Aeroelastic Optimization of Generalized Tube and Wing Aircraft Concepts using HCDstruct Version 2.0

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Major enhancements were made to the Higher-fidelity Conceptual Design and structural optimization (HCDstruct) tool developed at NASA Langley Research Center (LaRC). Whereas previous versions were limited to hybrid wing body (HWB) configurations, the current version of HCDstruct now supports the analysis of generalized tube and wing (TW) aircraft concepts. Along with significantly enhanced user input options for all aircraft configurations, these enhancements represent HCDstruct version 2.0. Validation was performed using a Boeing 737-200 aircraft model, for which primary structure weight estimates agreed well with available data. Additionally, preliminary analysis of the NASA D8 (ND8) aircraft concept was performed, highlighting several new features of the tool.

Nomenclature

AATT	= Advanced Air Transport Technology
BDF	= Bulk Data File
BWB	= Blended Wing Body
CAD	= Computer-Aided Design
CFD	= Computational Fluid Dynamics
DLM	= Doublet Lattice Method
ECFT	= Enhanced Correction Factor Technique
FEM	= Finite Element Model
FLOPS	= Flight Optimization System
HCDstruct	= Higher-fidelity Conceptual Design and structural optimization
HWB	= Hybrid Wing Body
LaRC	= Langley Research Center
MDO	= Multidisciplinary Design and Optimization
NASA	= National Aeronautics and Space Administration
ND8	= NASA D8
OML	= Outer Mold Line
OpenVSP	= Open Vehicle Sketch Pad
STL	= Stereolithography
SOL	= Solution Sequence
TTT	= Transformational Tools & Technologies
TW	= Tube and Wing

I. Introduction

Sizing conventional aircraft concepts is commonly performed using low-order regression methods with databases of relevant configuration data, such as those used in the Flight Optimization Performance System (FLOPS) tool.[1] However, these methods are ill-suited for situations where the target concept is

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unconventional in one or more ways. For example, hybrid wing body (HWB) or blended wing body (BWB) aircraft concepts are fundamentally unconventional aircraft due to their highly-integrated structures and streamlined outer mold line (OML). Similarly, recent efforts to structurally size double-bubble fuselage configurations,[2–4] as depicted in Fig. 1, using conventional sizing methods have suggested a need for more advanced approaches. In order to meet this demand, the Higher-fidelity Conceptual Design and structural optimization (HCDstruct) tool[2,5] was significantly enhanced to include a generalized tube and wing (TW) airframe sizing capability, and this latest version of the tool is presented in the current paper.

Whereas early development efforts and applications of HCDstruct were limited to HWB configurations,[2,5–9] recent development efforts have been focused on extending the structural optimization methodology to TW configurations. While the general structural optimization methodology remains the same, these new applications required significant modifications to the source code to account for the fundamental configuration differences associated with such concepts. Further, the user controls were significantly modified to account for the model configuration options available with such concepts.

Figure 1. MIT's D8 aircraft concept featuring a double-bubble fuselage design (NASA Photo).

For the current paper, an overview of the development efforts and capabilities comprising HCDstruct 2.0 are presented in section II, including primarily a generalized TW configuration modeling capability. Applications of HCDstruct 2.0 are then presented in section III, including a validation case using a Boeing 737-200 model in section III.A and an application to the current NASA D8 (ND8) aircraft concept being studied under the Advanced Air Transport Technology (AATT) project in section III.B. A summary of the current work, along with discussion of follow-on efforts, is presented in section IV.

II. HCDstruct Development

HCDstruct was developed at NASA Langley Research Center (LaRC) to fill a critical analysis gap between high level, lower order approaches commonly used for conceptual design and the low level, detailed, often finite-element-based optimization approaches commonly used for advanced preliminary design. Specifically, HCDstruct was developed to complement the FLOPS tool, which is a versatile, multidisciplinary suite of computer programs for conceptual and preliminary design and analysis of advanced aircraft concepts. However, the design sensitivities associated with off-design conditions for the regression-based sizing algorithms[1,10] used by FLOPS are generally inaccessible by such a simplified approach. While the detailed finite element based sizing analyses often performed later in the design cycle, such as those for the HWB by Boeing,[11] may theoretically offer such insights, the computational resources required for these efforts often limit them to single-point design analysis. Thus, HCDstruct was developed to bridge the gap between FLOPS' regression-based sizing techniques and current state-of-the-art finite element based approaches to advanced preliminary design data. In fact, the tool has evolved to provide a means of optimizing the primary structure for the fuselage and wing for a given aircraft configuration using finite element methods while only requiring FLOPS-level user data.

Since overviews of HCDstruct versions 1.0, 1.1, and 1.2 can be found in Refs. 5, 9, and 2, respectively, the current section only describes capabilities newly available in version 2.0. With this update, HCDstruct includes a structural optimization routine for TW aircraft configurations for which the same general sizing methodology used in earlier versions is employed. The HCDstruct methodology is presented in Fig. 2, where the analysis begins with an OpenVSP[12] model of the aircraft concept and a weights schedule comprised of payload, fuel, and subsystems weights. With this data, HCDstruct builds a completely parameterized finite-element model (FEM) of the primary aircraft structure, configures all the load cards for the selected load cases, and builds doublet lattice method (DLM) aerodynamic models for all lifting surfaces. These output are in the form of a complete set of bulk data files (BDFs) that are configured for direct use with NASTRAN[13] Solution Sequence (SOL) 200. Execution of SOL 200 results in an optimized primary structural weight subject to sizing constraints input by the HCDstruct user.

The execution of HCDstruct 2.0 assumes a standard naming convention for all input and output files, as shown in Fig. 3. Fig. 3 also illustrates the execution sequence, where the input decks (**.inp*), geometry input files (**.stl*), and output BDF files (**.bdf*) are ASCII data files, and the executables *HCDstruct* and *nastran* are the operating-system-specific code builds for HCDstruct and NASTRAN, respectively, located in the system path. The *HCDstruct* executable expects two input parameters, *inp_dir* and *out_dir*, which correspond to the directories containing the input and output data files, respectively. The *nastran* executable expects the *hcdstruct_exec.bdf* BDF file, which contains the executive control input deck for the current case and is written by HCDstruct. Finally, the output is written to the *hcdstruct_exec.f06* file directly by NASTRAN.

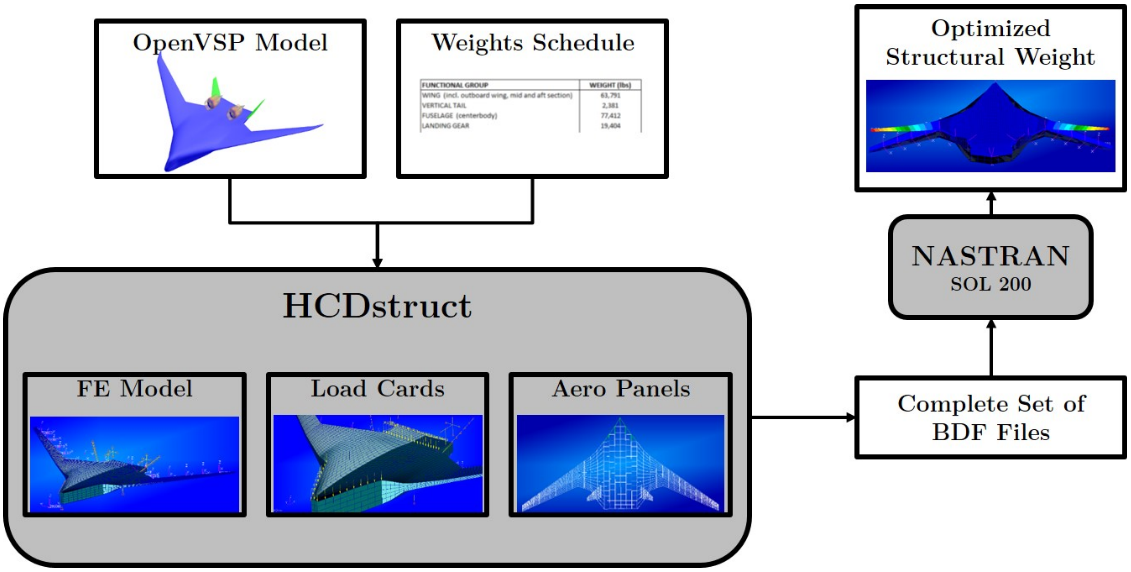


Figure 2. A notional flowchart detailing the general components of a structural optimization performed using HCDstruct.

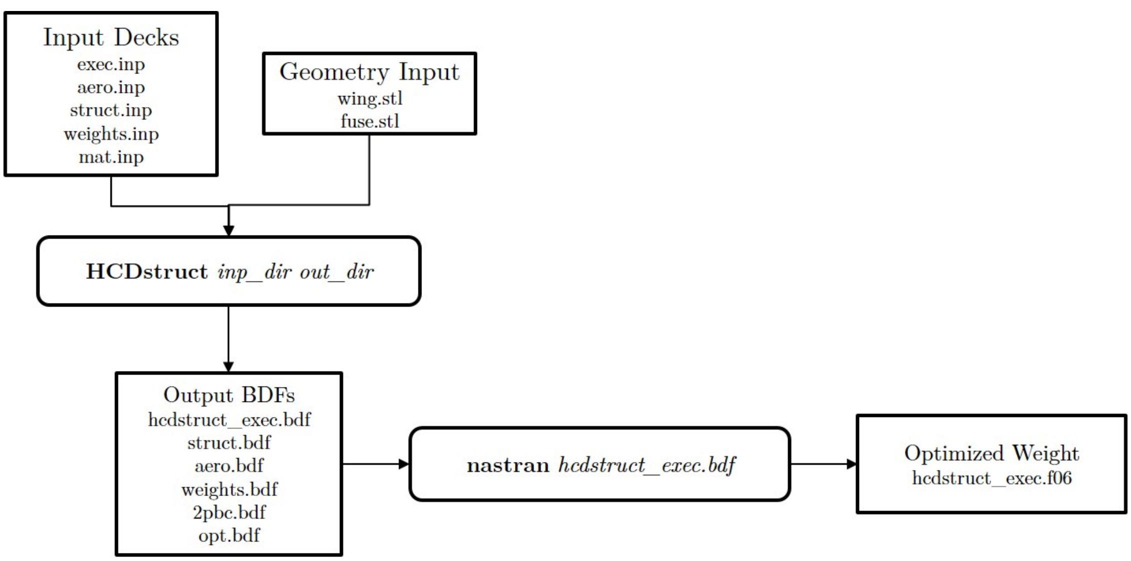


Figure 3. A notional flowchart detailing the general execution process for HCDstruct.

TW applications of HCDstruct utilize the same load cases that were implemented for previous versions and are described in Ref. 2. These cases include four symmetric loadings (2.5G pull-up, -1.0G push-over, 2P fuselage overpressurization, and 2G taxi bump) and two asymmetric loadings (dynamic overswing and rudder reversal). Details of the structural optimization problem using SOL 200 and application of these load cases via SOL 144 (Static Aeroelasticity Analysis) subcases are shown in Fig. 4. Each set of BDF files output by HCDstruct contains all the data required to execute an instance of NASTRAN SOL 200. The solution sequence is configured to optimize the primary structure by minimizing the total structural weight via the thickness of the PSHELL elements, and the load cases above are applied via SOL 144 subcases. For every CQUAD4 element comprising the FEM, an accompanying PSHELL element is configured to represent the shell properties. The PSHELL elements are linked to a design variable reference card (DVPREL1) and then to a design variable (DESVAR). For an application typical of HCDstruct, there may be thousands or tens of thousands of independent design variables, and both stress and displacement design responses are configured as functions of these design variables using the DRESP1 card. Material constraints are applied using the DCONSTR card. For each iteration of SOL 200, an instance of SOL 144 is spawned for the selected load cases, a static aeroelastic analysis is performed, and the design responses calculated. SOL 200 then uses a gradient-based method to modify the PSHELL thickness for each element of the model at each design cycle subject to the design constraints specified on the DCONSTR cards.

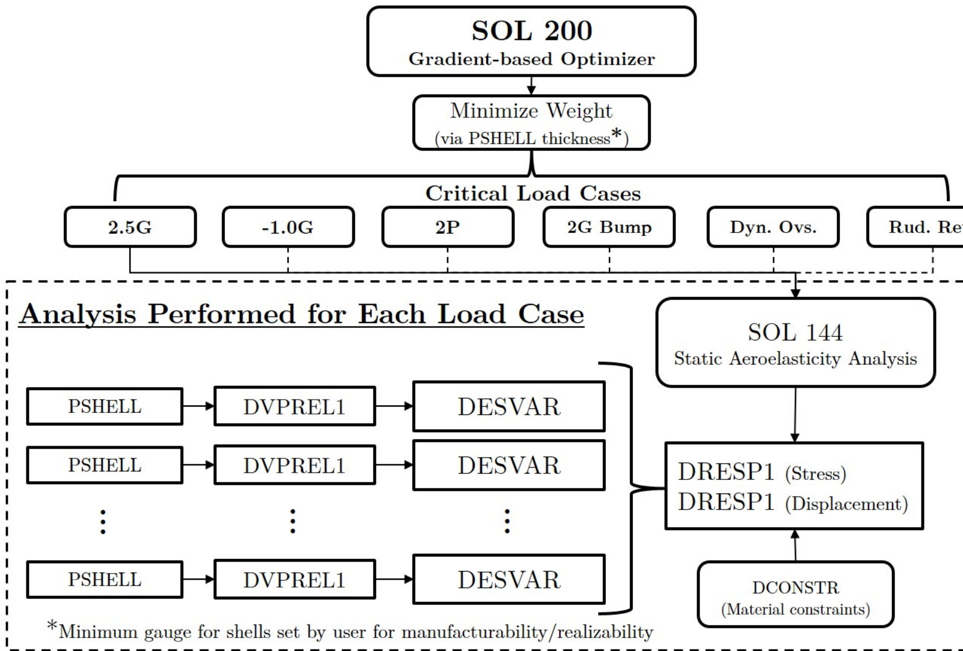
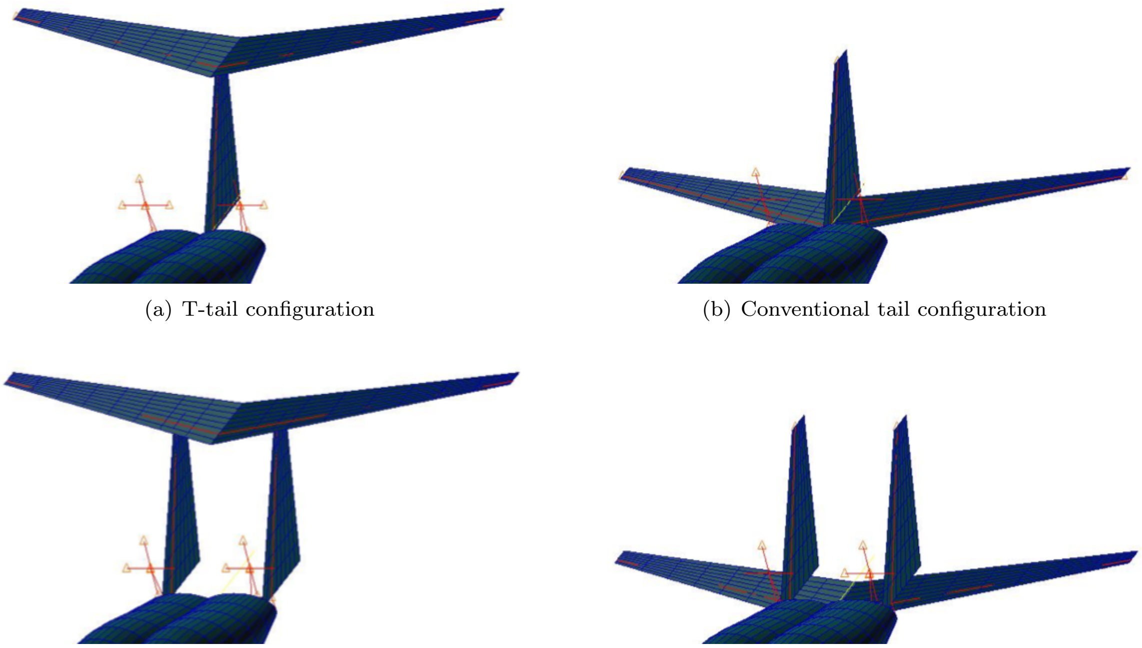


Figure 4. A notional flowchart describing the weight optimization formulation using SOL 200 with HCDstruct.

For TW applications of HCDstruct, the model geometry must be input as two stereolithiography (STL) files titled *wing.stl* and *fuse.stl* corresponding to the wing and fuselage OMLs, respectively. These files may come from any capable computer-aided design (CAD) tool, but applications to date have utilized the OpenVSP software. Independent FEMs of the wing and fuselage components are constructed by HCDstruct and then automatically connected using glued contact theory[13] near the points of intersection with a few identifying configuration lines in the HCDstruct input decks. The application of glued contact theory is new in version 2.0 and is only supported for TW configurations.

HCDstruct 2.0 offers many configurable features for TW models. Both horizontal and vertical tails can be configured directly using sweep, cant, and toe angles, and up to two vertical tails can be specified. The attachment point and orientation of the horizontal tail surface are customizable, permitting for conventional empennage assemblies to pi-tail assemblies to T-tail assemblies, and DLM aerodynamic panels are automatically created to model all the tail surfaces. Examples of the tail configurations supported by HCDstruct 2.0 are shown in Fig. 5. Engines can be placed anywhere on the fuselage or wing in the current release, allowing for the underwing mounting typical of production airliners like the 737-200.

A new key capability of HCDstruct includes a user-specified parameter referred to as *fuselage cuspedness*, which allows for the modeling of double-bubble-inspired fuselage concepts. This *cuspedness* term, referred to by *DBPCT* when using the tool, varies from 0.0 to 1.0 and represents the percentage *double-bubbledness* of the fuselage cross section. For example, when the cuspedness term is set to 0.0, the fuselage cross section resembles two concentric circles, and when the figure is set to 1.0, the fuselage cross section is circular or elliptical, dependent on the fuselage OML. The variation of cross section as a function of *DBPCT* is illustrated in Fig. 6, where each image shows the leading crosssectional slice of the ND8 fuselage. The NASA



(a) T-tail configuration

(b) Conventional tail configuration

(c) Pi-tail configuration

(d) Twin tail configuration

Figure 5. Horizontal and vertical tail configurations supported by HCDstruct 2.0.

D8 concept uses cuspedness values on the order of 0.5 to model the curvature of the primary structure. Further, the current release of HCDstruct allows for the aerodynamic modeling of the fuselage sections using slender body elements. Cross sectional slender body properties are computed automatically once the user requests fuselage aerodynamic modeling. This capability is key to simulating the net lifting effect of the widened ND8 fuselage concepts, as compared to standard circular cross sectional fuselages.

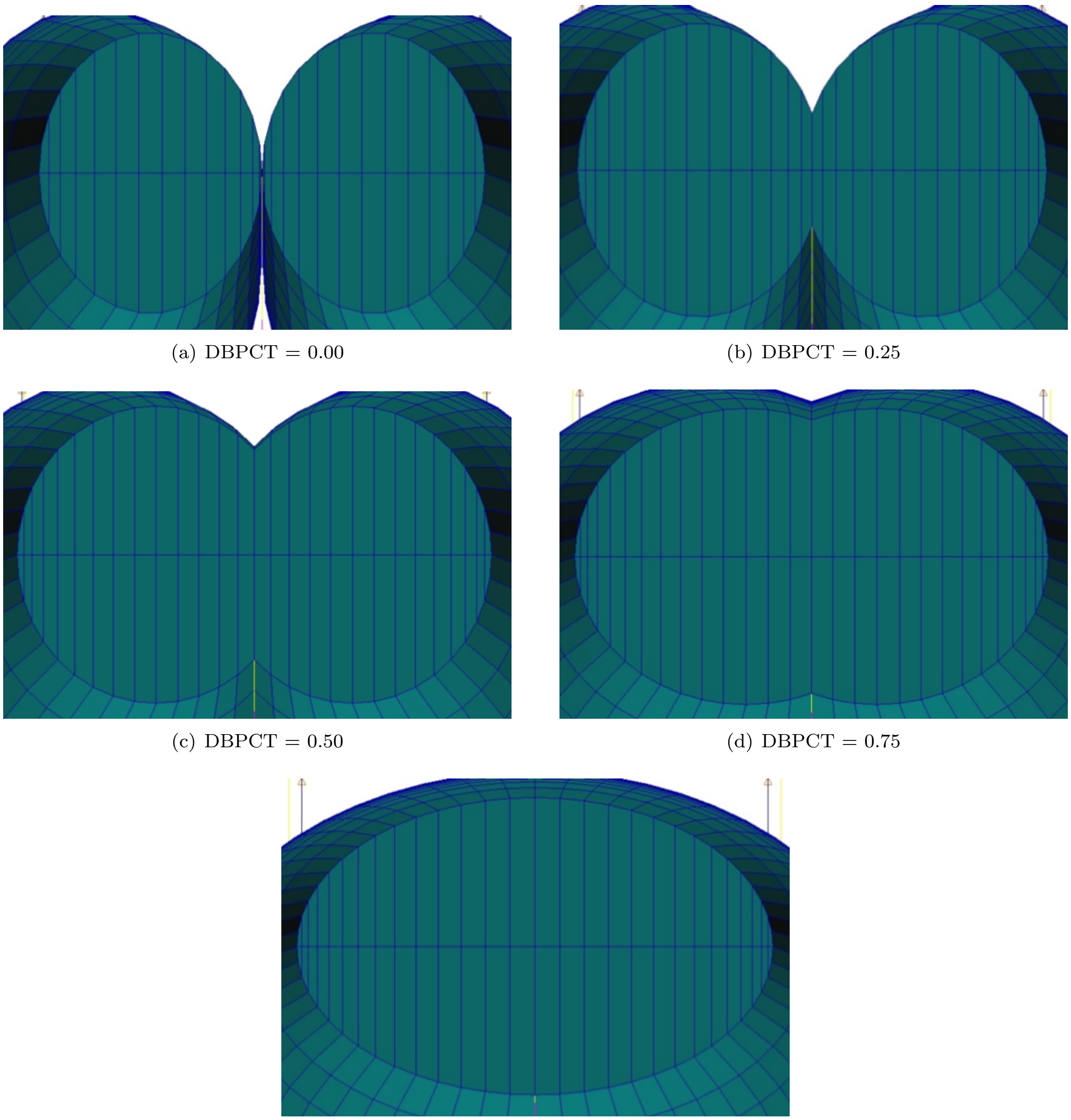
III. Application Cases

Unlike for previous versions of HCDstruct, which were applicable only to HWB aircraft concepts and for which no as-flown, full-scale weights data were available, the implementation of a generalized TW structural optimization methodology allows for validation applications using production aircraft data. For this paper, the first application of HCDstruct 2.0 is a validation study using the Boeing 737-200 aircraft. This analysis is presented in section III.A. The second application of HCDstruct 2.0 is the ND8 aircraft concept, for which preliminary results are presented in section III.B.

III.A. Boeing 737-200

The Boeing 737-200 aircraft was selected for initial validation of HCDstruct 2.0 due to its comparable size and passenger capacity to that of the ND8 and also due to the general availability of validation data and wide acceptance in the airline industry since initial production. The Boeing 737-200 represents a conventional TW aircraft design, with a circular cross sectional fuselage effectively residing over a swept, tapered main wing, as shown in Fig. 7. The aircraft has a single horizontal stabilizer and a single vertical tail, configured in a conventional manner.

A geometric model of the Boeing 737-200 was built using OpenVSP with data from several publicly-available sources.[14,15] A three-view depiction of the OpenVSP model is shown in Fig. 8, where several key dimensions are notated. The fuselage length and wing span are approximately 106.0ft and 94.75ft, respectively. For the purposes of this validation study, only the fuselage, main wing, and horizontal and vertical stabilizers were geometrically modeled using OpenVSP. The airfoil data was input directly to OpenVSP using the profile data available in Ref. 16.



(a) DBPCT = 0.00

(b) DBPCT = 0.25

(c) DBPCT = 0.50

(d) DBPCT = 0.75

(e) DBPCT = 1.00

Figure 6. Variation of the ND8 fuselage cross section as a function of *DBPCT*.

III.A.1. Finite Element Model

A three dimensional aeroelastic FEM of the Boeing 737-200 aircraft was developed based on the OpenVSP model and three view schematic shown in Fig. 8. The primary airframe FEM is shown in Fig. 9(a), which includes the fuselage and main wing components connected using glued contact theory. The complete aeroelastic FEM is also shown in Fig. 9(b), which shows the panel-based representations (CQUAD4) of the fuselage and main wing, with bulkheads placed at the front and rear of the fuselage. The front and rear wing spars were positioned at 12.5% and 62.5% of chord. Two elevators and one rudder were configured to permit the application of both the symmetric and asymmetric loading cases. The elevator and rudder hingelines were positioned at 75% of chord for the horizontal and vertical stabilizers, respectively.

Figure 7. An image of the Boeing 737-200 aircraft in flight (NASA Photo).

The horizontal and vertical tail structures were modeled using rigid bar elements (RBAR1) at the quarter chord locations along with point masses (CONM2) to simulate the inertial loadings. The landing gear and engines were also modeled using rigid bar elements with point masses and are shown in red. The DLM aerodynamic panels (CAERO1) are shown for the main wing and tail surfaces, and the slender body elements (CAERO2) are rendered simply as the yellow line through the center of the fuselage model, which does not show the slender body elements nor the corresponding interference tube cross sectional properties. The complete aeroelastic FEM consists of 3824 CQUAD4 elements, 43 RBAR1 elements, 70 CONM2 masses, 642 CAERO1 panels, and 37 CAERO2 elements. The corresponding SOL 200 case included 1912 DESVAR design variables and 8 DCONSTR design constraints in the form of von Mises stress and displacement limits based on available material properties and a safety factor of 1.5.

Due to the stiffened panel approach employed by HCDstruct, the user must specify the minimum gauge thickness for the PSHELL cards in conjunction with effective manufacturability or material properties limits. For the case of the Boeing 737-200, for which the material properties are known and available, the minimum gauge thicknesses were specified as 0.25in and 0.1in for the fuselage and wing panels, respectively, based on materials properties and manufacturing limits found in Refs. 17 and 18.

III.A.2. Structural Optimization Results

The Boeing 737-200 aircraft model presented in the previous section was structurally optimized using HCDstruct 2.0 subject to all the symmetric and asymmetric load cases described in Ref. 2, and the results of this optimization are compared to those of as-flown aircraft data found in Ref. 19. The weight convergence history is shown in Fig. 10, demonstrating relative convergence of the total structural weights for both the components and composite structure. Further, in Fig. 10, the as-flown aircraft data are presented as horizontal lines, and the ordinate has been normalized by the as-flown wing structure data. In Fig. 11, the component and composite structural weights of the optimized aeroelastic FEM are compared to those of the as-flown aircraft, where the component weights have been normalized by the as-flown aircraft data. The fuselage and wing structural estimates predicted by HCDstruct 2.0 differ from the as-flown data by approximately 5.0% and 8.9%, respectively. For the total airframe primary structure, HCDstruct predicts the weight to within approximately 1.6%, thereby supporting the validity of the HCDstruct 2.0 optimization methodology and the suitability of the selected load cases for the sizing of general TW aircraft concepts.

As was described previously in the discussion of the SOL 200 methodology in Fig. 4, the thicknesses of the PSHELL elements representing the structural FEM are optimized during the execution of HCDstruct and NASTRAN. One way to visualize the results of this optimization process is to examine the optimized thicknesses of the PSHELL elements over the FEM. For the Boeing 737-200 model, this data is shown in Fig. 12, where the FEM elements are colored by the corresponding PSHELL element thicknesses. In this figure, the important role of the minimum gauge thickness can be seen clearly in the coloring of the fuselage structure. In this application, the fuselage is sized predominately by the minimum gauge thickness, with regions near the front and rear bulkheads being sized by other factors, such as the inertial loadings of the

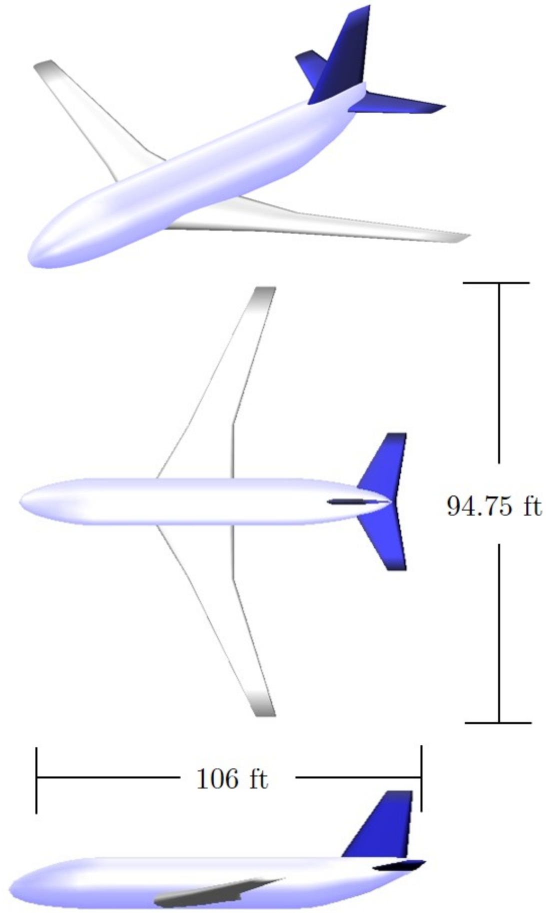
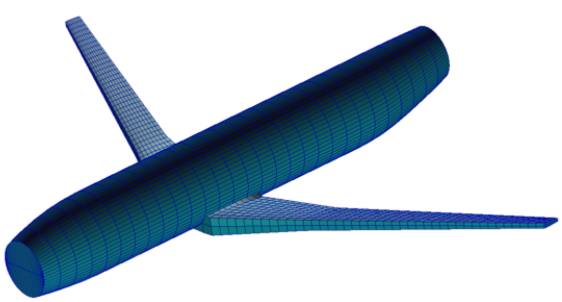
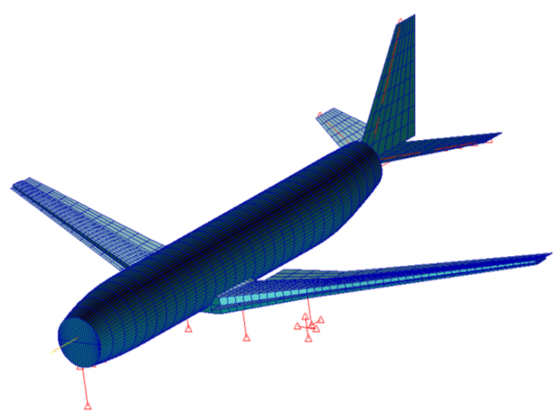


Figure 8. A three-view of the Boeing 737-200 aircraft OpenVSP model used by HCDstruct.



(a) The primary airframe structure FEM for the Boeing 737-200 model.



(b) The full Boeing 737-200 aeroelastic FEM model, including the aerodynamic panels, the primary structure, the empennage, engine systems, landing gear, and control surfaces.

Figure 9. NASTRAN renderings of the Boeing 737-200 structural FEM and the full aeroelastic FEM.

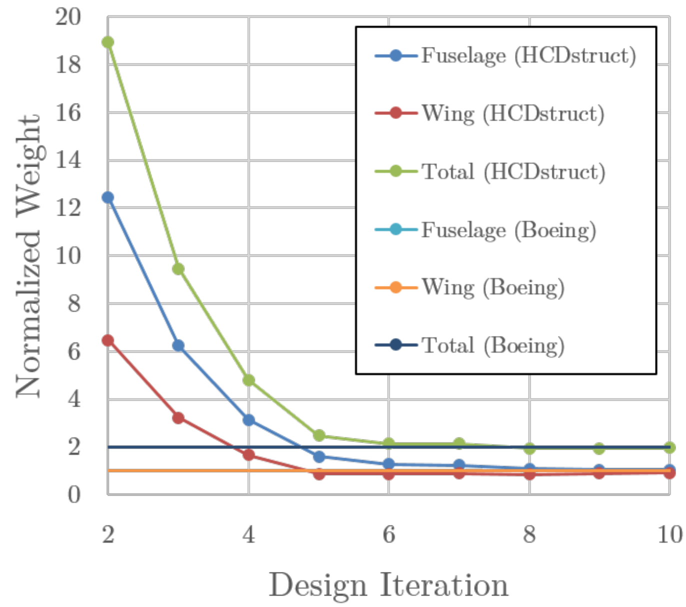


Figure 10. Structural weight convergence history of the optimization design cycles for the Boeing 737-200 aircraft model.

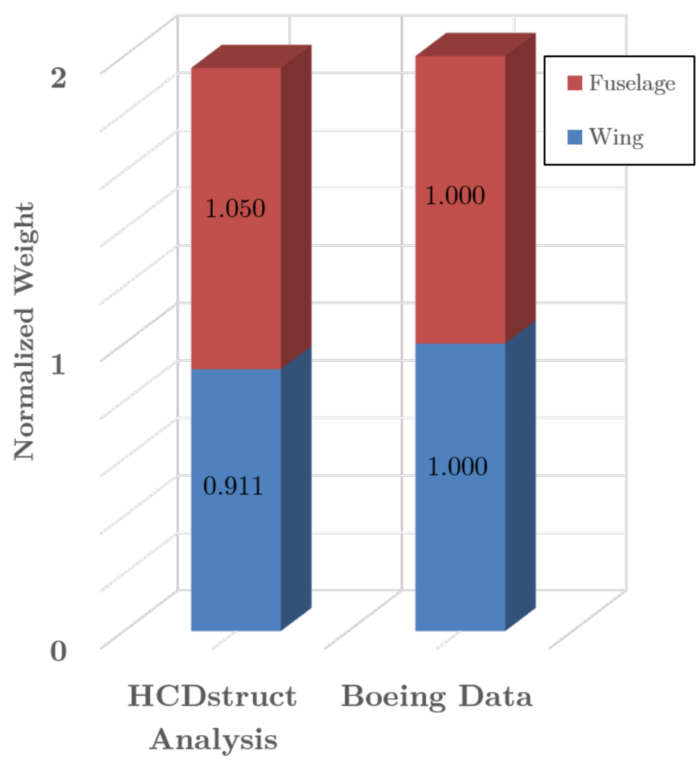


Figure 11. Comparisons of the optimized structural weights for the Boeing 737-200 concept using HCDstruct to those of the as-flown aircraft, normalized to the as-flown weights data.

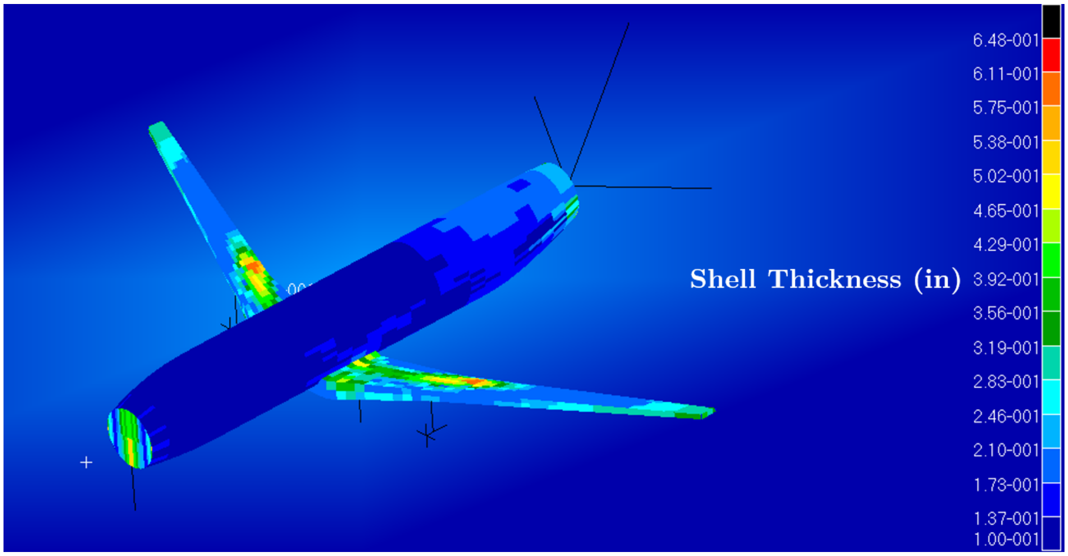


Figure 12. Optimized shell elements colored by PSHELL thickness for the Boeing 737-200 aircraft FEM.

empennage and gear. Additionally, while a substantial portion of the main wing is sized by the respective minimum gauge, the effects of bending at the root and stress concentrations around the points of engine attachment result in the thicker panels displayed in these locations.

III.B. NASA D8 Concept

The latest iteration of the ND8 concept is shown in Fig. 13, illustrating the widened fuselage, pi-tail, winglets, and overall vehicle configuration; the wing span, fuselage length, and fuselage width for the current design are approximately 118ft, 106ft, and 17ft, respectively. For ongoing multidisciplinary design and optimiztiaon (MDO) efforts leveraging FLOPS mission analysis and vehicle sizing methods, HCDstruct 2.0 is used to develop physics-based estimates for the airframe weights. With these weight estimates, effective corrective factors may be devised to size the fuselage and wing structures in FLOPS via the FRFU and FRWI cards, respectively. In this section, the ND8 aeroelastic model is presented, followed by a discussion of the structural weight optimization results.

Using HCDstruct 2.0, an aeroelastic model of the ND8 was constructed consisting of a FEM for the primary structure, as well as a DLM aerodynamic model for the fuselage and lifting surfaces. This aeroseroelastic model is presented in Fig. 14, where the CQUAD4 structural elements and CAERO aerodynamic panels are shaded blue and CONM2 masses, MPC connectors, and RBAR1 rigid bars are shaded red. The FEM is comprised of 3927 CQUAD4 elements, 83 CONM2 masses, and 59 RBAR1 rigid bars, and the aerodynamic model is comprised of 642 CAERO1 panels and 37 CAERO2 slender body elements. The model includes aileron, elevator, and rudder control surfaces, and the *DBPCT* parameter was set to 0.5.

The corresponding SOL 200 case included 1997 DESVAR design variables and 8 DCONSTR design constraints in the form of von Mises stress and displacement limits based on available material properties and a safety factor of 1.5. The minimum gauge thicknesses were specified as 0.50in and 0.09in for the fuselage and wing panels, respectively, based on representative composite materials properties and proprietary analysis for comparable concepts.

Structural weight optimization results are shown in Fig. 15, where the fuselage, wing, and total airframe structural weights are shown as a function of design iteration. Convergence of these figures occurs within about ten design cycles, and the results of a FLOPS sizing analysis are also shown on the plot as horizontal lines for comparison. The fuselage and wing weights converge to approximately 16,900lbs and 11,000lbs, respectively, for a total airframe structural weight of 27,900lbs. Comparing these to the FLOPS fuselage and wing weights of 18,300lbs and 10,600lbs, respectively, suggests the use of FLOPS fuselage and wing weight correction factors of 0.92 and 1.03, respectively.

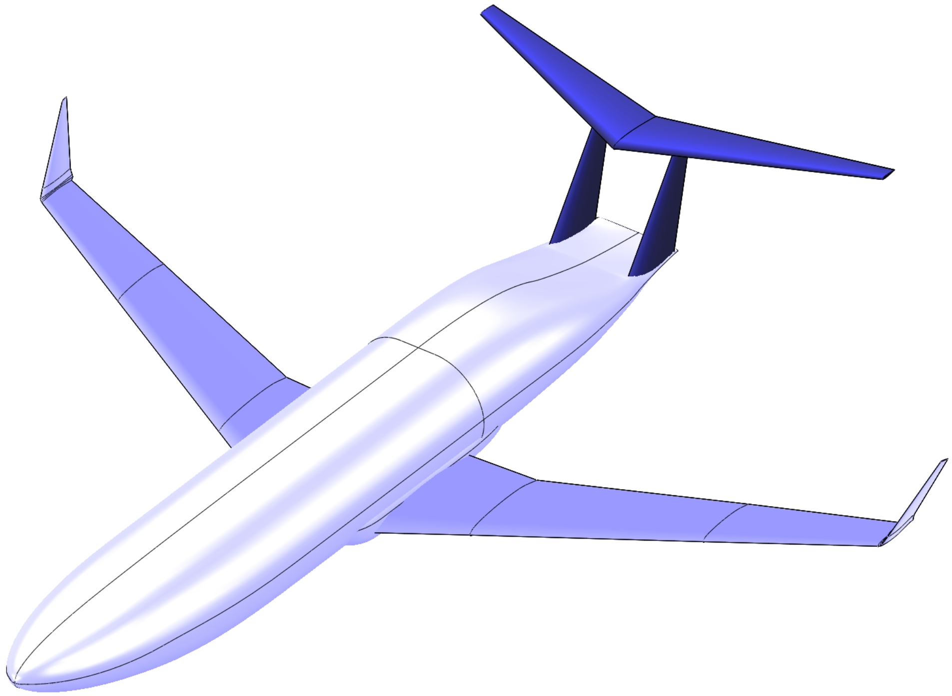


Figure 13. An OpenVSP rendering of the latest iteration of the ND8 aircraft concept.

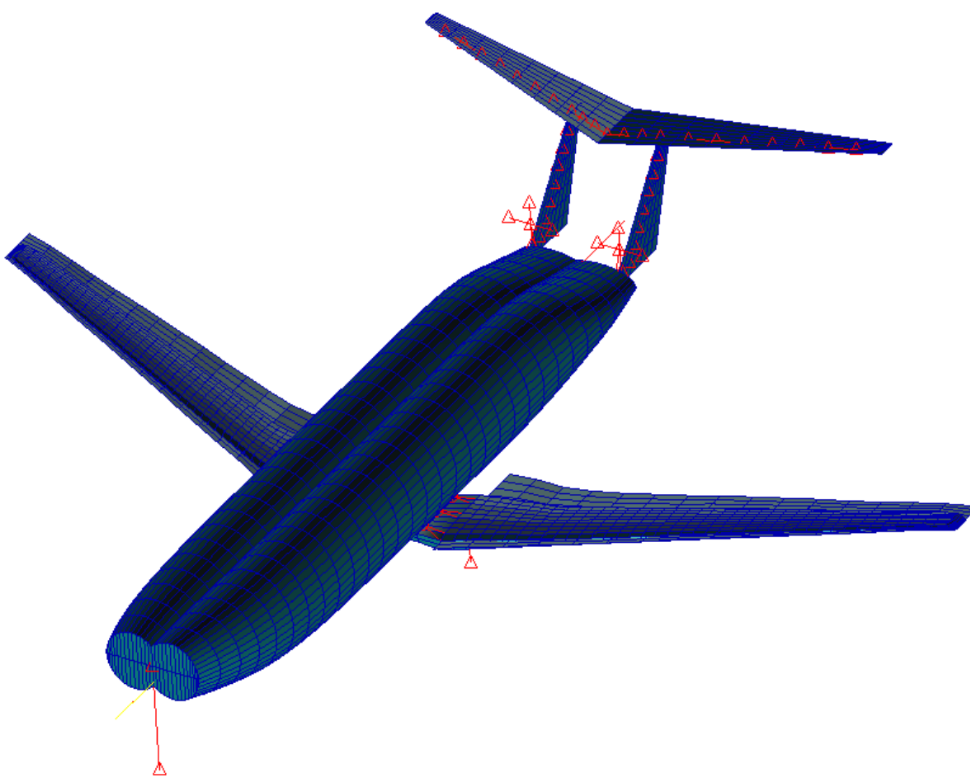


Figure 14. A depiction of the ND8 aeroservoelastic FEM, showing the structural FEM, aerodynamic models, landing gear, and engine mass models.

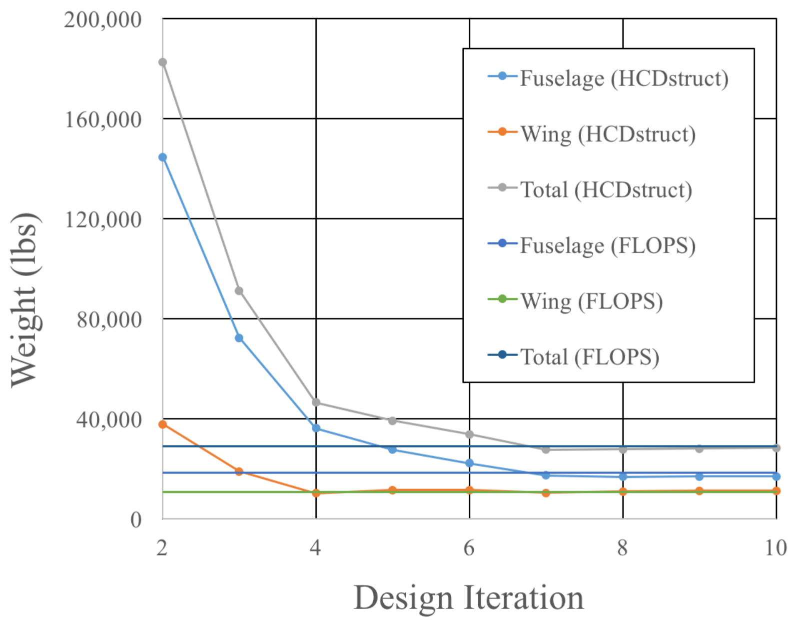


Figure 15. Structural weight convergence history of the optimization design cycles for the ND8 aircraft model.

IV. Summary and Future Work

In this paper, recent developments to HCDstruct, culminating in version 2.0 of the software, were presented. These developments included foremost a new, generalized TW aeroelastic structural optimization capability. Given any TW aircraft configuration modeled in OpenVSP (or any other CAD program offering STL export options), HCDstruct can now construct a complete aeroelastic FEM given few user inputs and compose all the files required to optimize the primary structural weight using NASTRAN SOL 200. This new capability was validated using the Boeing 737-200 aircraft, for which a custom OpenVSP geometry model was built. The structural weight optimization results for this model analysis agreed with available data for the 737-200 aircraft to within 1.6% for the complete primary airframe structure and to within 5.0% and 8.9% for the fuselage and wing structures, respectively. Additionally, a similar application of the current tool was performed for the latest iteration of the ND8 aircraft concept, which suggested corrective factors, FRFU and FRWI, for subsequent FLOPS analyses of 0.92 and 1.03 for the fuselage and wing weights, respectively.

Ongoing work includes the development and implementation of an aerodynamic matching utility for HCDstruct 2.1. With this new utility, the Enhanced Correction Factor Technique (ECFT)[20] is implemented to enable the calculation of W_{KK} correction matrices for use with NASTRAN's static and dynamic aeroelasticity solution sequences. With this correction matrix, the DLM aerodynamics within NASTRAN are corrected using a computational fluid dynamics (CFD) solution for surface pressures over the aircraft OML. The current developmental version of this utility, *aeroMatch*, supports the use of Cart3D CFD solutions. Following the completion of aeroMatch for HCDstruct 2.1, the tool will be used to perform dynamic aeroservoelastic analyses of advanced aircraft concepts like the ND8.

Acknowledgments

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