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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

Nomenclature

Symbols

$\boldsymbol{A}$	state matrix
$\boldsymbol{B}$	input matrix
h	altitude
I_{yy}	moment of inertia about y-body axis
$\boldsymbol{K}$	feedback gain matrix
m	aircraft mass
M	aerodynamic pitching moment
p	roll rate
q	pitch rate
r	yaw rate
$\boldsymbol{u}$	control input
V_t	total translational velocity
$\boldsymbol{V}$	achievable closed-loop eigenvalues
$\boldsymbol{x}$	state vector

Abbreviations

AMB	Aerodynamic Model Builder
ACBuilder	Aircraft Builder
BoM	Bill-of-Material
CEASIOM	Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods
CE	control effector
CG	centre of gravity
EA	eigenstructure assignment
FCS	Flight Control System
FCSA	Flight Control System Architecture
FCSDT	Flight Control System Designer Toolkit
FTA	Fault Tree Analysis
LQR	Linear Quadratic Regulator
MVO	Multi-Variable Optimisation
SAS	Stability Augmentation System
SCAA	Stability and Control Analyser Assessor
SimSAC	Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design

Greek letters

α	angle of attack
β	angle of sideslip
δ	input parameters
Δ_{HSTAB}	horizon stabiliser angle
η_{thrust}	demanded thrust
ϕ	roll angle
θ	pitch angle

design tools will enable the conceptual designer complete freedom over the early aircraft design phases.

The SimSAC program and the CEASIOM environment are focussed on realising this set of truly multi-disciplinary design tools within Matlab and Simulink. Although it is a conventional aircraft configuration, which is considered in this paper, the higher fidelity methods used within CEASIOM allow the designer to extrapolate beyond the conventional and consider unconventional configurations. Furthermore, the CEASIOM software brings together aerodynamic, mass estimation, control hardware and software designs, flight simulation and linear analysis into one environment. The boundaries between the subspaces have been expanded to allow optimisation of a wide range of aircraft concepts. Each specialist module within the environment retrieves and modifies a central database in order to ensure consistency in the models used for analysis. To improve the modelling capability, and extend the application beyond conventional configurations, the modules can employ high fidelity numerical methods as well as the traditional empirically derived ones.

2.1. Generating an aircraft model within CEASIOM

The aircraft model geometry is defined within the ACBuilder module in CEASIOM. This is achieved by defining a series of parameterised elementary objects, such as the lifting surfaces, or fuselage. From this initial concept, aerodynamic and structural models can be generated automatically.

For the aerodynamic model, the geometry is post-possessed into an appropriate set of aerodynamic mesh definitions, dependent on the solution method used. Once the meshes have been defined,

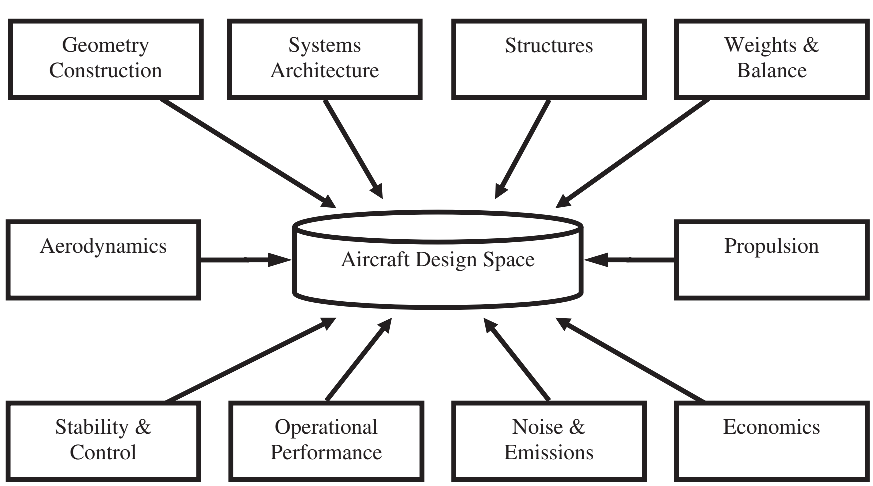

Fig. 2.1. Breakdown of the aircraft design space.

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along with the desired flight envelope, the Aerodynamic Model Builder (AMB) module within CEASIOM is run. This module produces a series of aerodynamic tables, the architecture of which is defined by Ghoreyshi et al. [8,9]. These are then processed automatically into an appropriate form for flight dynamics analysis. AMB also generates an initial propulsive model, parameters of which can be manually altered if needed.

The Flight Control System Designer Toolkit (FCSDT) module within CEASIOM operates with a standard Simulink model, the structure of which is shown in Fig. 2.2. This model is common to all configurations and all stability and control analysis operations within FCSDT.

2.2. Flight Control System design within CEASIOM

The first step in creating the Flight Control System is definition of the FCS topology. This is carried out using the Flight Control System Architecture (FCSA) interface within FCSDT, which is illustrated in Fig. 2.3 for the Boeing 747-100.

The interface layout shown in Fig. 2.3 provides the standard flight control surfaces and control effectors. Required control surfaces are selected, which are then automatically used to create a symbolic representation of the control system topology. For each individual control effector, the command-actuation system architecture is generated, as shown by the interface in Fig. 2.4. Within this system architecture, reference is made to the individual flight control computers, electrical systems and actuators. The numbers given within Fig. 2.4 relate to component reliability.

Note that individual components within each individual control effector system are not necessarily exclusive to that system. Many are shared in order to reduce systems weight and component count, whilst maintaining a reliable system that is robust to failures. A full components' list is available within FCSA, in order to aid the designer in rapid definition of the systems architecture. Once a design has been developed, reliability studies can carried out, including Fault Tree Analysis (FTA), generation of a Bill-of-Material (BoM) and failure analysis.

2.3. Stability and control analysis

The structure of FCSDT is shown in Fig. 2.5 with the three main elements: FCSA, which is used to create the Flight Control System Architecture as outlined in the previous section; SCAA, which is the Stability and Control Analyser Assessor and performs the stability analysis and LTIS, which can be used for control system design.

3. System analysis and control system design

Standard trim and linearisation routines are employed within CEASIOM to find steady or quasi-steady state flight conditions. The process of trimming an aircraft can be defined as the optimisation problem as given in

$$\dot{\mathbf{x}} = f(\mathbf{x},\mathbf{u}) + c(\mathbf{x}_{const},\mathbf{u}_{const})\min(|\dot{\mathbf{x}} - \dot{\mathbf{x}}_d|) \tag{1.1}$$

Mathematically this is a minimisation problem, minimising the difference between the desired and the actual derivative states. The function c contains the fixed states and inputs, producing a vector of constants, whereas function f contains the states and inputs that are free to vary, and are used to find the solution.

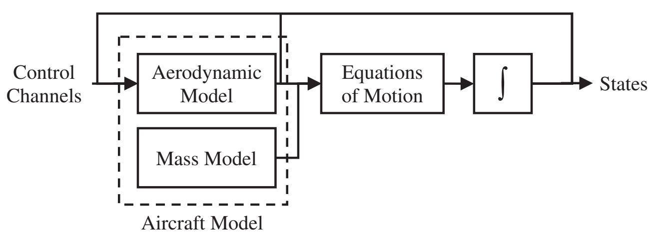

Fig. 2.2. FCSDT Simulink aircraft model.

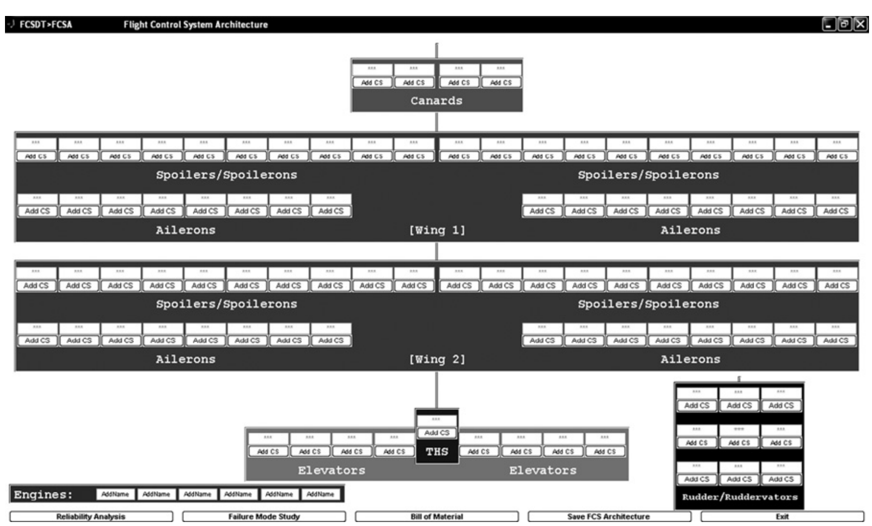

Fig. 2.3. FCSA Boeing 747-100 interface within CEASIOM.

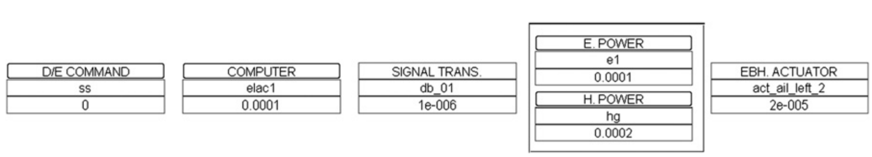

Fig. 2.4. FCSA systems design interface for individual control effectors.

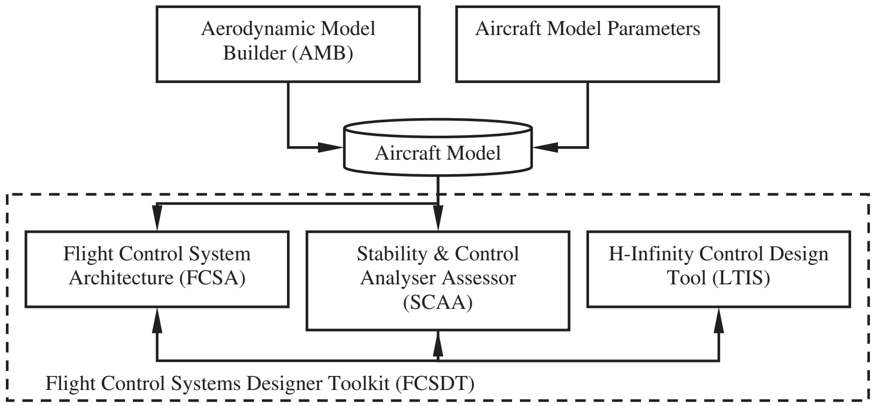

Fig. 2.5. SCAA main interface.

States and inputs that are selected as free or fixed are specified by the '*trim law*', which also specifies the desired derivative state values.

3.1. Longitudinal trims within CEASIOM

Longitudinal steady state trims generally require a solution where the aircraft velocity, altitude and dynamic state are unchanging. All lateral states and derivative states are also generally fixed and zero. Traditionally, angle of attack would be set to equal the pitch angle, which removes the requirement to solve the heave or altitude derivative equation. However retaining this equation enables specification of a quasi-steady flight conditions. Using the formulation presented in Eq. (1.1), the problem can be defined as in the following equation for an X–Z symmetric aircraft:

$$\begin{aligned}&\dot{\mathbf{x}}_d=[\dot{\alpha},\dot{V}_T,\dot{q},\dot{h}]\\&\mathbf{x}=[\alpha,\theta],\quad \mathbf{x}_{const}=[V_T,q,h]\\&\mathbf{u}=[\Delta_{HSTAB},\eta_{Thrust}]\end{aligned}\tag{1.2}$$

3.2. Asymmetric trims within CEASIOM

Multiple asymmetric trim cases can be defined within FCSDT. One lateral case of particular interest is the failure of an individual engine for a multi-engine wing mounted configuration. The offset of the engine typically generates a predominantly yawing moment imbalance. In the case of a four engine aircraft, such as the Boeing 747-100, a failed outboard engine would have the greatest effect on the aircraft trim and dynamic characteristics. Two different trim conditions are currently defined within FCSDT, as given in

$$\begin{aligned}&\dot{\mathbf{x}}_d=[\dot{\alpha},\dot{\beta},\dot{V}_T,\dot{p},\dot{q},\dot{r},\dot{h}]\\&\mathbf{x}=[\alpha,\beta,\theta],\quad \mathbf{x}_{const}=[V_T,p,q,r,\phi,h]\\&\mathbf{u}=[\Delta_{HSTAB},\delta_{ail},\delta_{rudd},\eta_{Thrust}]\end{aligned}\tag{1.3}$$

$$\begin{aligned}&\dot{\mathbf{x}}_d=[\dot{\alpha},\dot{\beta},\dot{V}_T,\dot{p},\dot{q},\dot{r},\dot{h}]\\&\mathbf{x}=[\alpha,\phi,\theta],\quad \mathbf{x}_{const}=[\beta,V_T,p,q,r,h]\\&\mathbf{u}=[\Delta_{HSTAB},\delta_{ail},\delta_{rudd},\eta_{Thrust}]\end{aligned}\tag{1.4}$$

The condition in Eq. (1.3) uses side-slip as an unknown whereas Eq. (1.4) uses roll angle as the additional unknown. Both of these strategies can be used to find a feasible solution and both require the use of all three roll, pitch and yaw control channels. One other alternative asymmetric flight condition in addition to the engine failed case is also presented within this paper. This is for the case where a control surface has failed asymmetrically, in which case the aircraft can also be trimmed using the equations given in Eqs. (1.3) and (1.4).

Table 3.1
Desired eigenvector elements.

Element	Required effect of the state
0	No effect in the mode
1	Dominant in the mode
x	Left unspecified: allows the unconstrained influence of the element in the mode

3.3. Linear control system design within CEASIOM

The following is a short description of Eigenstructure Assignment as it has been implemented in the CEASIOM environment. For additional information, please see [10–13]. The linearisation of a system where $\hat{\boldsymbol{x}}$ and $\hat{\boldsymbol{u}}$ are perturbations from the linearisation point can be written as

$$\dot{\hat{\boldsymbol{x}}}=\boldsymbol{A}\hat{\boldsymbol{x}}+\boldsymbol{B}\hat{\boldsymbol{u}}\tag{1.5}$$

If a state feedback scheme is considered then the input $\boldsymbol{u}$ can be expressed in terms of the states $\boldsymbol{x}$ and an appropriate feedback gain matrix $\boldsymbol{K}$. This will result in the closed loop system:

$$\dot{\hat{\boldsymbol{x}}}=\boldsymbol{A}\hat{\boldsymbol{x}}+\boldsymbol{B}\boldsymbol{K}\hat{\boldsymbol{x}}=\boldsymbol{A}_{cl}\hat{\boldsymbol{x}}\tag{1.6}$$

Using this linearisation, the gain matrix can be calculated using a linear design method such as Eigenstructure Assignment [7–10]. Alternative methods are available within CEASIOM for control system design such as H-infinity and LQR however Eigenstructure Assignment is used here as an example. The eigenvalues and eigenvectors are related to the closed-loop matrix via

$$\boldsymbol{A}_{cl}\boldsymbol{V}=\boldsymbol{\Lambda}\boldsymbol{V}\tag{1.7}$$

where $\boldsymbol{\Lambda}$ is a matrix that has the closed-loop eigenvalues on the principal diagonal and the achievable closed-loop eigenvectors are given in the modal matrix, $\boldsymbol{V}$.

It is not possible to simply specify and achieve any set of eigenvalues and eigenvectors—this is dependent on the number of feedback states that are available and the number of control inputs. The number of inputs tends to be much less than the number of states, hence it is usually only possible to define a desired eigenvector, which consists of the elements given in Table 3.1. These are then used to calculate a set of achievable eigenvectors, $\boldsymbol{V}$. The feedback gain matrix is calculated via

Eq. (1.8) whose derivation is given in [12]:

$$\boldsymbol{K} = \boldsymbol{Z_B}^{-1}\boldsymbol{U}_0^T(\boldsymbol{V}\boldsymbol{\Lambda} - \boldsymbol{A}\boldsymbol{V})\boldsymbol{V}^{-1} \tag{1.8}$$

where $\boldsymbol{Z_B}$ and $\boldsymbol{U_0}$ are obtained via a QR decomposition of the control matrix, $\boldsymbol{B}$. Hence the parameters that are required in order to calculate $\boldsymbol{K}$ are the state matrix $\boldsymbol{A}$, the input matrix $\boldsymbol{B}$ (and hence $\boldsymbol{Z_B}$ and $\boldsymbol{U_0}$), desired eigenvalues Λ and the achievable eigenvectors in the modal matrix $\boldsymbol{V}$. In multi-degree-of-freedom systems with multiple inputs, it is possible to use Eigenstructure Assignment to achieve not only the desired pole placement, but also to shape the response of each mode.

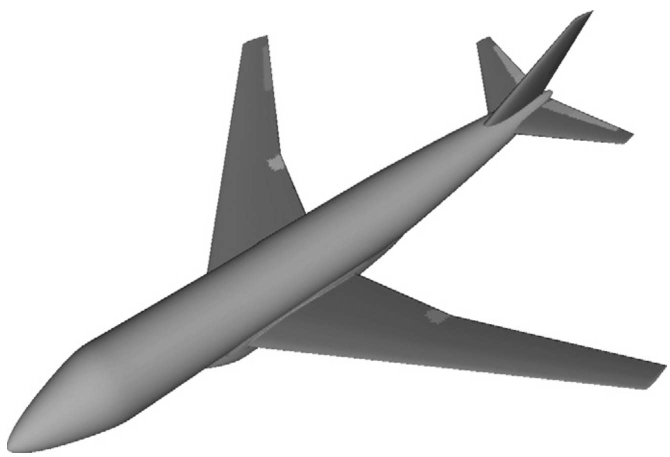

Fig. 4.1. Sumo 747 Model within CEASIOM.

4. Boeing 747-100 model

The Boeing 747-100 aircraft model was selected for this paper because it represents a conventional aircraft configuration and is an ideal baseline model. Second, the Boeing 747-100 was the focus of a 1971 NASA investigation [14], for which a comprehensive set of aerodynamic data and Flight Control System characteristics was generated. The information recorded and published in the documentation provides sufficient detail in order to build a complete aerodynamic model to compare to data generated within CEASIOM. Furthermore, the Boeing 747-100, as shown in Fig. 4.1, in contrast to smaller light aircraft, includes a relatively complex FCS including several control effectors and a highly developed command-actuation system. Details of these are also given in [14].

4.1. Flight Control Systems topology and systems architecture

The control surfaces include a tail mounted horizontal tail plane, an elevator (divided into 4 segments), two pairs of ailerons, inner and outer, and a pair of rudder surfaces. Furthermore, flaps, slats and spoilers are also present if required. The NASA documentation also provides a detailed account of the hydraulic system, outlining the components and systems design, as numbered in Fig. 4.2 and as implemented within CEASIOM.

Table 4.1 presents a summary of the reliability analysis data generated for the Boeing 747-100 using FCSA. This provides an overall probability and failure classification for each of the possible failure modes.

The probabilities given in Table 4.1 were computed using the default values for components within FCSDT and the architecture was obtained from the NASA document. Transmission failures

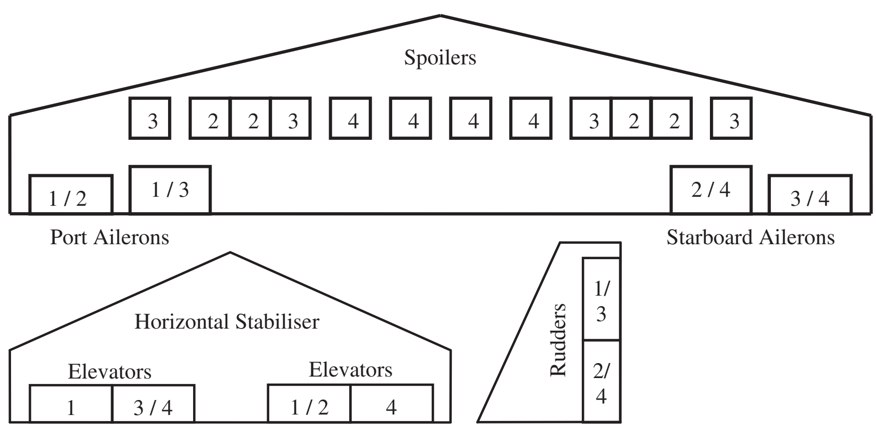

Fig. 4.2. 747-100 primary flight control surface topology.

Table 4.1
FCSA reliability analysis of the Boeing 747-100 actuation system.

Failure mode	Probability	Severity
All moving horizontal stabiliser	2.0169×10^{-6}	Major
Single outboard elevator	1.2100×10^{-4}	Minor
Both outboard elevator	1.4641×10^{-8}	Hazardous
Single inboard	2.1010×10^{-5}	Major
Single inboard, single outboard elevator	1.2541×10^{-8}	Hazardous
Both inboard elevators inoperative	4.4142×10^{-10}	Catastrophic
No operational elevators	5.6867×10^{-17}	Catastrophic
No operational longitudinal control surface (horizontal stabiliser or elevator)	1.0000×10^{-16}	Catastrophic
Single rudder surface	2.1010×10^{-5}	Major
Total rudder failure	4.4142×10^{-10}	Catastrophic

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were assumed significantly infrequent enough not to affect the actuation of the surfaces or dynamic performance of the aircraft, and are therefore not considered within this study. This is a fair assumption, as typically, the architecture responsible for command signal generation contains enough redundancy that transmission failures occur less than 1 in every 10^{15} flight hours for all flight surfaces. The results shown in Table 4.1 are reasonable for an aircraft of this type and demonstrate the capability within FCSA for generating fault tree analysis models, control system topology and overall system failure probabilities.

5. Aerodynamic model comparisons

There are several modules within CEASIOM, which can be used to generate the aerodynamic models. These can be used individually or can be integrated into an interlaced fidelity framework using Krigging [8,9,15] to combine the data from each method. This enables rapid low fidelity techniques to develop general trends, reserving computationally intensive methods to validate and correct the model where required. The format of the aerodynamic tables generated in CEASIOM is outlined by Ghoreyshi in [9].

5.1. Aerodynamic data comparison

The primary aerodynamic methods available within the CEASIOM environment are

- *Digital DATCOM*: Empirically derived for conventional aircraft configurations.
- *Tornado*: Vortex Lattice
- *EDGE*: Euler Solver

For the purposes of this paper, results were generated for a Mach range from 0.75 to 0.9 in increments of 0.05, and an angle of attack range between 1° and 6° in increments of 1°. Aerodynamic results are presented here for a Mach number of 0.8, as this is the trim point that is subsequently used to perform linear analysis and control system design.

5.2. Lift curve-slope results for the 747-100

Fundamental to any aircraft model is the lift curve slope. Fig. 5.1 presents the lift curve slope, C_L vs. α for the Boeing 747-100 for each

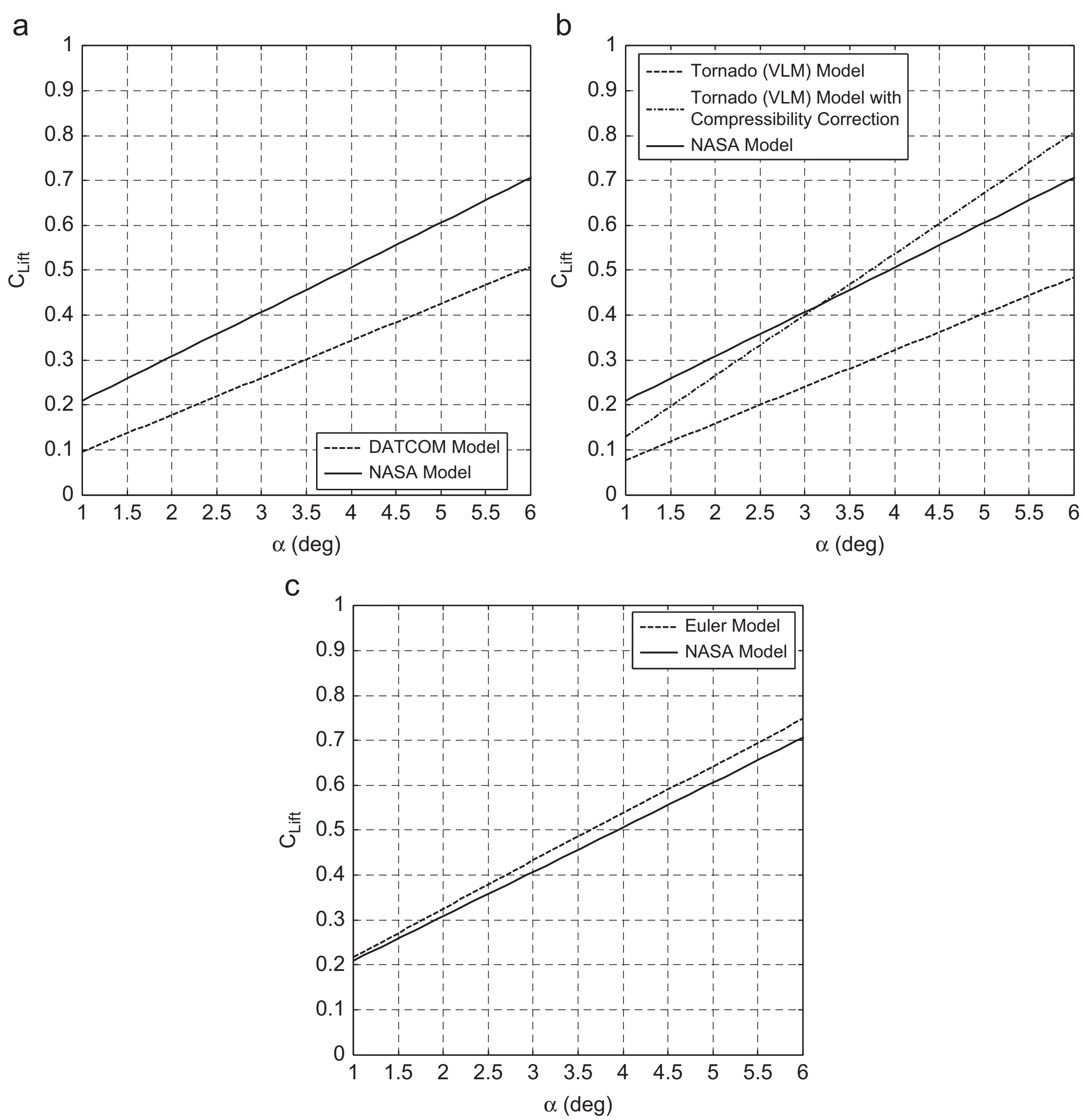

Fig. 5.1. Comparison of lift coefficient vs. angle of attack for (a) DATCOM vs. NASA, (b) Tornado vs. NASA and (c) Euler vs. NASA.

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of the solution methods, together with the NASA model for comparison. These are plotted on three separate graphs for clarity, however the same axes range has been used for each in order to aid comparison.

It can be seen from Fig. 5.1 that the Euler solver offers the closest correlation to the NASA reference model. The Euler absolute coefficient prediction is closer at lower angles of attack, the prediction gradually deviating as the angle of attack increases. Both the Tornado and DATCOM predictions are less than the reference model, in both absolute value and the derivative with respect to angle of incidence. For DATCOM, the prediction method is at the limit of what the code was designed for, which may account for the difference between the two models. Tornado generally under predicts, however with the compressibility correction applied the values are closer, albeit with an overestimate of the derivative. These results suggest that someone using CEASIOM might use a lower fidelity method such as DATCOM for initial analysis, moving on to the higher fidelity, higher computational cost EDGE model when the initial concept is refined.

5.3. Drag polar results for the 747-100

The drag polar describes the relationship between lift and drag coefficients, and is a measure of the efficiency at which lift is generated. In general the ratio of lift to drag (L/D) decreases as the lift increases, i.e. aerodynamic efficiency decreases as is shown for the 747-100 by the plots in Fig. 5.2. The zero lift drag is associated with the parasitic (friction and/or interference) drag, whereas the component associated with lift, describes the lift induced drag, related to the vortex strength across the wing planform.

The correlations from Fig. 5.2 show that DATCOM demonstrates the closest correlation with the NASA 747-100 model for these results. Tornado shows a similar trend with the aerodynamic efficiency decreasing with an increase in lift. The offset between the results can be explained by the lack of viscous modelling within Tornado. Poor correlation between the reference and Euler drag results is also observed. Although close in magnitude than the Tornado results, the Euler model is also shown to decrease aerodynamic efficiency rapidly with a greater slope relative to the reference model. The longitudinal long period dynamics are largely dependent on such derivatives and this is likely to affect the Phugoid results significantly. The fact that the DATCOM results more closely match the 747 results than the Tornado or EDGE models is not surprising since DATCOM includes empirical methods designed to estimate drag for this type of classical aircraft configuration. This does give confidence in the

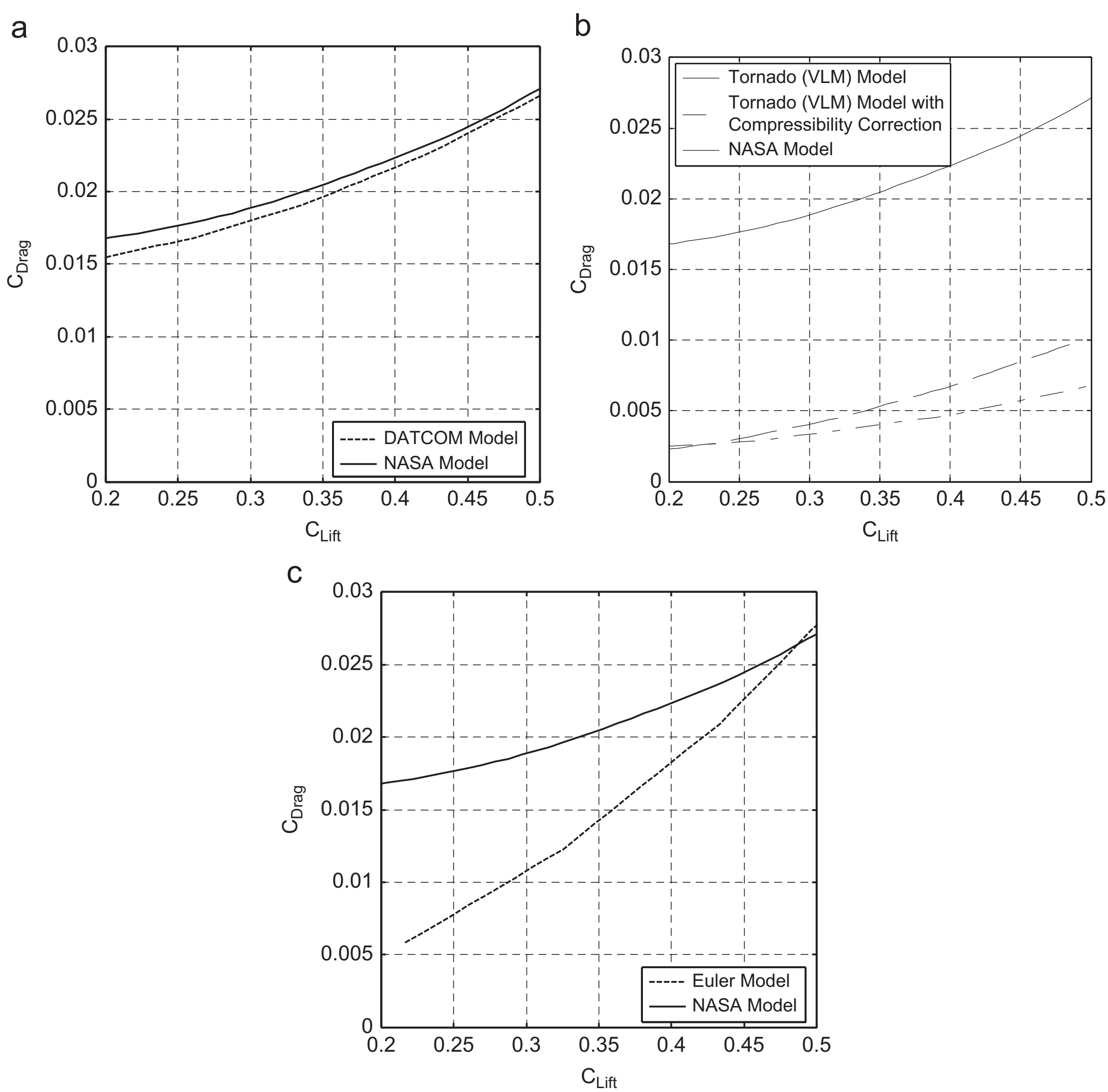

Fig. 5.2. Comparison of drag coefficient vs. lift coefficient for (a) DATCOM vs. NASA, (b) Tornado vs. NASA and (c) Euler vs. NASA.

use of DATCOM data for classical configuration design cases, however it does highlight the difficulty in estimating drag for more novel configurations. In these cases the results must be considered carefully and alternative methods may be considered.

5.4. Pitching moment results for the 747-100

The aerodynamic pitching moment has a significant impact on the aircraft trim results and associated dynamic response. The pitching moment derivative is closely linked to longitudinal stability and is generally sensitive to the longitudinal CoG position. Fig. 5.3 presents the pitching moment behaviour of the 747-100 with respect to angle of attack for each of the methods available within CEASIOM. As before, these are shown on three different figures, but with the same axis ranges to aid comparison.

From the results shown in Fig. 5.3 it can be seen that as expected, the EDGE Euler model generally predicts the pitching moment behaviour best with the plot closely matching that of the NASA results. In both the lift and pitching moment predictions, the Euler results are shown to be the best, however the DATCOM predictions for drag appear to be closer. In terms of time to solve, DATCOM is by far the fastest, taking only a few seconds to generate a model. Tornado is an order of magnitude longer and EDGE takes significantly longer again. All three can be used to produce dynamic models, with the user increasing fidelity as the design is refined and depending on the analysis required.

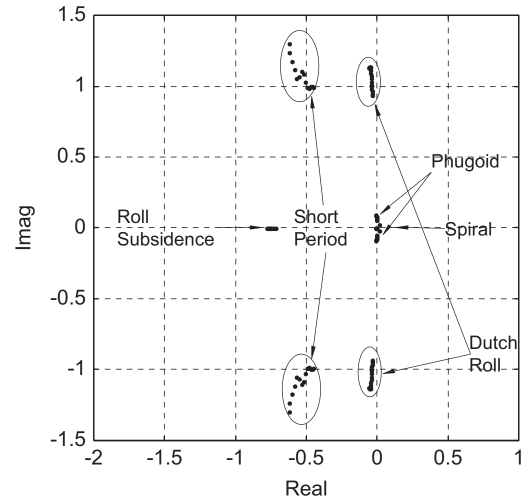

Fig. 5.4. Eigenvalues for the 747-100: Mach number 0.75 to 0.9.

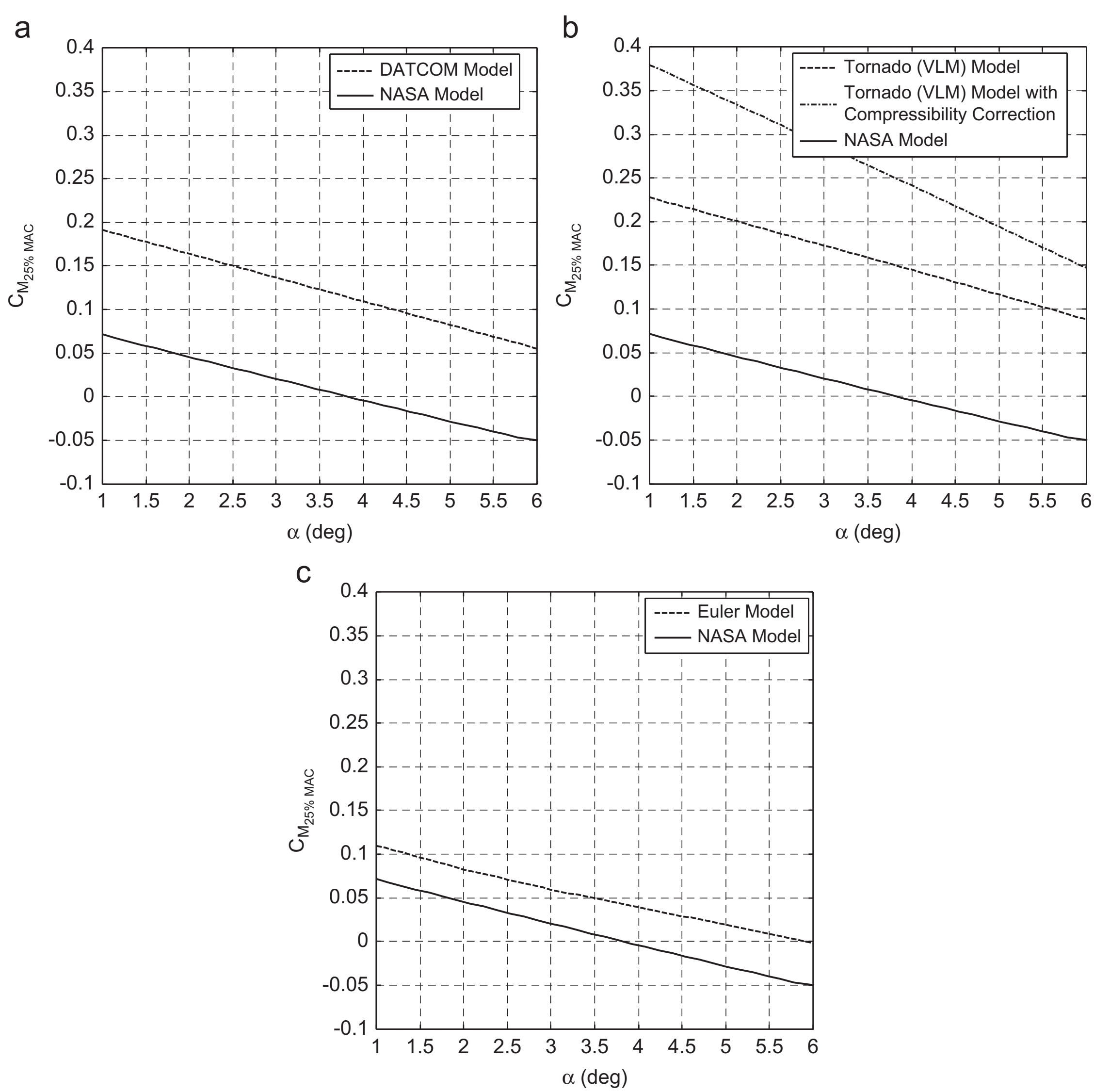

Fig. 5.3. Comparison of pitching moment coefficient vs. angle of attack for (a) DATCOM vs. NASA, (b) Tornado vs. NASA and (c) Euler vs. NASA.

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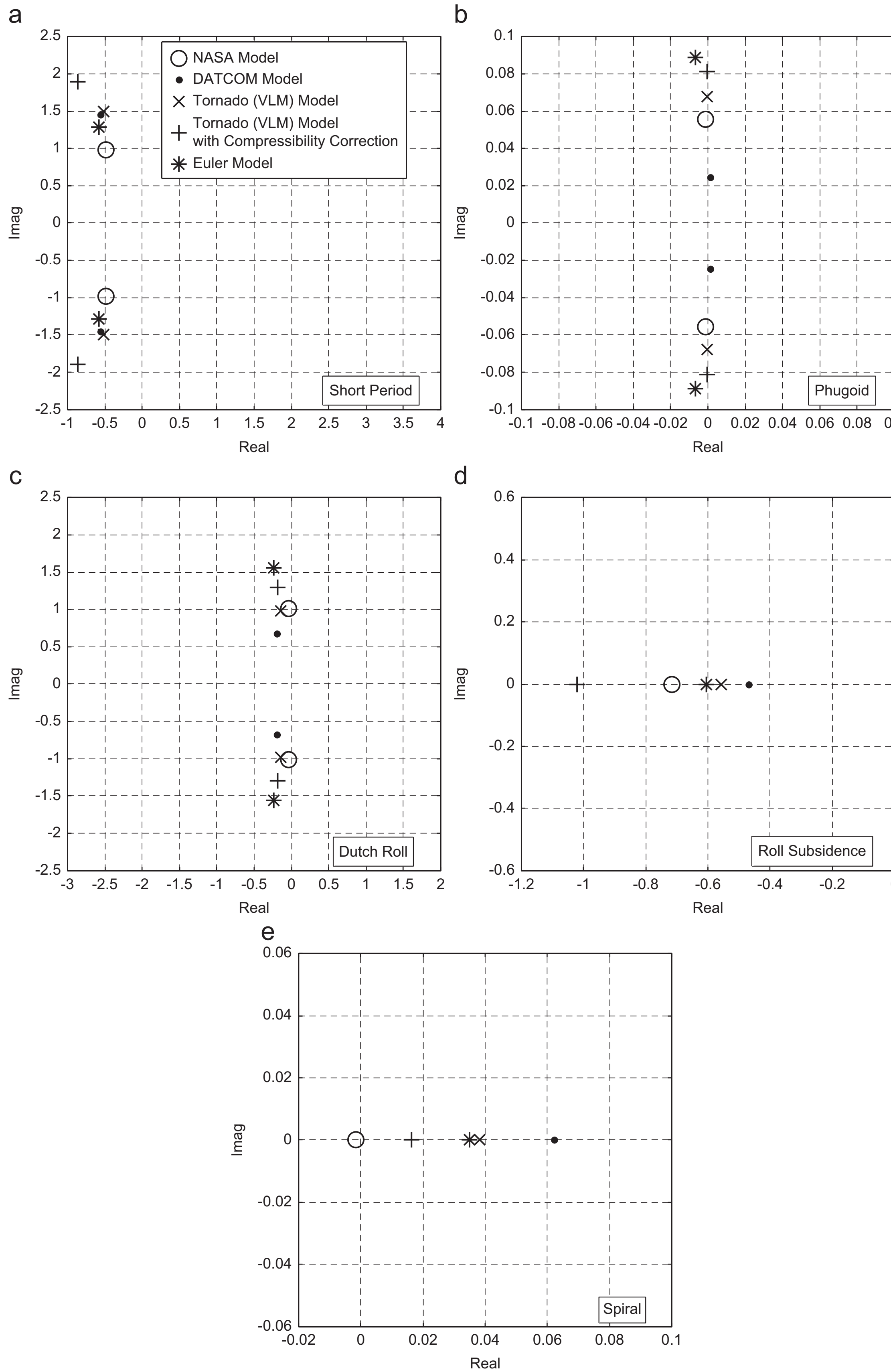

Fig. 5.5. Comparison of aircraft modes at Mach = 0.8; (a) short period, (b) Phugoid, (c) Dutch roll, (d) roll convergence and (e) spiral.

In terms of guidelines within CEASIOM, for cases where a classical configuration is being considered, DATCOM works very well; with more novel designs and cases where run time is critical then TORNADO might be used, and finally for accurate predictions of both lift and pitching moment for novel configurations then EDGE can be run.

5.5. Linearised results for the 747-100

A linearised model was then used to compute the dynamic characteristics for the B747-100 at trim points across the Mach number range 0.75–0.9. The system Eigenvalues for each of these models is shown in Fig. 5.4 and labelled according to the classical aircraft modes. These results are shown for the NASA B747-100 model using FCSDT to trim, linearise and plot the resulting modes.

Fig. 5.5 shows the five classical aircraft modes using linear models calculated for each of the aerodynamic models, NASA, DATCOM, Tornado and EDGE, all at Mach = 0.8. For the Short Period mode, the EDGE results are closest to the NASA based results, however all the methods slightly over predict the Short Period natural frequency and under predict the damping. For the remaining modes, there is not even one method that stands out as being obviously better than the others. All sets of results however are fairly tightly clustered around the actual Modal positions although there is a better prediction of the faster modes as opposed to the slower modes. For the faster modes alone, the EDGE results could be said to be closer overall.

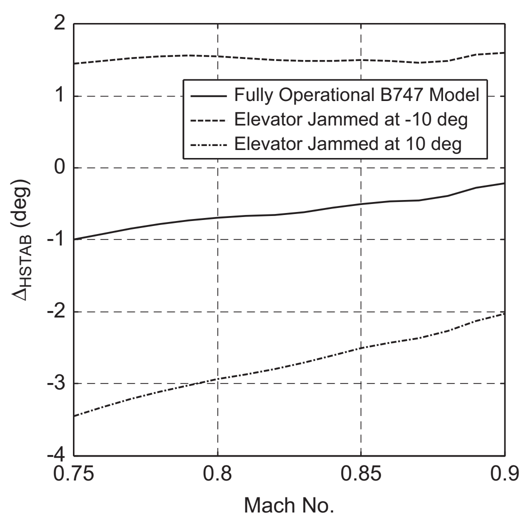

Fig. 6.1. Trimmed horizontal stabiliser angle.

6. 747-100 open and closed loop trim analysis

This section demonstrates the capability within FCSDT to solve for multi-input, asymmetric flight conditions and failed control surfaces. All the results in this section are for the NASA 747-100 model. For the purposes of these results, the aircraft model was trimmed at several Mach numbers and at an altitude of 37,000 ft. At these flight conditions, a variety of flight conditions were analysed, including fully operational and failed or jammed control surface conditions.

6.1. 747-100 longitudinal trims

Fig. 6.1 presents the horizontal stabiliser angle required for trim with and without a trimmed elevator deflection of 10°. The general trend shows that as Mach number increases, the required stabiliser angle increases. For the jammed case, the failed elevator at −10° provides a pitch up moment. This is in turn counteracted as expected by the horizontal stabiliser applying a deflection to provide more pitch down moment. The opposite behaviour is observed with the elevator failed at +10°.

Interestingly, the relationship between trimmed stabiliser angle and Mach number shown in Fig. 6.1 is nonlinear. This is not attributed to noise, and instead can be traced to the aerodynamic tables contained within the NASA 747-100 model. Two such examples of the nonlinearities that exist can be seen in Fig. 6.2.

6.2. 747-100 lateral trims

For demonstration of the asymmetric or lateral trim capability within FCSDT and CEASIOM, an engine failure and rudder failure trim solution is shown in this section. Two cases are presented for a failed outboard starboard engine, one at zero sideslip and constant bank angle, and the other at zero bank angle and constant side-slip. Fig. 6.3(a) shows the required sideslip angle for the engine failed case at zero bank angle and Fig. 6.3(b) shows the bank angle required for both the engine failed and the rudder jammed at −10° with sideslip set to zero.

It was also found, as expected, that both the failed rudder and failed engine cases were shown to increase the drag. Although the

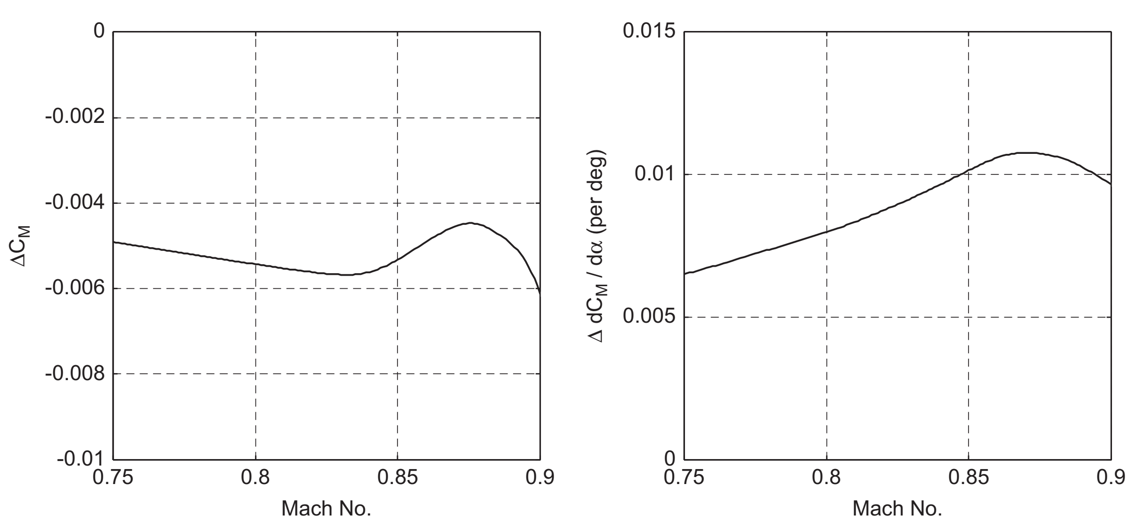

Fig. 6.2. NASA Boeing 747-100 nonlinearities at 37,000 ft.

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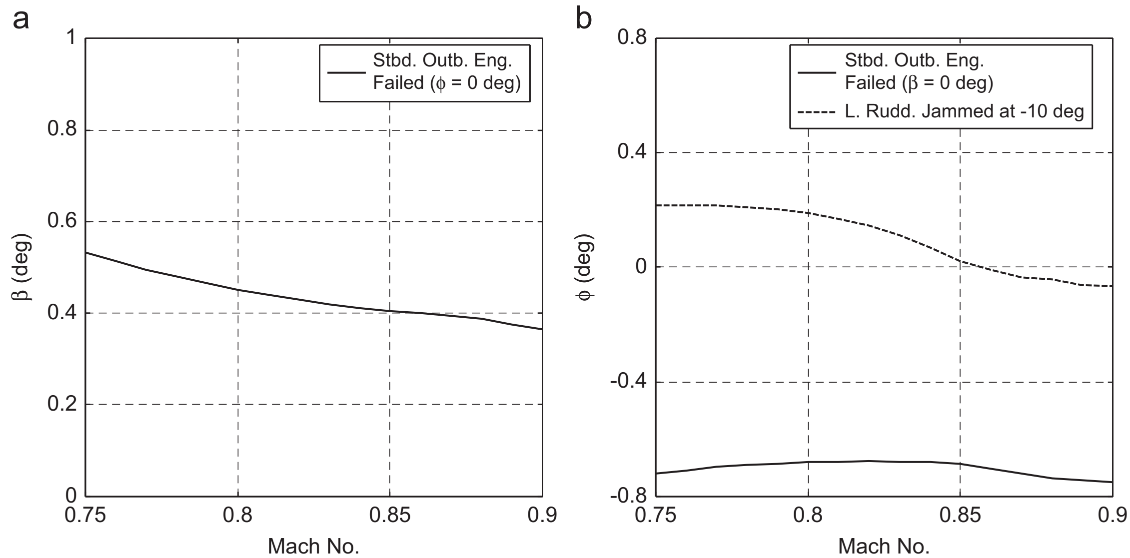

Fig. 6.3. 747-100 trimmed states—zero roll angle (a) and zero sideslip angle (b).

difference was marginal, the zero sideslip trim condition was shown to have the lower overall drag for the engine failed condition. The associated control surface deflections can also be plotted within CEASIOM if required.

6.3. 747-100 short period analysis

For the purposes of this section, the 747 model was trimmed and linearised at Mach 0.8 and a controller designed using Eigenstructure Assignment in order to move the Short Period mode to a design point of $-0.7\pm0.7i$. This controller was then applied to the nonlinear model and both the open and closed loop aircraft models trimmed and linearised over a range of Mach number. Finally, this was repeated for the closed loop model with a failed elevator. All three sets of results for this analysis are shown in Fig. 6.4.

The same trends are shown for each of the three sets of results with the fully functioning closed loop system moving the Root Locus to include the design point of $-0.7\pm0.7i$. Unsurprisingly, with the jammed elevator, the Short Period mode locus of points lies midway between the fully functioning control system results and the open loop model.

At the design point for a Mach number of 0.8, the fully functioning control system design places the characteristics precisely where required at $-0.7\pm0.7i$ using the Eigenstructure Assignment routines within FCSDT and CEASIOM. Variation in dynamic response can be seen for the range of Mach number and if required the same techniques could be used to synthesise a controller for each of these points, gain scheduled in order to ensure equivalent and consistent handling qualities throughout.

This relatively simple example has been chosen in order to demonstrate the capabilities within CEASOIM. An aircraft model concept can be created within ACBuilder, aerodynamics generated within AMB and the resulting 6dof model analysed within FCSDT. In additional, multiple control surfaces can be considered individually together with multi-variable controller design and failure case analysis of the resulting closed loop system.

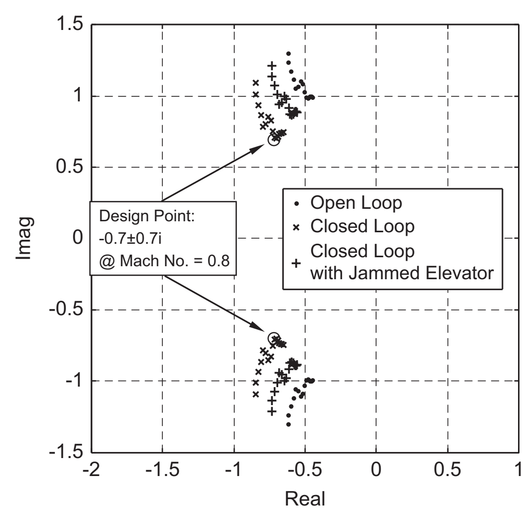

Fig. 6.4. Variation in short period eigenvalues with Mach number.

6.4. 747-100 simulation results

It is very easy within FCSDT and CEASIOM to carry out simulations using the full six degree of freedom generated by the AMB module. Two additional sets of results are shown here for the 747-100 in order to illustrate this capability. The first of these, shown in Fig. 6.5, is for the open loop aircraft response to a pitch rate perturbation. Three simulation traces are shown, the nominal open loop response, the response with the elevator jammed at -10° and the response with the elevator jammed at $+10^{\circ}$. What is particularly interesting here is that for the case where the elevator is jammed at -10°, the response is markedly different to the other two conditions.

The damping ratio of the Phugoid is typically low, depending on a number of pitching moment derivatives, as well as derivatives that are highly sensitive to the trim condition such as the position on the drag polar and its linear derivative. Because of the sensitivity of the Phugoid characteristics to the trim point, failure of the elevator can adjust the trim point and hence the phugoid characteristics. Although it is not shown here, this can be demonstrated via plotting of the Phugoid Mode eigenvalues, which show instability present in the relevant specific trim condition. This is therefore, the reason for the undesirable behaviour and instability demonstrated in Fig. 6.5.

The final plot in Fig. 6.6 is a comparison of the open and closed loop 747-100 response to a pitch rate disturbance. This is for the 0.8 Mach number. flight condition and where the Short Period Mode was placed at a Design Point of $-0.7\pm0.7i$. The simulation

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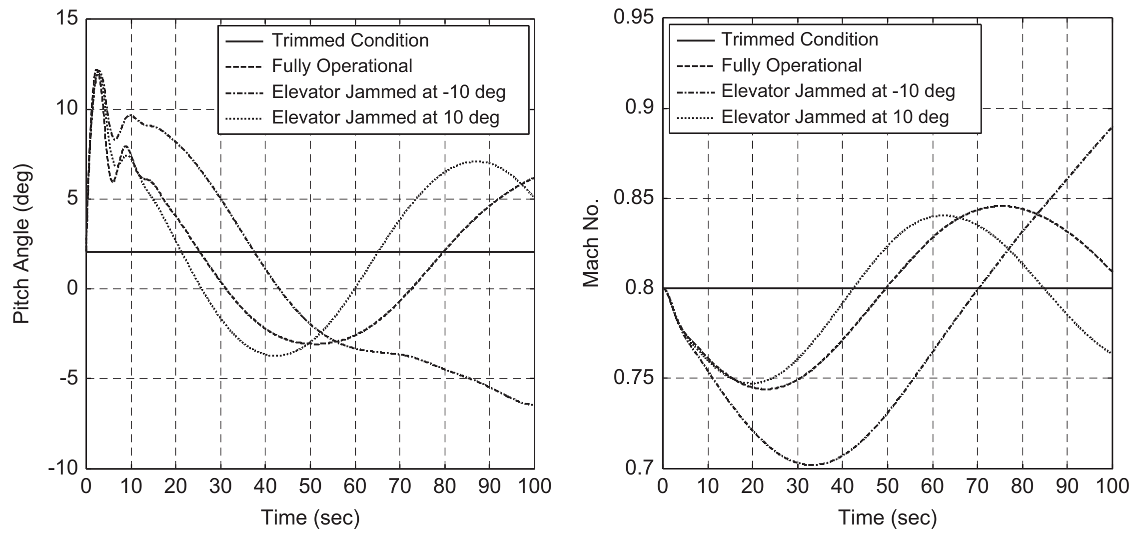

Fig. 6.5. 747-100 open loop response to a pitch rate perturbation.

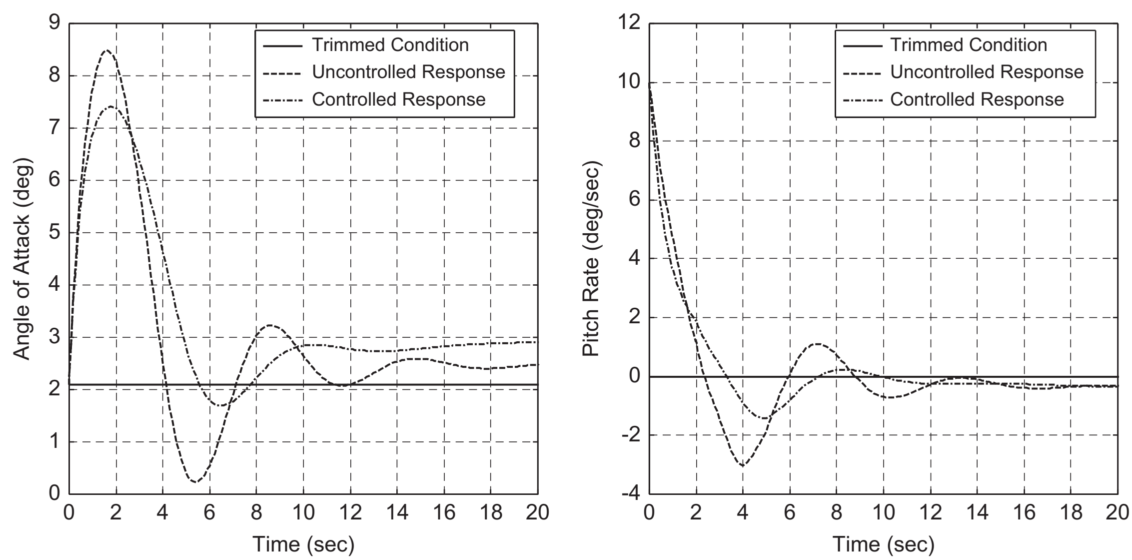

Fig. 6.6. 747-100 open and closed loop response to a pitch rate perturbation.

results tie in well with the Eigenvalues plotted in Fig. 6.4 and demonstrate a slightly lower undamped natural frequency and increased damping ratio when compared with the open loop response.

7. Conclusions

The objective of the work presented in this paper is both to demonstrate the capabilities of the CEASIOM environment, and to provide confidence in and a validation of, the results that are generated. In order to do this, 747-100 aerodynamic data was generated for three different aerodynamic modelling tools, DATCOM, TORNADO and EDGE, with all three compared to the results obtained for a 747-100 model published by NASA. All three were shown to compare favourably with the published results, with EDGE and DATCOM performing particularly well in terms of the lift and the drag estimates, respectively. It is suggested that the results presented do indeed provide confidence in the CEASIOM environment and point toward the potential offered by the use of adaptive fidelity models for aerodynamic model generation. Whereas appropriate guidelines have been drawn out of the results presented, which can be applied to CEASOIM and help guide the aerodynamic tool selection depending on configuration, desired fidelity and computation time.

The second part of this paper presents results for symmetric and asymmetric trims with an optional failed engine and failed control surface. Two lateral trim cases from within the FCSDT module are given and sample results presented for each. This clearly demonstrates the capabilities of the CEASIOM environment, which allows the user to build an aircraft model from a reduced set of parameters and take it through to a full 6dof asymmetric trim.

In the final section of the paper a state-feedback controller was designed in order to modify the longitudinal dynamics of the aircraft. Closed loop linear results were presented together with associated full nonlinear simulations. In summary, it is suggested that the CEASIOM software suite has been shown to be able to generate excellent quality aerodynamic data contained within a full nonlinear aircraft model to which linear analysis and control system design can indeed be easily applied.

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