A NEW APPROACH TO INTEGRATED WING DESIGN IN CONCEPTUAL SYNTHESIS AND OPTIMIZATION

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Abstract

Design-oriented analysis has become increasingly important as more and more problems traditionally solved in isolation are being approached from a multidisciplinary point of view. One such problem is the aeroelastic optimization of supersonic transport wings. Whereas simplified analytical techniques may not be sophisticated enough, and complex numerical models may be too cumbersome, this paper puts forward a new approach to achieving a balance between modeling fidelity and required accuracy. Higher fidelity analysis techniques, usually associated with design stages where key geometric variables have been fixed, are used to model a design space consisting of these important geometric variables. This is accomplished through the combined use of a Design of Experiment/Response Surface Method technique and parametric analysis tools (including an automated finite element grid generation procedure). The result is a prediction method for the structural weight of an aeroelastically optimized wing for use in an Integrated Product and Process Development environment, where cost, performance, and manufacturing trades can be accomplished. The technique is to be demonstrated on the aeroelastic design of a wing for a generic High Speed Civil Transport, based on a select set of planform and airfoil design variables. Finally, a framework for evaluating new technologies within the aeroelastic optimization is outlined.

Introduction

Increasingly, technological innovations which show promise for improving aircraft effectiveness (i.e. affordability and capability) are multidisciplinary in nature. The merit of these technologies no longer lies in the use of traditional metrics, such as weight or stress for a wing structural design. The key metrics are system level quantities, such as life cycle cost, robustness to uncertainty, and technology risk. To be capable of evaluating these new metrics, methods must be created which allow rapid analysis execution while still capturing the essence of the technology to an adequate degree of accuracy. Traditional sizing and synthesis is generally performed with first-order tools due to the impracticality of connecting complex codes together into an iterative sizing code. The use of statistical techniques in the proposed method allows for increased flexibility in searching design spaces (multidimensional region bounded by the range extremes for each design variable considered) by representing large amounts of knowledge (e.g. complex, expensive analysis codes or physical experiments) via Response Surface Equations (RSE).

The Integrated Product and Process Development (IPPD) approach specifically brings together design and manufacturing considerations to reduce time and cost. Within the IPPD framework are many needs, one of which is the ability to conduct multidisciplinary analyses among product (and between product and process) disciplines. Along these lines, a key goal of multidisciplinary design research is to bring design-oriented analysis, at a level usually reserved for preliminary design, into conceptual design stages, where the design "freedom" is still open and configuration changes are less costly[1]. The caveat has always been one of cycle time: given enough time and computing power, one could use more accurate analysis to investigate the entire design space. Practically, the situation is more difficult.

The approach described in this paper attempts to address cycle time problems via the use of approximate representations of sophisticated tools instead of lower fidelity approaches (e.g. parametric finite element analysis versus equivalent-plate methods embedded in a design code or the use of finite element modeling (FEM) only for periodic updates) to represent results for a highly coupled aeroelastic wing design problem. Further, an infrastructure is set up which can easily be extended to the study of an Active Flexible Wing (AFW) concept. AFW technology attempts to use wing flexibility to net benefit, by using the power of

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the airstream to deflect the wing in such a way as to cause desired forces and moments for trim and maneuvers. Control surfaces are used as tabs in the concept not as force generators themselves, thus allowing the use of surfaces beyond reversal. The benefits of AFW have been documented in several examples,[2] and the current research facilitates the incorporation of this new technology into the High Speed Civil Transport (HSCT) wing design process. Numerous recent studies of approximation methods, especially response surface methods, for single discipline analysis of wing design have shown promise [Refs. 3, 4, 5]. A good review of approximation methods in a multidisciplinary setting can be found in Ref. 6.

Previous Work

Numerous methods have emerged in recent years for the modeling of problems involving mutually interacting disciplines. This is especially true for the problem of wing design considering aerodynamics, structures, and controls, not only at a discipline level, but at a system level as well. Several key studies have provided insight into this problem, and a survey can be found in Ref. 7. Specifically, research in Ref. 8 has formed the genesis of the aeroelastic design methodology at the heart of this paper by performing a multilevel wing decomposition. FLOPS[9] (system level), ASTROS[10] (discipline level), and PASCO[11] (component level) are the tools used in this decomposition to estimate the wing weight considering stress, flutter, and buckling constraints and then size the aircraft based on this new wing weight.

The use of response surface equations, fundamental component of the methodology presented in this paper, in the design process is introduced in Ref. 12. A methodology is proposed that uses a Design of Experiments (DOE) approach to generate RSEs which capture the behavior of complex design and analysis tools. Ref. 4 discusses research in which a RSE is developed for wing bending material weight using finite element modeling. FEM is used there to provide periodic updates of less sophisticated analyses during the design optimization convergence. Using this RSE, an HSCT is optimized at the system level for minimum takeoff gross weight. The aforementioned AFW approach to wing design in Ref. 2 introduces the technology and discusses how it could be used to improve the maneuverability of an existing wing or to optimize a wing structure for minimum weight and drag. Through the use of AFW technology, which integrates aerodynamics, structures, and controls, significant system benefits were demonstrated on a single configuration design[2].

Additional research has also been conducted on aero-structure-control interactions without analyzing the effect on the entire vehicle. Ref. 13 documents an integrated structures/aerodynamics optimization via generalized sensitivity for a minimum wing weight design. Using ELAPS[14] (Equivalent Laminated Plate Analysis) for structural analysis and WINGDES[15] for load determination static stresses only were calculated for a symmetric airfoil wing. Livne et. al.[16] combined ELAPS with a Doublet Point Method for unsteady aerodynamics to obtain sensitivities of aeroservoelastic constraints due to changes in wing and control surface planform shape parameters. Research in Ref. 17 adopted a Multidisciplinary Structural Design Optimization (MSDO) approach to reduce design costs and time. The approach employed the use of ADOP (Aeroelastic Design Optimization Program) to optimize an HSCT model. Ref. 18 describes research in which finite element based design procedures are used to predict the wing weight of a subsonic aircraft (Fokker 100) and study the effect of aspect ratio on wing weight. To study this effect, a simplified finite element model was used that could be quickly generated. Additionally, in order to explore alternative designs efficiently, the structures and aerodynamic models share the same mesh discretization.

Present Work

To complement these works, this paper addresses a void in trade-off between design space search, modeling fidelity, and efficiency at the conceptual level by introducing the use of Design of Experiments and the Response Surface Methodology. This method includes an automated FE grid generation procedure (based on the work of Ref. 8) which provides the parametric capability demanded by the statistical techniques. These techniques will be used to bring complicated, interdisciplinary analysis to a conceptual design configuration optimization problem. The method will be demonstrated on a problem involving the coupling of aerodynamics, structures, external loads, and controls: the design optimization of a flexible wing for an HSCT aircraft based on analysis procedures developed at Rockwell International-North American Aircraft , a partner with Georgia Tech in Multidisciplinary Design Optimization (MDO) studies for NASA Langley. Neglecting aeroelastic considerations when making configuration decisions at the conceptual level may lead to suboptimal solutions at the preliminary design level. In terms of wing design, especially for a vehicle like a supersonic transport which is expected to experience large aeroelastic effects, details such as structural layout, wing flexibility, aerodynamic loads, control surface effectiveness, load alleviation, and flutter must be accounted for *early* in the design process. Finally, a link between cost and engineering variables is now feasible during design space exploration[5]. Once all of these techniques are integrated, the goal is to identify an optimal wing design with respect to shape, material, and process variables.

The method is developed in this paper as follows. A summary of the two critical analysis tools is given, followed by the definition of some terminology involved in the aeroelastic design and the discussion of the baseline model adopted. A detailed discussion of the aeroelastic approach and the methodology for information transfer between the disciplines and exploration of the design space is presented. The technique for combining structural optimization from ASTROS with external loads from a more generic code (ISMD) is also discussed. This paper closes with the Response Surface Methodology (RSM) framework in which the design-oriented analysis will be embedded.

Aeroelastic Wing Design Method

Automated Structural Optimization System (ASTROS)

ASTROS was developed by the Flight Dynamics Directorate, U.S. Air Force Wright Laboratory, as a multidisciplinary design and analysis tool for aerospace structures. ASTROS combines finite-element-based structural analysis, aerodynamic and aeroelastic analysis, and optimization algorithms to design a minimum weight structure subject to a variety of different constraints such as stress, strain, displacement, aerodynamic, and flutter constraints. Additionally, its capabilities include both static and dynamic structural analyses, as well as static and dynamic aeroelastic methods. ASTROS uses the USSAERO code to perform steady aerodynamic analyses, while Doublet-Lattice and constant pressure methods are used for the unsteady aerodynamic analyses. All data storage and manipulation is handled by ASTROS's own database system (CADDB), and the user can modify the standard ASTROS solution sequence using MAPOL program commands. MAPOL is the language developed for ASTROS and is used to control the solution sequence. In the analysis to follow, MAPOL program commands are used to modified the standard ASTROS solution sequence to allow for the inclusion of aerodynamic loads from an external source and for special information manipulation in and out of the CADDB, as described below.

Integrated Structures Maneuver Load Design (ISMD)[19]

ISMD was developed by Rockwell International's North American Aircraft Division. Its main function is the calculation of trimmed aerodynamic and inertial loads based on a flexible aircraft model. Specifically, it is used at Rockwell to study the AFW concept. AFW promotes the use of wing aeroelastic flexibility as a benefit instead of a hindrance. In the concept, control surfaces are used as 'tabs' to cause desired wing twist and effect a load alleviation. This flexure (and the power of the airstream) produces the control power in AFW designs instead of the surfaces themselves. The load alleviation results in reduced stress and thus reduced wing structural weight. Besides load relief, the wing may be twisted to shapes which minimize drag. Ultimately, then, benefits of AFW can include drag reduction, weight minimization, and the use of control surfaces beyond reversal.

ISMD requires several pieces of information to calculate the aeroelastic trim condition for a defined maneuver. These include a discretized model of the aircraft, structural and aerodynamic sensitivities of this model, control surface definition, and the flight condition. In this paper, the aircraft model is provided by a paneling of the major components, constructed using the Aerodynamic Preliminary Analysis System (APAS)[20]. Within the paneled model (Figure 1), leading and trailing edge control surfaces are defined for both the inboard and outboard portions of the wing as well as the horizontal tail.

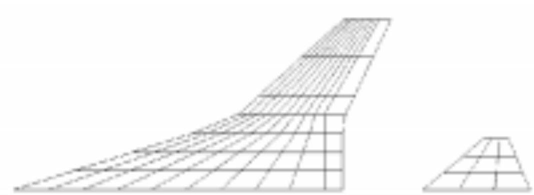

Figure 1 — Aerodynamic Paneling

The core aerodynamic analysis module in APAS is the Unified Distribution Panel (UDP) program, based on a modified Woodward panel method. UDP calculates the aerodynamic sensitivities needed by ISMD in the form of Aerodynamic Influence Coefficients (AIC). AIC relate aerodynamic loads to changes in local panel angles of attack. Thus, AIC allow for the translation of panel angles of attack to panel loads for a given Mach number and dynamic pressure. ISMD uses the AIC information to sum the loads over all the panels to calculate the total load on the vehicle. Structural sensitivities of the paneled model are also required by ISMD. These are defined through the Structural Influence Coefficients (SIC). SIC relate normal deflections of the panels with application of a unit load. The SIC represent the flexibility of the FEM and are arranged in a square matrix. Each row of the matrix contains entries which relate the flexibility of that panel to a load applied in the panel corresponding to each column. This matrix is the inverse of the stiffness matrix K.

Once all the information is provided, ISMD can perform a conventional trim or an 'AFW trim'. While a conventional trim only seeks to balance the forces and moments, in the AFW trim iterations occur on the control surface settings to minimize element stresses in the model (while still balancing the forces and moments). Thus, an AFW trim can be said to trim for minimum weight.

An aerodynamics shell-script written in awk[21], Tk/tcl[22], and Unix commands was developed to automate the execution of various aero codes used to generate an APAS input file. The generation of the SIC and the use of the external loads calculated by ISMD is described next.

The Baseline HSCT Finite Element Model

The finite element model of the representative 300 passenger, Mach 2.4, 5000 N.M. HSCT wing is divided into 3 major structural regions. These are shown in Figure 2 as a strake (1), inboard wing box (2), and outboard wing box (3).

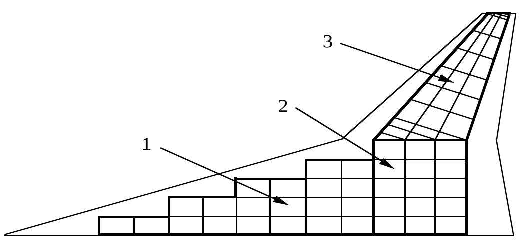

Figure 2 — Wing Structural Regions[23]
(Region 1: strake; Region 2: inboard wing box; Region 3: outboard wing box)

Within each of these three sections the wing is modeled as membrane elements (skin panels), shear panels (spar web and ribs), and rod elements (rib and spar caps), as shown in Figure 3.

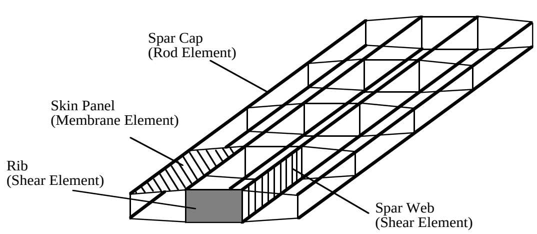

Figure 3 — Wing Box Model[23]

The model has four main spars and five ribs in the inboard region (inboard structural wing) and eleven ribs in the outboard region (Figure 4).

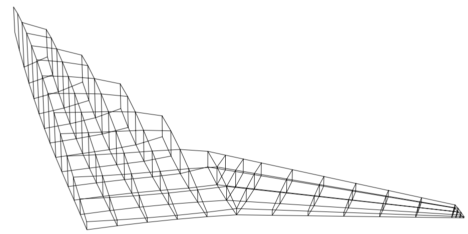

Figure 4 — Structural Discretization[23]

For the baseline HSCT configuration, the wing model consists of 694 elements, of which 421 are to be designed. These structural design elements are then linked to 62 different (local) design variables to reduce the number of ASTROS optimization iterations. To model the skin panels, 28 design variables are used ranging from linear two-dimensional shape functions for Region 1, to quadratic two-dimensional shape functions for Region 2, to one-dimensional quadratic shape functions for Region 3. The rib webs are represented as 15 design variables[8].

Additionally, non-structural mass such as fuel and leading edge (LE) and trailing edge (TE) devices are also modeled. Fuel weight is determined by FLOPS (aircraft system-level sizing and optimization code developed at NASA-Langley) for the baseline aircraft and then evenly distributed as concentrated masses at 180 nodes from Regions 1, 2, and 3. However, fuel is primarily carried in the inboard regions (1 and 2), with only 15 nodes from Region 3 carrying fuel. The leading edge weight is assumed to be 5244 lb. for the entire wing and distributed along non-structural grid points placed along the leading edge of the wing. Similarly, the weight of the trailing edge and trailing edge devices is assumed to be 11,031 lb. and is distributed along both the rear spar and non-structural grid points that define the trailing edge of the wing. The non-structural nodes defining the LE and TE are connected to the main structure via multi-point constraints[8].

A simplified representation of the fuselage is also considered in the model. Bar elements are used to represent the fuselage, and along each one is a distributed weight. The material used for the wing skin panels is Ti6-Al-4V, and for the remainder of the structure "advanced" aluminum is used. To determine material allowables, a safety factor of 1.2 was applied to the material yield properties[8].

All the above information is automatically generated from a given set of system's design variables. The basic information (planform definition, initial weight, engine position, etc.) is given to a set of FORTRAN-based codes that generates all the necessary Bulk Data entries for a generic HSCT wing. The internal discretization (including number of main spars) does not change with changes in the planform geometry. Most of the mesh generation is based on the code developed in Ref. 8.

Structural Optimization / External Loads Integration

ASTROS has the capability to generate trimmed loads. However, when more fidelity in this load prediction is required, or when *a new way to generate loads* (e.g. AFW) appears and is desired to be used, a methodology for efficiently including these external loads into an ASTROS analysis is required. To create and implement this methodology, the standard solution sequence of ASTROS has to be changed. The new procedure formed must accommodate several needs of this particular method and the particular loads program used (ISMD). However, the principles should apply to any general structural optimization / external loads exercise. This procedure is described next and the flow of information is shown in Figure 5.

External information has to be brought into the ASTROS database system (CADDB). Two new modules was specially created to bring the trimmed, aeroelastic loads calculated by ISMD into ASTROS. This is to be done off-line. Therefore, ASTROS is run once ("ASTROS #1" -- Figure 5) only to create the database and to load the information present in the Bulk Data deck into it. The first new module ("CADDB Manipulation #1" -- Figure 5) reads the loads file created by ISMD and incorporates the information in a new array in the CADDB. Then, ASTROS is restarted with a new procedure added to it ("ASTROS #2" -- Figure 5) that will take the loads information from the new array and parse it to the unstructured entity SMPLOD, where the loads information is usually stored. Before that actually happens, the loads, given at the centroid of the aero panels (defined in ISMD), must be converted into the original structural set (ASTROS g-set). This is done by using ASTROS's internal interpolation matrix (based on the infinite-plate spline method of Harder and Desmarais, 1971). This internal interpolation matrix (UGTKG) is defined based on the structural mesh and the unsteady aerodynamic grid, which was made to coincide with the ISMD discretization. The implementation of these operations was done by altering the standard MAPOL sequence. After the external loads in the structural set is loaded into SMPLOD, ASTROS continues its run for the optimization.

At the end of this optimization cycle (output of "ASTROS #2" -- Figure 5), ASTROS has the information needed by ISMD, i.e., the SIC matrix and the mass matrix (lumped mass). But this information is in ASTROS own structural set. Therefore, a transformation is necessary to convert the flexibility information from that set to the ISMD (aero) set. First the stiffness matrix is converted to the aero discretization set by similar means as described above for the loads. Then, the smaller square matrix is inverted to generate the flexibility in the aero set. All this is done within ASTROS by altering the MAPOL sequence. For the mass information, however, an external (off-line) post-processing is needed. The global mass matrix is accessed and from that the linear mass information is retrieved. By using a routine that associates uniquely each structural grid point of the ASTROS model to the corresponding aero panel (through a projection into the wing planform plane), it is then possible to calculate the lumped mass at the centroid of each of those aero panels. This is the mass (weight) information transferred to ISMD ("CADDB Manipulation #2" -- Figure 5).

After this point, as described in Figure 5, there are basically two loops in the optimization process for a given set of system design variables. The inner loop within ASTROS ("ASTROS #3" -- Figure 5) dealing with the minimization of the structural wing weight of the aircraft based on a set of constraints and the given trimmed loads coming from ISMD. While all the flutter constraints are fixed with the given set of system design variables, the static loading constraint depends on the results of ISMD. Since the loads from ISMD are part of the outer loop in this process, there is no need to let ASTROS converge for a given ISMD load. The strategy is to allow ASTROS to run for a certain number of iterations (5 is the chosen number based on previous experience[8]), resulting in a solution that approximates the converged one. As the iterations progress in the outer loop, the inner loop will be closer and closer to the converged solution. This occurs because at each updated static loading case from ISMD, ASTROS begins with the local design variables being initialized by the results of the last run. This strategy promises to be very effective and time-saving.

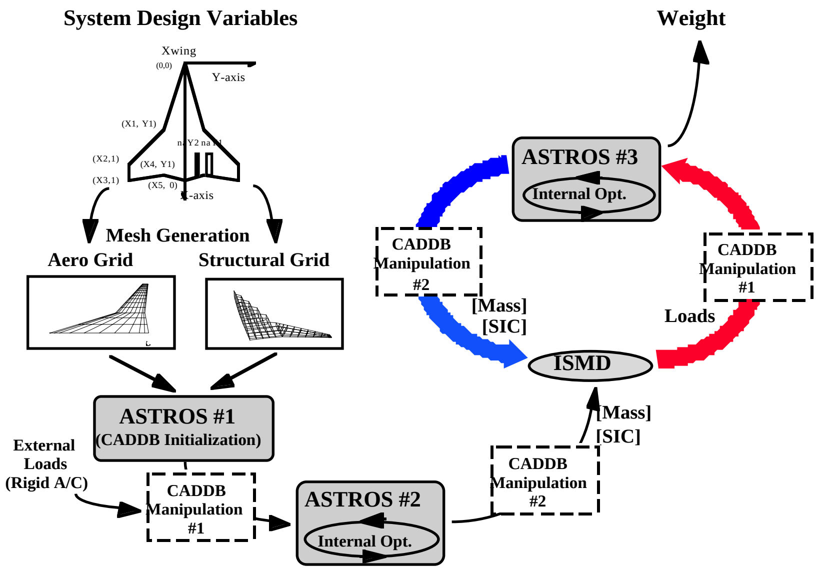

Figure 5 — Structures Methodology

Parametric Wing Weight Equation via Response Surface Method

Aeroelastic design procedures much more detailed than the above exist. What seems to be lacking, however, is the ability to translate (in a reasonable amount of time) parametric changes in wing geometry to changes in wing weight, gross weight, and even operating cost using FEM. The methodology for integrating loads and structural optimization outlined in this paper was developed with a parametric capability in mind. Having made the choice to use FEM analyses instead of a simplified approach, an approximation technique is needed to translate the essence of the analyses to something usable yet accurate. The use of DOE/RSM is one way of creating such design-oriented analysis. The implementation of the aeroelastic design procedure in a DOE/RSM scheme next.

The process begins with the selection of a set of wing-related design variables and associated ranges for them which together define the design space. This set of variables can include aerodynamic (e.g. planform shape, camber, twist), structural (e.g. spar and rib areas, skin thickness), and control (surface types/sizes) related quantities. Presently, however, the design space to be examined is initially small, as an investigation into the smoothness of the data generated is desired before more complete variable sets are tested. The current set proposed consists of five variables, four of which are related to the planform and one to the airfoil(s). These variables are summarized in Table I. The variables chosen, however, are based on screening tests performed in past studies of HSCT configurations [Refs. 3, 24]. The kink location variables have been found to be important, especially in light of the inevitable trade between subsonic and supersonic aerodynamic performance. The root chord and reference area variables capture sizing effects while the thickness-to-chord represents, in a limited way, airfoil shape effects. The sample planform in Figure 5 (left upper corner) illustrates the full parametric planform definition.

Table I -- Design Variables and Ranges

Description	***Design Variable Name***	***Min. Value***	***Max. Value***
Kink X-location	X1	1.54	1.69
Kink Y-location	Y1	0.44	0.58
Root Chord	X5	2.19	2.36
Wing Reference Area	Sref	8500	9500
Inboard-Outboard t/c	t/c	2.5 %	3.3 %

Figure 6 — Process Flow

To complete the multi-level design scheme, components are designed to meet engineering requirements. To do so, a design can employ the methods described in this paper. Recall that an RSE was formed from the aeroelastic wing design procedure. This was done by using a two-level optimization scheme employing the analysis tools ASTROS, APAS, AWAVE, WDES, and ISMD. This RSE is generated off-line and coded into the synthesis tool FLOPS for use in the determination of a satisficing solution as mentioned earlier.

Future Work

All the individual analysis components have been numerically tested as well as parts of the integrated procedure. The final integration is under way and the numerical results for the wing weight RSE will be reported in a future paper.

Once the wing weight RSE generation procedure is finalized for conventional trim, plans are for the process to be repeated with the full AFW trim optimization. Use of the equation resulting from this exercise in the system level optimization would complete the loop of technology evaluation from fundamental design. Further, to synthesize a system in a proper way, product and process design variables and constraints must be considered simultaneously. While product characteristics were the focus of this paper, process characteristics refer to those items related to how the product is designed, produced, and sustained over its lifetime. Process evaluation tools are in place so that the wing design procedure can be carried out for different material concepts and manufacturing processes, facilitating the process and product trades which form the heart of IPPD. Finally, expansion of the design space to cover more variables of interest is certainly desirable and critical to the practical use of the methods developed.

Conclusion

A new approach to integrate aeroelastic wing design in conceptual synthesis was presented. It addresses a trade-off between design space search, modeling fidelity, and efficiency at the conceptual level by means of Design of Experiments and Response Surface Methodology. In terms of wing design, especially for an HSCT, which is expected to experience large aeroelastic effects, details such as structural layout, wing flexibility, aerodynamic loads, control surface effectiveness, load alleviation, and flutter must be accounted for early in the design process. Higher fidelity analysis techniques, usually associated with later design stages where key geometric variables have been fixed, are used to account for these important design details. An automated finite-element mesh generation procedure provides the parametric capability demanded by the statistical techniques within a very short time. The result is a prediction method for the structural weight of an aeroelastically optimized wing for use in an Integrated Product and Process Development environment, where the goal is to identify an optimal wing design with respect to shape, material, and process variables.

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