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Review of aeroelasticity testing technology

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Abstract

Aeroelasticity is the study of the mutual interaction that takes place among the inertial, elastic and aerodynamic forces acting on the structural members exposed to an airstream and the influence of this study on the design. This review paper deals with the investigation of the aeroelasticity phenomena. The effect of the aeroelasticity phenomena occurring while designing the wing of the aircraft are stated in detail. Flutter suppression and its techniques are investigated in this paper. The aeroelastic testing techniques available in this field and the efficient methods to solve these problems are discussed. The aeroelastic optimization techniques processes are reported. The fluid and structure interaction of the non-linear flexible wing structure results have been discussed for the various methods. The application of the MSC software and finite element methods are discussed. The aeroelastic applications are also summarized

Keywords: Aeroelastic phenomenon;flutter suppression;aeroelastic optimization;aeroelastic testing techniques.

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1. Introduction

Airplane structures are not completely rigid, and aeroelastic phenomena arise when structural deformations induce changes on aerodynamic forces. Aeroelastic analysis is very important in aircraft design. To achieve desired minimum weight design of flight vehicles, the aeroelastic instabilities such as flutter and divergence of lifting surfaces must be taken into account before the initial flight tests. The additional aerodynamic forces cause an increase in the structural deformations, which leads to greater aerodynamic forces in a feedback process.

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These interactions may become smaller until a condition of equilibrium is reached, or may diverge catastrophically if resonance occurs. The aeroelastic system contains both structural and aerodynamic non-linearities. The flutter phenomenon of the aeroelasticity system is one of the most important issues especially in aircraft structures. Modern aircraft structures may be very flexible and this flexibility of the airframe makes aeroelastic analyses an important aspect of aircraft design and verification procedures. This field of study is summarized most clearly by the classical Collar aeroelastic triangle (Collar, 1978), seen in Figure 1, which shows how the major disciplines of stability and control, structural dynamics and static aeroelasticity each result from the interaction of two of the three types of force. Aeroelastic considerations influence the aircraft design process in a number of ways. Within the design flight envelope, it must be ensured that flutter and divergence cannot occur and that the aircraft is sufficiently controllable.

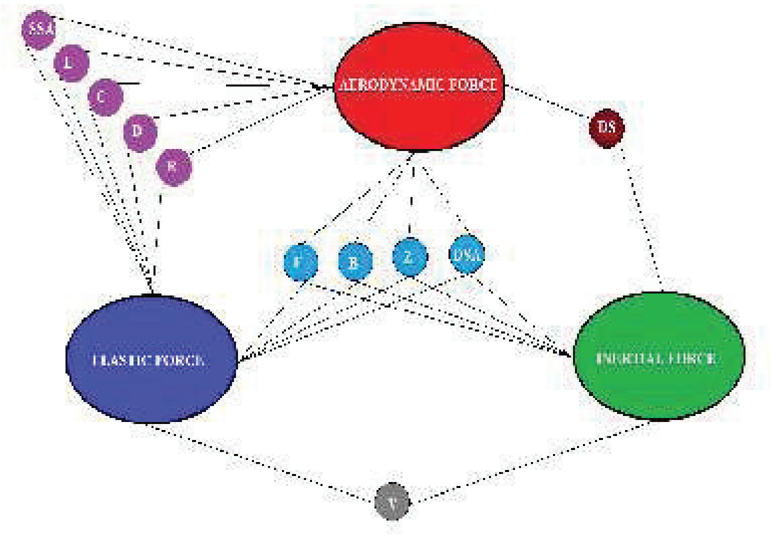


Fig:1 Aeroelastic collar triangle.

V – Mechanical vibration.
F – Flutter
Z- Dynamic response.
D – Divergence
R – Control System Reversal
SSA – Aeroelastic effects on static stability.
DS – Dynamic Stability.
B – Buffeting
L – Load Distribution
C – Control effectiveness.
DSA – Aeroelastic effects on dynamic stability

Aeroelastic phenomena are either static or dynamic. Static aeroelasticity concerned with non- oscillatory effect of aerodynamic force. Dynamic aeroelasticity is concerned with oscillatory effect of aeroelastic interaction. This instability involves two or more modes of vibration and arises from the unfavourable coupling of aerodynamic, inertial and elastic forces; it means that the structure can effectively extract energy from the air stream. The most difficult issue when seeking to predict the flutter phenomenon is that of the unsteady nature of the aerodynamic forces and moments generated when the aircraft oscillates, and the effect the motion has on the resulting forces, particularly in the transonic regime.

2. Aeroelastic phenomenon

Aeroelasticity is defined as the science which studies the mutual interaction between aerodynamic force, elastic force and inertial force. This phenomenon includes flutter, buffeting, dynamic response, load distribution, divergence, control effectiveness and reversal.

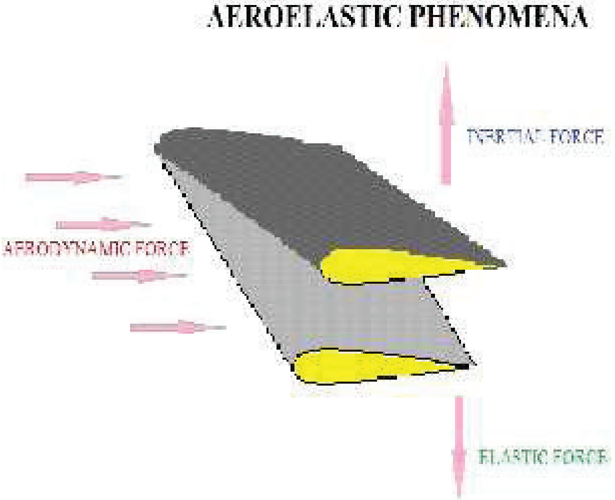


Fig2: Aeroelastic Phenomena

These effects will affect the performance of the aircraft. Although aeroelastic problems have occupied their current prominent position for a relatively short period, they have some influence on aircraft plane design since the beginning of powered flight. The load requirements placed on aircraft structures by design criteria specifications produced a structure sufficiently rigid to preclude most aeroelastic phenomena.

3. Effect of aeroelastic phenomena on design

The most important aeroelastic phenomena effects the airplane design are mass distribution, lifting surface platform and control system design. Aeroelastic phenomena are classified as static aeroelasticity and dynamic aeroelasticity. Static aeroelasticity studies the interaction between aerodynamic and elastic forces on an elastic structure. Static aeroelasticity includes divergence and control surface reversal. Dynamic aeroelasticity studies the interactions among aerodynamic, elastic, and inertial forces. Dynamic aeroelasticity includes flutter, dynamic response and buffeting.

3.1. Divergence

Divergence occurs when a lifting surface deflects under aerodynamic load so as to increase the applied load, or move the load so that the twisting effect on the structure is increased. The increased load deflects the structure further, which brings the structure to the limit loads and to failure.

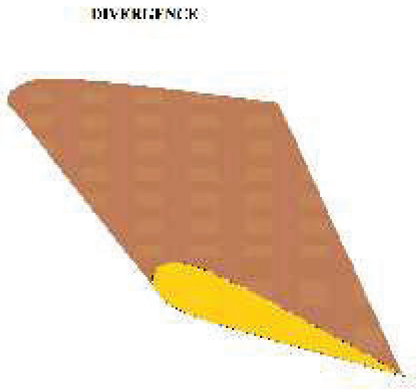


Fig3: Divergence

A static instability of a lifting surface of an aircraft in flight, at a speed called the divergence speed, where the elasticity of the lifting surface plays an important role in the instability. Torsional divergence is a common divergence problem occurring in the straight wing. Aileron plays an important role in the divergence effect.

3.2. Control effectiveness and reversal

A condition occurring in flight, at a speed called the control reversal speed, at which the effects of displacing of a given component of the control system are completely nullified by elastic deformation of a system. Control surface reversal is the loss (or reversal) of the expected response of a control surface, due to structural deformation of the main lifting surface. The aircrafts may suffer a serious loss of aileron, elevator and rudder control effectiveness because of the elastic deformation of the structure.

3.3. Flutter

A dynamic instability occurring in an aircraft during its flight called flutter speed, where the elasticity of the structure plays an essential part in the instability. Flutter is a self-feeding and potentially destructive vibration where aerodynamic forces on an object couple with a structure's natural mode of vibration to produce rapid periodic motion. Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamic forces.

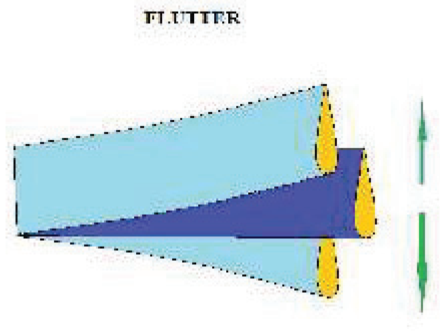


Fig 4: Flutter

That is, the vibrational movement of the object increases an aerodynamic load, which in turn drives the object to move further. If the energy input by the aerodynamic excitation in a cycle is larger than that dissipated by the damping in the system, the amplitude of vibration will increase, resulting in self-exciting oscillation. There are many kinds of flutter phenomena. They are classical and non-classical flutter. Classical flutter concerned with potential flow whereas non-classical flutter is more difficult to analyze in theoretical basis. Flutter may affect the control surface of the aircraft along the direction of aerodynamic, mass balance and degree irreversibility required in the actuating system.

3.4. Dynamic response

Transient response caused in aircraft structural components due to the rapidly applied loads like gust, landing, moving shock waves and other dynamic loads. Dynamic response or forced response is the response of an object to changes in a fluid flow such as aircraft to gusts and other external atmospheric disturbances. Forced response is a concern in axial compressor and gas turbine design, where one set of aerofoil's pass through the wakes of the aerofoil's upstream. Elasticity of the aircraft control surface plays an important role in the instability.

3.5. Buffeting

Due to the production of aerodynamic impulse by wake formation behind the wings, nacelles, fuselage pods, a transient vibration is formed in the aircraft component. Buffeting is high-frequency instability, caused by airflow separation or shock wave oscillations from one object striking another. It is caused by a sudden impulse of load increasing. It is a random forced vibration. Generally it affects the tail unit of the aircraft structure due to air flow downstream of the wing. By proper designing of a tail assembling and clean aerodynamic design buffeting can be eliminated.

4. Aeroelastic optimization of an aircraft wing

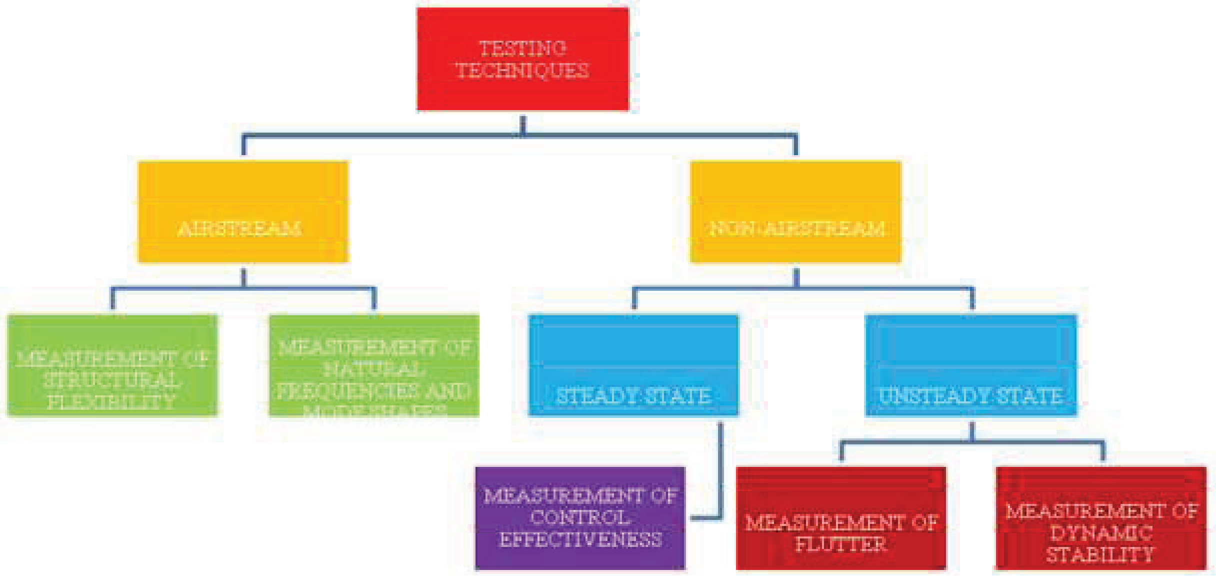
Optimization is something that is near but not close to the correct specification. Aeroelastic optimization is determining the approximate aeroelastic effect in aircraft structures. There are many techniques available in optimizing the aeroelastic effect.

Gradient-based deterministic method used by Shijun Guo for obtaining an optimal wing design and aeroelastic tailoring of an aerobatic aircraft wing structure [1]. Daniella is concerned with the structural design optimization. He has used computational fluid dynamics based aeroelastic analysis for load/stability estimates [2]. Marie and Kreindler have explained a longitudinal flight control of a forward swept wing through the combination of LQ optimization techniques [3].

5. Aeroelasticity testing techniques

In testing technique we describe the various kinds of techniques to test the aeroelasticity models. There are three testing techniques in the field of aeroelasticity. The first technique includes non-airstream testing and the second and third technique includes airstream testing.

In airstream testing it includes steady state like control effectiveness and unsteady state which consist of flutter and divergence. In non-airstream testing it helps in measuring static testing to find stiffness distribution and vibration testing to find natural frequencies and mode shapes.



5.1. Measurement of natural frequencies and mode shapes

The measurement of structural flexibility can be made in non-airstream testing. In measurement of natural frequencies and mode shapes is the test program for the prototype. Shake test is used to determine the normal modes of vibration. There are five types of testing. They are (a) single point excitation (b) multi point excitation (c) identification and measurements of normal modes (d) shakers and pickups (e) support of structures for vibration testing.

5.1.1. Response to single point excitation

In single point excitation, the size of the generalized force compared with the applied force depends on the point of application. It's maximum when applied at the point which has the largest amplitude and is zero when applied at nodal points. The measured response is differs because of the presence of some damping in the actual structure. It is called as structural damping. It exhibits the property that, the amount of damping is proportional to the amplitude of the motion. The same result could have been observed by moving the shaking force to the nodal points and not changing the point of observation.

5.1.2. Multipoint excitation

These responses were produced by exciting force on one wing. When two forces were employed symmetrically and the response in the anti symmetric mode will be zero and torsion remains constant. If we remember that our aircraft actually as a large number of normal modes. Many of the normal modes may be grouped into a small frequency range and separating the symmetric from the anti symmetric modes. Then adding another pair of symmetrically placed exciting pair which is driven synchronously with the first pair allows a point of a shifting of the point of application of the resultant applied forces by adjusting the ratio of the applied forces on the wing. The inertial loading at a point is proportional to the product of the oscillating amplitude at the point and the density at that point.

5.1.3. Identification and measurement of normal modes

In this we concern the scanning of the responses to judiciously applied shaking force of a structure whose vibration modes are measured. The various mode shapes are well separated and the structural damping is small only one shaking force is needed. The shaking frequency is varied slowly while the magnitude of the shaking force remains even approximately constant, a response-sensitive pickup will give a dramatic indication over the natural frequency. If two or more modes are grouped together in a small frequency range, the problem of determining their separate properties will be more difficult. This is particularly more common in structural damping is very high. It’s interesting to note that the operator usually finds it’s necessary to look at the vibrating structure itself while locating and measuring the mode.

5.1.4. Shakers and pickups

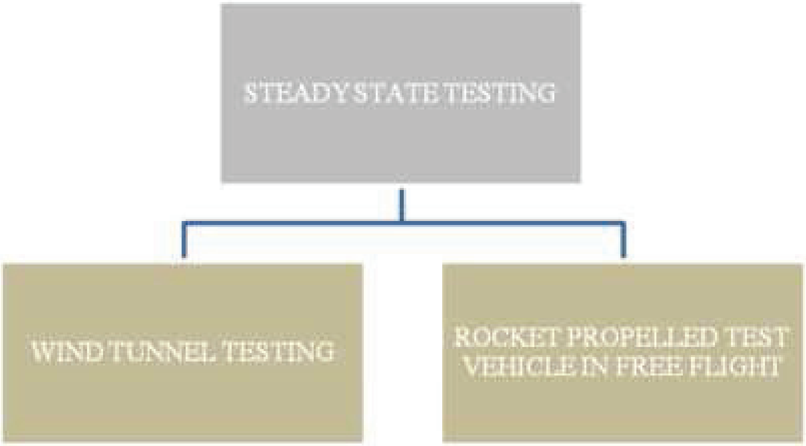
In this we consider the next requirement of the ideal shaking device and classify the existing types according to their capabilities. The fundamental requirement for shaking is that to apply desired forces at the structure without influencing the mass and stiffness properties to the structure. The shaking devices adds stiffness to the wing that is not part of the measured exciting force, it gives force increments. This criterion may be most restrictive at the low frequency modes. The requirements of ideal shakers it should be capable of synchronization with other shakers of the same variety. It operates on the fallowing principle they are electromagnetic shaking, air-jet shakers, reaction-jet shakers. The frequency range between 10 to 100 cps stroboscopic lighting devices can be used to slow down the vibration.

5.1.5. Support of structure for vibration testing

In this we deals with the supporting a structure during the vibration. The boundary condition should set correctly to the aircraft structure in free flight configuration. In this the weight of the structure must be supported without introducing the external constrainment which does not affect the vibration modes. Additional stiffness to the system is increased. The degree of freedom is increased by one number of natural frequencies. It is helpful to consider the essentially continuous structure of an aircraft or lumped parameter system. The accuracy of this representation is sufficient for all practical purpose.

5.2. Steady state testing

In this, the testing is considered in the presence of airstream. It includes the tests for surface load distribution, control effectiveness; roll rate, divergence and stability derivatives. These steady state testing can be done in two most common means by mounting the models in suitable wind tunnel or to use rocket propelled test vehicles in free flight.



Considering a low speed model in a wind tunnel the standard model support system found should be modified. In rocket vehicle for testing elastic model is particularly advantageous in the transonic regions.

5.3 Dynamic Aeroelastic testing – model scale

These tests are designed to investigate possible flutter conditions, evaluate dynamic stability and gust response and establish buffet boundaries. These tests are broadly classified into two types. The first type includes flutter and dynamic stability tests which are employed with stability characteristics and the second type includes gust response and buffeting tests which is concerned with strength of an airplane. The test includes (a) flight flutter testing (b) wind tunnel wall interference (c) simulating free flight in the wind tunnel (d) flutter models in wind tunnel (e) control and excitation in the wind tunnel (f) testing with rocket ant sled (g) measurements techniques and instrumentations. The disadvantage of rocket vehicle testing is generally difficulties of observations and measurement on a model speeding to the air over large distance. Measurement techniques and instrumentation is a best device for indicating the flutter mode shapes using cameras.

5.3.1. Coefficient evaluation in the wind tunnel

Most important techniques are based on the wind tunnel testing to move the air past model. It should give only acceptable boundaries to the airstream. It deals with the measurement of aerodynamic reaction on oscillating rigid surface and bodies. These bodies are either forced sinusoidal or distributed in order to observe the decaying oscillation. In low speed wind tunnel, the rigid models can be accomplished by rigid linkages connected to suitable mechanical drive system. It is very difficult to eliminate the effect on the measurement of the high acceleration to which the model and instrument or subjected. In high speed wind tunnel, the frequencies are very high in order to maintain reduced frequency in the face of large test velocities and smaller models. Thus the model is supposed to perform a pure pitching motion about its center of gravity the string flexibility can be adjusted so that a natural mode of string-model combination has a node at the model center of gravity and frequency at center of testing range.

5.3.2. Wind tunnel wall interference

The models which are kept in dynamic wind tunnel test must be of such a size as to keep interference effect of the wall to an acceptably small value. In supersonic wind tunnel model should be very small so that disturbance originating in the model are swept downstream of the modal. In subsonic wind tunnel the interference can never be zero. At very low reduced frequencies the interference can be predicted on a quasi steady basis using the ordinary steady correction factors. In the two dimensional case the model midway between the plane parallel walls, ratio of pitch is reduced. Increasing the tunnel height the interference effect of the wall but also lowers the resonant frequency.

5.3.3. Simulating free flight in the wind tunnel

The wind tunnel the test apparatus section must not exert any appreciable influence on the model which would not be present in the free flight. The model should be small enough to minimize the wall the wall effect. Low speed flutter model designers have grappled with the problem for many years and have been successful for two reasons. The first is the consideration of adequate support mechanisms was always severely limited and the second is provision of a force independence of a model motion over a distance of more than one inch. The combined requirements of large constant forces, large travel, and small moving mass have always forced severe compromises.

5.3.4. Flutter in the wind tunnel

In this testing many flutter test is not necessary to provide the complete simulation of free flight. This situation is likely to happen in the testing in low speed flutter model in which freedom of pitch and vertical translation is necessary to avoid serious modification in flutter characteristics. Here “rigid body stability” can be built into component models were needed. A slight positional stability can be achieved. The upward motion decrease the angle of attack and downward motion is increased. The Mach number then can be verified until the model flutters. It is desirable to find a supersonic flutter by varying stream rather than the model parameters as it is in subsonic testing.

5.3.5. Control and excitation in the wind tunnel

The control of flutter model during testing is quite difficult. It is particularly for the model with numerous rigid-body freedoms. The excitation of the model to measure degree of stability or to detect the nearest flutter. In large of the wind tunnel there is sufficient turbulence in the airstream to preclude the need for special excitation equipment. The prevent destruction of model during flutter a very careful control of airspeed is required. Thus a solenoid can quickly shift the position of a mass, or the precessional motion of a high speed fly-wheel can be suddenly and suitably restrained.

5.3.6. Testing with rocket and sled

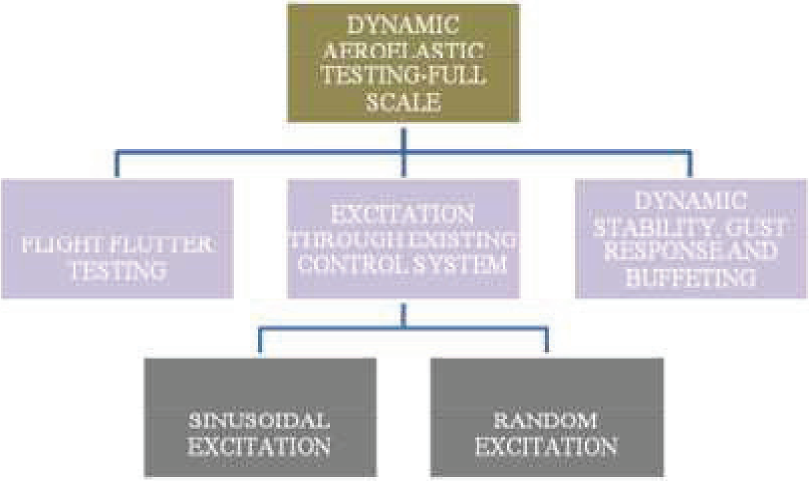
There are two means rather than a wind tunnel testing, first the mounting of aeroelasticity model of airplane model on free flight rocket vehicle have some advantage than wind tunnel testing. The testing of aeroelastic model on rocket propelled sled which skim along straight. Both the rocket and sled vehicle can adapted to either coefficient measurement or the investigation of aeroelasticity stability. These test techniques can be used with certain modification. The idea of testing a completely free aeroelastic model in a high speed unbounded airstream is quite intriguing.

5.3.7. Measurement techniques and instrumentation

To the aeronautical engineer, the most unusual feature of the measurement of the problem in dynamic aeroelastic testing is the large range frequencies which must be handled. The low speed models have frequencies of 2 to 3 cps and low aspect ratio supersonic model may range upto 200 cps. The fundamental tool in recording system is takes from multi channel recording oscillograph. It as desired galvanometer to cover desired range of frequency. The high performance multichannel tape recorder is an excellent device. Although accurate quantitative information may not be obtainable from the pictures. Synchronization of the camera and the oscillograph record by a timing signal is said to be proper data interpretation.

5.4 Dynamic aeroelastic testing – full scale

In dynamic aeroelastic testing is carried in full scale airplane. In this we investigate the flutter condition, dynamic stability, gust response and buffeting boundaries. It is classified into two categories. In first category it is concerned with stability characteristics and the second deals with airplane strength characteristics.



5.4.1. Flight flutter testing

In this we are considering a prototype airplane whose testing must be completed as quickly as possible. The flight flutter testing can be very dangerous even when approached with caution is borne out by the number of fatal accidents have occurred during such test. The test procedure as fallows as possible (1) the test must be carried without reducing too large of the element (2) the approach of critical flutter condition must be recognized by addition of subcritical airplane response (3) means of excitation should be used in subcritical response (4) the added mass of the test equipment should not be located as to the possibility of a dangerous flutter. The major disadvantage of these techniques is the, it is difficult to extract data from the recorded data.

5.4.2. Excitation through existing control system

This approach is adopted in instances where only a cursory investigation is needed to prove a chance of flutter. This can be assumed in variety of forms. It is seldom excite to a reasonable degree modes above 15 cps through existing specially modified control system. It is classified into three types. They are sinusoidal excitation, random excitation, and observation & interpretation. This excitation device consist basically of a rotating unbalanced wheel which impact a rotating force vector to the structure to which it is attached. The use of matched counter rotating unbalances produces a simple sinusoidal shaking force instead of a rotating force vector. In random excitation, the bane of all the techniques mentioned so far is the unavoidable presence of random hash on the record. In this case approach of the higher air speed curves to the origin indicates decreasing intensity. In some instances the use of logarithmic scales is advantageous.

5.4.3. Dynamic stability, gust response and buffeting

The basic difference between dynamic stability and flight flutter testing is reflected in the techniques which are employed. There are number of aeroelastic effects which may be of importance. In full scale investigation of gust responses are still in their infancy for several reasons. The close relationship between the gust response and buffeting and the importance of buffeting in the transonic range further motivates this development. Another strong influence aiding this development is being exerted by automatic control system designers who must optimize system performance in a rough as well as smooth air.

6. Flutter analysis

Flutter is an aeroelastic phenomenon which plays an important role in the aeroelastic models. Dynamic instability or flutter of the system is caused by increasing the free stream velocity causes the amplitude of the effect frequencies approaches zero and become positive. Computational Fluid Dynamics is used to predict the effect of the flutter. Moosari et al developed a procedure based on Galerkin method to predict the speed and frequency in which flutter occurs [4]. Mach number, frequency ratio of the plunging branch to pitching branch of the system has a great effect on flutter speed [5]. Zheng Yun done flutter analysis by a coupled fluid-structure method. He reported that his approach is based on the time domain solution of the fluid structure interaction [6]. Jin and Yuan performed flutter analysis of a turbine blade under a single vibration mode with a coupled fluid structure procedure [7]. Flutter analysis based on reduced order model [ROM] techniques and transonic flutter problems on an airfoil is explained by Weiwei Zhang [8]. An effective numerical simulation method, Line sampling technique is used to analyze the transonic flutter is done by Song Shufang et al [9]. Poirion used a first order perturbation method to calculate the probability of flutter for given uncertainty in structural properties [10].

7. Flutter Suppression Techniques

Flutter suppression is a technique used to control the flutter on the aircraft wing. The generalized predictive controller could successfully suppress the flutter for all testable mach numbers and dynamic pressure in the transonic region [11]. Flutter can be suppressed in the presence of different types of active feedback controllers. The controllers considered are designed using LQG, robustness optimization in the gap, loop shaping through weighted gap method, mixed sensitive minimization through H^{∞} design and robust performance optimization through μ synthesis [12]. Benchmark Active Control Technology (BACT) wing developed at NASA Langley research centre specifically to understand flutter and its suppression [13]. Ellen Applebaum has created a robust fuzzy gain scheduler for flutter suppression in unmanned aerial vehicle [14]. Piezo-ceramic Actuators are used to suppress active flutter in wing model which was explained by Lanjun Li et al [15]. The non-linear flutter suppression of a typical wing section is investigated. A Lyapunov-based controller was introduced for active flutter suppression in wing [16]. The application of adaptive flutter control was investigated when an aircraft is flying in turbulence. The adaptive flutter control is achieved using Adaptive Pole Assignment (APA) which complemented with LQG -based control is also investigated [17]. The robust adaptive switching control have non-linear dead zone characteristic. It allows a fast switching between all modes on different airspeed [18].

Hamilton Principle has been used in dynamic equation of piezo-electric composite plane is deduced. By the placement of optimal piezo electrical, better control can be obtained and flutter can be suppressed [19]. The aeroelastic force is applied on the wing is computed by double lattice method. The genetic algorithm optimization method gives the better suppression and control over vibrating bodies. By the phenomenon of limit cycle oscillation the aircraft reaches the maximum critical speed and non-linear flutter takes place [20]. The sliding mode control method is utilized with classical Range Kutta algorithm and the result estimates the system state fast [21]. The active flutter suppression is an attractive concern in aeroelastic field. By this non-linear stiffness the result obtained is effective.

8. Non-linear Aeroelasticity

Non-linear aeroelasticity is an interesting subject which deals with the interaction between flexible structure and surrounding fluid. The non-linear aeroelastic characteristic with both structural and aerodynamics non-linearities focus on the following points. (i) Geometric non linearity solution for a shell structure. (ii) Coupled algorithm fluid structure solver in time domain [22]. The improved procedure in correct LCO behavior and improved fluid/structure system will be the best tool to solve non-linear aeroelasticity. In non-linear aeroelasticity the fluid structure discritization minimize the problem desired in aeroelasticity. In non-linear aeroelasticity, the panel flutter problem, by 2D Euler equation and structure strip from Von-Karman plate is described. A predictor scheme desires from proposed descritization [23]. The height aspect ratio flexible wing that is of high altitude, long endurance wing is investigated by structural geometrical non-linearities and dynamic stall [24]. As the flight speed increases, the amplitude and complexity of LCO increases and dynamic stall also increases. The computational efficient, high fidelity, integrated static aeroelastic analysis procedure have been demonstrated [25]. To resolve the non-linear fluid, both the surface and volume must be discritized. The static aeroelastic response has been investigated for all flow in a wing. A loosely coupled algorithm is used in conducting non-linear static aeroelastic computations of a high aspect ratio flexible swept wing. The difference between the maximum deflection of a linear wing structure and non-linear wing structure increases substantially with the increase of aerodynamic loads is given detail in [26].

9. Recent improvements in aeroelasticity

Many improvements have done in the field of aeroelasticity in recent years. Applications of software like FLUENT and NASTRAN plays an important role for this improvements. T. J. Leger et al has proposed an aeroelastic stability property using a direct method. In this he reported, for NACA 64A006 flapped airfoil improved accuracy of the enhanced boundary conditions for zero and non-zero angle of attack results were shown. For a 1^0 static pre twist analysis at a free stream mach number of 0.84, the new boundary condition resulted in over a 75% decrease in the flutter speed error [27].
Recent progress in flapping wing aerodynamics and aeroelasticity is developed by Shyy et al. they reported that a 3-D low aspect ratio wing can produce higher lift than 2-D aerofoil but not supported by classical wing theory which suggests that Tip Vortices decrease performance [28].

10. Aerodynamic Application

Viscous effects are shown to generally result in larger values of flutter speed. Since transonic effects are alleviated by the boundary layer. Flutter predictions are made using TSP theory, linearized TSP, TSP with quasi-unsteady boundary layer and doublet lattice. Both frequency domain and time marching methods are used in these flutter predictions. Further aeroelastic applications has summarized in the reference [29]. The problem of discritizing a class of fluid/structure interface conditions and exchanging aerodynamic and elastodynamic data between a flow solver and a structural analyzer is reported by C. Farhat et al. he also reported the aeroelastic applications [30]. Fluid-structure interaction for aeroelastic applications was investigated by Ramji Kamakoti. He shown the computational methodology that couples a linear structure solver and a complex flow solver can exhibit capabilities to predict flutter characteristics in an accurate manner [31].

12. Conclusion

The topic aeroelasticity is an advanced topic in aerospace engineering. It plays an important role in designing any aircraft. This review paper gives an idea about the aeroelastic effects and its phenomena to the readers. This paper covers the techniques used for flutter suppression and about the non-linear aeroelasticity. It also reveals the aeroelastic optimization in designing. The application of aeroelasticity is discussed in this paper.

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