Aeroelastic Design of an All-Moveable UAV Fin

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Abstract

This paper demonstrates aeroelastic design of an all-moveable vertical fin for used with a UAV. The fin is made up of aluminium and fibreglass. Aeroelastic analysis is achieved by interfacing ANSYS into MATLAB. With various configurations of fin attachment being employed, aeroelastic characteristics are computed. The results are compared and discussed.

1. Introduction

An Unmanned Aerial Vehicle (UAV), since it was introduced, has been widely used in a wide range of applications e.g. military and air force operation and agricultural activities. Since it is unmanned, the design constraints of this kind of aircraft are different from that of conventional manned aircrafts. For example, human discomfort can be ignored and the UAV can be more agile and faster. UAV designs often result in unusual configurations depending on initial design concepts such as oblique-wing, large-jointed wing, X-wing and flying-wing UAVs [1]. Nevertheless, whether it is manned or unmanned, the vehicle structure must fulfil all safety requirements and design criteria, which include aeroelastic phenomena.

In the past, classical aircraft design simply minimised the elastic structural deflections of a large and stiff lifting surface structure so as to reduce undesirable aeroelastic phenomena [2] & [3]. Later, with the development of Multidisciplinary Design Optimisation (MDO) technology, the use of elastic deflections to enhance the aerodynamic performance of practical structures has become possible. Weight and size reductions and performance improvements can be expected by using the advantages of structural flexibility.

A vertical aircraft tail or fin is one of the most important lifting surface structures of traditional aircrafts as it is used to provide a lateral stability and manoeuvrability about the yaw axis. A typical vertical fin with a rudder has to be designed to be sufficiently large and stiff to reach the required aerodynamic performance [4]. The idea to reduce the vertical fin size, while maintaining or even exceeding aeroelastic effectiveness, can be achieved by using of an all-moveable fin as illustrated in Figure 1 [5], [6] & [7]. More advantage in using such a fin is that it is less complicated to construct.

The work in this paper is aimed at demonstration of aeroelastic design of an all-moveable vertical fin for used with a UAV. The fin is made up of material that can be easily provided in Thailand i.e. aluminium and fibre glass. Structural dynamic analysis is carried out by using the commercial software ANSYS whereas aerodynamic analysis is coded in MATLAB. This means that aeroelastic analysis is achieved by interfacing ANSYS into MATLAB. With various configurations of the fin attachment being assigned, aeroelastic characteristics are computed. The results are compared and discussed. It is shown that an efficient all-moveable fin can be obtained exploiting multidisciplinary analysis and design.

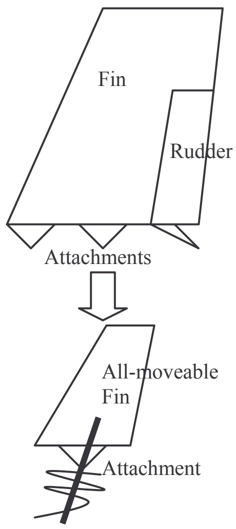

Figure 1 All-moveable fin concept

2. Aeroelasticity

Aeroelasticity is a study of aerodynamic forces acting on flexible structures. As external forces acting on an aircraft are the forces due to aerodynamic loads, aeroelastic analysis consists of three kinds of force that are aerodynamic, elastic (strain energy) and inertial (kinetic energy) forces. These forces are said to be mutually interactive since, when the structural configuration is changed due to the aerodynamic force, the deformed structure simultaneously causes the change of aerodynamic force. The inertial force is involved when dynamic analysis is solved.

Aeroelastic phenomena are usually referred to as being undesirable causing the loss of design effectiveness or structural instability. It can be classified as static and dynamic aeroelasticity. Static aeroelasticity is the analysis where the elastic and steady aerodynamic forces are taken into consideration while dynamic aeroelastic analysis is concerned with all those three forces. The aeroelastic phenomena that are conventionally taken as important criteria in aircraft design are lift and control effectiveness, divergence and flutter.

It might be supposed that the lifting surfaces (wings and tails) are perfectly rigid when performing aerodynamic design but the fact is that the structures are flexible, as a result, lift forces due to the displaced surface can be more or less than expected. This has a serious effect on aircraft controls. The ratio of the lift on the flexible structure to the lift on its rigid counterpart is called *lift effectiveness*. Divergence can be described as when the work done by steady aerodynamic force overcomes the restoring energy or strain energy leading the structure to neutral equilibrium. The aircraft speed at this occurring is called *divergence speed*. Flutter is a dynamic instability of the structure consisting of a violent unstable oscillation. During flight, the dynamic characteristics change with airspeed and altitude. At some speed, the modes will interact in such a way that motion becomes unstable. The critical speed at which the instability occurs is called the *flutter speed*.

A linear flutter model can be described by a special type of undamped forced vibration as [8]:

$$\mathbf{M}\ddot{\mathbf{r}} + \mathbf{K}\mathbf{r} = q\mathbf{A}(k)\mathbf{r} \qquad (1)$$

where **M** is structural mass matrix

K is structural stiffness matrix

A is the matrix of unsteady aerodynamic loads

q is dynamic pressure

k is a reduced frequency

and **r** is the vector of structural displacement.

Substituting **r** by $\mathbf{r}_0 e^{\omega t}$ leads to

$$\mathbf{K}\mathbf{r}_0 - \omega^2\mathbf{M}\mathbf{r}_0 = q\omega^2\mathbf{A}\mathbf{r}_0 \cdot \qquad (2)$$

Flutter speed can be computed from this equation by using the *V-g* method. Lift effectiveness of the fin can be obtained by the relation [9]

$$\eta = \frac{\mathbf{S}_a^T[AIC]_F\,\boldsymbol{\alpha}}{\mathbf{S}_a^T[AIC]_R\,\boldsymbol{\alpha}} \qquad (3)$$

where η is the lift effectiveness of the fin

$\mathbf{S}_a$ is the vector of aerodynamic panel areas

$[AIC]_R$ is the aerodynamic influence coefficient matrix

$[AIC]_F$ is the aerodynamic influence coefficient matrix when structural flexibility is taken into account

and $\boldsymbol{\alpha}$ is the vector of panel angles of attack.

$[AIC]_R$ can be obtained by using an aerodynamic panel method e.g. the vortex lattice method while $[AIC]_F$, the flexible-surface aerodynamic influence coefficient matrix, is computed from

$$[AIC]_F = [\mathbf{I} - q[AIC]_R[SIC]\mathbf{S}_a]^{-1}[AIC]_R \qquad (4)$$

where [*SIC*] is called a structural influence coefficient matrix.

Divergence speed can be achieved by solving the eigenvalue problem

$$\{[SIC]\mathbf{S}_a[AIC]_R - \lambda\mathbf{I}\}[\Delta\boldsymbol{\alpha}] = \mathbf{0}. \qquad (5)$$

The maximum eigenvalue gives the minimum divergence speed.

A simple aeroelastic model can be illustrated by considering the three axes of the three forces which are aerodynamic, elastic and mass cg axes as depicted in Fig 2. The aerodynamic axis is the locus of the centres of aerodynamic pressure along the fin span. Similarly, the elastic and mass cg axes are the loci of the shear centers and mass cg of the fin sections along the wing span. The aerodynamic and elastic axes play a role in both static and dynamic analyses while the mass cg axis affects the flutter behaviour.

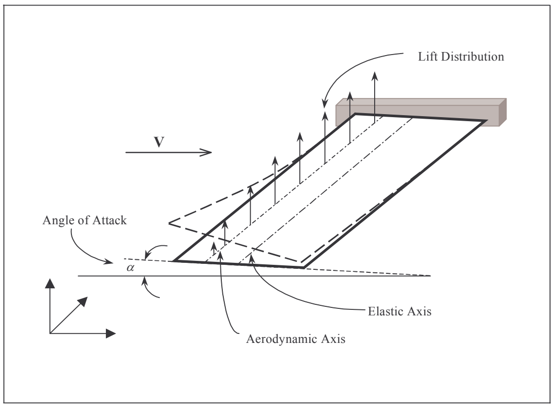

Figure 2 Aerodynamic and elastic axes

3. An All-Moveable Fin

Figure 3 shows the finite element model of an all-moveable fin in this research work. The assembly of the fin is illustrated in figure 4. The fin consists of three main parts that are skins, stiffeners (ribs & spars) and attachment. The upper, lower and front skins are made of fibreglass whilst the other parts are made of aluminium. The fin has 0.5 m height with 0.4 m root chord length and 0.25 m tip chord length. Note that this fin structure is not an advanced technology in terms of material used. It is supposed to be built up using material easily obtainable in the country. This means that the fin structure is inexpensive compared to those made of high technology material such as carbon fibre composite.

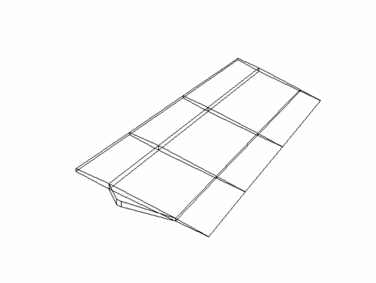

Figure 3 All-moveable fin model

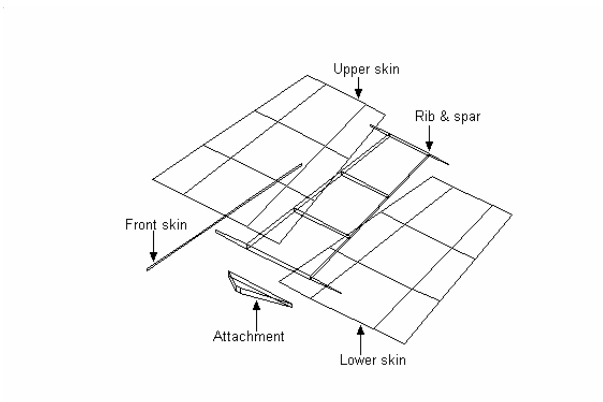

Figure 4 Fin assembly

4. Implementation

The computation of equations 2), 3) and 5) can be accomplished by the use of finite element analysis and aerodynamic panel methods. Figure 5 displays the computational flowchart of the aeroelastic analysis in this work. The process is the interface of ANSYS finite element software into MATLAB environment where the main operator is in MATLAB. As structural and aerodynamic data being input, structural analysis is carried out in ANSYS whereas aerodynamic analysis takes place in MATLAB. The Vortex Lattice Method (VLM) [10] is used for steady aerodynamics while unsteady aerodynamic analysis is computed by using the Doublet Lattice Method (DLM) [11]. Solving flutter speed, lift effectiveness and divergence speed are operated in MALAB program as shown.

Design case study is the aeroelastic analysis of the all-moveable vertical fin. Design parameters are the fin attachment configurations in Figure 6. Seven attachment shapes are defined as Att1, Att2, Att3, Att4, Att5, Att6 and Att7 as shown. With each attachment being applied to the fin, natural frequencies, lift effectiveness, flutter and divergence speeds are computed and will be compared and discussed.

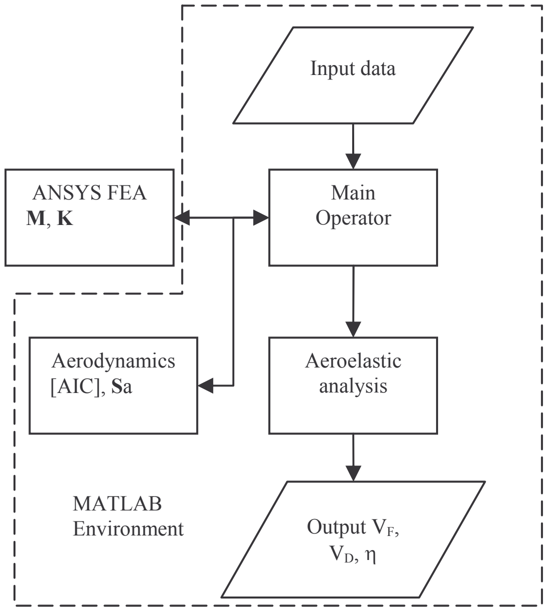

Figure 5 Computational procedure

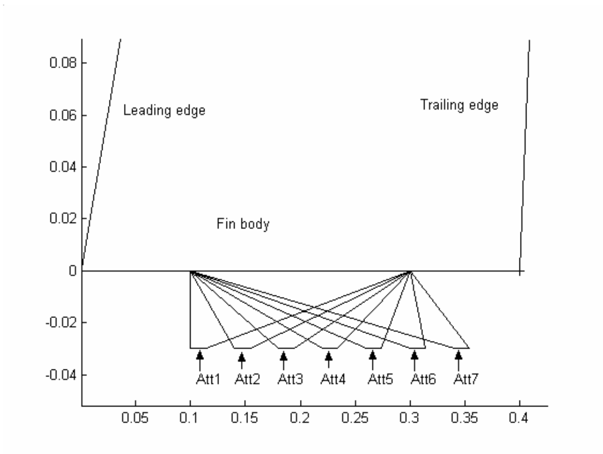

Figure 6 Attachment configurations

5. Design Results

Figures 7 to 11 illustrate the first five mode shapes of the fin with Att2 attachment. The plot of the first five natural frequencies versus the fin aspects is shown in Figure 12. Overall, the Att4 fin has the highest frequencies (for almost every mode) while the Att3 fin comes second. The lift effectiveness of the fin with these various attachments at various air speeds is illustrated in Figure 13. The results shown that, the higher air speed results in the higher lift effectiveness and the attachments configurations do not make a significant impact on the value of the lift effectiveness of this all-moveable fin. Figure 14 displays the V-g diagram of an Att2 fin. It is illustrated how the V-g method is used to compute a flutter speed. The relation between lift effectiveness and flutter speed versus the attachment aspects at 0.9 Mach is shown in Figure 15. It is shown that, to obtain higher fin effectiveness, flutter speed has to be sacrificed or vice versa and clearly the trade off between these parameters has to be decided by a designer.

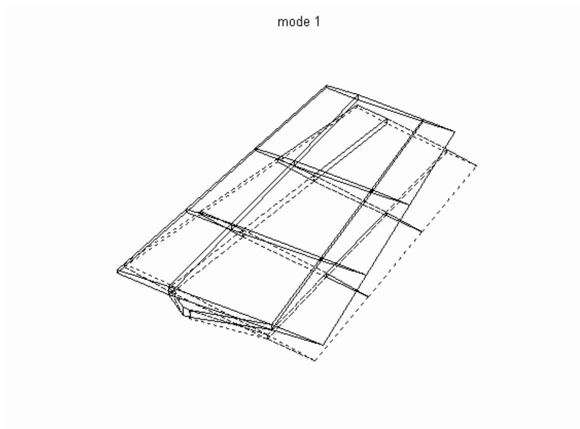

Figure 7 Fin mode #1

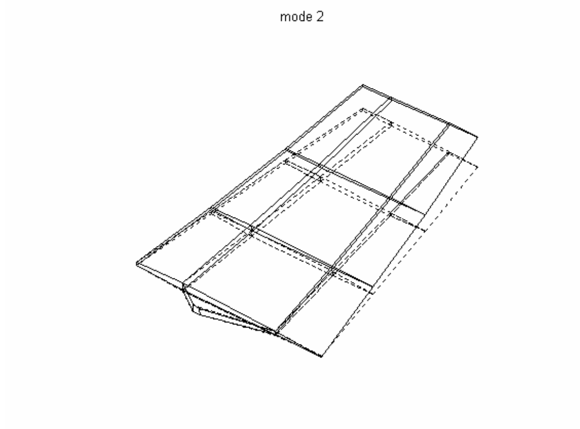

Figure 8 Fin mode #2

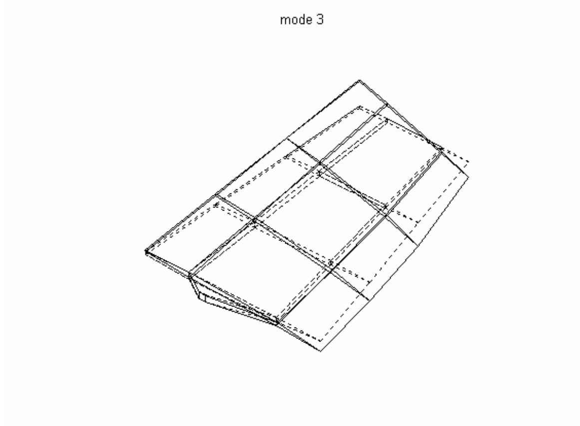

Figure 9 Fin mode #3

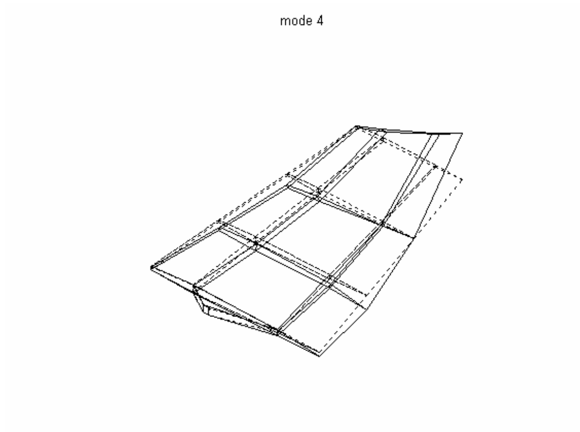

Figure 10 Fin mode #4

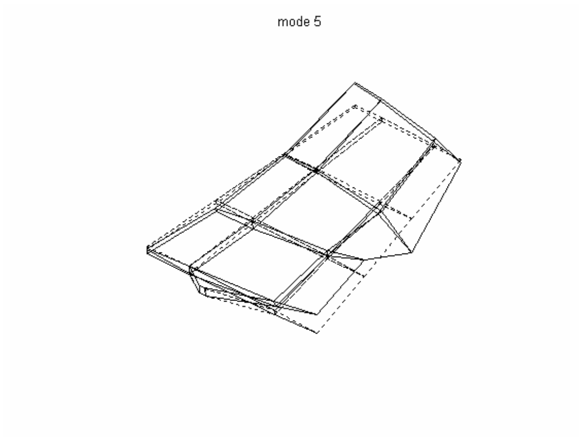

Figure 11 Fin mode #5

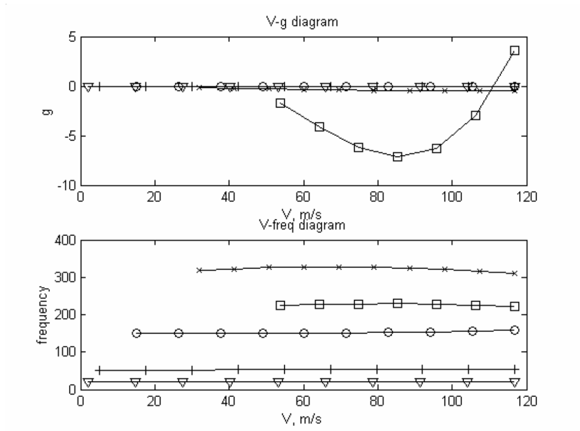

Figure 14 V-g diagram

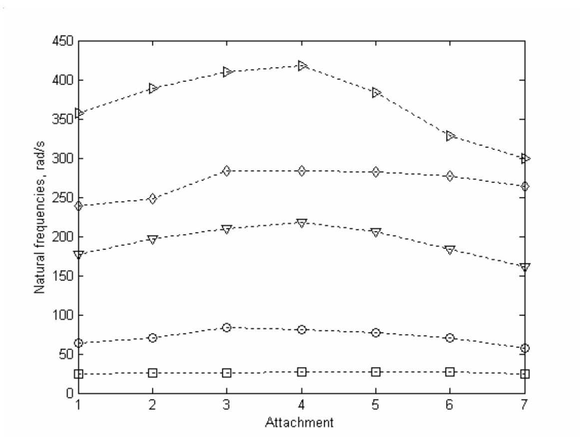

Figure 12 Natural frequencies VS attachments

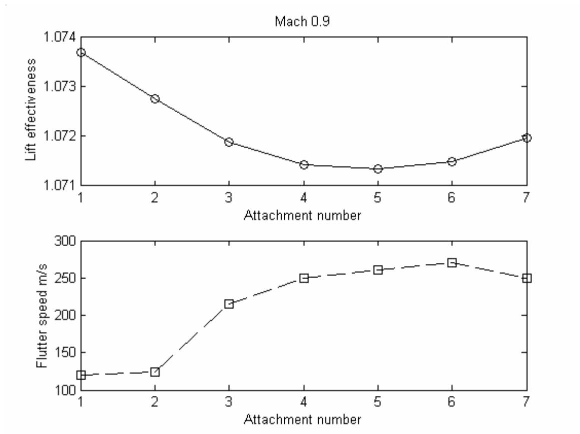

Figure 15 Lift effectiveness & flutter speed VS attachments

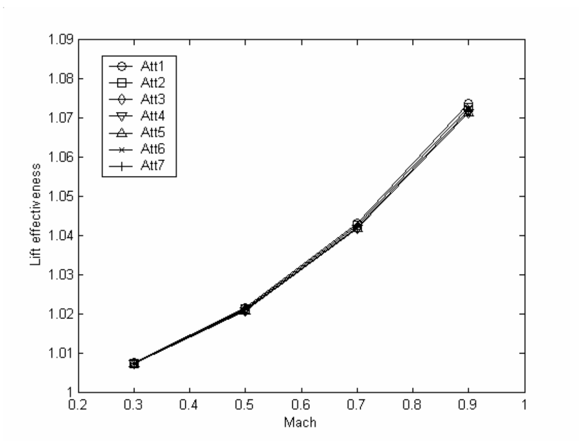

Figure 13 Lift effectiveness VS attachments and Mach numbers

In order to have more understanding with the results, the elastic axes of the fins are determined. The axis can be thought of as a beam representing the whole fin structure. By definition, the elastic axis of the fin is the locus of the shear centres of fin cross-sections. As the structure is usually complicated, it is difficult to compute and define the elastic axis mathematically. The more sophisticated way in determining an elastic axis is that the use of finite element analysis. Figure 16 demonstrates the procedure to indicate the elastic axis of a particular structure. By twisting at the tip of the structure, the elastic axis is the locus of points on the structure which have no deflection. The elastic axes of the all-moveable fin with various attachment aspects are shown in Figure 17 together with the aerodynamic axis that is obtained from using the VLM. From the figure, all the axes are completely kinky. This means that the axis that is swept forward would have increased angle of attack when loaded by external force. The gap between the aerodynamic axis and the elastic axis also has an important role as this determines the yawing moment about the elastic axis. It is difficult to explain the results in Figure 15 using the physical insight from Figure 17. The kink of Att1 fin is forward swept at the beginning and then backward swept and forward swept again around the tip. The forward swept axis at the root and the tip could lead to a higher effectiveness. However, as the elastic axis is far from the aerodynamic axis, the fin with this attachment has the lower flutter speed. The other fin, for example Att7 fin, has the behaviour like a forward swept fin though the fin itself looks actually backward swept. This can make the fin having high aerodynamic performance (more than 1.00 lift effectiveness). Another observation is that the fins that have the kinky elastic axes almost coincident to the aerodynamic axis at the tip end seem to have higher flutter speed (of course the flutter also relies on some other structural parameters e.g. structural natural frequencies). The multidisciplinary system still needs more development particularly in aerodynamic section. The future version would also have the more complete subsonic and supersonic aerodynamic codes.

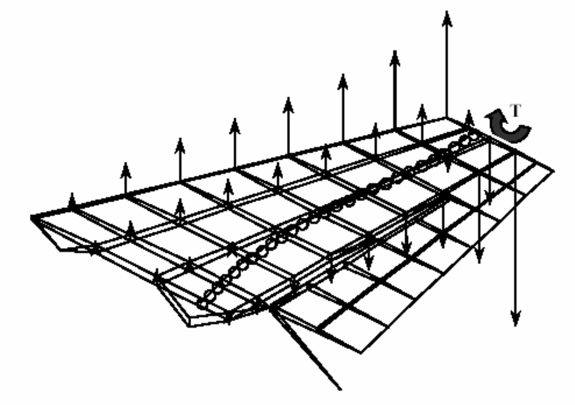

Figure 16 Structural elastic axis

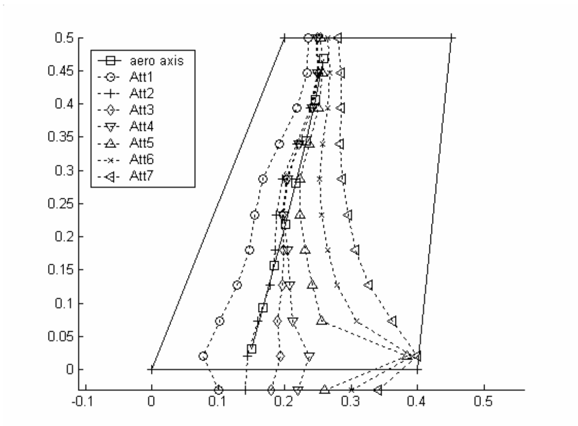

Figure 17 Aerodynamic and elastic axes

6. Conclusions and Suggestions for Future Work

The fin with a number of attachment aspects has different aeroelastic characteristics. The fins that have higher lift effectiveness trend to have lower flutter speeds and vice versa. The developed multidisciplinary system is said to be a powerful tool for aircraft design. In the future, it is possible to apply the active aeroelastic concept to the fin. Optimisation is also an important tool to enhance the passive aeroelastic design. The idea can, furthermore, be extended to other aircraft lifting surface structures.

7. References

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