A Study on Aeroelastic Flutter Suppression and its Control Measures –Past and Future

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Abstract— In a cruising mission, an airplane wing is subject to intense dynamic pressure changes with different magnitudes. The variable pressures exerted on the wing geometry will cause the redundant vibrations by flutter effect. The unkind Aeroelastic instabilities have an influence on the airplane performance and its structural life to a large extend. To overcome the instabilities, (particularly flutter modes) an Active Flutter Suppression (AFS) technique has been proposed during the year of 2002. In this review article, the contributions of different researchers in the field of AFS over the years are investigated. Mathematical models for various control designs provided are capable enough to link the response of wing structures against the oncoming airflow. It includes the structural and fluid dynamic properties required to design an active control to capture the effects of flutter frequency. Mass balancing and stiffness enhancement with control systems are the different methods available to implement AFS. In the critical flutter speed, the non linear characters play a vital role in the view of complex systems design and accuracy. Consequently, with the aid mass balancing, the non linear effects such as Limit Cycle Oscillations (LCO), baggy control system linkages and Internal Resonance are eliminated or reduced. Therefore, for increased airplane performance and efficiency, AFS is a key approach in the field of unconventional aeroelasticity.

Keywords—Flutter suppression, active controllers, dynamic vibrations, Finite Element Methods (FEM), CFD.

I. INTRODUCTION

Aeroelastic analysis is an investigation of interplay among the aerodynamics and structural mechanics along with the inertial forces. Within that, the flutter phenomenon is a dynamic aeroelastic instability that results in catastrophic mechanical failure of an Aircraft wing. In addition to this, there is an interaction between the aerodynamics, structural dynamics and flight control system is called Aeroservoelasticity [1]. Present aeroelasticity is the combination of computational structural dynamics (CSD) and computational fluid dynamics (CFD) subjects. In particular, the coupling of CFD models of various forms with CSD models in a simulation of a fluid/structure interaction is the origin of computational aeroelasticity (CAE). CAE can manifest itself, in a high- amplitude limit cycles or unacceptable wing motions and will be the catastrophic destruction of a wing at some point in the flight [2]. AFS is anticipated to be more important, as the Aircraft design moves to lighter-weight materials in efforts to improve the fuel efficiency. Therefore, an aircraft is able to move rapidly and easily by enhancing its flutter speed. Moreover, during the certification process [3], Airplane flutter testing is a mandatory part that should be undertaken to demonstrate the Aircraft is a flutter free one in its entire flight envelope. So far, aeroelastic instabilities such as flutter have been treated just passively through proper wing structural design. However, for the high- performance [4] air vehicles of the future, suppression of aeroelastic instabilities will depend on the active controls. To accomplish this mission, the flutter phenomenon exist in the aeroelastic system must be well controlled against the issues resembling in airframe design.

An airfoil that is kept in the subsonic or supersonic airflow is an example for typical nonlinear system with both structural and aerodynamic nonlinearities [5]. The redundant oscillations (e.g., flutter) are induced because of the Coupling between the motions of a structure and the neighbouring flow. If the flexibility of a structure is to be incorporated as a design, then it is likely to require the AFS system to remove the aeroelastic instabilities [6]. The coupling is described by the normal force component to the airfoil velocity vector representing motions of the structure (which provides boundary conditions for the normal component to the flow velocity on the airfoil) and the resulting aerodynamic loads (forcing functions for the ordinary differential equations). Typically, the flutter boundary for the wing is conservatively defined below the Airplane speed [7], and limited altitudes. An obligatory thing to design an active control is to have a good model which captures the salient characteristics of the aeroelastic phenomena along with manageable control design [8]. In the present technology, flutter prevention is done by using passive control methods (i.e.,) impart enough stiffness to the main wings or dynamic mass balancing. These two methods are not attractive, because of the weight penalty imposed on the structures as it is implemented. Theoretical and experimental investigations of aeroelastic systems have been revealed that nonlinear effects must be taken into account for the more accurate analysis. It is even more complicated to design the control system, if the aeroelastic systems that possess higher structural flexibility, complex control systems, and large flight envelopes [9], [10]. Typical phenomena resulting from the existence of nonlinearities include internal resonance, limit cycle oscillations (LCOs) and even chaotic vibrations. Structural nonlinearities are caused by the irregular material properties, control linkages and/or substantial structural deflections.

Frequencies associated with the flutter phenomenon are generally high about the bandwidth of typical flight control systems. The high frequency, coupled to the fact that catastrophic structural damage be able to occur within a few uncontrolled cycles of flutter. It is an important issue in the design of an adaptive system. The uncertainty exists in the model is amplified with increasing frequency [11]. This is true with respect to the phase relationships involving inputs and outputs. Adaptive Control Schemes (ACS) is effective for flutter suppression. The few problems are addressed by different experts against ACS as follows:

(a). For a modern high- performance Aircraft, the constraints of an aeroelastic system fluctuates quickly within the flight envelope. Hence, it is a hard-hitting task to achieve ideal performance by one adaptive controller that is designed by classical ACS [12]. Further, it needs the parameters to be changing gradually for current Aircraft, which is barely met.

(b). It is quite intricate to design various adaptive controllers for flutter suppression, at different air speeds within the given flight envelope. Furthermore, the global stability in the system must be assured within the flight boundary [13].

The difficulties to implement ACS for an airplane have been analyzed by the researchers over many years. The results that are ended with successful conclusions are completely reviewed subsequently. Flutter suppression anticipates that a designed feedback stabilize an unstable aeroelastic system with nonlinear torsion and bending stiffness around nominal zero- pitch and plunge balance [3]. It has the ability to set back the commencement of limit cycle oscillations (LCO) [14]. As a dynamic instability, the flutter corresponds to the complex aeroservoelastic system, and its aerodynamic characteristics vary apparently in the different airspeeds within the flight envelope. It confines the flight envelope and causes large oscillations that result in failure of the wing structure by fatigue [15].

However, when the flight speed fluctuates rapidly, (i.e.,) the aeroelastic parameters change quickly, the stability and the performance of the closed-loop system cannot be guaranteed [16]. As the flight speed reaches the critical flutter speed, the vibration amplitude and dynamic stress acting on the Aircraft structures will increase rapidly. It is often capable enough to destroy the Aircraft structural components immediately by producing catastrophic frequencies [17]. Therefore, it is necessary to suppress the flutter in a time as short as possible by increasing the flutter speed without weight penalties. Thus, it is imperative that the event of flutter phenomenon on wings must be suppressed, to avoid the failure of structural components through large deformation/deflection.

II. DEVELOPMENTS IN AEROELASTICITY – A REVIEW

The knowledge of aeroelasticity became more widespread, as the aircraft speeds are improved and the Aircraft structures are made stiffer to avoid the aeroelastic interaction problems. The basic approach to analyse and control the aeroelastic effects became centred on four general areas:

- Development of analytic and numerical studies for flutter and dynamic vibrations.
- Experimental prototype testing using Wind- Tunnels (Low and High speeds).
- Ground vibration tests to check the natural frequencies and stiffness properties of the actual Aircraft.
- Optimized techniques to do the flight testing of actual Aircraft.

In the beginning of 1950’s, aeroelasticity was recognized as an important phase of the Aircraft design process. An excellent historical review of developments in aeroelasticity up to this period was found by Garrick and Reed [18]. A seminal article that marked the emergence of the field was given by Collar [12] in 1946. Further Collar was delivered a notable review, emphasizing the British efforts in aeroelasticity up to this period [19]. At that time, most dynamic data were taken with oscillographs, which had to be subsequently read, and the timing speeds should be adjusted carefully to record the frequencies of interest. Furthermore, one could statistically analyse the data in real -time, while the experiment was proceeding.

In the middle of 1950’s, the effect of aerodynamic heating on an airplane structure was addressed by Bisplinghoff at high-speed flight [26]. It was further explored and found that could be treated by allowing the loss of stiffness in the structure because of the thermal stresses and reduced material properties. Careful consideration of transient and steady- state temperature distributions are essential for arbitrary structural configurations by finite element modelling (FEM) [27]. Additional insights into the mechanism of flutter were appeared in the late 1950s. The investigations of simple bending– torsion flutter criterion of a typical section confirm that flutter could occur even in the absence of damping forces because of the coalescence of bending and torsion frequencies [28],[29].

The flutter of aircraft skin panels at supersonic speeds became an attractive topic of study in the early 1960’s [30], [31]. Although it is not a critical problem during cruise, it was allowed remarkable investigations into structural nonlinearity, limit cycles, chaotic motion, and anisotropic plate effects [32], [33].

By the early 1970’s, the entire Aircraft was represented aero elastically by a finite element structural model together with a set of aerodynamic panel surfaces. Such a kind of discrete model could be conveniently analyzed for static aeroelastic responses and its behaviour [34]. For dynamic response and flutter, the model should be reduced to a much smaller number of significant vibrations modes of interest [35], [36].

By the middle of 1970’s, the analysis of aeroelastic problems with control systems had reached a refined state. To assist with control systems in the time domain, Aircraft flutter analysis was often reformulated from the frequency domain to the more flexible time domain [37]. This conversion helps to get harmonically oscillating aerodynamic forces easily [38] for the time domain. Also, it leads to reach convenient transient response and root locus stability interpretations of flutter phenomenon [39], [40].

In the late 1970’s, the composite structures made of graphite- epoxy materials was considered because of their light weight, high stiffness and strength characteristics. One could also obtain bending–torsion and extension– torsion couplings by designing the ply lay-ups effectively. Further, it was proposed that favourable bending–torsion structural coupling in the wings could offset the statically unstable aeroelastic behaviour for the swept forward wings [41]. This proposal is prompted much exploration of the static divergence and flutter behaviour of these composite tailored wings. Later, applications of composite materials are focused on the wing designs to achieve certain optimum shapes during the flight regimes [42].

TABLE I
Active Flutter Suppression- Yearly Improvements

Year	Research growth towards AFS problem
1950	• General introduction of digital computers • Prediction of the effects of aerodynamic heating • Supplementary insights into the flutter mechanism • Flutter of structural skin panels
1960	• FEM for airplane structures • Propeller whirl flutter • Surface panel methods for air forces
1970	• Complete Aircraft representation by structural elements and aerodynamic panels • CFD • State- space illustration of control systems • Structural nonlinearities (stiffening springs, dead zones, etc.)
1980	• Digital data gathering techniques • Introduction of composites and aeroelastic tailoring • Flutter of compressor fan blades • Piezoelectric actuators and dynamic control techniques
1990	Nonlinearities and LCO’s (large geometric deflections, stall flutter, transonic flows)
2000	• Rapid developments in CSD simulations • Assessment of fatigue life of structures due to Aeroelastic oscillations
2010	Optimized Aircraft structures to overcome low speed flutter characteristics by Composite materials.
2012	Investigation of composite materials behaviour using advanced computational tools against the AFS associated problems

By the time of sixth decade of flight, it appears that aeroelasticity had reasonably matured. The analytical methods are usually centred on two, three, or four degree-of-freedom (DoF) flutter analysis focused on a separate wing or tail components. The methods have been generally organized into efficient matrix formulations and the computations are done by a group on mechanical desk computers. Then, CFD was emerged as a practical technique for numerically solving the partial differential equations (PDE) of fluid flow in the compressible flow regimes [20], [21]. It has proven ability to formulate the entire flutter programs and mechanized for optimization [22], [23]. In this period, the control system characteristics are formulated and incorporated conveniently into the Aircraft's flutter programs [24], [25]. The use of active structural elements such as piezoelectric materials began to appear in the middle of 1980's [44]. The concept of warping of a wing cross section to minimize its gust response and extend the flutter boundary was revealed in several wind-tunnel tests on small and medium-sized models [45].

Nonlinearities are common in much aeroelastic behaviour, particularly when steady oscillations are observed. Linear theory is useful in predicting the stability boundary and the growth of oscillations, but it does not predict the final amplitude in cases where the flutter is mild. Also, nonlinearities can play a precarious role among the disturbances of enough magnitude can excite the flutter condition. Some early examples of nonlinear effects on flutter were examined in the frequency domain using describing functions to model the effects of free play or Coulomb friction in a control system [15],[46]. Later investigations included the effects of large static wing deflections [47], [48], aerodynamic stall effects on flutter [49], and the earlier mentioned transonic flow regime [6]. With the increase of computing power, many of these nonlinear effects could be examined in the time domain, rather than in the frequency domain as formerly used. The Table I present the development of flutter suppression and the causes over the years. It represents the rapid development in AFS achieved in the twenty first century by the efficient computational methods. In particular, after the invention of robust optimal controllers, flutter suppression was achieved earlier through the normal acceleration than the conventional methods.

III. AEROELASTIC FLUTTER SUPPRESSION - MULTI DIMENSIONAL APPROACH

Flutter phenomenon and its effects have been studied by the airplane designers for the past 50-60 years. The solutions, offered by the researchers to overcome the consequences of flutter are insufficient. It is well known that, the sensor signals have contributions from all the excitation modes, and the control surfaces influence those modes of vibration. AFS systems must stabilize the flutter mode without destabilizing others. Thus, the determination of appropriate combinations of sensor signals and dynamic compensators is a major issue in the design of flutter restraint systems [18].

Few noteworthy efforts were made by the NASA to identify the AFS in a realistic approach. The Benchmark Active Controls Technology (BACT) wing was developed at NASA Langley Research Centre specifically to better understand the flutter phenomenon and its suppression [50]. In this method, the vibration frequency of an airfoil section changes significantly as a function of Mach number and dynamic pressure. It is modelled as a linear system, whose parameters depend on a linear fractional manner adjacent to the dynamic pressure and Mach number. The design of active control strategies for flutter suppression in an aeroelastic system, consisting of a 2-D airfoil section dynamically coupled to the surrounding flow [21], [51]. Modern airplanes incorporate flexibility in their structural design to boost its performance, efficiency, or decrease its weight and cost. Hence, the AFS problem has received much attention, in the form of the Active Flexible Wing (AFW) program. This program is also capable to emphasize, the need of AFS system to eliminate aeroelastic instabilities of a flight vehicle [52].

During a Robust Adaptive Switching Control (RASC) scheme, fast switching between the models and their equivalent controllers are endorsed to wrap the aeroservoelastic system dynamics inside the flight envelope [22]. The aeroservoelastic system dynamics is modelled as a switched system shown in Fig.1. A RASC scheme is projected for flutter suppression that improves the performance and allows system parameters to vary fast [23].

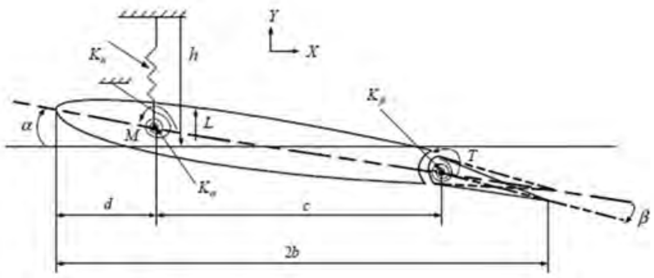

Fig 1. The 2-D wing- flap section of a typical airfoil

CFD based aeroelasticity is an emerging technology that helps to build up the design of active controllers for complex airframe and wing configurations [20]. Now, the aeroelastic model is attained for the flexible mode shapes using CFD-based input-output data for the identification of aerodynamic forces. This approach is applicable to any complex airframe or wing geometry. Recently, the prediction of flutter mode shape has been done using the Kalman filter, and this estimate is observable from wing-tip mounted accelerometers [16]. Later, Adaptive flutter control is achieved using an Adaptive Pole Assignment (APA) scheme which complements the LQG (Linear Quadratic Gaussian) -based control [53].

IV. CONTROL SYSTEM APPROACH - INPUTS AND OUTPUTS

Control theory deals with the influencing behaviour of dynamical systems in an inter-disciplinary engineering science and mathematics. Control systems are having four essential functions such as; Measuring, Comparing, Computing, and Correcting. Five elements are used to complete these four functions: Detecting element, Transducer, Transmitting element, controller and Final Controlling Element. It is well known that the first two elements are crucial in the process of AFS because of the uncertainty in the frequency measurements. Aircrafts are different from locomotives and automobiles because it has six DoF: Three associated with angular motion about the aircraft's centre of gravity and three associated with the translation about the centre of gravity [54]. Because of this greater freedom of motion, aircraft control problems are usually more complicated than those of other vehicles. Those qualities of an aircraft which tend to make it resist any changes in its velocity vector [55]. The ease with that the velocity vector can be changed is get along to the aircraft's quality of control.

The controls are used for steering and every aircraft contains motion sensors that provide measures of changes in motion variables. The changes in velocity vector occur, as the aircraft responds to the pilot's commands or as it encounters some external disturbance [56]. The signals from these sensors are used to provide enough information to the pilot with a visual display. Sensor signals act as feedback signals for the Automatic Flight Control System (AFCS). The commanded motion is match up to the measured motion using the controller. If any discrepancy exists, it is employed to generate command signals to actuator, in accordance with the required control law. The control surface deflections are produced about the command signals which result in the exact force or moment being applied [6]. Thus, the aircraft to respond appropriately in turn the measured and commanded motions are finally in correspondence. The foremost approximations made to develop an estimation of control algorithm for the real time operation are [18],

- Constant filter gains should be used and second order derivatives of the residuals are neglected.
- Iterative optimization steps using a single segment of data are replaced by a succession of single optimization steps on overlapping data segments.
- Optimization about the six components of the vector ‘p’ is approximated by successive optimizations regarding four parameter subsets.

The selection of sensors combination and filtering of their output to provide a feedback signal is a key factor in AFS. The flutter mode rate is an ideal feedback signal for flutter suppression. The signal data are processed to detect the onset of flutter and discriminate between the possible flutter phenomena associated with different store configurations [57]. If flutter is detected and discrimination is successful, active control is engaged using the appropriate feedback signal. The detector also provides initial estimates of the flutter mode parameters.

V. SIMILARITY OF MATHEMATICAL MODELS USED FOR THE FLUTTER PREDICTION

The different methods adopted for AFS must be compared to identify their consistency. Three most popular techniques used for the flutter suppression and their implementation is reviewed.

A. Least Squares procedure

Among the various mathematical and numerical techniques proposed for AFS, Least Squares (LS) procedure is simple and consistent one. To construct a signal that approximates the ideal feedback signal, a LS procedure was used [56]. In this procedure, Eq. (1) shows proportional gains, a_i, and integral gains, b_i, are selected to minimize the error function.

$$E(a_{i,} b_i) = \sum_k [d(s_k) - \sum_i (a_i + b_i / s_k) h_i(s_k)]^2 \tag{1}$$

In the LS procedure, four accelerometer signals are combined and filtered for each store configurations in the algorithm. Segments of the resulting data are stored to use in the detection, estimation, and control command sections of the algorithm. For each of the flutter outputs and the corresponding filtered input, estimates of the coefficients, p_i, i = 1,2,3,4, in the finite difference equation are obtained by LS using a data segment of N-S (Navier -Stokes) samples. The N-S simulation code is widely used to predict the flutter modes until today for various simulation techniques [71]. The damping ratio and frequency corresponding to the parameter vector are computed using the following Eq. (2), (3), and (4),

$$y_{k+1} + p_2 y_k + p_2 y_{k-1} = p_3 u_k + p_4 u_{k-1} \tag{2}$$

$$p_1 = \exp(-2\xi\omega\Delta T) \tag{3}$$

$$p_2 = -2\sqrt{p_1}\cos(\omega\Delta T\sqrt{1-\xi^2}) \tag{4}$$

Where, ΔT is the sampling interval. The major limitation in this technique is the position of accelerometer on the airplane wings. It requires the wide range of measurements because of its flexibility nature but the range of accelerometers is limited.

B. Generalized Predictive Control

The GPC system for the Benchmark Active Controls Technology (BACT) plant consists of four components: the BACT plant - to specify the desired performance reference signal used as a replica of the plant; the Cost Function Minimization (CFM) algorithm - to verify the control surface position, command - which is essential to create the required performance [58]. The CFM and BACT model blocks are the main components of GPC algorithm. The GPC system was used in a regulator mode for the BACT plant, where zero is meant for reference signal. The output of the CFM algorithm is also applied as an input to the BACT model. The double-pole and double- throw switch is positioned to the BACT model, when the CFM procedure has resolved for the preeminent input that minimizes a specified cost function [1]. CFM algorithm is employed to calculate the next control input from the predictions of response from the model. Once for minimized cost function, this control input is conceded to the BACT model as a control surface location command. The GPC algorithm is observed in a few simple steps, (i.e.,)

- Start with the formerly computed control input and envisage the performance of the BACT plant for the specified number of time steps.
- Calculate a novel control input that diminishes the cost function.
- Repeat the first two steps until the needed minimization is attained.
- Forward the original predicted control input, to the BACT model.
- Replicate the whole process for every time step.

The function used for the BACT model is given by Eq. (5),

$$J=\sum_{j=N_1}^{N_2}[yn(n+j)]^2+\sum_{j=i}^{N_u}\lambda_u[\Delta u(n+j)]^2+\sum_{j=1}^{N_u}\left[\frac{S}{u(n+j)-lower}+\frac{S}{upper-u(n+j)}-\frac{4S}{upper-lower}\right]\rightarrow \quad (5)$$

There are four tuning parameters available in the cost function, (i.e.,) N_1, N_2, N_u, and λ_u. The plant's output is predicted from N_1 and N_2 upcoming time steps. The jump on the control prospect is N_u. The limit on the values of N_u and N_1 is that it must be below or equal to N_2. The subsequent summation includes a weighing factor, λ_u that is launched to control the balance between the first and second summation. The third summation in 'j' defines that constraints are placed on the control input. The prime benefit of this GPC is that the input best meets the constraints produced when the cost function is diminished. This control input normalizes the quantified acceleration to the specified range.

The GPC simulation portrayed in the BACT Plant Analysis section was applied to find out the perceptible ranges for the control parameters prior to the wind- tunnel test [12]. The reduced order model and the mathematical model were developed for a Mach number about 0.77, Dynamic pressure of 732.21 kg / m^2, (i.e.,), a flight situation that is below the flutter boundary. The nominal values of control parameter for the open loop and closed loop responses vary in the magnitude about 10 db. Then it has a good agreement as the frequency value exceeds 10 Hz and coincides over the frequency range of 100 Hz in the GPC simulation given as Fig. 2. It also clarifies that the BACT wing model is used to collect high quality unsteady aerodynamic data close to transonic flutter conditions. Design of active control systems along with Flaps and spoilers combination creates adverse nonlinear trim of free-flying aircraft.

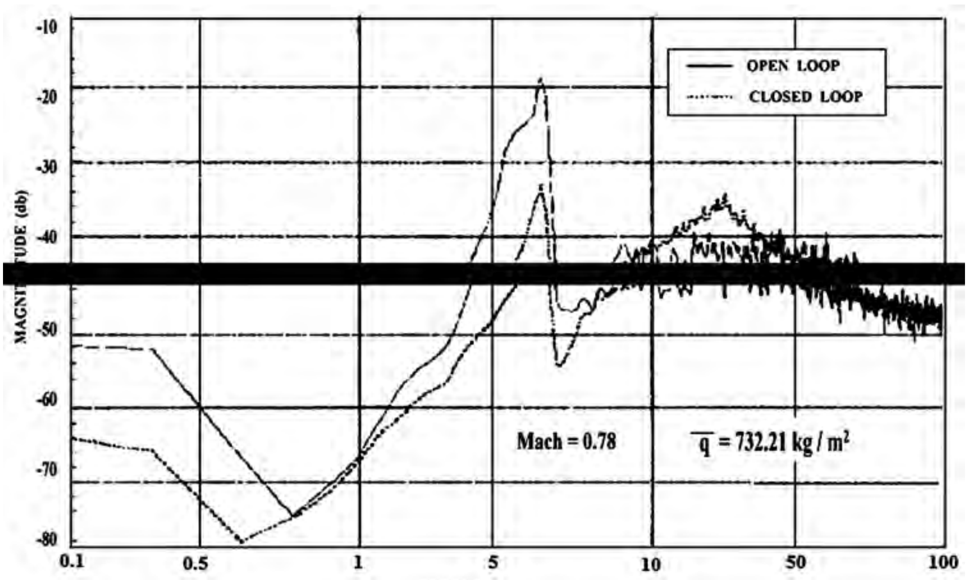

Fig 2. Comparisons of the open loop and closed- loop responses

VI. EXPERIMENTAL METHOD FOR VALIDATING THE CONTROL EFFECTIVENESS

Wind tunnel tests are usually conducted to verify the control law effectiveness. Test setup for flutter control by PZT (Piezo Ceramic Element) is a popular method in the recent years [59]. The displacement of wing tip is measured by CCD (Control Captured Displacement) laser displacement sensor. A sampling frequency is 1 kHz. The signal output from DA converter board is amplified 24 times with power amplifier, and is imposed on PZT actuator. Maximum output voltage is 240V. The control law is designed by LQG method. When LQG controller is applied [63], flutter suppression is achieved considerably. Arbitrary motions of the wing and the control surface are formulated by a linear combination of mode shapes multiplied by a generalized displacement. The aerodynamic force applied on a surface around a structural node is obtained by creating a CFD mesh around the wing.

A. *State feedback Sliding Mode Control (SMC) system*

The closed- loop system incorporated with the state feedback SMC system is good to measure the flutter frequency. It is particularly suitable when the system is having several DoF. Three conditions need to be considered to achieve a satisfied design [60].

- Existence: The sliding mode motion should exist.
- Reach ability: The states should be enforced to move toward the sliding surfaces and reach the surfaces in finite time, starting from arbitrary initial positions in phase space.
- Stability: The sliding mode motion should be stable. All the system states should decay to zero.

The motion of the airfoil is described by the three positions: the plunge displacement h, the pitch angle α and the aileron deflection β, where h is along the y axis, measured positive downward. Here, 'α' is the pitch angle, measured from the horizontal at the elastic axis of the airfoil, positive upward; 'β' is the aileron deflection rotating about the flap hinge point, measured as positive down (Fig.1). The coefficients K_α, K_β and K_h are the pitch stiffness, torsional stiffness, and the plunge stiffness respectively, 2b is the airfoil chord length. Plenty of mathematical models were proposed by different experts for the representation of flutter suppression control systems. Nevertheless, few methods are practical to achieve significant amount of flutter suppression as it is implemented. It is also observed that for the effectiveness of a control system against AFS the following methods must be adopted:

- Designing a multiple-input multiple-output (MIMO) control law for the active aeroelastic system
- Flutter velocity increases up to 15% by assigning the poles against the suitable wind speed.

B. *Response of LQG and LQR controllers against the Flutter mode*

Flutter mode frequency and displacement measurement are essential to do the airplane design against it. The pitch and plunge displacements over time is measured for the corresponding frequency values. Then, the suitable controller should be incorporated to do the AFS to the maximum extend. For the nominal plant, an LQG controller stabilizes the flutter with a phase margin of around 70° and a gain margin of 14 db. But phase uncertainty is a major problem near the flutter frequency [12], [19]. Therefore, the adaptive controller should stabilize the aircraft even in the presence of a phase error larger than 70° in the flutter mode.

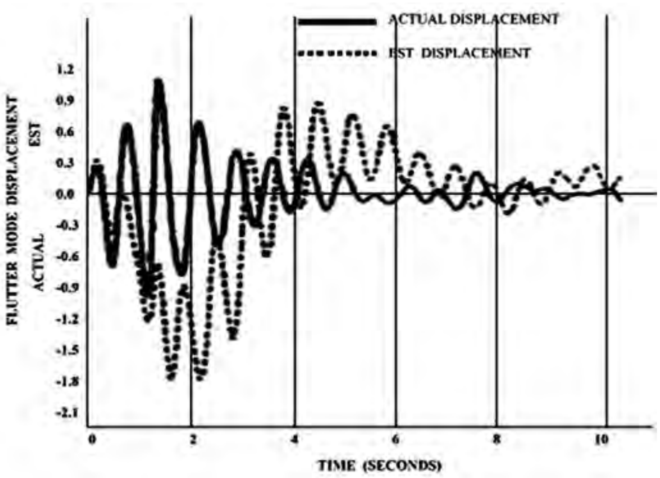

Fig 3. Response for the LQG- APA controller without Turbulence (3 m / sec) [12]

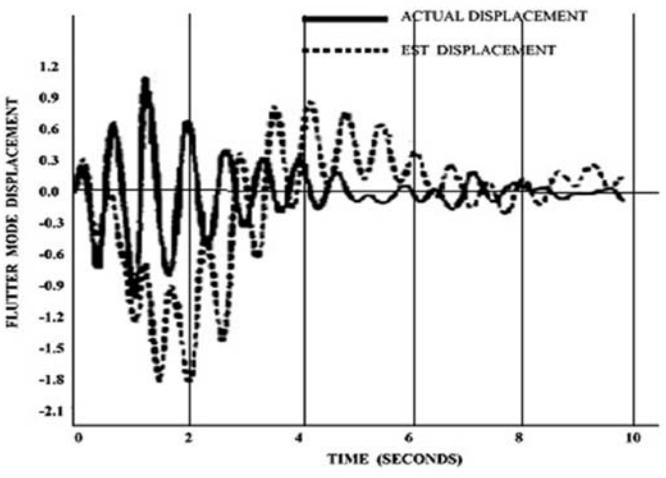

Fig 4. Response for the LQG- APA controller with Turbulence (3 m / sec) [12]

In the Flutter mode displacement without turbulence, the actual Amplitude is changing from 1.2 mm to -0.8 mm. It reaches the stable value over the time period after 5 seconds as indicated in Fig. 3. But in the estimated displacement using LQG controller indicates an oscillation from -1.6 mm to 1.0 mm whereas, in the presence of turbulence also the Flutter displacement signifies the similar effect without any uncertainty exemplified in Figure 4. The major advantage of this technique was the simplified form of flutter suppression without any control system modifications [19]. But this method cannot control the fluttering tendency, if the structure is highly stiffened. Similarly, Fig 5. Illustrates Flutter displacement causes the Aileron control must be deflected about -0.50^0 to 0.10^0 for Adaptive LQG with Good IC's. It is a small amount of deflection, but it is essential because the amplitude increases at high cruising speeds. For Bad IC's the deflection ranges from -2.0^0 to 4.0^0 and for Inadequate Excitation it is -0.5^0 to 0.7^0. However, nearly 30% of effective Aileron deflection is spoiled because of the Flutter induced displacement and the range has been improved in contrast with LQG - APA controller configuration.

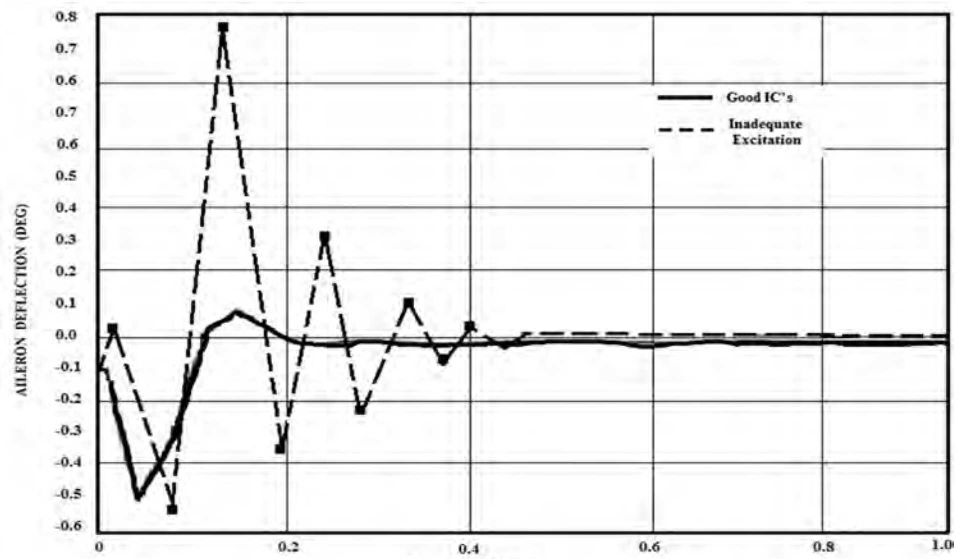

Fig 5. Aileron Deflection (Adaptive LQG with Good IC's and Inadequate Excitation)

In the increased stability margin, critical pressure and critical airspeed are tremendous from the data match up to with the Robust Aeroelastic System (RAS). The desire is to control the plunge and pitch motion from the time simulation [61]. The nominal aeroelastic system has a limit cycle oscillation (LCO) and reaches the stability (airspeed simulation below the critical speed), when the controller is activated the motion of the wing is damped quickly with a limit oscillation.

The Impulse response over time period of 60 seconds for a two DOF wing model was calculated using a time response analysis [59]. It was simulated by using the control system block diagram to predict the initial impulse during the non linearity in the aerodynamic forces (Fig. 6). It is observed that from the beginning to the time period up to 10 seconds the severity of impulse amplitude was excessive enough to cause permanent structural deformations. Hence, the effect of LQG control on the impulse response must be predicted over the range of airspeeds.

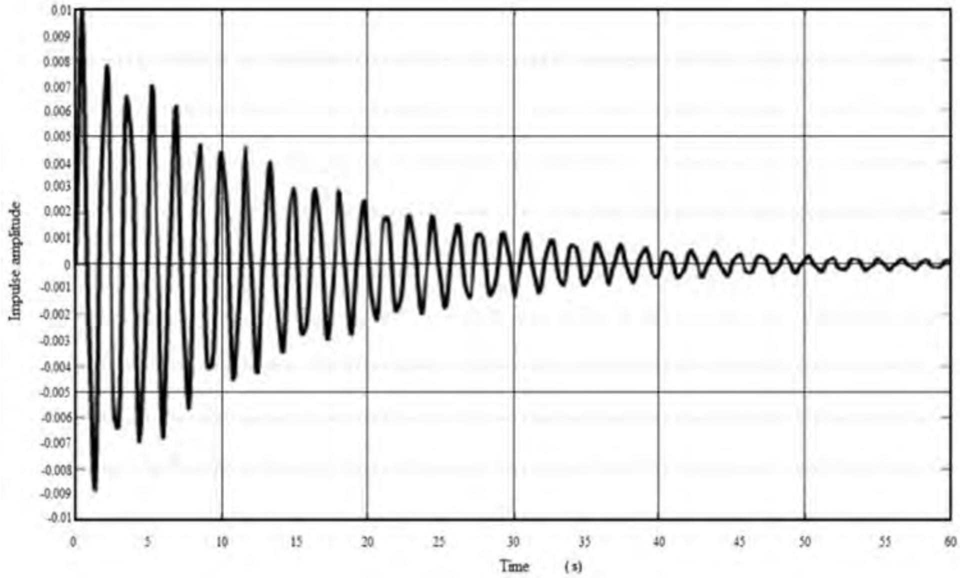

Fig 6. Impulse response

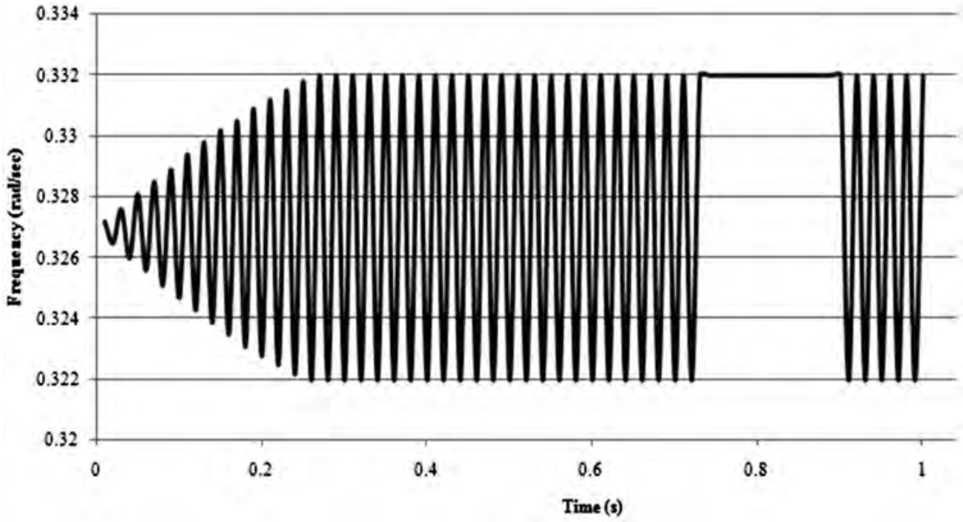

Fig 7. Linear frequency response for Mode 1

The wing structure exhibits the similar behaviour up to the yielding pressure magnitude. Although, when the Mach number reaches M = 0.81, the impulse frequency prevails after a long range of time step simulations. The flutter speed index obtained for the impulse frequency is 1.223. The number of time steps and computational requirements are exceptionally high to obtain the flutter speed index. Nevertheless, the Fig. 7 and 8 are indicated here to point out the response of the wing structure over time in opposition to the flutter frequency.

For a two DOF system, the Wagner function is approximated using a transform pair in terms of reduced frequency. It will introduce the ‘lag roots’ through Rational Function Approximations. The time period between 0.75 seconds to 0.85 seconds (Fig. 8) the cluster of Eigen values occurred and hence the negative stability behaviour is revealed for this time step [37].

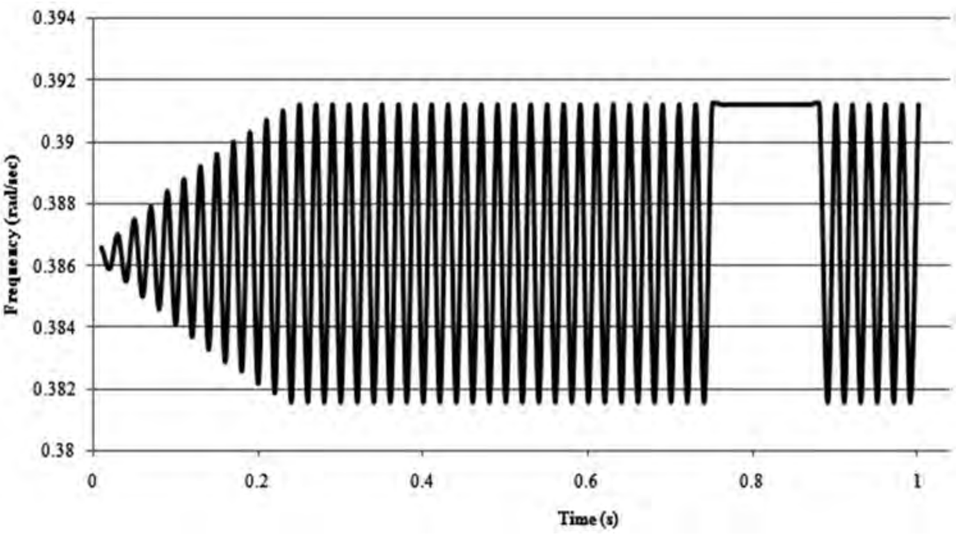

Fig 8. Torsion frequency response for Mode 2

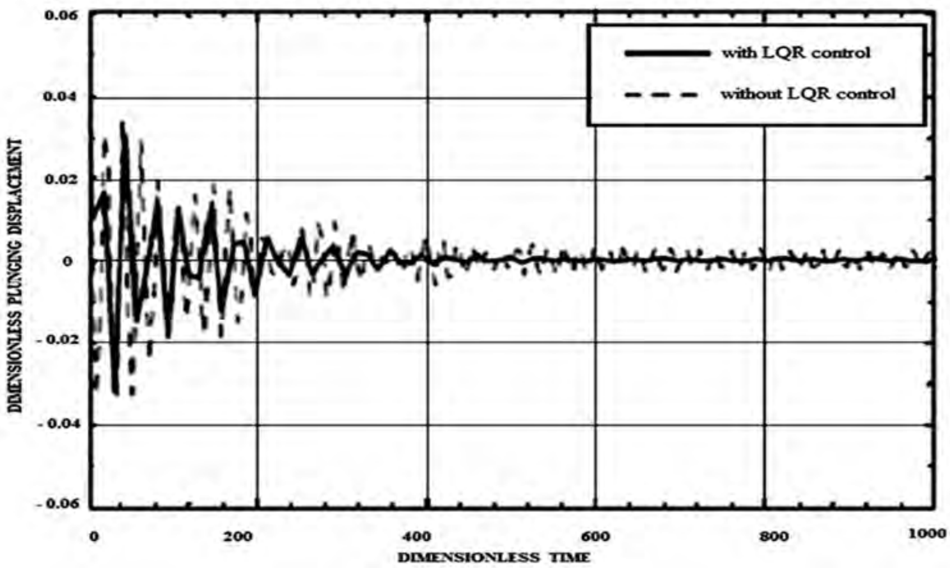

Fig 9. The response of LQR controlled and uncontrolled airfoil at the flight speed of V^* @ 3.0Ma [25]

For supersonic case, the AFS using LQR controlled system given a matchless influence to diminish the vibration amplitude [25]. Fig. 9 represents, the vibration amplitude of the LQR controlled system is declined slightly when matches with the uncontrolled system at the speed of $V^* = 3.0\ M_a$. It means that up to the M = 3.0 the plunge displacement is well controlled using the LQR incorporated system. As the Mach number increases to M = 3.9 the dimensionless plunge displacement is severely changing over the period of time. It has been confirmed that the AFS with LQR control reduces the plunge displacement almost half of its original magnitude. Further, if the Mach number increases to M = 5.4 the dimensionless plunge displacement magnitude will reach 3 times of higher value than the previous case.

It is observed from Fig. 10 AFS with LQR control trimmed down the plunge displacement almost one third of its original magnitude. Hence, for higher velocities this technique provides better control over flutter suppression with minimum assumptions. It's a good advantage exist in this method when compared with conventional active controllers.

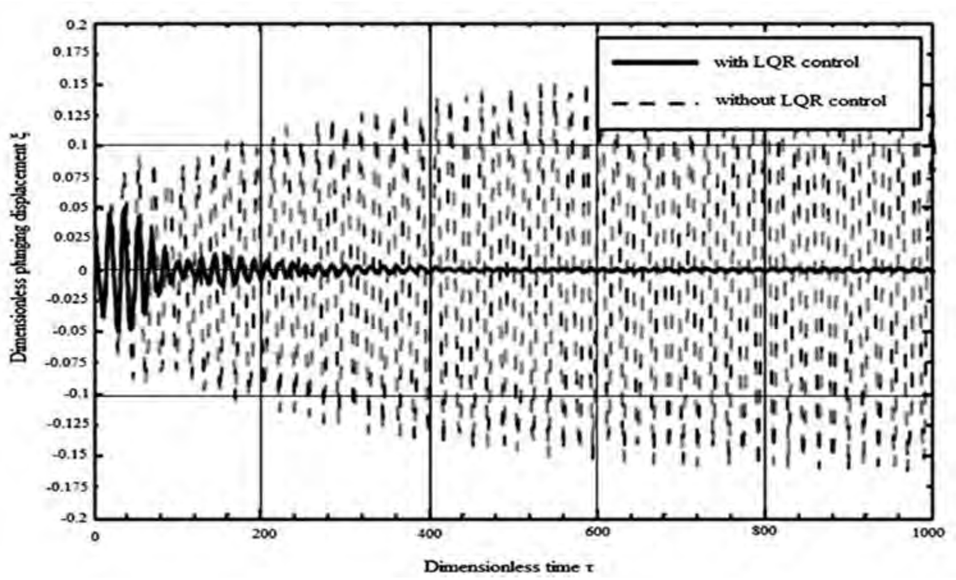

Fig 10. The response of LQR controlled and uncontrolled airfoil at the flight speed of V^* @ M = 5.4

VII. OBSERVATION SUMMARY AND FUTURE WORK

For non linear aeroelastic structures, Active controls are incredible technology for the flutter suppression. In the conventional active controllers, the generalized aerodynamic forces for each structural deformation mode were estimated over a span of frequencies. Hence, because of its less consistency, it was failed to capture various unsteady characteristics. However, the aeroelastic responses are purely based on these characteristics as transonic flow and shock induced separation.

So to enhance the effectiveness of AFS Technique, it is necessary to predict the non linear aeroelastic responses accurately. Most-recent technique to achieve this accuracy is using a CFD / CSD coupled analysis. The selection of a CFD / CSD solver is purely based on the nature of analysis and the number of DoF [70]. The output of a controller should able to achieve flutter suppression well earlier within a lower peak normal acceleration.

The several bending-torsion modes taken into account are another factor that determines the response of a controller. If the motion is unstable through excessive acceleration, then the controller input must be enough to suppress the flutter within the prescribed time period [64]. Hence, from the various literature and analysis results acquired, it is observed that, positioning the controllers and their inputs for the suitable condition are vital to achieve AFS in an efficient manner.

- In the future work, to achieve good results for AFS with the selected frequency range, an efficient numerical model with a limited number of DoF must be adopted. The design of active control systems using this method provides satisfactory results relatively superior than an over-detailed and expensive numerical model.
- The results over viewed and obtained in this article indicate the need to adopt practical high-fidelity simulation tools to verify the control system performances.
- Efficient analysis tools also required to modify the design to predict the real system behaviour precisely. By this, the cost and several experimental tests can be eliminated.
- For Complex industrial applications, an optimization loop based on the high-fidelity model must be used to do nonlinear trim against Shock waves and gust loads. CFD simulations are highly useful to serve this purpose in the process of design and validation.

VIII. CONCLUSIONS

Flutter suppression and its behaviour capturing methods are reviewed and analyzed in a multidimensional approach. It is observed that, the unsteady nonlinear motion induces structural failures even though the airplane is cruising with moderate velocities. The timely prediction is a significant importance in the event of excess coupled oscillations. Hence, AFS using sensors, micro devices and smart materials is a core focus in the near future. In the recent 20 years, this research area is constantly revealing various possibilities and modifications in AFS techniques using advanced feedback control systems. Above all, Aeroservoelasticity, smart structures and morphing of airplane structures are the non-conventional techniques preferred for futuristic flight vehicles. The selected phenomenon in this article is crucial from the reliability point of view in the commercial airplanes. In brief, the motivation towards this new field of airplane science is unstoppable.

ACKNOWLEDGEMENTS

Anna university support for the work in terms of experimental facilities is greatly acknowledged. The Author(s) express the sincere thanks to Prof. Dr. A.P. Haran for his valuable guidelines towards the production of this article.

Appendix 1

Notations

h(s), d(s)	=	Transfer Functions
J	=	Matrix Vectors
p(t), f(t)	=	Past and Future Vectors
V	=	Air Speed (m/s)
ΔT	=	Sampling Interval
a_i	=	Proportional Gain
b_i	=	Integral Gain
p_i	=	Parameter Vector
$s_{k,}$ ω	=	Response Frequencies (rad / sec)
u_k	=	Scalar Input
w_k	=	Scalar Disturbance
x_k	=	State Vector
y_k	=	Scalar Output
ϕ	=	Velocity Potential
ρ	=	Density (kg / m^3)
Γ	=	Circulation (m^2/s)
η	=	Aerodynamic Coordinate vector
μ	=	Structured Singular Value
ζ	=	Damping Ratio

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