DESIGN OF COMPENSATED FLUTTER SUPPRESSION SYSTEMS

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ABSTRACT

The paper presents a method to design compensated flutter suppression systems by eigenvalue assignment. The compensator is designed as a state observer by paralleling the Luenberger approach. The eigenvalues of the aeroelastic system and compensator are obtained by imposing a stationary value to a suitable norm of the gains, under the constraint of satisfying the aeroelastic eigensystem for assigned stable eigensolutions, and without any problem on the modelling of the unsteady aerodynamic forces. The compensator can be used not only to reconstruct lacking states, but also to insure insensitivity to different flight conditions.

A method is presented to mechanize, and possibly to reduce in order, the aeroelastic observer.

Some simple examples illustrate the use of the method along with comments on the stabilization of an aeroelastic system by eigenvalue assignment techniques.

INTRODUCTION

Recent analytical development, wind tunnel and flight test demonstrations show that active flutter suppression is emerging as an effective tool that can greatly improve the stability characteristics of an aircraft structure, without adding undue weight [1-6].

This technology can be helpful in widening the flight envelope, by insuring a wider speed clearance for flutter troubled configurations.

Since a flutter suppression system can appreciably change the dynamic response of an aircraft, it should be important to validate its performances also from the point of view of structural response and load alleviation, and in fact the two aspects have to be integrated in the design procedure.

Nevertheless, in evaluating candidate control designs, one must be assured that the scheme in hand is suitable to stabilize the aeroelastic system for widely changing flight conditions and/or configurations, before any optimization could be undertaken in view of load alleviation. Thus effective design tools are needed that can allow a fast screening of different flutter suppression system layouts, in order to establish their suitability for the stabilization task. This is generally done in order to obtain the best compromise amongst designs that can differ in the number and location of sensors and control surfaces, in the signal conditioning adopted and in the controller type, which can range from a simple proportional feedback to a complicated compensator along with possible passive elements, i.e. tuning masses and dampers.

It is to be noted that, owing to the wide spectrum of operating conditions, an adaptive controller seems to be the most appropriate solution. Even if test applications [7] of this concept are being undertaken in research oriented applications, it is yet to be proved that an adaptive controller can be generally superior to an insensitive time invariant control system configuration or to a slightly more complicated gain scheduling of simple mechanization, especially for multi input-output systems.

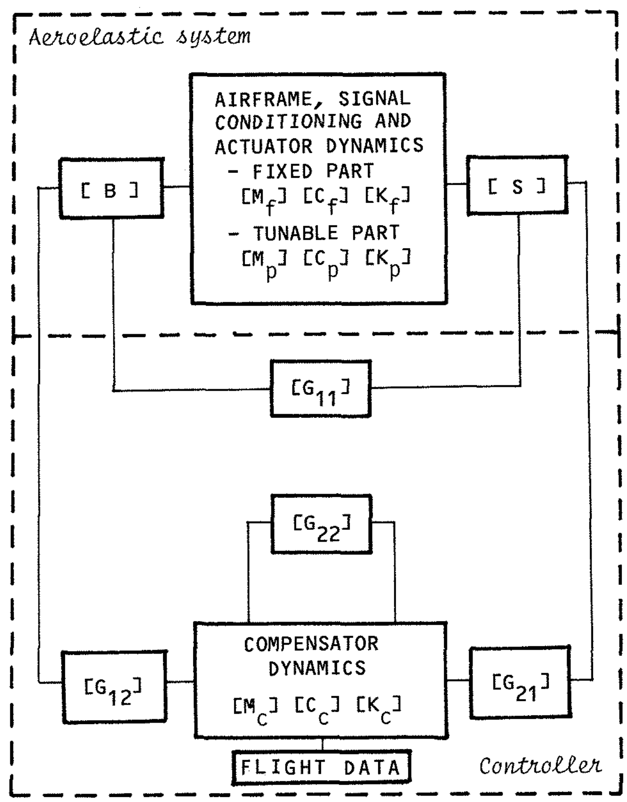


FIGURE 1 - Active flutter control scheme

Other aspects, such as excitation, adaption speed, disturbances, reliability and control computers [8], seem to indicate that, following the experience of flight control systems [9], fully integrated adaptive flutter suppression systems will emerge in the long run, after sufficient experience will have been accumulated in more conventional control systems, possibly complemented by partially adaptive functions.

This paper attempts to develop a general approach to active flutter stabilization, that can provide the designer with an efficient tool in the evaluation and development of control strategies, capable to insure the full flutter clearance over a wide range of flight conditions. This aim is achieved by the use of simple controllers with fixed or easily scheduled gains, in order to produce effective designs which result in the best tradeoff with regard to the suppression system components.

AEROSERVOELASTIC MODELLING

The model of the aeroservoelastic system is described by a set of n generalized coordinates $\{q\}$, which are representative of all the structural degrees of freedom and of all the states of the actuators, sensors and signal conditioning systems, which are assumed as known.

Then a fairly general way to represent the system in the open loop mode in the Laplace Transform domain is the following:

$$\begin{aligned}&[s^2([M_f]+[M_p])+s([C_f]+[C_p])+\\&+([K_f]+[K_p])+\tfrac{1}{2}\rho V^2[A(\tfrac{sb}{2V},M)]]\ \{q(s)\} \quad (1)\\&=[B]\{u(s)\}\end{aligned}$$

in which :

- [M], [C] and [K] are generalized mass, damping and stiffness matrices, respectively;
- [A] is the transfer function of the aerodynamic forces;
- ρ is the air density;
- V is the asymptotic flow speed;
- b an aerodynamic reference chord;
- M the Mach number.

The [M], [C] and [K] matrices are split into the sum of two terms, denoted by the suffices f and p, indicating that they are related either to an unchangeable or to a tunable part of the system. This tunable part in the open loop mode allows what will be referred to as passive control. It can be related to those parameters, such as tuning masses, dampers, stiffnesses, elements of the conditioning system, the designer can use to improve the system behaviour, either with or without closing the loop on the controller.

A general way to synthesize Eq.(1) from individual structural components, actuators, sensors and signal conditioning transfer functions is presented in Ref.[10].

The main difficulty for the direct utilization in the design of a control system is related to the presence of the aerodynamic matrix in Eq.(1). In fact the aerodynamic matrix represents the aerodynamic forces in an input-output form, typical of a transfer matrix, which contains many hidden aerodynamics states. Moreover this transfer function is known only at discrete values of sb/2V, and generally only for an imaginary s.

This prevents the application to Eq.(1) of the many powerful tools made available by modern control theory.

Since the modern control approach is a proved powerful tool in controller design, stemming from early rationalization [11,12] of subcritical flutter calculations with harmonic aerodynamics, many approaches has been developed [13-16] to identify an approximate modelling for the hidden aerodynamics states. This can lead to an efficient time invariant approximation of the aerodynamic subsystem with an acceptable number of aerodynamic states which can be used for a stabilization by pole placement techniques and for response optimization by LQG design [6],[17-20],[23].

The result of these approaches to flutter suppression system design is generally a high order system. It will insure appropriate stability obtainment only at a single flight point and configuration, with the hope that sufficient robustness has been built into the controller in order to maintain the actively controlled aeroelastic system well stable even far out from the design point.

Then, despite of the "optimal control", many redesign cycles are needed. They have to be complemented by extensive flutter calculations to ascertain their behaviour at each flight condition and configuration of interest.

A great problem in the practical adoption of these approaches comes from the need to adopt compensators of large dimensions to cope with the incomplete measurement [21-24] of the states, as complete measurement is impractical for the servostructural system and impossible for the retained aerodynamic states.

In view of the previous remarks there has been a strong motivation to develop design methods for active flutter suppression that were particularly suited to the problem formulation of Eq.(1)[25-29].

This paper aims to widen the approach of Ref.[28] and [29] to include the design of dynamic controllers, that can be of help when simple algebraic feedback cannot be able to produce acceptable stability margins at varying flight conditions.

Referring to Fig.(1), we see that the aeroelastic system and compensator are appropriately described in the open loop mode by an augmented system of the type :

$$s^2\begin{bmatrix}[M_f]+[M_p] & \emptyset\\ \emptyset & [M_c]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix}+$$

$$+s\begin{bmatrix}[C_f]+[C_p] & \emptyset \\ \emptyset & [C_c]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix}+$$

$$+\begin{bmatrix}[K_f]+[K_p] & \emptyset \\ \emptyset & [K_c]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix}+ \qquad (2)$$

$$+\tfrac{1}{2}\rho V^2\begin{bmatrix}[A] & \emptyset \\ \emptyset & [A_c]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix}=\begin{bmatrix}[B] & \emptyset \\ \emptyset & [I]\end{bmatrix}\begin{Bmatrix}u\\ u_c\end{Bmatrix}$$

with output :

$$\begin{Bmatrix}y\\ y_c\end{Bmatrix}_{\ddot{q}}=s^2\begin{bmatrix}[S]_{\ddot{q}} & \emptyset \\ \emptyset & [I]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix} \qquad (3a)$$

$$\begin{Bmatrix}y\\ y_c\end{Bmatrix}_{\dot{q}}=s\begin{bmatrix}[S]_{\dot{q}} & \emptyset \\ \emptyset & [I]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix} \qquad (3b)$$

$$\begin{Bmatrix}y\\ y_c\end{Bmatrix}_{q}=\begin{bmatrix}[S]_{q} & \emptyset \\ \emptyset & [I]\end{bmatrix}\begin{Bmatrix}q\\ q_c\end{Bmatrix} \qquad (3c)$$

in which the suffix c is used to indicate the compensator related quantities and the $[S]_{\ddot{q}}$ $[S]_{\dot{q}}$ and $[S]_q$ matrices are the output matrices of the aeroelastic system and they are related to the term of q or its derivatives.

In Eq.(3) it is obviously implied that the compensator states are completely available.

It is important to note that the structure of Eq.(2) implies the need of a mechanization that must be tuned to the actual flight conditions.

The system and compensator are coupled by a gain law of the type :

$$\begin{Bmatrix}u\\ u_c\end{Bmatrix}=s^2\begin{bmatrix}[G_{11}]_{\ddot{q}} & [G_{12}]_{\ddot{q}} \\ [G_{21}]_{\ddot{q}} & [G_{22}]_{\ddot{q}}\end{bmatrix}\begin{Bmatrix}y\\ y_c\end{Bmatrix}_{\ddot{q}}+$$

$$+s\begin{bmatrix}[G_{11}]_{\dot{q}} & [G_{12}]_{\dot{q}} \\ [G_{21}]_{\dot{q}} & [G_{22}]_{\dot{q}}\end{bmatrix}\begin{Bmatrix}y\\ y_c\end{Bmatrix}_{\dot{q}}+ \qquad (4)$$

$$+\begin{bmatrix}[G_{11}]_{q} & [G_{12}]_{q} \\ [G_{21}]_{q} & [G_{22}]_{q}\end{bmatrix}\begin{Bmatrix}y\\ y_c\end{Bmatrix}_{q}$$

In practice, with the use of a compensator we are adding a dynamic system that provides us with an increased number of parameters, which can be determined in order to hopefully insure the desired stability over the whole flight envelope.
It must be remarked that there is a certain degree of redundancy in the combination of Eq.(2),(3) and (4), as the direct compensator gains, i.e. the matrices $[G_{22}]$, because of the structure of Eq.(3), add straightforwardly to the $[M_c]$, $[C_c]$ and $[K_c]$ matrices of the compensator. Moreover the designer can suppress some coupling terms, if they are not deemed necessary in improving the controller performances.

Once the aeroelastic system has been modelled and a compensator structure has been chosen, we can design the whole system. This will be done in the following by the use of an eigenvalue assignment technique and of a compensator predesign.

Many and important design steps are taken for granted in Eq.(4), i.e. :

- matrix [B] implies number and location of control surfaces;
- matrices [S] implies number, location and type of sensors;
- the order m of the compensator is assumed as given;
- signal conditioning and actuator dynamics are included in the model and they can be modified only in those elements placed in the passive part of the aeroservoelastic model.

Since only partial and limited procedures of integrated design of the previous item plus controller are available [30,31], the design relies on the experience of the engineers and on repetitive modifications of a certain layout, which showed itself uncapable of satisfactory performances. However this fact is present, whichever is the design method used.

EIGENVALUE ASSIGNMENT

The well established techniques of pole assignment, developed in modern control theory, are not adoptable to Eq.(1).

A method has then been developed [28,29] to directly cope with Eq.(1), and, since this method is basic to this presentation, it is briefly recalled for an easy reference.

We name $\{p\}$ the vector of the parameters corresponding to the passive parameters and to the coefficients of the [G] matrices that are available to be designed, according to a control structure established by the designer. Then, when the feedback law of Eq.(4) is applied to Eq.(2), for each imposed eigenvalue s_i^*, we have to satisfy a set of equations:

$$\begin{cases}[F_i(s_i^*,\{p\})]\ \{q_i^*\} = \emptyset & (5a)\\ \tfrac{1}{2}\{q_i^*\}^T\{q_i^*\} = 1 & (5b)\end{cases}$$

in which the eigenvector $\{q_i^*\}$ is unknown and it cannot be null, because of Eq.(5b). Eq.(5) can be viewed as a set of n+1 or 2n+2 real equations, according to the assignment of real or complex eigenvalues. In the latter case complex conjugacy is assured by the properties of the aerodynamic transfer matrix and by the fact that the matrices are real.

Then the design parameters can be obtained by minimizing an arbitrary norm of the type :

$$J = \tfrac{1}{2}\{p\}^T[W]\{p\} \tag{6}$$

with a number of constraints of the type of Eq.(5) equal to the number of imposed eigenvalues. In Eq.(6) [W] is a suitable, generally diagonal, matrix employed for scaling purposes or to appropriately weigh the various components of {p}.

By the use of the Lagrange's multipliers technique we are led to the imposition of a stationary value to :

$$J^* = \tfrac{1}{2}\{p\}^T[W]\{p\} + \sum_N^1{}_i(\bar{\lambda}_i(\tfrac{1}{2}\{q_i^*\}^T\{q_i^*\}-1) + \{\lambda_i\}^T[F_i]\{q_i^*\}) \tag{7}$$

in which N is the number of assigned eigenvalues. For sake of conciseness Eq.(7) is written for the case that all the assigned eigenvalues are real. The case of complex conjugate ones is conceptually trivial, but somewhat cumbersome for the presentation.

Thus we are led to the following set of nonlinear equations :

$$\begin{aligned}
\frac{\partial J^*}{\partial\{q_i^*\}} &= \{\lambda_i\}^T[F_i] + \bar{\lambda}_i\{q_i^*\} = \emptyset \\
\frac{\partial J^*}{\partial\{\lambda_i\}} &= [F_i]\{q_i^*\} = \emptyset \\
\frac{\partial J^*}{\partial\bar{\lambda}_i} &= \tfrac{1}{2}\{q_i^*\}^T\{q_i^*\} - 1 = \emptyset \\
\frac{\partial J^*}{\partial\{p\}} &= [W]\{p\} + \sum_1^N{}_i\{\lambda_i\}^T\left[\frac{\partial F_i}{\partial\{p\}}\right]\{q_i^*\} = \emptyset
\end{aligned} \tag{8}$$

which can be solved with the use of the Newton-Raphson method, that implies the iterated solution of a set of linear equations of the following structure :

$$\begin{bmatrix}
[\bar{\lambda}_i] & [F_i]^T & \{q_i^*\} & \left[\frac{\partial F_i}{\partial\{p\}}\right]^T\{\lambda_i\} \\
[F_i] & \emptyset & \emptyset & \left[\frac{\partial F_i}{\partial\{p\}}\right]^T\{q_i^*\} \\
\{q_i^*\}^T & \emptyset & \emptyset & \emptyset \\
\{\lambda_i\}^T\left[\frac{\partial F_i}{\partial\{p\}}\right] & \{q_i^*\}^T\left[\frac{\partial F_i}{\partial\{p\}}\right] & \emptyset & [W]
\end{bmatrix} *$$

$$\left\{\Delta\{q_i^*\} \quad \Delta\{\lambda_i\} \quad \Delta\bar{\lambda}_i \quad \Delta\{p\}\right\}^T = - \left\{\frac{\partial J^*}{\partial\{q_i^*\}} \quad \frac{\partial J^*}{\partial\{\lambda_i\}} \quad \frac{\partial J^*}{\partial\lambda_i} \quad \frac{\partial J^*}{\partial\{p\}}\right\}^T \tag{9}$$

In Eq.(9) the blocks suffixed with i must be intended repeated for N times in the appropriate order.

In view of the use of modal coordinates and of the defined control law, the parameters {p} appear in matrices of the form:

$$[M] = [X][G][Y] \tag{10}$$

in which [X] and [Y] can be the input-output matrices or the modal shapes. Thus the derivative $\partial F/\partial\{p\}$ can be easily computed by means of a decision matrix, describing the topology of the unknown parameters in the acceleration, speed and displacement gain matrices $[G]_{\ddot{q}}$, $[G]_{\dot{q}}$, $[G]_q$, and in the unreduced passive inertia, damping and stiffness matrices.

For higher order systems, {p} vector and many eigenvalue assigned, the system implied in Eq.(9) can be very large, but it is symmetric and it consists of many diagonal blocks, coupled only by the $\partial F/\partial\{p\}$ terms. These features allow a very effective solution both in processing time and core requirements, that, together with the good convergence features of the Newton-Raphson method, make it possible to solve Eq.(8) in a quite effective and stable way.

This effectiveness and stability can be further improved by setting Eq.(8) and (9) in a continuation form, and moving gradually from a given starting eigensolution, which satisfies Eq.(5), to the desired s_i^* and $\{q_i^*\}$.

A basic assumption of this approach is that the hidden eigenvalues of the [A] matrix are well stable and that they cannot appreciably be changed during the imposition of the new eigenvalues. This assumption is simply taken for granted, as no proof can be given for it. It is only heuristically proved by the long experience in flutter analyses and by the fact that, when appropriate augmentation of states has been used to describe the aerodynamic component of Eq.(1), the related eigensolutions have always shown to be insensitive to the control law used for flutter suppression.

Another important thing to note is that, when there is no convergence to a solution for Eq.(8), it is impossible to establish the reasons of the trouble, as the constraint equations (5) are only necessary conditions, but they don't give any indication about the requirements under which they can be satisfied. However, even in the case of time invariant linear systems, no general conditions for the pole assignment under arbitrary controller structure are established.

It may now be noted that in this approach we need only a good interpolation method to calculate [A] for arbitrary reduced frequencies and Mach numbers. Such interpolation can be afforded by fitting rational function of sb/2v to each term of [A]. Even the so called rough p-k approximation [32], or an improved causal interpolation [33], which operates directly on harmonic data, can profitably be used [28].

COMPENSATOR DESIGN

In general we tend to achieve acceptable stability over a whole set of flight conditions in the simplest way, that is with as reduced measurements, control forces and controller, as possible.

The simplest possible controller is a simple algebraic feedback law, but, if this is incapable to satisfy the design objective, a gain scheduling technique or the use of dynamic compensation, either tuned or untuned to flight conditions, can be taken into consideration.

The utilization of the eigenvalue assignment technique, previously described, allows the design of a compensator as that presented in Eq.(2),(3) and (4), beginning from any suitable initial trial solution, provided that it couples the system and the compensator.

This approach can be successful, but, for large order systems, it can be exhausting and it can require a large number of trials in order to provide an acceptable solution.

A more systematic approach can be developed by paralleling the Luenberger approach [21] to observer like compensator design. This approach consists in designing separately, through eigenvalue assignment, two algebraic control laws for Eq.(1). The first one is obtained by assuming complete measurement, i.e. all the [S] matrices are identity matrices, and [B] as input matrix; it gives a set of gain matrices [L], with n columns and a number of rows equal to the inputs of the system. The second one assumes an identuty matrix for [B], i.e. there are n independent control forces, and the actual structures of the [S] matrices; it leads to a set of matrices [H], with n rows and as many columns as the related measurements.

A compensator of order n to be tuned to the aerodynamic transfer function can be given by :

$$[M_c] = [M_f]+[M_p] \tag{11a}$$

$$[C_c] = [C_f]+[C_p] \tag{11b}$$

$$[K_c] = [K_f]+[K_p] \tag{11c}$$

$$[A_c] = [A] \tag{11d}$$

and

$$[G_{11}]_{(\ddot{q},\dot{q},q)} = \emptyset \tag{12a}$$

$$[G_{12}]_{(\ddot{q},\dot{q},q)} = -[L]_{(\ddot{q},\dot{q},q)} \tag{12b}$$

$$[G_{21}]_{(\ddot{q},\dot{q},q)} = [H]_{(\ddot{q},\dot{q},q)} \tag{12c}$$

$$[G_{22}]_{(\ddot{q},\dot{q},q)} = -[B][L]_{(\ddot{q},\dot{q},q)}+[H]_{(\ddot{q},\dot{q},q)}[S]_{(\ddot{q},\dot{q},q)} \tag{12d}$$

It can be easily shown that the substitution of Eq.(11) and (12) into Eq.(2), (3) and (4) leads to a compensated aeroservoelastic system that has the same eigenvalues of the two systems produced by the separated complete measurement and complete input designs.

An important requirement in the design of observer like compensator for time invariant systems is that these are controllable and observable. These two properties are difficult to be established on the structure of Eq.(1) or (2). Nevertheless, important, even if not rigorous, checks of these properties can be easily performed on rational approximations of Eq.(1), possibly carried out as in Ref.[32] in order to remain within the same framework utilized in eigenvalue assignment. These checks can be also helpful in evaluating a posteriori the goodness of sensors and control forces type and location.

Even if the system can be made observable by a single measurement, in the complete input design we cannot freely assign all of its eigenvalues, because we have constrained the compensator to maintain the structure of Eq.(1), which requires at least two measurements in order to make available the minimum number of parameters required to arbitrarily assign all of its eigenvalues.

This is not believed to be a drawback, because the eigenvalue placement procedure shown need not to place them either all together or at the same speed.

Full advantage of this feature can be even taken in order to make the two basic designs the more insensitive as possible, at changing flight conditions.

MECHANIZATION

Two main problems are posed by the mechanization of Eq.(11) and (12) : realization of the aerodynamic term and possible order reduction.

The latter is often mandatory unless the designed compensator is related to a suitable system of reduced order, but, since it requires an appropriate wiring of the aerodynamic terms, it is left to later comment.

If we are ready to accept a compensator which needs a tuning to actual flight conditions, the aerodynamic matrix can be simplified to :

$$[A_c]=(\tfrac{1}{2}\rho b^2 s^2[M_a(M)]+\tfrac{1}{2}\rho bVs[C_a(M)]+\tfrac{1}{2}\rho V^2[K_a(M)])\ \{q\} \tag{13}$$

by approximating the aerodynamic matrix [A] over a range of reduced frequencies of interest [33].

Even if the approximation of Eq.(13) is a rather crude one, it is expected that no significant change is produced with respect to the original design and that it can possibly be corrected by applying an appropropriate set of eigenvalues again.

Eq.(13) still contains a Mach number tuning, that can be obtained by interpolation or simply by discrete switching over predermined values of M with a continous tuning on the ρ and V terms only.

An untuned mechanization can be produced by fixing ρ,V and M after the previous step has been undertaken, but, in this case, the aeroelastic system and its compensator will produce the desired performances over a reduced range of flight conditions. Its behaviour outside this range has to be ascertained and eventually the produced controller has to be modified in order to cope with unwanted instabilities.

As previously stated, especially for large order aeroelastic models, the compensator now at hand must be looked as a suitable predesign, over which we can work to reduce its order in some systematic way, without starting with randomly choosen first temptative designs. A natural way that can be adopted to reduce the order of the compensator is that of eigenvalue matching between the original and the reduced order design. This matching can be obtained in an easy way in the continued solution of the eigenvalue assignment procedure. In this case the solution is started from the given eigenvalues and the structure of the compensator is reduced to the wanted one, while maintaining the set of given eigenvalues, possibly at different speeds.

In this process it is useful to produce direct feedback links, that did not appear in the original design, i.e. $[G_{11}]\neq 0$.

The procedure is suitable both for the tuned and for the untuned compensator, and it can be well applied to a tuned version, after which the compensator of reduced order obtained can be put in the untuned version.

Other known methods, such as simple truncation, residualization and frequency response matching [23],[35],[36], can be applied. Not all of them are suitable for an easy reduction of the tuned compensator; in particular, while plane truncation can be carried out quite easily in the case of a tuned compensator, the residualization approach will be rather difficult to apply. Frequency response matching can be able to cope with a tuned design only if a suitable fit can be obtained by taking simultaneously into account the matching at different flight conditions in the performance index.

Whichever method is adopted, the final reduced system produced can be taken as a starting design, which can be perfected by reapplying the eigenvalue assignment, till an acceptable flutter suppression is produced.

It must be pointed out that, even if the number of available measurements and control forces allows a simple, algebraic, stabilization without any dynamic compensator, the adoption of this can be of some help in producing a controller capable to afford larger stability margins at critical conditions.

PROS AND CONS

It is believed that the use of a pole placement-compensator technique to design a flutter suppression system, in the approach presented here and in the related references, offers many advantages over the procedure of augmenting the system with some aerodynamic states, in order to produce a time invariant system to which apply the usual pole placement technique of the modern control theory.

These advantages are :

- no state augmentation;
- possibility to make use of a simple method of interpolation to model the aerodynamic matrix;
- mantainment of the second order structure of the system;
- possibility to disregard the modes that are insensitive to the controller action and that have to be retained for good modelling;
- the eigenvalues can be assigned at different speeds, even for a single mode, in order to try to insure a certain adaptativity, even without tuned gains;
- arbitrariness in defining the control structure with the possibility to design a compensator;
- a mix of passive and active flutter suppression can be obtained within a single design method.

The drawbacks of this approach are not related to the method here presented, but to the eigenvalue placement technique itself [37]. They are mainly due to the fact that during the design process no control exists upon the actuators efforts and on the quality of the response, which has been afforded by the controlled aeroelastic system to dynamic enviroment encountered in flight, i.e. gusts and manoeuvres.

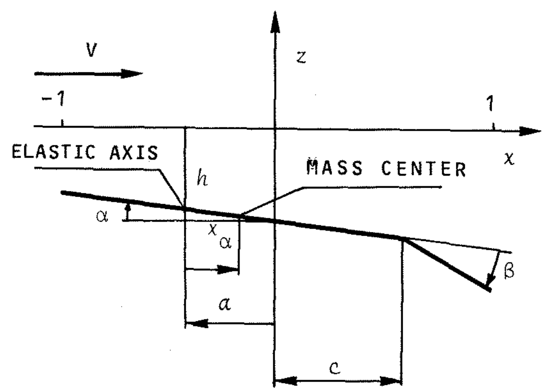
The imposition of the minimization of the cost function of Eq.(6) can be viewed as a way to try to reduce actuators activity, while the availability of the eigenvector in constraint equations (5) could be exploited to control response qualities, but a practicable way to do it has not been found yet.

Moreover, for larger order systems, the design and the tuning of a temptative system, augmented by the compensator dynamics in order to obtain a controlled aeroelastic system adapted to all the flight conditions, can be an exhausting task. This task can be successfully undertaken only in the case when just a few modes are responsible of the critical conditions and they can be made sensible to the control activity, while the others only improve the modelling of the system.

Even in this case some trials are required in order to ascertain which eigensolutions, and at what speeds, must be imposed, and which instead can be left free. In this process the designer is helped by the availability, in the continuation solution, of the parameter derivatives with respect to each eigenvalue shift, and he must continously loop between eigenvalue placement and flutter analyses to verify the behaviour of the design at hand at different flight regimes.

All these facts seem to demonstrate that the cons outnumber the pros of active flutter suppression system design, with or without dynamic compensators, by means of an eigenvalue assignment technique.

It has been already stated in the introduction, that, if the design for stability, response quality and load alleviation has to be integrated in order to produce a unique and effective design, the capability to insure wide stability margins over a wide set of flight conditions is a clear prerequisite of any temptative design. And it is just in the phase of definition and evaluation of such basic characteristics, as the number and the location of sensors and control surfaces, the choice of control law, with or without a dynamic compensator, with or without a flight tuning of the controller parameters that the eigenvalue placement can be very useful in choosing the most promising solution, by the help of a CAD like interactive procedure. Then the design refinement and the detailed evaluation can be carried out only on the few most promising solutions emerged from the previous phase.



x,z NON-DIMENSIONAL COORDINATES

h PLUNGE COORDINATE

α PITCH COORDINATE

β TRAILING EDGE FLAP COORDINATE

a LOCATION OF ELASTIC AXIS WITH RESPECT TO ORIGIN

c DISTANCE FROM ORIGIN TO TRAILING EDGE CONTROL SURFACE HINGELINE

x_α LOCATION OF MASS CENTER WITH RESPECT TO ELASTIC AXIS

FIGURE 2 - Typical section with trailing edge control surface

NUMERICAL EXAMPLES

The numerical procedure of eigenvalue assignment above outlined has been implemented as a module of the computer program AIACE (An Interactive program for the design of Active Control flutter suppression systems by Eigenvalue assignment), and it has been applied to the typical section of Fig.(2) in incompressible flow, with the section parameters of Tab.(1).

$\omega_\alpha = 100\ s^{-1}$	$\mu = 40$	$x_\alpha = .2$
$\omega_h = 50\ s^{-1}$	$a = -.4$	$x_\beta = .0125$
$\omega_\beta = 300\ s^{-1}$	$c = .6$	$r_\alpha^2 = .25$
	$\zeta_\beta = .0$	$r_\beta^2 = .00625$

TABLE 1 - Section parameters

The open loop s-V plots of this three-degrees-of-freedom section are reported in Fig.(3): even if this numerical example is deliberately simple, it performs its duty of demonstrating the usage of the design procedure here proposed, because of its inherent difficulty to be controlled [19].

In practical applications more structural modes and more complicated actuator dynamics could be taken into account, but in general only few modes affect the flut-

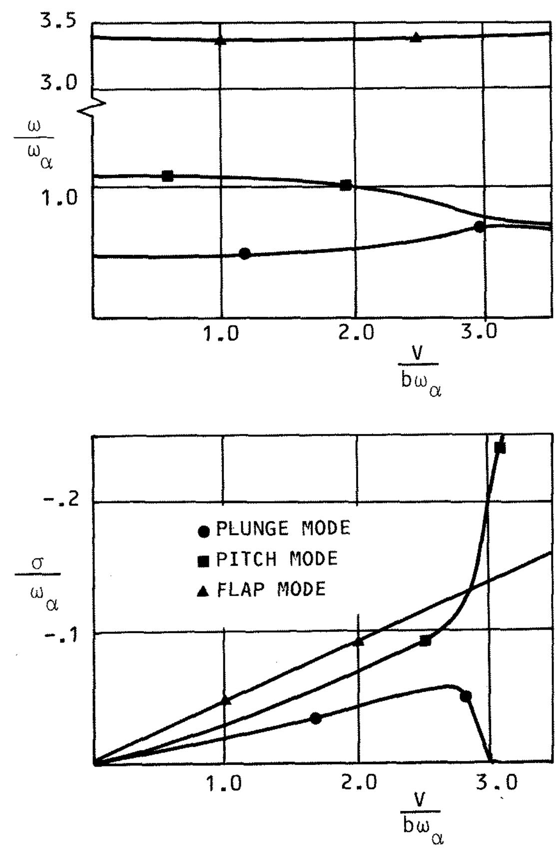


FIGURE 3 - Open loop s-V plots. ($s=\sigma+i\omega$)

ter mechanism, while the other ones can be rather insensitive to it.

Assuming first the availability of the displacement and of the velocity of the pitch coordinate, a full order tuned compensator has been designed, and the resulting s-V plots for the original system, augmented by the compensator, is shown in Fig.(4).

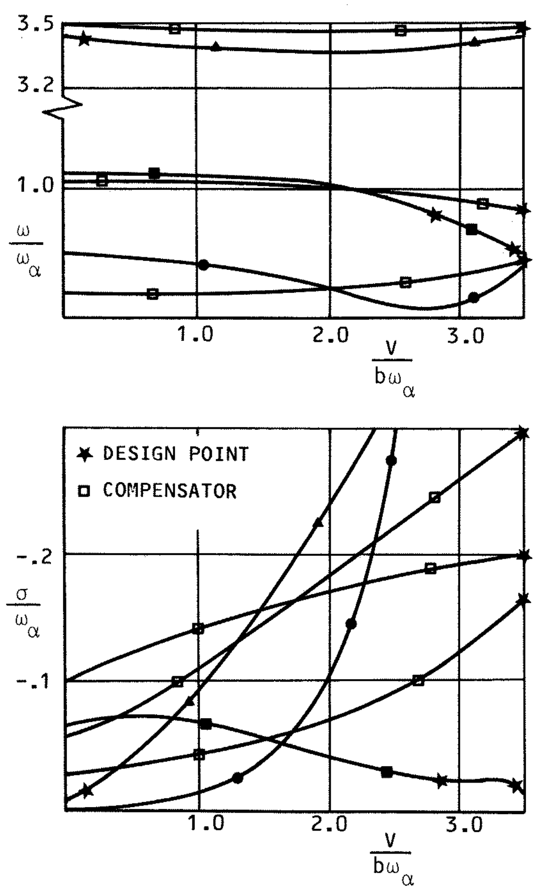


FIGURE 4 - Closed loop s-V plots of the flutter suppression system with full order tuned compensator.

It can be seen that an appreciable increase in flutter speed has been achieved. Further trials to simplify the compensator structure and/or to reduce the order of the controller were unsuccessful, because of the poorer designs produced.

This example can be taken as a typical application in which it is wanted to adopt a compensator in order to alleviate the lack of sensors. In fact, Fig.(4) results from the plane tuned combination of the two basic designs produced by assuming the availability of all of the states and of the complete input. Thus the first case can be used by itself to produce the same stabilization, with a simple algebraic law.

Since the previous design has shown that the compensator can alleviate only the lack of sensors without improving the stability margins of the full state design, a first order untuned compensator has been combined to the full state measurement, in order to try to improve the stability behaviour.

After some trials to synthesize a reduced order compensator from the previous one, the adopted controller layout has been perfected by the eigenvalue assignment technique and the behaviour shown in Fig.(5) has been obtained. It can be seen that now no flutter is present and that the stability margins are more considerable.

These examples, even in their simplicity, are representative of some types of the problems which can be faced in deciding a flutter suppression system structure.

The work done during the development of these control laws has confirmed the remarks made in the previous paragraph.

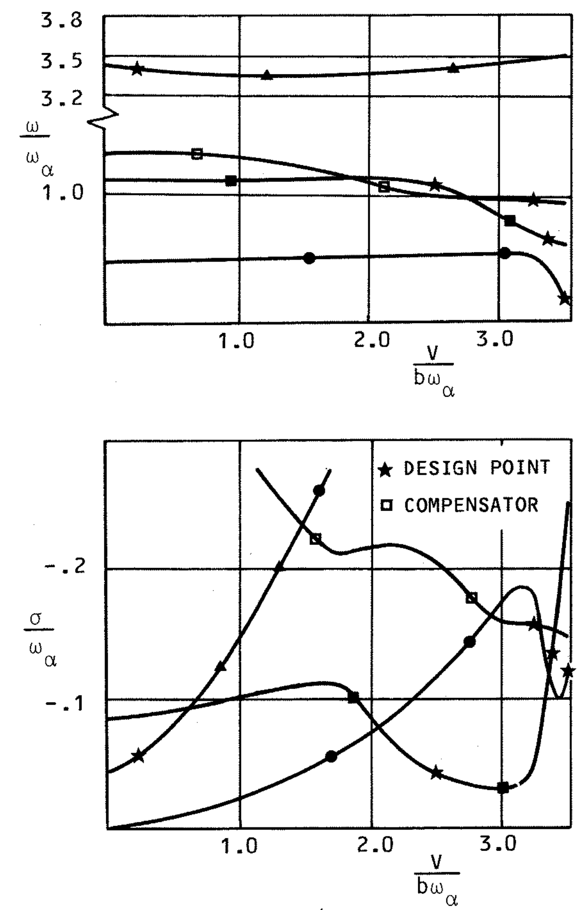


FIGURE 5 - Closed loop s-V plots of the flutter suppression system with first order untuned compensator.

CONCLUDING REMARKS

The eigenvalue assignment and compensator design methods, presented in this paper, can be a valuable tool in a preliminary design phase of active flutter suppression systems, because they can be straightforwardly applied to the modelling used in typical aeroservoelastic stability analyses.

In particular, the application of the

whole design procedure to some simple numerical examples has demonstrated some of the possibilities provided to the designer by the use of some types of compensator.

Nevertheless, the limitations of the eigenvalue placement technique in producing a final design that properly takes into account the integration of the yielded active flutter suppression system in the improvement of the aeroelastic system response, have been emphasized.

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