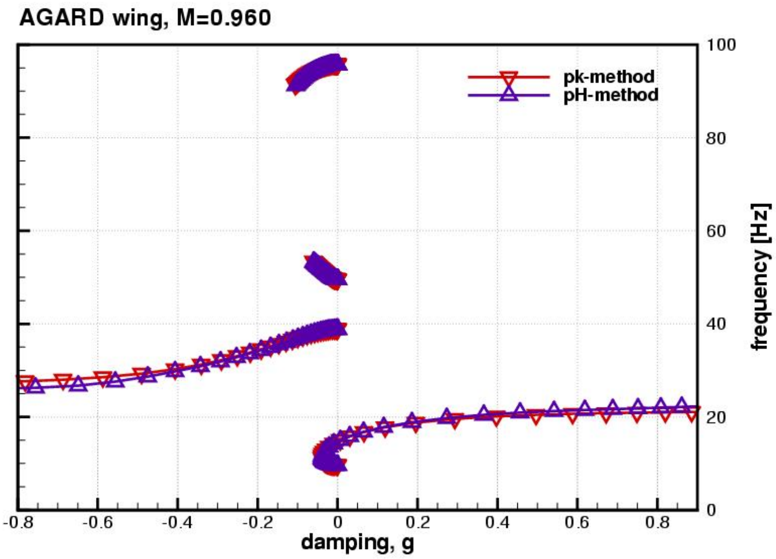
Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Managementsamenvatting

H flutter analysis method

A direct harmonic interpolation method



Probleemstelling
De berekening van flutter stabiliteitsgrenzen vindt normaliter plaats met methoden die weliswaar de correcte fluttersnelheid en frequentie berekenen, maar die de demping en frequentie trends foutief dan wel alleen in kwalitatief opzicht correct voorspellen. Dit geldt met name wanneer de berekeningen gebaseerd zijn op aerodynamische luchtkrachten die strikt genomen alleen gelden voor harmonische trillingen.
De berekening van demping en frequentie trends wordt verbeterd door de hier voorgestelde nieuwe methodiek.

Beschrijving van de werkzaamheden
Een nieuwe flutter analyse methode is geïntroduceerd. De methode wordt aangeduid als de H flutter analyse methode. The H flutter analyse methode continueert automatisch de aerodynamische luchtkrachten die verkregen zijn voor strikt harmonische trillingen naar luchtkrachten voor algemene gedempte en ongedempte trillingen middels een fit vrije interpolatie techniek. Hiermee wordt de voorspelling van demping en frequentie trends verbeterd.

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M.H.L. Hounjet

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Resultaten en conclusies
De fit vrije interpolatie techniek is beschreven en succesvol geverifieerd voor een twee dimensionale vlakke plaat. Resultaten van een flutter analyse voor de AGARD Wing 445.6 laten zien dat in vergelijking met de gangbare *pk* flutter analyse methode er verschillen optreden met betrekking tot de demping en frequentie trends bij hogere waarden van de demping.

Toepasbaarheid
De H flutter analyse methode helpt de aeroelasticus bij het assisteren van vluchtproeven door het nauwkeuriger voorspellen van demping en frequentie trends en biedt potentieel voor FCS design/analyse.

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B.J.G. Eussen

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Lt.Kol. T. Haringa

Programmaleider
S. Storm van Leeuwen

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Summary

A novel flutter analysis method, called the *H* flutter analysis method is introduced. The *H* flutter analysis method automatically extents the aerodynamic forces data obtained for purely harmonic oscillatory motions to damped and diverging oscillatory motions by means of fitting free interpolation. The fitting free interpolation is described and verified for a two dimensional flat plate. In addition flutter analysis results are depicted.

Contents

Abbreviations

C_i	Coefficient of spline interpolation
CN	Wing normal force coefficient
CM	Wing moment about the quarter chord coefficient
E	Core function
GAF	Generalised aerodynamic force
G	Reduced damping
G_c, K_c	Coordinate on S_c
L_{ref}	Reference length
K	Reduced frequency
N	Number of support points
R_c	Core size
R	Distance
S_c	Surface of core
V	Speed [m/s]
δ	Delta function
Δ	Laplace operator
Subscripts	
M	Support point indices

1 Introduction

Flutter analysis is usually performed with basically two methods:

- **k class** the k [1] method which predict the correct flutter instability; however the damping and frequency trends of the k method are known to be false;
- **pk class** the pk [2] method which in addition predicts the damping and frequency trends fairly correct near zero damping.

The aforementioned methods are usually based on generalised aerodynamic forces obtained for purely harmonic oscillatory motions. The prediction of the damping and frequency trends can be further improved by methods belonging to the *pk* class such as:

- **g** the *g* method [3] which improves the damping and frequency trends of the *pk* method automatically near zero damping by taking into account the derivative of the generalised aerodynamic forces with respect to the damping at zero damping;
- **p** the *p* method [4] which improves the damping and frequency trends by taking into account the effect of non-zero damping by means of generalised aerodynamic forces which are approximately valid for the damping-frequency area under consideration. However, methods which generate the aforementioned forces do hardly exist (with exclusion of [5]). In general, analytical continuation of the generalised aerodynamic forces is applied with approximation errors as side-effect due to the fitting procedures [6,7] associated with the generalised aerodynamic forces for purely harmonic oscillatory motion.

Also the more recent μ [8] flutter analysis method belongs to the latter category since a fitting procedure is needed to transform the aerodynamics to the state space. A novel flutter analysis method belonging to the *pk* class is introduced and described in this work. This so-called *H* flutter analysis method automatically extents the aerodynamic data obtained for purely harmonic oscillatory motions to damped and diverging oscillatory motions by means of a direct harmonic interpolation method thereby improving the prediction of dampings and frequencies. The latter procedure will be described and verified for a pitching flat plate. Results of a flutter analysis application will be presented for the well known AGARD flutter test case.

2 The direct harmonic interpolation method

This section describes the interpolation/continuation method with respect to the generalised aerodynamic forces. To obtain the generalised aerodynamic forces for non zero dampings, the generalized aerodynamic forces, which are computed for zero damping, have to be warped to the non zero dampings space. Therefore, an interpolation is needed that provides implicitly the analytical continuation. Methods based on the class of spline techniques are used that are robust, automatic and cardinal. For a theoretical background on the spline techniques Refs. [9,10] should be consulted. Ref. [9] introduces the volume spline and various core functions and discusses their behaviour and implementation aspects extensively. Ref. [10] deals with recent developments.

Supposing the generalized aerodynamic forces $GAF(0,k_m)$ with respect to purely harmonic oscillating motions are calculated for N distinct frequencies k_m we interpolate the data by:

$$GAF(g,k) = C^0 + C^g\ g + C^k\ k + \sum_{m=1}^{N} C_m\ E(g,k;0,k_m) \quad (1)$$

where C are the coefficients which are determined by satisfying the afore mentioned equation at the N support points m and additional closure relations:

$$Im\ GAF(g,0) = 0\ \forall\ g. \quad (2)$$

$$Re \sum_{m=1}^{N} C_m = 0 \quad (3)$$

$$Im \sum_{m=1}^{N} C_m\ k_m = 0 \quad (4)$$

$$Im\ C^0 = 0 \quad (5)$$

$$Re\ C^g = Im\ C^k \quad (6)$$

$$Im\ C^g = Re\ C^k = 0. \quad (7)$$

The linear problem governed by equations 1-7 is solved separately for the real and the imaginary parts. In particular equation 2 is satisfied for the real and the imaginary parts by assuming a symmetric and anti symmetric C_m distribution with respect to the g plane, respectively.

In this work it is required that the interpolation is harmonic, meaning that the kernel function E satisfies the Laplace equation in a two dimensional space spanned by the reduced damping *g* and the reduced frequency *k:*

$$\Delta E = \delta g \delta k. \quad (8)$$

Two types of kernels are considered:

- **Discrete source kernel** The Laplace kernel is consistently regularized according to an analogy with the determination of the auto influence of a Laplace field panel as developed in [11]:

$$E(g,k;0,k_m)=\begin{cases}\frac{\ln r}{2\pi} & r\geq R_c;\\ E(0,k_m;0,k_m)(1-\frac{r}{R_c})+E(G_c,K_c;0,k_m)\frac{r}{R_c} & 0<r<R_c;\end{cases} \quad (9)$$

$$E(0,k_m;0,k_m)=\tfrac{1}{2\pi}\ln R_c-\tfrac{1}{\pi} \quad (10)$$

$r=\sqrt{(k-k_m)^2+g^2}$ is the distance to the source location k_m and R_C denotes the core size which is taken as the minimum distance between the support points: $R_C=\sqrt{(K_C-k_m)^2+G_C{}^2}$. G_C and K_C are locations on the cylinder with size R_C. Firstly the singular kernel is regularized by redefining the value of $E(0,k_m;0,k_m)$ in the form of a weighted sum of neighbouring values, and secondly by linear interpolation of E between r=0 and $r=R_c$. The following property is used in redefining/regularizing the value of E at the origin:

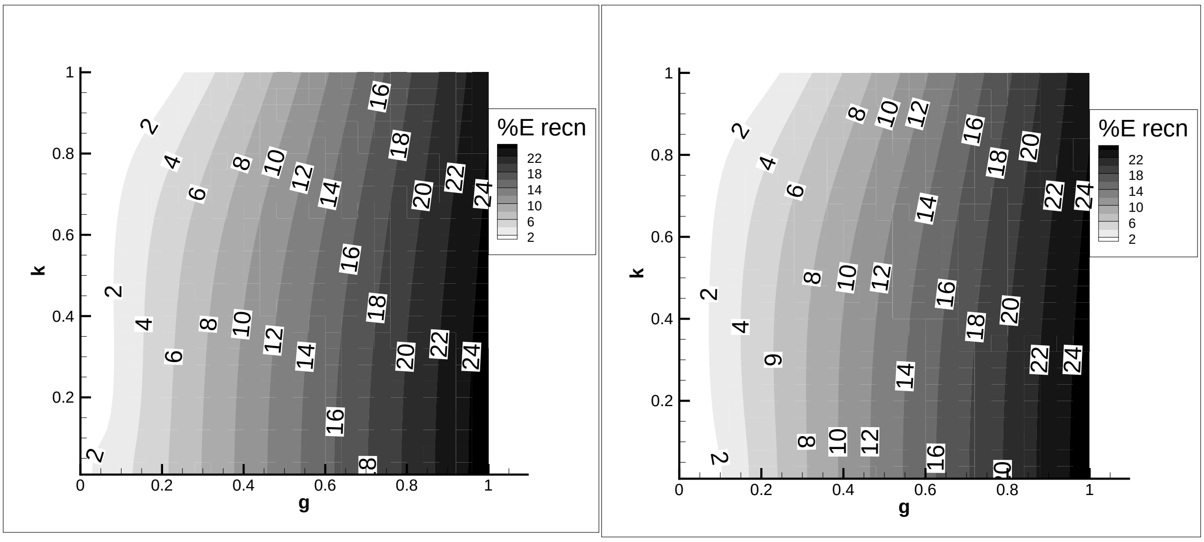
$$\int_{S_c}\Delta E dkdg=1 \quad (11)$$

where S_c denotes the cylinder with size R_c.

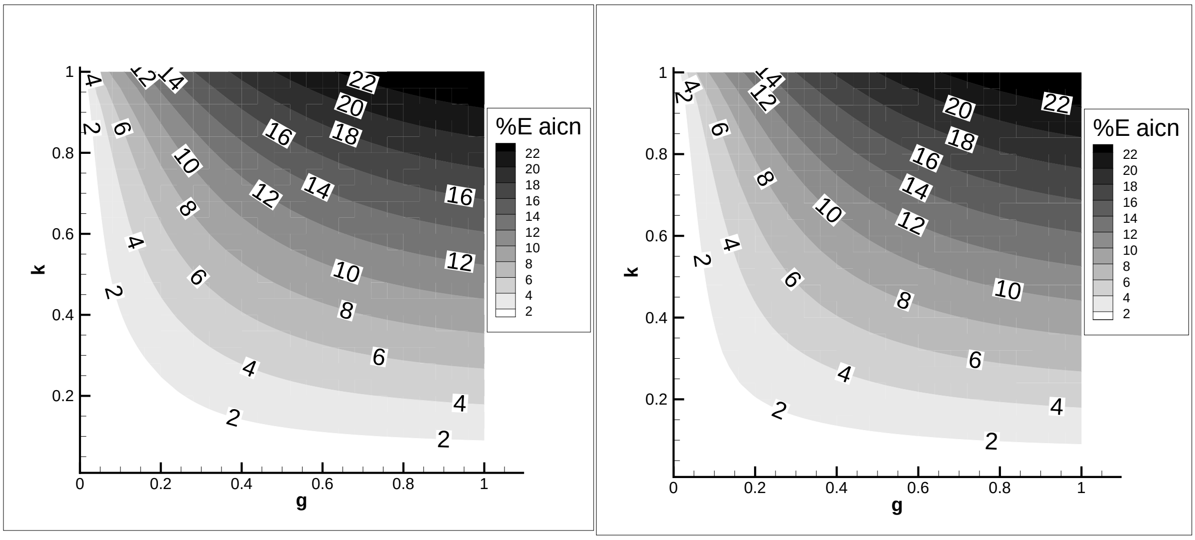
- **Continuous linear source kernel** As an alternative, a distributed core is applied which avoids the aforementioned regularization. The distributed core chosen here is a linear tent-like distribution of source singularities through successive frequency support points.

3 Verification

To verify the direct harmonic interpolation method use is made of the `d2dl` doublet lattice method [5] developed at NLR. The latter method is a two-dimensional doublet lattice method that operates for harmonic frequencies and non zero dampings. Results obtained with this new approach are presented in Figs. 1-2 for a flat plate that performs a pitching motion about the quarter chord at a Mach number of 0.8. The wing normal force coefficient CN and moment about the quarter chord coefficient CM have been calculated. The `d2dl` method is first applied for the pitching flat plate in the range $g = 0..1$ and $k = 0..1$ with a step size of 0.04. The selected range is typical for aero elastic studies. Next the data for $g = 0$ is used by the aforementioned direct harmonic interpolation method and warped to $g \neq 0$ with the discrete kernel and the continuous kernel, respectively.
Figures 1 and 2 shows a comparison of the original data to the warped data using the aforementioned core and linear kernels in terms of the relative error in percentages. Figure 1 shows a contour plot of the relative error in the real part and the imaginary part of the lift coefficient, respectively. Figure 2 shows a contour plot of the relative error in the real part and the imaginary part of the moment about the quarter chord coefficient, respectively. At reduced dampings approaching zero the error is very small for both kernels. The more simple to apply discrete core kernel is almost level with the continuous core kernel. Fairly good agreement is obtained even for large values of g . Further reduction of the differences might also be obtained by using more points along the interval or by increasing the borders and/or with better-suited conditions (radiation) at the outer borders.

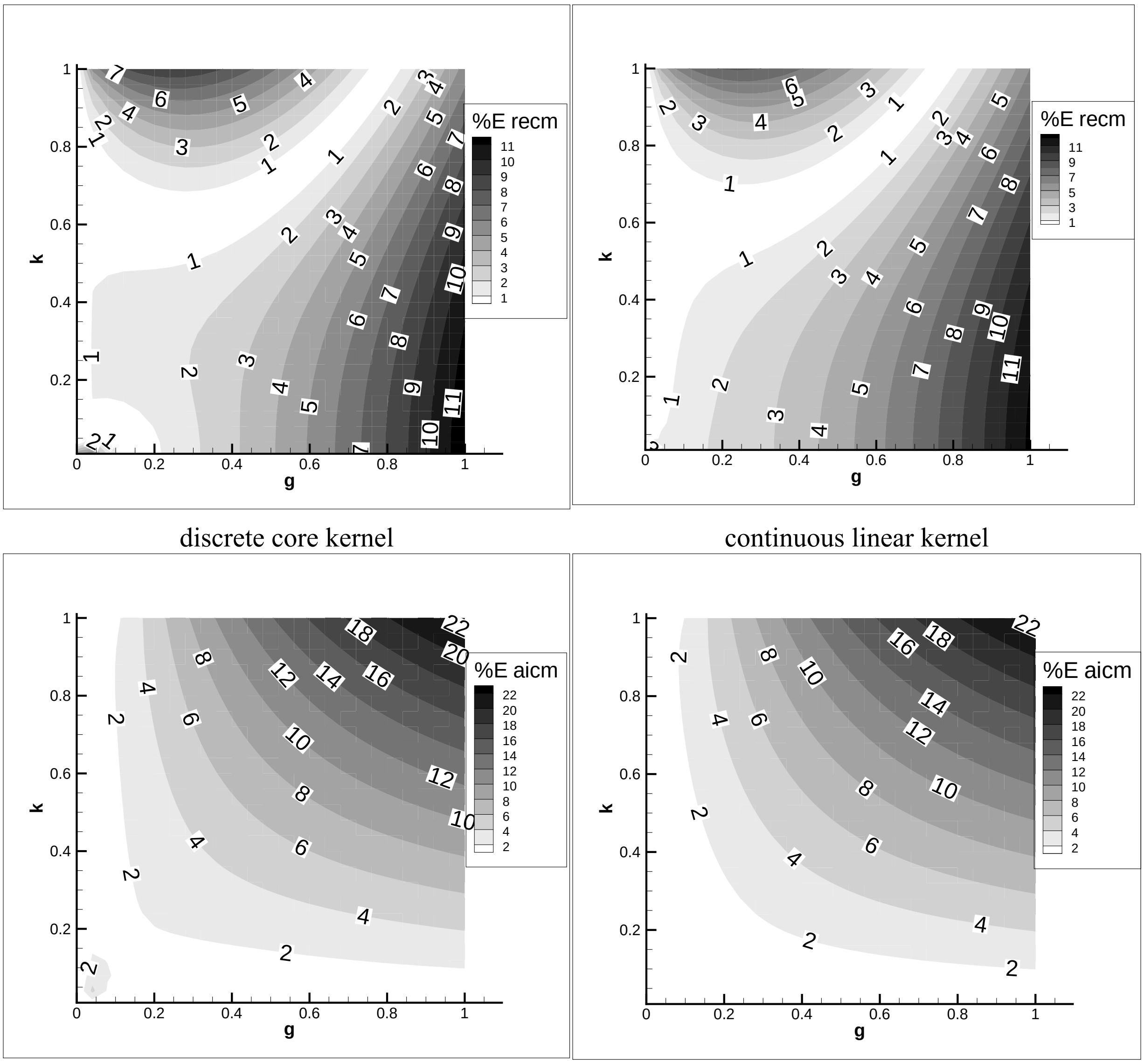


discrete kernel continuous linear kernel



discrete kernel continuous linear kernel

Figure 1 Relative error in real and imaginary part of normal force coefficient of a pitching flat plate at Mach=0.8, for the discrete source kernel and for the continuous linear kernel



discrete core kernel   continuous linear kernel

discrete core kernel   continuous linear kernel

Figure 2 Relative error in real and imaginary part of the moment about the quarter chord coefficient of a pitching flat plate at Mach=0.8, for the discrete source kernel and for the continuous linear source kernel

4 Flutter Application

Results of the *H* flutter analysis method for the AGARD wing at Mach number 0.96 are compared in Figure 3 with results obtained with the pk flutter analysis method. The unsteady aerodynamic data for this analysis is computed using the lifting surface theory. Both methods predict the same flutter instability mechanism. Starting at zero velocity, the relative dampings ($=\frac{g}{k}$) and frequencies $=\frac{kV}{2\pi l_{ref}}$ of both methods agree up to high levels of the relative damping and the velocity, thus affirming the well-known fact that the results of the *pk* flutter method are fairly correct near zero damping. The H method seems to lower the damping levels and predicts a tighter connection between the flutter mode shapes after the flutter point has been passed.

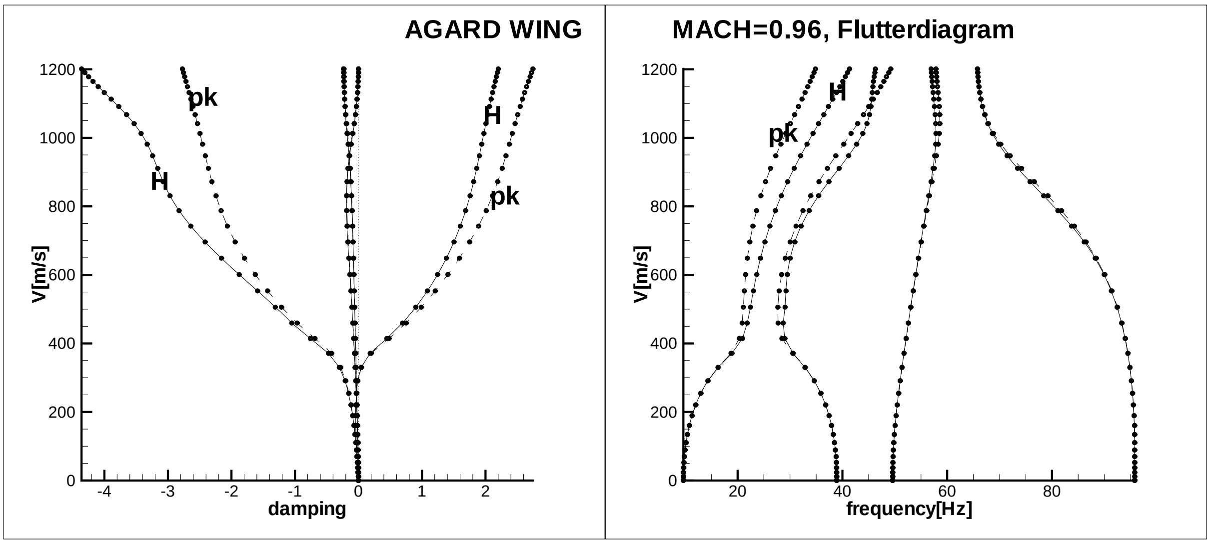


Figure 3 Flutter diagram for the AGARD wing 445.6 at Mach number 0.96 using the pk flutter analysis method (dashed) and the H flutter analysis method (solid)

5 Conclusion

A novel flutter analysis method, called the *H* flutter analysis method is introduced. The *H* flutter analysis method contains a simple procedure that automatically extents the aerodynamic forces data obtained for purely harmonic oscillatory motions to damped and diverging oscillatory motions by means of fitting free interpolation. The fitting free interpolation is described and verified with fairly good success for a two dimensional flat plate. In addition flutter analysis results for the AGARD Wing 445.6 demonstrate in comparison to the *pk* flutter analysis method different damping trend capturing at high levels of dampings. This procedure may help the aeroelastician in making improved estimates of aerodynamic dampings to support flight flutter testing and probably offers potential for FCS design/analysis.

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