AIAA SciTech Forum
9 - 13 January 2017, Grapevine, Texas
55th AIAA Aerospace Sciences Meeting

10.2514/6.2017-0463

Design and Optimization of Unconventional Aircraft Configurations with Aeroelastic Constraints

Anil Variyar[*], Thomas D. Economon[†], and Juan J. Alonso[‡]
Stanford University, Stanford, CA 94305, U.S.A.

The focus of this paper is the inclusion of aeroelastic constraints in the conceptual design loop for conventional and unconventional aircraft design. For configurations like the strut-braced wing, aeroelastic (flutter) instability is a major problem, and the inclusion of aeroelastic constraints early in the conceptual design phase is essential in order to ensure that the design obtained is flight safe. In this paper, we first describe the design tools and their development for performing aeroelastic calculations (static,gust and flutter). The paper then describes a multi-fidelity approach to obtain accurate, yet inexpensive, aeroelastic predictions including flutter speeds. Finally, these aeroelastic predictions are included in the design loop as constraints for the design and optimization of a strut-braced wing configuration.

I. Introduction

Over the past few years, increasing global concern over the environmental impact of emissions coupled with the energy crisis stemming from the shortage of fossil fuels and soaring fuel prices has made reducing emissions and fuel burn a major focus of the transportation industry.[1–6] With the aviation industry contributing significantly to the transportation-based emissions, the pressure on aircraft manufacturers to come up with reduced-emissions aircraft has increased substantially. A possible introduction of emission taxes is another incentive for airlines to move towards environmentally friendly aircraft. The fact that fuel costs now account for forty to fifty percent of the direct operating cost also adds to the increased urgency in the airline industry to come up with energy efficient aircraft technologies.

While individual system or component improvements, such as boundary layer ingestion,[7] open rotors,[8] or electric propulsion systems, are being studied in great detail, and system level effects[3,9,10] are also being looked at, there is a belief that a shift away from the conventional tube-and-wing aircraft configurations to radical configurations like the blended-wing body and the strut-braced wing[11] can result in a much greater reduction in fuel burn and emissions.[12] Preliminary studies and wind tunnel tests on both the blended wing body and the strut-braced wing have shown promise with respect to fuel burn reduction. However, questions related to stability and control and aeroelastic stability for these configurations still persist.

Aeroelastic analysis is mostly performed as a post-processing step in aircraft design. Typically, the aircraft structure is designed with simple structural constraints, and then aeroelastic stability (flutter speed evaluation) is verified at a large number of load cases. However, if the final design is found to be aeroelastically unstable, either during later design stages or during the testing phase, then the cost incurred in revisiting and correcting the design can be extremely high. In most cases, simple structural strengthening is performed that offsets most of the efficiency improvements predicted during the conceptual/preliminary design stage. Therefore, the inclusion of aeroelastic constraints in the conceptual/preliminary design loop and accurate prediction of the aircraft's primary structural weight is critical, especially for unconventional configurations whose aeroelastic responses are unknown.

A previous paper by the authors[13] looked at the effect of FEA-based primary structural weight estimation of the strut-braced wing. Work on the application of the aeroelastic constraints to the design of a blended

*Ph.D. Candidate, Department of Aeronautics & Astronautics, AIAA Student Member.
†Postdoctoral Scholar, Department of Aeronautics & Astronautics, AIAA Senior Member.
‡Professor, Department of Aeronautics & Astronautics, AIAA Associate Fellow.

wing body has been performed by Gern et al.[14] There have also been feasibility studies on the strut-braced wing,[15–20] and studies that look at the computation of flutter parameters for strut-braced aircraft configurations[21] and design with flutter constraints.[22,23] The work presented here describes a physics-based approach for the accurate, yet inexpensive, prediction of aeroelastic instability (flutter speed) using multi-fidelity simulations and the inclusion of these as design constraints in the conceptual/preliminary design process.

The design tools developed for this purpose are described in great detail in Section II. Section III describes how aeroelastic constraints (including flutter) are introduced into the design loop. Section IV describes the validation studies performed on simple wing configurations and design and optimization results for simple wing and strut-braced configurations.

II. Methodology

This section describes in detail the design methodology developed to perform design optimizations on unconventional aircraft with the inclusion of aeroelastic constraints. Section II.A gives an overview of the overall framework used for the study, section II.B introduces the conceptual design tool used, section II.C describes the computation of the aeroelastic parameters (flutter speed), and section III describes the formulation of the aeroelastic constraints.

A. Aeroelastic Design Framework

The overall design framework used for this study consists of SUAVE,[24] a multi-fidelity conceptual design framework, which is coupled with ASWING[25] using an aeroelastic analysis driver, pyASWING (developed as part of this work), described in Section II.C. The aeroelastic analysis tools can be directly linked to python-based optimization packages like Scipy,[26] VyPy[27] and pyOpt[28] using pyASWING's optimization interface or via the optimization interface available in SUAVE for mission-based optimizations of full aircraft. A schematic of the overall aeroelastic design framework is shown in Figure 1, and the components of the framework are described in the subsections below.

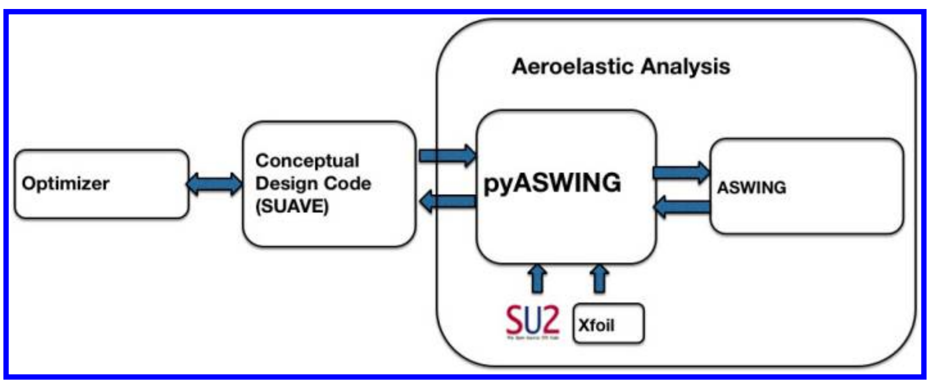

Figure 1. The diagram shows the organization and flow of control in the Overall Aeroelastic Design Framework

B. SUAVE

SUAVE[24,29] is an open-source conceptual design framework under development at the Aerospace Design Lab at Stanford University. It allows the definition of arbitrary aircraft configurations as a collection of wings, fuselages, and engines along with the definition of multiple missions composed of customizable segments. It has modules for the computation of aerodynamics, weights, propulsion, stability, and mission performance parameters, e.g., take-off and landing field lengths, for conventional tube and wing as well as unconventional configurations. SUAVE also has a built-in optimization interface which allows it to be coupled in an efficient way with Python optimization packages, such as pyOpt, VyPy and Scipy.

For this study, the aircraft (strut-braced wing) is defined in SUAVE, and the basic analysis modules, mission solver, and optimization capability are leveraged. The modularity of SUAVE, its ability to integrate external modules, and the ease of setting up multi-fidelity calculations are all leveraged in order to link in the new aeroelastic analysis capability developed as part of this study and to perform optimizations with flutter constraints. Figure 2 illustrates how the analysis modules in SUAVE are supplemented by the aeroelastic tools. Each mission in SUAVE is built of mission segments that consist of evaluation points where performance analysis is performed. The aforementioned analysis modules are queried by the mission solver at each of these mission segment evaluation points. The results from the aeroelastic analysis tool are fed back to the aerodynamic, weight/structural sizing, and aeroelastic analysis modules where they are supplemented by correlation-based methods for drag prediction and secondary (and other component) weight predictions. These outputs are then used by the mission solver for the prediction of the overall aircraft performance or fed back to an optimizer for use as objective or constraint values when driving full aircraft optimization problems.

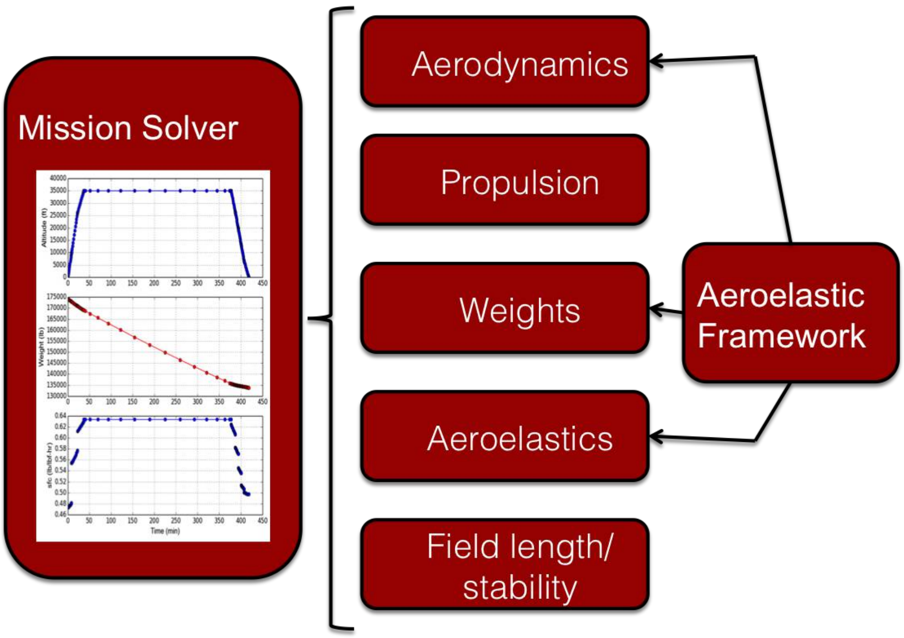

Figure 2. The figure illustrates the data flow between SUAVE and the Aeroelastic Analysis Framework(ASWING)

C. Aeroelastic Analysis

The inclusion of aeroelastic predictions in the design loop is the main focus of this paper. The aeroelastic parameters of interest (flutter speed, damping ratio, and gust response) and aero-structural parameters (stress, lift, and drag) are computed using ASWING with a Python driver framework (pyASWING) serving as a pre- and post-processor to ASWING. Figure 3 shows the flow of data in the aeroelastic analysis framework. The pyASWING tool serves as the driver for the analysis. It parses aircraft geometry information and then drives the computation of more detailed geometric and structural parameters (needed by beam models) required for ASWING execution. The flexible framework permits the definition of arbitrary configurations, which makes the analysis of unconventional configurations easy and robust. The computed properties are translated into the ASWING input format, and once the evaluation conditions are defined, the geometric parameters and conditions are passed on to the evaluation functions that act like interfaces to ASWING. Interfaces for the computation of static aero-structural solutions, fully unsteady gust response predictions, and flutter speed predictions have been developed. These functions communicate with ASWING in an automated fashion to obtain the performance parameters of interest. Sections 1 and 2 describe this in more detail.

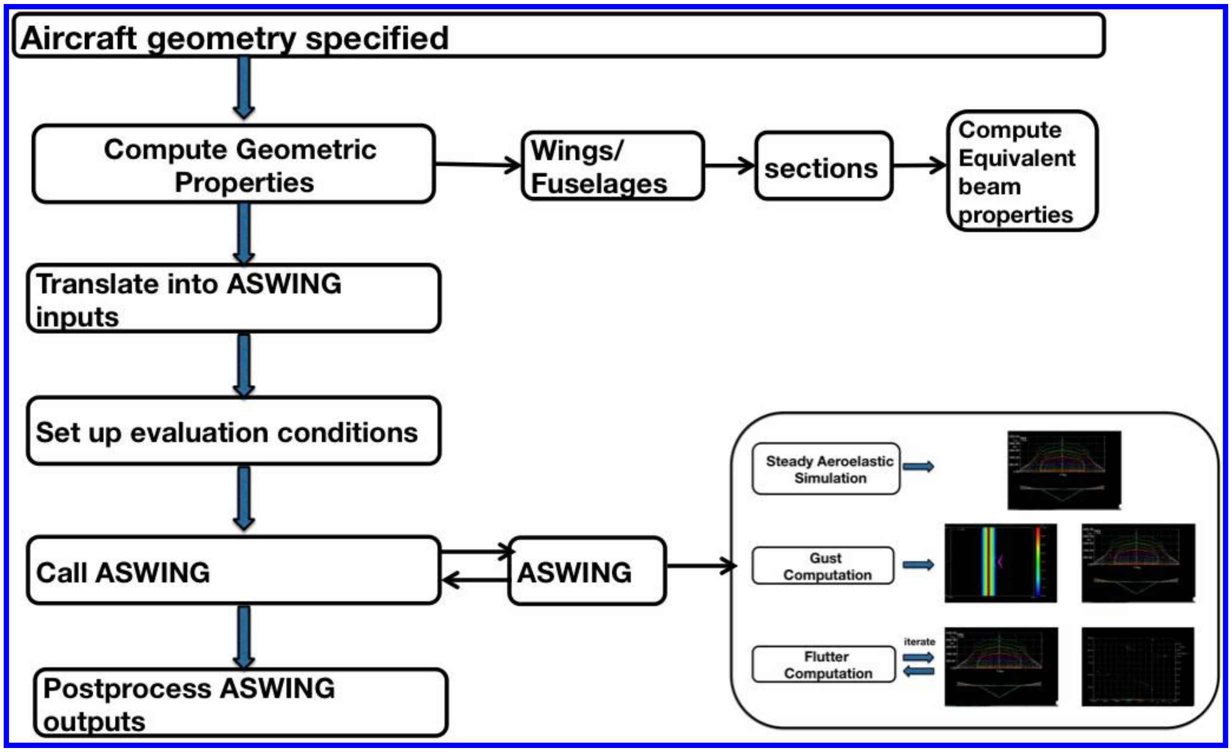

Figure 3. The diagram shows the data and control flow in the Aeroelastic Analysis tool with ASWING and pyASWING

1. *ASWING-Based Flutter Computation*

Aeroelastic computations for wing and aircraft configurations are performed using ASWING,[25,30,31] an aero-structural analysis tool developed by Mark Drela at MIT. The tool uses an unsteady Prandtl lifting line formulation for the aerodynamic analysis of configurations. The wing and fuselage structures are modeled as nonlinear beams. To compute the aeroelastic parameters of interest for a given configuration, first the atmospheric conditions and corresponding free-stream velocity are specified (defined as an evaluation point). At each evaluation point, the static aeroelastic solution is first computed. For simple static evaluation conditions in our framework, the evaluation is terminated at this point, and the results are returned. For gust simulations, the gust is defined using user defined parameters (gust velocity and gust gradient), and then a fully unsteady simulation is performed. Here, the aircraft is flown through the gust, and the results at each point in time are returned. For flutter computations, the static solution is first computed, and then the aero-elastic eigenmodes of the deformed configuration are obtained. This can be done for multiple evaluation points as well. The eigenmodes, deformations, and stresses corresponding to each evaluation point are returned to pyASWING where they are post-processed to compute parameters of interest, such as the flutter speed and failure condition. The reference manuals of ASWING[25,30,31] give a detailed description of its capabilities.

2. *ASWING Driver (pyASWING)*

The pyASWING module is a stand-alone Python module that automatically transforms an aircraft conceptual model, such as the one defined natively by SUAVE, into an equivalent beam model, as shown in Figure 4. The aircraft is broken down into a collection of wings and fuselages, which are further divided into sections. For a wing or fuselage section, the section geometry in terms of airfoil coordinates at different span-wise locations, the number of ribs, and the skin and rib thicknesses are specified by the user (in this case, from SUAVE). The pyASWING interface computes the structural properties at each section automatically, as described in Section II.C.3. For wing configurations, the aerodynamic properties of the airfoil (C_{L0}, dC_l/d_α, C_m) at each span-wise section, computed as described in Section II.C.3, are also parsed by the interface.

The interface then generates a .asw input file automatically for ASWING. Once the conditions at which the aeroelastic solution needs to be computed are specified (either directly or by a root finder), the 'evaluate' function is called, which executes ASWING with the specified input geometry at the specified conditions. ASWING returns the beam stresses, displacements, and aeroelastic eigenvalues, which are post-processed to compute the total stresses and aeroelastic parameters (damping ratio and damped frequency).

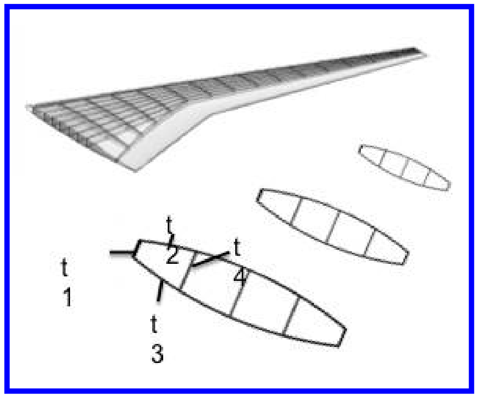

Figure 4. Beam model generation from aircraft, t1, t2 etc are the section member thicknesses which are used as design variables in structural sizing/optimization

Static and gust evaluation are straightforward and do not require iteration with ASWING. To compute flutter speed, however, the 'evaluate' function will be driven by a root solver (root solvers in Scipy[26] are used) that iterates between different flight velocities or atmospheric conditions to find the point at which the aeroelastic eigenvalues cross over to the positive real axis.

3. Computing The Structural Properties

The structural properties at each span-wise section of each wing or fuselage component are computed numerically. Once the section airfoil geometry, the number and location of the ribs, and the shell thicknesses are known for a section, the shell structure is discretized into 2D trianglular elements, and the structural properties (EI, GJ, EA, etc.) are obtained.[32] The bending stiffness, the rotational inertia, and the weight of each section are found by computing the properties for each mesh triangle and then appropriately summing up the contributions.[32] To compute the torsional stiffness, a numerical torsional shear flow analysis[33] is performed, and the elastic axis (shear center) is computed with a numerical flexural shear flow analysis.[33] The pyASWING framework has been developed to do this in an automated manner for each section with any airfoil geometry.

Once the structural and aerodynamic properties at each section are computed, the properties of the different sections are assembled together to form the sectional properties of the parent component (wing or fuselage).

4. Computing The Aerodynamic Properties

To compute the aerodynamic section properties, we use XFOIL[34] or SU2.[35,36] A database of the lift-curve slope (dC_l/d_α), the lift coefficient at zero angle of attack (C_{L0}), and the moment coefficient (C_m) for different sets of conditions and airfoils is generated and used as input to the interface at initialization. During evaluation at each section, the aerodynamic properties corresponding to the airfoil type, chord, and angle of attack at the section are used. While CFD data can be used to improve transonic predictions, in this work, transonic/compressibility effects from CFD have not been used. A Prandtl-Glauert correction is used to account for compressibility.

III. Inclusion of Aeroelastic Constraints

A. Flutter Speed Constraint Formulation

The inclusion of flutter constraints (flutter speed) in the aircraft design optimization loop is critical to this study. Thus, for a given set of atmospheric conditions, the flutter speed is computed using the aeroelastic analysis methods described in Section II.C in an automated fashion. The flutter speed constraint shown in Equation 1 is added to the larger set of aircraft optimization constraints to ensure appropriate structural sizing:

$$g_i(\mathbf{x}) = f_i - 1.2 * V_D \geq 0, i = 1, \ldots, N, \tag{1}$$

where $g_i(\mathbf{x})$ is the i_{th} constraint, f_i is the computed flutter speed at the flight condition i, V_D is the dive speed at the appropriate flight condition i, and N are the number of conditions at which the flutter constraints are enforced.

B. Stress Constraints

Stress constraints are imposed at the maneuver load conditions (2.5g and -1g maneuver) and the 2g taxi bump load condition. Stress constraints due to gust loads are also imposed. For the FAA FAR-based critical gust conditions (Table 6), the aircraft is flown through the specified gust, the stress are computed at each point in time, and the maximum stress from all of the gust conditions at all points in time is obtained and chosen as a stress constraint.

C. Multi-disciplinary Design Optimization (MDO) Architecture

In order to perform optimizations in an efficient manner, appropriate management of the sensitivities of the flutter speed with respect to the design parameters (geometric parameters and thicknesses) is important. In this study, the MDO problem is formulated by solving the optimization problem as a global one, where the structural thicknesses are included along with the aircraft-level design variables (wing span, sweep, etc.). The stress and flutter constraints are included as part of the global constraints (such as take-off and landing field lengths, etc). The aeroelastic analysis module returns the flutter speed and the maximum stress due to taxi, maneuver, and gust conditions, which are constrained to meet the feasibility requirements. The sensitivities of the objective and all of the constraints in the global list are obtained by finite differencing the global problem. This implies that the aircraft need not be feasible (structurally, or any other feasibility requirement) at each evaluation point. However, the finally converged solution is feasible and optimal for the given analysis fidelity, design variable, and constraint choice. This is a risky approach in that if the optimization does not converge, then none of the intermediate solutions are guaranteed to be feasible (so even an improved design might not be obtained). In practice, the design tool converges robustly in most cases, and the cost reduction obtained by this approach is significant.

IV. Results

A. Analysis/Validation Of Flutter Tools

Detailed validations of the aero-structural capabilities of ASWING have been published previously,[25] and therefore, they are not described here again. Only the studies performed for validation of the flutter analysis and optimization modules and interfaces are described below.

1. Wing Cases

First, the flutter analysis modules are validated using simple wing-only models, the Goland Wing[37] and the Agard Wing.[38] The Goland wing is a rectangular wing with its geometry and structural properties specified in Table 1. The Agard 445.6 is a swept and tapered wing for which experimental flutter data is available. Flutter speeds are evaluated for both these wing models (shown in Table 2) and the results agree fairly well with available data.[37–43] We now move on to optimizations for the simple wing configurations and then to a more complicated problem: the analysis and optimization of a strut-braced wing configuration.

Table 1. **Goland and Agard 445.6 Wing Geometry and Structural properties[37–39]**

Properties	Goland Wing	Agard 445.6
Wing Span (m)	6.09	0.762
Wing root chord (m)	1.83	0.56
Sweep ($degrees$)	0	45
Taper	1.0	0.66

Table 2. Flutter validation Data

Case	Computed Flutter Speed (m/s)	Validation Data(m/s)
Goland Wing	161.05	137,[41] 164,[42] 165[43]
Agard Wing (weakened)	284.8	310[38]

2. Weight Minimization Of A Wing With A Flutter Speed Constraint

Now that the aeroelastic analysis tools and the interface for automation have been validated in Section IV.A, we move on to design optimization using flutter constraints. We first test the framework with the optimization of a simple wing configuration for weight minimization while ensuring flutter stability, as described in Equation 2. The wing skin and rib thicknesses are chosen as the design variables, as shown in Figure 4.

$$\min_{\mathbf{x}\in\mathbf{R}^N} (\text{Kg fuel}(\mathbf{x}))$$
$$\text{such that} \quad g_i(\mathbf{x}) \leq 0, i = 1, \ldots, M, \tag{2}$$

where $\mathbf{x}$ is a vector of the design variables (shown in Table. 3) and $\mathbf{g_i}$ are the constraints (shown in Table 3) enforced to ensure feasibility of the design. We start optimization studies with the Agard configuration described in Section IV.A.

Table 3. List of the design variables with bounds for the Agard wing case

	parameters	lower bound	upper bound
Objective	Weight		
Design Variables	Shell thickness (m)	0.0008	0.09
Constraint	Flutter Speed (m/s)	>=flutter speed constraint	

The optimization problem is run with 3 different flutter speed constraint values as shown in Table 4. Two of the speeds (200 and 250 m/s) are speeds lower than the baseline predicted flutter speed for the configuration, and as expected, the wings become lighter with redesign. The third speed is larger than the baseline predicted flutter speed. As the flutter speed constraint is increased, the wing thickens, and so its weight increases. For all three cases, the flutter speed constraint is active. The Agard wing is flutter sensitive, so redesigning with just stress constraints (no flutter) could result in an infeasible wing that would flutter at very low velocities.

The next optimization study investigates the effect of increasing the number of design variables. The wing is parameterized by dividing it into n span-wise sections with each section having an upper and lower skin and $n + 1$ ribs (Figure 4). Each of these $2n$ skins and $n + 1$ ribs are chosen as design variables. Table 5 shows the results of optimizations performed with increasing n. As expected, increasing the number of design variables allows the wing sections to be sized better, with the sections that contribute less to stress or flutter becoming thinner and the critical sections staying thicker. Thus, as the number of design variables increases, the optimal wing weight decreases.

Table 4. **Increasing the flutter speed constraint.**

Flutter Velocity (m/s)	percentage weight reduction
200.0	58.7
250.0	36.5
300.0	14.16

Table 5. **Increasing the number of design variables.**

no of design variables	weight reduction
4	36.5
8	52.9
12	67.5

B. Design/Optimization Of A Strut-Braced Wing Configuration

1. Structural Sizing/Optimization Of A SBW With Aeroelastic Constraints

Now that we have performed validation and optimization case studies (tests on the effect of the flutter speed constraint and the number of design variables) on the simple wing configurations and understand the behavior of the design variables and the flutter constraint, we look at the structural sizing of a strut-braced wing aircraft configuration. The Sugar-Volt aircraft configuration[11] is selected. Basic geometric parameters parameters are shown in Table 8. A snapshot of the wing-strut configuration modeled in ASWING is shown in Figure 5.

For this case, the geometry of the aircraft is held constant. The element thicknesses are the only design variables, and these are optimized to get the optimal primary structural weight of the wing-strut combination with the appropriate stress and flutter constraints applied. The fuselage and the tails are not modified. Only the primary structure of the wing and strut are allowed to change. First, only the stress constraints associated with the static (maneuver) and gust conditions (loads) are applied to the structural sizing. Then for the second case study, a flutter speed constraint at cruise (flutter speed less than 1.2 V_D) is applied, along with the stress constraints at the maneuver and gust conditions. The load cases used are shown in Table 6. The results for both cases are shown in Table 7.

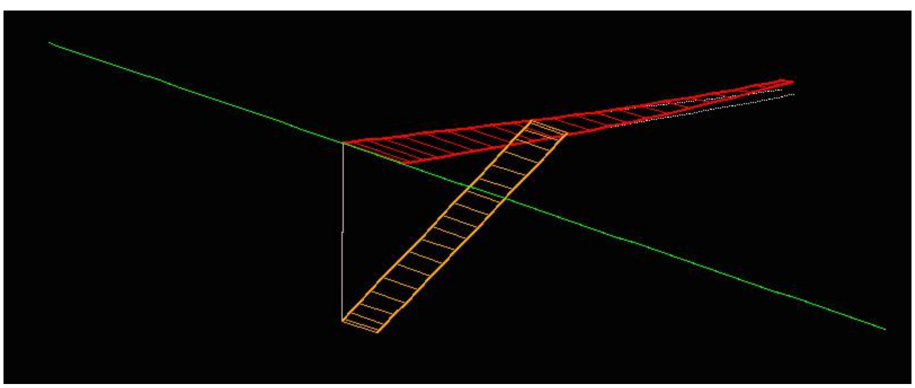

Figure 5. ASWING model of the strut braced wing.

A naive initial guess (same value for all design variables) is chosen to ensure a feasible design. The structure is over-designed as the structural weight indicates, but it meets the stress and flutter constraints, none of which are active. For the first sizing case (stress-only), the results indicate that the wing structure can be made a lot thinner with a significant weight reduction while meeting the stress constraints. At the optimum for this case, the stress constraints are active, but met. However, as a flutter constraint is not enforced, it is observed that the "optimal design" does flutter. For the second case study with the flutter conditions applied at cruise, it is observed that in order to meet the flutter constraint, the wing structure has to be strengthened, resulting in an increase in primary structure weight compared to the first case without a flutter constraint. Here, the optimum meets both the stress and flutter constraints, and the flutter constraints are active for the optimal solution, while the stress constraints are met with ease and are not active. These results indicate that the inclusion of flutter speed constraints could be critical for realistic sizing of the primary structure.

Table 6. Load cases for the SBW sizing and SBW Optimization Case.

Static Conditions	2.5g Maneuver
	-1.0g Maneuver
	2.0g taxi bump
Gust Conditions	altitudes (0, 10, 20, 30, 40) kft
	5 Gust gradients from 30,350 ft
	Reference gust velocity at each altitude based on FAR 25.341
Flutter Conditions	at cruise conditions, $V_{flutter} < 1.2 * V_D$

Table 7. Strut Braced Wing structural sizing/optimization.

Parameters	Initial	Optimum w/ Stress	Optimum w/ Stress+Flutter
Weight (kg)	49679	3326	5686
Max stress constraint (max stress/yield)	0.37	0.99	0.73
Flutter speed/ Flutter speed constraint	1.055	0.57	1.001

2. Design Optimization Of A SBW With Aeroelastic Constraints

After looking at the structural sizing problem in isolation, we now look at the full aircraft optimization problem, i.e., the optimization of the strut-braced configuration for minimum fuel burn, as shown in Equation 2 formulated in Section IV.B. For these cases, the structural/aeroelastic analysis and optimization are not run in isolation, but rather as a part of a complete aircraft design loop as explained in Section III.C. The design variables and constraints used for this problem are shown in Table 9. For these full-aircraft optimizations, we allow the aircraft wing-strut geometry, the engine size, as well as the cruise altitude of the aircraft to change as shown in Table 9. The skin and rib thicknesses of the structure are also added to the design variable list. The objective is the minimization of the fuel burn for a specified design mission, while ensuring that the field length constraints are met. The mission is the design mission of a B737-800 class aircraft: 2950 nautical miles mission with a single-aisle class aircraft design payload and a cruise Mach number of 0.78.

A number of feasibility constraints are imposed on the design. These include take-off and landing field length constraints, the ability to carry fuel plus reserves (fuel margin), second segment climb gradient constraints, engine feasibility (max throttle and engine clearance constraints), a max wing span constraint to restrict the spans from becoming exceedingly large, and the stress (at maneuver and gust conditions) and flutter constraints. The stress and flutter constraints and load cases are the same as imposed on the strut-braced structural sizing case (Section IV.B.1) described in Table 6.

The initial design parameters result in an aircraft that does not meet the feasibility constraints. The configuration does flutter and does not meet the field length, fuel margin and stress constraints. The results of the optimizations are specified in Table 10. Three sets of optimizations (3 separate cases) are performed in order to observe the importance of the aeroelastic constraints. For all the cases, the same design variables are used, and the zero fuel margin, take-off and landing field length, second segment climb gradient, max throttle, engine clearance, and wing span constraints are imposed.

CASE 1 For the first case, only the stress constraints due to the maneuver load cases (2.5g, -1g, and taxi bump) are applied. The results indicate that the optimizer is able to unsweep the wing (compared to the initial guess of 26 degrees) and change the structural thicknesses to reduce the wing weight significantly, while still meeting the stress constraints that are active at the converged solution. This results in a more efficient design. A small wing span increase, resulting in an induced drag reduction, is also observed without a significant weight penalty and while meeting all of the aircraft-level feasibility constraints. The resulting aircraft configuration is also more fuel efficient than the initial guess. However, we see that the configuration is susceptible to flutter.

CASE 2 The second case then adds the max stress due to the gust loads as an added stress constraint alongside the maneuver constraints. It is observed now that the wing has to be strengthened more to meet the stress constraints, resulting in an increased wing weight and a larger operating empty weight and MTOW. The wings have to be larger in order to generate the necessary lift and meet the field length constraints, which further adds to the weight increase. The optimizer tries to increase the area by increasing the wing span, so that a reduction in induced drag is obtained. The span constraint permits this. The engines are also becoming larger, as the configuration with increased area results in a drag increase compared to Case 1. The optimal fuel burn thus increases compared to Case 1, but the more stringent stress constraints are met and active at the converged solution. We also observe that for this case, as in Case 1, the wing is susceptible to flutter, and the additional increase in the structural thicknesses at different sections without considering its aeroelastic impact results in a reduction in its flutter speed compared to Case 1.

CASE 3 Finally, the flutter speed constraint is added to the stress (maneuver and gust) constraints, and optimizations are performed. We see that this results in a further structural strengthening of the wing-strut combination, and increases in the wing area, wing weight, as well as the operating empty weight, and take-off gross weight as compared to Cases 1 and 2 in order to meet the more stringent constraints (inclusion of flutter). The wings are swept slightly more compared to Case 2 in order to reduce compressibility drag, and a slight reduction in wing span (which increases the induced drag) compared to Case 2 is observed in order to meet the flutter constraint. As expected, the engines have to be larger due to the higher drag. Overall, the fuel burn is larger compared to Cases 1 and 2. However, we now observe that the flutter constraints are also met and are active at the converged solution. The stress constraint is also met but not active at the optimum.

Based on the three cases, we observe that the inclusion of all the aeroelastic constraints in the loop is essential to ensure realistic and feasible aircraft configurations. For all cases, the optimizer is able to reduce the fuel burn, as compared to the initial guess, but as more realistic structural constraints are applied, the perceived reduction in fuel burn goes down. Design of these configurations without the inclusion of the appropriate constraints could result in misleading (extremely fuel efficient) results.

Table 8. Strut-braced Wing Geometry and Aeroelastic properties.[11]

Properties	SBW Wing
Wing Span (m)	22
Wing root chord (m)	3.2
Wing tip chord (m)	1.6
Strut location	50 % of span

V. Conclusions

In this work, an approach for the inclusion of aeroelastic constraints in the conceptual design loop of conventional and unconventional aircraft configurations is described. The paper covers the design methods and tools developed as part of this effort and how these are used to inexpensively predict aeroelastic instability (flutter) for unconventional configurations. These methods are validated and then used for the design and optimization of a simple wing for minimum weight. A more complicated application is demonstrated with the structural sizing and then aeroelastic design of a strut-braced wing. A complete strut-braced configuration is redesigned for minimum fuel burn over a design mission with different sets of structural constraints applied (3 cases). The framework is able to redesign the configurations robustly. The results highlight the importance of imposing aeroelastic constraints, including gust and flutter. Not including these constraints

Table 9. List of the aircraft design variables and constraints.

Objective	Constraints
MTOW	Zero fuel margin
Design Thrust	TOFL , LFL
Wing Sref	2nd Segment climb gradient
Wing AR	Max throttle
Wing sweep	Engine clearance
Cruise altitude	Wing span
Wing/strut thicknesses	Stress constraints - static
	Stress constraints - gust
	Flutter speed constraint

Table 10. List of the critical parameters with bounds for the strut-braced wing case.

Design Variables	lower bound	M	M + G	M + G + F	upper bound
$MTOW(kg)$	60000	70331	80856	85025	150000
Design Thrust (N)	10000	24564	26250	29069	55000
$WingArea(m^2)$	70	97	117	124	250
$WingAR$	6.0	16.6	16.6	16.3	25.0
Wing Sweep (deg)	5	24.8	22.5	24.7	35.0
Cruise Altitude (km)	8.05	10.1	10.7	9.8	12.0
fuel burn (kg)		22529	24650	25845	
Stress*fos/yield		0.99	0.99	0.75	1.0
Flutter Speed/Flutter speed constraint	1.0	0.91	0.6	1.001	

could result in unrealistic designs that appear extremely efficient but might not be feasible or stable. More work is being done to make the studies more complete. Inclusion of the transonic effects using CFD data, bucking constraints, and improved prediction of sensitivities to further reduce computation cost are being investigated.

VI. Acknowledgements

We would like to thank Professor Mark Drela at MIT Aero-Astro for providing us with the ASWING tool which has been used for aeroelastic analysis. We also want to thank the SUAVE and SU2 development teams. Some of the wing and aircraft configurations pictures have been generated using GeoMACH[44] a tool developed at the Multidisciplinary Design Optimization Laboratory at the University of Michigan. We would like to thank Dr. John Hwang and Professor Joaquim Martins for this tool.

References

[1]Zeinali, M. and Rutherford, D., "Trends in Aircraft Efficiency and Design Parameters," *International Council on Clean Transportation, http://www.theicct.org/2010/03/trends-aircraft-efficiency/*, 2010.

[2]Bonnefoy, P., "Potential CO_2 Standards for Commercial Aircraft," *http://web.mit.edu/aeroastro/labs/icat/masdar/Workshop/Agenda_files/5_Bonnefoy_Project30.pdf*, 2010.

[3]Cumpsty, N., Alonso, J. J., Eury, S., Maurice, L., Nas, B., Ralph, M., and Sawyer, R., "Report of the Independent Experts on Fuel Burn Reduction Technology Goals," *CAEP-SG/20101-WP/11, Doc 9963*, 2010.

[4]Rutherford, D. and Zeinali, M., "Efficiency Trends for New Commercial Jet Aircraft: 1960 to 2008," *International Council on Clean Transportation, http://www.theicct.org/2009/11/jet-efficiency-trends/*, 2009.

[5]ICAO, "37th Session of the Assembly, Resolution A37-19: Consolidated statement of continuing ICAO policies and practices related to environmental protection and Climate change," *http://www.icao.int/icao/en/env2010/Assembly.htm*, 2010.

[6]ICAO, "Report of the Eighth Meeting of the Committee on Aviation Environmental Protection (CAEP)," *http://www.icao.int/ENVIRONMENTAL-PROTECTION/Pages/CAEP.aspx*, 2010.

[7]E. Hastings, J., Schoenster, J., Obara, C., and Dodbele, S., "Flight research on natural laminar flow nacelles - A progress report," *22nd Joint Propulsion Conference*, June,1986.

[8]Blythe, A. and Smith, P., "Prospects and problems of advanced open rotors for commercial aircraft," *21st Joint Propulsion Conference,Monterey, California*, July, 1985.

[9]Economon, T., Copeland, S., Alonso, J. J., Zeinali, M., and Rutherford, D., "Design and Optimization of Future Aircraft for Assessing the Fuel Burn Trends of Commercial Aviation," *AIAA 2011-267, 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Orlando, Florida*, 2011.

[10]Variyar, A., Lukaczyk, T. W., Colonno, M., and Alonso, J. J., "Fuel-Burn Impact of Re-Designing Future Aircraft with Changes in Mission Specifications," *52nd Aerospace Sciences Meeting, AIAA Scitech, National Harbor, Maryland*, January 2014.

[11]Bradley, M. K. and Droney, C. K., "Subsonic Ultra Grenn Aircraft Research Phase II : N+4 Advanced Concept Development," Tech. rep., NASA/CR-2012-217556, 2012.

[12]Drela, M., "Design Drivers of Energy Efficient Transport Aircraft," *SAE PAPER 2011-01-2495*, 2011.

[13]Variyar, A., Economon, T. D., and Alonso, J. J., "Multifidelity Conceptual Design and Optimization of Strut-Braced Wing Aircraft using Physics Based Methods," *54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, San Diego, California,(AIAA 2016-2000)*, January, 2013.

[14]Gern, F., "Finite Element Based HWB Centerbody Structural Optimization and Weight Prediction," *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii*, April 2012.

[15]Bhatia, M., Kapania, R., van Hoek, M., and Haftka, R., "Structural Design of a Truss Braced Wing: Potential and Challenges," *50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Palm Springs, California*, May 2009.

[16]Gur, O., Bhatia, M., Schetz, J., Mason, W., Kapania, R., and Mavris, D., "Multidisciplinary Design Optimization of a Truss Braced Wing Aircraft," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), Hilton Head, South Carolina*, September 2009.

[17]Gur, O., Bhatia, M., Mason, W., Schetz, J., Kapania, R., and Nam, T., "Development of Framework for Truss-Braced Wing Conceptual MDO," *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference,Orlando, Florida*, April 2010.

[18]Gur, O., Schetz, J., and Mason, W., "Aerodynamic Considerations in the Design of Truss-Braced Wing Aircraft," *28th AIAA Applied Aerodynamics Conference,Chicago, Illinois*, July 2010.

[19]Nam, T., Chakraborty, I., Gross, J. R., Mavris, D. N., Schetz, J. A., and Kapania, R. K., "Multidisciplinary Design Optimization of a Truss Braced Wing Concept," *14th AIAA Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia*, June 2014.

[20]Gur, O., Schetz, J. A., and Mason, W. H., "Aerodynamic Considerations in the Design of Truss-Braced-Wing Aircraft," *Journal of Aircraft*, Vol. 48, No. 3, 2014/11/10 2011, pp. 919–939.

[21]Bhatia, M., Kapania, R. K., and Haftka, R. T., "Structural and Aeroelastic Characteristics of Truss-Braced Wings: A Parametric Study," *Journal of Aircraft*, Vol. 49, No. 1, 2014/11/10 2012, pp. 302–310.

[22]Bhatia, M., Kapania, R. K., and Haftka, R. T., "Multidisciplinary Design Optimization of Medium Range Transonic Truss-Braced Wing Aircraft with Flutter Constraint," *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Structures, Structural Dynamics, and Materials and Co-located Conferences, (AIAA 2013-1454)*, 2013.

[23]Mallik, W., Kapania, R., and Schetz, J., A., "Structural and Aeroelastic Characteristics of Truss-Braced Wings: A Parametric Study," *Journal of Aircraft,Vol. 49, No. 1, 2014/11/10 2012, pp. 302310*, 2012.

[24]Lukaczyk, T. W., Wendorff, A. D., Colonno, M., Economon, T. D., Alonso, J. J., Orra, T. H., and Ilario, C., *SUAVE: An Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design*, American Institute of Aeronautics and Astronautics, 2015/11/04 2015.

[25]Drela, M., "Integrated simulation model for preliminary aerodynamic, structural, and control-law design of aircraft," *40th Structures, Structural Dynamics, and Materials Conference and Exhibit,Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics*, 1999.

[26]Jones, E., Oliphant, E., Peterson, P., and et al., "SciPy: Open Source Scientific Tools for Python," 2001-.

[27]Lukaczyk, T. W., "VyPy: An Optimization Toolbox," .

[28]Perez R.E., J. P. and J.R.R.A., M., "pyOpt: A Python-Based Object-Oriented Framework for Nonlinear Constrained Optimization," *Structures and Multidisciplinary Optimization*, , No. 45(1):101-118, 2012.

[29]Botero, E., Wendorff, A. D., MacDonald, T., Variyar, A., Vegh, J. M., Lukaczyk, T., Alonso, J. J., Orra, T. H., and Ilario, C., *SUAVE: An Open-Source Environment for Conceptual Vehicle Design and Optimization*, American Institute of Aeronautics and Astronautics, January, 2016.

[30]Drela, M., "ASWING 5.99 Technical Description - Steady Formulation," 2015.

[31]Drela, M., "ASWING 5.99 Technical Description - Unsteady Extension," 2015.

[32]Damkilde, L., "Stress and stiffness analysis of beam sections," *Report, Department of Structural Engineering and Materials, Technical University of Denmark, Lyngby*, Nov, 2000.

[33]Sun, C., "Mechanics of Aircraft Structures," *John Wiley and Sons INC*, 206.

[34]Drela, M., "XFOIL: An Analysis and Design system for Low Reynolds Number Airfoil," *Lecture Notes in Engineering, Proceedings of the Conference Notre Dame, Indiana, USA, Series Volume 54,pp 1-12*, 1989.

[35]Economon, T., Palacios, F., Copeland, S., Lukaczyk, T., and Alonso, J., "SU2: An open-source suite for multiphysics simulation and design," *AIAA Journal*, Vol. 54, No. 3, 2016, pp. 828–846.

[36]Palacios, F., Alonso, J., Duraisamy, K., Colonno, M., Hicken, J., Aranake, A., Campos, A., Copeland, S., Economon, T., Lonkar, A., Lukaczyk, T., and Taylor, T., "Stanford University Unstructured (SU^2): An open-source integrated computational environment for multi-physics simulation and design," *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine (Dallas/Ft. Worth Region), Texas*, January 2013.

[37]Goland, M., "The Flutter of a Uniform Cantilever Wing," *Journal of Applied Mechanics, Vol. 12, No. 4, pag. A197-A208*, 1945.

[38]Yates, E. C. J., "Agard Standard Aeroelastic Configurations for Dynamic Response. Candidate Configuration I. WING 445.6," *NASA Technical Memorandum 100492*, 1987.

[39]Raymond L. Bisplinghoff, Holt Ashley, R. L. H., *Aeroelasticity*, Dover Publications, 1955.

[40]Palacios, R. and Epureanu, B., I., "An Intrinsic Description of the Nonlinear Aeroelasticity of Very Flexible Wings," *52nd AIAA/ASME/AHS/ASC Structures, STructural Dynamics and Materials Conference, Denver, Colorado*, 2011.

[41]Wang, Z., Chen, P., Liu, D., M. D., and Patil, M., "Time Domain Nonlinear Aeroelastic Analysis for HALE Wings," *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics adn Materials Conference, Newport, Rhode Island, AIAA Paper 2006-1640*, 2006.

[42]Murua, J., Hesse, H., Palacios, R., and Graham, J., "Modelling of Nonlinear Flexible Aircraft Dynamics Including Free-Wake Effects," *AIAA Guidance, Navigation and Control Conference, Toronto, Canada*, 2010.

[43]Sotoudeh, Z., Hodges, D., and Chang, C. S., "Validation Studies for Aeroelastic Trim and Stability Analysis of Highly Flexible Aircraft," *Journal of Aircraft, Vol 47, No 4 , pp 1240-1247*, 2010.

[44]Hwang, J. and Martins, J., "GeoMACH: Geometry-Centric MDAO of Aircraft Configurations with High Fidelity," *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, September 2012.

This article has been cited by:

1. Christopher A. Lupp, Carlos E. Cesnik. A Gradient-Based Flutter Constraint Including Geometrically Nonlinear Deformations . [Citation] [PDF] [PDF Plus]