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Control-point-placement method for the aerodynamic correction of the vortex- and the doublet-lattice methods

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ABSTRACT

The use of correction factors to improve the accuracy of the aerodynamic influence coefficient (AIC) matrices produced by the vortex-lattice and the doublet-lattice methods has been an engineering practice in the field of aeroelasticity. In order to account for either viscous or transonic flow effects not considered in the linearized formulation of such methods, the most frequent correction techniques have been to pre-multiply or to post-multiply the AIC matrices by diagonal matrices comprising semi-empirical weighting factors. This paper proposes a different correction approach: the control-point-placement method (CPPM), based on the idea of displacing the control point of each panel – the point where the boundary condition of flow tangency must be satisfied. Both the vortex- and the doublet-lattice methods have been developed with the singularities placed at the quarter-chord line of the panels and the control points at three quarters of their mean chords. With the calculation of modified control point positions, the CPPM intrinsically changes the mutual aerodynamic influence between the panels and allows the lifting surface methods to predict steady-state pressure distributions that match or approximate with minimum error those derived from wind tunnel measurements or higher-fidelity CFD solutions. Different approaches to extend the aerodynamic correction for application at non-zero reduced frequencies in the doublet-lattice method are then studied. Results are presented that are in acceptable agreement with benchmark wind tunnel data and comparisons are made between the proposed methodology and the traditional diagonal matrix corrections.

1. Introduction

Since it was published in 1969 [1], the doublet-lattice method (DLM) has played a significant role in the aeronautical industry world-wide, allowing the prediction of both the subsonic aeroelastic stability and the aeroelastic response of general configurations. The DLM has proved to be versatile, since it can be applied to problems with multiple nonplanar surfaces and control surfaces without difficulties [5], with the advantages of a very reasonable cost and of its availability in widespread programs, like MSC/NASTRAN [33].

Based on the linearized potential flow equation, with the assumption of small disturbances in both the velocity potential and the displacements, the DLM allows the aerodynamics in the subsonic regime to be modeled in terms of matrices of aerodynamic influence coefficients (AIC), which relate the displacements of the lifting surfaces to the resulting loads on them. The capability to address the aerodynamics of the lifting surfaces by means of AIC matrices greatly simplifies the mathematical formulation, allowing the typical aeroelastic system stability analysis to be expressed in the form of an eigenvalue problem.

The integral equation upon which the DLM is based relates the pressure and the normalwash distribution in unsteady subsonic three-dimensional potential flows, and was first derived by Küssner back in 1940 [[22], *apud* [5]]. The referred equation reads [5, 15]:

$$\frac{w(x,y,z)}{U_\infty} = \frac{1}{8\pi}\iint_{L \cdot S \cdot} \Delta C_p(\xi,\eta,\zeta) K(x-\xi, y-\eta, z-\zeta, \omega, M_\infty) d\xi d\eta, \quad (1)$$

where $w(x,y,z)$ is the normalwash velocity at point (x,y,z); U_∞ is the free stream velocity; and $\Delta C_p(\xi,\eta,\zeta)$ is the unsteady pressure coefficient difference at the point (ξ,η,ζ). K is the kernel function of the integral relation. It depends on the relative position $(x-\xi, y-\eta, z-\zeta)$, an assumed harmonic circular frequency,

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ω, and the free stream Mach number, M_∞. The integration is over all the lifting surfaces.

The origins of the DLM have intrinsic relations with the vortex-lattice method (VLM). Actually, the VLM, as developed in its modern form by Hedman [19,20], provided the basis for the DLM [32], and the DLM may be seen as an extension of the VLM [42]. Additionally, since the kernel in Eq. (1) cannot be integrated analytically, it was assumed in the development of the DLM that the numerator of the quotient which defines the kernel varied quadratically – recent studies suggested a quartic interpolation to be a better option [34,35]. To eliminate the approximation error at zero frequency, Hedman's downwash factor is added to the kernel equation, and the one calculated by the interpolation is subtracted [32]. Therefore, the DLM, in the steady regime, is rigorously Hedman's VLM.

In both the vortex- and the doublet-lattice methods, the lifting surfaces are ideally discretized into trapezoidal planar panels, alternatively called boxes, with two side edges parallel to the undisturbed flow, assumed by convention to be aligned with the x direction of the system of coordinates. The bound leg of the horseshoe vortex and the doublet line both stand along the quarter-chord ($1/4\ c$) line of the panel. Both methods need a control point position to be specified for each panel. This control point is sometimes named collocation or downwash point and it is where the linearized boundary condition of tangential flow is satisfied.

The control points have been fixed by experience to the three-quarters of the panel mean chord ($3/4\ c$). It was in 1937, in a paper by Pistolesi [[29], *apud* [11]], that the $1/4-3/4$ rule first appeared [11]. Pistolesi proved this approximation to yield, for a two-dimensional wing section, exactly the same sectional lift and moment, at constant angle of attack, as the ones predicted by thin airfoil theory in incompressible flow [11]. Later, the rule was successfully applied to sections with multiple chordwise panels. Both Hedman [19] and Albano and Rodden [1] assume the $1/4-3/4$ rule in their developments.

The previous arguments seem sufficient to justify no change in the $1/4-3/4$ rule in the VLM and the DLM, since it yields consistent results for some specific cases where the hypotheses of the methods are clearly not violated. However, it cannot be forgotten that Pistolesi's findings assumed incompressible two-dimensional flow. Moreover, derivations of more precise vortex and control point locations have already been made in lifting surface methods, e.g. Lan's quasi-vortex-lattice method that enables the correct determination of the leading edge suction force and that is more accurate when flap deflections are present [23]. Therefore, in the case of more complex flow regimes, it can be investigated whether or not keeping the $1/4-3/4$ rule is still the most interesting approach.

In the flow regimes characterized by nonlinear effects due to compressibility and viscosity, it is clearly expected that the application of the DLM will not produce accurate results. One typical problem is when it is needed to accurately determine hinge moments on control surfaces, which are most typically near the trailing edge of the main surfaces, where the viscous effects are stronger due to the boundary layer thickening, and the linear methods may be inaccurate even in the subsonic regime [28].

Another problem is the transonic regime, where it is known that the aeroelastic behavior of an aircraft is critical, due to complex nonlinear phenomena related to viscosity and to (moving) shock waves [38]. The linear theory is markedly non-conservative under these flow conditions, where such nonlinear phenomena lead to a drop in the flutter boundary known as the transonic flutter dip. The capability to predict the bottom of the dip is then crucial to the design of any flight vehicle that operates in the transonic regime, including modern airliners and military transport aircraft [3,36]. Schuster et al. [36] provide a summary on the main aspects regarding the transonic dip, and Bendiksen [3] presents a broader physical understanding of the phenomenon enlightened by the mathematical theory of unsteady transonic flow.

In what refers to aeroelasticity in the context of the aeronautical industry, it is known that possibly thousands of flutter runs are needed in the certification process of modern aircraft, a number that is a function of the amount of different configurations the aircraft can assume – concerning variables such as Mach number, mass distribution, deployment of control surfaces, landing gears, installation of external stores, etc.

Even considering the extraordinary developments in computational algorithms and computer hardware, fluid–structure interaction (FSI) simulations based on the full Navier–Stokes equations coupled with structural-dynamic finite-element methods, that would produce the most reliable theoretical results for the problem, are not yet practical for production flutter analysis [3]. Furthermore, transonic wind tunnel testing of aeroelastic models involves expensive models and high operational costs [38,46]. Flight flutter testing is a hazardous and also expensive option in terms of operational costs [38].

Other computational methods of intermediate fidelity between the linear methods and the full-Navier–Stokes-based CFD codes, such as the ones based on the Euler, the full-potential or the transonic-small-disturbance (TSD) equations, can produce results that are more reliable than those of linear methods. Nevertheless, although some of these higher-fidelity methods also allow the convenience of operating with AIC matrices [2], e.g., the transonic doublet-lattice method (TDLM) by Lu and Voss [26,43] and the overset-field panel method by Chen et al. [7] implemented in the ZTRAN module of the ZAERO software [47], they are characterized by greater turnaround times than that of the DLM [37], with more complex model preparation.

Therefore, thinking of production flutter analysis, it is still very reasonable to deal with aerodynamic corrections to the DLM in the transonic regime [46]. The correction procedures produce modified AIC matrices to be used in the flutter analysis of cases spanning the whole flutter-clearance envelope of the aircraft. The flutter data then generated guide the aeroelastician to the most critical configurations for that aircraft, and these are the ones that should be preferably analyzed in higher-fidelity, more complex tools, as described by SenGupta [37].

Efforts to increase the range of applicability of the DLM have been made since the 1970's [16,28]. The general approach is to somehow introduce into the method higher-fidelity data obtained from wind tunnel tests or from nonlinear Navier–Stokes CFD simulations. The aerodynamic corrections of the AIC matrices are then performed at prescribed values of Mach number and reduced frequency. Hence, these empirical methodologies preserve the computational advantages of the DLM, being adequate tools for engineering-level applications, mainly in the preliminary design of an aircraft [38].

Palacios et al. [28] present a brief literature survey of correction methods. Silva [38] presents a more comprehensive review of the various methodologies that have been applied over the years. Amaral [2] revisited the subject by comparing different correction methods available in the literature. Therefore, for a deeper and broader perspective on the different correction methodologies, it is suggested that the reader consult Refs. [28,38] and [2].

A close review of the correction methods published thus far shows that no other author has yet considered dealing with the control point locations to determine corrected AIC matrices. In the control-point-placement method (CPPM) proposed in the present paper, the control point locations are interpreted as parameters of the lifting surface methods. The main idea is that, by correctly changing these parameters, taking as reference nonlinear pressure distributions, the complete AIC matrix can be modified. Conse-