REVIEW OF FLUTTER SUPPRESSION USING MODERN CONTROL THEORY

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ABSTRACT

Aeroelasticity is the study of the mutual interaction that takes place among aerodynamic, elastic, and inertia forces acting on aircraft structures exposed to an airstream. Aircraft structures are not completely rigid and aeroelastic phenomena arising when structural deformations induce changes in aerodynamic forces. The aeroelastic phenomena include flutter, divergence, control reversal or effectiveness, etc. This paper presents the investigations of flutter suppression control scheme with modern control theory. These techniques are important for the designs of modern aircraft. The flutter is now a part of aircraft certification and flight envelope expansion.

KEYWORDS: Aeroelasticity, Flutter suppression, Modern control Theory

1. Introduction

Aeroelasticity is the study of the mutual interaction between aerodynamic forces, elastic forces, and inertia forces. The field of study can be demonstrated clearly by the classical Collar's aeroelastic triangle [1], as shown in Figure 1.

In the history of aviation, Samuel Langley's aircraft, the so-called Aerodromes [2], Figure 2, was a tandem-wing design with an aft-mounted tail. Langley's design was to provide the aircraft with structural stability, independent of the pilot's effort. The aerodrome was launched from a houseboat-mounted catapult. However, the Aerodrome quickly dove into the Potomac River, with no flight being achieved.

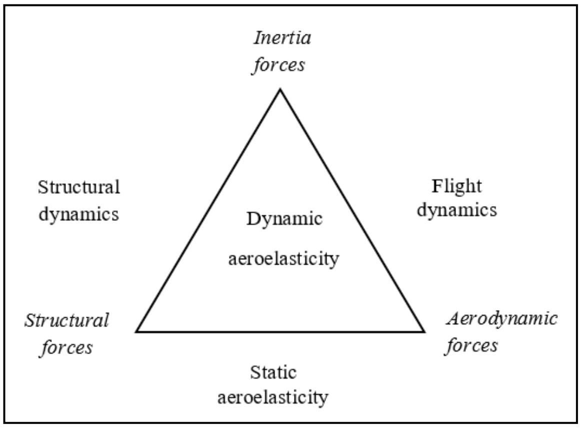

Figure 1 **Collar's aeroelastic triangle**

As understanding of aeroelastic effects progressed, the notion will grow that the Aerodrome's failure was due to wing torsional divergence. In 1914, Langley's Aerodrome was modified by Curtis and flew successfully [2].

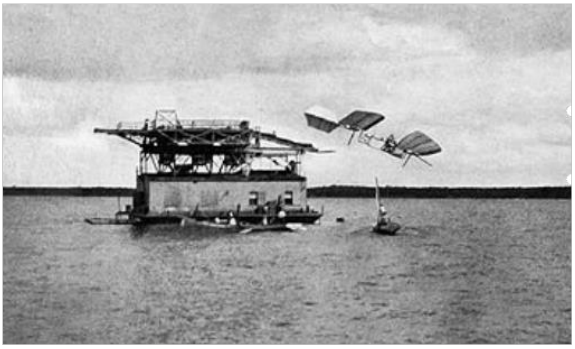

Figure 2 **Langley's Aerodrome during the test**

On December 17, 1903, nine days after the Aerodrome's failure, the Wright brothers flew their bi-plane aircraft successfully [2] (Figure 3).

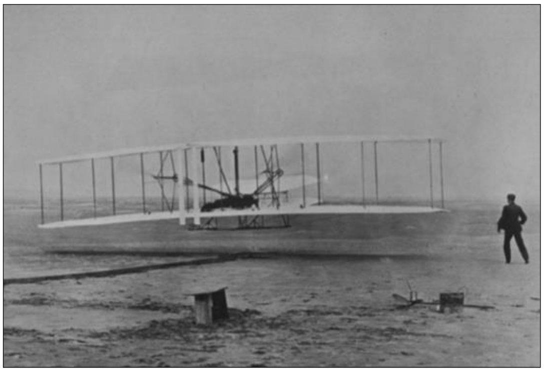

Figure 3 Wright Brother's Bi-plane aircraft

Fokker D-8 had a great performance but suffered from wing failures in steep dives. Early monoplanes had insufficient torsional stiffness resulting in wing flutter, wing aileron flutter, and loss of aileron effectiveness. The solution found was to increase the torsional stiffness, and mass balancing [2].

The first recorded flutter incident involved Hadley Page's O/400 bomber Bi-plane in 1915 with 'violent oscillations' of the tail flutter problem [2] (fuselage torsion coupled with elevators).

In 1959, Braniff International Airways Flight 542, a Lockheed L-188 Electra disintegrated in mid-air approximately 6.1 km southeast of Buffalo, Texas. The accident was caused by cycles of reverse bending or flutter [3].

In 2006, the second prototype of Grob G180 SPn, a low-wing twin-engined composite corporate jet was destroyed and the pilot was killed after the aircraft crashed due to flutter in the elevators and tail-plane [4].

The first formal flutter test was carried out by Von Schlippe in 1935 in Germany. His approach was to vibrate the aircraft at resonant frequencies at progressively higher speeds and plot amplitude as a function of airspeed (Figure 4). The above idea was applied to many German aircrafts until a Junkers JU 90 fluttered and crashed during flight tests in 1938 [5].

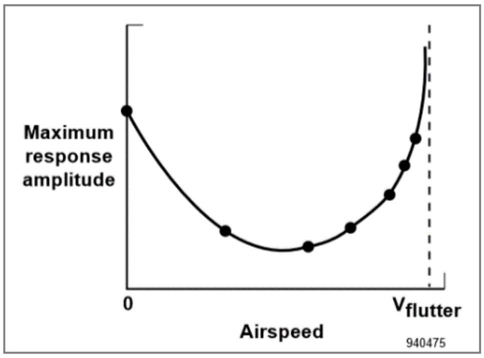

Figure 4 Von Schlippe's Flutter test method

2. Flutter behavior and mathematical model

In understanding the flutter phenomenon, let us consider a cantilevered wing mounted in a wind tunnel with a small angle of attack. At first, there is no flow in the wind tunnel and then if the wing model is disturbed, the oscillation occurs and then is damped out gradually. Then, the flow is increased gradually, the rate of damping of the oscillation of the wing first increases. When the flow speed is further increased, a point is reached at which the damping decreases rapidly and a self-sustained oscillation is maintained with a steady amplitude. At this point, the airfoil structure starts to extract the energy from the airstream and this flow speed is called the critical flutter speed. Above this critical speed, flutter begins to occur [2].

In the analysis of flutter, for the first step, the equation of motion of the structure will be formulated by using the Finite element method (FEM). Then, the integration of aerodynamic forces acting on the surface into the equation of motion to become the aeroelastic equation, and subsequently, the solution for flutter is solved from this equation. The mathematical model of the wing must be able to yield natural frequencies and normal mode shapes up to the frequency range of interest, typically 0 - 40 Hz for a large aircraft and 0 - 60 Hz for a small aircraft [2]. In structural mechanics, the equation of motion is of the form [2,6]

$$\mathbf{M}\ddot{\mathbf{x}}+\mathbf{K}\mathbf{x}=0, \tag{1}$$

where $\mathbf{M}$ and $\mathbf{K}$ is the $N\times N$ mass and stiffness matrices respectively and $\mathbf{x}$ is the $N\times 1$ vector of structural displacement/rotation. To reduce the number of equations, the equation (1) has to be transformed to modal coordinates using the following transformation

$$\mathbf{x} = \mathbf{\Phi q}, \tag{2}$$

where $\mathbf{\Phi} = [\phi_1, \phi_2, ..., \phi_n]$ is the modal matrix and $\mathbf{q}$ is the $n \times 1$ vector of generalized coordinates. The equation (2) is substituted into equation (1) and because of the orthogonality property, pre-multiplied the result by $\mathbf{\Phi}^T$ then the equation becomes

$$\mathbf{A\ddot{q}} + \mathbf{Eq} = 0, \tag{3}$$

where $\mathbf{A} = \mathbf{\Phi}^T \mathbf{M\Phi}$ and $\mathbf{E} = \mathbf{\Phi}^T \mathbf{K\Phi}$ are the diagonal $n \times n$ generalized mass and stiffness matrices respectively. Thus, the *N* finite element equations of motion have been reduced to a smaller set of *n*.

The next step of estimating of flutter behavior of the wing is to introduce the aerodynamic forces into the equation of motion (3). The aerodynamic forces are obtained in the frequency domain by calculating them from the oscillatory motion of the airfoil at different frequencies. The modal generalized unsteady air load is generated by specifying the Mach number and the range of the so-called reduced frequency.

The reduced frequency [6] is defined as

$$k = \frac{\omega c}{V}, \tag{4}$$

where is ω circular frequency (rad/s), V is the true airspeed, and c is the reference chord (Figure 5).

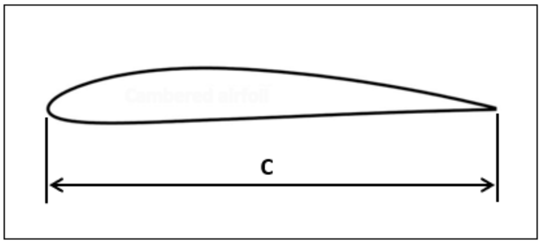

Figure 5 Reference chord

In aeroelastic systems, there are the interactions between the structure and aerodynamical forces, so in an analysis, the aerodynamic forces will be added to the structural equation (3) to become a classical form of flutter equation [4] which is expressed in generalized coordinates, $\mathbf{q}$ as follows [6],

$$\mathbf{A}\ddot{\mathbf{q}}+(\rho V\mathbf{B}+\mathbf{D})\dot{\mathbf{q}}+(\rho V^2\mathbf{C}+\mathbf{E})\mathbf{q}=0, \tag{5}$$

where ρ is the density and $\mathbf{B}$ and $\mathbf{C}$ are the aerodynamic damping and aerodynamic stiffness matrices, respectively. $\mathbf{D}$ and $\mathbf{E}$ are the structural damping and structural stiffness matrices, respectively. For $\mathbf{B}$ and $\mathbf{C}$, in comparison with $\mathbf{D}$ and $\mathbf{E}$, a difference is that the aerodynamic damping and aerodynamic stiffness matrices are non-symmetric, so there is coupling between modes which is a key element of the flutter instability [4]. Note that $\mathbf{B}$ and $\mathbf{C}$ are function of reduced frequency, k. The structural damping matrix, $\mathbf{D}$ can be estimated by measurement during the ground vibration testing (GVT). Equation (5) is one of the most important equations in flutter analysis and describes the fundamental interaction between the flexible structure and the aerodynamic forces.

The equation (5) can be solved by assuming a solution of the form [6]

$$\mathbf{q}(t)=\mathbf{q_0}\,e^{\lambda t} \tag{6}$$

where $\mathbf{q_0}$ is the amplitude vector and λ is the complex eigenvalue which is an exponent that shows stability.

Substituting equation (6) into equation (5) and rearranging the terms, yielding

$$[\lambda^2\mathbf{A}+\lambda(\rho V\mathbf{B}+\mathbf{D})+(\rho V^2\mathbf{C}+\mathbf{E})]\mathbf{q}_0=0. \tag{7}$$

Equation (7) is an eigenvalue problem. If the real part of the complex variable λ is negative, the system becomes stable. When the real part is zero, the system has a sustained motion and flutter starts to occur and the system becomes unstable if it is positive.

However, if the variable λ is real, then the root is non-oscillating, and if it is positive real, the system becomes statically unstable, that is the case of the divergence phenomenon.

The review in this paper covers historical development, basics of flutter, modern control schemes and techniques, system identification, piezoelectric actuation, and smart materials, experiments, and testing and the presentation will be arranged in chronological order as much as possible.

3. Historical development and basics of flutter

Aeroelasticity covers many disciplines and it is now recognized as a multi-disciplinary subject. Subjects such as aerodynamics, flight dynamics, structural dynamics, mechanical vibrations, computational fluid dynamics (CFD), control, and stability now combine to form close links with each other particularly when it is in design and testing processes. This was not the case towards the 1940s. It has increasingly been the case since the 1960s and today subjects that were once regarded as independent from each other have become closely linked [7].

Garrick and Reed III [8], in their review paper on aircraft flutter, present problems arising in these areas and how they were attacked by aviation's pioneers and their successors. This paper gives a short history of aircraft flutter, with emphasis on the conceptual developments, from the early days of flight to about the mid-1950s.

Rose and Jinu [9], in this review article, the contributions of researchers in the field of Active Flutter Suppression (AFS) over the years were investigated. The research area is constantly revealing possibilities and modifications in AFS techniques. AFS using sensors, microdevices, and smart materials is a main focus in the future.

Battoo [7] presented the paper in 1997 that gave the introduction of aeroelasticity to readers who may not be familiar with this field. The paper covers four main sections includes reviewing papers in the field, publications, a list of references and a list of useful technical journals, a brief note about software, and useful worldwide websites. This is the paper recommended for a newcomer.

Panda and Venkatasubramani [2], this paper gives an introduction of static and dynamic aeroelasticity problems aiming for the readers to get an idea about the subject. The paper covers the general aeroelastic phenomena including divergence and aileron reversal. This paper also covers the study of flutter, the mathematical model, and its solution.

In the paper of Kamakofi and Shyy [10], the authors reviewed the recent advancements in the field of fluid-structure interaction, with specific attention to aeroelastic applications.

Several techniques were reviewed in this paper. The flutter predictions performed on an AGARD 445.6 wing at different Mach numbers were chosen to highlight the advancement in computational and modeling issues.

Livne [11], his paper presented an in-depth overview of more than 50 years of research and development in the active flutter suppression (AFS) area. Key historical developments and the current state of the art in all relevant disciplines were surveyed. Technology and research needs were identified. A full list of the bibliography contains references that cover all areas of AFS technology. The work would contribute to the preservation of the experience and knowledge in this area.

In the next section, control methodologies that are used for flutter control, including the applications of piezoelectric and smart material and research papers on experiments and testing will be presented. This investigation will give the reader the ideas of the control schemes that were applied to control the flutter of the aircraft or the part of it.

4. Modern Control Theory

In this section, some techniques in flutter suppression are reviewed. Modern control schemes applied in this field are such as Positive position feedback (PPF), Linear parameter-varying (LPV) control, adaptive control, Linear Quadratic Gaussian (LQG), H-Infinity control, etc. Some of the control methods are explained briefly for the reader to obtain some ideas in the next few paragraphs.

Positive position feedback (PPF)is used to add damping to the unstable flutter mode. The control system consists of two equations i.e. the structural equation and the compensator, respectively as follows [12],

$$\ddot{\xi} + 2\zeta\omega\dot{\xi} + \omega^2\xi = g\omega^2\eta, \tag{8}$$

$$\ddot{\eta} + 2\zeta_f\omega_f\dot{\eta} + \omega_f^2\eta = \omega_f^2\xi, \tag{9}$$

where ξ is the modal coordinate, η is the filter coordinate, ω and ω_f are the structural and filter frequencies, respectively, and ζ and ζ_f are the structural and filter damping ratios, respectively. The function of the compensator is to add a high damping ratio into the system.

This method is not sensitive to spillover in a reduced-order model i.e. the unmodeled higher modes will not be excited.

For the Linear parameter-varying [13] (LPV) control, in the past, a gain scheduling was widely used in aviation, but for scheduling multivariable controllers, it can be a very tedious and time-consuming task. For the LPV techniques, it provides a more systematic design for gain scheduled multivariable controllers. For the LPV methodology, the system is expressed as follows

$$\dot{\mathbf{x}} = f(\mathbf{x}(t), \mathbf{p}(t), \dot{\mathbf{p}}(t), \mathbf{u}(t)), \tag{10}$$

where $\mathbf{x}$ is the state of the system, $\mathbf{p}$ is the exogenous variable whose evolution is not understood or complicated to model, but is measurable in real-time using a sensor. The state and output equations can be expressed, respectively in matrix form as follows

$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{p}(t))\mathbf{x}(t) + \mathbf{B}(\mathbf{p}(t))\mathbf{u}(t), \tag{11}$$

$$\mathbf{y} = \mathbf{C}(\mathbf{p}(t))\mathbf{x}(t) + \mathbf{D}(\mathbf{p}(t))\mathbf{u}(t), \tag{12}$$

where $\mathbf{A}$ is the system matrix, $\mathbf{B}$ is the control matrix, $\mathbf{C}$ is the output matrix and, $\mathbf{D}$ is the feedforward matrix. To control this kind of system, control schemes such as single quadratic Lyapunov function, parameter-dependent quadratic Lyapunov function, etc. can be applied.

Linear quadratic Gaussian (LQG) [14] control system contains a linear quadratic regulator (LQR) together with a Kalman filter state estimator. It is the most fundamental optimal control problem. The system is driven by additive white Gaussian noises. The dynamic system can be represented as follows,

$$\dot{\mathbf{x}} = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}(t)\mathbf{u}(t) + \mathbf{v}(t), \tag{13}$$

$$\mathbf{y} = \mathbf{C}(t)\mathbf{x}(t) + \mathbf{w}(t), \tag{14}$$

where $\mathbf{x}$ is the vector of state variables, $\mathbf{u}$ is the vector of control inputs, $\mathbf{y}$ is the measured outputs, $\mathbf{v}(t)$ is the white Gaussian noise and $\mathbf{w}(t)$ is the white Gaussian measurement noise. The LQG controller that solves the LQG control problem is specified by

$$\dot{\hat{\mathbf{x}}}(t)=\mathbf{A}(t)\hat{\mathbf{x}}(t)+\mathbf{B}(t)\mathbf{u}(t)+\mathbf{L}(t)[\mathbf{y}(t)-\mathbf{C}(t)\hat{\mathbf{x}}(t)],\quad \hat{\mathbf{x}}(0)=E[\mathbf{x}(0)] \tag{15}$$

$$\mathbf{u}(t)=-\mathbf{K}(t)\hat{\mathbf{x}}(t), \tag{16}$$

where $\mathbf{L}(t)$ is the Kalman gain of the Kalman filter, $\hat{\mathbf{x}}(t)$ is the estimates of the state $\mathbf{x}(t)$ and E denotes the expected value. The matrices can be found using two matrix Riccati differential equations i.e. the linear quadratic estimation (LQE) and the linear quadratic regulator (LQR).

For the other control schemes or methodologies used in the flutter control problem, the reader can find in many control texts or documentations that are widely available.

In 1982, 1985, 1986 Moore et al [15,16], Chakravarty and Moore [17], presented an adaptive approach to flutter mode suppression. Adaptive flutter suppression schemes offered the 180° effective phase margins at the flutter frequency. The design approach combined the linear quadratic Gaussian (LQG) and adaptive synthesis techniques to achieve a robust control law with good performance.

Horikawa and Dowell [18], their paper presented an elementary explanation of wing flutter suppression with active feedback control using a root locus method. A study was done on a typical section airfoil with pure gain feedback. Information was obtained for various kinds of the feedback signal.

Juang and Phan [19], in 1994, presented the identification problem of a system operating in a closed loop with a feedback controller. The system was excited by a known excitation and the resulting response and the feedback are measured. Markov parameters of an observer are computed. The results are demonstrated by an example using wind tunnel aircraft flutter test data (Figure6).

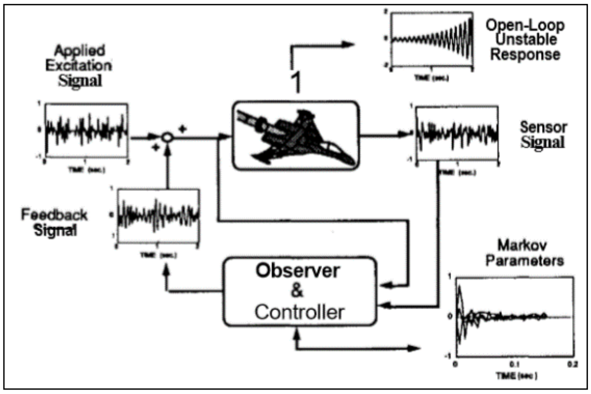

Figure 6 **Identified control system from experimental data**

The results from a joint Volvo Aero and Saab Aerospace research project were presented by Norlander et al [20]. A LQG and a parametric LQ controller have been designed. A wind tunnel model has been tested and evaluated and showed that flutter could be avoided using active control and the parametric LQ techniques were suitable for the design of high-performance low order controllers.

Choi et al [21], the paper presented the LQG algorithm for flutter suppression flutter of an aeroelastic wing. A state-space model for aerodynamic forces was modeled using the autoregressive moving average identification method. A combined state estimator and a linear quadratic regulator were designed. Figure 7 shows the block diagram of the aeroservoelastic model, where h,α,δ_E and u are heave, pitch, control surface displacement, and control command, respectively. Simulation results showed the effectiveness of the controller.

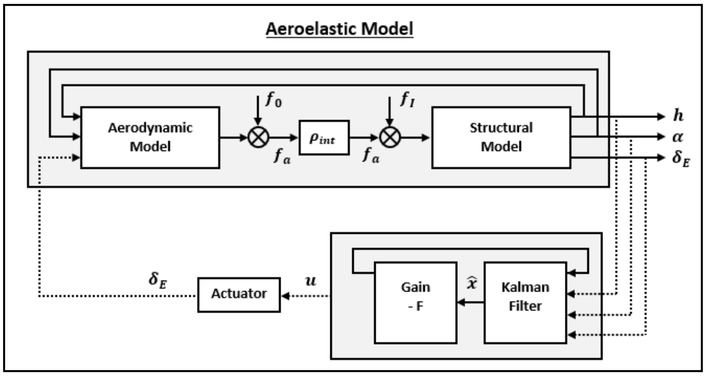

Figure 7 **The block diagram of the aeroservoelastic model**

Moosavi et al [22] developed a procedure based on the Galerkin method to predict the flutter speed and frequency. An eigenvalue problem with non-symmetric matrix coefficients was derived. If free stream velocity increases up to a certain velocity, the real parts of eigenvalues have negative signs. Further increasing of velocity causes the real parts to become positive, which indicates the occurrence of flutter.

Mevel et al [23] presented a covariance-driven subspace identification method for output-only observations. The method as applied to the in-flight situation. A simulator was built using the identified modal parameters. Experiments were made with the use of SCILAB.

In 2007, McEver et al [24], their research used the technique of Q parameterization to identify an unstable model of an airfoil above its flutter boundary. A nominal controller and a new-designed controller using the Evans root-locus technique were compared. From wind tunnel tests, the controller increased the flutter boundary by 30%, and the redesigned controller increased by 52%.

Lum and Lai [25] presented a correlation approach for the identification of a Hammerstein model of unsteady aerodynamics using CFD data. From a numerical example of the AGARD 445.6 wing, it showed that the method could accurately approximate the linear aerodynamic response.

Mahmoodi et al [26], in this paper, a Positive Position Feedback controller was modified. A new modified PPF controller separated the damping and stiffness controls. Experimental results showed that the new controller was able to provide good vibration suppression and could be used to control more than one natural frequency simultaneously.

In 2014, Wenmin et al [27], in their study, a MIMO time-delay feedback controller was designed to actively suppress the flutter. The model used was a multiple-actuated-wing (MAW) wind tunnel model. Firstly, the LQG controller was designed, but because of the time delay in the control loop, the stability margin was no guaranteed. This was compensated by the first-order Pade approximation. The experiments showed that this controller could expand the flutter boundary effectively.

Feixin et al [28], the equivalent linearization method (ELM) was modified to investigate the nonlinear flutter system with cubic damping. The frequency of limit cycle oscillation (LCO) was chosen as an active increment to produce bifurcation charts. Numerical examples showed that this modification made the ELM much more efficient and the LCOs obtained were in good agreement with numerical solutions.

In 2015, Nguyen et al [29] presented an adaptive control approach of an adaptive aeroelastic wing with a variable camber continuous trailing edge flap design. The control was based on the optimal control modification method augmented to a LQG optimal control design. Simulation results showed that this adaptive control design was effective in suppressing the flutter.

Singh [30], in this paper, flutter suppression was done by partial-pole placement using active state feedback with a single time delay in the control loop. A numerical example showed that poles associated with a targeted flutter mode could be stabilized without affecting the other aeroelastic modes.

Visser et al [31], his paper compared four LPV identification methods i.e. local, global, and glocal, for flutter prediction and modeling. Important properties of the methods were highlighted and simulations were performed to compare the performance, using a bending-torsion flutter model from the literature. Results showed that a trade-off between bias and variance exists for the local and global method, after which a glocal method can further improve performance.

Huang et al [32], in his study, a delayed controller was designed for active flutter suppression of the 3-D wing model. In the first step of design, a short time delay was artificially introduced into the control loop to get a set of delay-free state-space equations. For the second step, using the theory of optimal control, the control law was synthesized. In the experimental results in the wind tunnel, the critical flutter speed was effectively increased from 36.5 m/s to 39 m/s.

Theis et al [33], in 2016, presented the design of a controller for active flutter suppression on an unmanned aircraft. The aircraft is modeled as a grey box. An H_∞ -norm optimal controller is designed to increases structural damping and suppressing flutter. Robustness tests for clearance in the absence of a high-fidelity nonlinear model is also developed.

Liu et al [34] presented a LQG-based model predictive control (MPC) method to suppress the gust loads of aircraft. Light detection and ranging (LIDAR) systems were used to get information of the turbulence. The method used both the infinite prediction horizon and infinite control horizon. The advantages of the proposed method were that the stability property was improved and the number of online optimized control variables was reduced.

Al-Hajja and Al-Jiboory [35] proposed a novel technique of linear parameter varying (LPV) modeling, where the smart airfoil has a groove along its chord with a moving mass. The position of the moving mass and the free stream airspeed were considered as the scheduling parameters in the study. LPV gain-scheduling controller guaranteed with H_∞ performance. The simulations showed the effectiveness of the proposed method.

Liuet al [36] applied a Sliding Mode Control (SMC) scheme to design an active controller. Numerical results indicated that the given SMC methodology was effective to suppress the vibration of a two-degree-of-freedom viscoelastic airfoil model.

The development in the field of flutter suppression, smart material has motivated many researchers to work with. The smart structure can be defined as the structure that can sense external disturbance and respond to that with active control in real-time to maintain the mission required. Smart structures consist of active devices and processor networks. The active devices are sensors and actuators either embedded or attached to a structure. In the field of flutter suppression, piezoelectric materials are widely used. A material that, when subjected to mechanical loading, will produce an electric charge and is said to have piezoelectric properties. Piezoelectric materials can be produced from ceramics and polymers by applying a large electrical field across the material.

Fanson et al [12], in 1990, a new technique called Positive Position Feedback (PPF) for vibration suppression in large space structures was investigated in the laboratory.

In this method, piezoelectric materials were used for actuators and sensors to simulate a piezoelectric active member. The first six bending modes of a cantilever beam were controlled. The modal damping ratios were increased by a factor of 2 to 130.

Heeg [37], the research was to study the capabilities of piezoelectric actuators for suppressing flutter. An aeroservoelastic model was constructed using FEM, laminated plate theory, and aeroelastic analysis tools. The converse piezoelectric effect was utilized to actuate a structure by applying a voltage. Command signals exerted control over the damping and stiffness properties. The results showed that small, carefully placed actuating plates can be used effectively to control aeroelastic response.

Meyer et al, in 1996 and 1998 [38, 39], proposed the paper presenting the positive position feedback (PPF) control and linear–quadratic Gaussian (LQG) control for vibration suppression of a flexible structure. Experiments were conducted using piezoceramics as an actuator. PPF control is effective in providing high damping for a certain mode. LQG control provided damping to all modes; however, except for high damping for a specific mode.

In 2000, Giurgiutiu [40] has reviewed the application of active materials induced-strain actuation to counteract aeroelastic and vibration effects in helicopter rotor blades and fixed-wing aircraft. For fixed-wing aircraft, an active flutter control, buffet suppression, gust load alleviation, and sonic fatigue reduction were discussed. Directions for further work were also presented.

Suleman and Costal [41], in 2004, an adaptive aeroelastic flight vehicle demonstrator concept was designed and tested. Piezoelectric actuators were used. The results of Closed-loop buffet attenuation, gust response alleviation, and flutter suppression were presented.

Kawai [42], an element of piezoceramics (PZT) was used in this study to control flutter. The wing model was a rectangular aluminum plate having one element of PZT attached on its one side which was the so-called control of the one-sided effect. The proportional control was used for flutter control. The conclusion was that even a single element of PZT was confirmed to be effective to control flutter.

Ardelean et al [43], in this research, a new V-stack piezoelectric actuator was designed. A typical wing was constructed and tested in the wind tunnel. Positive position feedback (PPF) control was used to add damping to the unstable flutter mode. With this method, the flutter speed was increased by more than 30%.

Makihara et al [44] studied the suppression of flutter of a cantilevered plate wing employing the finite element method and the quasi-steady aerodynamic theory. The use of smart circuits composed of piezoelectric materials and electric devices, (Figure8).

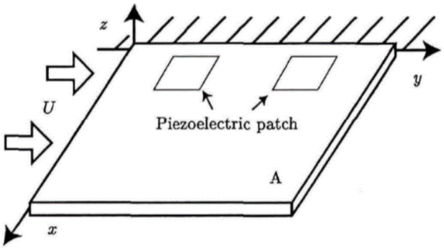

Figure 8 **Plate wing with piezoelectric patches**

Two approaches were presented; an energy-recycling semi-active approach which is referred to as a state-switching damper (Figure9) and a negative capacitance approach, which increased the wing's stiffness (Figure10). The critical dynamic pressure drastically increased as much as 24 % with the control using a negative capacitor.

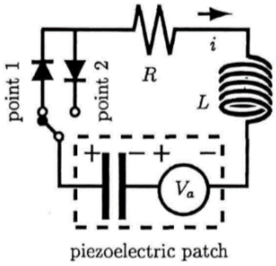

Figure 9 Energy-recycling semi-active approach

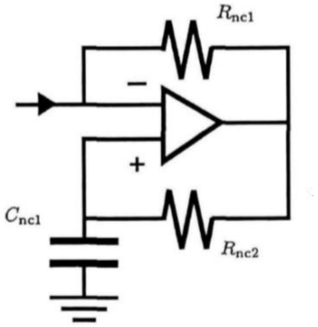

Figure 10 Negative capacitance approach

Han et al [45], his paper presented a numerical and experimental investigation on active flutter suppression (AFS) of a sweptback cantilevered lifting surface using piezoelectric (PZT) actuation, (Figure11). A FEM, a panel aerodynamic method, and the minimum state-space realization were used in formulated the equation of motion in state-space form. H_2 and μ-synthesized control laws were used in the flutter suppression. The μ-synthesized controller showed an improved behavior over a wide flow speed range. The performance was evaluated in the wind tunnel testing.

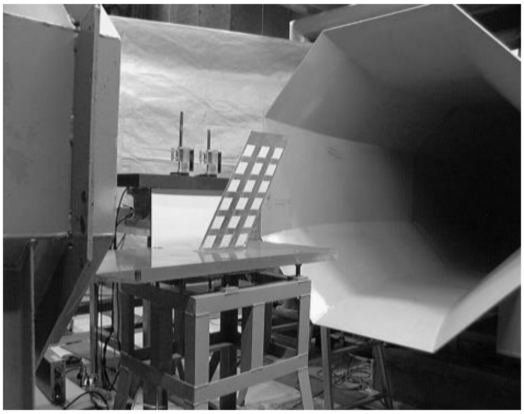

Figure 11 The experimental setup.

In 2006, Li et al [46], in the paper, a single piezoceramic element (PZT) was introduced to the wing model and tested in a wind tunnel for active flutter suppression. For the wing modeling, FEM analysis was used and aerodynamics were calculated using the doublet point method. A proportional control and the LQG were used as a control laws. The LQG control law was able to control the flutter successfully.

Raja and Upadhya [47], in their work, the wing model was constructed to have a bending–torsion flutter. The control surface was actuated by a flexure-hinged PZT stack mechanism acting as an aerodynamic effector. The wing response was measured by sensors, which are used to generate the feedback control to vibrate the control surface in antiphase motion with respect to the main surface. The flutter envelope was expanded by around 20%.

Munteanu [48], her work is the investigating of the capabilities of piezoelectric actuators used as active vibration control devices for wing. The equations of motion were formulated using ANSYS FEM structural modelling. The robust LQG/LQG synthesis was used. Numerical simulations were presented to show the efficacy of the piezo actuators.

Papatheou et al [49] in 2012, in their paper, the receptance method was used for flutter suppression. With this method, structural mass, damping and stiffness including aeroelastic damping, and stiffness were unnecessary, only vibration measurements were required. Two piezo-stacks in a ‘V’ configuration were used as an actuator. Preliminary experimental results were presented.

In 2016, Tsushima and Su [50], presented active and passive flutter suppression for flexible wings using piezoelectric transduction. The structural dynamic equations were coupled with an unsteady aerodynamic formulation. An active piezoelectric control and energy harvesting from wing vibrations were integrated. A LQG controller was developed for the active control of wing limit-cycle oscillations. The controller was effective for flutter suppression.

In 2020, in the paper of Adsadi and Farsadi [51], the thin-wall wing-engine system using composite piezoelectric actuation was investigated. In active control, LQG scheme was used as an active control algorithm. At the same time, in passive control, the effect of fiber angle orientation of composite wing was studied. The effect of the locations of the engine on the wing was also examined.

The clearance process for new aircraft-related aeroelastic issues during the design and certification phases, besides the success of the numerical modeling implementation such as Computational Fluid Dynamics (CFD), it has to be confirmed by testing i.e. ground vibration test, wind tunnel test, structural coupling test, and flight flutter test. These tests give the necessary information for the validation of the mathematical models used. Research papers on experiments and testing from the 1990s until to date are reviewed.

In 1990, Rickett [52], reported the results of NASA conducting wind-tunnel experiments to understand the aeroelastic characteristics of flight vehicles. Reviews of facilities, measurement techniques include past experimental programs. Needs for future experimental R&D programs were described.

Kehoe [5] in his paper of 1995, reviews the flight flutter test techniques developed over the last several decades. Structural excitation, instrumentation, data processing, and identification algorithm were described. Comments for future developments were also presented.

Brenner et al [53], NASA Dryden Flight Research Center conducted research to improve the flight flutter test process. The effort included excitation mechanism, techniques for signal processing, stability and identification, and flutter prediction. The investigation using data from the F/A-18 Systems Research Aircraft

Cooper [54] reviewed the current flight flutter testing, so the certification procedure could be improved (Figure12). The relevant technologies were also considered. Suggestions were made for speeding up the test and reducing the cost.

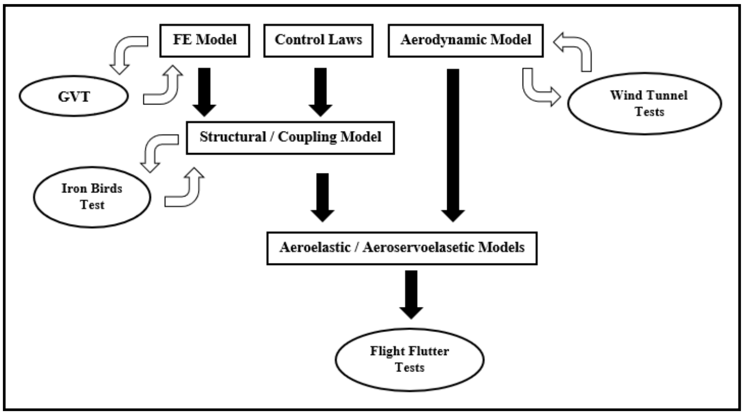

Figure 12 Aircraft Certification Procedure.

CFD requires validation for complicated flow problems, Qin [55] in his paper gave some examples to demonstrate how CFD may be used in a reversed way to help wind tunnels meet the challenges for both better understanding of flow physics and CFD validations.

In 2007, Marqui Junior et al [56], having developed a flexible mount system. The dimensions were determined by FEA and verified with an aeroelastic model. An identification algorithm, ERA, was used to determine modes shape and frequencies. The flutter behavior was demonstrated by FRF and obtained by a V-g-f plot. Mode coupling, damping, and oscillatory behaviors characterizing the flutter were studied.

In 2012, Sundresan et al [57], in their paper, flutter suppression techniques were investigated. Various testing techniques available were discussed. Optimization techniques and the fluid and structure interaction were reported. MSC Software and FE method were also discussed.

Papatheouet al [58], in 2013, presented an experimental study for the implementation of the method of receptances to control flutter. It was demonstrated experimentally that an increase in the flutter margin was increased by separating the frequencies of the heave and pitch modes.

Jiang et al [59], his paper provided an airworthiness inspection experience for civil aircraft flight flutter test. All key techniques for flutter stability verification were briefed.

Tang and Dowell [60] in 2016, presented examples of experimental model designs, wind tunnel tests, and correlation with a new theory. Their paper also provided new insights into nonlinear aeroelastic phenomena, flutter, limit cycle oscillation (LCO), and gust response.

5. Conclusions

This review paper gives some ideas to the reader about the modern control schemes for flutter suppression. These techniques play an important role in the design of modern aircraft.

The paper begins with some important events concerning flutter problems in the past until now. Mathematical fundamentals for flutter analysis are briefly presented. The flutter equation incorporates the aerodynamic forces into the structural equation and is expressed in generalized coordinates.

The review starts with the papers on historical developments in the field of a flutter from the early days until the present day. The control techniques in the field of flutter suppression are given in the subsequent section. Modern control schemes can be used for flutter suppression with varying successes. Control methods of many researches, such as Linear quadratic Gaussian algorithm, the proportional control, System Identification technique, Positive Position Feedback controller, pole placement method, etc. were presented.

Researches on piezoelectric and smart material as actuators and sensors are very active and promising area. This material can be used with adaptive control schemes which are suitable for the unpredictable environment around the aircraft.

The success of the clearance process for a new aircraft-related aeroelastic issue during the design and certification phases is a combination of numerical modeling and Computational Fluid Dynamics (CFD) and also confirmed by testing i.e. ground vibration test, wind tunnel test, structural coupling test, and even flight flutter test. These tests give the necessary information for the validation of the mathematical models used.

At present and future research, the control methodologies that employed the concepts of the active flutter suppression (AFS) is a promising area. It can sense or detect the changing flight conditions or disturbances and respond accordingly and properly which provides a powerful and effective solution to flutter problems.

And for the not-so-distant future, an ideal concept for flutter suppression is a morphing aircraft i.e. the aircraft can smoothly adapt the external shape to changing flight conditions or mission requirements. These concepts are based on the belief that new smart material will soon offer the required characteristics to create such structures e.g., the wing aspect ratio or wing area can be changed for different flight conditions. The research papers on this concept are widely available but beyond the scope of this article.

Acknowledgement

The Authors thank the department of mechanical engineering, faculty of engineering, Kasem Bundit university for all the supports.

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Article History:

Received: November 24, 2020

Revised: June 8, 2021

Accepted: June 11, 2021