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COUPLED TRANSIENT ANALYSIS OF A UAV COMPOSITE WING

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Abstract: *This article focuses on the flexibility influence over aerodynamic forces on a mini-airplane wing. For the flow around the flexible wing a transient structural analysis and a CFD analysis were coupled. The results were compared with the CFD analysis over a rigid wing structure.*

Keywords: *coupled systems, FEM, aero-elasticity*

1. INTRODUCTION

Aero-elastic and loads considerations play a part across much of the design and development of an aircraft. The aero-elastic and loads behavior of the aircraft have an impact upon the concept and detailed structural design, aerodynamic characteristics, weight, jig shape, FCS design, handling qualities, control surface design, propulsion system, performance (effect of flight shape on drag), landing gear design, structural tests, etc.

A coupled system is one in which physically or computationally heterogeneous mechanical components interact dynamically.

The interaction is called one-way if there is not feedback between subsystems, as illustrated in Figure 1(a) for two subsystems identified as X and Y. The interaction is called two-way (or generally multiway) if there is feedback between subsystems, as illustrated in Figure 1(b). In this case, which will be the one of primary interest here, the response has to be obtained by solving simultaneously the coupled equations which model the system. "Heterogeneity" is used in the sense that component simulation benefits from custom treatment.

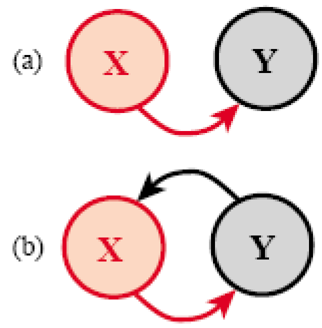

Fig. 1. Interaction between two subsystems X and Y: (a) one way, (b) two way.

As noted above the decomposition of a complex coupled system for simulation is hierarchical with two to four levels being common.

A coupled system is characterized as two-field, three-field, etc., according to the number of different fields that appear in the first-level decomposition.

For computational treatment of a dynamical coupled system, fields are discretized in space and time. A field partition is a field-by-field decomposition of the space discretization. Asplitting is a decomposition of the time discretization of a field within its time step interval (Figure 2). In the case of static or quasi-static analysis, actual time is replaced by pseudo-time or some kind of control parameter.

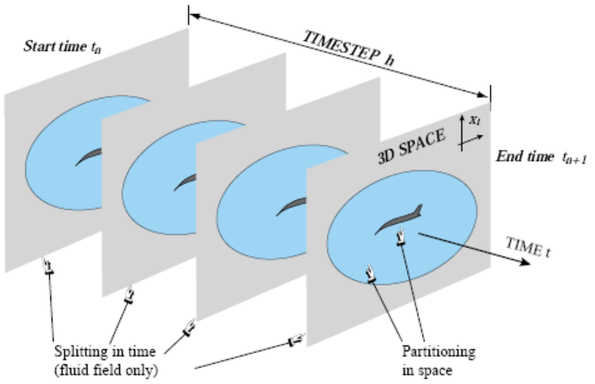

Figure 2. Decomposition of an aero-elastic FSI coupled system: partitioning in space and splitting in time. 3D space is shown as "flat" for visualization convenience.

Partitioning may be algebraic or differential. In algebraic partitioning the complete coupled system is spatially discretized first, and then decomposed. In differential partitioning the decomposition is done first and each field then discretized separately.

2. ANALYTICAL MODEL

One important interest in aircraft design is the aero-elastic deflections of the flexible wing, more specifically the aerodynamic influence on the effectiveness of the control surfaces in comparison to the rigid wing. It is known that as the speed increases the effectiveness reduces until at some critical speed – the reversal speed – there is no response to application of the control surface. At speeds greater than the reversal speed, the action of the controls reverses, a phenomenon known as control reversal. Although not necessarily disastrous, it is unacceptable that at speeds near to the reversal speed, the aircraft responds either very slowly or not at all to application of the controls, and that has the opposite response to that demanded occurred beyond the reversal speed.

Static aero-elasticity is the study of the deflection of flexible aircraft structures under aerodynamic loads, where the forces and motions are considered to be independent of time. Consider the aerodynamic lift and moment acting upon a wing to depend solely upon the incidence of each chord-wise strip. These loads cause the wing to bend and twist, so changing the incidence and consequently the aerodynamic flow, which in turn changes the loads acting on the wing and the deflections, and so on until an equilibrium condition is usually reached. The interaction between the wing structural deflections and the aerodynamic loads determines the wing bending and twist at each flight condition, and must be considered in order to model the static aero-elastic behavior. The static aero-elastic deformations are important as they govern the loads in the steady flight condition, the lift distribution, the drag forces, the effectiveness of the control surfaces; the aircraft trim behavior and also the static stability and control characteristics. The aero-elastic wing shape at the cruise condition is of particular importance as this has a crucial effect on the drag and therefore the range.

There are two critical static aero-elastic phenomena that can be encountered, namely divergence and control reversal. Divergence is the name given to the phenomenon that occurs when the moments due to aerodynamic forces overcome the restoring moments due to structural stiffness, so resulting in structural failure. The most common type is that of wing torsional divergence. In general, for aero-elastic considerations the stiffness is of much greater importance than the strength.

The static aero-elastic behavior is considered initially using an iterative approach and then a direct approach.

The rigid aero-foil section is symmetric (so has no inherent camber) and is attached to a torsional spring of stiffness k_θ at a distance d aft of the aerodynamic center on the quarter chord. The lift-curve slope is a_1. The aero-foil has an initial incidence of θ_0 and twists through angle θ due to the aerodynamic loading.

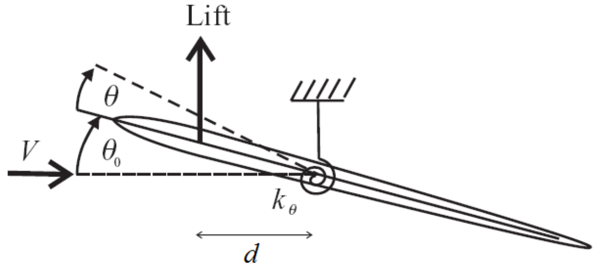

Figure 3. Two-dimensional aero-foil with a torsional spring

The lift acting on the aero-foil at air speed V (true air speed, or TAS) and initial angle of incidence θ_0 causes a pitching moment of

$$M = \left(\frac{1}{2}\rho V^2 c a_1 \theta_0\right)\cdot d = q d^2 a_1 \theta_0 \qquad (1)$$

to act about the flexural axis, where q is the dynamic pressure and ρ is the true air density. The equation for the aero-foil will be obtained using Lagrange's equations. Since only static aero-elastic effects are being considered, the kinetic energy term can be ignored. The potential (or strain) energy U is found from the twist of the torsional spring, namely

$$U = \frac{1}{2} k_\theta \theta^2 \qquad (2)$$

The generalized moment may be obtained from the incrementalwork done by the pitching moment acting through the incremental angle $\delta\theta$ and is given by

$$Q_\theta = \frac{\partial(\delta W)}{\partial(\delta\theta)} = \frac{\partial\left(q d^2 a_1 \theta_0 \delta\theta\right)}{\partial(\delta\theta)} = q d^2 a_1 \qquad (3)$$

Then application of Lagrange's equations for coordinate θ gives

$$k_\theta \theta = q d^2 a_1 \theta_0 \qquad (4)$$

Consequently,

$$\theta = \frac{q d^2 a_1}{k_\theta}\theta_0 = qR\theta_0 \qquad (5)$$

where $R = d^2 a_1 / k_\theta$.

Thus having applied the initial aerodynamic loading, the aero-foil has twisted by angle θ, as determined in equation (5). In performing this calculation, it has been assumed that the pitching moment has not changed due to the twist. However, as a consequence of the twist, the aerodynamic moment now changes to allow for the new angle of incidence. This new loading, in turn, causes the aero-foil twist to change again, leading to a further modification in the aerodynamic loading, and so on.

The stepping between application of the aerodynamic load on the aero-foil, changing the aero-foil twist and then determining the new aerodynamic loading illustrates the fundamental interaction between a flexible structure and aerodynamic forces that gives rise to aero-elastic phenomena.

At first iteration, the incidence of the aero-foil includes the initial incidence and the estimate of twist, so the revised pitching moment becomes

$$M = q d^2 a_1 \left(\theta_0 + qR\theta_0\right) \qquad (6)$$

and, since the potential/strain energy term remains the same as in equation (2), application of Lagrange's equations gives a revised elastic twist angle of

$$\theta = q d^2 a_1 \frac{1 + qR}{k_\theta}\theta_0 = qR(1 + qR)\theta_0 \qquad (7)$$

Repeating the above process continues by using the updated elastic twist value in the pitching moment and work expressions, leading to an infinite series expansion for the elastic twist in the form

$$\theta = qR\left[1 + qR + (qR)^2 + (qR)^3 + \cdots\right]\theta_0 \qquad (8)$$

Now, remembering that the binomial series is written as

$$\left(1-x\right)^{-1}=1+x+x^2+x^3+\cdots \tag{9}$$

in the limit, the aero-foil twist becomes

$$\theta=\frac{qR}{1-qR}\theta_0 \tag{10}$$

It should be noted, however, that the single step (strongly coupled) approach is only feasible if there is a direct mathematical relationship between the aerodynamic forces and the deflections. If advanced static aero-elastic calculations for an entire aircraft, involving the coupling of computational fluid dynamics (CFD) methods with finite element methods, are applied, then such an approach requires use of a loosely coupled approach somewhat similar to the iterative process shown above.

It should be remembered that there are a number of significant assumptions in the above analysis. Sweepback (or sweep-forward) will increase the aerodynamic interactions between different parts of the wing, which will make the strip theory aerodynamics more inaccurate. It has been assumed that the wing behaves as a beam-like structure, and consequently that the flexural axis remains parallel to the axis of sweep along the mid-chord line. In cases where the wing behaves more like a plate, such as for low aspect ratio tapered swept wings, the structural bending/torsion coupling effects for the swept wing must also be included.

3. NUMERICAL MODEL

The traditional approach to determining a mathematical model for aircraft with fairly slender high aspect ratio wings was to recognize that the structure is ‘beam-like’ and then to represent the major aircraft components (e.g. wing, front fuselage, rear fuselage, tail-plane, fin) by beams lying along reference axes positioned at, for example, the locus of shear centers (or flexural axis). The beams are capable of bending, shear, torsional and axial deformations. In such an approach, each beam is divided into several sections or elements. The combination of such ‘beams’ for all parts of the aircraft is called a ‘stick’ or ‘beam’ model.

The flexural rigidity *EI* and torsional rigidity *GJ* of the beam are traditionally estimated from the member section properties by classical structural analysis methods. The structural stiffness behavior of each element is represented by a stiffness matrix (effectively the finite element method employing beam elements).

The problem with employing beam elements directly for an aircraft structure is that for such a complex structure, the calculated stiffness distribution is rather inaccurate. It may be suitable for an aircraft in early design where the detailed structure has not yet been defined and where scaled stiffness and mass properties from previous aircraft might be employed, but not at the later stages of design and certification where structural detail is available and important.

It should be emphasized that the model employed for dynamics purposes may not be as detailed in structural representation as the model used for stress analysis. The dynamic idealization for an aircraft structure is relatively crude though the level of sophistication is continually growing.

When modelling a detailed component such as a machined bracket using ‘brick’ elements, say, the FE model will represent the load paths well and the stresses derived from the stiffness matrix and element deformations will be quite reliable. However, for a complex stiffened aircraft box structure, the level of detail that can be accurately modelled is limited and so the stress output can be rather unreliable. Therefore the FE method often tends to be used to determine load paths via nodal forces that can subsequently act as input loads to a more detailed FE model of a local structure or to a structural element where dedicated design formulae/programs are available.

The UAV wing is 100% composite materials, e-glass type woven fabric being used. These are plain weave balanced fabrics with 0/90 degrees fiber orientation. For the matrix material epoxy is used. The airfoil is E197, the wingspan is 1000 mm, root chord length has 150 mm, and the end chord is 80 mm (Figure 3). The wing has twenty ribs and two spars and two cylindrical reinforcement tubes.

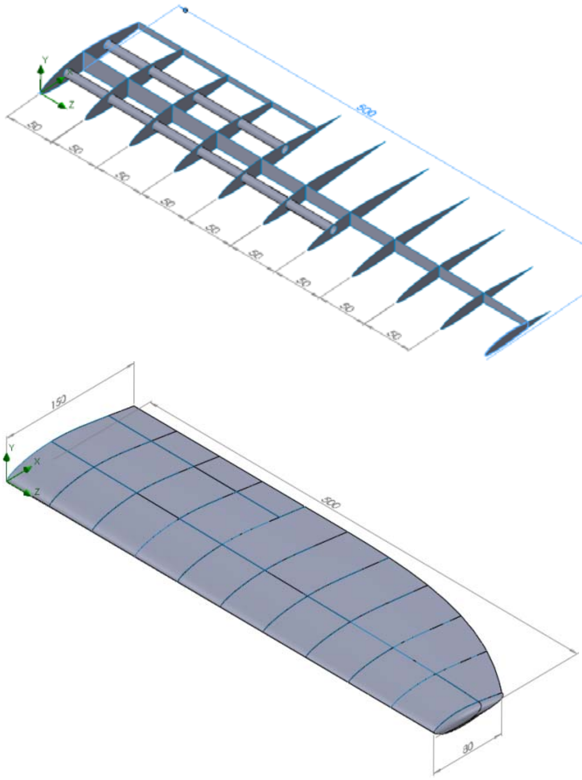

Figure 4. The wing structure – geometry model

To determine the loads, it is considered the air flow over the half of wing with the speed of 15 m/s, the airfoil attack angle at 5°. The solver calculate all the flow parameters, in figure 5 is presented the pressure field).

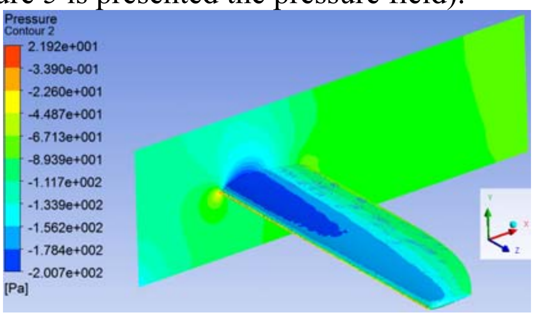

Figure 5. Flow analysis (pressures on the wing and in the symmetry plane)

The fibers used in the UAV are plain weave fabrics, which have a complicated structure and detailed meso scale models are required for the analysis. In this study, the method used for modeling the woven structure is to consider the woven lamina as a single equivalent layer by assuming $E_1 = E_2$. The numerical results from the structural analysis, at the last time step (2 sec), are presented below.

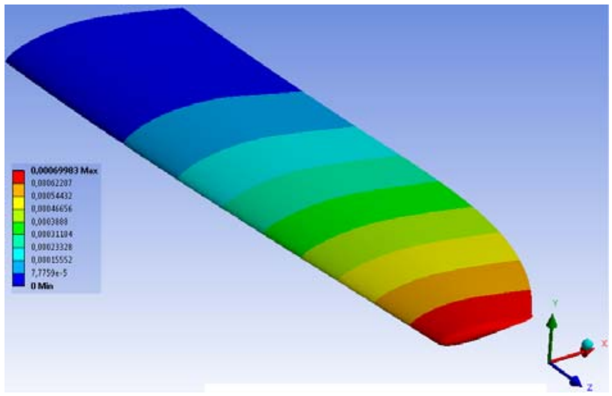

Figure 6. Total displacement field (mm)

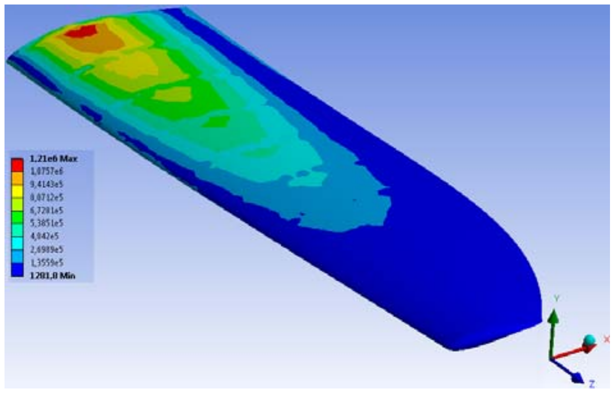

Figure 7. Equivalent Von Mises stress field (Pa)

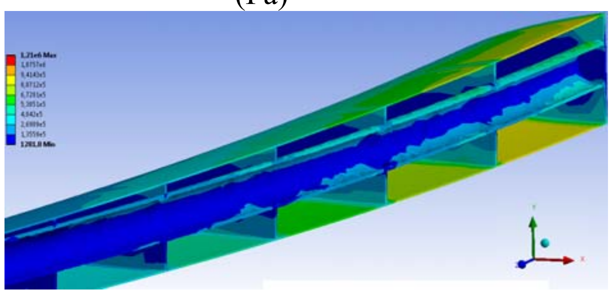

Figure 8. Equivalent Von Mises stress field (Pa) in section along the first spar

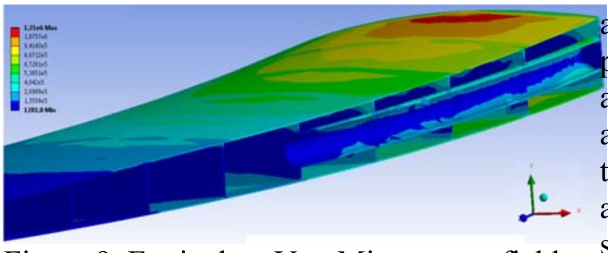

Figure 9. Equivalent Von Mises stress field (Pa) in section along the second spar

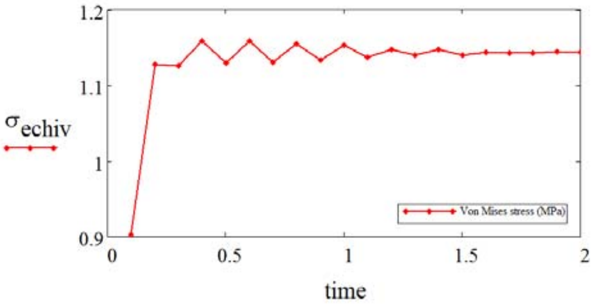

Figure 10. Time variation for maximum Von Mises stress (flexible wing)

Table 1: Aerodynamic forces on wing

	Lift (N)	Drag (N)
Flexible wing	6.456	0.708
Rigid wing	6.5	0.699

4. CONCLUSIONS & ACKNOWLEDGMENT

The results from the coupled transient structural analysis with flow analysis were compared this classic case of a flow over the rigid wing. The study was realized on a UAV composite wing with 1 m span.

By comparing the aerodynamics forces on the wing (table 1), it can be noticed that the wing deformation for the flexible wing case induces a very small decrease on lift (0.67%), and a slight increase of drag (1.25%). The differences are expected to be larger if the wing span increses.

The flight regime is stable (as can be seen in figure 10) because of wing stiffness.

This study involved a simplified composite airframe, considering equivalent material properties. However, for a complex stiffened aircraft structure, the level of detail that can be accurately modelled can be increased and so the stress output can be more realistic. This also implies using failures theories for structural analysis.

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REFERENCES

1. Megson, T.H.G., *Aircraft Structures for Engineering Students*, 5th ed, Elsevier (2012).
2. Park, K.C. Felippa, C.A., *Partitioned Analysis of Coupled Systems,* Chapter 3 in *Computational Methods for Transient Analysis*, Belytschko T. and Hughes T.J.R., eds., North-Holland, Amsterdam–New York (1983).
3. Hodges D.H., Chang, Pierce G.A., *Introduction to Structural Dynamics and Aeroelasticity, Second Edition*, Cambridge University Press, UK (2011).
4. NAFEMS, *A Finite Element Primer*, DTI, (1987)
5. Wright, J.R., Cooper, J.E., *Introduction to Aircraft Aeroelasticity and Loads*, John Wiley & Sons Ltd, West Sussex, UK, (2007)

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