Fluid-Structure Interactions studies of a Blended Wing Body aircraft using Free and Open-Source Software based Hybrid-Fidelity Framework

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Abstract. Research on Blended Wing Body (BWB) aircraft has received impetus in recent past due to the advantages of higher aerodynamic efficiency, low fuel consumption, and less emissions as compared to conventional tube-and-wing aircrafts. However, a proper multi-disciplinary optimization of the external geometry of BWB needs to be carried out to gain these advantages. In light of this aspect, the present paper reports the development of a hybrid-fidelity one-way fluid structure interaction framework by digital threading of the free and open source software. Seamless functioning of the hybrid-fidelity framework is demonstrated for the BWB aircraft. OpenVSP, an open-source parametric modeling tool, is used for generating 3D CAD model using parametric modeling approach. VSPAERO, the panel method based numerical solver, is employed for low fidelity aerodynamic analysis. FreeCAD, an open-source CAD software with CFD and FEM workbench modules, and meshing tools, is used to receive the CAD model from OpenVSP in STEP format. FE mesh is generated using Netgen in FreeCAD environment. Python scripting is used to map the surface pressure distributions, predicted using VSPAERO, onto the FE mesh in the FreeCAD environment. FEM workbench module of FreeCAD is used to carry out static stress analysis and modal analysis using open-source finite element solver, CalculiX. Advantage of this hybrid fidelity framework is that it uses less computational resources and less time for carrying out one-way FSI studies and would be immensely useful to carry out Design of Experiment studies during conceptual design phase.

Keywords: blended wing body, CalculiX, Fluid Structure Interaction, FreeCAD, Netgen, OpenVSP, VSPAERO

1 Introduction

Aerial bodies, including unmanned aerial vehicles and next-generation aircraft configurations, require efficient conceptual design frameworks that balance rapid iteration with reliable structural and aerodynamic assessment. Increasing technical complexity, sustainability requirements, and the need for rapid design cycles highlight the importance of robust and accessible digital design tools [1 - 3] of various fidelity levels.

Open Vehicle Sketch Pad (OpenVSP), originally developed by NASA, is an open-source parametric aircraft geometry tool that enables users to rapidly create, modify, and analyze 3D models of aircraft and its components [4,5]. Its integration with

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VSPAERO enables low-fidelity aerodynamic and stability analysis, making it well-suited for conceptual and preliminary design stages [6].

However, low-fidelity aerodynamic tools alone are insufficient for getting the holistic view of its effect on the structure. High-fidelity structural analysis paradigms like Finite Element Methods (FEM), which are often computationally expensive and not directly integrated into conceptual design environments, have to be coupled to the aerodynamic framework to assess the fluid-structural interactions. It is thus desirable to realize a framework that digitally weaves a rapid conceptual modeling framework with aerodynamic and structural analysis framework for this purpose.

While researchers have made efforts to realize frameworks using proprietary software [7] and Multidisciplinary Design Analysis and Optimization (MDAO) have been attempted [8], the present effort reports development of a Free and Open-Source Software (FOSS) based hybrid fidelity framework that combines rapid low-fidelity modeling and aerodynamic analysis in OpenVSP and VSPAERO with high-fidelity structural and modal evaluation in FreeCAD and CalculiX. Customized python script is used to interface the aerodynamic and the structural solver modules. VSPAERO predictions have been validated against benchmark experimental observations and CalculiX predictions have been validated against canonical analytical benchmarks to ensure reliability of their predictions at individual levels. The present work is limited to demonstration of the framework for a Blended Wing Body (BWB) configuration.

2 Literature Review and Problem Definition

Modern aircraft design increasingly relies on integrated frameworks that combine geometry modeling, aerodynamic analysis and structural evaluation in the conceptual design stage. Early-stage design tools such as OpenVSP and JPAD Modeller enable rapid prototyping and iterative optimization [9,10], while multidisciplinary design optimization frameworks integrate aerodynamic, structural and propulsion analyses [10 - 12].

Many frameworks leverage low-fidelity analysis tools such as vortex lattice and panel methods for quick aerodynamic and stability assessments, while high-fidelity solvers based on as CFD and FEM are used for detailed structural and performance analysis [4][5]. Automation and scripting are commonly used to reduce manual labour and error in transferring data between tools [9][12].

Despite these advances, most published frameworks focus on a single fidelity level or are tool-specific and require significant expertise and resources. Integration of low-fidelity and high-fidelity analysis tools is limited. High-fidelity tools are computationally intensive and not always practical for early conceptual design stages, while low-fidelity tools may lack the accuracy needed for detailed design. At the same time, costly proprietary tools are beyond the financial reach of start-up firms and local MSMEs during the initial stage of any product development.

Hence, there exists a scope for developing FOSS based hybrid fidelity frameworks that can digitally thread rapid aerodynamic analysis with detailed structural analysis within a single integrated framework. The present work addresses this aspect by developing FOSS based hybrid fidelity computer aided engineering analysis framework by using parametric 3D model generation in OpenVSP, low-fidelity aerodynamic analysis in VSPAERO, digitally threading the outputs using customized python scripting and carrying out high-fidelity FEM analysis using CalculiX FE solver within the FEA workbench in FreeCAD environment. This framework enables quick feedback and the ability to iterate on multiple configurations to make conceptual design decisions. Since the framework is based on FOSS, the financial burden on the start-ups or local MSMEs, at initial stage of product development, is eliminated.

3 Methodology

Details of the in-house developed FOSS based hybrid fidelity framework is shown in Fig. 1. Finer details of the framework is reported in the next subsection

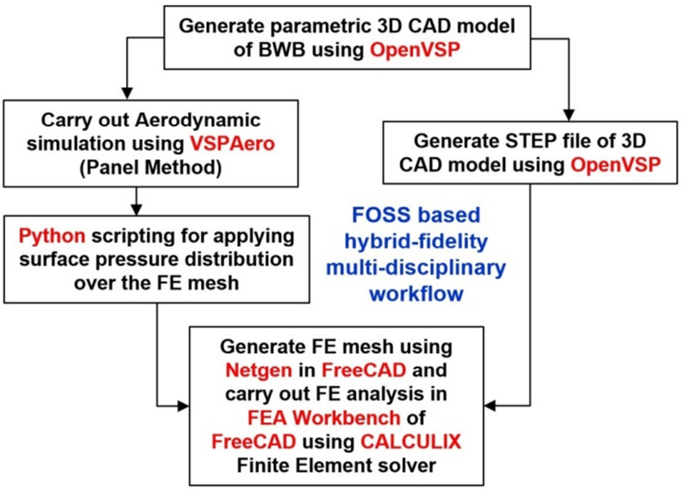

Fig. 1. Details of the framework

3.1 Overview of the framework

The framework begins with creating an aerial vehicle's 3D parametric model in OpenVSP, where main body and components such as fairings, propulsion, storage, and seats can be modelled and assembled. Mass properties, including total mass, centre of gravity, and moments of inertia, are ascertained using OpenVSP. Parametric modelling approach is adopted so that changes in configurations during conceptual design iterations can be easily implemented or the process can be easily automated.

Aerodynamic and stability analyses are performed using VSPAERO and pressure coefficient (C_p) data over the aerial vehicle's surface are generated. The geometry is exported as a trimmed STEP file and imported into FreeCAD. In the FreeCAD environment, finite element mesh is generated using Netgen Mesher. Aerodynamic pressure coefficient (C_p) data, generated using VSPAERO are mapped onto the FEM model using a customized Python script developed in-house. Static structural and modal analyses are then carried out using CalculiX FE solver available in the FEA workbench of FreeCAD. The next sub-section reports finer details about the methodology for the benefit of the readers.

3.2 Geometric modeling of aerial platform

For the present study, Blended Wing Body (BWB) is considered as the aerial platform. Geometry of the BWB aerial platform is based on the design reported by Roberto [13] and Carlsson et al. [14]. Parametric geometry of a BWB aircraft was modelled in OpenVSP using parametric wing sections [11]. The default wing geometry was split into sections, and span, chord, dihedral, and sweep were adjusted to obtain the BWB shape. Leading and trailing edges were blended to produce the required planform, and suitable airfoils were applied at each cross-section. The model (shaded as well as wire-frame) is shown in Fig. 2. For demonstrating the capability of the FOSS based hybrid fidelity framework, only the shell of BWB has been considered.

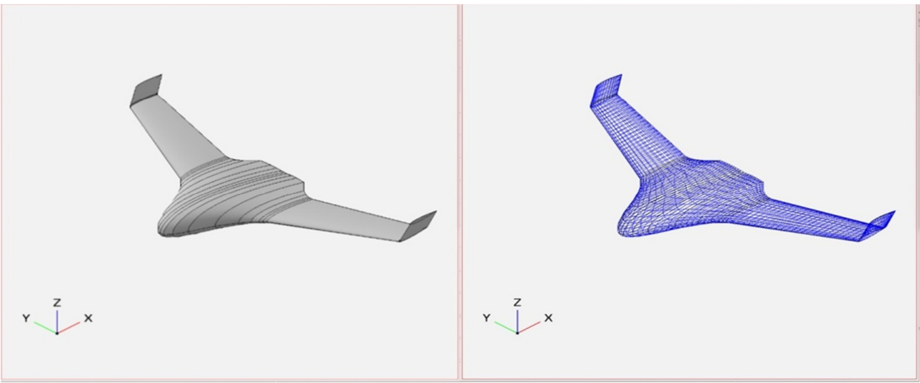

Fig. 2. 3D CAD model of BWB created using OpenVSP

3.3 Estimation of Inertial, Aerodynamic and Stability properties

Mass properties of the material were inputted in OpenVSP to get the mass, centre of gravity location, and moments of inertia (I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{yz} and I_{zy}). Stability analysis i.e. estimation of the static stability margin was performed using VSPAERO. Internal components were represented as simplified mass elements because VSPAERO stability analysis focuses on external geometry for meshing. Flow conditions and angle of attack were specified and aerodynamic as well as stability analysis were carried out for range of angles of attack. Surface pressure coefficients, neutral point location, and subsequently static margin were computed. Pressure coefficient (C_p) distributions (Fig. 3) were exported for carrying out static structural analysis. Predicted aerodynamic efficiency from VSPAERO were compared with wind tunnel tests to validate VSPAERO.

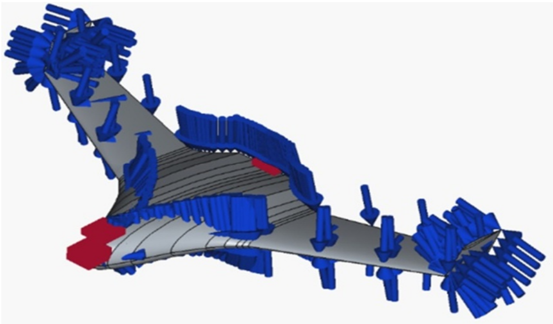

Fig. 3. Prediction of surface C_p using VSPAERO

3.4 Pressure Mapping and Structural FEM Analysis

The aircraft model was exported as a trimmed STEP surface and imported into FreeCAD FEM Workbench. Material properties and boundary conditions were defined, and surface mesh was generated. Pressure distribution data, estimated using the VSPAERO (Fig. 3), was converted into physical pressures using the flight conditions (reference area, air speed, and air density) and mapped onto the FEM mesh using a custom Python script that assigns pressures to faces based on nearest C_p data points. Static structural analysis and modal studies, under the influence of the surface pressure, were carried out using the open-source FE solver, CalculiX. This solver is available in the FEA workbench of FreeCAD.

FEM solver's validation was performed by simulating the case of a cantilever beam under axial, bending and torsional loads. Simulation results were compared with analytical solutions.

4 Results and Discussion

This section reports the findings of the one way fluid structure interaction (FSI) analysis carried out for the BWB aerial platform using the FOSS based hybrid fidelity framework. The next subsection reports the findings of the validation studies of the individual aerodynamic and structural solver, followed by the details of the findings of the various analysis carried out using the FOSS based hybrid fidelity framework.

4.1 Individual validation studies of VSPAERO and CalculiX

Prior to developing the framework, the individual aerodynamic and structural FOSS solvers used in the framework, were validated. The findings of these validation studies are reported in this subsection

4.1.1 Validation studies of VSPAERO.

Aerodynamic force coefficient ratio (lift to drag) of the BWB aerial platform were predicted using VSPAERO module and compared with results of the experimental wind tunnel tests conducted at BIT Mesra, Ranchi [15]. Comparative plot is shown in Fig. 4. It is observed from the comparative plot that the predicted force coefficients are in agreement with the experimental values for different angle of attack.

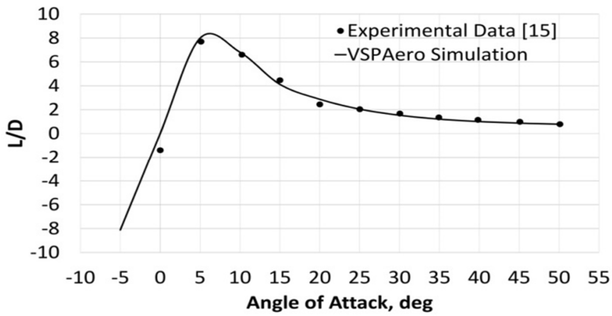

Fig. 4. Validation study of VSPAERO

4.1.2 Validation studies of CalculiX

FEM solver's validation was carried out by simulating a simple cantilever beam subjected to various loading conditions and comparing the predictions against analytical cantilever beam solutions. Comparision of the predictions from CalculiX with the values based on analytical calculation are reported in Table 1. It is observed from the comparative values that the predicted structural parameters are in agreement with the analytical values for deflections, stress, and modal frequency.

Table 1. Validation study of CalculiX

Parameters	Analytical	Prediction from CalculiX
Deflection in mm (Axial loading)	5.7143e-6	5.7e-6
Deflection in mm (Bending)	2.2857e-3	2.29e-3
Stress in Pa (Axial Loading)	1600.00	1883.19
Stress in Pa (Bending)	96000	95110
First Mode in Hz	327.0	328.5

4.2 Details of the estimated inertial properties

Mass property analysis is carried out for the BWB aerial platform using OpenVSP. For the given density of the shell material, the mass of the BWB aerial platform was predicted to be 637.485 kg. Coordinates of the Centre of Gravity of the BWB was estimated to be located at (12.109, 0.0, 0.559) along X-axis, Y-axis, and Z-axis. The origin of the coordinate system was considered at the nose of the BWB aerial platform and the dimensions were in meters. The estimated inertial properties of the shell of the BWB aerial vehicle are reported in Table 2.

Table 2. Inertial properties of BWB aerial platform shell

Sl. No.	Inertial properties	Estimated value (kg m^2)
01	I_{xx}	33862.75
02	I_{yy}	15401.16
03	I_{zz}	48422.37
04	I_{xy}	-8.244
05	I_{yz}	6.671
06	I_{xz}	75.588

It is observed from the above estimate that amongst the moment of inertia about the principle axis, value for I_{zz} is highest and I_{yy} is the least. This implies that BWB aerial platform has more inertial resistance to movement about Z axis and less inertial resistance to movement about Y axis. Physical interpretation is that the body shape is longer along the y direction and flatter in the plane perpendicular to Z axis. As the values of I_{xy}, I_{yz}, and I_{xz} are negligible as compared to I_{xx}, I_{yy}, and I_{zz}, the body is almost symmetric about the respective axes and the CG is close to the reference point.

4.3 Stability Analysis

Under the static stability analysis of the BWB aerial platform, the static margin at various angular orientation of the inflow air was estimated using VSPAERO module. Findings of the study are reported in Table 3.

Table 3. Static Margin at different angle of attack

Sl. No.	Angle of Attack (°)	Static Margin (%)
01	-5°	7.12 %
02	-2.5°	6.77%
03	0°	6.82 %
04	2.5°	6.90 %
05	5°	7.89 %

Since all the values of the static margin are positive, the BWB aerial platform is longitudinally stable for angle of attack range of -5° to +5°, and in spite of any disturbance about the pitch axis, the platform would naturally return to trim condition.

Since the values of the static margin vary between 6.77 % to 7.89 %, the BWB platform will have moderate static stability. As the change in the static margin with respect to change in the angle of attack is less, the location of neutral point is almost constant and the shape is aerodynamically consistent in behaviour.

4.4 Structural and Modal Analysis

Static structural analysis under aerodynamic pressure loading were carried out. The surface stress distribution and structural deformation are shown in Fig. 5 and Fig. 6 respectively. Quantitative details of the analysis are reported in Table 4. Modal analysis was carried out to predict the first ten modes of the BWB aerial platform. Predictions of the first three modes are reported in Table 5.

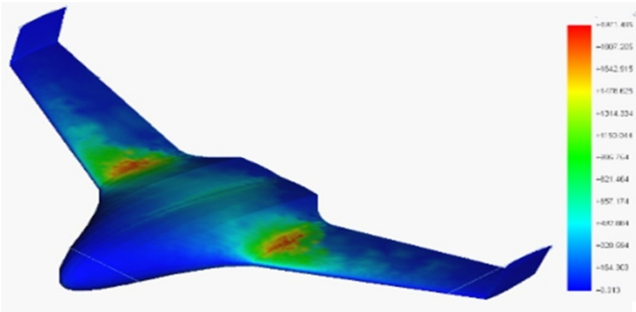

Fig. 5. Stress distribution over BWB model

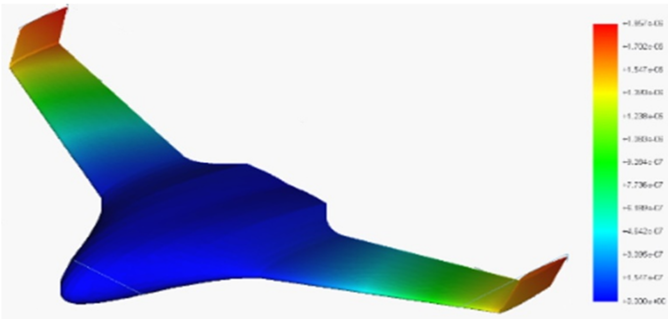

Fig. 6. Deflection of BWB model

Table 4. Finding of the static structural analysis

Structural Parameter	Predicted values
Min Displacement (mm)	0
Max Displacement (mm)	1.86E-03
Min Stress (Pa)	0.03
Max Stress (Pa)	2011.25

Table 5. Findings of the modal analysis

Mode	Frequency (Hz)
1	11.12
2	13.22
3	35.53

These results demonstrate the capability of the developed FOSS based hybrid fidelity framework to evaluate the static stresses and modal frequencies of a pressure-mapped conceptual geometry.

5 Conclusion

The present paper reports in-house development of a FOSS based hybrid multi-fidelity framework that digitally threads the rapid conceptual modeling and aerodynamic analysis in OpenVSP and VSPAERO with high-fidelity structural and modal analysis in FreeCAD and CalculiX using customized python scripting. Functionality of framework is demonstrated by carrying out a one way FSI analysis of a BWB aerial platform. Due to the FOSS component, this framework will offer a low cost and computationally inexpensive option to the startups and the local MSMEs during the conceptual design phase of a product development.

While the present study has been confined to one way FSI analysis, it is also envisaged to extend the framework to two way FSI analysis in future. The challenges, that would have to be overcome to realize the two way FSI framework include (but not limited to), conversion and export of the deformed STEP file from FreeCAD environment back to the OpenVSP's parametric 3D modeling environment in a compatible format, automation of the entire process of 3D CAD modeling and aerodynamic analysis using angle-script, structural analysis including running of the customized python script for digital threading of the two solvers and FE mesh generation, and running the entire FSI cycle in a batch mode till the convergence is achieved.

While the validation of the individual low fidelity and high fidelity solvers are carried out, it is envisaged to carry out an inclusive validation of the entire FSI framework before proceeding with the usage of this framework for sensitivity studies, automated optimization and expanded multidisciplinary integration to improve scalability and design exploration capability.

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