design process. Work was carried out within the SimSAC project however whose purpose was to provide tools, which could help to directly inform the decision making itself and therefore move closer to a real decision making environment. This remains one of the longer term goals of the CEASIOM software implementation.

This paper uses the Boeing 747-100 model as a baseline example to demonstrate the capabilities within FCSDT and CEASIOM. Section 2 outlines the design approach taken within SimSAC, Section 3 discusses linearisation within CEASIOM and the associated control system design. Section 4 outlines the aircraft model and the control system topology. Section 5 provides a comparison of the aerodynamic data and Section 6 presents the open and closed loop results. Finally in Section 7 conclusions and recommendations for further work are presented.

2. Conceptual aircraft and Flight Control System design

In this section a brief overview of the aircraft design space within CEASIOM is presented. The classical approach to aircraft design involves partitioning the design space into several disciplines. This was a concept that was first introduced by Sir George Cayley [7], but has evolved into a model, which is presented in Fig. 2.1.

Given the model shown in Fig. 2.1, each subspace then inherits the set of parameters, which are to be optimised locally. Few parameters, however, are exclusive to a single subspace. For example wing span and area have a significant impact on both the aerodynamic and the structural design. Furthermore, few subspaces or parameters can be truly optimised independently. Traditional synthesis methods rely on a largely manual iterative process to modify the design. Even after the advent of digital computing, optimisation methods were often restricted to one-dimensional problems, relying primarily on manual protocols to modify and update the central design.

With recent mass developments in computing, a new generation of multi-disciplinary design tools is being developed. Ideally these are contained in a single environment, where each analysis application is linked to a central database. Additionally, Multi-Variable Optimisation (MVO) can be introduced, combining multiple subspaces to satisfy a defined set of objectives. This generation of truly multi-disciplinary