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Requirements for Computer Generated Aerodynamic Models for Aircraft Stability and Control Analysis

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Abstract

For aircraft stability and control analysis tabular aerodynamic models are considered in this work, with computational fluid dynamics being the source of data. These tables are evaluated for an aerofoil case for a number of conditions including the presence of shocks and/or stalled flow. It is seen that for a large range of conditions the tables are sufficient to predict the forces and moments but the quality of the prediction is degraded when complex flow regimes are encountered due to history effects. The use of dynamic derivatives to introduce the rate effects is shown to be insufficient in these regimes.

Key words: Flight Dynamics; Flight Simulation; Tabular Aerodynamic Models; Computational Fluid Dynamics

Introduction

The calculation of stability and control of aircraft requires the aerodynamic forces and moments to be related to the aircraft motion. This is traditionally done using pre-computed or measured tables with data from dynamic wind tunnel tests such as that carried out for the X-31 aircraft in [1]. Flight simulators such as that described in [2] make use of computational models of tabulated aerodynamic data. The large look up tables provide a simple and rapid way of evaluating the loads and moments on an aircraft throughout given manoeuvre. There are a number of advantages to generating the tables using CFD, relating to the earlier availability of the data compared with wind tunnel testing, and the improved realism compared with semi-empirical methods. Methods for over-coming the large computational cost potentially involved were discussed in reference [3].

A framework for establishing the limits of these tabular aerodynamic models for flight dynamics was presented in [4] by running a number of manoeuvres for the SDM aircraft case using the tables and comparing these with a time-accurate solution obtained from the CFD solver. Good agreement was seen in this study for low rate of change manoeuvres although the tables were seen to struggle for high rates. The addition of dynamic derivatives to the tabular data improved on the accuracy of the models, although there was still some disagreement. This study was taken further in [5] extending to several cases including an unmanned combat air vehicle (UCAV). Again good agreement was seen for the majority of the manoeuvres except those with high rates of change of the aircraft angles. The static tables were implemented in the HELIFLIGHT flight simulator for the Ranger 2000 model for further assessment.

The aerodynamic tables typically cover a parameter space including the Mach number, incidence, sideslip and control surface deflections for the force and moment coefficients. To deal with the large database which would be created, the coupled parameter influence, for example between the sideslip and control surface deflections, is assumed negligible allowing decomposition into four three-dimensional tables [M,α,β], [M,α,δ_{ele}], [M,α,δ_{ail}] and [M,α,δ_{rud}]. A typical table is shown in Table 1. where the "x" indicates a non-zero entry.

Table 1: Example aerodynamic table

M	α	β	δ_{ele}	δ_{ail}	δ_{rud}	C_L	C_D	C_Y	C_l	C_m	C_n
x	x	x	-	-	-	x	x	x	x	x	x
x	x	-	x	-	-	x	x	x	x	x	x
x	x	-	-	x	-	x	x	x	x	x	x
x	x	-	-	-	x	x	x	x	x	x	x

The tables are usually based on static calculations of the aerodynamics with some studies looking at introducing dynamic effects through the calculation of dynamic derivative terms for each configuration. Dynamic derivatives describe the response of the loads and moments for a given rate. The calculation of these terms from CFD data is described in [6]. The static loads and moment coefficients are modified using the dynamic derivative terms by the following:

$$C_j = C_{j_0} + \bar{C}_{j_\alpha}\alpha + \bar{C}_{j_q} q \frac{c}{2U_\infty}$$

Where the "j" subscript indicates the force or moment coefficient of interest, the "0" subscript indicates the static value and the bar terms are the composite dynamic derivatives. The linearization of the coefficients through retaining the first Fourier harmonic represents a quasi-steady model. The effect of this linearization will be studied later.

When a large parameter space is required, the number of entries in the tables can be of the order of hundreds of thousands. This presents a problem when using CFD solvers to generate the aerodynamic data. Typically low fidelity data are used for example from the DATCOM [7] database. A data fusion approach to improve the fidelity of the tables whilst reducing the number of CFD simulations required was originally proposed in [8] where a 30% reduction in computational time was achieved without loss of accuracy. In [9] this approach was modified to use the DATCOM database as the source of the low-fidelity data being studied using a commercial jet aircraft case with changing geometry. In each of these approaches, Kriging interpolation is an integral part of the formulation to effectively fill the tables and locate points in the parameter space where a high-fidelity solution is required. For this study however, only CFD data is used due to the low cost involved in computing the data points for the cases presented.

To simulate manoeuvres, the aircraft can be "flown" based on tabular forces and moments. At each point within the manoeuvre, the angles and rates of the aircraft are known. The loads and moments are then obtained for the given conditions from the tables. The next position in the prescribed motion is then used to determine the new loads and moments. This then generates a history which can be used to view the aircraft behaviour for a given manoeuvre. With many data points obtained within the parameter space, this process is very rapid compared with running a full order CFD simulation.

A number of relevant questions can be considered using CFD. First, the validity of the tables can be tested. Issues that can reduce the realism are (a) lack of resolution which leads to non-linear variations being missed; (b) history effects in the motion of interest; (c) assumptions in the parametric variations which are used to reduce the dimensionality of the tables. The validity of the tables can be tested using a time accurate calculation to replay representative motions of the aircraft through a CFD calculation. The resulting forces and moments can then be compared with the tabular values to check consistency as described in [4].

Secondly, is the question of how accurate the CFD has to be if the intention is to use the data to investigate aircraft stability and control. Discrepancies with measurements may not be significant if they simply change the values of the control states by a small value whilst preserving the system dynamics.

The paper will consider these questions for an aerofoil test case to complement previous work by the authors on more complex aircraft test cases. A quantification of the three issues listed above for cases when shocks and/or stall are present to introduce complex aerodynamics is attained.

Results

In order to assess the tabular models, a 2D NACA 0012 aerofoil has been taken as a test case. The aerofoil has also been modified to have a trailing edge flap to be used as a control surface. The aerofoils have been created to work with the PML [10] CFD solver which uses a meshless scheme. As such the aerofoils are point clouds rather than meshes and the flap case is run with the overlapping functionality described in [11] by having two point clouds, one for the aerofoil body and one for the flap, then using the pre-processor to combine the clouds into one large domain with the given positions of the two bodies. The clouds are shown in Fig. 1.

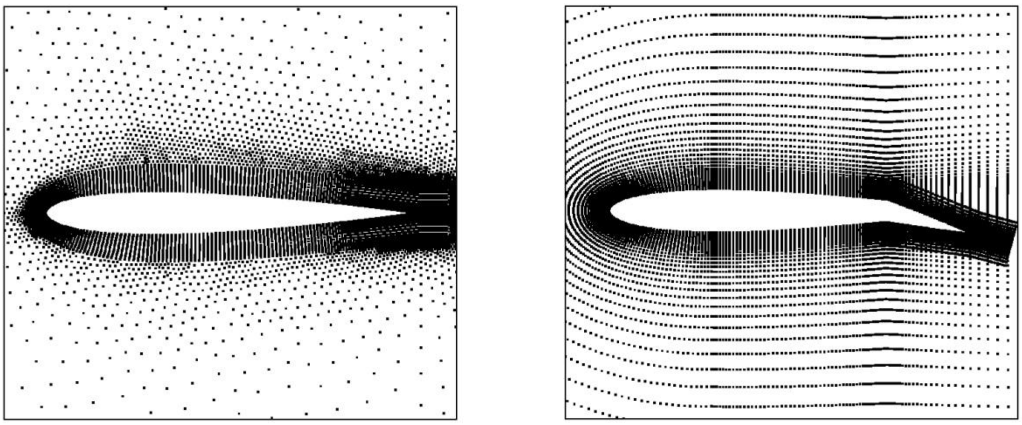

Figure 1: Aerofoil clouds (left: RANS cloud, right: Euler cloud with flap at 15 degrees deflection)

The RANS equations are solved with a Spalart-Allmaras turbulence model with Edwards' correction. All manoeuvres are run as forced motions. The CFD predictions are first validated against experimental data. A motion ranging from the linear region to stall and back has been chosen for this purpose due to the complex flow with dynamic stall present. The motion is described in [12] as case 8 ($M = 0.3$, $Re = 4x10^6$, $\alpha_0 = 10°$,$\alpha_A = 10°$, $k = 0.1$). The CFD solution is compared in Fig. 2 against the experimental data for both C_L and C_M.

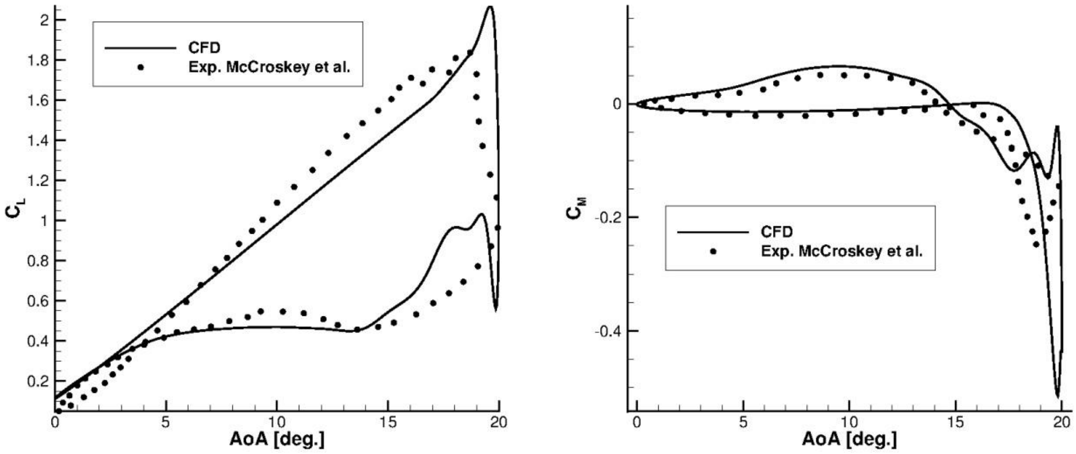

Figure 2: CFD validation (McCroskey case 8)

It is seen that the CFD solution is in good agreement with the experimental data through the majority of the motion. There are discrepancies in the deep stall region which could be attributed to turbulence modelling or three dimensional effects.

Dynamic derivatives are used to modify the static data in order to capture the effects of the motion on the aerodynamic forces and moments. In practice, this is typically done by taking a single value which has been calculated near to conditions of the desired motion. An assessment of this assumption can be carried out by calculating the terms for a number of different frequencies and oscillatory amplitudes to be able to view the effect of these on the tabular predictions. For each manoeuvre, a number of conditions have been taken to calculate the dynamic derivatives and are summarised in Tables 2 and 3.

Table 2: Dynamic model flow conditions used for the ramp motion case

Dynamic Case	Mean Incidence	Oscillatory Amplitude	Reduced Frequency
1	0.0°	1.0°	0.0125
2	0.0°	5.0°	0.0125

Table 3: Dynamic model flow conditions used for the oscillatory motion case

Dynamic Case	Mean Incidence	Oscillatory Amplitude	Reduced Frequency
1	0.0°	1.0°	0.1
2	13.0°	1.0°	0.1
3	0.0°	1.0°	0.0125

Two sets of manoeuvres of varying difficulty are used to assess the validity of the tables and are compared against the CFD time-accurate replay. The first manoeuvre is a ramp motion with rates ranging from 0.3°/s to 10°/s. This is the most simple of the cases with a constant rate applied throughout the manoeuvre. The incidence ranges from 0° to 10° at Mach 0.4 and Re=4.8×10^6, remaining below stall throughout to analyse the adequacy of the tables where the forces and moments behave in a linear manner. Comparison is shown in Fig. 3.

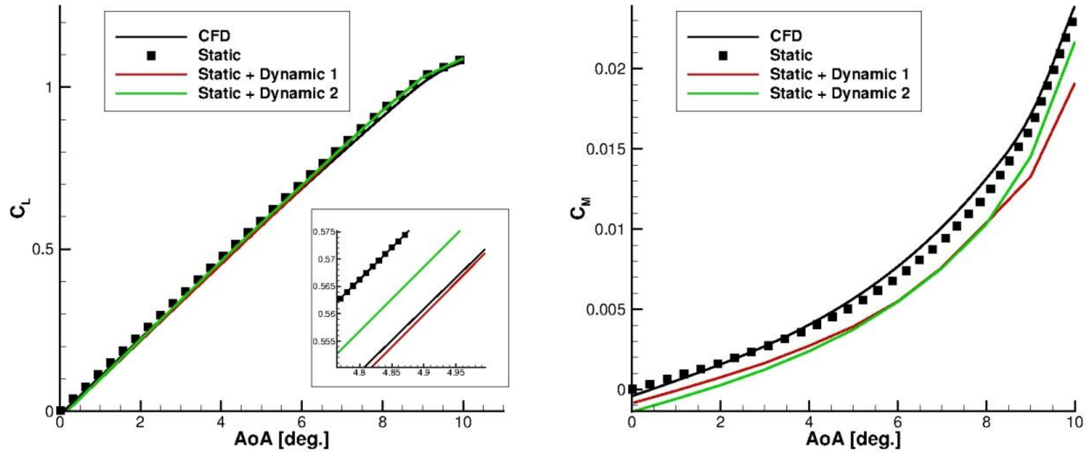

Figure 3: Ramp replay at 10°/s

It is seen that for the ramp manoeuvre at 10°/s, good agreement is obtained between the CFD and the static + dynamic solution. The slower rate manoeuvres are in excellent agreement although are not shown here. There is a small difference between the CFD and static solutions; however, the addition of the dynamic terms does improve the model prediction to the time-accurate replay for the lift coefficient. The pitching moment coefficient is not as well predicted with the dynamic modification possibly due to the higher rate.

The second set of manoeuvres consists of a number of sinusoidal motions in the stall region. The motions are described in [12] with the experimental data coming from the same source. Case 8 is again chosen due to the complexity of the motion passing in and out of the stall region where both linear and non-linear effects will be present. The solutions for this are shown in Fig. 4.

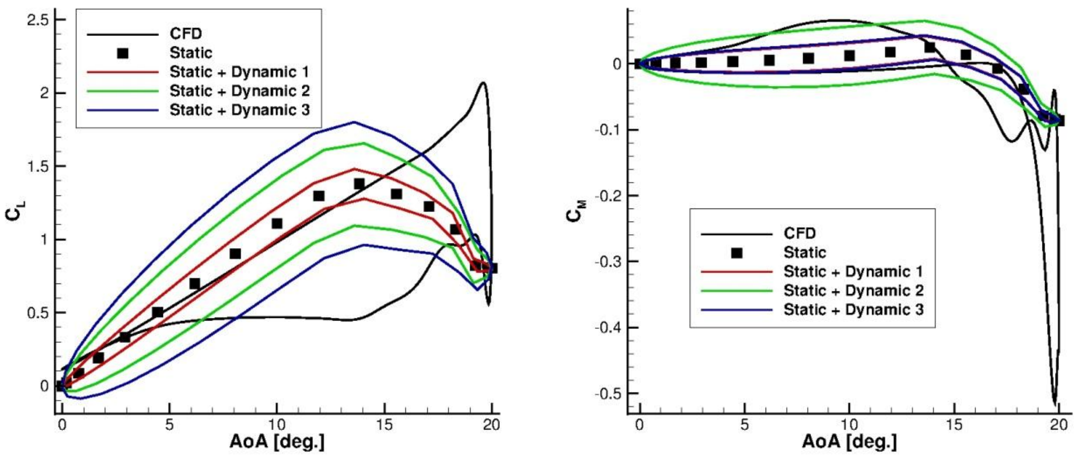

Figure 4: McCroskey case 8 replay

It is seen that for this case where dynamic stall is present, the agreement of the model predictions against the CFD is poor. It is also seen that for this case, the choice of dynamic derivative value greatly affects the model prediction. The most reasonable is that calculated about zero incidence for a reduced frequency equal to that of the motion (dynamic 1). This discrepancy indicates that the dynamic derivative model can introduce large errors depending on the value chosen. In order to view how much the time history is contributing to the solution, a quasi-steady (i.e. no time-history) calculation has been run for the above manoeuvre. The solutions are shown in Fig. 5.

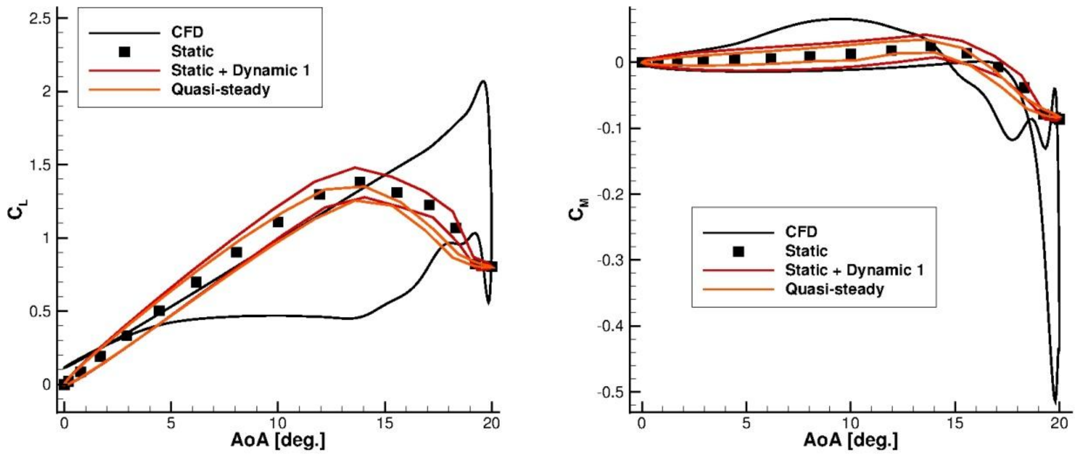

Figure 5: Effect of time history on model prediction

The good agreement seen between the quasi-steady solution and the static + dynamic prediction suggests that the effect of time history is very significant. This is unsurprising due to the presence of dynamic stall. With time history not being included in the model formulation, the predictions will never match that of the CFD replay. Any differences between the static + dynamic and the quasi-steady solution when the dynamic derivatives are calculated at the same flow conditions can be attributed to the use of a single value for the dynamic derivative in the dynamic model.

In order to view what is happening at the points where there are large differences between the model and the unsteady CFD, the flow field solutions can be plotted at a number of points in the cycle. Figs. 6 and 7 show the turbulent contribution for case 8.

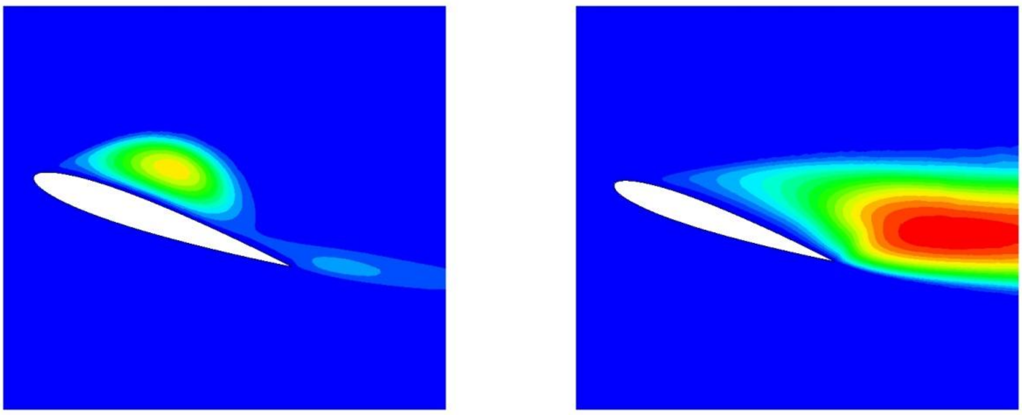

Figure 6: Turbulent nu term at 19.24 degrees on the upstroke (left: unsteady, right: quasi steady)

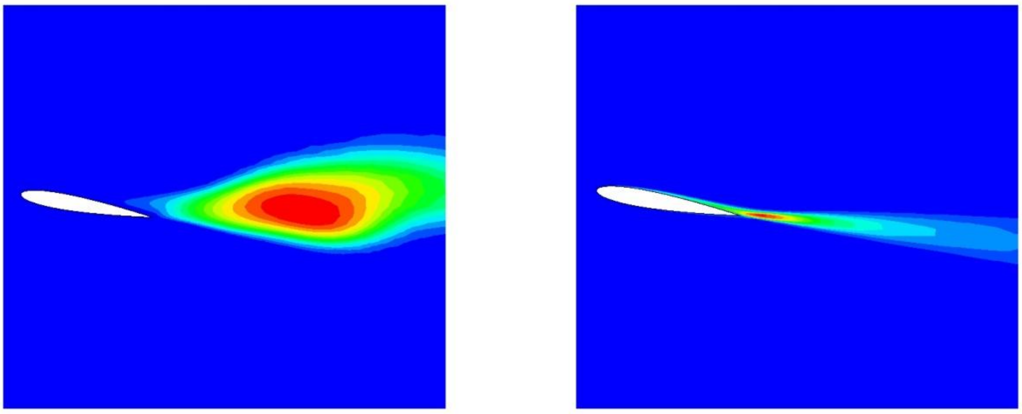

Figure 7: Turbulent nu term at 10 degrees on the downstroke (left: unsteady, right: quasi steady)

It is seen that for the two points taken, the turbulent terms are greatly dependent on the time history of the flow. The difference between the quasi-steady and the unsteady solutions show this due to the only difference in the two approaches being the neglecting of history effects for the former. Again this result leads to the conclusion that the model will never be able to match the unsteady CFD for cases where a large history effect is present. The best that can be achieved is to match the quasi-steady solution.

The dynamic derivatives play an important part in the accuracy of the model predictions and as such, the way in which they are calculated must be considered. For all of the above cases, the dynamic terms are considered to be constant values and independent of the frequency of oscillation and the amplitude. Using a single value for the dynamic terms means that the value is only strictly relevant to the mean incidence of the cycle from which it was calculated and is linearised about that point. Ideally, the dynamic terms will be calculated for each angle of incidence in the cycle and at the same frequency in order to accurately model the rate effect; however this would be prohibitive and would be more cost effective to just calculate each unsteady motion using a time-accurate CFD simulation. In the model for calculating the dynamic terms relevant to each manoeuvre, tabulated values of derivatives are used and the values interpolated from this. The tables however assume no coupling between the Mach number, mean incidence, amplitude of the oscillation or frequency. In the linear regimes, this may be a valid assumption; however, as has been shown in this work, the presence of non-linearities leads to this assumption no longer being valid.

An insight into the behaviour of the dynamic derivatives can be obtained by calculating the values for various Mach numbers, mean incidences, oscillatory amplitudes and frequencies and viewing how they change with each of these parameters. If the values change rapidly, the tabulated model and the assumption of having negligible coupling is probably no longer correct when manoeuvres are encountered for the corresponding conditions. In order to test this, a number of calculations have been run where a parameter is varied and all others are held constant. The values used for each case are shown in Table 4 and the solutions given in Figs. 8, 9 and 10.

Table 4: Flow conditions for dynamic derivative analysis

Varied Parameter	Mach	Mean Incidence	Oscillatory Amplitude	Reduced Frequency
Mach number	-	0.0°	1.0°	0.05
Mean incidence	0.3	-	1.0°	0.05
Reduced frequency	0.3	0.0°	1.0°	-

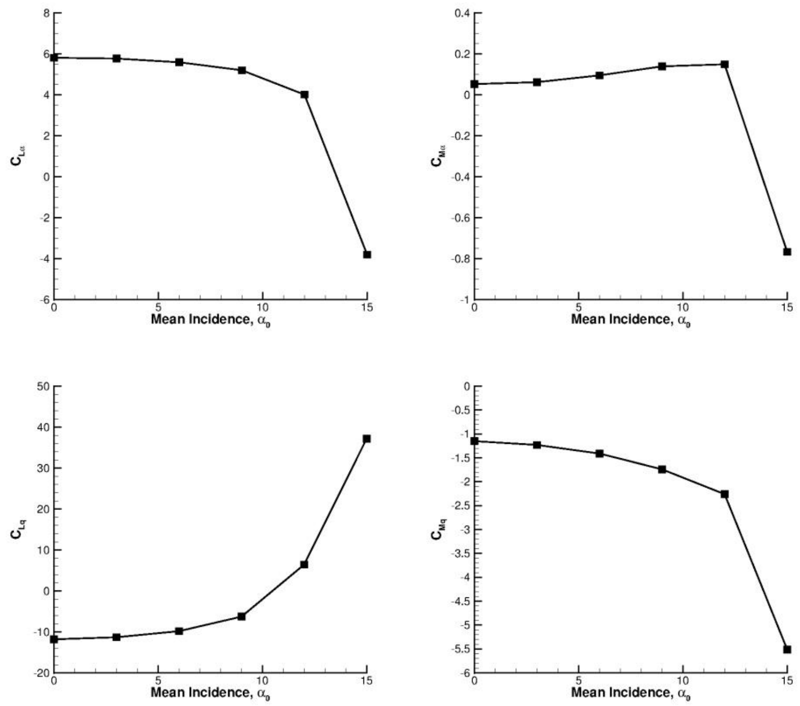

Figure 8: Variation of dynamic derivatives with mean incidence

It is seen that through the linear regime, the value of the derivatives remains fairly constant. It is only into the non-linear stall region when the values begin to deviate and as such will introduce errors in the model prediction.

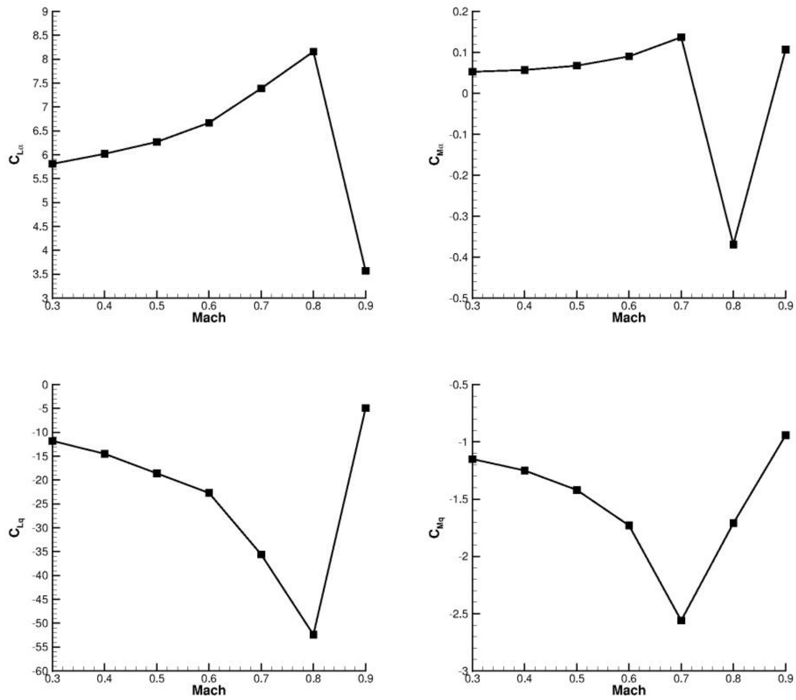

Figure 9: Variation of dynamic derivatives with Mach number

The variation of the dynamic terms with Mach number is more pronounced than that against mean incidence. The higher Mach numbers begin to introduce non-linearities when shocks begin to form on the aerofoil and this becomes clear in the transonic regime where large deviations of the terms are seen.

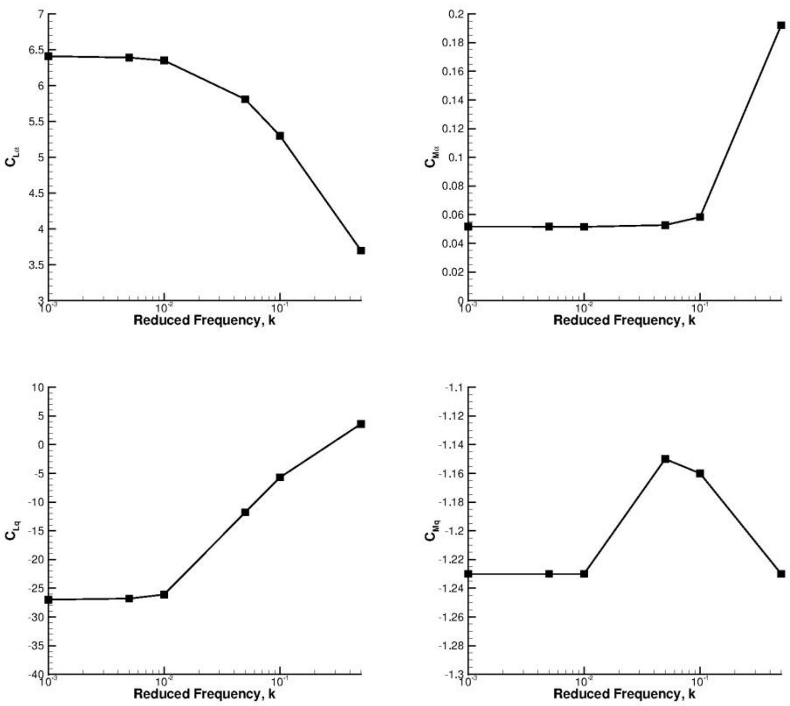

Figure 10: Variation of dynamic derivatives with reduced frequency

The variation with reduced frequency appears to be less significant at the lower values where the behaviour of the aerodynamics with respect to the grid movement will be linear. However, as the reduced frequency is increased, the lag between the aerodynamics and the grid position introduces non-linear effects which again will introduce errors in the model predictions. For example in the ramp motions, the reduced frequency was low where the dynamic derivative model will perform well and did so; however for the stall case, the conditions were in the region where the dynamic terms are varying greatly and as such the model fails to effectively predict the forces and moments.

Conclusions

This paper assesses the validity of a tabular aerodynamic model for an aerofoil. This model was generated using CFD. First, the CFD was validated for a difficult dynamic stall case. A level of discrepancy consistent with other RANS CFD predictions was seen.

Next, the tabular predictions were compared with time accurate CFD calculations for a ramp and an oscillatory pitching motion. Significant discrepancies were seen that were ascribed to flow history by using a quasi-steady CFD calculation for comparison. The tabular model cannot hope to predict history effects from the aerodynamics. The tabular models for these comparisons included dynamic derivatives from a single parameter combination, as is sometimes used in practice.

Semi-empirical models [13] are well known to model the oscillatory aerofoil dynamic stall flow. The example presented here illustrates the way in which tabular models can lead to large discrepancies in challenging flow regimes. Future work will involve identifying examples relevant to UCAV configurations arising from leading edge vortex dynamics.

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