Calculation of Aerodynamic Models for Flight Simulation

Abstract

The validation of aircraft designs for dynamic stability is seeing a shift toward using computational methods rather than the traditional wind tunnel tests. This has the benefit of faster turn-around, monetary savings and more detail about the design, thus allowing a designer to test many more configurations for optimisation and finding the efficient aircraft of the future. This work presents methods to allow the rapid calculation of dynamic stability data to facilitate this vision. Also presented is a novel approach to improving the performance of these methods.

Linear Frequency Domain

The Linear Frequency Domain (LFD) solver was originally developed for turbo-machinery flows. It has been implemented in the DLR-TAU code, developed by the German Aerospace Centre, for use with external aerodynamic problems. The semi-discrete flow equations:

$$\frac{d\mathbf{W}(t)}{dt} + \mathbf{R}(t) = 0 \tag{1}$$

are written as a linear system by assuming the terms W (flow variables), x (grid point locations) and \dot{x} (grid point velocities) can be modelled as a steady mean value plus a small

Results

Results are shown for a 2D pitching aerofoil where a strong shock is present in the motion.



Introduction

The use of Computational Fluid Dynamics (CFD) for obtaining dynamic stability data has become a strong topic of research. There are several advantages over the standard approach of using a wind tunnel including:

- monetary savings
- quicker assessment of designs
- obtaining more detail about the aircraft response



Fig.1 Unsteady flow field solution for civil transport aircraft Industry is starting to see the benefit for design, with a focus on developing more efficient aircraft with better performance characteristics; this method of dynamic analysis is a key enabler. perturbation as:

$$\mathbf{x}(t) = \bar{\mathbf{x}} + \tilde{\mathbf{x}}(t)$$

giving the complex linear system:



This linear system of the form **Ax** = **b** can then be solved using an efficient iterative linear solver.

Preconditioning

A key part of any linear solver is the preconditioning employed. Preconditioning should make a system easier to solve, thus reducing the number of iterations to solution. This is done by multiplying both sides of Ax = b by a preconditioner matrix to form:

 $\mathbf{P}^{-1}\mathbf{A}\mathbf{x} = \mathbf{P}^{-1}\mathbf{b}$

(4)

(5)

(2)

The preconditioner matrix is based on matrix **A**, and ideally the matrix $\mathbf{P}^{-1} = \mathbf{A}^{-1}$. However, the matrices encountered in CFD are usually very large and sparse requiring a large amount of time and computational resource to invert. An approximation is then obtained using an Incomplete Lower-Upper (ILU) decomposition.

Fig.4 Pitching moment coefficient response

In this case, the limit has been reached for the LFD and HB with 1 harmonic due to the complex flow conditions present. Higher numbers of harmonics capture the detail very well.

Speed up

Table 1 Speed up with respect to time-accurate solver

Method	HB-1	HB-3	LFD	Implicit- LFD
Speed up	16.26	10.37	27.99	124.2

A significant improvement in solution time compared to a time-accurate solver is seen. However, there is a trade-off between accuracy and speed.

Preconditioner speed up

When only the linear solver part of LFD is considered, the preconditioned LFD is around a factor of 10 quicker than the current solution method. The new approach to preconditioning is also a factor of 5 quicker than the usual use of a preconditioner based on the first-order spatial discretisation.



Fig. 2 DNW Wind tunnel model of aircraft in fig.1 In order to obtain the dynamic stability data for a model, a forced periodic oscillatory motion is applied. In CFD, an unsteady time-accurate simulation is usually used moving the computational grid at each time step. Due to periodicity, frequency domain methods can be used instead.



$$\mathbf{P}_{\alpha} = \propto \mathbf{P}_{2nd} + (1 - \alpha) \mathbf{P}_{1st}$$

For a CFD problem, the preconditioner is usually based on the first-order spatial discretisation due to the second-order matrix proving unstable for some cases. In this work, a mix of first and second-order discretisations is used (eq.5).

Harmonic Balance

The Harmonic Balance (HB) technique is a method of calculating one period of an oscillatory motion from solutions at just a few points around the cycle.

This approach takes eq.1, models the flow variables and residuals as a Fourier series, which is truncated to a specified number of harmonics N_H . Balancing the harmonic terms gives a system of $N_T = 2N_H + 1$ equations expressed in matrix form as:

$$\omega \mathbf{A}\widehat{\mathbf{W}} + \widehat{\mathbf{R}} = 0 \tag{6}$$

Discretising the cycle into N_{τ} sub-intervals at which the CFD solutions are calculated, allows solution in the time-domain.

Dynamic Derivatives

Table 2 Value of pitching moment aerodynamic damping

Method	Time- accurate	HB-1	HB-3	LFD
$C_{M_{\dot{\alpha}}} + C_{M_q}$	-2.59	-3.57	-2.52	-1.88

As with the response reconstruction in fig.4, table 2 shows the values of the dynamic terms also improve with an increased number of retained harmonics.

Conclusions

It is shown that frequency domain methods offer a viable alternative to using time-accurate CFD methods for obtaining dynamic stability data of aircraft models, whilst offering large savings in time to improve the throughput in the optimisation process.

Fig.3 Mean pressure coefficient plot for transport aircraft wing The focus of this work is to make use of frequency domain methods, namely the Linear Frequency Domain (LFD) method and the Harmonic Balance (HB) method, for the calculation of dynamic stability data for use in the simulation of flight. The system is then formulated with a pseudo-time term to allow calculation with a CFD solver:

$$\frac{d\mathbf{W}_{hb}}{d\tau} + \omega \mathbf{D} \mathbf{W}_{hb} + \mathbf{R}_{hb} = 0$$
⁽⁷⁾

Once a solution has been obtained for W_{hb} , Fourier coefficients are obtained and the time domain signal is reconstructed.

It is also shown that the new approach to preconditioning of linear systems has the potential to further improve the current methods.

Further work to be carried out includes making use of these solvers for the generation of data in tabular derivative models for flight simulation and the possibility of extending the use for aeroelastic problems.



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