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COMPUTATIONAL DYNAMICS OF AN ELASTIC AIRPLANE

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Summary: *This paper presents the work performed by the Institute of Aerospace Engineering, Brno University of Technology. Purpose of the project was to compare the results obtained from classical analytical solutions and a complex numerical simulation of airplane's aeroelastic response. Compared to the analytical solution, which reduces the entire process to a straightforward manipulation with time proven graphs and tables, the numerical simulation offers a more complex description of the investigated dynamic processes. A complex simulation, in contrast to the analytical solution providing us with only one estimated parameter, allows monitoring selected quantities in the time domain thus, giving us a tool for a visual qualification of the investigated process. In the past, dynamic aeroelastic properties have been estimated utilizing simplified stick beam models. The desire for more complex aeroelastic simulations led to the concept of advanced aeroelastic model coupling advanced 3D structural FEM models with proven aerodynamic theory in the form of DLM panel Metod.*

1 Introduction

Optimized lightweight design resulted into slender wing, which in turn imposed new problems in airplane's dynamics area. Estimation of the dynamic response qualities became an important issue. Prior numerical simulation all the estimations have been done using data derived from flight measurements. Modern concepts utilize proven computational algorithms in a combination that creates a virtual representative of the investigated system. The necessity to extend the dynamic analysis beyond the classical approaches arose from the changing requirements imposed on aeronautical structural design motivated mainly by advances in aerodynamics and material sciences. Slender wings are more likely to be subjected to larger deformations resulting into potential load redistributions and variations of handling qualities.

2 Computational Flight Dynamics

Mathematical modeling of the investigated system under operational conditions is a task of flight mechanics. The interdisciplinary nature of aeroelasticity based flight mechanics

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combines specific fields of structural dynamics, aerodynamics and elasticity. Aeroelastic model, as a virtual representative of an elastic system subjected to external aerodynamic loading, consists of two major sub models – the first comprises dynamic characteristics (usually designated as 'dynamic' or elasto-inertial model). The second represents aerodynamic forces acting on the structure (referred as the aerodynamic model). Interpolation techniques used to transfer loads and displacements between dynamic and aerodynamic part play a critical role in the modeling process.

The intention of the extended research is to pursue the area of classical aeroelastic computation and put it further towards modeling aircrafts' flying qualities, stability and control – mathematical modeling of elastic aircraft's flight dynamics.

Description of the unsteady aerodynamic forces loading the aeronautical structure still represents the biggest challenge in the process of creating a reliable aeroelastic model. The more straightforward the model's physical boundaries could be modeled; the complicated is the fluid's description. Traditionally, various panel methods have been developed in order to predict the aerodynamic characteristics.

However, compared to the more advanced finite volume algorithms, the panel methods still offer reasonable results without the time, storage and computational penalty. Application of specific mathematical concepts for aerodynamic loading estimation underlines the need for careful consideration of modeled flight conditions. Panel methods based on the potential flow theory are not able to capture flow separation effects frequently occurring during maneuvers at lifting surfaces. To capture the effects of flow non-linearities corrective methods need to be implemented.

Utilization of aerodynamic modeling techniques based on panel methods relies heavily on their time efficiency and overall simplicity. Even advanced coupling methods to join complex structural and aerodynamic model have been developed, implementation of a less sophisticated couple was found suitable for the initial research attempt.

A generally accepted illustration of classical aeronautical structure was projected to the simplified beam model. Long slender wings, tubular fuselages, monocoque or semi-monocoque structures allowed to use the beams with varying cross section instead of complex 3D bodies. These simplifications proved to be adequate for some groups of computational tasks. The idea behind using more complex structural representative finds its roots in the search for one advanced model, which could be used for several sets of tests, ranging from simple static loadings to dynamic maneuver response evaluations. However, the more complex the description of the model gets, the more obstacles can be expected in the computational process.

The complex geometry of an airplane modeled in terms of finite elements tends to create significant concerns in the modal analysis part of the computational process where parasitic vibration modes may accompany the process. Even the simple 'beam' representative can be treated by some straightforward techniques; its complex counterpart is basically sentenced to the very own idea of complex modeling.

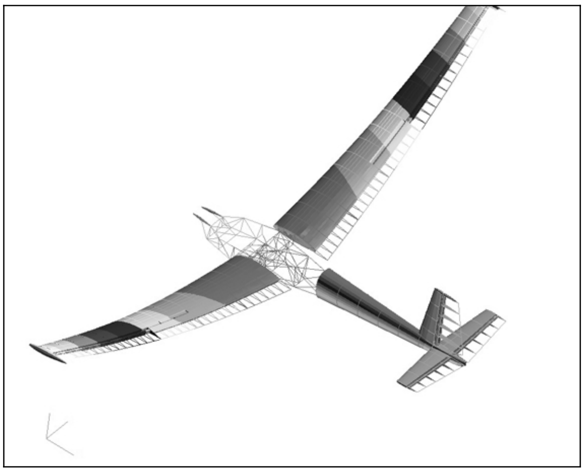

Figure 1 Modal analysis – 1st symmetric bedning

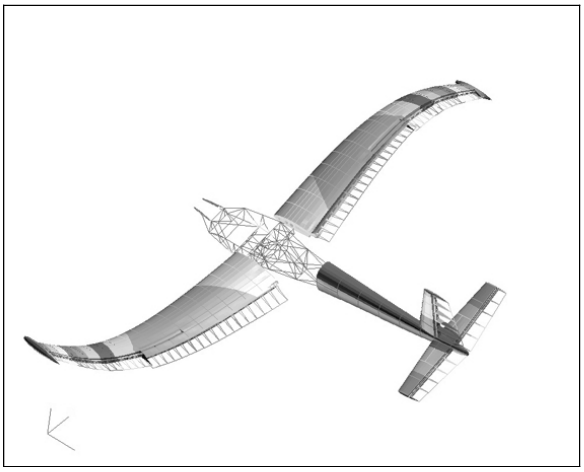

Figure 2 Modal analysis – 1st antisym. bending

Considering all major structural elements offers relatively solid basis for modal based computational approaches. To avoid the occurrence of 'noise' - parasitic vibration modes, the main modeling process focuses on the primary structure 'limiting the presence' the non-stressed parts.

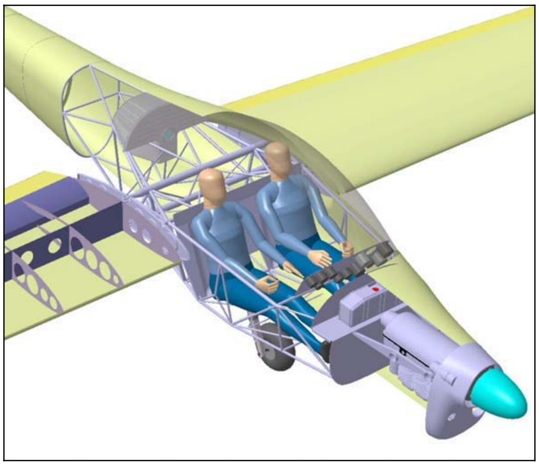

Figure 3 CAD model

The main purpose of the research was to create a realistic dynamic model while considering all the restrictions in computational capacity. Using simplified representatives of parts of secondary interest accelerated the own computational phase.

3 Modeled Aeroelastic System

The investigated system is a powered glider. The fuselage features a full-equipped two-seat cockpit. Its rear part consists of a longeron stiffened semi-mocoque structure. The metallic wing is equipped with ailerons and landing flaps. According to its conventional design features a main spar and an auxiliary spar as load carrying elements. Sufficient structural stiffness was achieved by adding a system of stringers. The metallic stressed skin is attached to the system of ribs and spars using riveting technology. Tail unit was designed following the same principles.

3.1 FEM Dynamic Model

Figure 4 shows the resulting MSC/NASTRAN finite element full span model used in the analysis. The complex model integrates all major airframe structural components. The model mass is continuously distributed over the entire structure. In special cases involving masses of non-load carrying elements, these were substituted by concentrated masses respecting their actual physical position on the airplane.

Control surfaces and high lift devices have been modeled as separate features using the same principles vital for the primal structure. This can also be seen on Figure 3. Structural mesh of the wing includes elements representing the main and auxiliary spars, ribs, skin panels and individual groups featuring ailerons and landing flaps.

The structural design of control and high lift devices has a common classical core. The non-stressed fabric covered control surfaces and landing flaps were modeled neglecting the skins load carrying capability.

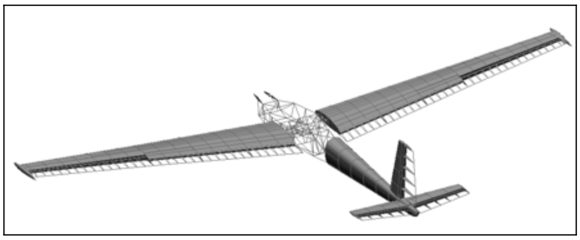

Figure 4 FEM model

3.2 Aerodynamic Model

The aerodynamic conditions were defined by Doublet–Lattice Method (DLM). The wing was divided into dorsal and ventral part. The horizontal and vertical tails also feature aerodynamic panels. Separate aerodynamical panes have been added to the control surfaces and high lift devices.

The theoretical basis of the DLM, used to compute the unsteady aerodynamics, is linearized aerodynamic potential theory. All lifting surfaces are assumed to lie parallel to the flow.

The modal displacements of aerodynamic boxes are related to displacements of the structural grids by a surface splining technique. The aerodynamic theory (DLM) used in this case didn’t allow the definition of camber, twist or angle of incidence.

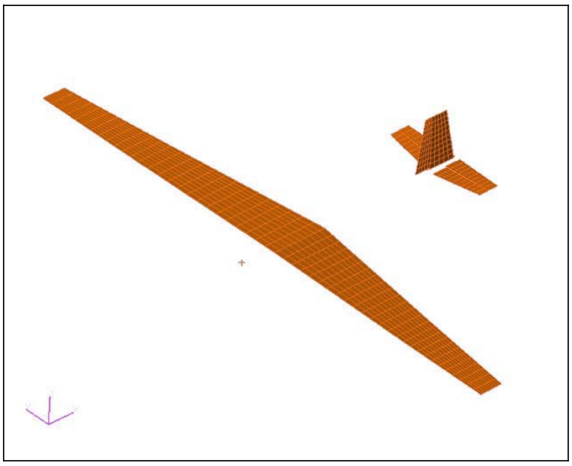

Figure 5 Aerodynamic model

4 Response to Input

The estimation of the response parameters is an important part of the design processes. Conventional analytical methods support procedures derived to predict flying qualities and performances of rigid aeronautical structures. Main goal of the computational process was to estimate Lateral Directional Stability derivatives from the results of dynamic numerical simulation. The input signal of a square shape subjected the aircraft to rotate around its longitudinal axis. Aileron input of 0.25 sec duration featured 15 deg deflections in both directions.

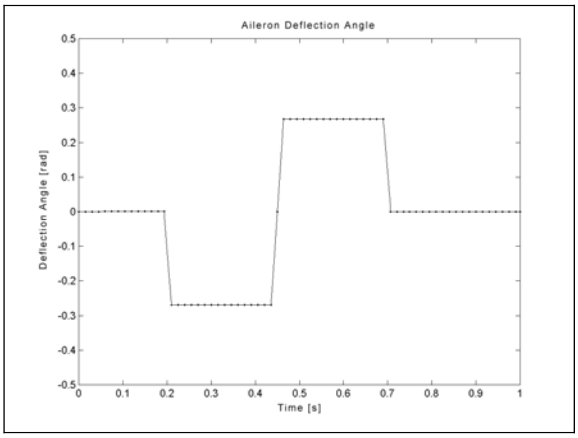

Figure 6 Aileron input signal

This complies with the small disturbance theory assumption used as theoretical basis for the computations. The investigated quantities were steady roll rate coefficients and related stability derivatives. Time histories of monitored quantities were obtained after running a series of simulations. Since our interest focused on the estimation of flying characteristics resulting from aileron input the roll angle time history represented the desired data source for subsequent processing. Additional mathematical operations were used to extract steady roll rate and stability derivatives.

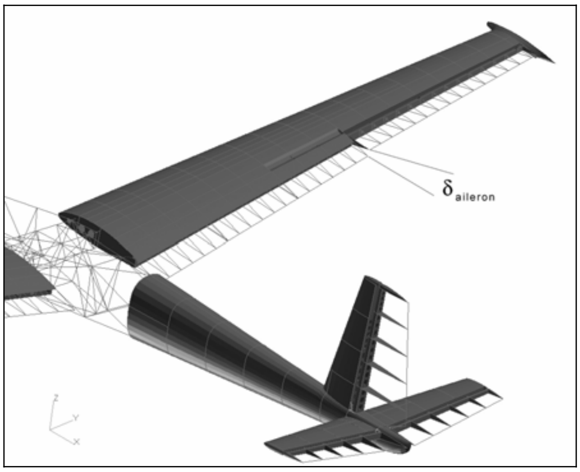

Figure 7 Aileron deflection

A curve representing the change of roll angle as a function of time (or in other words – the roll rate) was added to the graph of computed roll angle time history in order to compare the results obtained from numerical simulation with those based on conventional analytical approach. Regarding the curves' slope similarity we can point at the suitability of the numerical procedure on the field of light aircraft design. Estimation of the stability derivative ratio was based on the knowledge of the steady roll rate due to aileron deflection. The roll rate value was obtained from computed roll angle curve slope.

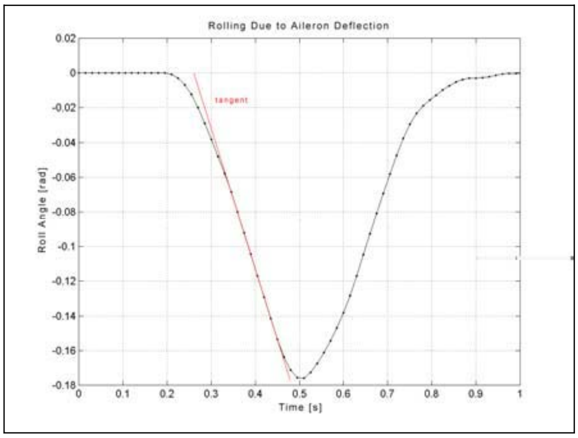

Figure 8 Roll angle time history

Following lines show the procedure used to estimate the non-dimensional ratio of stability derivatives based on the results obtained from complex numerical simulation:

$$\frac{C_{l\delta}}{C_{lP}} = \frac{p \cdot l}{2 \cdot V \cdot \delta_{aileron}} \qquad (1)$$

$$\frac{C_{l\delta}}{C_{lP}} = -0.6256[1]$$

The non-dimensional ratio of the stability derivatives was also obtained by utilization of an analytical approach using time proven graphs and tables for following flight conditions:

Altitude	1000.0 m
True Air Speed (TAS)	44.0 $m.s^{-1}$
Dynamic Pressure	1076.06 Pa
Aileron Deflection	15 deg

Table 1 Flight conditions

By comparing the results of both estimation procedures we can see the same level of 'good match' as it was in the case of roll rate calculation.

Analytical solution	Dynamic solution
-0.6237 [1]	-0.6256 [1]

Table 2 Comparison of results

A similar technique can be used to monitor responses due to pilot's inputs to the remaining control surfaces (rudder or elevator). Following picture depicts rudder deflection during one of the computational stages.

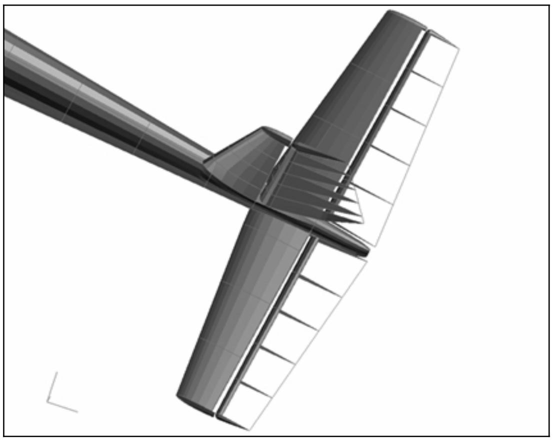

Figure 9 Rudder deflection

5 Conclusion

An early assumption regarding the rigidity of the investigated system was confirmed by the results of the simulation process. The 'conventional' analytical solution and the 'competing' mathematical simulation are complementary tools in the process of light aircraft's flying qualities estimation.

Complex structural models can be advantageously further used for optimization purposes as well as for other types of structural analysis. The complex scope of detailed modeling returned in the form of highly illustrative results.

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