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# Numerical simulations study of coupled fluid-structure interaction on an aircraft wing for aeroelastic applications

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## Abstract
This paper presents a methodology suitable for fluid-structure interaction (FSI) analysis in the context of nonlinear aeroelastic responses. The analysis focuses on Van's Aircraft RV-10 wing, a single-engine, light-sport aircraft in order to capture nonlinear aeroelastic responses and predict early transitions to flutter. Assessment between structural and fluid model applying the steady-state and transient models using the SST K-Omega Navier-Stokes showed a good correlation, validating the use of FSI framework for torsional divergence speed. Despite simplifications on FSI solver, the proposed framework demonstrates robust predictive capability in assessing the aeroelastic performance in the early stages of aircraft design.

**Nomenclature**

| | |
|---|---|
| $\alpha$ | Angle of attack |
| $\Delta$ | Variation |
| $\mu$ | Molecular viscosity coefficient, doublet strength |
| $\rho$ | Density |
| $\sigma$ | Source strength or volumetric rate |
| $\omega$ | Natural frequency |
| $\Phi$ | Velocity potential |
| AR | Wing aspect ratio |
| E | Young's modulus |
| G | Shear modulus |
| M | Structural Mass matrix |
| K | Structural Stiffness matrix |
| p | Pressure |
| t | Time |
| T | Temperature |

**Glossary**

| | |
|---|---|
| FSI | Fluid-Structure Interaction |
| CFD | Computational Fluid-Dynamics |
| CAE | Computer-Assisted Engineering |

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# 1. Introduction

This study reports the numerical Simulations for a Fully Coupled Fluid-Structure Interaction to predict the aeroelastic properties of wings in the early stages of aircraft design. A challenging problem that arises in the Aeroelasticity domain is to provide insight into high-accuracy fluid-structure interaction by the numerical and experimental analysis of a fully-coupled model on an aircraft wing, with an unsteady pressure field. This topic highlights the problem statement in the research field based on ensuring a robust prediction tool for analysis of aeroelastic nonlinearities responses that may result in a premature transition to flutter and/or Limit-Cycle Oscillation (LCO).

This study is motivated by the need to develop an accurate, robust prediction tool for the analysis of Fluid-Structure Interaction (FSI) on an aircraft wing subjected to aerodynamic forces and the associated nonlinear-aeroelastic response. A fully-coupled FSI model is analysed by the implementation of structural and unsteady aerodynamics as a unique aeroelastic system that could lead to a premature transition to flutter and/or LCO of the structure. According to [1], flutter, an unstable self-excited vibration in which the structure extracts energy from the air stream, is analysed as dynamic instability which may eventually result in stall or buffeting conditions or classical bending and torsion coupling actions. This coupling occurs when the aerodynamic forces associated with motion cause the modes to the couple in an unfavourable manner. Flutter is an unstable self-excited vibration in which the structure extracts energy from the air stream and often results in catastrophic structural failure. Aeroelasticity is a scientific field that studies the behaviour of structures under the interaction of inertial, structural, and aerodynamic forces. Aeroelastic systems may exhibit nonlinearity due to some phenomena occurring in the structure, aerodynamics, and servo-controlled systems. These nonlinearities affect this phenomenon in ways that cannot be predicted using linear analysis methods. The effects of different structures and aerodynamic nonlinearities on aeroelastic systems are discussed. The typical nonlinear aeroelastic response phenomenon is limited cyclic oscillation, which can be regarded as finite flutter phenomenon [2].

This study provides insight of aeroelastic phenomenon by a coupled numerical analysis, in which the nonlinear equations of motion for the wing structure are solved simultaneously with a set of governing Navier-Stokes equations, resulting in a coupled dynamic system in which the fluid and structure components are treated as a unique system [3,4]. High-order operators are used in the numerical simulation to provide accurate solutions to this aeroelastic problem. This coupling occurs when the aerodynamic forces associated with motion in two modes of vibration cause the modes to the couple in an unfavourable manner. Fluid and Structural Dynamic Models were designed on ANSYS to discretize both fluid and structural domains. FSI Methods are validated with one-way and two-way coupling methods [5,6]. Reynolds Averaged Navier-Stokes equation and Turbulence Transport equations governing the flow were integrated with the FSI solver. Steady and transient models will be analysed by applying different turbulence models for one and two degrees of freedom (DOF) scenarios involving pitching and plunging. Furthermore, numerical results will be post-processed to obtain the phase difference exerted by the fluid onto the wing airfoil [7].

These approaches have been influential in the aeronautical field because of the importance of structural response over aerodynamic loads on flight dynamics. Recent theoretical developments have revealed that Fluid-Structure Interaction (FSI) models allow the aeroelastic phenomenon to be predicted by a coupled numerical analysis. Several works have shown that this problem can be overcome by simultaneously solving the nonlinear equations of motion for the wing structure with a set of governing Navier-Stokes equations [8].

## 1.1 Aeroelastic Model

Computational fluid dynamics involves the analysis of fluids in motion in a medium. Solve the Navier-Stokes equations and fluid-structure interface domains using dynamic meshes and boundary conditions. Assumptions are made for the continuity equation regarding the conservation of mass; the conservation of momentum, where the momentum equation is solved by applying Newton's second law; and finally, the conservation of energy given by the first law of thermodynamics. This study develops and implements a Fluid-Structure interface to evaluate and study the aeroelastic response in a viscous flow solver. The monolithic and interleaved solvers perform fully coupled nonlinear aeroelastic, aerodynamic, and inertial analysis of the transient response of structures. Due to the complexity of fluid dynamics equations, with multiple unknowns for each integer, numerical methods are required to predict the behaviour of flow fields.

Therefore, computational fluid dynamics (CFD) is implemented to obtain an approximate solution to this system of equations. After unfolding the disclaimer of complex equations in fluid mechanics, the next step is to choose the most accurate mathematical model that has a reasonable approximation to the physical problem. In our example, the potential

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flow is assumed, and the panel method is applied in each node of the fluid domain. Compressibility effects are not considered in the analysis.

The general form of the 2-DOF motion of a fixed-wing can be derived using the Lagrangian equations and considering the total momentum of the centroid of the wing section. This approach leads to a set of nonlinear equations of motion for the airfoil pitch and the amplitude of the pitch y = h(t) and α(t), respectively. These two flexible supports restrict the motions of the airfoil except for the two modes of translation and rotation. For the case of zero damping, the equations of motion of the airfoil subjected to a uniform flow are obtained by the following equation:

$$M_s\ddot{v} + K_s v = \begin{bmatrix} -Lift \\ Moment \end{bmatrix} \tag{1}$$

where *v(t)=[h(t), α(t)]* is the displacement vector, and Lift, L(t), and Moment, M(t), are the lift and pitching moment about the rotation axis, correspondingly. Figure 1 shows the 2D assumptions to solve the aeroelastic behavior of the wing.

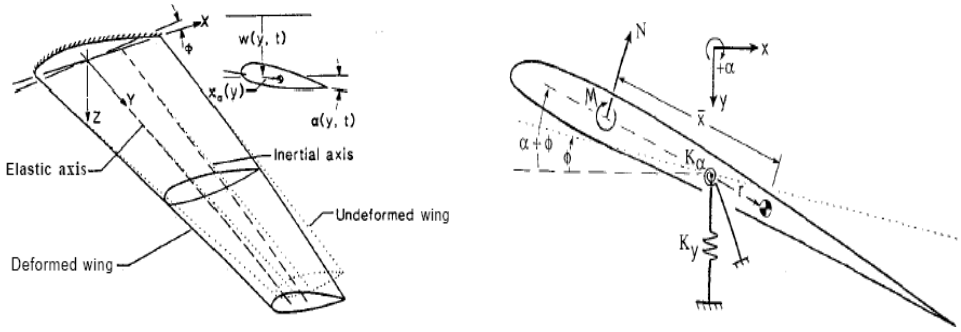



**Figure 1.** Binary Flutter Model Aeroelastic Model. [9]

It is necessary to take into account to include the structural wing section properties including the linear mass matrix $M_s$ and the stiffness matrix $K_s$, given by the following equation, which assumes no damping:

$$\begin{bmatrix} m & mx_\alpha b \\ mx_\alpha b & I_g + m(x_\alpha b)^2 \end{bmatrix} \begin{Bmatrix} \ddot{h} \\ \ddot{\alpha} \end{Bmatrix} + \begin{bmatrix} k_\alpha & 0 \\ 0 & k_\alpha \end{bmatrix} \begin{Bmatrix} h \\ \alpha \end{Bmatrix} = \begin{bmatrix} -L \\ Lec + M_{ac} \end{bmatrix} \tag{2}$$

Where denotes the total mass of the wing section, “m” is the mass moment of inertia, “I” is the static moment. Theodorsen's unsteady aerodynamic model was implemented to analyze the pitching and torsion motions of the airfoil in the frequency domain by assuming small amplitudes of 5% chord. In the analysis performed, the flow is assumed to be inviscid and incompressible with no flow separation to simplify the study. The monolithic and staggered solvers acquire the capability to conduct fully coupled nonlinear aeroelastic, aerodynamic and inertial analyses of the structure's unsteady responses [10,11].

By imposing a harmonic function to the motions in both torsion and bending modes:

$$\begin{Bmatrix} h \\ \alpha \end{Bmatrix} = \begin{Bmatrix} \hat{h} \\ \hat{\alpha} \end{Bmatrix} e^{i\omega t} \tag{3}$$

The aerodynamic loading can be represented as the expression:

$$F_{aero} = \begin{bmatrix} -L \\ Lec + M_{ac} \end{bmatrix} = \frac{1}{2}\rho {U_\infty}^2 Q_f \begin{Bmatrix} h \\ \alpha \end{Bmatrix} \tag{4}$$

To validate the aeroelastic response module, it is assumed no structural damping effect in the equation of motion. Hence, to investigate the airfoil response near the flutter boundary, V-g method will be implemented [10,11]. In V-g analysis, the structural damping of all the modes of vibration is assumed to have one unknown value, g.

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$$M\ddot{h} + Mx_\alpha\ddot{\alpha} + K_h\left[(g_h + g)\frac{\dot{h}}{\omega} + h\right] = -Le^{i\omega t} \tag{5}$$

$$I_\alpha\ddot{\alpha} + Mx_\alpha\ddot{h} + K_\alpha\left[(g_\alpha + g)\frac{\dot{\alpha}}{\omega} + \alpha\right] = M_\alpha e^{i\omega t} \tag{6}$$

V-g method is based on the balance of energy between the flow and the motion of the structure corresponding to the flutter boundary for a linear aeroelastic system. The analysis is conducted in the frequency domain where harmonic motions in pitching and plunging are imposed on the dynamic response of the structure to represent the state of the aeroelastic system in the stability boundary. Subsequently, the equations of motion will lead to the solution of the eigenvalues problem. To perform this analytical analysis, the corresponding mass, inertial and geometric parameters will correspond to the numerical design for validation purposes. Table 1 shows the properties of the wing to be solved in the aeroelastic model.

**Table 1.** Literature structural properties of Van's RV-10 wing.

| Structural Parameters | Value |
|---|---|
| **Mass, $m_T$** | 200 kg |
| **Stiffness constant, $k_h$** | 2800 N/m |
| **Mass Moment of Inertia, $I_\alpha$** | 40.4 Kg·m |
| **Spring constant pitch, $k_\alpha$** | 23.3 N/m |
| **Wing chord, c** | 1.44 m |
| **Wing span, s** | 9.72 m |

In order to proceed with the validation of the results, Figure 2 shows the results for the two modes (roots of the flutter determinant) for a simple 2-DOF airfoil model in frequency versus velocity and damping versus velocity curves. In Figure 2 (b), The conservative assumption of zero structural damping is made and the velocity at which the upper curve passes through g = 0 corresponds to the flutter velocity of the model. The flutter frequency of the model can then be determined by introducing the values obtained in the previous figure into Figure 2 (a), and the unstable mode frequency value at the flutter velocity value is obtained. The slope of the damped velocity curve as it passes through the flutter velocity can be used as a qualitative measure of the severity of oscillations during accelerated flight.

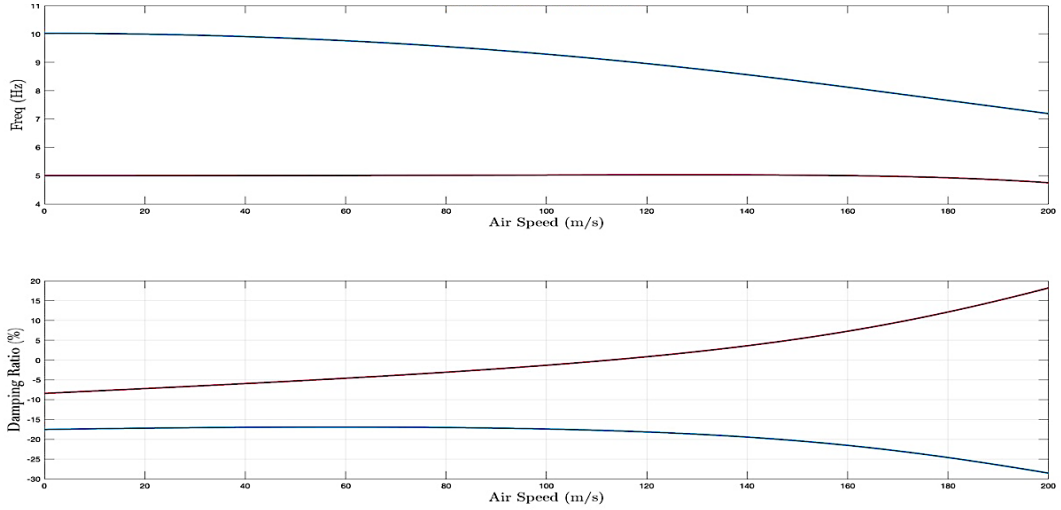



**Figure 2**. P-K method for critical flutter speed velocity using analytical V-g model.

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## 2. Fluid-Solid Numerical Solver

Higher-order operators in computational solutions were used to provide accurate results consistent with aeroelastic solutions. In a monolithic model, fluid, structural, and dynamic mesh equations are solved simultaneously. When there are nonlinearities in the fluid or structural equations, the model is computationally challenging, mathematically suboptimal, and difficult for software to manage [13]. Alternatively, the fluid and structural equations can be solved by a staged procedure consisting of successive decoupled integrations of the structural and fluid fields [3]. Thus, each domain is frozen during the temporal integration of the other domain, which brings many advantages such as being able to use unidirectional or bidirectional schemes and methods for two separate domains. The main disadvantage is that this method is not always stable and mesh convergence anomalies may occur during performing the iterations.

In this study, only staggered procedures will be considered, which are a high-mathematical challenge but a simple way to predict aircraft aeroelastic behavior [6]. Several aeroelastic tests will be performed on a 3D wing using different coupling procedures. Figure 3 describes the coupling algorithm of ANSYS Fluent and ANSYS Mechanical selected to perform the analysis. The cross-section of the wing was NACA2412 airfoil in the stream-wise direction. The wing dimensions are a chord of 1.44 m and a span of 9.72 m. Table 1 shows the properties of Van's rV-10 aircraft wing. The simulations are modeled with an angle of attack of 4º. Rib distribution is preserved as the original model.

To obtain the fluid simulation results in accuracy with the real case, the fluid domain is spatially discretized and with hybrid unstructured grids. At the fluid domain near the wing walls, a denser mesh is set up to ensure high-accuracy results on the Fluid-Structure Interface. The application of inflation and refinement actions on the wing proximity was performed with the aim of robust boundary layer thickness throughout the whole algorithm [14]. Figure 4 shows the final mesh to perform the computational fluid dynamic simulation, with 735585 elements.

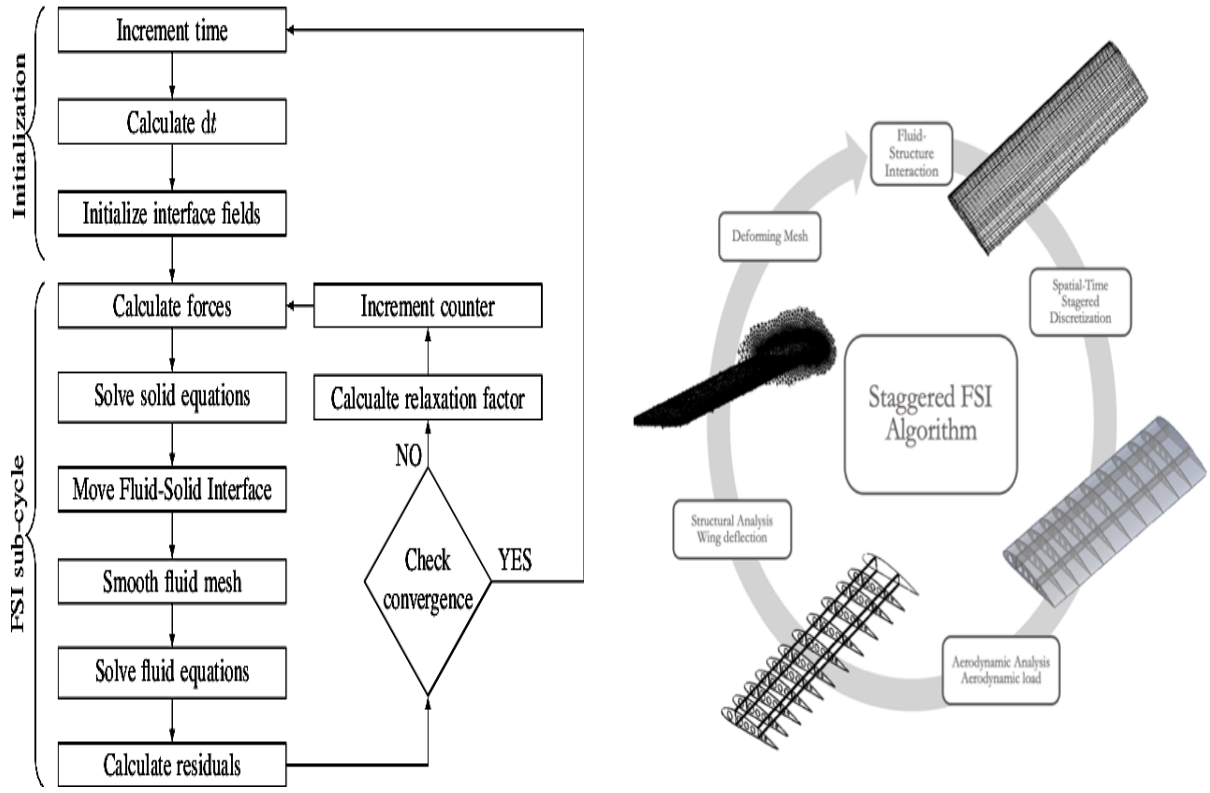



***Figure 3.*** Fluid-Structure Interaction solvers using interfacing methodologies for aeroelastic numerical simulation.

To perform the simulations NACA2412 airfoil is selected, this series of foil shows a laminar-incompressible flow as far aft as 50% of the chord with a low angle of attack (AoA). Precise control over the spatial domain is essential during the FSI algorithm. This spatial domain has been controlled by several iterations where mesh ratios were analyzed. As shown in Figure 4, different mesh factors were applied to fluid domain close to the volume of interest for this study.

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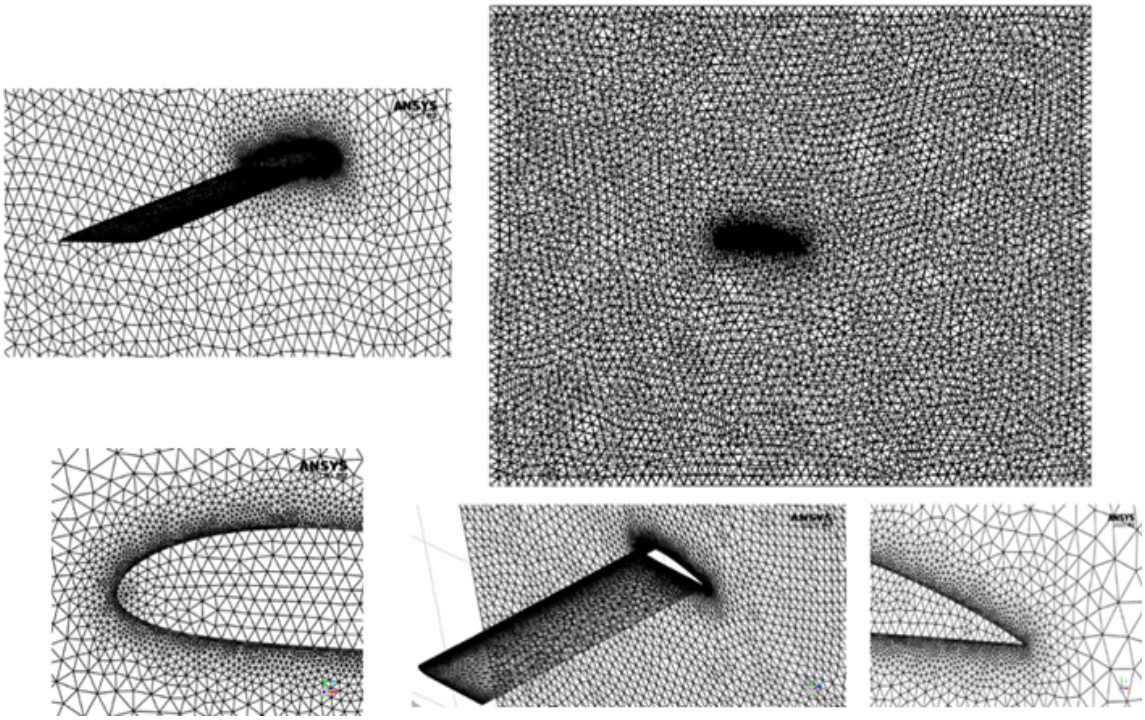
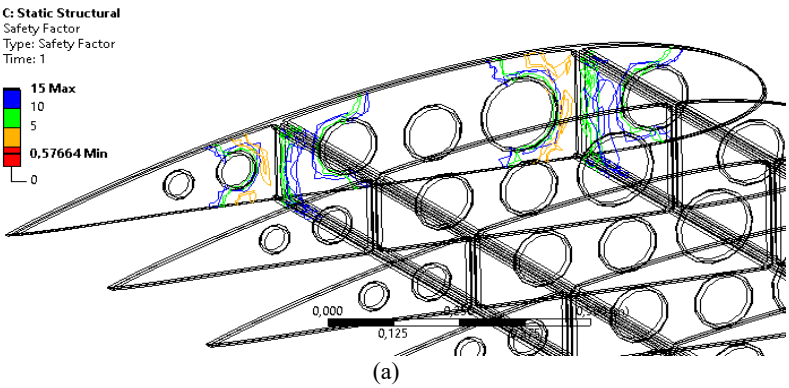


**Figure 4.** Geometry and Mesh set up for Fluid-Structure Interaction CFD-SCD solver.

## 3. Results

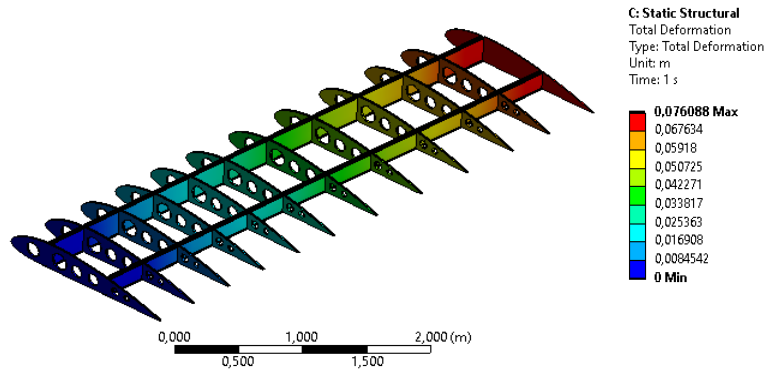
The results obtained in the FSI are presented by coupling Structural and Fluid Analysis with 2 different interfaces: one-way (linear) coupling and two-way (cycle iteration) such as pressure contours, displacements, shear, normal stresses, lift coefficients, and phase and frequency response. SST Transition model, which is based on the coupling of the SST k - w transport equations was applied to predict transition instead of assuming fully turbulent flow. Figure 5 presents the results of the steady structural and fluid analysis simulations, considering structural displacement and aerodynamic loads. It is observed that the maximum deflection occurs at the wing tip. It can be stated that this is the point where the oscillation begins during the aeroelastic forces. Numerical results on shear stress indicate that lightweight structures based on internal holes are subject to high shear stress. Therefore, light sport aircraft are manufactured with light structures to reduce inertia moment by paying a penalty in stress concentration. Stresses have a maximum sharpness in the hole area and decrease with increasing the distance from the stressed zone.



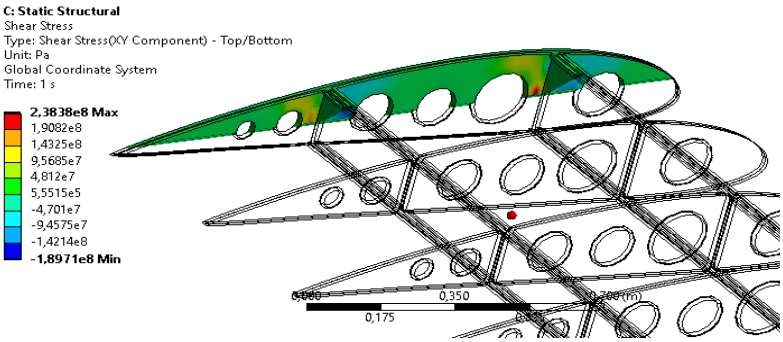

(a)

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(b)




(c)

**Figure 5.** (a) Non-Coupled Steady Structural Analysis of Safety Factor. (b) Non-Coupled Steady Structural Analysis of Internal Ribs Structure Displacement. (c) Non-Coupled Steady Structural Analysis of Shear Stress on Ribs.

The pressure distribution obtained by the CFD is linked with the one-way structural wing analysis. Equivalent Von-Misses stresses and Shear Stresses for numerical results were obtained with two different programs commercial ANSYS and NASTRAN & PATRAN. In the case of the NASTRAN & PATRAN model, a physical simplification of a flat plate was introduced as mesh quality was difficult to control in this software. Similarities in numerical results are observed comparing analytical derivation and ANSYS results.

Table 2 shows the comparison of the results for the different applied methods to determine the modes of the wing. Results obtain both, analytically and numerically, indicate that aeroelastic coupling depends on critical flutter speed. Shear and Normal Stresses are computed under coupling action at the given torsional and bending mode frequency, 50 Hz. Comparing total deflections for the first three mode shapes values with the obtained in the Steady Non-Coupled Analysis, it can be stated that aeroelastic has not only an effect on aerodynamics and elastic forces, but also on elastic forces that interacts together while coupling.

**Table 2.** Numerical and Analytical results comparison for total deformation for One-Way and Two-Ways Fluid-Structure Interaction under SST Turbulence Model for critical divergence velocity.

| Mode | Analytical deformation [m] | Numerical one-way FSI deformation [m] | Numerical two-ways FSI deformation [m] |
|---|---|---|---|
| **1st Flapwise Bending** | 0.0300 | 0.03306 | 0.32908 |
| **1st Chordwise Bending** | 0.0420 | 0.04601 | 0.04578 |
| **1st Torsion & Bending** | - | 0.04781 | 0.47190 |

Figure 6 shows the results of the simulations of the structural response at 7.78 Hz of frequency, for the 1st Flat-wise. The maximum deformation, as expected, is on the wing tip and the value is 0,0336m. The result of the 1st edged-wise,

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at the frequency of 45 Hz is shows that the critical is located at the wing tip. The harmonic response for torsional and bending shows that the maximum deformation is 0,047m. Wing pitch and plunging motion are easily identified in the first sequence, where the pressure distribution causes aerodynamic loads on the aircraft wing. Depending on whether the aerodynamic forces delay or lead to displacement, oncoming airflow absorbs or supplies energy from the aircraft wing, dampening or amplifying the motion. Therefore, it is important to evaluate critical airspeed limits for proper structural and aeroelastic design.

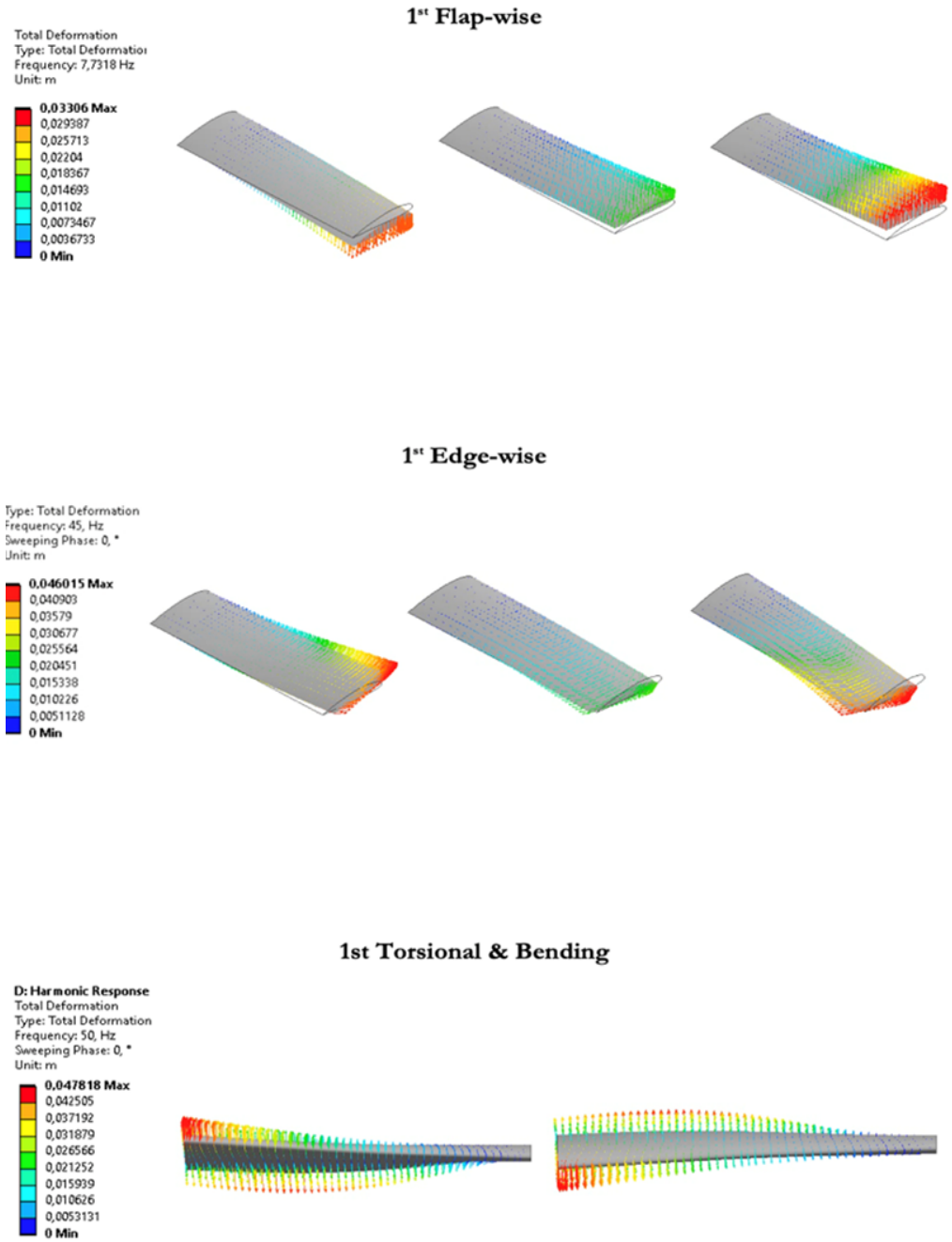



**Figure 6.** Numerical results for total deformation flap, chord and torsion coupling modes for Critical Flutter Speed.

Wing tips displacements have been analytically solved by applying Castigliano's Theorem [12]. The numerical results are based on solid coupled and there are small differences obtained by the analytical results. Measure the pitch and plunging time histories of the aircraft wingtip displacement in meter and radian, accordingly, have been measured using ANSYS point displacement function over a mesh node. This action allowed to determine pitching and plunging amplitude to formulate the aircraft movement as a function of time for the Critical Flutter Speed.

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Figure 7 shows the plunging and pitching time history for Critical Flutter Speed. Pitching and plunging time stories for the aircraft wing tip displacements have been measured using ANSYS point displacement function over a mesh node. This action allowed us to determine to pitch and plunging amplitude to formulate the aircraft movement as a function of time for the Critical Flutter Speed.

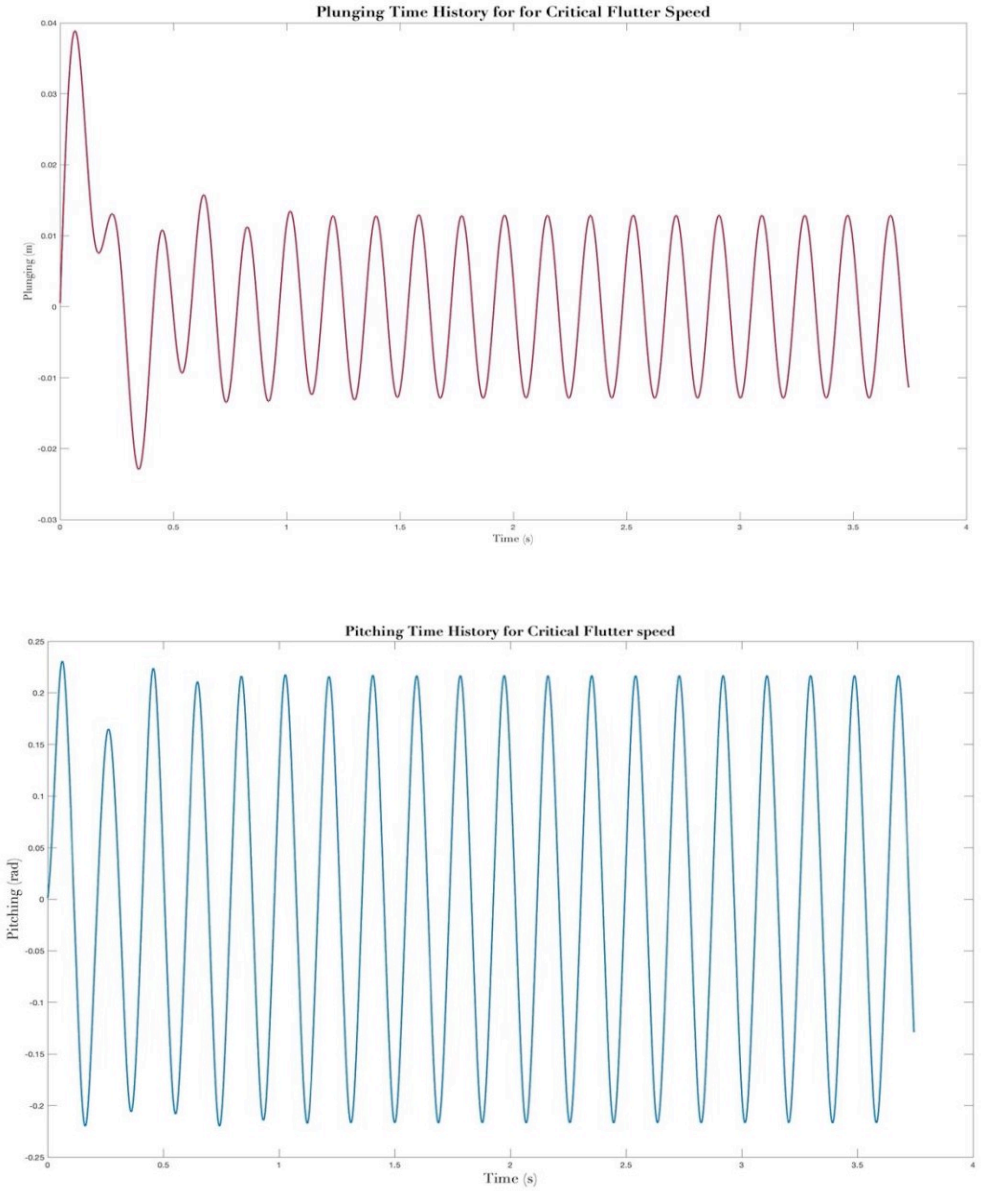



**Figure 7.** Plunging and Pitching Time History for Critical Flutter Speed.

Therefore, as the pressure field is leading the displacement motion, the incoming flow absorbs energy from the aircraft wing, and the motion is amplified. Coupled bending-torsion motion has been obtained for the given free stream conditions. Hence, it is important to evaluate the critical airspeed limit for proper structural and aeroelastic design. Figure 8 shows the displacement and unsteady pressure field phase difference and the corresponding Critical Frequencies. Unsteady flow fluctuations, attributed to an unsteady pressure field due to natural vibration motion, influence the flow field as has been proved in the non-coupled static analysis. Nevertheless, pressure fluctuations are harmonic in time and also, and they have the same frequency and a phase shift as the motion vector. Therefore, the only component that can amplify the mode of vibration and induce flutter is the imaginary component. Thus, the phase will establish whether the system is stable or not.

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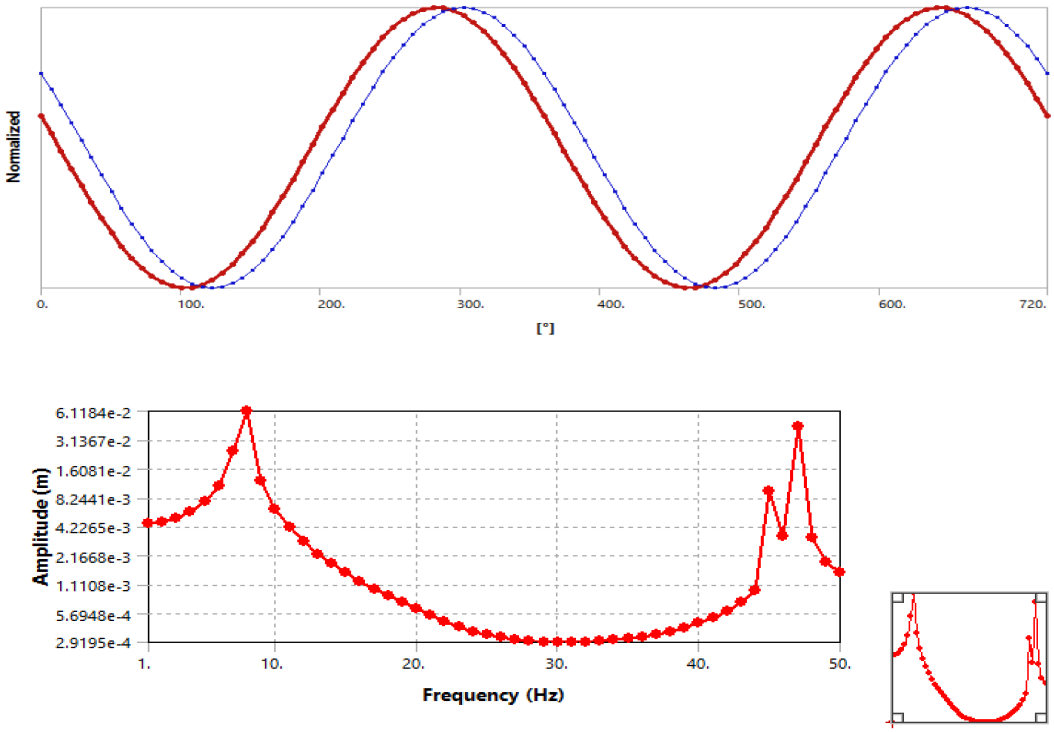



**Figure 8.** Displacement (blue) and Unsteady Pressure Field (red) phase difference and the corresponding Critical Frequencies for stability analysis.

The main reason that generates purely structural natural modes to the couple in an unfavourable manner due to the interaction of aerodynamic forces, depends on the mass ratio of the aircraft wing mass to the mass of the surrounding fluid. In order to validate the results, lift coefficient versus angle of attack graph for different mesh element sizes was performed, showing accurate relationship with literature review [1] and [3].

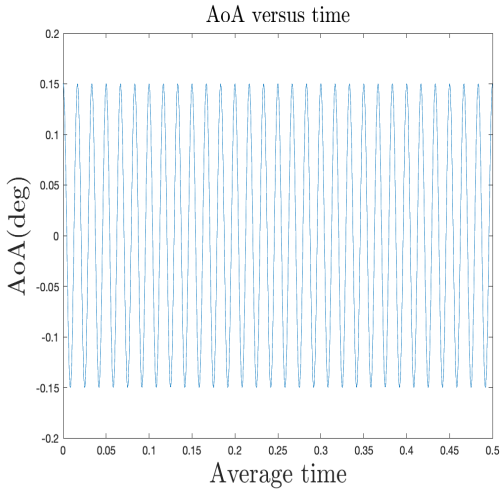



***Figure 9.*** Angle of Attack variation as a function of average time for stability analysis.

As it is simply an instability due to the phase between the aerodynamic forces acting on the aircraft wing and the structural displacements. Different geometrical and design factors that influence the flutter coupling are the free stream velocity, spar location, and sweep angle. Figure 9 shows the results of the wing tip deformation running for different Mach numbers. It is observed that the deformations are attenuated when the Mach number is increasing at the same flow conditions.

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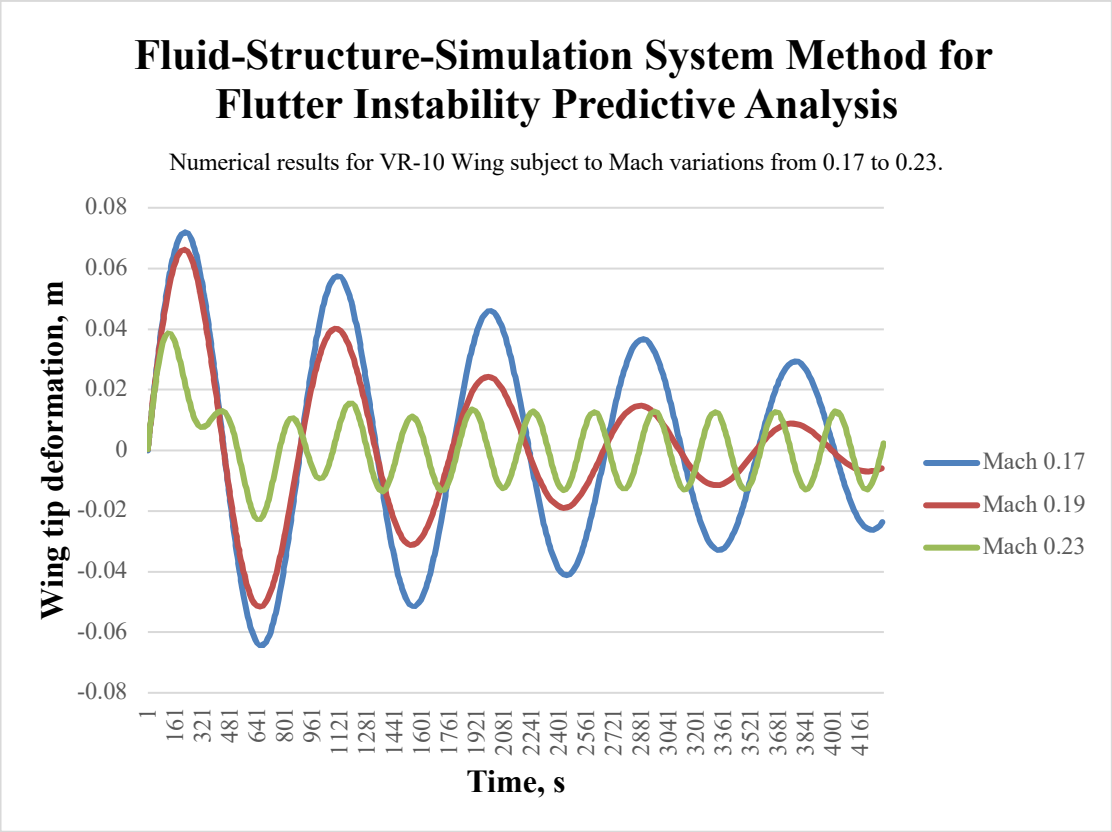



**Figure 10.** Instability analysis to identify and predict flutter phenomenon.

Figure 10 presents Fluid-Structure simulation results on flutter instability analysis in order to provide evidences for FSI method validation and structural natural modes not to couple in an unfavorable manner due to the interaction of aerodynamic forces and the wing structural system of interest. This system is highly dependent on the mass ratio and stiffness matrix. Increasing mass ratio introduces a penalty on weight, and thus on aircraft performance, fuel consumption, production costs and certification. As it is simply an instability problem due to the phase lag between the aerodynamic forces acting on the aircraft wing and the structural displacements, we can analyze different geometrical and design factors that will influence flutter coupling. In order to prevent aeroelastic phenomenon to occur, different Mach numbers were analyzed by increasing the free stream velocity and thus the average Lift Coefficient. The influence of Mach Number is presented as a function on wing tip deformation showing underdamped systems with variations on decay ratio. Spar location will influence also torsional stiffens and bending moment frequency.

## 4. Conclusion

The aeroelastic behavior of a three-dimensional RV-10 aircraft wing by coupled staggered Fluid-Structure Interaction has been predicted by high-accuracy numerical interaction of aerodynamic, elastic, and inertial forces. Critical flutter speed, as unstable self-excited vibration, was associated with aerodynamic forces and structural flap and edge-wise modes. The coupling results show that the critical velocity and frequency are 120 m/s and 50 Hz respectively. K-P Method was defined to analytically establish critical flutter speed and flutter limits. It can be stated that the results show reasonable agreement for the first two coupling modes, however, when increasing the frequency spectrum, the results show certain discrepancies with the models. FSI Methods were validated with one-way and two-ways coupling methods. The steady analysis is in agreement with the published literature review on the NACA2412 database. The transient results are consistent with the phase difference and classical coupling motion of the first two modes. It indicates unstable flow for the selected Critical Flutter Speed. Despite the simplifications implemented in both the fluid and structural solvers, this framework is proven to be a powerful and potential tool to predict the aeroelastic performance of a general aviation wing in the initial stages of aircraft design.

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