Advanced linear methods for T-tail aeroelasticity

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Contents

Abstract

Flutter is one of the primary aeroelastic phenomena that must be considered in aircraft design. Flutter is a self-sustaining structural vibration in which energy is extracted from the air flow and transferred to the structure. The amplitude of the vibration grows exponentially until structural failure occurs. Flutter stability requirements often influence the design of an aircraft, making accurate flutter prediction capabilities an essential part of the design process. Advances in computational fluid dynamics and computational power make it possible to solve the fluid flow and structural dynamics simultaneously, providing highly accurate solutions especially in the transonic flow regime. This procedure is, however, too time-consuming to be used in the design optimisation process. As a result panel codes, e.g., the doublet lattice method, and modal-based structural analysis methods are still being used extensively and continually improved.

One application that is lagging in terms of accuracy and simplicity (from the user's perspective) is the flutter analysis of T-tails. The flutter analysis of a T-tail usually involves the calculation of additional aerodynamic loads, apart from the loads calculated by the standard unsteady aerodynamic codes for conventional empennages. The popular implementations of the doublet lattice method do not calculate loads due to the in-plane motion (i.e., lateral or longitudinal motion) of the horizontal stabiliser or the in-plane loads on the stabiliser. In addition, these loads are dependent on the steady-state load distribution on the stabiliser, which is ignored in the doublet lattice method.

The objective of the study was to extend the doublet lattice method to calculate the additional aerodynamic loads that are crucial for T-tail flutter analysis along with the customary unsteady air loads for conventional configurations. This was achieved by employing the Kutta-Joukowski theorem in the calculation of unsteady air loads on lifting surface panels. Calculating the additional unsteady air loads for T-tails within the doublet lattice method significantly reduces the human effort required for T-tail flutter analysis as well as the opportunities for introducing errors into the analysis.

During the course of the study it became apparent that it was necessary to consider the quadratic mode shape components in addition to the linear mode shape components. Otherwise the unsteady loads due to the rotation ("tilting") of the steady-state load on the stabiliser, one of the additional aerodynamic loads that are crucial for T-tail flutter analysis, would give rise to spurious generalised forces. In order to reduce the additional burden of determining the quadratic mode shape components, methods for calculating quadratic mode shape components using linear finite element analysis or estimating them from the linear mode shape components were developed.

Wind tunnel tests were performed to validate the proposed computational method. A T-tail flutter model which incorporated a mechanism for changing the incidence angle of the horizontal stabiliser, and consequently the steady-state load distribution on the horizontal stabiliser, was used. The flutter speed of this model as a function of the horizontal stabiliser incidence was determined experimentally and compared to predictions. Satisfactory correlation was found between predicted and experimentally determined flutter speeds.

Keywords: Aeroelasticity, T-tail, Doublet lattice method, Quadratic mode shape components

Uittreksel: Gevorderde lineêre metodes vir T-stert aero-elastisiteit

Fladder is een van die primêre aero-elastiese verskynsels wat in die ontwerp van ‘n vliegtuig in ag geneem moet word. Fladder is ‘n self-onderhoudende strukturele vibrasie waarin energie van die lugstroom na die struktuur oorgedra word. Die amplitude van die vibrasie groei eksponensieel totdat die struktuur faal. Fladdervereistes beïnvloed dikwels die ontwerp van ‘n vliegtuig, daarom is die vermoë om fladder akkuraat te voorspel ‘n belangrike komponent van vliegtuigontwerp. Vooruitgang in berekeningsvloeimeganika en rekenaarvermoëns maak dit moontlik om die vloei en die struktuur se dinamika gelyktydig op te los. Dit bied besonder akkurate oplossings, veral in die transoniese vloeibestek. Hierdie prosedure is egter te tydrowend om in die ontwerp optimeringsproses te gebruik. Gevolglik word paneelmetodes, bv. die doebletroostermetode, en modale basis struktuuranalise steeds algemeen gebruik en verder ontwikkel.

Een toepassing wat agterweë gebly het ten opsigte van akkuraatheid en eenvoud (uit die gebruiker se oogpunt) is die fladderanalise van T-sterte. Die fladderanalise van ’n T-stert behels gewoonlik dat bykomende lugdinamiese kragte bereken moet word, buiten dié wat deur die gewone ongestadigde lugdinamiese programme vir konvensionele stertvlakke bereken word. Die gewilde weergawes van die doebletroostermetode bereken nie die kragte a.g.v. die in-vlak beweging (m.a.w. laterale en longitudinale beweging) van die horisontale stertvlak of die in-vlak kragte op die stertvlak nie. Verder is hierdie kragte afhanklik van die gestadigde lasverspreiding op die horisontale stertvlak, wat deur die doebletroostermetode geïgnoreer word.

Die doel van die studie was om die doebletroostermetode uit te brei om die bykomende ongestadigde ludinamiese kragte wat vir T-stert fladderanalise benodig word, tesame met die kragte vir konvensionele stervlakke, te bereken. Dit is gedoen deur gebruik te maak van die Kutta-Joukowski stelling om die ongestadigde lugdinamiese kragte op hefvlakpanele te bereken. Deur hierdie kragte binne die doebletroostermetode te bereken word die menslike inspanning wat vir T-stert fladderanalise benodig word, asook die geleenthede om foute te maak, beduidend verminder.

In die loop van die studie het dit geblyk dat dit nodig is om die kwadratiese modale verplasing sowel as die lineêre modale verplasing in ag te neem. Andersins sou die ongestadigde krag a.g.v. die rotasie (“kanteling”) van die gestadigde lasverspreiding op die horisontale stertvlak, een van die bykomende omgestadigde kragte wat vir T-stert fladderanalise in ag geneem moet word, aanleiding gee tot vals veralgemeende kragte. Ten einde die bykomende las om kwadratiese modale verplasings te bereken te verlig, is metodes om die kwadratiese modale verplasings d.m.v. lineêre eindige elementanalise te bereken, of om dit van die lineêre modale verplasings te beraam, ontwikkel.

Windtonneltoetse is uitgevoer om die geldigheid van die voorgestelde berekeningsmetode te toets. ‘n T-stert fladdermodel met ‘n ingeboude meganisme om die invalshoek van die horisontale stertvlak, en gevolglik die gestadigde lasverspreiding op die horisontale stertvlak, te verander, is vir die doel vervaardig. Die fladderspoed van hierdie model as funksie van die invalshoek van die horisontale stertvlak is eksperimenteel bepaal en met voorspellings vergelyk. Bevredigende korrelasie tussen berekende en eksperimenteel bepaalde fladderspoede is verkry.

Sleutelterme: Aero-elastisiteit, T-stert, Doebletroostermetode, Kwadratiese modevorms

Preface

The article format has been selected for this thesis. The thesis comprises of the following five articles:

I. Van Zyl, L.H., “Robustness of the subsonic doublet lattice method”, *The Aeronautical Journal*, Vol. 107, No. 1071, May 2003, pp. 257-262.

II. Van Zyl, L.H., “Unsteady Panel Method for Complex Configurations Including Wake Modeling”, *Journal of Aircraft*, Vol. 45, No. 1, January-February 2008, pp. 276-285, DOI: 10.2514/1.29267

III. Van Zyl, L.H., and Mathews, E.H., “Aeroelastic Analysis of T-Tails Using an Enhanced Doublet Lattice Method”, *Journal of Aircraft*, Vol. 48, No. 3, May-June 2011, pp. 823-831, DOI: 10.2514/1.54645

IV. Van Zyl, L.H., and Mathews, E.H., “Quadratic Mode Shape Components from Linear Finite Element Analysis”, *Journal of Vibration and Acoustics*, Vol. 134, No. 1, February 2012, pp. 014501.1-014501.7.

V. Van Zyl, L.H., and Mathews, E.H., “Quadratic Mode Shape Components from Ground Vibration Testing”, *Journal of Vibration and Acoustics*, Vol. 134, No. 3, June 2012, pp. 034504.1-034504.7.

The student was responsible for all the technical content of every article. Articles III to V are submitted as part of the thesis with the permission of the co-author, Prof. E.H. Mathews.

Permission has been obtained from the editors of the respective journals to include copies of the articles in this thesis. The letters of permission are reproduced in the Appendix, together with the relevant articles.

Glossary of terms

The following list defines the most common terms used in this thesis

Aeroelasticity
The study of the interaction of elastic, inertial and aerodynamic forces acting on an object, usually applied to aircraft.

Airplane
A fixed-wing aircraft.

Computational fluid dynamics (CFD)
A numerical procedure for solving the flow around an object by discretizing the flow region into volume elements, from which solutions to the Navier-Stokes, Euler or full potential equations can be obtained.

DMAP Alter
A programming tool allowing users to modify the solution sequences of the MSC/NASTRAN finite element program.

Doublet lattice method (DLM)
A panel method for calculating unsteady air loads on harmonically oscillating lifting surfaces or combinations of lifting surfaces and non-lifting bodies.

Edge code
A fluid-structure interaction code developed by FOI of Sweden.

Empennage
The lifting surfaces attached to the rear of an airplane fuselage to provide stability and a means of control. It usually consists of a vertical stabiliser and two horizontal stabilisers.

Fin
The vertical stabiliser of an empennage, including the rudder.

Fluid-structure interaction (FSI)
The simultaneous solution of the flow around and object, usually using CFD, and the structural dynamic response of the object. The structural dynamic response can either be solved using modal-based methods or a finite element discretization of the structure.

Flutter
A self-sustained vibration in which energy is transferred from the air flow to the structure.

Ground vibration test (GVT)
An experimental procedure for determining the natural mode shapes and corresponding modal parameters of a structure.

Horizontal tailplane (HTP)
The collective name for the left (port) and right (starboard) horizontal stabilisers of an airplane. The term includes the elevators, if fitted.

MSC/NASTRAN
The version of NASTRAN developed and marketed by the McNeal-Schwendler Corporation.

NASA
The National Aeronautics and Space Administration of the United States of America.

NASTRAN
A finite element analysis program originally developed for NASA.

Panel method
A numerical method for solving the flow around an object by discretizing only the boundaries of the flow region into surface elements to obtain solutions to the linearized potential equations.

Pitch
A rotation about the lateral axis of an aircraft.

Roll
A rotation about the longitudinal axis of an aircraft.

Stabiliser
A lifting surface forming part of an airplane's empennage. The term includes the relevant control surface, i.e., the rudder in the case of the vertical stabiliser and an elevator in the case of a horizontal stabiliser.

T-tail
An empennage consisting of a vertical stabiliser with the horizontal stabilisers mounted at or near the tip.

Trim load
The steady-state load on the horizontal tailplane of an airplane required to maintain balanced flight. The trim load can act either upwards, tending to pitch the aircraft nose down, or downwards, tending to pitch the aircraft nose up.

Yaw
A rotation about the vertical axis of an aircraft.

ZONA
ZONA Technology, a private company that develops and markets a range of unsteady aerodynamic and flutter analysis codes.

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1 INTRODUCTION

1.1 Background

Aeroelasticity is the study of the interaction between aerodynamic, elastic and inertial forces. It applies mostly to aircraft, but also to structures exposed to wind such as bridges and buildings. The primary phenomenon of interest is flutter, an oscillatory instability in which the amplitude of the oscillation grows exponentially until structural failure occurs. Other phenomena include static deflection, loads during manoeuvres and gust response, i.e., the structural dynamic response of an aircraft flying through atmospheric disturbances. Apart from the fact that flutter can have catastrophic consequences, the elimination of a flutter problem in a late stage of development of a new aircraft type can be very expensive. It is therefore important to consider flutter from the early design stages and during design optimisation.

Analytical solutions to aeroelastic problems are rare. However, Lagrange's equation is applicable to most aeroelastic problems. The degrees of freedom are often chosen to be the natural mode shapes of the structure. It is then relatively simple to express the kinetic and elastic potential energy of the structure in terms of these modal coordinates. The calculation of the generalised aerodynamic forces involves calculating the pressure distributions associated with each mode, and integrating them with the modal displacement of each mode as weighting functions. With the resulting matrix of generalised forces the equations of motion can be solved in the frequency domain.

In cases where the aerodynamic loads are significantly non-linear functions of the structural deformation of the aircraft, e.g., in transonic flow, it is necessary to solve the equation of motion in the time domain. This type of solution is referred to as fluid-structure coupled or fluid-structure interaction (FSI) solutions. FSI methods are presently too slow to be used in design optimisation.

Linear methods have therefore been the primary means of aeroelastic analyses over the past four decades. Of these methods the doublet lattice method and the ZONA family of commercial codes are used extensively. "Linear methods" refers to methods that entail solutions of systems of linear equations, eigenvalue problems and limited iterative solutions, e.g., Newton-Raphson solutions of small matrix equations. This includes panel codes, but excludes computational fluid dynamics (CFD) codes that solve the Euler or Navier-Stokes equations and therefore also FSI solutions.

1.2 Motivation for the study

A number of accidents and incidents in the 1950s and 1960s highlighted the lack of understanding of T-tail flutter. In July 1954 a British Handley Page Victor bomber crashed due to T-tail flutter, and on 11 July 1957 the first XF-104 prototype, a T-tail fighter, crashed due to tail flutter while flying chase for F-104A flight tests. The American Lockheed C-141 cargo aircraft also experienced unexpected unstable oscillation of the horizontal tail. This lack of understanding prompted experimental and analytical investigations into T-tail flutter (Baldock 1958, McCue et al. 1968, Gray & Drane 1974, Jennings & Berry 1977).

At about this time the doublet lattice method (DLM), a panel method for calculating unsteady air loads on oscillating lifting surfaces and wing-body combinations, became a popular tool in flutter analysis (Rodden 1997). However, despite four decades of development, the popular implementations of the DLM are not adequate for the analysis of T-tails, mainly for the following reasons:

1. The horizontal stabiliser of a T-tail is attached to the top of a flexible vertical stabiliser, or fin. Bending and torsion of the fin result in significant in-plane motion, i.e., chordwise and spanwise motion, of the horizontal stabiliser. These in-plane motions as well as in-plane loads are not modelled.
2. The aerodynamic loads on the horizontal stabiliser generated by in-plane motion of the horizontal stabiliser, as well as in-plane loads generated by motion normal to the plane of the horizontal stabiliser, depend strongly on the steady-state load on the horizontal stabiliser. The steady-state load distribution is, however, ignored in the DLM.
3. Quadratic mode shape components, which are routinely used in analyses ranging from buckling of beam-like structures to rotor blade vibration, have hitherto been ignored in T-tail flutter analysis. The steady-state trim load on the horizontal stabiliser can have a significant stiffening or softening effect on the fin bending modes that must be accounted for by considering the quadratic mode shape components.

The deficiencies of the DLM for T-tail flutter analyses are commonly compensated for by the calculation of additional aerodynamic terms, outside of the unsteady DLM calculation (Suciu 1996, Quaranta et al. 2005). These terms are added to the matrix of generalised forces before the equation of motion of the structure is solved.

Apart from the deficiencies of the DLM that add to the tedium of a T-tail flutter analysis, it is also necessary to perform a trim analysis for each flight condition for which a flutter solution is required. In addition to the angle of attack, side slip angle and control surface deflections, it is also important to determine the steady-state deformation of the structure. In particular, bending of the horizontal stabiliser induces either anhedral or dihedral, which significantly affects T-tail flutter.

1.3 Objectives of the study

The present study aims to make the aeroelastic analysis of T-tails more accurate and less tedious through the following contributions:

- A steady-state solution sequence was added to the DLM, using the same geometric input as for the unsteady solution and accounting for angle of attack and side slip as well as camber of lifting surfaces. The steady-state solution is required for the trim analysis and also affects the calculation of unsteady pressures on body surface panels, as well as having a significant effect on the unsteady loads on the horizontal tail plane (HTP).
- A more advanced surface panel body model, separated wake model, and wing-body interference model for the DLM were developed, making both the steady-state and unsteady analyses more accurate.
- The DLM was extended to calculate the additional unsteady aerodynamic terms, related to the in-plane motion and in-plane loads on the HTP, that are commonly calculated outside of the DLM.
- The steady-state load distribution and the quadratic mode shape components were taken into account in the calculation of generalised forces.
- Since the proposed method for T-tail flutter analysis requires quadratic mode shape components as input, which are not commonly determined in ground vibration testing or finite element normal modes analyses, methods for measuring or calculating quadratic mode shape components for general structures were developed.

1.4 Layout of the thesis

In the following sections an overview of the relevant literature is given, followed by a summary of the contribution of the present study. Recommendations for further improvement are given. The articles on which this thesis is based are presented in the Appendix.

2 LITERATURE SURVEY

2.1 The doublet lattice method

The doublet lattice method (DLM) is the *de facto* standard method for calculating unsteady air loads for aeroelastic analyses. Rodden (1997) gives a comprehensive overview of the development of the DLM, which will not be repeated here. He describes the DLM as a finite element version of the kernel function method of Watkins et al. (1959), as opposed to the earlier "assumed pressure-mode methods". The application of the assumed pressure-mode methods had to be extended one configuration at a time, e.g., for two lifting surfaces (Davies 1974, Stark 1964a) and for T-tails (Davies 1966, Stark 1964b). The DLM, on the other hand, could be applied to any configuration and was also applied to T-tails (Kalman et al. 1970). All of these T-tail applications were concerned with the calculation of the unsteady downwash matrix and did not consider the effect of steady-state loading on the horizontal tail plane.

Isogai and Ichikawa, however, developed an assumed pressure-mode method for wings oscillating in sideslip and yaw and for T-tail configurations, which takes the steady-state load distribution into account in the calculation of the unsteady loads (Isogai & Ichikawa 1973, Isogai 1974).

Lifting surfaces seldom occur alone – they are usually attached to a fuselage and may in turn have bodies attached to them, e.g., external stores such as fuel tanks, ordnance, or engines. The requirement to model bodies and lifting surface/body interference was addressed in the DLM by slender body theory and either an interference panel method (Giesing et al. 1971) or the method of images (Giesing et al. 1972a). The latter method is restricted to bodies of elliptical cross section and uses an un-tapered elliptical body to form the images of the lifting surfaces. The range of body shapes that can be modelled by this method is therefore limited.

Roos et al. (1977) describe a DLM that uses unsteady source panels on the body surfaces to model the flow about the bodies, along with a method of images to eliminate numerical problems at the attachment of the lifting surfaces to bodies. In their method the unsteady boundary conditions on the body surfaces are coupled to the steady flow solution through the second spatial derivatives of the steady disturbance velocity potential. However, this term resulted in numerical instabilities and was usually neglected (Bennekers et al. 1974). Even without this term they found good correlation with experimental results.

Chen et al. (1993) presented an advanced method for calculating unsteady aerodynamic loads on wing-body configurations. They avoided the numerical problems encountered by Roos et al. by employing the body-fixed coordinate system of Garcia-Fogeda and Liu (1987). In addition, they modelled the separated wake behind blunt-based bodies. The effect of the separated wake was shown to be significant for pitch damping calculations of blunt-based bodies. The lifting surface model employed by Chen et al. was, however, not a doublet lattice method, but a constant pressure panel method.

Liu et al. (1996) presented numerical results for a number of lifting surface cases comparing the constant pressure panel method results to DLM results. Apart from showing generally improved convergence of the constant pressure panel method compared to the DLM, they showed that the DLM produced erratic pressure distributions for a 70 degree delta wing example. They argued that the erratic behaviour of the DLM was due to its lower order (lifting line) compared to the constant pressure panel method. Van Zyl (1999) presented consistent DLM results for the delta wing case of Liu et al. to demonstrate that the erratic behaviour was not due to the fundamentals of the DLM, but rather to the implementation in the DLM code used by Liu et al. The relative merits of lifting line methods and the constant pressure panel method was the subject of debate between Chen et al. (2004) and Rodden (2005).

2.2 T-tail flutter analysis

The loss of a British Handley Page Victor bomber in 1954 due to T-tail flutter prompted experimental and theoretical investigations into T-tail flutter. The accident occurred at a speed at which the aircraft had been flown before without incident. After the crash, bolts from the fin-tailplane junction were found to have fatigue failures, which may indicate that the fin-tailplane junction stiffness had been reduced (Baldock 1958). Further wind-tunnel tests and calculations performed on the Victor tail unit revealed the dependence of fin flutter speed on tailplane dihedral and static lift. In flutter flight testing of the second prototype and production models, rigging of the ailerons was used to change the trim load on the stabiliser in order to determine the effect of the trim load, and also reduce the actual flutter speed to fall within the aircraft flight envelope.

In the United States of America, T-tail configurations were chosen for cargo aircraft and jet-powered flying boats. The Glenn L. Martin company developed the P6M Seamaster strategic bomber flying boat with a T-tail and invested a significant effort in the flutter clearance of the T-tail (Kachadourian et al. 1958).

Pengelley et al. (1954) conducted a series of wind-tunnel tests to identify the parameters that affect T-tail flutter and to provide data for validating theoretical T-tail flutter predictions. They experimentally investigated the effects of mass and stiffness variations, but not trim load, on flutter.

A series of wind tunnel investigations into T-tail flutter characteristics of the C-141 cargo aircraft was conducted by Ruhlin, Sandford and Yates from 1964 to 1975. In the first series of tests (Ruhlin et al. 1964) variations in stiffness of various structural elements and mass and inertia of the stabiliser were studied, in addition to seeking confirmation that the nominal design was flutter free within the intended flight envelope. Static load limitations on their model precluded a significant variation in trim load, a major factor in anti-symmetric T-tail flutter.

This aircraft did however encounter T-tail flutter due to non-linear aerodynamic effects (Livne & Weisshaar 2003), in particular symmetric stabiliser flutter was precipitated by substantial elevator deflections. Symmetric flutter of the stabiliser of a T-tail is not substantially different from that of a conventional stabiliser because of the limited in-plane motion. In this case both upward and downward elevator deflections precipitated flutter. The solution to this problem was to increase the elevator balance weights on the real aircraft, and this was also found to be effective on the model (Sandford & Ruhlin 1969).

Transonic effects on T-tail flutter of the C-141, and specifically the extent of the transonic dip for anti-symmetric flutter, were also investigated experimentally by Sandford et al. (1968) using the same model, but with a weakened fin spar. They found a substantial reduction in flutter dynamic pressure of 41% at Mach 0.7 compared to the low-speed value.

A similar study was conducted by Ruhlin and Sandford (1975) for an even larger cargo aircraft, the C-5, which also revealed a significant transonic dip (i.e., reduction in flutter dynamic pressure at transonic Mach numbers) between Mach 0.92 and Mach 0.98. The fin of this aircraft was stiffened as a result of this investigation (Cole et al. 2003).

McCue, Gray and Drane specifically investigated the effect of stabiliser incidence (i.e., trim load) on the flutter behaviour of a T-tail model (McCue et al. 1968, Gray & Drane 1974). They correlated their experimental results with analytical results obtained from Davies's theory (Davies 1966), augmented by the addition of the following aerodynamic terms:

a) a lateral component of the lift force caused by angular displacement of the tailplane in roll,

b) a rolling moment caused by angular displacement of the swept tailplane in yaw,

c) a rolling moment caused by angular velocity of the tailplane in yaw, and

d) a rolling moment caused by lateral velocity of the tailplane.

In their experimental setup the pitch angle of the whole model was adjusted to achieve the desired tailplane angle of attack. This is not the same as changing the incidence of the tailplane relative to the fin. For nose up pitch angles of the model, the fin would generate a restoring rolling moment if the fin was displaced in roll, whereas for nose down pitch angles the fin would generate a divergent rolling moment. This "weathercock" tendency of the fin was not considered in their analysis.

Jennings and Berry (1977) conducted a series of wind-tunnel tests to investigate the effect of stabiliser dihedral and steady-state lift on T-tail flutter. In this case the tailplane incidence could be changed relative to the fin, thereby eliminating the weathercock tendency of the fin. They adapted strip theory to calculate a similar set of additional aerodynamic forces using the concepts of Queijo (1948, 1968). Queijo used lifting line theory and the interaction between the air flow and spanwise as well as chordwise bound vortices to calculate the forces and moments on wings executing in-plane motions.

Rodden (1978) pointed out that the yawing moment due to roll rate, which was neglected by Jennings and Berry, is of the same order of magnitude as the rolling moment due to yaw rate. Suciu (1996) also used strip theory to calculate additional loads to augment DLM results and also neglected the yawing moment due to roll rate. Suciu’s method allows for modelling of transonic effects by factoring of individual elements of the influence coefficient matrix, based on empirical data.

Wind-tunnel testing of the Tu-154 airliner empennage also revealed a strong dependence of flutter speed on stabiliser deflection. A distinction was made between varying the angle of attack of the entire model and changing the stabiliser incidence angle relative to the fin, while keeping the model incidence fixed. However, the differences between the corresponding flutter speeds were small. Chuban (2005) investigated a procedure for modelling this effect, focussing on induced drag, and achieved good correlation between theoretical and experimental flutter speeds. Results were however only presented for upward trim loads, resulting in reduced flutter speed compared to zero trim load.

The broad approach of augmenting generalized forces calculated using lifting surface theory by additional unsteady aerodynamic loads was also used by Quaranta et al. (2005) in an optimization study of a T-tailed aircraft.

2.3 Quadratic mode shape components

The concept of quadratic mode shape components was introduced by Segalman and Dohrmann (1990) to facilitate the rigorous treatment of vibrations of rotating flexible structures. The method was also applied to buckling problems (Dohrmann & Segalman 1996) and further examples are given by Segalman and Dohrmann (1996) and Segalman et al. (1996).

The method proposed by Segalman et al. for computing quadratic mode shape components requires multiple non-linear, finite element, static deflection analyses. The loadings are derived from the linear mode shapes, multiplied by the mass matrix of the structure.

The method of quadratic mode shape components was applied to T-tail flutter analysis by Van Zyl et al. (2007, 2009). Following the lead of Van Zyl et al., Jung et al. (2008) applied the quadratic mode method to the fluid-structure coupling of a high aspect ratio wing.

No other reference to the application of the quadratic mode method to airplane aeroelasticity could be found.

2.4 Fluid-structure interaction

Computational Fluid Dynamics (CFD) codes generally do not need special treatment to calculate all the unsteady aerodynamic loads required for T-tail flutter analysis. In addition, CFD is the only practical and reliable means of accounting for transonic effects, which have been shown to be significant for T-tail flutter.

Meijer et al. (1998) applied the NLR's AESIM system to the flutter analysis of a transport-type, T-tail fuselage configuration. The AESIM system encompasses flow solvers of varying fidelity, up to a thin-layer Navier-Stokes (TLNS) solver. The structural dynamics model, however, only allows for linear mode shapes.

Transonic Euler solutions for a T-tail flutter model were presented by Arizono et al. (2007). They also used a modal representation of the structural dynamics of the model. For the wall-mounted T-tail flutter model there was no need to consider the aeroelastic trim problem.

A complete CFD-based T-tail flutter solution of a free-flying aircraft, including solution of the trim load and static deformation, was presented by Attorni et al. (2011). Apart from the flow separation issue, mentioned in relation to the C-141 cargo airplane, this represents the ultimate T-tail flutter solution. The one major deficiency in their method is the use of a linear modal displacement model.

The effect of shock-induced flow separation on T-tail flutter (Ruhlin & Sandford 1975), is still a challenge and Euler solutions, which are popular for aeroelastic analyses, would not be sufficient to capture this effect. At least a TLNS solver, as implemented in the AESIM system of NLR, would be required.

3 CONTRIBUTIONS OF THE STUDY

The original contributions of the present study to the different aspects of T-tail aero-elasticity are summarised in the following sections, with reference to the literature survey and the appended articles. Extracts from the articles as well as additional examples are presented to illustrate the contributions.

3.1 Robustness of the DLM

The DLM has been criticized in the literature for a lack of robustness. Liu et al. (1996) presented erratic unsteady DLM results for a pitching delta wing. This author found that his version of the DLM did not produce erratic results and published results for the same cases showing well-behaved DLM results (Van Zyl 2003). This article is included in the Appendix as Article I.

Chen et al. (2004) also presented erratic DLM results, calculated using the N5KQ code (Rodden et al. 1998), for a 70 degree delta wing at a steady angle of attack. Knowing that the erratic behaviour did not apply to the DLM in general, and that it also appeared for steady flow cases, the error in the DLM code used by Liu et al. was traced to the steady downwash calculation in the DLM code N5KA (Giesing et al. 1972b). The same routine is also used in the N5KQ code. The delta wing results presented by Chen et al. are reproduced in Figure 1. Results for the same case, analysed using the original N5KA code and a corrected version, are shown in Figure 2. The erratic behaviour of the original code reported by Chen et al. is accurately reproduced, and the corrected version eliminates the erratic behaviour. The identification of the programming error and this correction, therefore, resolve the robustness issue.

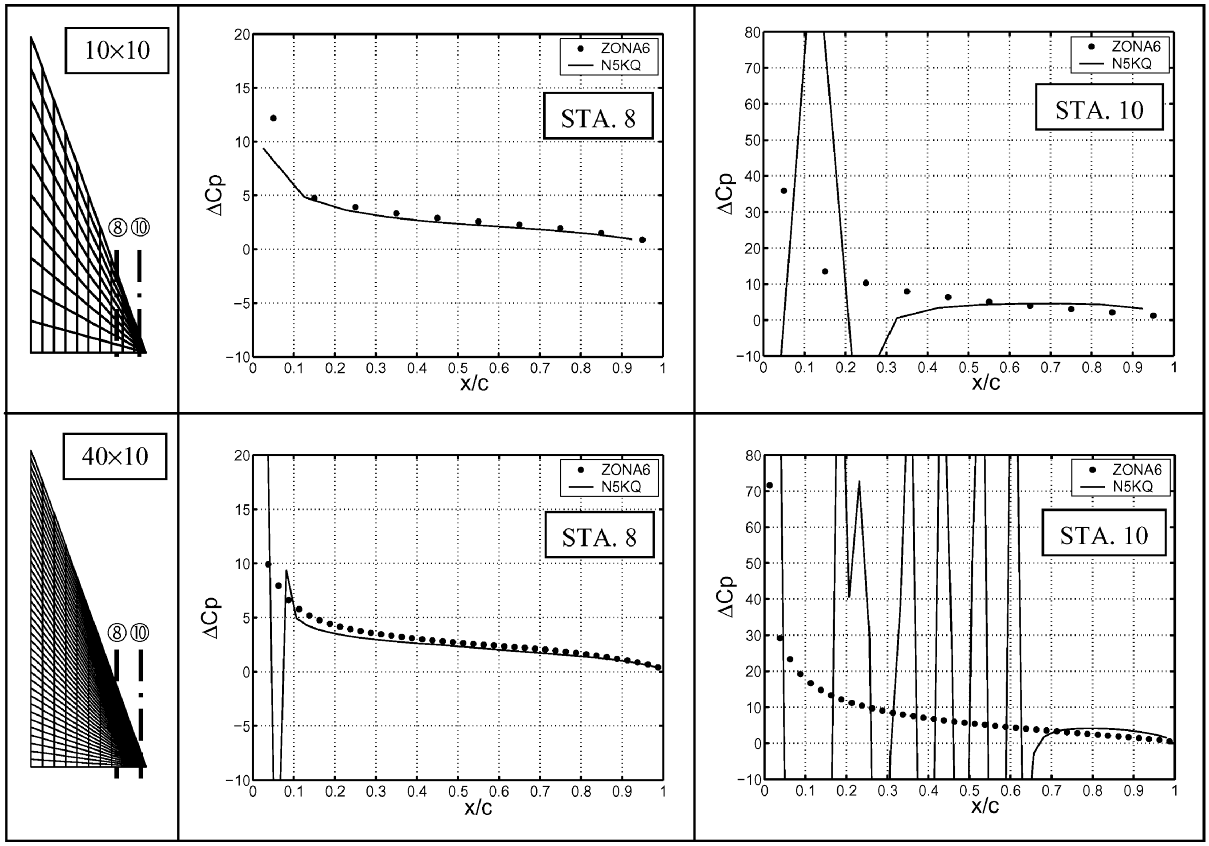

Figure 1: Steady-state lifting pressure profiles on a 70 degree delta wing at *M* = 0.8, from Chen et al. (2004), reprinted with permission of the American Institute of Aeronautics and Astronautics.

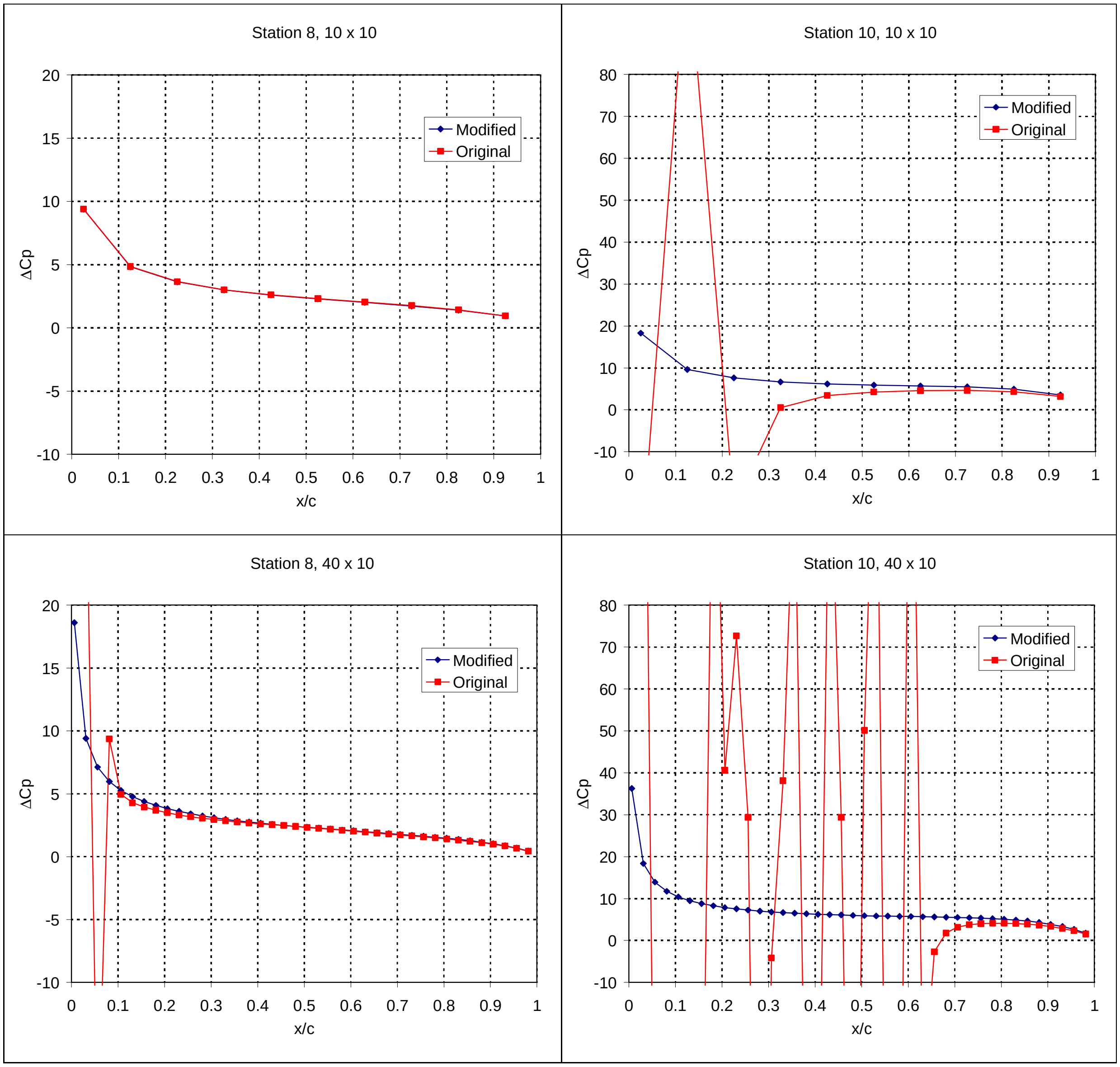

Figure 2: Steady-state lifting pressure profiles on a 70 degree delta wing at *M* = 0.8, calculated using the original and the corrected N5KA codes.

3.2 Wing-body modelling using the DLM

T-tail empennages are always attached to fuselages. Therefore, the modelling of bodies and the aerodynamic interference between bodies and lifting surfaces have a significant effect on the overall accuracy of the aeroelastic analysis of T-tail configurations. A doublet lattice method for modelling wing-body combinations in subsonic unsteady flow was described by Van Zyl (2008). This article is included in the Appendix as Article II.

The body and wing-body interference models in the popular implementations of the DLM are limited in the body shapes that could be modelled. In the case of the N5KA and the improved N5KQ codes (Giesing et al. 1972a, Rodden et al. 1998), the DLM versions implemented in MSC/NASTRAN, the body shape is limited to an elliptical cross section. The body flow field is modelled by axial singularities and the interference flow by the method of images. A body tapering to the rear would also lead to numerical problems because the trailing vortices from the image panels would penetrate the body surface.

In the present study, a surface panel body model, similar to that of Roos et al. (1977), was implemented in a DLM code. The more general boundary condition that is required for the body surface panels was also applied to the lifting surfaces.

Instead of the single strip image used by Roos et al., a two-strip image is used in the present method. The first image strip is intended to form a mirror image of the first actual strip of the lifting surface attached to the body, in order to minimize the induced velocities normal to the body surface. The second image strip is intended to move the trailing vortex to a convenient location to exit the body, thereby eliminating the problem with tapering rear bodies.

A separated wake model, based on the method of Chen et al. (1993), was also added to the DLM. Chen et al. showed that the separated wake flow has a significant effect on the pressure distribution over a blunt-based body. They used a point source in the wake region to model the steady wake flow and an unsteady velocity potential doublet to model the unsteady wake flow. Their method also enforces a constant, optionally user specified, base pressure. In the present implementation both a steady and an unsteady point source, and a steady and an unsteady doublet, are used to model the base flow. This allows for consistency between quasi-steady pressure distributions (the difference between two steady solutions) and unsteady solutions at zero frequency. In addition, an unsteady base pressure is calculated as part of the solution instead of being forced to be zero.

The steady-state and unsteady flow fields around bodies are coupled through the non-linear expression for the pressures on body surface panels. In order to obtain the correct unsteady pressure distribution over a body, it is therefore necessary that the steady pressure distribution is known. A steady flow solution sequence was added to the DLM, which uses the same geometry definition as the unsteady solution sequence. For the sake of the steady solution sequence, camber of lifting surfaces and angle of attack and sideslip of the whole configuration can be specified.

In addition to improving the fidelity of the modelling of wing-body combinations, the development of a DLM for wing-body combinations also encompassed two important steps towards a DLM for T-tails, viz. the more general boundary condition and the steady flow solution sequence. The more general boundary condition is required for T-tails as it takes account of the dihedral/yaw coupling and the in-plane motion of the HTP. The steady-state load distribution on the HTP of a T-tail has a significant effect on a T-tail flutter, therefore the steady solution is required for calculating the unsteady air loads on a T-tail.

3.3 T-tail aeroelasticity

The DLM for wing-body configurations of Van Zyl (2008) was extended to calculate generalised forces for T-tail flutter analysis. The method is described by Van Zyl and Mathews (2011) and is included in the Appendix as Article III. The DLM for T-tails implements two further elements necessary for T-tail flutter analysis:

a) the way in which unsteady forces on lifting surface boxes are calculated was changed to incorporate the concepts of Queijo (1968), and

b) the quadratic mode shape components were taken into account in the calculation of the generalised aerodynamic forces.

The method of Queijo is commonly used to calculate most of the aforementioned additional unsteady aerodynamic loads on the HTP of T-tail configurations, viz.

a) a rolling moment caused by angular displacement of the swept tailplane in yaw,

b) a rolling moment caused by angular velocity of the tailplane in yaw, and

c) a rolling moment caused by lateral velocity of the tailplane.

The downwash equation in the DLM is usually cast in a form that relates the induced downwash velocity to the pressure difference over an aerodynamic box (Giesing et al. 1971). In reality, the method calculates the downwash induced by an acceleration potential doublet line located at the box quarter-chord. The aerodynamic force is assumed to act at the centre of the acceleration potential doublet line. In the present method the acceleration potential doublet line is replaced by a corresponding quasi-steady horseshoe vortex and the forces on the aerodynamic box are calculated using the Kutta-Joukowski theorem. In applying the Kutta-Joukowski theorem, the motion of the horseshoe vortex elements are taken into consideration and the forces on the chordwise-bound vortices are also calculated. All of the aforementioned HTP forces, as well as the lateral component of the trim load due to angular displacement in roll, the incremental normal force due to longitudinal motion of the HTP, and the yawing moment due to angular velocity in roll, are calculated by this procedure.

The essence of the quadratic modal displacement model is that the linear expression for the displacement of a point on a structure,

$$\mathbf{x}(t) = \sum_{i=1}^{n} q_i(t)\mathbf{u}_i \tag{1}$$

is replaced by a quadratic expression (Dohrmann & Segalman 1996)

$$\mathbf{x}(t) = \sum_{i=1}^{n} q_i(t)\mathbf{u}_i + \sum_{i=1}^{n}\sum_{k=1}^{n} q_i(t)q_k(t)\mathbf{g}_{ik} \tag{2}$$

where the q_i are the generalised coordinates, the $\mathbf{u}_i$ are the linear mode shape components and the $\mathbf{g}_{ik}$ are the quadratic mode shape components.

The need to consider the quadratic mode shape components in T-tail flutter analysis is illustrated by the example of a rigid T-tail with height h, hinged at its base with torsional stiffness K_t about the hinge line, and mass moment of inertia I_{xx} about the hinge line. The hinge line is parallel to the flow. We consider the case of an HTP generating an upward load of constant magnitude F, with the HTP (and the force) rolling with the fin. The load acts at the junction of the fin and the HTP, as illustrated in Figure 3.

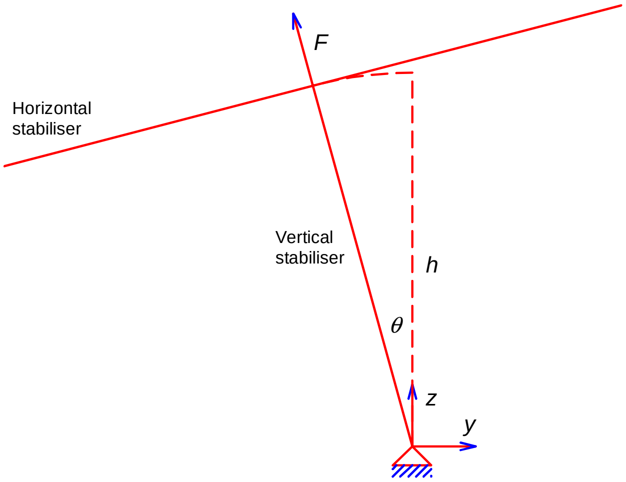

Figure 3: Rear view of the hypothetical T-tail

The force will have no effect on the dynamics of the T-tail because the force always acts through the hinge line. However, when we analyze the T-tail using Lagrange's equation and a linear modal displacement model, we get a different result. Lagrange's equation applied to the T-tail simplifies to

$$I_{xx}\ddot{\theta} + K_t\theta = Q \tag{3}$$

where θ is both the angular deflection of the fin in radians and the generalised coordinate, and Q is the generalized force defined by

$$\delta W = Q\delta\theta \tag{4}$$

δW is the virtual work that would be performed by the applied force if the fin was displaced through a virtual angular deflection $\delta\theta$. The virtual work is given by the dot product of the force and the virtual displacement vectors, viz.

$$\delta W = \mathbf{f} \cdot \delta\mathbf{x} \tag{5}$$

According to the linear modal displacement model, the displacement and virtual displacement of the top of the fin are given in terms of the generalised coordinate by

$$\begin{aligned} \mathbf{x} &= (0, -h\theta, 0) \\ \delta\mathbf{x} &= (0, -h, 0)\delta\theta \end{aligned} \tag{6}$$

The force is approximately equal to

$$\mathbf{f} = (0, -\theta F, F) \tag{7}$$

and the virtual work is equal to

$$\delta W = \mathbf{f} \cdot \delta\mathbf{x} = (0, -\theta F, F) \cdot (0, -h, 0)\delta\theta = hF\theta\delta\theta \tag{8}$$

Comparing Eqs. (4) and (8) reveals that

$$Q = hF\theta \tag{9}$$

Substituting this expression for the generalised force into Lagrange's equation, Eq. (3), gives

$$I_{xx}\ddot{\theta} + (K_t - hF)\theta = 0 \tag{10}$$

Therefore the T-tail is predicted to diverge if the product of the upward force magnitude, F, and the fin height, h, exceeds the torsional stiffness about the hinge line, K_t, which is incorrect.

According to the quadratic modal displacement model, the displacement and virtual displacement of the top of the fin are given by

$$\begin{aligned} \mathbf{x} &= \left(0, -h\theta, -\tfrac{1}{2}h\theta^2\right) \\ \delta\mathbf{x} &= \left(0, -h, -h\theta\right)\delta\theta \end{aligned} \tag{11}$$

The virtual work is equal to zero:

$$\delta W = \mathbf{f} \cdot \delta\mathbf{x} = \left(0, -\theta F, F\right) \cdot \left(0, -h, -h\theta\right)\delta\theta = 0 \tag{12}$$

The steady-state load is therefore predicted to have no effect on the dynamics of the T-tail, which is correct. In reality there will, however, be roll damping and a corresponding reduction in frequency with increasing dynamic pressure. The roll damping should be independent of the steady-state load.

This problem was analyzed using the DLM as well as the FSI code Edge (Eliasson 2001, Smith 2005). The latter is a typical FSI code using a linear modal displacement model. The quadratic mode method was implemented in the Edge code in a rudimentary fashion for this comparison.

The model parameters chosen for this study correspond to an existing wind-tunnel model and are as follows: fin height (h) 0.3 m, HTP span 0.5 m, fin and HTP chord 0.1 m, mass moment of inertia about the hinge axis (I_{zz}) 0.052178 kg.m², and modal frequency 5 Hz. We consider three HTP incidences covering a range over which linear aerodynamic behaviour of the wind tunnel model could be expected, viz. zero, -6º and +6º.

Three DLM solutions are considered:

a) The standard DLM, which ignores the steady-state load and calculates only roll damping (which is the correct result in this case).

b) The DLM with additional loads, in particular the lateral component of the steady-state load due to HTP roll. This is essentially equivalent to the method of Suciu (1996), and gives an erroneous result as illustrated above.

c) The T-tail DLM of Van Zyl and Mathews (2011), which includes the customary additional loads as well as accounting for the quadratic mode shape components in the calculation of generalized forces. This method yields the same results as the standard DLM, but for the right reasons.

For the Edge solution, a grid was generated with the base of the fin, i.e., the hinge line, on the axis of a cylindrical domain with a diameter of 2 m. Due to the axial symmetry of the setup, rotation of the T-tail should not change the pressure distribution on the T-tail. The Euler equations were solved using Edge for a free stream Mach number of 0.3. (The Edge code cannot solve for incompressible flow.)

The analyses consisted of a steady-state solution, followed by a prescribed, sine-squared, disturbance of 0.03 radians (corresponding to 9 mm lateral displacement at the fin tip), followed by a coupled time-domain simulation. The Edge results for the linear and quadratic modal displacement models, respectively, are presented in Figures 4 and 5. In the case of the linear modal displacement model, the T-tail response is significantly affected by the HTP incidence. The free vibrations have significantly different frequencies with an upward steady-state load resulting in a much reduced frequency, which is consistent with the result of the analytical study. In the case of the quadratic modal displacement model, the response is much less affected by the angle of incidence of the HTP, with all three responses having practically the same frequency. Due to a degree of asymmetry in the grid, the steady-state load did not act perfectly through the hinge line, resulting in a slight offset of the equilibrium position.

The damping and frequency of each response were extracted from the Edge results and compared to the DLM results in Figures 6 and 7. The lines are labelled according to the results of the DLM with customary additional HTP loads, but without considering the quadratic mode shape components. The 0° line represents the only correct solution for all three incidence angles. The Edge results for the three incidence angles using the linear modal displacement model fall close to the respective erroneous DLM results, whereas the Edge results for the three incidence angles using the quadratic modal displacement model lie on the 0° line.

It has been shown that the quadratic mode method is effective and essential for T-tail flutter analysis. The method has been fully implemented in the DLM and demonstrated in an FSI code.

In addition to the problem of calculating unsteady generalised aerodynamic forces, T-tail flutter analysis also requires the solution of the static aeroelastic trim problem. The present DLM was written in such a way that it can be invoked iteratively from the flutter solver, instead of calculating tables of generalised forces at predetermined conditions (Van Zyl, 2011).

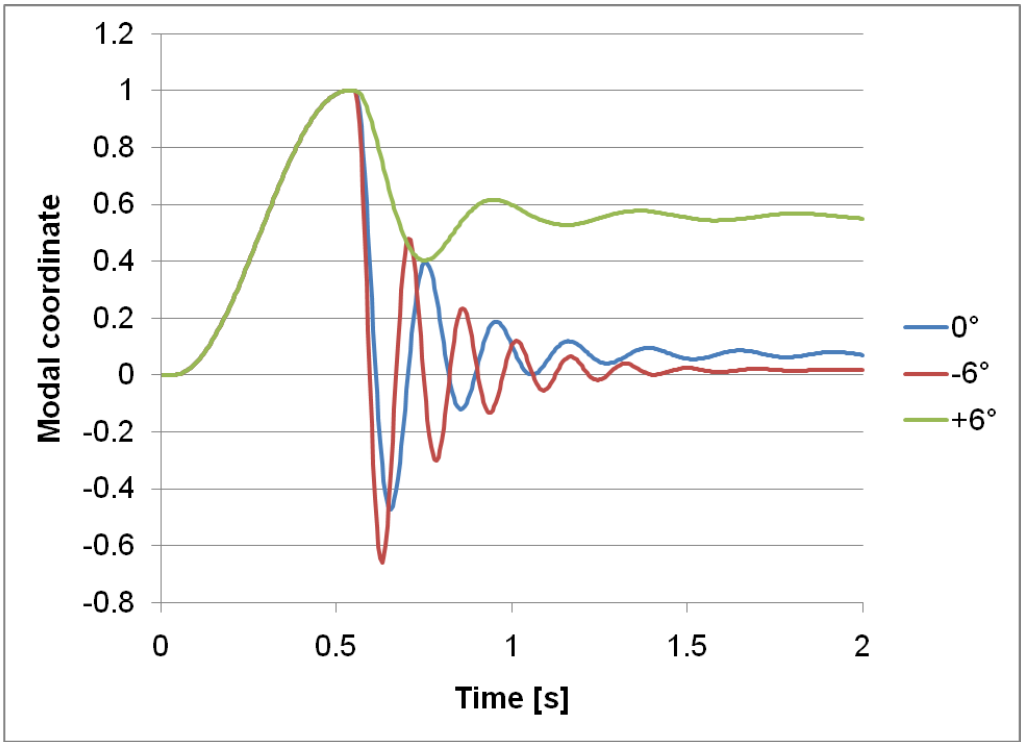

Figure 4: Edge results for the hypothetical T-tail with three different HTP incidence angles using a linear modal displacement model

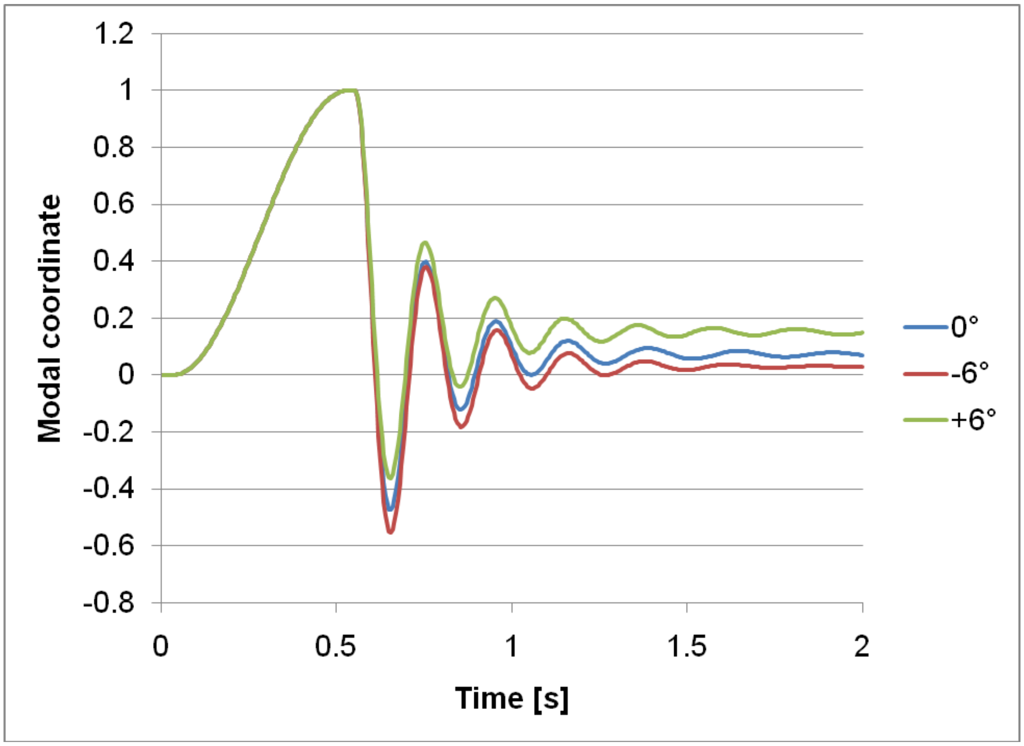

Figure 5: Edge results for the hypothetical T-tail with three different HTP incidence angles using the quadratic modal displacement model

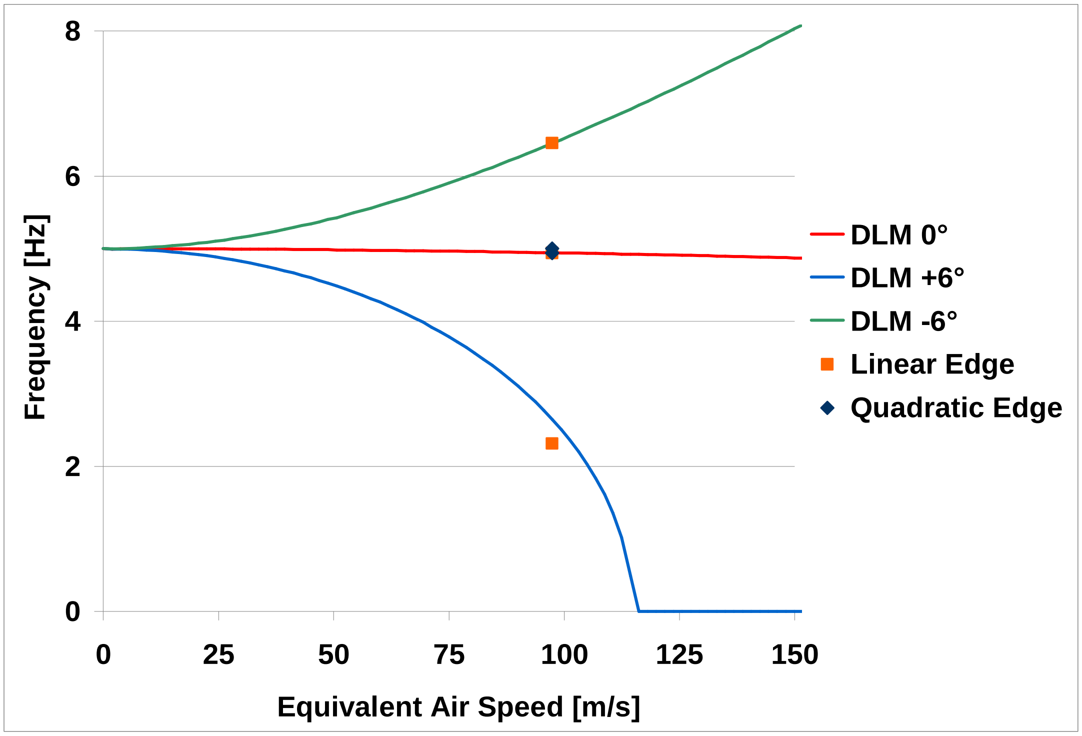

Figure 6: DLM frequency results for the hypothetical T-tail with three different HTP incidence angles, with Edge results superimposed

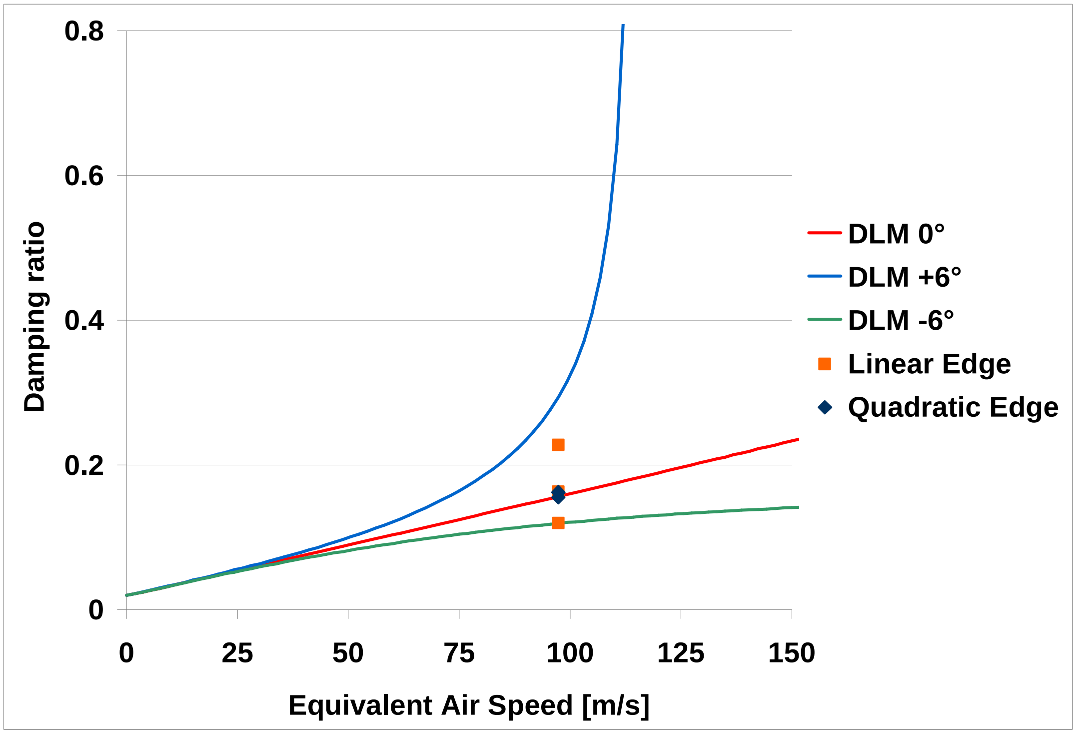

Figure 7: DLM damping results for the hypothetical T-tail with three different HTP incidence angles, with Edge results superimposed

3.4 Quadratic mode method

The present study introduced T-tail flutter analysis as a new application for the quadratic mode method of Segalman and Dohrman (1990) and also contributed three new ways of determining the quadratic mode shape components: calculating them using linear finite element analysis, the subject of the article included in the Appendix as Article IV, and measuring them in a sine-dwell GVT or estimating them from the linear mode shape components, described in the article included in the Appendix as Article V.

The application of the quadratic mode method to T-tail flutter was fully implemented in a DLM code and also demonstrated in a rudimentary fashion in an FSI code. In both instances the method yielded the expected results.

A method for determining quadratic mode shape components from linear finite element analysis, using energy considerations, was initially developed for truss structures. In addition, a method for calculating residual higher order stiffness terms was developed. Several examples confirmed the validity of the method. The method was subsequently implemented in MSC/NASTRAN for more general structures in the form of a DMAP Alter.

The method for measuring quadratic mode shape components in a sine-dwell ground vibration test is based on a simple expression for the quadratic mode shape component involving the mean offset and second harmonic of the accelerometer output. The method was successfully implemented and tested on a simple test piece, but is expected to have limited applicability due to the low signal levels of the mean offset and the second harmonic of the accelerometer outputs, compared to the first harmonic components. The method is also only capable of measuring the quadratic mode shape components of individual modes.

An approximate method for estimating the quadratic mode shape components from the linear mode shape components was therefore developed. This method treats the connections between measurement nodes, used to visualise mode shapes, as inextensible structural members in order to calculate the quadratic mode shape components.

3.5 Experimental work

An experimental investigation of the effect of the steady-state load on the HTP of a T-tail was undertaken, similar to the many studies mentioned in the literature survey. It was not possible to compare calculated results with these earlier experiments because insufficient data were presented to perform the calculations. Due to editorial restrictions of the specific journal, sufficient information for the model of this study could also not be published in the article included as Article

III in the Appendix (Van Zyl & Mathews 2011). The necessary additional information is included at the end of this section.

The model used in this investigation had a stiff horizontal tail plane, thereby eliminating the uncertainty of the static deflection of the HTP. The main focus was on the aerodynamic effects of the trim load. The plan forms of the fin and horizontal tail plane were loosely based on that of the A400M transport aircraft. The torsional flexibility was mainly confined to the fin, while the "bending" flexibility was mainly confined to the support system, which is shown in Figure 8. The base of the support system was bolted to the wind-tunnel floor. The upper beam of the support system, to which the fin of the T-tail was bolted, was supported by four flexible plates. This arrangement provided a stiff support in all translational degrees of freedom and in pitch and yaw, while allowing flexibility in roll. The stiffness in roll could be changed by changing the width and thickness of the flexible plates. The mounting system also contained a brake mechanism which could be used to stop flutter of the model.

The internal structure of the model is shown in Figure 9. The fin structure consisted of Aluminium ribs and spars and was covered with plastic film. The horizontal stabiliser structure consisted of steel tube spars and steel ribs and was covered with Balsa wood. A steel tube pivot connected the stabilisers to each other and to the fin. The fin tip fairing contained an electrically powered linear actuator which was used to change the stabiliser incidence. The stabilisers had non-symmetric NACA 23015 profiles to enable larger lift coefficients to be achieved without stalling, and could be mounted either upright or upside down.

The output of the tests was flutter speed as a function of stabiliser incidence. Flutter speed was expressed as equivalent air speed, which was calculated from the dynamic pressure measured in the wind-tunnel test section. For each HTP incidence angle a flutter speed uncertainty range was determined. The lower end of the range was the highest speed at which the model did not flutter, even with an initial disturbance. The upper end of the range was the lowest speed at which the model fluttered without any initial disturbance apart from the natural wind tunnel turbulence. The range was seldom more than 1 m/s and never more than 2 m/s.

There are two sets of results in the article, one for the stabiliser mounted upright and one for the stabiliser mounted upside down. As a matter of interest, all the data are plotted against stabiliser lift coefficient in Figure 10 and is seen to converge. The correlation between predicted and measured flutter speed was satisfactory, varying between 8% over-prediction and 2% under-prediction of flutter speed over the range of incidence angles tested.

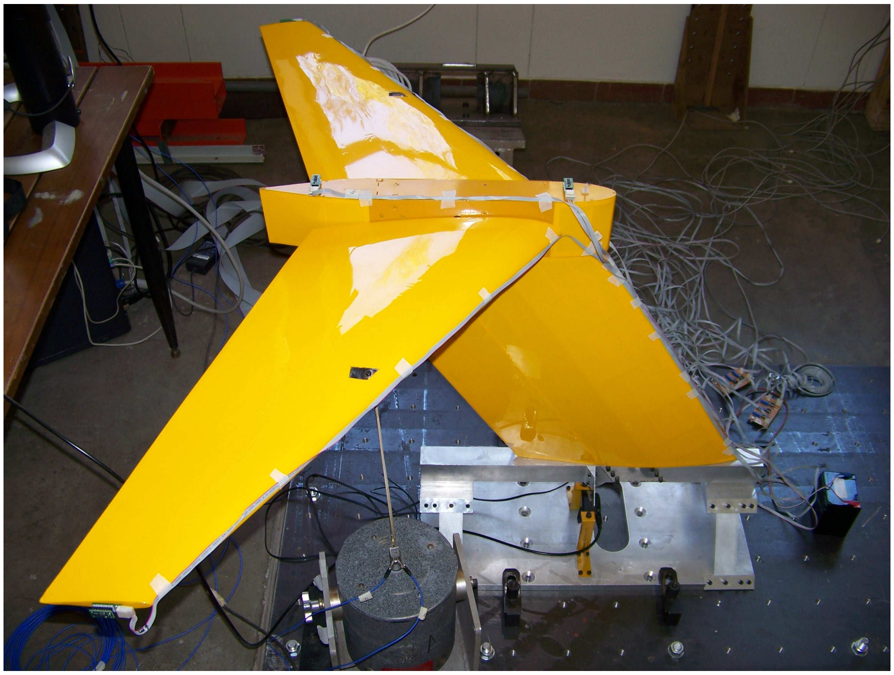

Figure 8: T-tail flutter model mounted on its support system during the GVT

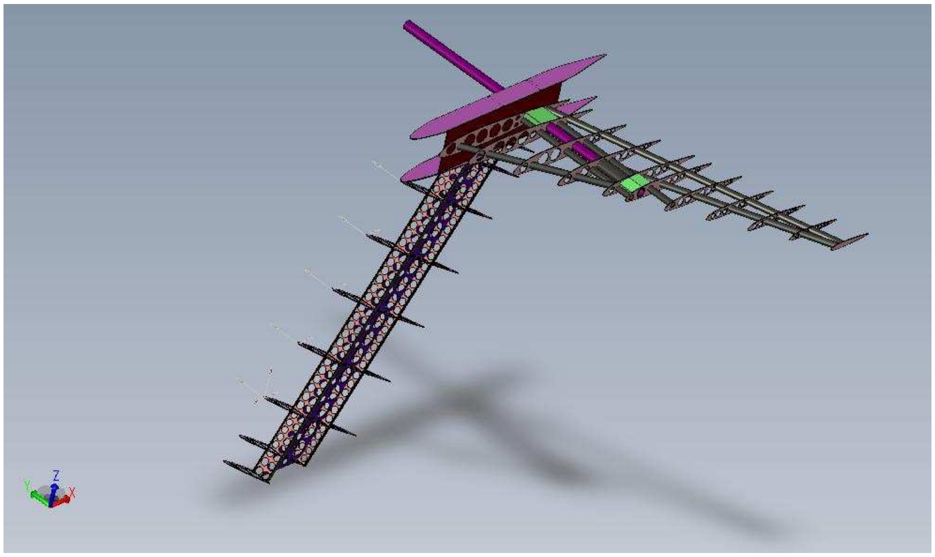

Figure 9: Internal structure of the T-tail flutter model

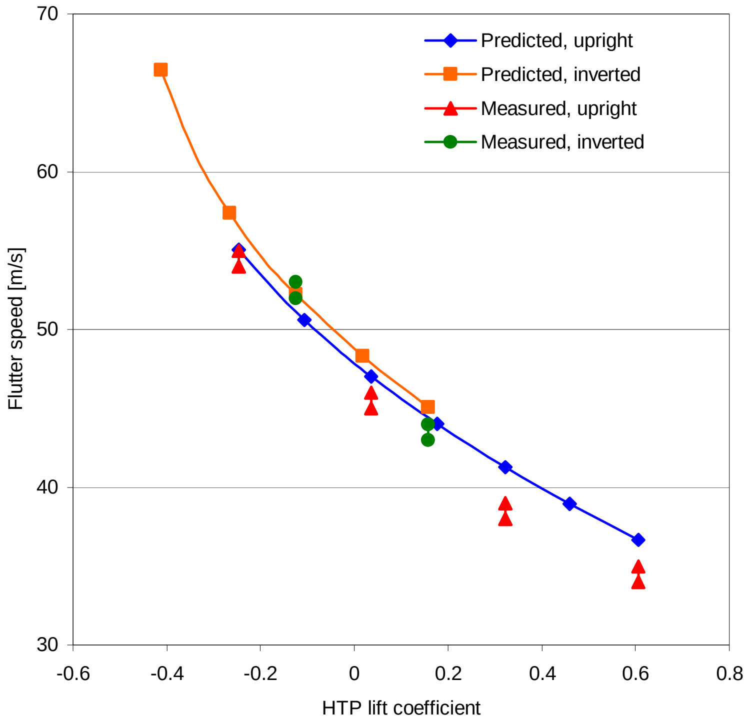

Figure 10: T-tail flutter model flutter speed vs. stabiliser lift coefficient

The geometry of the T-tail flutter model is defined in terms of chord line leading edge coordinates and chord lengths in Table 1. The $z = 0$ reference plane of the global coordinate system was the tunnel floor and the $y = 0$ reference plane coincided with the vertical tunnel centre plane. The streamwise coordinate, x, was defined as positive downstream, the vertical coordinate, z, as positive upward and the lateral coordinate, y, as positive to the right.

Table 1: T-tail flutter model chord lines

Chord line	*x* [m]	*y* [m]	*z* [m]	Chord [m]
Fin root	0.000	0.000	0.217	0.425
Fin tip	0.324	0.000	0.714	0.425
Fin tip fairing root	0.324	0.000	0.714	0.528
Fin tip fairing tip	0.324	0.000	0.812	0.528
Stabiliser root	0.375	0.000	0.763	0.363
Stabiliser tip	0.838	±0.625	0.763	0.100

The first three mode shapes and corresponding modal properties of the model were measured using a sine-dwell test technique. The modal properties are listed in Table 2.

Table 2: Modal properties of the T-tail flutter model

Mode no.	Description	Frequency [Hz]	Damping ratio	Modal mass [kg]
1	First fin bending	2.621	0.0062	3.947
2	Fin torsion	4.641	0.0211	3.589
3	Second fin bending	13.695	0.0345	3.366

The mode shapes were approximated by polynomials expressed in a local coordinate system for each element. The origin of each local coordinate system is at the root leading edge of the element; the chordwise coordinate, ξ, is normalized by the root chord, and the spanwise coordinate, η, is normalized by the span of the element. The polynomial approximations to the linear mode shape components are given in Eqs. (13) to (44). The displacements in these expressions are in the global coordinate system and subscripts denote the mode number corresponding to Table 2.

Fin

$$\xi = x / 0.425 \qquad (13)$$
$$\eta = (z - 0.217)/0.497 \qquad (14)$$
$$y_1 = -0.106510 - 0.558676\eta + 0.079981\xi\eta - 0.509418\eta^2 \qquad (15)$$
$$y_2 = 0.002565 + 0.575753\eta - 1.409752\xi\eta + 1.265927\eta^2 \qquad (16)$$
$$y_3 = 0.049624 + 0.856267\eta - 1.075774\xi\eta + 1.267945\eta^2 \qquad (17)$$

Fin tip fairing

$$\xi = (x - 0.324)/0.528 \qquad (18)$$
$$\eta = (z - 0.714)/0.098 \qquad (19)$$
$$y_1 = -1.113630 + 0.099365\xi - 0.180162\eta \qquad (20)$$
$$y_2 = 0.769517 - 1.751409\xi + 0.227724\eta \qquad (21)$$
$$y_3 = 1.353715 - 1.336491\xi - 0.329526\eta \qquad (22)$$

Right stabiliser

$$\xi = (x - 0.375)/0.363 \qquad (23)$$
$$\eta = y / 0.625 \qquad (24)$$
$$x_1 = -0.117620\eta \qquad (25)$$
$$y_1 = -1.194113 + 0.068313\xi \qquad (26)$$
$$z_1 = 1.148991\eta \qquad (27)$$
$$x_2 = 2.073164\eta \qquad (28)$$
$$y_2 = 0.714209 - 1.204094\xi \qquad (29)$$
$$z_2 = -1.452323\eta \qquad (30)$$
$$x_3 = 1.582021\eta \qquad (31)$$
$$y_3 = 1.059859 - 0.918838\xi \qquad (32)$$
$$z_3 = 2.101571\eta \qquad (33)$$

Left stabiliser

$$\xi = (x - 0.375)/0.363 \qquad (34)$$
$$\eta = -y / 0.625 \qquad (35)$$
$$x_1 = 0.117620\eta \qquad (36)$$
$$y_1 = -1.194113 + 0.068313\xi \qquad (37)$$
$$z_1 = -1.148991\eta \qquad (38)$$
$$x_2 = -2.073164\eta \qquad (39)$$
$$y_2 = 0.714209 - 1.204094\xi \qquad (40)$$
$$z_2 = 1.452323\eta \qquad (41)$$
$$x_3 = -1.582021\eta \qquad (42)$$
$$y_3 = 1.059859 - 0.918838\xi \qquad (43)$$
$$z_3 = -2.101571\eta \qquad (44)$$

4 CONCLUSION

4.1 Consolidation of the work done

The aim of the present study was to develop linear methods for the flutter analysis of T-tail configurations that would address the shortcomings of the widely used DLM. The new methods were implemented in a DLM code (Van Zyl & Mathews 2011).

The choice of the DLM as the basis for this development could be questioned in the light of allegations that the DLM lacked robustness (Liu et al. 1996, Chen et al. 2004). The robustness of the DLM was therefore asserted through two journal articles (Van Zyl 1999, Van Zyl 2003). The error in the DLM code that was used to question the robustness of the DLM was identified and corrected.

In recognition of the fact that lifting surfaces in general, and T-tail empennages in particular, usually occur in conjunction with fuselages and possibly other bodies, an improved body model and wing-body interference model for the DLM were developed (Van Zyl 2008). This DLM code was used as the basis for the enhanced DLM for T-tails.

The main drawback of the standard DLM, when applied to T-tail configurations, is that in-plane loads (i.e., loads in the plane of the HTP), loads caused by in-plane motion of the HTP, and the effect of the steady-state load distribution on the HTP are not accounted for. This deficiency is well known and the usual way of compensating for it is to calculate additional unsteady aerodynamic loads outside of the DLM. In the present DLM these loads are accounted for through a more general boundary condition and using the Kutta-Joukowski theorem to calculate the loads on aerodynamic boxes. By eliminating the need to calculate additional aerodynamics forces outside of the DLM, the human effort required for a T-tail flutter analysis as well as the opportunities for introducing errors into the analysis are reduced.

One of the additional loads that are typically added to standard DLM results is the unsteady lateral force resulting from the rotation of the steady-state load (trim load) on the HTP. It has hitherto not been recognised that this force leads to spurious generalised unsteady aerodynamic forces unless the curved path of motion of the horizontal tail plane is taken into account. The spurious generalised forces are of the same order of magnitude as the generalised forces associated with the additional loads that are customarily added to the DLM results. The quadratic mode method (Segalman & Dohrmann 1990) was implemented in the present DLM to account for the curved path of motion of the HTP.

The present DLM for T-tails can analyse T-tail configurations with the same accuracy and for a similar effort as conventional configurations, provided that the quadratic mode shape components are available. The means for obtaining quadratic mode shape components were hitherto limited to integration of the angular deflection of simple structures such as beams, and using multiple, non-linear, finite element analyses for general structures (Segalman & Dohrman 1996, Segalman et al. 1996). Alternative means for obtaining quadratic mode shape components were developed, viz. measuring them in a GVT, estimating them from the linear mode shape components, and calculating them using linear finite element analysis.

4.2 Aspects meriting further investigation

The present DLM is still limited in its application by transonic effects and flow separation. In view of the increase in computational power, the appropriate way of performing transonic T-tail flutter analysis is using FSI methods. These methods calculate the correct pressure distribution on the HTP of T-tail configurations without special treatment, but they are subject to the same potential errors as the DLM in calculating the unsteady generalised aerodynamic forces. It would therefore be required to implement the quadratic mode method in an FSI code in order to obtain reliable transonic T-tail flutter analysis results.

The aeroelastic challenges of the joined wing configuration are currently attracting considerable attention. According to Demasi and Livne (2005) the aeroelastic analysis of joined wing configurations requires non-linear analysis due to, amongst others, the compressive stress in the rear (upper) wing. The quadratic mode method should in principle be able to model the effects of this compressive stress without resorting to non-linear analysis. An investigation of the applicability of the quadratic mode method to this configuration seems warranted.

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APPENDIX: Copies of Journal Articles

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Article I

Van Zyl, L.H., “Robustness of the subsonic doublet lattice method”, *The Aeronautical Journal*, May 2003, Vol. 107, No. 1071, pp. 257-262.

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2. Green, J.E., Weeks, D.J. and Brooman, J.W.F. Prediction of turbulent boundary layers and wakes in compressible flow, ARC R&M No 3791, 1979.

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Van Zyl, L.H., and Mathews, E.H., "Aeroelastic Analysis of T-Tails Using an Enhanced Doublet Lattice Method", *Journal of Aircraft*, Vol. 48, No. 3, May-June 2011, pp. 823-831, DOI: 10.2514/1.54645

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[2] Books: Turner, M. J., Martin, H. C., and Leible, R. C., "Further Development and Applica-tions of Stiffness Method," *Matrix Methods of Structural Analysis*, 1st ed., Vol. 1, Wiley, New York, 1963, pp. 6–10.

[3] AIAA Book Series: Sutton, K., "Air Radiation Revisited," *Thermal Design of Aeroassisted Or-bital Transfer Vehicles*, edited by H. F. Nelson, Vol. 96, Progress in Astronautics and Aero-nautics, AIAA, New York, 1985, pp. 419–441.

[4] Reports: Book, E., and Bratman, H., "Using Compilers to Build Compilers," Systems De-velopment Corp., SP-176, Santa Monica, CA, Aug. 1960.

[5] Transactions/Proceedings: Soo, S. L., "Boundary-Layer Motion of a Gas-Solid Suspension," *Proceedings of the Symposium on Interaction Between Fluids and Particles*, Vol. 1, Inst. of Chemi-cal Engineers, New York, 1962, pp. 50–63.

[6] AIAA Meeting Papers: Bhutta, V. A., and Lewis, C. H., "Aerothermodynamic Performance of 3-D and Bent-Nose RVs under Hypersonic Conditions," AIAA Paper 90-3068, Aug. 1990.

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Van Zyl, L.H., and Mathews, E.H., “Quadratic Mode Shape Components from Linear Finite Element Analysis”, *Journal of Vibration and Acoustics*, Volume 134, Number 1, February 2012, pp. 014501.1-014501.7

Van Zyl, L.H., and Mathews, E.H., “Quadratic Mode Shape Components from Ground Vibration Testing”, *Journal of Vibration and Acoustics*, Volume 134, Number 3, June 2012, pp. 034504.1-034504.7

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Acknowledgments may be made to individuals or institutions not mentioned elsewhere in the work who have made an important contribution.

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> *Example:* It was shown by Prusa [1] that the width of the plume decreases under these conditions.

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Sample References

[1] Ning, X., and Lovell, M. R., 2002, “On the Sliding Friction Characteristics of Unidirectional Continuous FRP Composites,” ASME J. Tribol., 124(1), pp. 5-13.

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[8] Kwon, O. K., and Pletcher, R. H., 1981, “Prediction of the Incompressible Flow Over A Rearward-Facing Step,” Technical Report No. HTL-26, CFD-4, Iowa State Univ., Ames, IA.

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