An overview of methods for investigation of aeroelastic response on high aspect ratio fixed-winged aircraft

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Abstract. The thrust of increasing environmental and economic constraints on aircraft has enthused accelerated research in design of more economical and higher performance aircraft. Extensive experience in aerodynamic has established the use of high aspect ratio wings to improve the lift-to-drag ratio, a key parameter in determination of aircraft efficiency. Application of long slender wings has even more so intensified in the last decade due to emerging need for medium-to-high altitude long endurance (MALE/HALE) unmanned aerial vehicles (UAVs). However, such a wing comes at a trade-off of efficiency and safety. Longer wings tend of be more flexible and easily deform under load, hence are more vulnerable to the detrimental nature of aeroelastic effects. Divergence, control reversal and flutter are some major aeroelastic effects, which range from mere discomfort to complete destruction of body in flight. UAVs are most susceptible to this behaviour as their design incorporates very high aspect ratio wings. Numerous researches are available in literature which have focused on the explanation, calculation, and suppression of aeroelasticity; a subject which is as old as first heavier-than-air flight. This paper has attempted to cover the major aspect of aeroelasticity and summarize the state-of-the-art methods and approaches proposed by esteemed authors in this field for flutter prediction and suppression.

Keywords— Aeroelasticity; Aircraft; Divergence; Fixed-wing; Flutter; HALE; High-aspect ratio; MALE, UAV

1. Introduction

Aeroelasticity is an inter-disciplinary study of the combined effects of aerodynamic, elastic and inertial forces. It is the aeroelastic phenomena, which mostly puts a restrain on the flight envelop or more importantly, the maximum speed of flight for any vehicle (Figure 2). Aeroelastic effects can result in divergence, control reversal and flutter. Divergence is theoretically defined as the point where the aeroelastic twist of the structure becomes infinite and structure fails. If it is studied as a function of pressure, then aerodynamic pressure at which it occurs is known as the divergence pressure. At this point, the restoring forces of the elastic structure are not able to withstand the aerodynamic loads and eventually gives away. In control reversal, the effectiveness of the control surfaces, such as aileron is reduced, and further reversed from its intended functionality. Flutter is a dynamic aeroelastic phenomenon, in which the aerodynamic, elastic and inertial forces interact to create a diverging vibrational response (Figure 1).

When the parameters which characterize the fluid-structure interaction (FSI) reach specific values where flutter occurs, they are called the critical values. In terms of physical phenomena, flutter is the point where “the energy of the flow is rapidly absorbed and transformed into the energy of mechanical vibrations” [2]. Flutter absorbs energy from the surroundings by the virtue of the fluid flow interaction over its surface that rapidly increases the amplitude of vibration.
Aeroelastic behavior of an aircraft has to be avoided either by the design of structure or use some active/passive control mechanism that prevents or at least reduce the harmful effects. It is imperative to understand that the divergence, control reversal and flutter phenomena are an inherent property of structure and they cannot be eliminated. It can be observed even in many natural phenomena such as wings of birds, insects etc. The determination of its onset parameters such as speed on man-made machines helps to decide the conditions which should be avoided. Machines are designed such that aeroelastic effects initiate outside of the normal operating regime. Whole structure of aircraft deforms in flight due to the aerodynamic loads and its elastic nature, therefore, complete aircraft body should be treated as an elastic body rather than a rigid body [2].

Although the effects of aeroelasticity are experienced over the whole body of an aircraft, its manifestation is exhibited most vibrantly by the wings and tails. These areas are subject to aeroelastic effects the earliest and they are most prone to fail under these effects. High aspect ratio (HAR) surfaces are more susceptible to this effect as they inhibit higher flexibilities and hence experience greater deflection under load. However, high-aspect ratio wings are important from the perspective of aerodynamic performance. Such wings are widely used in many aircraft as they give better fuel consumption and thus higher economy, with less environmental pollution. HAR wings reduces the aerodynamic drag, which accounts for almost half of the total drag of transport aircraft flying at cruise conditions [3]. This aerodynamic benefit is even greater at slower speed regimes [4].

The concept of aeroelasticity is as old as the first aircraft, or even older than that [5]. Various tests such as Ground vibration tests (GVT), wind tunnel testing of dynamically-scaled model, theoretical analysis and flight flutter testing constitute an essential phase of aircraft design and development process. Researches aimed at devising improved models, approaches and method for such testing as well as techniques for suppression and control of aeroelastic effects are abundant in literature. It is still an active area essential for calculation, control and optimization of aeroelasticity, which is mandatory for certification and clearance of any aircraft, which is aspiring to take flight. All newly designed aircraft, or aircraft that goes through major modification in design or control system, or even has additional store attached to it, goes through this process of investigation.

Afonso et al. [6] discussed the various methodologies used to investigate the nonlinear aeroelastic effects which may arise due to nonlinearity in structure, aerodynamics and controls. Kehoe [7] presented a survey on the development of flight flutter testing techniques in which he discussed various in-flight excitation systems, instrumentation and data reduction methods which are used for the analysis of flight results. An overview of topics in aeroservoelasticity (ASE), computational and nonlinear aeroelasticity, rotary wing, and new technologies such as smart/adaptive structures are discussed by Friedmann [8]. Dowell et al. [9] provided a stability analysis on panel flutter, where
plate and shell geometries have been discussed separately in addition to the analysis over theoretical and experimental discussion over the subject. Collar et al [10] provided with a brief insight on decade wise advances in the field for the first fifty years of the introduction of aeroelastic concept. Anderson et al [11] presented a review of latest techniques, analytical approaches and hardware used for the implementation of active aeroelastic control (AAC) in flutter suppression of aircraft. Livne [12] provided a 50 years summary of research and development in the area of active flutter suppression. When it comes to aeroelasticity, literature is abundant in collections that have provided valuable reviews and surveys of previous researches, challenges and future work to be carried out in this everlasting subject [13–18].

![Figure 2. Figure shows a typical V-n diagram in which the flight speed (V) and load factor (G) boundaries are defined, that should not be exceeded to maintain structural integrity of aircraft.](image)

The current survey paper briefly discusses the major aspects of aeroelasticity on aircraft surfaces, particularly high aspect ratio wings that are most vulnerable to the detrimental nature of such effects. This includes the various analytical, computational, and experimental approaches as well as flight testing methods used for investigation, calculation and optimization of divergence/flutter boundaries that is of primary focus until present. Verification, validation, procedure-refining techniques on methodologies adopted to improve from previous mistakes and breakthroughs in research have been discussed. An analysis of methods proposed in the past for aeroelastic suppressing and expansion of flutter boundaries, which constitutes the subject of aeroservoelasticity has been summarized herein. The aim of paper is to extract reliable sources in the field of aeroelasticity that have provided novel methods and useful results. This would help readers better understand the phenomenon supported by results, and suggests the way forward for researchers interested in this area for a systematic and reliable study. Additionally, problems which continue to contest the advancement in fields of aeroelasticity and roadblocks to future developments have been discussed as challenges to this topic.

2. Analytical flutter analysis
Analytical flutter analysis can be regarded as the most powerful investigation tool as it allows for easy calculation of solution with variation of parameters. Hence it allows for a sensitivity study. Analytical analysis comes very early, whereas methods of experimental studies and flight-testing comes later in the design process. Therefore, analytically calculating the aeroelastic analysis of structure gives a good idea about the true behavior which is later evaluated using other approaches. The analytical process can be tailored in the later design phase when results from experiments and numerical analysis are available. Hence, after adjusting the analytical process, parametric and sensitivity studies can be carried out. The experimental setups are expensive and time consuming and can only be carried out for
certain cases. Flight-testing, considered as the most dangerous of any test, comes latest in the design process.

Aeroelastic analysis can be divided into fully linear, quasi linear (linearized) and fully non-linear systems based on the linearity of three subsystems; structure, aerodynamics and control [5]. However, only structure and aerodynamic system will be discussed in this paper. The aeroelastic problem of fixed-wing aircraft is primarily the coupling of bending and torsion modes, which is essentially a linear problem [8]. Dowell et al [19] compared the experimental and theoretical results of a thin slender (high aspect ratio) wing using nonlinear uniform beam theory [20] and aerodynamic model form of ONERA. The effect of geometric nonlinearity on aerodynamic stall and flutter, that comes from the ratio of the ratio of flap and chord wise bending stiffness, $E_{II}/E_{II}$. The flutter stability boundaries are reduced for higher values of this ratio. Lee et al carried out investigation of the flutter boundaries on the 2-D airfoil placed in potential flow under the influence of cubic restoration structural force [21]. Wong et al [22] and Gong et al [23] have applied the methods developed for coupled nonlinear mechanical systems to predict the response on an airfoil with structural nonlinearities. Lee et al [24] used the Duffing's equation to model and solve the coupled 2 DoF system with cubic nonlinearities in both DoFs; bending and torsion.

Steady-state problems pose simple equations, like $A\mathbf{m} = \mathbf{n}$, where $A$ is a square matrix. However, for equations such as $\frac{dv}{dt} = Av$, the solution is constantly changing with time, and hence cannot have a discreet value. The solution maybe simple sinusoidal, or continuously decaying or growing in nature. Hence, Eigen vectors or values are most significant in analyzing dynamic system. In eigenvalue framework, divergence occurs at the shifting of sign of real part of complex Eigen value. However, also the frequency at this point is 0 Hz. This is because divergence is a static phenomenon and it is not harmonic or oscillatory hence does not have any frequency associated with it. Flutter on the other hand is a dynamic phenomenon, which has a harmonic response that has an associated frequency with it. So in aeroelastic analysis, the sign-shifting of damping parameters with no frequency is the divergence point, and point with some associated frequency is the flutter point (Fig 3).

Not much emphasis has been given in the past to the optimization of flutter boundaries of structure, which is evident from the lack of research available in this area. Keeping some aspects constrained such as mass, area or geometry of the structure, the optimal values for the remaining parameters can be calculated to obtain the best possible objective function. Objective function in the case of flutter is dynamic pressure which is meant to increase. Particle swarm optimization is an effective approach to find the optimal solution of a problem by iteratively evaluating a problem and grading based on a given property or quality of system. It works in the same way as a swarm of insects. It was first proposed by Kennedy and Eberhert [26] and since then has been used by many research for optimal solution of their given problem. Researcher have applied this approach in the solution of their aeroelastic analysis to obtain parameters which would increase the aerodynamic pressure of aircraft, which is usually the single most significant design objective to achieve. Solution optimization of should be given its due significance as it provides good result with little or no trade-off.
Torabi et al. [27] carried out optimization of flutter boundaries for a trapezoidal plate made of FGM sandwich plates. They used first order shear deformation theory and piston theory for the modelling of FGM sandwich plates and aerodynamic pressure respectively. FGM plates consists of an isotropic interior metal core, sandwiched between FG sheets that has an Al2O3 ceramic rich exterior and Al rich metal interior. Transition between the materials is carried out using a power law function. Differential quadrature method (DQM) was used to solve the governing equations and boundary conditions for trapezoidal-shaped cantilevered FG sandwich plate in supersonic regime. Their result were optimized using particle swarm optimization (PSO), which yields the best values of plate design parameters. Their study proved that the adopted approach yields results with acceptable accuracy and fast convergence rate. This type of constrained optimization is quiet useful for designing of wings and tail of aircraft [28, 29].

3. Computational Aeroelasticity
Software that use computational methods for the solution of fluid flow are termed as computational fluid dynamic (CFD) and for structural analysis are called computational structural dynamics (CSD). Packages that couple these two tools for aeroelastic analysis are called Computational Aeroelasticity (CAE) software [30]. However, it is injustice to constrain CAE to such simplistic definition considering the extensive research which has led to its current state.

3.1 Fidelity of models
Advancement in computational capability has led to the development of higher fidelity models. However, the type of models to be selected depends on factors such as the complexity of structure, accuracy requirement, computational time, and available funding for the project. Low-to-medium fidelity models are used at the initial levels of analysis for quicker results which help to make bigger decisions in the design process. Once the design process is finished, refined and higher fidelity models are employed for capturing of detailed aeroelastic picture which is not adequately addressed in low fidelity models. However, using discretization methods (FE) with potential flow aerodynamics in inviscid, incompressible and low compressible region is ideally used in medium fidelity models. For aerodynamic modelling, either 2-D strip theory, 3-D lifting surfaces theories or 3-D panel theories (incorporates thickness) maybe used depending on the requirement [31]. Doublet lattice Method (DLM) is considered most popular for flutter prediction [32, 33]. Higher fidelity CFD models are restricted to Euler (inviscid) and Navier Stokes equations (viscous) [34, 35].

3.2 Meshes
Meshing of geometries is carried out either using structured or unstructured methods. Structured mesh offer better computational efficiency and does not require a connectivity matrix for solution. Unstructured meshes are easier to use for complex configurations as it reduces the human and computational effort [30]. Researchers are expected to have sufficient knowledge about mesh refinement and areas where it needs to be incorporated for capturing of relevant phenomena. FSI packages are designed using adaptive algorithms, which try to adjust according to requirement. Still some input and care by the user is required to ensure accuracy of results.
4. Experimental analysis
A single approach to research in an area is never considered reliable unless the researcher has some reference values from which the result of that study can be compared. A validation in the approach and methodologies adopted needs to be carried out to convince the readers about the validity of the results. In the case of aircraft, it becomes even more so important because a single approach, no matter how rigorous, is not dependable in any area. The next step in aeroelastic investigation of aircraft is experimental study, in which reduced models are used for wind tunnel experiments or flight flutter testing (or both). The scaling is done to adjust the size of model inside the test section of wind-tunnel. Ground vibration test is done prior to wind-tunnel experiment to determine the modal behaviour of scaled down model. These tests provide a valuable insight in the behaviour of structure, which otherwise is left unexplained in numerical study. The experimental results not only provide answers in a short span of time, but also assist in adjusting and aligning the development of its theory and numerical model.

4.1 Aeroelastic scaling
Downscaling of life-sized model is carried out to accommodate the model inside the limited space of test sections as wind-tunnel experiment of full-scale model is not feasible. Sizing has to be done with regards to scaling laws so that the behavior of the actual model can be reproduced. Beside researches, wind tunnel tests are also carried out for testing of modifications, testing of active-control, and mandatory for flutter clearance requirement. Classical scaling techniques have been compiled by Bisplinghoff [37] for linear aeroelasticity, however, literature is not very abundant in research for nonlinear scaling methods. Recently some work has been done in this area due to the increasing use of high aspect ratio wings [38]. Bond et al. [39] was able to match the first natural frequencies of first three modes, their mode shapes and damping ratio for non-linear aeroelastic scaling. Cesnik et al [40] used nonlinear stiffness matrix to account for the geometric nonlinearities and concluded that the Froude number should be catered for scaling structures. Spada et al [41] presented an updated version on Ricciardi et al [42] and compared his results with classical scaling techniques to prove their methodology gave better flutter speeds, frequencies and other modal results. For cases where flutter response is of primary interest, one should ensure that the rigid and dynamic modes remain same for reduced and full scale model.

4.2 Ground vibration tests (GVTs)
Before moving on to conducting wind-tunnel experiment of flight testing of aeroelastically reduced scaled models, it is recommended to first carry out model updation and validation through ground
vibration tests. Research on the GVT methodologies on high aspect ratio wings is scarce in literature as the dynamic response for high aspect ratio wing aircraft is difficult to analysis as compared to a conventional aircraft. The method has become even more difficult with the introduction of complex design in structures and use composite materials in the inner structure of wing [43, 44]. NASA has played a key role in analysis of such cases under project PAAW (Performance adaptive Aeroelastic Wing) in which GVT of a flying wing aircraft is presented [45]. While many researches have focused on assessing the presence of non-linearity, very few have actually suggested ways in which it could be addressed [46].

4.3 Wind Tunnel Experiments
Wind tunnels provide a closed environment for a controlled study of wing. Some safety aspects need to be covered to ensure the safety of model as well as the wind tunnel. Results from wind tunnel helps to validate the numerical and theoretical models. Reliable extraction of data from wind tunnel requires carefully calibrated mechanisms, and a sensitive measuring, and excitation device. A choice of model support system for mounting of model also needs to be considered to effectively capture aeroelastic trends. Sting mount and side-turn table was suggested by Ricketts et al [47] as the simplest form of support. Traditional wind tunnel tests in which the aircraft is constrained are not suitable for a high aspect ratio wing aircraft SU et al. [48] as it does not allow for the coupling of rigid and dynamic structural modes. Keeping in view, a support that caters for the flexibility of the structure is proposed by Tang et al. [49].

4.4 Flight Flutter Tests
For commercial airliners, it is the requirement of aviation regulation authorities to prove through flight-testing that aircraft is free from aeroelastic effects well beyond the normal flying envelop of aircraft so that safety of vehicle as well as passenger(s) is ensured. UAVs and drones are also flight tested for flutter to ensure airworthiness of wings and testing of any applied controlling technique. It is imperative to carry out flutter test on new aircraft, or aircraft that has undergone structural and/or controls modification. Even the installation of additional external stores on aircraft such as drop tanks or missile necessitates the need for flight-testing. Flutter flight test is one of the most dangerous in aviation. Data is collected through various sensors such as accelerometers attached on aircraft. The structure is excited for its vibration modes. Using data, the damping characteristics and how it changes with flight conditions is evaluated [7, 50]. There is a damping response of each mode, and some modes are highly damped whereas some modes are not. The point where the mode damping becomes equivalent to the structural damping is the flutter point for that mode, and beyond this point, amplitude of self-excited oscillation continues to increase and aircraft enters into flutter. The point where this damping occurs at the lowest aerodynamic pressure is obviously the most important and the restricting

Figure 5. An example of structural and aerodynamic modelling of launch vehicle for computational flutter analysis is shown [36].
factor of maximum aircraft speed.

For flight flutter test, pilots are briefed to attain the targeted speed, and keep going until flutter is experienced. Actually, the purpose is not to enter the flutter domain, but come close to it as it only takes a matter of seconds for a structure to completely disintegrate if it flies past the flutter boundary. Therefore, the pilot or controller in case of UAV always approach flutter speed and sense the points where they start to feel discomfort in the aircraft behavior. The speed of aircraft at which this indication occurs is noted and is regarded as the never exceed speed. The normal operating range of aircraft is set well below this point. Results of flight flutter testing are rarely report in literature. Kehoe [7] presented a survey on the development of flight flutter testing techniques in which he discusses various in-flight excitation systems, instrumentation and data reduction methods which are used for the analysis of flight results.

5. Active Flutter suppression

Traditional passive flutter suppression techniques such as mass balancing and local stiffening are inefficient as they add to the overall weight of structure [51]. Perhaps the only remedy to reduce the detrimental nature of flutter without any design modifications in the long span wing of MALE/HALE UAV is the introduction of an actively controlled mechanism in the system. Extensive research in this area has been carried out in the recent years, where a suitable feedback system continuously monitors some parameters on the vehicle and accordingly adjusts an actively controlled mechanism that prevents or delays the onset of flutter. An example of such system would be the movement of control surfaces according to a control law, which relates the motion of the surfaces with the dynamic pressure over the wing. The forces are modified in such a way that the structural turbulence is alleviated and hence the safety margin is increased. Recent flight test demonstrations, wing tunnel tests and analytical works have shown promising results.

Implementation of hydro-servo systems for active control techniques used in surface deflections such as flaps, aileron, elevens etc. are accompanied with problem of response time. Hydraulic actuator movement is sluggish, and not quick enough to immediately address flutter onset or gust alleviation. Hence, such a system cannot cope with high frequency oscillations. Lu et al. [52, 53] have contributed in the study of thin airfoil flutter suppression using active acoustic excitation. Acoustic devices have the advantage of simple hardware implementation, large frequency range and most importantly the very quick response which is essential in dealing with high frequencies on oscillating body. They [53] have shown in paper that a simple loudspeaker can be appropriately adjusted to stabilize an airfoil experiencing flutter. The incident acoustic wave interacts with the trailing edge to produce favourable vortex shedding that suppresses the flutter motion. The location of source field, gains constants, and phase of gain constants plays in significant role in the acoustic control design.

The thrust of research in smart structures has led to the used to such materials in giving continuous structural deformation of the wings and other lifting surfaces which can be used to alter the unsteady aerodynamics loads and suppress flutter. Several studies on the use of piezoelectric materials in static aeroelasticity as well as suppression of flutter using piezoelectric actuation are available in literature. Much of its potential is demonstrated through wind-tunnel tests for incompressible flow which are available in literature.

Friedmann et al [54] have shown using piezoelectric actuation, increase of dynamic pressure by as much as 12%, hence improving the flutter margin. Despite having a substantial potential of piezoelectric actuators in aeroservoelasticity, not much research on the scaling of such actuators have been carried out which would relate the behavior of actual wing with that a different sized models. Moniz et al [55] devised a novel scaling technique for flow in compressible regimes in which feedback control using piezoelectric actuators, or conventional trailing edge flaps are used to control and extend the flutter margin.

6. Morphing aircraft
All aircraft ever made are subject to a range of flight conditions such as during climb, descent, cruise, maneuver, and landing/taking off. A wing that operates optimally at all these varying speeds and environments does not exist. Therefore, aircraft designers use wing that operates most efficiently in the dominant part of the vehicles flight and operates sub-optimally at other regimes. Small and low aspect ratio wings allow for higher speeds and better maneuverability but have poor aerodynamic performance. High aspect ratio wings such as those used on MALE/HALE UAVs may offer good range and efficiency, but lack maneuverability and are prone of flutter at higher speeds. Advancements in materials, structural concepts, methods of actuation, and MIMO (many input many output) system has motivated research and development of variable-shape vehicles; the morphing vehicles [14, 56, 57]. Multidisciplinary optimization (MDO) is obtained through the integration of smooth shape variation, major planform change, smart actuation and active flow control system to obtain desired flow patterns in areas of geometric and flow discontinuity. These features distinguishes the morphing airplane from conventional shape-changing aircraft, which considers limited shape-variations in sweep, camber, and dihedral angles. A novel concept for a simple wing morphing technique was proposed by Gamboa et al. [58], in which the span of a composite wing was made to change in flight. Wing consisted of an inboard part, housing smaller, moveable outboard moving part that is slid using servomotor. It was shown that the safety margin was flight speed was improved by 44% A gear driven autonomous twin spar (GNATSpar) was used by Ajaj et al. [59] in which inner space of opposite wing is used to house the unused length of the spar. Spar extends and retracts based on velocity feedback that in turn changes the wingspan. Lift to drag ratio of the wing was increased by 30% without any aeroelastic penalty.

Though a promising technology, manufacturers are still skeptical of benefits offered by morphing mechanism to adopt in their design [60]. Many interesting concepts for application of morphing technology in airplane have been proposed, but very few have actually been proven through wing tunnel testing and even fewer have flown. Morphing wing system is also accompanied by an additional weight penalty, which must be overcome.

7. Conclusion
Credit for the creation of engineering marvels likes the F-16 and Concorde commercial aircraft goes to the generations of aeroelasticians who have brought aeroelasticity to its current state. Surely, the biggest constrain in the desire for higher speeds and more economy comes from the grave nature of aeroelastic effects. Any contribution in the solution for the challenges posed by this field is considered a breakthrough. Sincere efforts must also be put in to preserve the work of past challenges, their breakthroughs and lesson which come from extensive experience. It is indeed a rich and complex multidisciplinary field and it is difficult to cover the details of every area within the confines of this paper. However, the present paper is an educational effort that is aimed to compliment recent surveys
with minimum overlap. Topics of various methods employed for the study, calculation and suppression of aeroelastic response in general and flutter in particular have been considered. The targeted audience of this survey are novice researchers in this field, which intends to allow them to grasp the basic idea of this phenomena as well as identify the gaps, which would lead readers in direction of active research. This survey paper has effectively discussed topics of analytical, computational, and experimental techniques, aeroservoelasticity and aeroelastic design optimization of high aspect ratio wings. Paper contains reference to further surveys and researches, which should be read for an extensive insight on a particular subject. Aeroelasticity is an extensive field, not bound by the limited areas touched upon in this paper. Despite its history, topic of aeroelasticity is far from saturation, and there exists a wide area in all headings highlighted in this paper, where a great potential for research exists.

8. Recommendation
In most flutter investigation, the immobility of fuselage is considered which neglects any rolling motion of the plane, so that the wing motion is entire due to its structural deformation. The inclusion of fuselage mobility could be included in future research, which accompanies an additional degree of freedom. Although the complexity of the problem would be increased, study could be carried out to determine the extent to which the results are improved. A research gap is observed in the GVT of scaled models in which research for checking the presence of non-linearity in high aspect ratio wings is available, however methods to address those non-linearity are scarce in literature. Active control system such as piezoelectric actuation provide a novel solution for suppression of static and dynamic aeroelastic effect on wings. Validation of its effect on scaled model through wind tunnel testing requires scaling. No significant work has been reported for the aeroelastic and aeroservoelastic scaling since the 1960s. Future research could be focused on suggesting ways in which the scaling of actuation systems could be carried out so that the response on full-scale models could be predicted. Active research in smart materials that utilizes the advancements in material and structures technology, aerodynamics, sensing, actuation and control system for multidisciplinary design optimization (MDO) should be encouraged. Morphing wings allow for major shape variation throughout the flight envelop which is well beyond the old, conventional variable-shape vehicles that holds great potential in drastic flutter suppression and prevention, which is most imminent for application on UAVs.

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