

AN ENHANCED CORRECTION FACTOR TECHNIQUE FOR AERODYNAMIC INFLUENCE COEFFICIENT METHODS

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ABSTRACT

The present Enhanced Correction Factor Technique (ECFT) is intended to provide an improved solution to the classical problem of correcting the Aerodynamic Influence Coefficients (AIC) formulation produced by panel methods, such as the Doublet Lattice Method (DLM). In the case of MSC/NASTRAN aeroelastic analysis methods, provisions are made for inclusion of correction matrices which premultiply the AIC matrix in order to provide a level of accuracy of the aerodynamic forces consistent with experimental and/or CFD data. Classical techniques use a diagonal correction matrix allowing for limited correction capabilities: typically, one mode. By contrast, the present ECFT uses a full correction matrix that can handle multiple modes simultaneously, allowing a complete correction capability including any interference effects. Further, it is possible to define by means of ECFT several correction matrices that tackle nonlinearities for a given Mach number.

Several comparisons are presented which cover a wide range of application cases. The results obtained with ECFT are shown to match the input data.

Introduction

The method of Aerodynamic Influence Coefficients (AIC) yields fast and reliable estimates of aerodynamic forces and, because of this, is widely used in aeroelastic analysis applications such as MSC/NASTRAN. The AIC method implies a discretization of the external configuration in “boxes” and provides a linear relationship between the distributions of normal velocity $\{w\}$ (hereafter named downwash) and aerodynamic forces $\{f\}$:

$$\{f\} = [A]\{w\} \quad (1)$$

where, $[A]$ is a function of reduced frequency and Mach number; it could also depend on the set of initial conditions approximated.

However, the aerodynamic theories that are used to compute the AIC matrix can lead to significant errors in transonic regime and/or when dealing with hinge moments. To rectify this shortcoming, provisions are made in all MSC/NASTRAN aeroelastic solution sequences to include a premultiplying correction factor matrix $[C_F]$, see ref.[1]:

$$\{f\} = [C_F][A]\{w\} \quad (2)$$

The correction matrix $[C_F]$ must be supplied by the user, based on experimental and/or CFD data. Although there are many aero matching methods in use, probably the best known is due to Giesing et al [2] and uses a diagonal correction matrix. Usually, diagonal correction matrices are derived from data referring to a single mode, e.g. Surampudi et al [3].

Other correction methods have been proposed that rely on a predetermined number of “given” modes, such as Suci et al [4] and Baker [5], but these do not provide an explicit correction matrix and their use in frequency domain methods such as MSC/NASTRAN requires extensive modifications.

From the point of view of users in the aviation industry, the advantage of correction matrices is that, once determined, they can be applied to repeated calculations of the same condition (e.g. Mach number), irrespective of changes in mass and structural properties.

Unfortunately, the use of a diagonal correction matrix leads to various problems. Two main deficiencies have been identified in ref.[2] concerning the use of diagonal correction matrices, namely:

- (i) one diagonal correction matrix is not good for all modes, particularly for dissimilar modes;
- (ii) diagonal correction matrices cannot change qualitatively theoretical results, for example to induce a discontinuity in the pressure distribution at the location of a shock.

The present paper describes a methodology for computing full correction matrices, designed to eliminate the shortcomings associated with diagonal correction matrices while preserving the advantage of repeated use of a single matrix.

Enhanced Correction Factor Technique (ECFT)

A given mode used in aeroelastic analysis can be defined in terms of its geometric order, which relates to the complexity of the shape, and its reduced frequency as presented in Fig. 1.

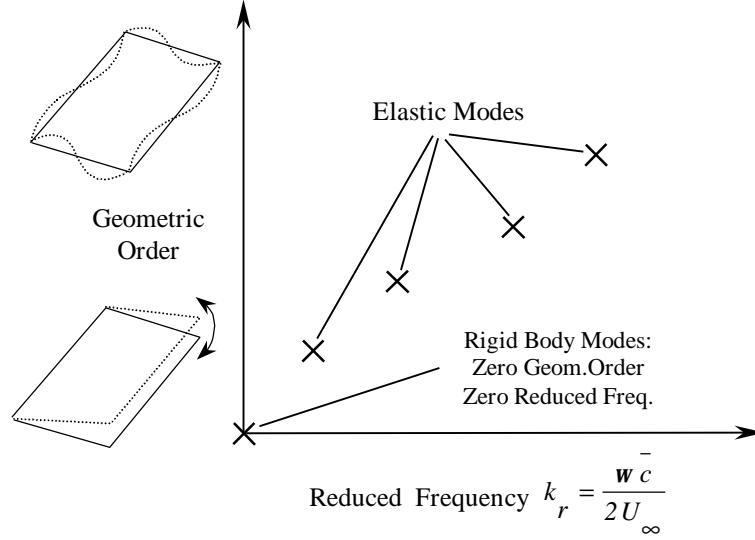


Figure 1. Definition of Modes in Terms of Shape and Reduced Frequency

For an AIC formulation of order N , the geometric order concept is used to define a set of N downwash vectors $\{w_i\}$, which form a base in the downwash vectors space. For example, in the case of a wing with l chordwise and m spanwise equally spaced boxes ($N = l \times m$), a trigonometric series expansion may be considered such that:

$$\begin{aligned} w(g_{chord}, g_{span}, m_{chord}, m_{span}) &= \\ &= \cos\left[\frac{(2g_{chord} - 1)(m_{chord} - 1)\mathbf{p}}{2l}\right] \times \cos\left[\frac{(2g_{span} - 1)(m_{span} - 1)\mathbf{p}}{2m}\right] \end{aligned} \quad (3)$$

where, $g_{chord} = 1, \dots, l$ and $g_{span} = 1, \dots, m$ represent the geometric location to which the downwash w refers;

$m_{chord} = 1, \dots, l$ and $m_{span} = 1, \dots, m$ represent the geometric order of the modes used to define the downwash vector shape.

Eq. (3) can be used to determine the N downwash vectors $\{w_i\}$ required to form a base by taking $i = m_{chord} + (m_{span} - 1) \times l$.

It should be observed that for $i = 1$, $m_{chord} = m_{span} = 1$, and therefore the downwash mode $\{w_1\}$ equals 1 everywhere. This corresponds to a rigid body unit angle of attack.

Further, it should be noted that the downwash modes depend on geometry alone, requiring no prior knowledge of the structural properties such as structural mode shape and frequency. However, the structural and geometric modes are obviously related, see Fig. 1, since all structural modes can be expressed as linear combinations of the (geometric) downwash modes base.

Starting from the base formed by the downwash vectors $\{w_i\} \quad i = 1, \dots, N$, the Enhanced Correction Factor Technique (ECFT) can be defined as follows:

(1) Define the Downwash Modes Matrix;

The original downwash mode vectors $\{w_i\}$, defined previously, are assembled as columns in the Downwash Modes Matrix $[W]$ of size $N \times N$. From the total set of N vectors $\{w_i\}$, a subset of M vectors is identified for which Given Aero Data is available. This subset is named Given Modes and contains the downwash vectors $\{w_i\} \quad i = 1, \dots, M$, with $M \leq N$. If data is provided for a Given Mode that does not have a counterpart in the set of original vectors $\{w_i\}$, then that particular Given Mode will need to be substituted to the “closest” original mode. Although the process of defining the subset of Given Modes is not unique, 2 basic rules are of particular interest:

- a) The Given Modes must be linearly independent,
- b) Substituting a Given Mode to the “closest” original mode must not lead to an ill-conditioned matrix $[W]$.

After defining the Downwash Modes Matrix and the Given Modes as explained above, it is good practice to check that $[W]$ can be inverted without numerical problems.

(2) Calculate Original Forces due to Downwash Modes;

For all modes contained in $[W]$, the corresponding aerodynamic forces $[F_o]$ can be readily obtained from Eq. (1):

$$[F_o] = [A][W] \quad (4)$$

For each of the downwash vectors $\{w_i\}$ making up the columns of $[W]$ there corresponds a set of forces $\{f_i\}$, columns in $[F_o]$.

(3) Calculate Constrain Forces due to Given Downwash Modes;

Corresponding to the M Given Modes defined at step (1), certain Given Aero Data is available. For example, a unit uniform angle of attack mode like $\{w_i\}$ discussed above can be used to match a detailed aero load distribution or global coefficients (e.g. lift coefficient slope C_{L_a} , moment coefficient slope C_{M_a} , control surface hinge moment due to angle of attack C_{h_a}). Replacing the Given Aero Data into $[F_o]$ yields the Constrain Force Matrix $[F_i]$.

(4) Calculate Correction Factor Matrix;

Observing that:

$$[F_i] = [C_F][A][W] = [C_F][F_o] \quad (5)$$

The Correction Factor Matrix can be finally expressed as:

$$[C_F] = [F_I][F_0]^{-1} \quad (6)$$

Results and Discussions

A first set of comparisons concerns the experimental studies of Hertrich [6] used by Giesing et al [2] to validate their correction methodology. It involves an untapered wing of aspect ratio 3.1 with sweep angle 25° in incompressible flow. The wing has a full span control surface extending over 30% chord. The paneling scheme uses 11 spanwise and 10 chordwise boxes. Along the span, from root to tip, the widths of the strips are: 0.11, 0.08, 0.075, 6 strips of width 0.09 and finally 0.045 m. Along the chord the boxes are equally spaced. Data is available for two modes, rigid body angle of attack and control surface deflection. Global coefficients results are presented in Table 1.

Table 1. Global Coefficients Comparison with Hertrich [6] and Giesing et al [2]

	Experiment Hertrich [6]	DLM No Correction	DLM Corrected Giesing et al [2]	DLM Corrected ECFT
C_{L_a}	3.13	3.21	3.13	3.13
C_{M_a}	0.148	0.18	0.148	0.148
C_{L_d}	1.77	1.93	1.77	1.77
C_{M_d}	-0.392	-0.42	-0.392	-0.392
C_{h_d}	-0.0289	-0.0525	-0.0289	-0.0289

The results involving deflection angle d in Table 1 refer to rotation around the swept hinge line. Upon inspection of the global coefficients, it can be observed that the original DLM results agree quite well with the experiment except for the hinge moment. Further, the corrected results obtained by Giesing et al [2] lead to perfect correlation with experiment, and the same is true for ECFT.

The actual correction matrices are presented in Fig. 2. For the diagonal matrix used in ref. [2] the correction factors range roughly between 0.3 and 2.0. The full correction matrix generated by ECFT resembles closely a unit matrix, with the diagonal terms within the range 0.9 to 1.1 and off-diagonal terms less than 0.3 in modulus. To compare the amount of change produced by each of the correction matrices the following norm is defined:

$$\|A\| = \sqrt{\sum_{i,j} |a_{ij}|} \quad (7)$$

From Eqs. (4) and (5), the actual change in terms of force distribution is:

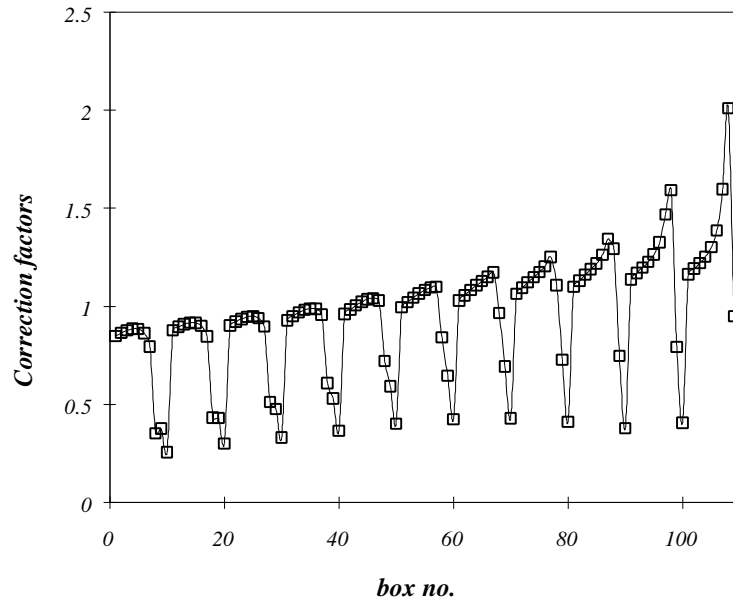
$$[DF_I] = [F_I] - [F_0] = ([C_F] - [I])[A][W] \quad (8)$$

where $[I]$ is the unit matrix with 1 on the diagonal and 0 elsewhere. The norm (7) of $([C_F] - [I])$ equals 1.96 for ECFT and 3.29 for the diagonal matrix. Further, the ECFT matrix changes “mostly” off-diagonal terms, which are smaller than the diagonal ones. Therefore, it can be concluded that the full matrix correction technique leads to a lesser overall distortion of the AIC matrix.

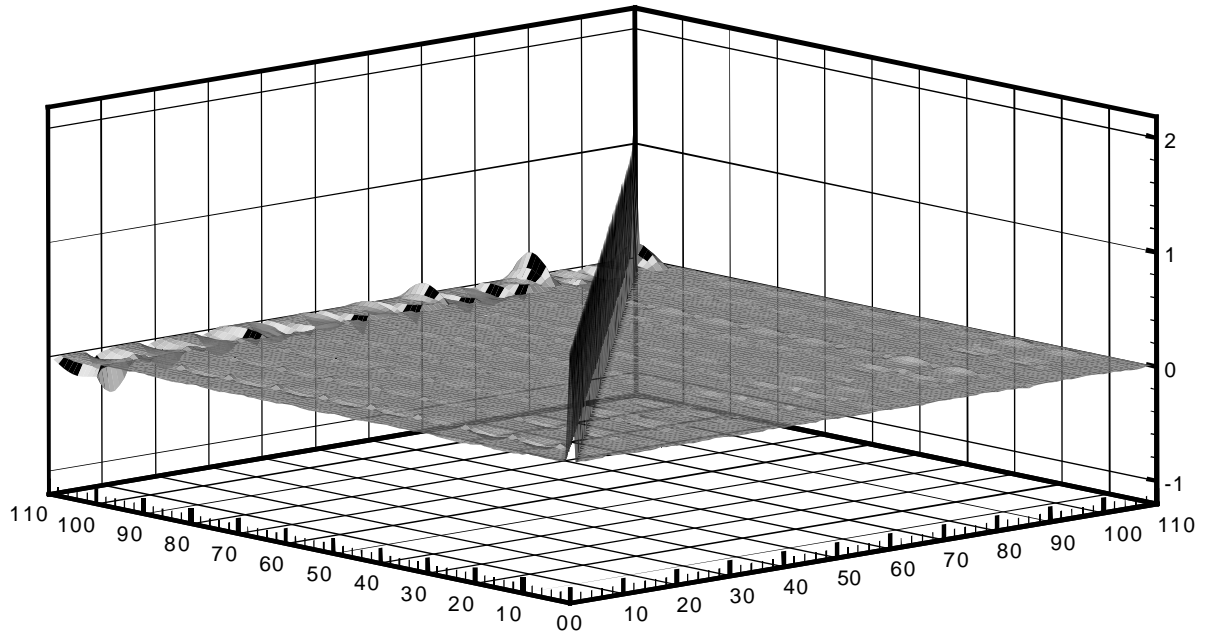
The results obtained in terms of pressure distributions using the two correction matrices are compared to experiment in Figs. 3 and 4. Three sections have been considered: VI, IV and II that corresponds to DLM strips no.4, 8 and 10. The comparison in Fig. 3 covers the case of change in angle of attack, with no flap deflection. The original DLM results are in good agreement with the experiment, and the diagonal matrix correction improves the correlation with experiment. However, the results obtained with the full matrix are identical to experiment. The comparison in Fig. 4 tackles the case of flap deflection, at zero angle of attack. The original DLM results approximate the experiment well on the fixed part of the wing, but overestimate the flap distribution. The diagonal correction matrix improves to a certain extent the flap distributions, whereas the ECFT results are again identical to the experimental ones. It must be noted that the paneling scheme chosen, with 10 chordwise boxes does not enable a sufficiently fine resolution in the flap LE region.

Finally, it should be observed that ECFT can provide perfect correlation with a desired pressure distribution allowing for inclusion of any local peculiarities, see Section II in Fig.4. Therefore, it can be inferred that ECFT can produce qualitative changes to the pressure distributions, as for example in the case of shock waves.

The ECFT methodology presented herein has been applied to the flutter analysis of Hawker Horizon, a transonic business jet. For each Mach number, a correction matrix is computed that simultaneously matches 19 global coefficients involving lift, moment, hinge moments and downwash against wind tunnel and CFD input data. The same correction matrix incorporates data about spanwise load gradings involving lift and moment distributions for wing, fuselage and tail. A representative set of global coefficients is presented in Fig. 5 related to aileron and aileron tab deflections. As observed in conjunction with the Hertrich wing previously, the total lift due to aileron deflection (one side) estimated by DLM without any correction agrees fairly well with experimental data. However, the hinge moments are not so well approximated and they require extensive matching. The main feature to be observed here is the ability of ECFT to handle multiple modes, including interference effects (aileron tab over aileron). The results obtained with the full matrix approach are shown to closely reproduce the input data.



a) Diagonal Correction Matrix – after Giesing et al [2]



b) Full Correction Matrix - ECFT

Figure 2. ECFT Correction Matrix – for correlation with Hertrich [6]

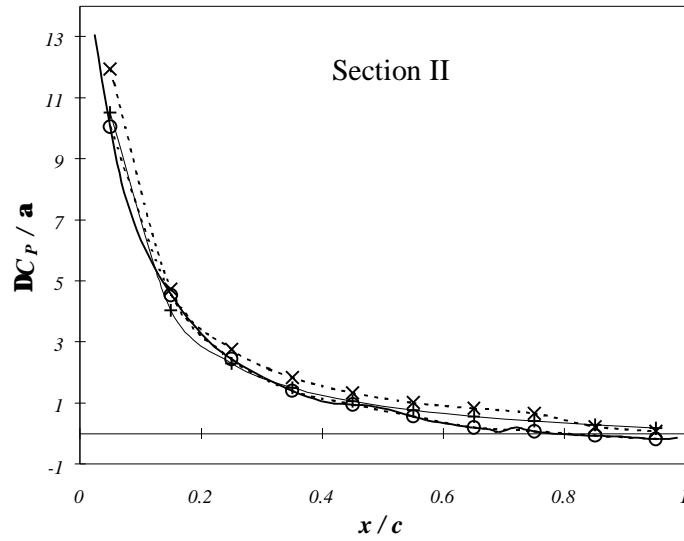
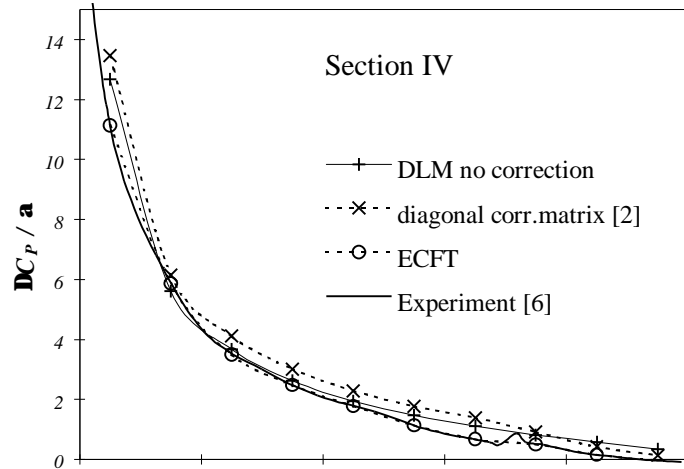
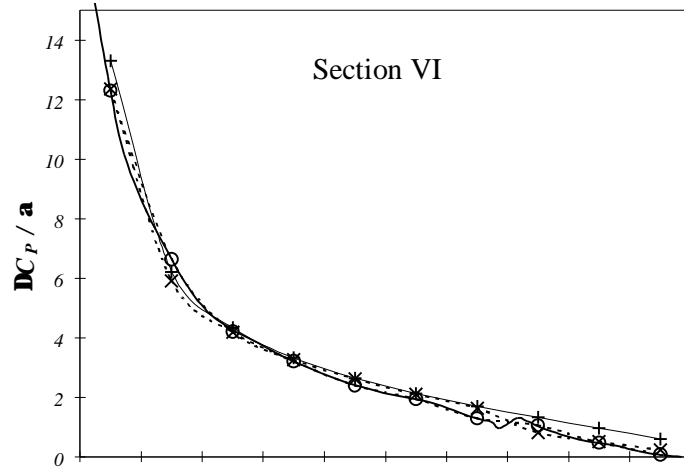


Figure 3. Angle of Attack Pressure Distributions – after Hertrich [6]

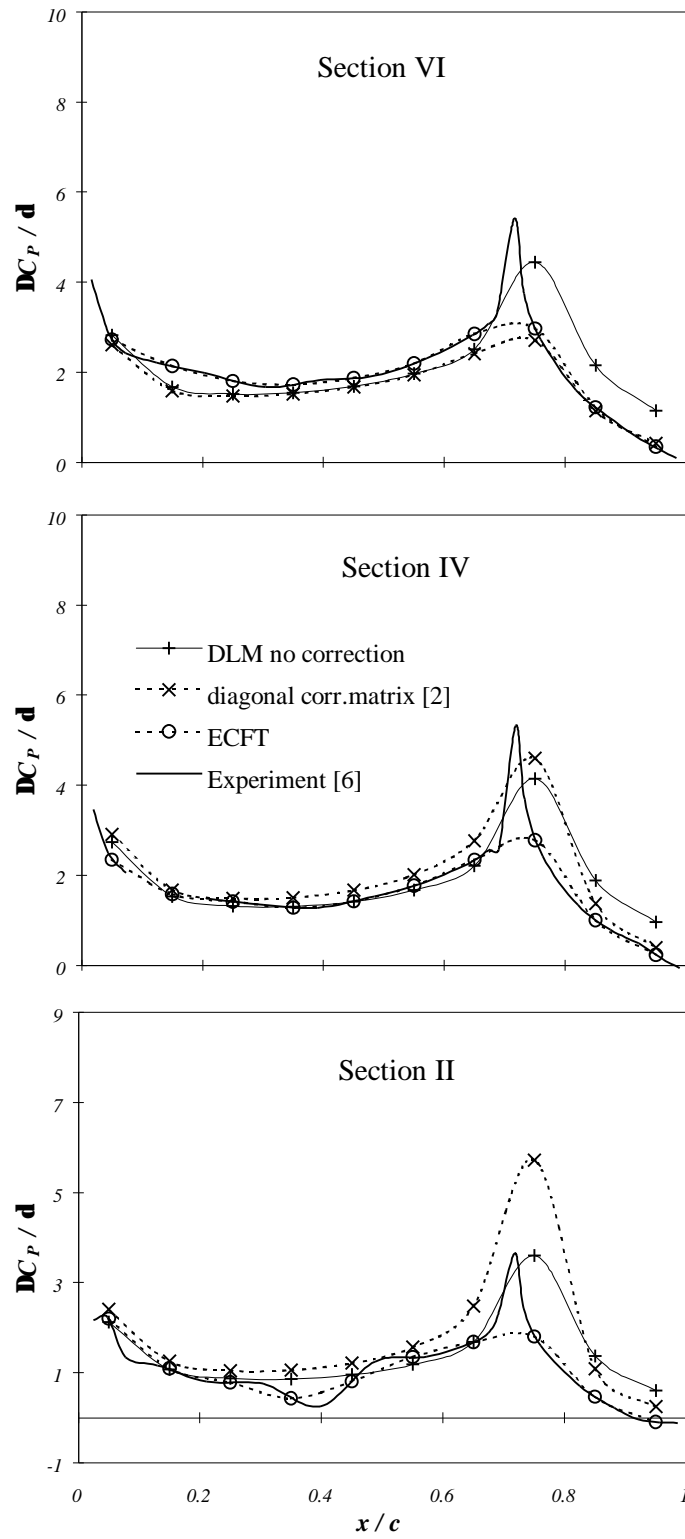
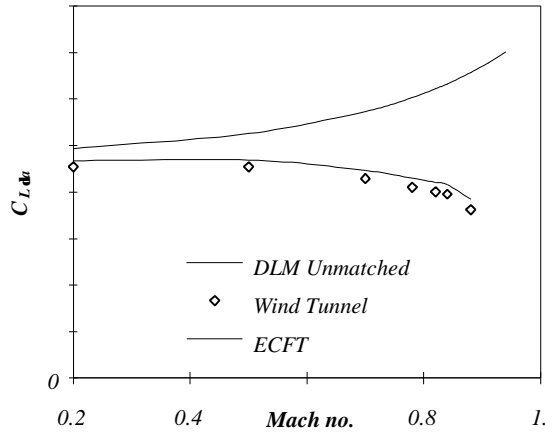
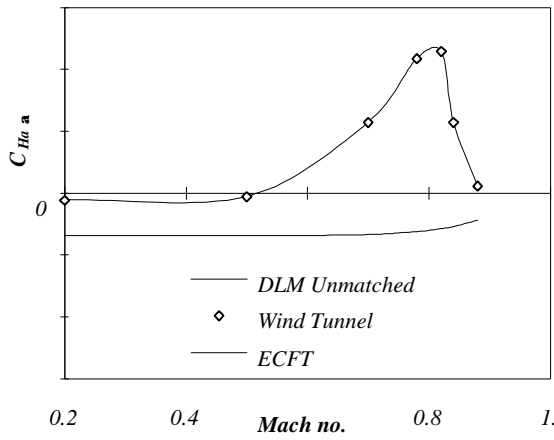


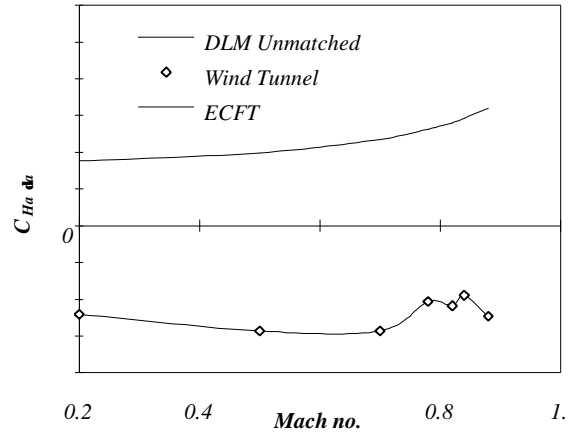
Figure 4. Flap Deflection Pressure Distributions – after Hertrich [6]



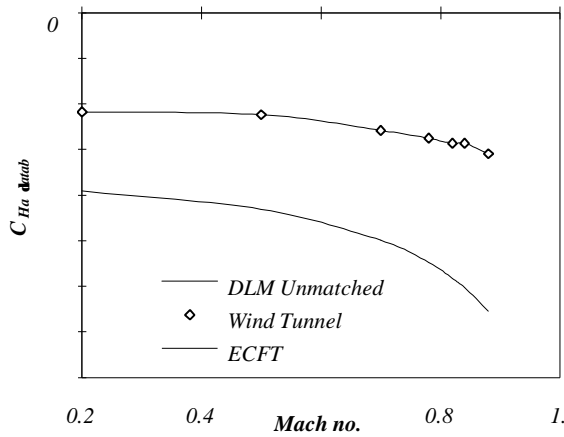
Lift due to Aileron Deflection



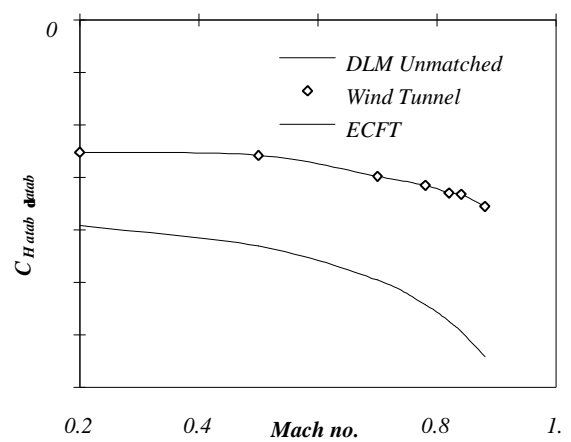
Aileron Hinge Moment due to Incidence



Aileron Hinge Moment due to Aileron Deflection



Aileron Hinge Moment due to Aileron Tab Deflection



Aileron Tab Hinge Moment due to Aileron Tab Deflection

Figure 5. Comparison of Stability Derivatives for Hawker Horizon - Transonic Business Jet

Conclusions

1) Input Data Source and Format:

ECFT can be used to match all aerodynamic data available, irrespective of their source: wind tunnel experiment, CFD, etc. No restrictions are made as to the form of the aerodynamic input data required which can be either in the form of pressure distributions or global coefficients. Any target pressure distribution can be imposed; thus ECFT can produce qualitative changes to the pressure distributions, as for example in the case of shock waves. These features allow the user to obtain a level of accuracy equivalent to the “best” aerodynamic data available.

2) Interference Effects:

Since the present approach is based on a full correction factor matrix, it supports bilateral interference effects. For example, ECFT makes possible the matching of separate aileron hinge moments generated by deflections of the aileron and aileron tab, respectively. A set of such results related to the aileron is presented in Fig. 5.

3) “Geometrical” Modes Matched:

ECFT does not require prior knowledge of structural modes, hence $[C_F]$ is derived as a function of only the geometry of the configuration and the aerodynamic data available. This feature can be very useful when assessing the influence of changes in mass or stiffness distributions.

4) Nonlinearities:

Using the local linearization concept, ECFT can be used to tackle the influence of nonlinearities defined as changes in the aerodynamic coefficient slopes. In this case several correction matrices $[A]$ are derived, each corresponding to an AIC formulation for a certain initial condition, reduced frequency and Mach number.

5) Validation:

ECFT is based on physically meaningful quantities, which facilitates the validation of the results. It should be observed that a direct means of verification is provided in the case of MSC/NASTRAN, which supplies information concerning stability derivatives and hinge moments resulted when using a given correction factor matrix.

6) Computational Requirements:

The execution time required by ECFT for a typical application is relatively small, less than a regular MSC/NASTRAN flutter run for the given configuration. ECFT generates the correction matrix $[C_F]$ outside the aeroelastic analysis loop and therefore it does not impact directly the time required to carry out the analysis.

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Trademark Acknowledgements

NASTRAN is a registered trademark of NASA. MSC/ NASTRAN is an enhanced, proprietary version developed and maintained by MacNeal-Schwendler Corporation.

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