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COMPARISON OF AERODYNAMIC MODELS FOR 1-COSINE GUST LOADS PREDICTION

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Abstract: A method for correcting the UVLM based on a downwash correction is presented. This is compared to the equivalent correction approach using DLM. The methods are compared for predicting the loads due to encounters with "1-cosine" gust defined by the CS-25 requirements. Two configurations are investigated. The first is a high altitude UAV wing and the second case is the NASA Common Research Model. Results are presented for both rigid and aeroelastic simulations and compared to full CFD results.

1 INTRODUCTION

Current trends in the commercial aircraft sector, along with environmental targets of Flightpath 2050, are pushing towards lighter structures and higher aspect ratios in order to produce more efficient next-generation aircraft. As a result of exploring these new designs, are likely to be more flexible and undergo larger deflections. Encounters with atmospheric turbulence are a vitally important consideration in the design and certification of aircraft often defining the maximum loads that these structures will experience in service. The large number of gust load cases to be considered for each design together with the experimental data used in the current process makes this an expensive task. Typically for industrial loads processes use linear methods such as the Doublet Lattice Methods (DLM) to solve the large number of gust cases required. To take into account of aerodynamic nonlinearities DLM is commonly corrected using nonlinear static aerodynamic data from wind tunnel tests or CFD.

There are a wide range of correction approaches available. They commonly reply on modifying the Aerodynamic Influence Coefficient (AIC) matrix by either multiplying by or adding correction factors or replacing the AIC matrix entirely. Traditionally these approaches have focused on providing corrections for flutter problems. Reviews of common correction approaches can be found in [1–3]. Recently there has been work done on correcting DLM with a focus on gust loads, [4, 5]

The non-linear aeroelastic corrections are based on static experimental data and thus history effects are only from the linear DLM. The DLM formulation assumes small out-of-plane harmonic motions of the wing, and a flat wake. So the method is not applicable when large deformations occur. An alternative to DLM is to use the Unsteady Vortex Lattice Method (UVLM) which is capable of simulating large deformations and does not rely on the flat wake assumption. The UVLM method can also be corrected in a similar way to the DLM using static data to improve its prediction of aerodynamic nonlinearities. This work will compare the aerodynamic gust loads predicted using corrected DLM and UVLM approaches with loads calculated using CFD. The two approaches will be compared for a high altitude UAV wing and a transonic case for the NASA Common Research model.

2 AERODYNAMICS

Three aerodynamic models have been used in this paper. The first two methods are based on solving the potential flow equations. This is a boundary-value problem. It the body surface a boundary condition is specified that enforces the flow is tangential to an impervious surface. At the farfield the disturbances have to vanish. In 3D singularity sources are used as they naturally decay as they tend to infinity. These are then distributed over the surface and the source strengths solved to find a solution with no through flow at the surface. The frequency domain approach is refereed to as the DLM and in the time domain the UVLM. Further details are given below. For comparison results are also presented using CFD. Details of how the gust is added to the CFD solution is given in Section 2.3.

2.1 Doublet Lattice method

The DLM method is based on the integral solution of the linearized potential flow equations. The solution is obtained by integrating an kernel function that describes a periodic motion of the lifting surface. Doublet singularity elements used to describe the surface and the wake shape has fixed periodic motion. This forms the bases of the DLM developed by Albano and Rodden [6]. This leads to a linear set of equations relating the downwash induced on each panel and the pressure difference across each panel. The downwash on each panel is given by normal velocity induced by the inclination of the surface to the flow. This means that the following system of equations can be solved for the surface pressures,

$$\mathbf{C_p} = \mathbf{A}\mathbf{w} \tag{1}$$

where $\mathbf{C_p}$ are the pressure coefficients on the DLM panels, $\mathbf{A}$ is referred to as the Aerodynamic Influence Coefficient (AIC) matrix and $\mathbf{w}$ is the downwash vector. The forces and moments on the panel are then obtained by integrating the pressures,

$$\mathbf{F} = \mathbf{S}\mathbf{C_p}. \tag{2}$$

where $\mathbf{F}$ are the loads and moments at the locations of interest and $\mathbf{S}$ is the integration matrix.

2.2 Unsteady Vortex Lattice Method

The unsteady vortex lattice method solves the incompressible potential flow equations using vortex singularity elements. Quadrilateral elements made up of vortex line segments, forming vortex-rings, are used to descretise the geometry. At each time step the wake panels are shed from the trailing edge elements with a circulation equal the the circulation in the shedding panel. After a number of times steps the wake vortex ring elements are converted to equivalent vortex particles. The vortex particles are convected with the local flow velocity, forming a force free wake. The problem is then solved by enforcing a Neumann type boundary condition at the surface. This is done by requiring that the normal velocity through a control point on each surface panel is zero. This allows problem to be written as a linear system on equations relating the surface panel vortex strengths to the normal velocity at the surface due to the inclination of the flow, surface motion and the induced velocity due to the wake as follows

$$\mathbf{w} = \mathbf{A\Gamma} \tag{3}$$

where $\mathbf{w}$ is the downwash at the collocation points, $\mathbf{A}$ is the AIC matrix and $\mathbf{\Gamma}$ are the panel vortex strengths.The resulting aerodynamic pressures are then computed from the resulting vortex strengths using the Kutta-Joukowsky theorem and can be written as

$$\mathbf{C_p} = \mathbf{Z\Gamma} \tag{4}$$

where $\mathbf{Z}$ is the matrix relating the panel pressure coefficients to the panel circulation [7].

For a large vortex particles, calculating interaction between all the particles results in a problem of order O(n2). This means that the computational cost grows rapidly with the number of time steps, as the number of particles in the wake grow. To reduce the computational cost it is possible to partition the problem into near-field and farfield regions. In the near field the influence on a vortex particle of the other particles in the nearfiled is calculated directly. The influence on a vortex particle by particles in the farfield region are approximated by agglomerating the particles together and calculating a single interaction. This reduces the number of direct interactions that have to be calculated with particles faraway reducing the computational cost. This functional usually takes the form of either a full Fast Multipole Method (FMM) [8] or a naive tree-code [9, 10]. The latter is sometimes also referred to as an FMM, however they are not true multipole expansions as they only contain what can be considered the first term of the full expansion, hence the use of the term naive.

2.3 CFD

The gust was added to the CFD using the Split-Velocity Method (SVM), which prescribes the instantaneous gust velocity throughout the computational domain. A brief summary is given below, more details can be found in [11, 12]

The SWM approach is derived by decomposing the velocity as follows

$$u = \tilde{u} + u_g \quad v = \tilde{v} + v_g \quad w = \tilde{w} + w_g \tag{5}$$

where u_g, v_g and w_g are the prescribed gust velocity components and $\tilde{u}$, $\tilde{v}$ and $\tilde{w}$ are the remaining velocity components. These are solved for so that the total velocities are a solution of the Navier-Stokes equations. This resulting equations can be written in a form similar to a standard moving mesh formulation plus some source terms. As the prescribed gust function is known the analytical derivatives of the gust velocities can be used. This minuses the dissipation of the gust and allows a gust to be convected through the course cells found near the farfield of a typical CFD mesh. These source terms are expected to be negligible except when there are either large gradients in either the prescribed gust or the flow field (such as close to a body surface). The split velocity method has been implemented in a modified version if the Tau CFD code [12–14]. For the turbulence model the Spalart-Allmaras negative model was used [15].

3 COUPLING

The MSC.NASTRAN software development kit allows the development of interfaces between MSC. NASTRAN and external codes such as Tau. The OpenFSI [16] interface allows the NASTRAN to send displacements and velocities to and external code and receive back nodal forces and moments. The OpenFSi interface supports two different approaches for coupling dynamically coupling. The first is explicit coupling where the codes are loosely coupled performing one iteration per time step. The second is implicit coupling where multiple iterations are carried out per time step until the structure and aerodynamic are in equilibrium. This requires some modification to Tau to allow restarting a physical time step multiple times to enable implicit coupling. This is achieved by modify the Tau data streams through Tau-python, see [17] for details. The same framework has been used to couple MSC.NASTRAN to the UVLM code. For the ULVM and CFD results the strong coupling has been used for the aeroelastic simulations.

4 CORRECTIONS

The aerodynamic strip loads due to a gust disturbance calculated using the Doublet Lattice Method in NASTRAN [18] can be expressed as:

$$\mathbf{F}^{DLM} = \bar{q} w_g \mathbf{PP}(k)\mathbf{S}\mathbf{A}^{-1}\mathbf{w}(k). \tag{6}$$

where $\bar{q}$ is the dynamic pressure, w_g is the gust scale factor, $\mathbf{PP}$ is the frequency variation in the gust, k is the reduced frequency. The aim is to correct the DLM so that sectional loads match the sectional loads calculated using CFD. This can be done in NASTRAN by supplying a downwash correction matrix. This correction matrix is calculated based on the approach found in [19] and summarised below. The steady corrected DLM the is now given by,

$$\mathbf{F}^{DLM} = \bar{q}\mathbf{S}\mathbf{A}^{-1}\mathbf{W}^{w}\mathbf{w}. \tag{7}$$

Equating the corrected DLM loads to the CFD loads results in the following equation:

$$\mathbf{F}^{CFD} = \bar{q}\mathbf{S}\mathbf{A}^{-1}\mathbf{W}^{w}\mathbf{w}. \tag{8}$$

There isn't a unique correction matrix $\mathbf{W}^w$ that will match the sectional DLM results to the CFD data. Instead the idea is to find a correction that minimises the change to the DLM aerodynamic coefficient matrix. The aim is to produce a correction matrix as close to the identity matrix. This can be done by minimising the weighted sum of the squares of the difference between the correction matrix and unity, given by:

$$\epsilon^{w} = \mathbf{W}^{w} - \mathbf{I}. \tag{9}$$

combining the above equation with equation (8)

$$\mathbf{F}^{CFD} = \bar{q}\mathbf{S}\mathbf{A}^{-1}\mathbf{I}\mathbf{w} + \bar{q} w_g \mathbf{S}\mathbf{A}^{-1}\epsilon^{w}\mathbf{w}. \tag{10}$$

The first term on the right hand side is the uncorrected DLM for a single gust frequency, so the above equation can be rewritten as:

$$\mathbf{F}^{CFD} = \mathbf{F}^{DLM} + \bar{q}\mathbf{S}\mathbf{A}^{-1}\epsilon^{w}\mathbf{w}. \tag{11}$$

Taking the difference between the CFD and DLM strip loads,

$$\Delta\mathbf{F} = \mathbf{F}^{CFD} - \mathbf{F}^{DLM}, \tag{12}$$

equation (11) can be written as

$$\Delta\mathbf{F} = \bar{q}\mathbf{S}\mathbf{A}^{-1}\epsilon^{w}\mathbf{w}. \tag{13}$$

The matrix ϵ^{w} is diagonal and $\mathbf{w}$ is a column vector. These swapped by turning $\mathbf{w}$ into a diagonal matrix and ϵ^{w} into a column vector, giving

$$\Delta\mathbf{F} = \bar{q}\mathbf{S}\mathbf{A}^{-1}\mathbf{w}\epsilon^{w}. \tag{14}$$

In the above equation $\Delta\mathbf{F}$ is known from CFD and uncorrected DLM. The matrices $\mathbf{S}$, $\mathbf{A}^{-1}$ and $\mathbf{w}$ are known from the DLM model. This means that the correction ϵ^{w} can be solved for using a least squares approach.

UVLM CORRECTION METHOD

The UVLM solves a system of equations for the circulation on a panel for a given downwash,

$$\mathbf{w} = \mathbf{A}\mathbf{\Gamma}, \tag{15}$$

where $\mathbf{w}$ is the downwash vector, $\mathbf{A}$ is the Aerodynamic Influence Coefficient (AIC) matrix, and $\mathbf{\Gamma}$ is the panel circulation. The results from the UVLM can be modified to better match experimental or CFD data by modify the downwash vector. The method used applies two correction matrices to the downwash vector leading to the new system of equations given by:

$$\mathbf{W}_0 + \mathbf{W}_w\mathbf{w} = \mathbf{A}\mathbf{\Gamma}, \tag{16}$$

where $\mathbf{W}_0$ is a downwash correction for the zero lift condition and $\mathbf{W}_w$ is a scaling of the down wash to correct the lift curve slope.

The relationship between the circulation and panel forces $\mathbf{f}$ can be written as:

$$\mathbf{f}^{UVLM} = \bar{q}\mathbf{Z}\mathbf{\Gamma}. \tag{17}$$

Combining equations (16) and (17) gives the following relationship between the downwash and the panel forces:

$$\mathbf{f}^{UVLM} = \mathbf{Z}\mathbf{A}^{-1}\mathbf{W}_w\mathbf{w} + \mathbf{Z}\mathbf{A}^{-1}\mathbf{W}_0. \tag{18}$$

The panel forces can be integrated to give sectional loads,

$$\mathbf{F}^{UVLM} = \mathbf{S}\mathbf{Z}\mathbf{A}^{-1}\mathbf{W}_w\mathbf{w} + \mathbf{S}\mathbf{Z}\mathbf{A}^{-1}\mathbf{W}_0, \tag{19}$$

The correction process aims to find the matrices $\mathbf{W}_0$ and $\mathbf{W}_w$ such that the theoretical sectional loads $\mathbf{P}_t$ match the experimental or CFD loads $\mathbf{F}^{CFD}$. There aren't a unique pair of matrices that can be used to correct the UVLM, so the idea is to find two matrices that minimise the change to the UVLM solution. So the aim is to find a $\mathbf{W}_0$ matrix as close as to zero as possible and a matrix $\mathbf{W}_w$ close to the identity matrix. The $\mathbf{W}_w$ matrix can be replaced by,

$$\mathbf{W}_w = \mathbf{I} + \epsilon_w \tag{20}$$

and the objective becomes to minimise ϵ_w. This leads to a set of equations with two unknowns to be minimised,

$$\mathbf{F}^{CFD} = \mathbf{SZA}^{-1} \left[\mathbf{I} + \epsilon_w\right] \mathbf{w} + \mathbf{SZA}^{-1}\mathbf{W}_0, \tag{21}$$

The first term of the right hand side is the theoretical uncorrected load so the above equation can be rewritten as

$$\mathbf{F}^{CFD} = \mathbf{F}^{UVLM} + \mathbf{SZA}^{-1}\epsilon_w\mathbf{w} + \mathbf{SZA}^{-1}\mathbf{W}_0, \tag{22}$$

The difference between the experimental loads and the theoretical loads is given by

$$\Delta\mathbf{F} = \mathbf{F}^{CFD} - \mathbf{F}^{UVLM}, \tag{23}$$

leading to

$$\Delta\mathbf{F} = \mathbf{SZA}^{-1}\epsilon_w\mathbf{w} + \mathbf{SZA}^{-1}\mathbf{W}_0, \tag{24}$$

This results in a set of equations where there are two unknowns, ϵ_w and ϵ_0. These means that at least two steady CFD simulations are required to solve for the correction matrices. Once again Equation (24) is solved using a least-squares approach.

The above correction method works in a single step if the downwash is fixed. However the downwash vector for the UVLM $\mathbf{w}$ is made from two compenents given by

$$\mathbf{w} = \mathbf{w}_{body} + \mathbf{w}_{wake}, \tag{25}$$

where $\mathbf{w}_{body}$ is the downwash on the body due to the external flow and $\mathbf{w}_{wake}$ is the downwash due to the wake. Introducing the correction matrices changes the strength of the shed wake particles resulting in a different downwash component due to the wake. As a result the correction process has to be iterated until a set of correction matrices are found where the difference between the downwash used to generate the correction matrices and the downwash produced using the corrections is minimised.

5 RESULTS

5.1 UAV wing

The first test case is a representative high altitude UAV wing, designed for the AEROGUST project. The wing is unswept, untapered, with no dihedral a span of 25m and a constant chord of 2m. The aerofoil is NASA LRN 1015 which is a 15.2% thick aerofoil. The wing has a linear twist distribution with 3°twist at the root and 0°twist at the tip. The individual wing mass is 425kg and the full aircraft mass is 7,000kg. The wing structural model is a beam stick model. The wing is designed to have a tip deflection on 1m at trim cruise condition. The first and second bending modes occur at 1.79Hz and 9.84Hz respectively; the first torsion mode occurs at 15.26Hz. The flight case for this aircraft is

Gust length(m)	Gust amplitude(m/s)
18.288	11.700
91.440	15.310
213.360	17.634

Table 1: '1-cosine' gust parameters used for UAV wing

an altitude of 55,000ft at Mach 0.55. The three different '1-cosine' gust lengths were used and are given in Table 1. Both the UVLM and DLM were corrected to match static lift and pitching moments, using steady CFD data between 2°and 6°. First gust simulations were performed on the rigid UAV geometry and compared to CFD results shown in Figure 1. This shows that the uncorrected DLM over predicts the lift and pitching moment. The uncorrected UVLM nearly predicts the correct lift for the shortest gust but is slightly over for the longer gust lengths. However the uncorrected UVLM over predicts the pitching moment slightly more the DLM. Applying the correction the DLM still over over predicts the lift for the longer gusts, but is quite close for the shortest gust. The pitching moments shows better agreement for the longer gusts although it now under predicts the shortest gust. The UVLM which was predicted the lift better now under predicts the lift for the shortest two gusts when the correction is applied. However the correction does improve the UVLMs prediction of the pitching moment. In all cases the DLM and UVLM predict the peak response slightly latter the the CFD.

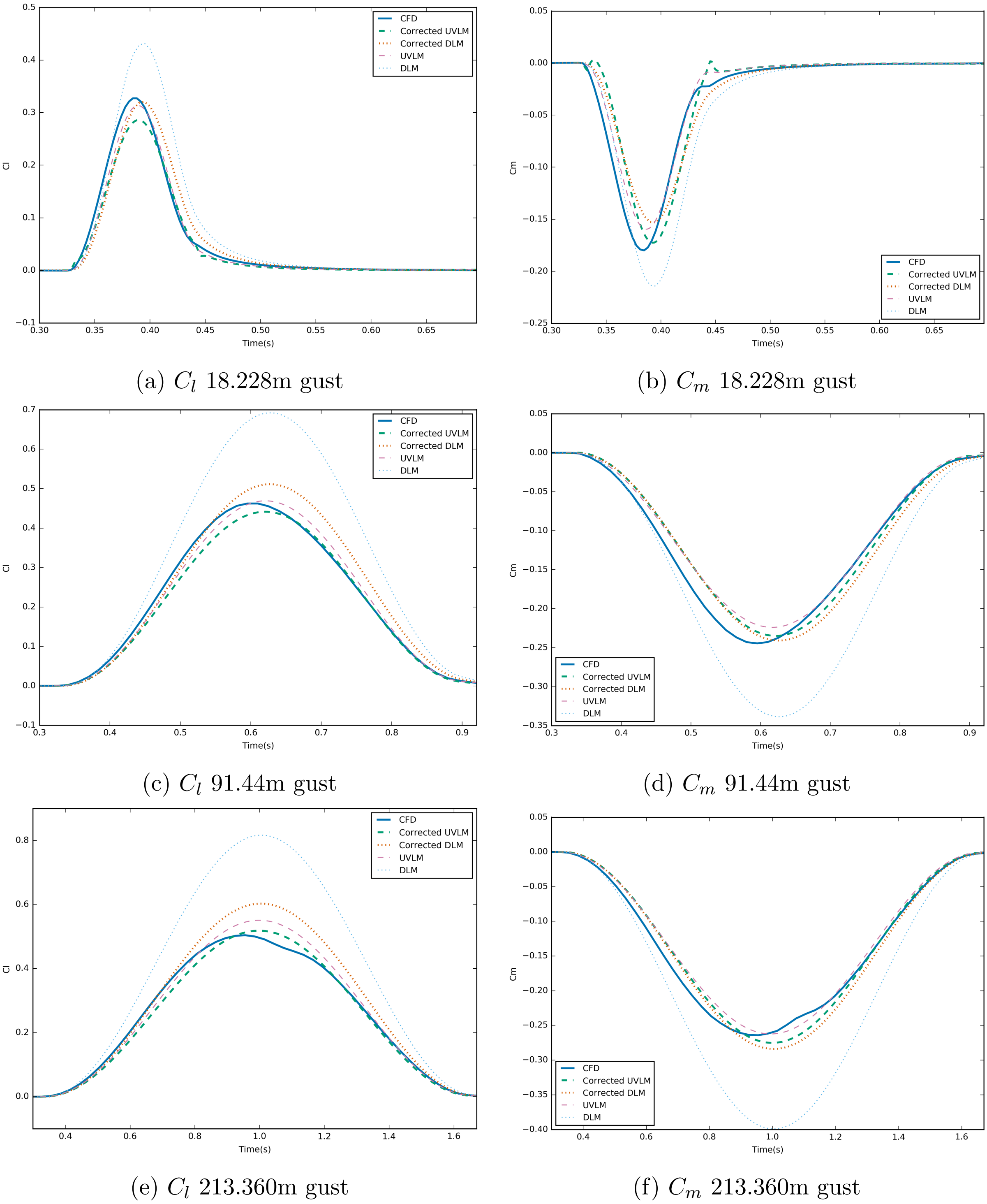
Next the corrections were applied to an aeroelastic simulation of the UAV wing encountering a gust with the wing route fixed, shown in Figure 2. For both the UVLM and CFD results the aircraft was trimmed to match the flight C_l and achieve a steady aeroelastic shape to start the gust simulations from. The results for the aeroelastic case show similar trends to the rigid case. For the lift the corrected DLM produces better results for the shortest gust while the corrected UVLM is closer for the longer two gusts. Both corrected approaches under predict the moment for the shortest two gusts but are both fairly close for the longest gust. Once again the peak loads are predicted slightly later.

5.2 NCRM

The second test case is the NASA Common Research Model (NCRM), which is representative of civil airliner. The structural model is a condensed beam stick model based on the FERMAT NCRM structural model [20]. The Maximum take off weight case of 26000kg was used. For the CFD wing body tail configuration from the 4th drag prediction work shop was used [21]. For the UVLM and DLM models the same mesh was used, based on the wing planform. The flight case for this aircraft is an altitude of 29,000ft at Mach 0.86. The three different '1-cosine' gust were lengths used and are given in Table 2. Both

Gust length(m)	Gust amplitude(m/s)
18.288	11.244
91.440	14.704
213.360	16.936

Table 2: '1-cosine' gust parameters used for NCRM wing



(a) C_l 18.228m gust

(b) C_m 18.228m gust

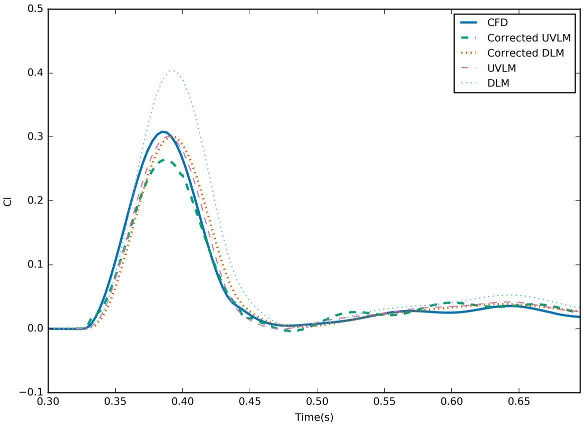
(c) C_l 91.44m gust

(d) C_m 91.44m gust

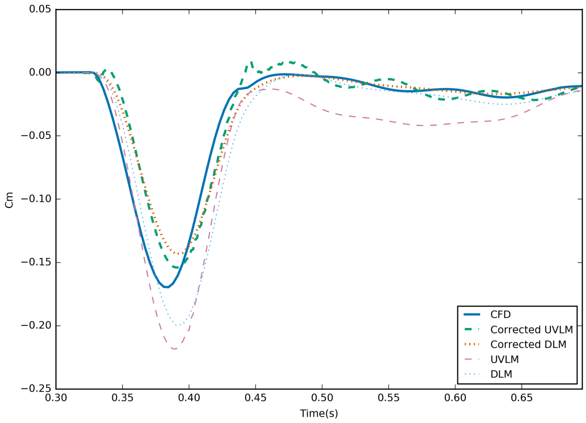
(e) C_l 213.360m gust

(f) C_m 213.360m gust

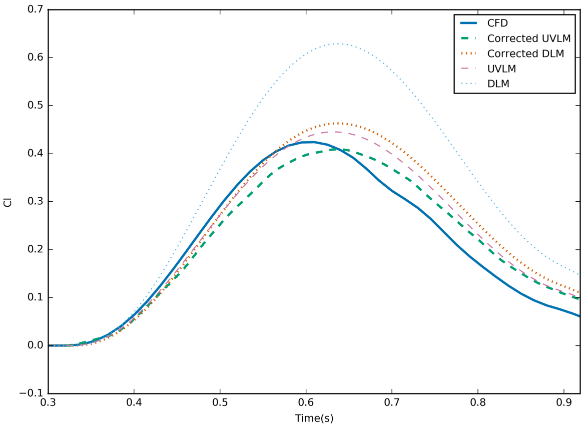
Figure 1: Gust responses for rigid UAV wing



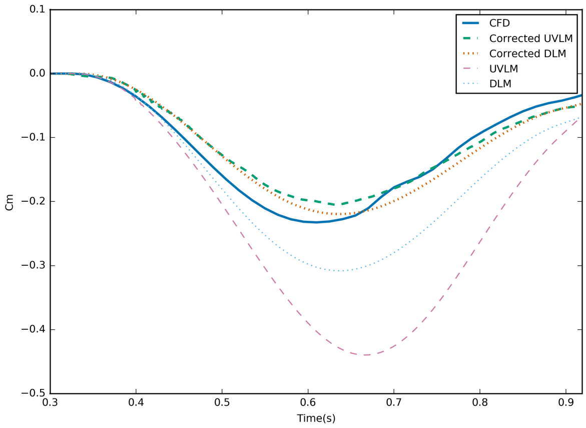
(a) C_l 18.228m gust



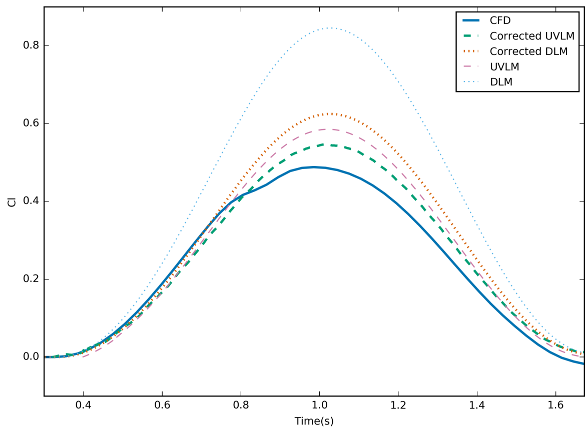
(b) C_m 18.228m gust



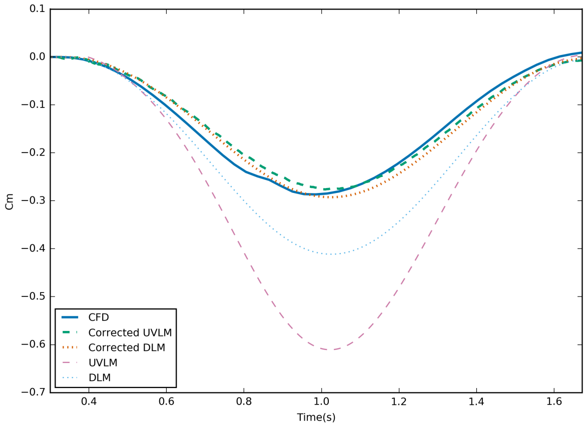
(c) C_l 91.44m gust



(d) C_m 91.44m gust



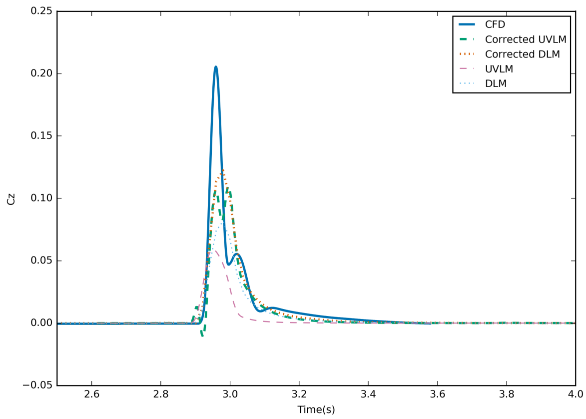
(e) C_l 213.360m gust



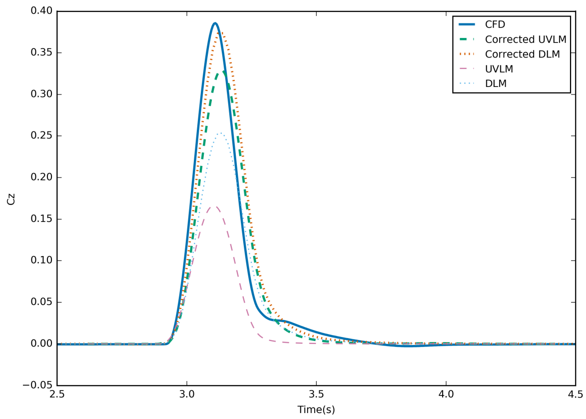
(f) C_m 213.360m gust

Figure 2: Aeroelastic response of the UAV to gust encounters

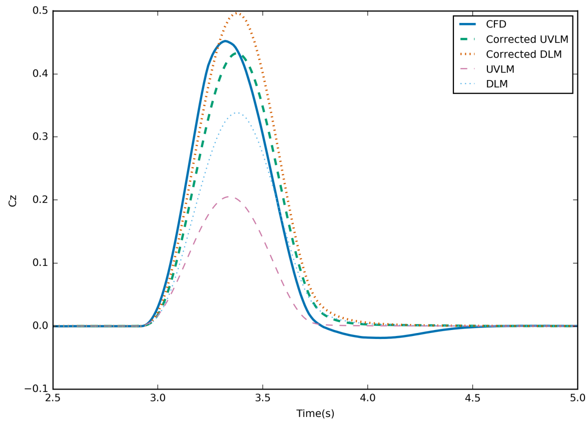
the UVLM and DLM were corrected to match static lift and pitching moments, using steady CFD data between 0°and 2°. First the wing loads were compared for the rigid NCRM model encountering a gust, see Figure 3. The DLM results always predict the higher lift then UVLM even when both are corrected. For the uncorrected case this is likely to be largely down to the fact that the UVLM code has now built in compressibility correction while the DLM use the prandtl glauert correction. Both under predict the lift for the shortest two gusts, but the corrected DLM gets quite close for the 91.44m gust. For the longest gust the DLM over predicts the response and while the UVLM is close closer to the peak lift it is still under predicting the response. For the shortest gust the corrected UVLM also shows an oscillation and a double peak which aren't seen in any of the other results. This is likely due to the fact that the corrections have been applied to match sections and the cordwise distribution of correction has no physical meaning. For the shortest length is less then 3 chord lengths, which means that there is more variation in gust velocity cordwise across the wing. As a result the correction factors aren't being applied evenly chordwise likely leading to the oscillations seen.



(a) 18.228m gust



(b) 91.440m gust

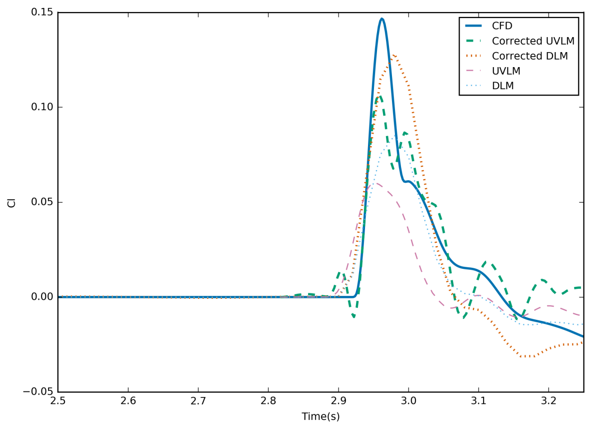


(c) 213.360m gust

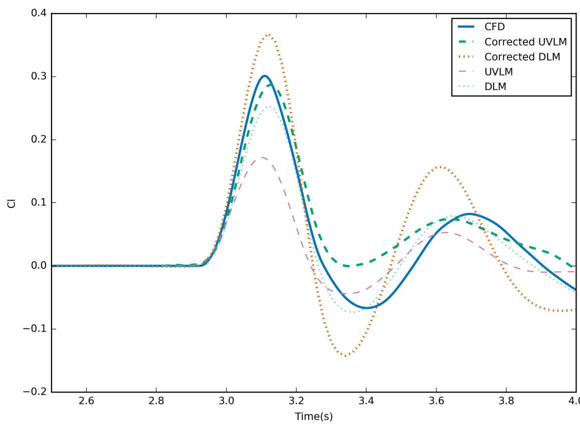
Figure 3: Wing lift response for the rigid NCRM encountering 3 different length gusts

Next the corrected models were compared for an aeroelastic simulation of the NCRM. In this case the structure was constrained at the wing root and only the wing loads applied to the structure. A comparison of the wing lift for the different gust lengths can be seen in Figure 4. For the UVLM and CFD cases the model was trimmed to achieve the aeroelastic flight shape at the flight C_l, from which the gust simulations were started.

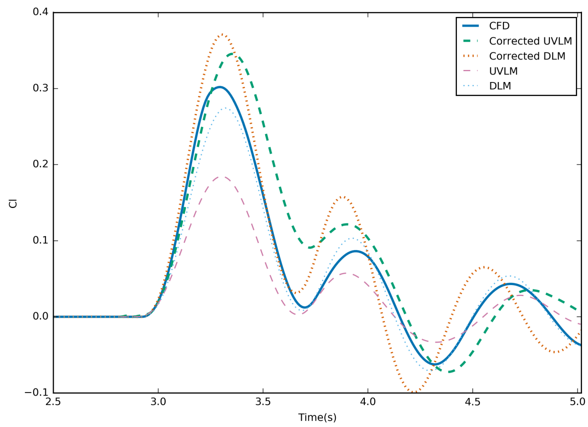
The DLM once again predicts higher loads then the UVLM. However for the aeroelastic case the DLM over predicts the lift for the two longest gusts. The corrected UVLM shows better agreement of the maximum lift with CFD for the 91.44m gust and over predicts the maximum lift for the 231.36m gust.



(a) 18.228m gust



(b) 91.440m gust



(c) 213.360m gust

Figure 4: Lift response of the NCRM with a flexible wing encounter gusts

6 CONCLUSIONS

A method for correcting the UVLM based on a downwash correction has been compared to the equivalent approach for the DLM. The two approaches haven compare for two configurations encountering three different length ”1-cosine” gusts representative of these prescribed in the CS-25 requirements. For the cases investigated the correct DLM method predicts higher loads then the corrected UVLM method. Generally the DLM matches the shortest gust well and over predicts the longer gusts. While the corrected UVLM under predicts the shortest gust be improves as the gust lengths increase.

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