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Parametric reduced order model approach for rapid dynamic loads prediction

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ABSTRACT

A parametric reduced order methodology for loads estimation is described that produces a fast and accurate prediction of gust and manoeuvre loads for different flight conditions and structural parameter variations. The approach enables efficient prediction of the peak loads whilst maintaining the correlated time histories for different loads. It is then possible to determine correlated loads plots with reduced computation without losing accuracy. The effectiveness of the methodology is demonstrated by considering loads arising from families of gusts and pitching manoeuvres acting upon a numerical transport aircraft aeroservoelastic model with varying flight conditions and structural properties.

1. Introduction

Loads calculations play an important part across much of the design and development of an aircraft, and have an impact upon structural design, aerodynamic characteristics, weight, flight control system design and performance. They determine the most extreme stress levels, fatigue damage and damage tolerance. The certification of large commercial aircraft is covered by the EASA CS-25 documents [1] which define a range of load cases that has to be accounted for, and are a primary prerequisite for assuring structural integrity over the operating environment of the aircraft. Loads requirements are defined in the context of the flight envelope. The regulations require that enough points on, or within, the boundary of the flight envelope are investigated to ensure that the most extreme loads for each part of the aircraft structure are identified.

The flight conditions which provide the largest aircraft loads are not known a-priori. Therefore the aerodynamic and inertial forces have to be calculated at a large number of conditions to give an estimate of the maximum loads, and hence stresses, that the aircraft will experience in service. It is of great interest for aircraft design to identify which are the critical loading events and at what design configuration and flight conditions they occur. A typical aircraft loads design process involves monitoring many of so-called Interesting Quantities (IQs) (e.g. bending moments, torques, accelerations, etc.) for a wide range of different load cases that the aircraft is likely to experience in-flight and on the ground. Each "loads loop" simulates the response of a numerical aeroelastic aircraft model to these loads and determines the critical cases, and these results are fed into the structural design. Such a process is extremely time consuming and furthermore, has to be repeated every time that there is an update in the aircraft structure.

It is usual to determine the extreme loads cases for 1D (single IQs) and 2D (correlated IQs) events. In the latter case, pairs of IQ response time histories (e.g. bending moment and torque at a single position on the aircraft) are visualized against each other for a range of different load cases. The extreme vertices of the envelope encompassing these correlated time histories characterize the critical load cases that are then used to perform stress calculations.

There is interest in developing methodologies that are able to determine the worst case gust loads without excessive computation; however, approaches such as Matched Filter Theory [2], Statistical Discrete Gust [3] and Evolutionary Algorithm [4] methods all determine arbitrary gust time histories that give the worst 1D response. The time domain approaches defined in the airworthiness regulations [1,5] are based upon finding the tuned "1-Cosine" gust that causes the worst response. Previous work in the FFAST EU FP7 project [6–8] investigated the use of several surrogate models and optimization methods for fast and efficient prediction of the worst case gust loads for each IQ of a large transport aircraft

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Nomenclature

$\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{D}$	State-space system matrices of Full Order Model
$\boldsymbol{A_r}, \boldsymbol{B_r}, \boldsymbol{C_r}, \boldsymbol{D_r}$	State-space system matrices of Reduced Order Model
$\boldsymbol{A_a}$	Matrix coefficients of Rational Function Approximation of aerodynamics
$\boldsymbol{A_g}$	Matrix coefficients of Rational Function Approximation of gust aerodynamics
$\boldsymbol{B_a}$	Matrix coefficients of Rational Function Approximation of aerodynamics
$\boldsymbol{B_g}$	Matrix coefficients of Rational Function Approximation of gust aerodynamics
$\boldsymbol{C_a}$	Matrix coefficients of Rational Function Approximation of aerodynamics
$\boldsymbol{C_g}$	Matrix coefficients of Rational Function Approximation of gust aerodynamics
$\boldsymbol{C_{hh}}$	Generalized damping matrix
$\boldsymbol{D_0}, \boldsymbol{D_1}, \boldsymbol{D_2}$	Matrix coefficients of Rational Function Approximation of aerodynamics
$\boldsymbol{D_{0g}}, \boldsymbol{D_{1g}}, \boldsymbol{D_{2g}}$	Matrix coefficients of Rational Function Approximation of gust aerodynamics
$\boldsymbol{D_{0c}}, \boldsymbol{D_{1c}}, \boldsymbol{D_{2c}}$	Matrix coefficients of Rational Function Approximation of control surface aerodynamics
$\mathcal{F}$	Functional of the extended Rational Function Approximation
G_h	Open-loop actuator transfer function
h	Altitude
H_c	Closed-loop actuator transfer function
i	Imaginary unit
$\boldsymbol{I}$	Identity matrix
k	Reduced frequency
k_c	Gain of closed-loop actuator transfer function
k_h	Hydraulic gain
$\boldsymbol{K}$	Stiffness matrix in physical coordinates
$\boldsymbol{K_{hh}}$	Generalized stiffness matrix
l_a	Aerodynamic reference length
M	Mach number
$\boldsymbol{M}$	Mass matrix in physical coordinates
$\boldsymbol{M_{hh}}$	Generalized mass matrix
n_a	Number of aerodynamic poles
n_d	Number of parameters of the model
n_h	Number of generalized coordinates
n_k	Number of reduced frequencies
n_p	Number of sampling points
n_r	Order of Reduced Order Model
n_z	Vertical load factor
N	Order of Full Order Model
p	Complex reduced frequency
$\boldsymbol{p}$	Vector of parameters of the model
q_∞	Dynamic pressure
$\boldsymbol{q_h}$	Generalized coordinates
$\boldsymbol{Q_{AA}}$	Aerodynamic forces matrix on structural degrees of freedom due to structural displacements
$\boldsymbol{Q_{Ag}}$	Aerodynamic forces matrix on structural degrees of freedom due to gust
$\boldsymbol{Q_{hh}}$	Generalized aerodynamic forces matrix due to structural displacements
$\boldsymbol{Q_{hg}}$	Generalized aerodynamic forces matrix due to gust
$\boldsymbol{Q_{hc}}$	Generalized aerodynamic forces matrix due to control surfaces
s	Laplace variable
$\boldsymbol{T}$	Generalized basis matrix for structural modifications
$\boldsymbol{T_B}$	Balanced truncation basis matrix
V	Airspeed
$\boldsymbol{V}$	Left reduced order basis matrix
$\boldsymbol{W}$	Right reduced order basis matrix
V_A/M_A	Design manoeuvering speed/Mach number
V_C/M_C	Design cruise speed/Mach number
V_D/M_D	Design diving speed/Mach number
$\boldsymbol{u}$	State-space model input vector
u_c	Pilot command input
w_{ij}	Weighting factor of the optimization process for the extended Rational Function Approximation
w_g	Gust velocity
$\boldsymbol{x}$	State-space states vector of Full Order Model
$\boldsymbol{x_r}$	State-space states vector of Reduced Order Model
$\boldsymbol{x_g}$	Gust aerodynamics states vector
$\boldsymbol{x_a}$	Aerodynamic states vector
$\boldsymbol{x_g}$	Gust aerodynamics states vector
$\boldsymbol{y}$	State-space model output vector
β_l	Aerodynamic poles of Rational Function Approximation
δ	Control surface deflection
ε_{ij}	Normalized squared error between tabulated and approximated i–j terms of generalized aerodynamic matrix
$\boldsymbol{\Delta M}$	Additional mass matrix containing structural modifications
$\boldsymbol{\Delta K}$	Additional stiffness matrix containing structural modifications
$\boldsymbol{\Phi}$	Matrix of eigenvectors
$\boldsymbol{\Phi_{RB}}$	Matrix of rigid body modes
ζ_h	Hydraulic damping
ω_h	Hydraulic natural frequency

Abbreviations

DLM	Doublet Lattice Method
DOF	Degree Of Freedom
FOM	Full Order Model
GAF	Generalized Aerodynamic Forces
IQ	Interesting Quantity
LC	Load Case
LTI	Linear Time Invariant
MAC	Modal Assurance Criterion
MTOW	Maximum Take-Off Weight
PROM	Parametric Reduced Order Model
RFA	Rational Function Approximation
RMSE	Root Mean Square Error
ROB	Reduced Order Basis
ROM	Reduced Order Model
SVD	Singular Value Decomposition