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Flutter Phenomena Effected By The Aerodynamic Load

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Abstract

The basic aim of this project is to define and investigate the flutter condition which occur at the wing and fuselage of the aircraft structure or any flying aerofoil such as engine fins during flight under different conditions and high speeds where the flutter causes a vibration on the wing and fuselage of the aircraft structure also on the structure of the fins which leads to a high risk of structure failure, if these vibrations are not controlled. The project gives some method of calculating flutter also the project suggests some answers to this problem by giving an example on airfoil fins model during high velocity with the basic equations and data.

الخلاصة

إن الغرض الأساسي من هذا البحث هو لتوضيح وتعريف حالة الرفرفة التي تحدث على جناح وهيكل الطائرة أو أي جسم طائر أو دوار كريش محرك الطائرة أثناء الطيران بسرع طيران عالية ومختلفة حيث تحـدث تلـك الحالـة مسـببة أهتزازات على جناح وهيكل الطائرة أو ريش المحرك مما يولد خطراً على عموم هيكل الطائرة وبنية تلك الريش إذا لم يتم تدارك تلك الإهتزازات ويقـدم البحـث بعض الطرق المقترحة لحساب تلك الحالة كما يوضح كيفية تجاوز تلـك الحالـة ويناقش البحث بالتفصيل حالة الرفرفة التي تحدث على ريش المحرك للطـائرات أثناء الدوران بسرع مختلفة .

Keywords

AR	Aspect ratio	-
b	Chord length	mm
c/a	Mid thickness to radius ratio(thickness ratio)	-
C_D	Drag coefficient	-
C_L	Lift coefficient	-
C_m	Moment coefficient	-
C_N	Normal force coefficient	-

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E	Modules of elasticity	N/m^2
f_b	Bending frequency	Hz
f_t	Torsional frequency	Hz
L	Length mm	
h_o	Fundamental amplitude	-
p	Power KW	
s	Area mm^2	
t	Time sec	
v	Velocity	m/sec
V_f	Flutter speed	m/s
W/T	Work over time	J/s
(A_1, B_1, C_1)	Influence Coefficient	-
α^o	Angle of attack	degree
θ	The instantaneous angular displacement	degree
μ	Mass of the blade	gm
σ	Logarithmic decrement	mm
ω	Eigen frequency	rad/sec
ρ	Air density	kg/m^3

Introduction

The dynamic stability can be divided into three types of problems which are : *Flutter , Buffeting* and *Dynamic response* .

Our project concentrates on flutter condition which has been defined as the dynamic instability of an elastic body in an air stream and is produced by aerodynamic forces which result from the deflection of the elastic body from it's undeformed state. The determination of critical or flutter speeds for the continuous structure of an aircraft is a complex process since such a structure possesses an infinite number of natural or normal modes of vibration .Simplifying assumptions such as braking down the structure into a number of concentrated masses connected by weightless elastic beams (lumped mass concept) are made but whatever method is employed the natural modes and frequencies of vibration of the structure must be known before flutter speeds and frequencies can be found . It is found most frequently in aircraft structures subjected to large aerodynamic loads such as wings ,tail units and control surfaces .Flutter occurs at a critical or flutter speed V_f which in turn is defined as the lowest air speed at which a given structure will oscillate with sustained simple harmonic motion . Flight at speeds below and above the flutter speed represents conditions of stable and unstable, that is divergent, structural oscillation respectively.

Old Methods of Calculating Flutter

Generally an elastic system having just one degree of freedom cannot be unstable unless some peculiar mechanical characteristic exists such as a negative spring force or a negative damping force .However it is possible for systems with two or more degrees of freedom to be unstable without possessing unusual characteristics .The forces associated with each individual degree of freedom can interact causing divergent oscillations for certain phase differences .The flutter of a wing in which the flexural and torsional modes are coupled is an important example of this type of instability .Some indication of the physical nature of wing bending – torsion flutter may be had from an examination of aerodynamic and inertia forces during a combined bending and torsional oscillation in which the individual motions are 90^o degrees out of phase[1]. In a pure bending or pure torsional oscillation the aerodynamic forces produced by the effective wing incidence oppose the motion ; the geometric incidence in pure bending remains constant and therefore dose not effect the aerodynamic damping forces while in pure torsion the geometric incidence produces aerodynamic forces which oppose the motion during one half of the cycle but assist it during the other half so that the overall effect is nil .Thus pure bending or pure torsional oscillations are quickly damped out .This is not the case in the combined oscillation when the maximum twist occurs at zero bending and vice versa, that is a 90^o degree phase difference .

The wing shown in fig.(1) in various stages of a bending–torsion oscillation .At the position of zero bending the twist of the wing causes a positive geometric incidence and therefore an aerodynamic force in the same direction as the motion of the wing. A similar but reversed situation exists as the wing moves in a downward direction; the negative geometric incidence due to wing twist causes a downward aerodynamic force . It follows that although the effective wing incidence produces aerodynamic forces which oppose the motion at all stages the aerodynamic forces associated with the geometric incidence have a destabilizing effect. At a certain speed, the flutter speed V_f , this destabilizing action becomes grater than the stabilizing forces and the oscillations diverge .In practical cases the bending and torsional oscillations would not be as much as 90° degrees out of phase, however the same basic principles apply .

We can see from fig.(1) the importance of the relative positions of the inertia axis of the wing (the axis linking the centers of gravity of the wing sections) and the flexural axis .If , for example the inertia axis were aft of the flexural axis then the inertia forces act in a sense increasing wing twist whereas in a forward position the inertia forces create the opposite effect .The position of the inertia axis may be adjusted by a redistribution of wing weight, a process known as mass–balancing. Other factors affecting the tendency of the wing to flutter are its elastic stiffness both in bending and torsion and the flexural axis; the latter should be as near the quarter chord position as possible since this will place it in close proximity to the aerodynamic center thereby reducing the magnitude of the aerodynamic twisting moment. However adjustments to all these parameters are influenced by factors other than flutter prevention; of these weight considerations are of primary importance.

The estimation of flutter speeds and frequencies is a complex problem; the degree of complexity has been increased by the complication of modern aircraft structures. However the accuracy of the computation has been improved by the introduction of digital and analogue computers which enable a comparatively large number of degrees of freedom to be included in the idealized model of the actual structure .Generally flutter calculations are based on an assumption or determination of the normal modes of the aircraft .Some years ago the standard procedure for calculating normal modes was to represent the aircraft structure by a finite number (≤ 60 usually) of masses connected by a series of weightless elastic beams .The normal modes where then obtained by calculating influence coefficients for the masses and applying procedures similar to the calculation of springs motion .This method of structural representation is still applicable to structures of high AR ratio but has been replaced in cases of high sweep and low AR ratio by methods based on the newer structural analysis techniques , for example the force and displacement methods of Argyris [2] .

These methods give influence coefficients at the node points in the actual structure so that it only remains to break down the weight into concentrated masses at these nodes for the normal modes to be found as before .A review of flutter calculation is given in ref.[3] .While Bisplinghoff , Ashley and Halfman [4] give extensive coverage of the theory, David [5] described flutter and oscillatory pressure test on a 727 aileron in a wind tunnel and sub critical flutter characteristics of a rigid full scale 727- wing segment were presented .

We have noted previously that normal mode estimation may be carried out by wind tunnel test on flutter models . These are often used to check theoretical calculations if the aircraft design incorporated some new feature or the aircraft flies in the transonic region .The model is not required to be highly representative as long as the basic structural characteristics of the actual aircraft are included . It should be capable of alteration so that different parameters may be changed as desired .Again , for a detailed account of flutter models and flutter model testing reference should be made to Bisplinghoff , Ashley and Halfman [4].

All newly designed aircraft are subjected early in the life of a prototype to a ground resonance test to determine actual normal modes and frequencies . The primary objects of such tests are to check the accuracy of the calculated normal modes on which the flutter predictions are based and to show up any unanticipated peculiarities in the vibrational behavior of the aircraft .Usually the aircraft rests on some low frequency support system or even on it's deflated tyres. Electro –

dynamic exciters are mounted in pairs on the wings and tail with accelerometers as the measuring devices. the test procedure is generally to first discover the resonant frequencies by recording amplitude and phase of a selected number of accelerometers over a given frequency range. The aircraft response is measured by accelerometers ,recorded on sensitized paper or magnetic tape and the damping found from Kennedy–Pancu polar plots .Another excitation technique, known as "Bonking", uses impulse rockets placed in positions where they are able to excite a mode with reasonable purity .

In addition to the ground resonance test modern prototype aircraft are subjected to flight flutter tests . Initially the aircraft's speed is limited to a value lower than the limit speed and then gradually increased by safe increments , each increment being based on the previous flight flutter tests. The method most frequently employed is to apply a continuous sinusoidal excitation to the aircraft in flight .This type of excitation is capable of exciting all the modes so that their damping can then be measured. Types of sinusoidal exciter include rotary inertia exciters, linear inertia exciters, exciting a control surface by applying an electrical signal to the control unit and so on.

Other type of flutter involve control surfaces. Although control surface flutter is not usually catastrophic it can be unpleasant. However in most modern aircraft the control surfaces are operated by power units possessing sufficient stiffness to prevent flutter occurring. Previous remedies included mass balancing of the control surface to redistribute the inertia forces for similar reasons to those applicable to wing bending torsion flutter .Aileron Buzz is a form of flutter associated with shocks oscillating on the upper and lower wing surfaces and interacting with the boundary layer in an unsteady fashion .Empirical methods are used to predict and avoid this phenomenon .

Flutter on Engine Fins
Stall Flutter :-

The non–linear aerodynamic reaction to the motion of the airfoil structure and the one – degree of freedom property are very useful for analysis of the subsonic stall flutter behavior.

That means the analysis of bending stall flutter is completely independent from that of torsion. In this section, the governing equations for the two flutter types are presented.

Bending Stall Flutter

Two dimensional study for a typical section will be carried out. With the properties of subsonic stall flutter , if the W/T done by the force acting throughout the displacement is positive , then the amplitude will increase and stall flutter is to be expected Ref.[6] .

$$P=\frac{1}{2}\rho V^3 b\left[A\left(\frac{wh\delta}{V}\right)^2+B\left(\frac{wh\delta}{V}\right)^4+C\left(\frac{wh\delta}{V}\right)^6+\dots\right] \quad (1)$$

and with highly simplified case of $\alpha_{ss}=\varphi=0$, then ,

$$A=a_1=\left.\frac{dC_n}{d\alpha}\right|_{\alpha=0} \quad (2)$$

$$B=\frac{1}{2}\left.\frac{dC_n}{d\alpha}\right|_{\alpha=0}+\frac{1}{8}\left.\frac{d^3C_n}{d\alpha^3}\right|_{\alpha=0} \quad (3)$$

$$C=\frac{1}{12}\left.\frac{dC_n}{d\alpha}\right|_{\alpha=0}+\frac{1}{192}\left.\frac{d^5C_n}{d\alpha^5}\right|_{\alpha=0} \quad (4)$$

With $\cos\varphi\rightarrow 1(\varphi\geq 0)$, a positive power can only occur if a_1 is sufficiently negative ,i.e. if C_n Vs characteristic has a negative slope at the static operation incidence .In general, Case A ,B and C individually may be either positive , zero or negative. There are eight important cases as illustrated in table (1) .

The critical velocity of the bending stall flutter (V_{BSF}) can be evaluated from :

$$V_{SBF}\geq\frac{2\sigma\mu f_b}{\rho b\left[\frac{dC_L}{d\alpha}+C_D\right]} \quad (5)$$

Torsional Stall Flutter in General

For torsional vibration the dynamic angle of incidence depends on the following two effects:-

1. The instantaneous angular displacement "θ" .
2. The instantaneous linear velocity in a direction normal to the cord .

Both of these effects are function of time ,while only the second effect is a function of the cord position of point X ($X_{3/4}$).

As in bending stall flutter , the power which caused the stall flutter in torsion Ref.[7] is :-

$$P_1 \equiv \frac{1}{2}\rho V^3(4b)K\sin\varphi$$
$$\left[A_1\theta_o^2 + B_1\theta_o^4 + C_1\theta_o^6 + \ldots\right] \quad (6)$$

With $K = \dfrac{wb}{V}$ and ;

$$A_1 = -\frac{1}{2}\frac{dC_m}{d\alpha}\bigg|_{\alpha=0} \quad (7)$$

$$B_1 = -\frac{1}{16}\frac{d^3C_m}{d\alpha^3}\bigg|_{\alpha=0} \quad (8)$$

$$C_1 = -\frac{1}{384}\frac{d^5C_m}{d\alpha^5}\bigg|_{\alpha=0} \quad (9)$$

Similar to the bending case (if $\sin\varphi \neq 0$) the several conditions for torsion stall flutter will be summarized as in following table:

The critical velocity of the torsional stall flutter (V_{TSF}) can be evaluated from :

$$V_{TBF} \geq \frac{2I_\alpha \sigma_\alpha f_\alpha}{\rho b^3\left[\dfrac{dC_m}{d\alpha}\right]_{\alpha\to 0}} \quad (10)$$

As we have seen, the bending and torsion stall flutter depends on many parameters some of them are

$$\left(\frac{dC_L}{d\alpha}\right), C_D \quad and \quad \left(\frac{dC_m}{d\alpha}\right),$$

which can be computed from the quasi – static simplification experiment, that gives a simple way to determine the aerodynamic forces acting on the blade (typical section).

To check the theoretical results for stall flutter in blade cascade a typical axial compressor stage was chosen. It consists of 32 aluminum cantilever blades .

The value of C_m , C_L and C_D for the reference cross – section of such a blade (taken at 0.75) of blade length) where obtained experimentally using a geometrical model of three blades in a low speed wind tunnel .

Then the values of C_m , C_L and C_D at various values of the angle of attack (α^o) are experimental work which denotes the geometrical angle of attack . The two outer models blades were "dummy" simulating only the influence of cascade interference on the values of the normal force coefficient C_n were calculated using the relation :

$$C_N = -(C_L + C_D\tan\alpha)\sec\alpha \quad (11)$$

By numerical differentiation values of

$$\left(\frac{dC_n}{d\alpha}\right),\left(\frac{d^3C_n}{d\alpha^3}\right) \quad and \quad \left(\frac{d^5C_n}{d\alpha^5}\right)$$

are obtained, and values of

$$\left(\frac{dC_m}{d\alpha}\right),\left(\frac{d^3C_m}{d\alpha^3}\right) \quad and \quad \left(\frac{d^5C_m}{d\alpha^5}\right)$$

and the critical values of 1st bending and torsional stall flutter are evaluated by using equation 5 , 10 respectively all above values are in the results

Results and discussion

The essential feature of stall flutter is nonlinear aerodynamic reaction to the motion of the airfoil / structure. Thus although coupling and phase lag may be alter the results some what, the basic instability and its principal features are explicable in terms of nonlinear normal force and moment characteristic [8]. Stall flutter of blades is associated with various values of angle of attach, to obtain such characteristics and evaluated the stall flutter on blades the quasi – static simplification experiment was used. The geometrical model of three blades in a low speed wind tunnel were considered, to obtain the different values of C_m , C_L and C_D, in addition to it's derivatives, see table (1), (2) and (3). In general cases the coefficients individually may be either the positive, zero or negative, the behavior of stall flutter is variable through the different angle of attack which are shown in figures (2) , (3) and (4).

Figure (2) show the effect of angle attack on the stall flutter behavior which exhibit the critical flutter amplitude at angle of attack 30°, while the figure (3) show the critical flutter amplitude of occurs at angle of attack 35°. The figure (4) shows how the flutter amplitude changes with angle of attack 15°, 25° and 35°.

Conclusion

If the structural damping of the blade is increased , the critical velocity of bending stall flutter rises consequently . From this point of view the composites are promising for fan and axial compressor blades .On the other hand , their small specific mass leads to smaller values of V_{BSF} .

It is clear that subsonic stall flutter occurs usually at (0.6 ~ 0.8) of $(RPM)_{max}$ because in this region of revulsions the angle of attack may reach the critical values (above 20°) .Hence not the full value of $(RPM)_{max}$ is substituted into the calculations of bending frequency for rotating blade. The influence of the air density at the compressor inlet should be evaluated for actual flight conditions of the jet engine .The compressibility effects at high subsonic velocities may lead to substantially higher air density at the engine's inlet .It is found that the smaller the length of the blade's chord , the higher the critical velocity of bending stall flutter (V_{BSF}) which requires more deep analysis of the aerodynamic effects.

It was observed, that values of C_D, C_L and C_m on an individual blade standing in the cascade depend on the cascade arrangement (stepping angle between the blades, and distance between two individual blades). These relations need a more deep study in the future. The results of the dynamic cascade model (containing plastic blades) were used for checking of the actual deflection , caused by bending stall flutter at the typical references section positioned at (0.75) span of the blade and on measuring the angular deformation due to torsional stall flutter at the same typical section .This dynamic test gives more information which were not used due to the simplified theory used in this research, the results obtained in this research are valuable for practical use in design and development of heavily loaded military jet engines.

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1	$A_1 < 0$ $B_1 < 0$ $C_1 < 0$	No Flutter
2	$A_1 > 0$ $B_1 > 0$ $C_1 > 0$	Flutter with increasing amplitude in time .
3	$A_1 > 0$ $B_1 < 0$ $C_1 < 0$	Flutter amplitude grows smoothly from zero to finite amplitude Where $(\theta_{2o})_3 = \left(-\lvert B_1\rvert + \sqrt{B_1^2 + 4A_1\lvert C_1\rvert}\right)/2\lvert C_1\rvert$
4	$A_1 < 0$ $B_1 > 0$ $C_1 > 0$	No Flutter at small amplitudes if an external disturbance carries the system beyond a critical amplitude ; then the flutter will continue to grow up to very large amplitudes. Negative power is only above this critical value of amplitude the power is zero.
5	$A_1 > 0$ $B_1 > 0$ $C_1 < 0$	Soft flutter starts from zero amplitude up to equilibrium amplitude , Value of $(\theta_o^2)_5$ usually larger than $(\theta_o^2)_3$
6	$A_1 < 0$ $B_1 < 0$ $C_1 > 0$	Similar to case (4) but critical amplitude $(\theta_o^2)_6$ > $(\theta_o^2)_4$
7	$A_1 > 0$ $B_1 < 0$ $C_1 > 0$	Similar to case (2) if B_1 is very small and similar to case (4) if C_1 is very small . (very large amplitudes excluded)
8	$A_1 < 0$ $B_1 > 0$ $C_1 < 0$	Similar to case (1) if B_1 is very small and similar to case (4) if C_1 is very small .

Table (1) General Conditions of torsional stall flutter .

α°	C_N	$\frac{dC_N}{d\alpha}$	$\frac{d^3C_N}{d\alpha^3}$	$\frac{d^5C_N}{d\alpha^5}$
5	-1.279075	-6.4749	+30.913	+402.800
10	-1.844024	-5.79281	+58.239	-3323.400
15	-2.226139	-4.48086	+91.708	-9947.030
20	-2.626512	-2.83062	+52.865	-17698.40
25	-2.770009	-0.0014	-150.480	+12462.95
30	-2.625511	+1.6617	-440.390	+44527.80
35	-3.392558	-3.56406	-12.9720	+120.4000
40	-3.731571	-3.88494	+322.70	-11104.70

Table (2) Values of aerodynamic normal force coefficient and it's derivatives.

α°	C_m	$\frac{dC_m}{d\alpha}$	$\frac{d^3C_m}{d\alpha^3}$	$\frac{d^5C_m}{d\alpha^5}$
5	+0.2396	+3.77034	+101.9333	-1294.1216
10	+0.5686	+1.17120	+114.0081	-1999.0572
15	+0.6708	+0.12432	+106.3752	-2436.1880
20	+0.5778	-0.55470	+77.27190	-2674.0002
25	+0.5511	-0.28170	+36.61750	-1185.2641
30	+0.4638	+0.07290	-40.90700	+3538.6778
35	+0.5383	+0.95442	-69.24010	+4653.1703
40	+0.4907	-0.545420	-51.30750	+1672.1606

Table (3) Values of aerodynamic moment coefficient and it's derivatives.

α°	C_L	$\frac{dC_L}{d\alpha}$
5	1.2687	+6.2537
10	1.8142	+3.6225
15	2.1303	+1.8725
20	2.2937	-1.0405
25	2.2029	-4.3441
30	1.8238	-0.5301
35	2.1566	+3.8141
40	1.9274	-2.6272

Table (4) Values of aerodynamic lift coefficient and it's derivative.

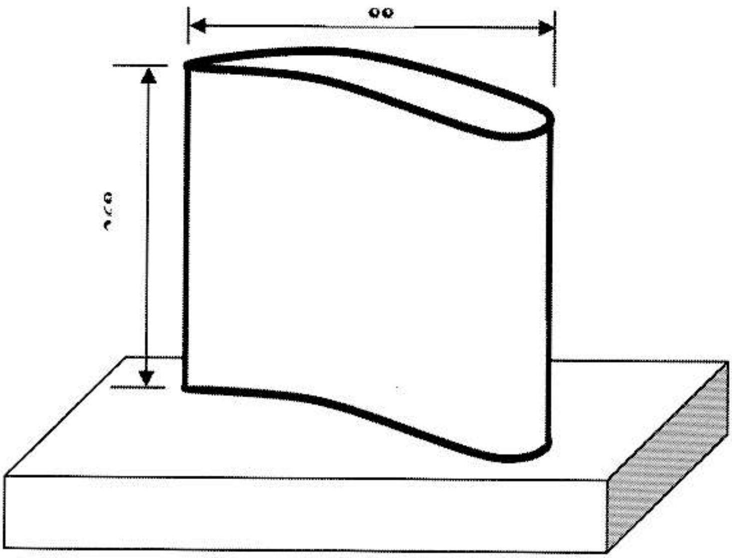

Fig . (1): Aluminum (actual blade)

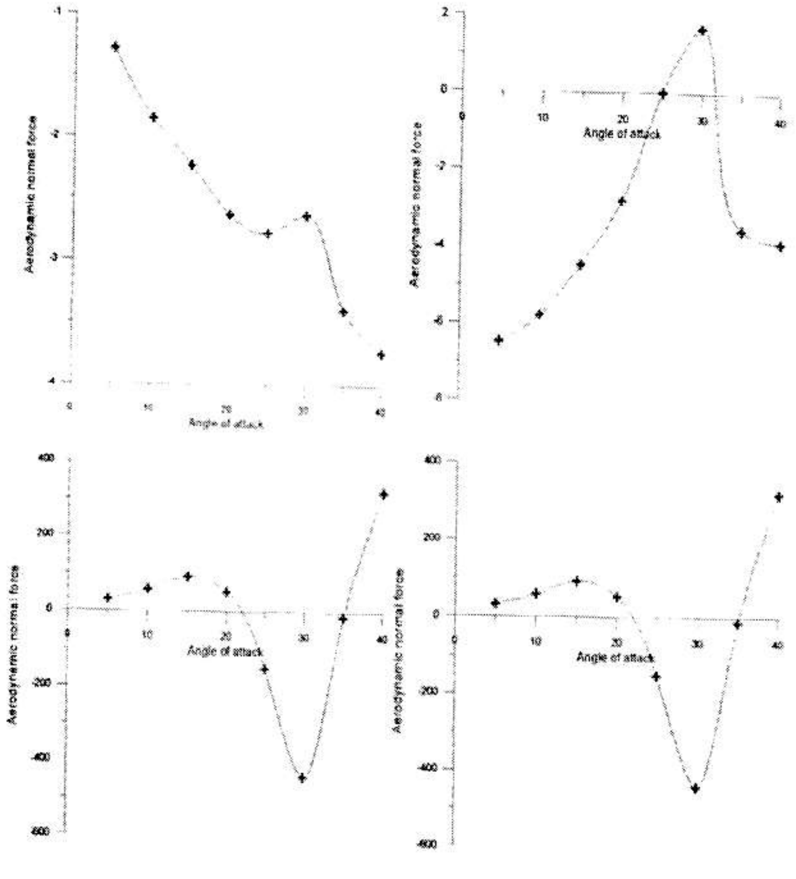

Fig.(2): Aerodynamic normal force and it's derivatives against angle of attack

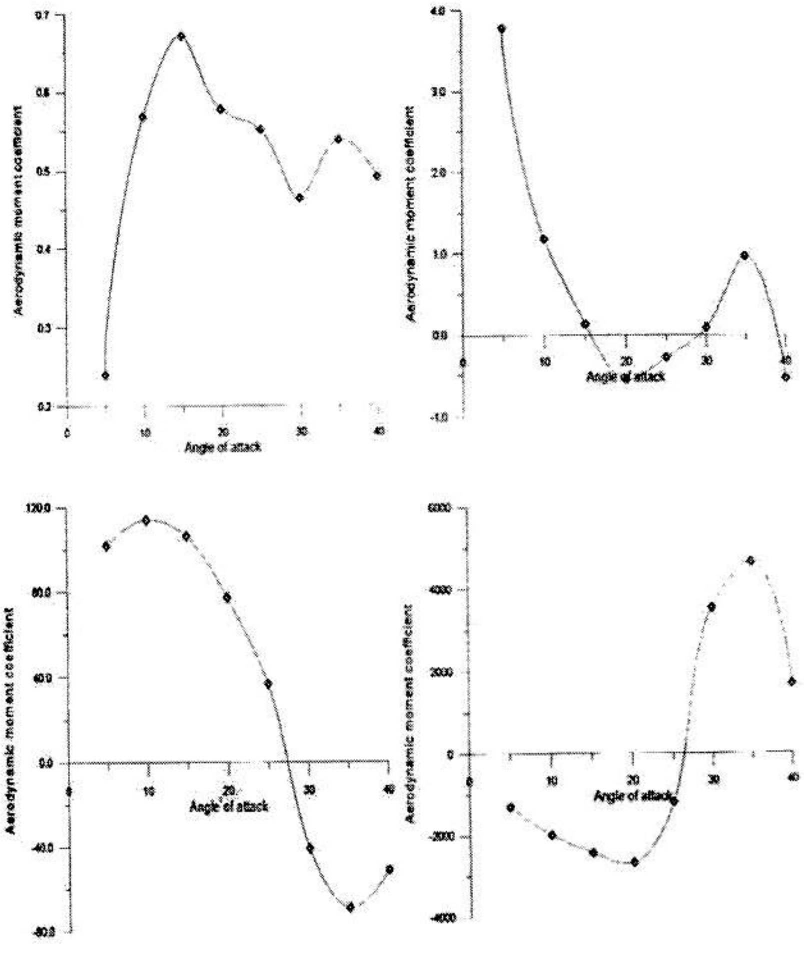

Fig.(3): Aerodynamic moment and it's derivatives against angle of attack

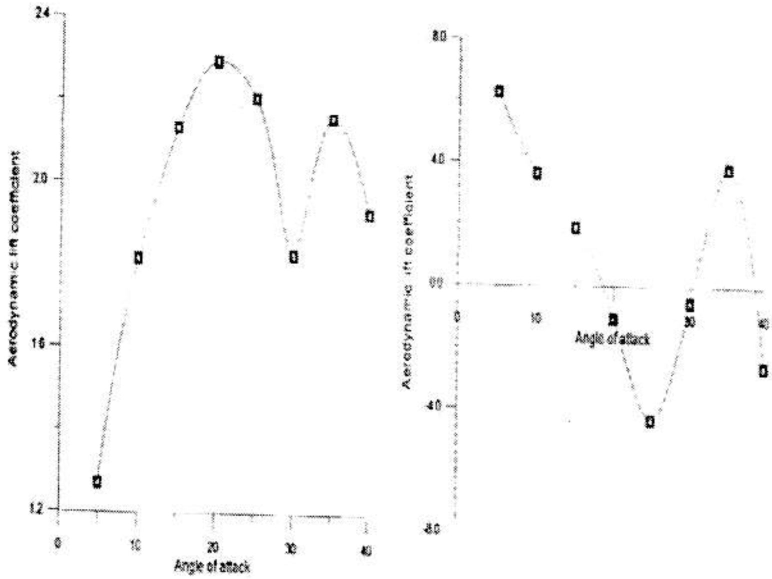

Fig.(4):Aerodynamic lift coefficient characteristic and it's derivative against angle of