COMPUTATION OF AEROELASTIC EFFECTS ON THE WING OF AIRCRAFT

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This paper deals with static aeroelastic wing computation. Suitability of the Fluid Structure Interaction (FSI) method for aeroelastic computing is examined in Ansys software interface. It is investigated if the FSI method in Ansys is appropriate for monolithic wing structure. After the solution of the problem with created structural and aerodynamical meshes with consistent interface, it is concluded that the Ansys FSI is applicable for aeroelastic computing of the thin walled structure with complicated geometry, probably with the external meshing software.
K e y w o r d s: aeroelasticity, aileron reversal, Fluid Structure Interaction (FSI).

1 INTRODUCTION

“Aeroelasticity” is the term used to denote the field of study concerned with the interaction between the deformation of an elastic structure in an airstream and the resulting aerodynamic force. The mutual connection between aerodynamic, dynamic and elastic forces is shown illustrated on Fig.1.

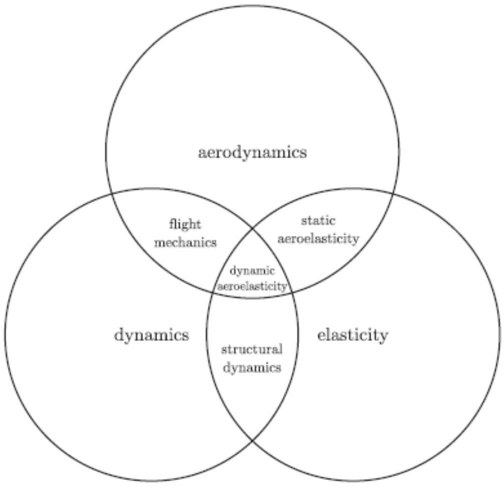

Fig. 1 Schematic of the field of aeroelasticity[1]

Classical aerodynamic theories provide a force prediction on a body of given shape. Elasticity provides shape prediction of the elastic body under external loads. Intensity of the aerodynamic forces isn't known until the elastic deformation occur. In general, external loads acting on body does not depend on object deformation. Dynamics deals with the effects of inertial forces [2].

The interaction of aerodynamic, elastic and aerodynamic fields resulting in loads combination between:

- elasticity and dynamics (i.e., structural dynamics),
- aerodynamics and elasticity (i.e., static aeroelasticity - divergence, aileron reversal)
- aerodynamics, elasticity and dynamics (i.e., dynamic aeroelasticity - flutter, buffeting)

Elasticity of the wing is independent on airplane speed, but aerodynamical forces strictly depend on it and rapidly increases with airspeed. There can be a critical airspeed causing wing construction instability. Thus, it is not difficult to imagine the situation where the aerodynamic forces overpower the elastic restoring forces.

2 STATIC AEROELASTIC LOADS

Essential instance of aeroelasticity can be described on an idealized unswept cantilever wing which has a straight elastic axis normal to a fuselage with symmetrical airfoil Fig. 2. For this wing general load distribution can be acting on elastic axis and a distributed twisting moment about elastic axis. First of them produces bending (no change in angle of attack) second one cause twisting of the element about elastic axis [1].

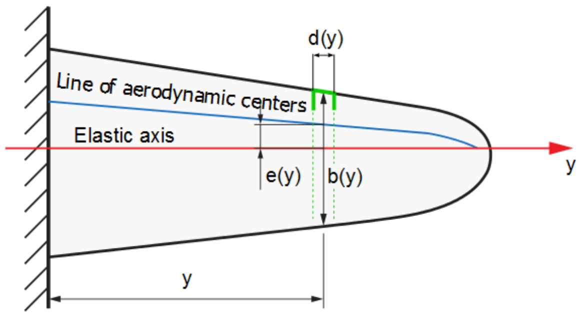

Fig. 2 Idealized unswept cantilever wing [2](modified)

For this wing the aerodynamic lift acts through the line of aerodynamic centers (aerodynamic axis). Let L be the lift force per segment width and e is the eccentricity of the elastic axis from the aerodynamic center. Then the aerodynamic moment about elastic axis is $L.e(y)$ per segment. At the critical divergence speed the aerodynamic moment about elastic axis balances the elastic moment due to twisting [1].

[1] Hodges 2011, [1]

[2] Fung 1969, [1]

Equation defining lift force is given by

$$dL(y) = c_l(y) \cdot q \cdot b(y) \cdot dy \qquad (1)$$

where $c_l(y)$ is lift coefficient at segment, q is dynamic pressure, $b(y)$ is chord length of segment and $d(y)$ is segment width. Aerodynamic moment about elastic axis is

$$dM(y) = q \cdot c_l(y) \cdot b^2(y) \cdot e(y) \cdot dy \qquad (2)$$

where $e(y)$ is eccentricity of the elastic axis from the aerodynamic centre.

Total angle of wing twisting $\theta(x)$ at x is defined by

$$\theta(x) = \int_0^{l/2} \frac{1}{G.J}(x, y) \cdot M(y) \cdot dy \qquad (3)$$

where $1/G.J$ is stiffness of the wing construction [1]. From last equation we can se that the larger wing stiffness is the less wing twists.

We have defined that aerodynamic axis is introduced by line of aerodynamic centers. In case aerodynamic application the wing strength is represented by the elastic axis defined by the line connecting shear centers of the object cross section.

3 WALL MOUNTED MODEL FOR THE STUDY OF AILERON REVERSAL

The main difference from idealized wing is trailing edge flap (aileron) angle β set by flight-control. In case of aileron reversal we consider wall mounted model in aerodynamic tunnel with positive aileron deflection Fig. 3.

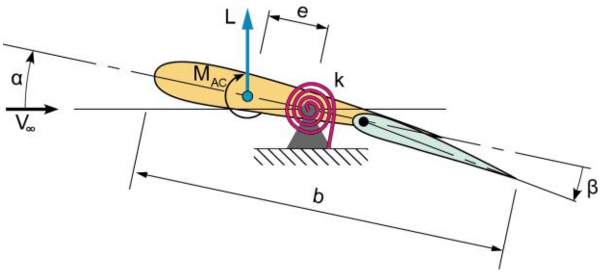

Fig. 3 Schematic of the airfoil section of two-dimensional wing in a wind tunnel[3](modified)

"Aileron reversal" is the reversal of the aileron's expected response due to structural deformation of the wing. For example, wing torsional flexibility can cause ailerons to gradually lose their effectiveness as dynamic pressure increases; beyond a certain dynamic pressure that we call the "reversal dynamic pressure," they start to function in a manner that is opposite to their intended purpose. The primary danger posed by the loss of control effectiveness is that the pilot cannot control the aircraft in the usual way [2].

Aerodynamic axis is represented by aerodynamic center AC and elastic axis is represented by spring stiffness k. Eccentricity e is distance between aerodynamic center and pivot hinge point. In this case we do not consider gravity, so it not shown in the figure. Moment equilibrium for this system about the pivot requires that

$$M_{AC} + L \cdot e = k \cdot \theta \qquad (4)$$

where M_{AC} is aerodynamic moment about aerodynamic centre, L is lift force and θ is wing twist.

Significant role in aileron reversal play dynamic pressure at which the reversal occurs q_R. This pressure is defined by

$$q_R = -\frac{k \cdot c_{L_\beta}}{b \cdot S \cdot c_{L_\alpha} \cdot c_{M_\beta}} \qquad (5)$$

where k is spring stiffness, $c_{L\beta}$ is lift coefficient at deflection β, b is model chord, S is surface of the model of wing, $c_{L\alpha}$ is coefficient of angle of incidence, $c_{M\beta}$ is moment coefficient of model due to aileron angle β. Obviously, a stiffer k gives a higher reversal speed, and a model that is rigid in pitch will not undergo reversal.

The wing twist is determining θ to be

$$\theta = \frac{q \cdot S \cdot \left[e \cdot c_{L_\alpha} \cdot \alpha_r + \left(e \cdot c_{L_\beta} + b \cdot c_{M_\beta}\right) \cdot \beta\right]}{k - e \cdot q \cdot S \cdot c_{L_\alpha}} \qquad (6)$$

where β is angle of aileron deflection.

We see that because of the flexibility of the model in pitch (representative of torsional flexibility in a wing), θ is a function of β [2].

4 SUPERMARINE SPITFIRE ELLIPTICAL WING

After searching available suitable publication about static aeroelasticity (aileron reversal), it was decided to solve aileron reversal problem exhibited by Supermarine Spitfire wing, illustrated on Fig. 4, using a numerical computational method.

[3] Hodges 2011, [1]

Fig. 4 Supermarine Spitfire Mk.I cutaway[4]

According to Technical reports from 40's the aileron reversal speed of Spitfire aircraft is 760 km/h. At 640 km/h there is 65% aileron efficiency loss due to wing twist.

Construction of elliptical wing was very complicated at the beginning of second world war, but the idea of using it on Spitfire was clear choice from English designers.

The main wing construction consist of: skin, main spar, rear spar, 23 ribs, flap, aileron, landing gear mechanism and wheel well, wing armaments, armaments with ammunition box, draw rod and pulleys, radiator etc. Length of wing is 5650 mm.

5 FLUID STRUCTURE INTERACTION (FSI) AND MONOLITHIC WING

For computational realization I used Ansys software 12.1 version which were available for our purpose. Software package from Ansys company consist more subprograms, they are:

- for Fluid Dynamics (CFX-Pre, Fluent),
- for Static Structural (Mechanical APDL),
- for Meshing ICEM-CFD,
- et.c.

The newer one is Ansys Workbench which is capable to solve complicated solutions using implemented subprograms. For aeroelasticity usage I worked with Static Structural (Ansys) in conjunction with Fluid Flow (CFX).

5.1 FLUID STRUCTURE INTERACTION

Fluid structure interaction (FSI) computational method is suitable for aeroelastic effect and many other situations with interface between fluid flow and structural analysis. Advantage of FSI method is sharing and data transfer using a communication canal created between Solid (structural analysis) and Fluid (fluid dynamics). FSI method is divided to:

- one-way FSI
- two-way FSI

One way FSI can transfer data from Fluid to Solid neglecting the influence of object deformation to airflow. Two way FSI can transfer data in both directions so, the object deformation dislocate the airflow thus the change in pressure distributions occur Fig. 5.

Using MFX solver between Fluid Flow (CFX) and Static Structural (Ansys) is possible to compute static aeroelastic effects.

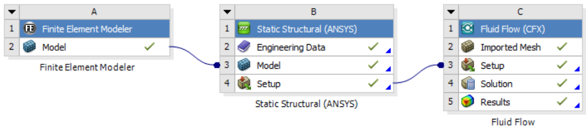

Fig. 5 Block scheme of two-way FSI in Ansys Workbench interface

5.2 MONOLITHIC MODEL OF WING

To ensure the aptitude of using FSI method, I made a simple monolithic model of wing at first (without any cavities). In Ansys Workbench it is possible to import variable mesh files from external meshing software. This is done by Finite Element Modeler shown on Fig. 5 (first block from left).

Monolithic model mesh was exported from ICEM CFD with file format *.uns for Fluid and Solid.

Editing the Model cell of Static Structural template I set up imperative settings like boundary conditions, geometry thickness if necessary, fluid solid interface etc. The fluid solid interface is very important for FSI because it define the interface surface between Fluid and Solid for pressure apply from fluid dynamics.

Editing Setup cell of Fluid Flow (CFX) template, opens CFX-Pre subprogram where I set up necessary settings for FSI. In Analysys type, the External Solver Coupling should be set to ANSYS MultiField which provide a bidirectional communication and another important parameter is Mesh Motion defined in Wall boundary details which should be set to Total Mesh Displacement. These options are representing the main FSI settings which should not be forgotten. Results from CFX is shown Fig. 6.

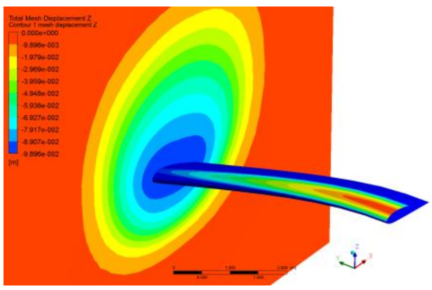

Fig. 6 Total mesh displacement of the monolithic wing model in z-direction

[4] Lowe 2008, [3]

6 THIN WALLED WING CONSTRUCTION AND FSI

6.1 MODEL CONSTRUCTION

Model of elliptical wing construction from Supermarine Spitfire aircraft was created in Rhinoceros software according to Spitfire wing drawings Fig.7. During the process of modeling I made some simplification to shorten the time of modeling and numerical computing. Whole model was created using surface 2D element (type Shell).

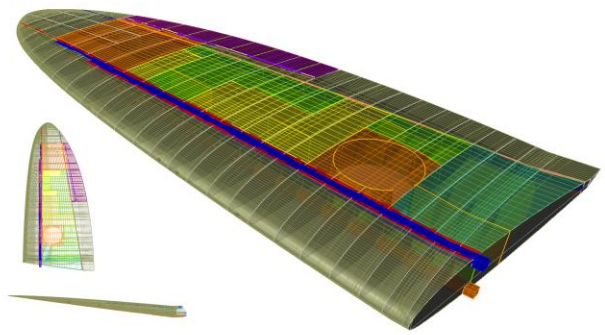

Fig. 7 Ghosted view of Spitfire wing construction in perspective

To simulate aileron reversal there must be an aileron deflection on wing. The simplify aileron model is shown on Fig. 8 where the two deflection was created independently.

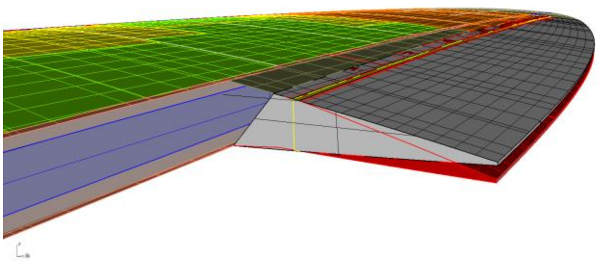

Fig. 8 Aileron deflection of wing model (red color represents +4° down, and black color represents 0° deflection)

Picture Fig.8 show model simplification of real Spitfire aileron, which construction is Frise type. For our purpose the leading edge of Frise aileron was neglected because of complication of the aileron hinge and drawing absence.

6.2 MODEL MESHING (SOLID)

Because of Ansys Workbench mesh importing capability I mesh the model using external mesh software (too complicated geometry for the Workbench meshing tool).

Geometry exported from Rhinoceros was IGES format containing surface elements only, which helps me to create the mesh using triangles and quadrilaterals for Static Structural analysis (Solid). Every single element of mesh is connected by its nodes, thereby a whole mesh form an closed one piece construction with no movable part. Whole mesh consist of 56 420 elements with standard element size of one inch. The mesh check with warpage, jacobian, skew, min and max angle (trias, quad) criteria was made for finalization. Wing construction of meshed model is shown on Fig.9.

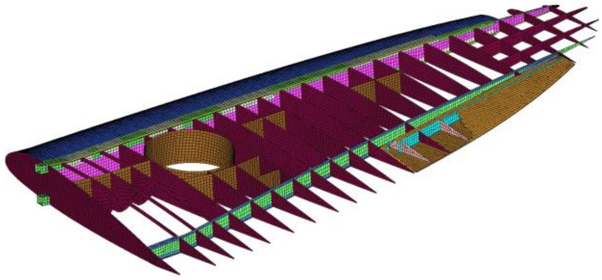

Fig. 9 Wing construction final mesh

6.3 MODEL MESHING (FLUID)

The model geometry exported with IGES format from Rhinoceros was used to mesh applying for aerodynamic purpose. All structure with non interference to airflow is neglected for fluid meshing (spars, ribs etc.).

Mesh was created in ICEM CFD program. The fluid can be presented as hemisphe, which I used for my wing model Fig.10.

Fig. 10 Fluid mesh generated in ICEM CFD

Using a block, a structural mesh with total number of more than one million elements was created. This high number of elements will ensure a optimal smooth flow around the deflected aileron and expected lift pressure distribution over wing.

5 CONCLUSION

Fluid Structure Interaction method seems to be suitable for numerical computation of aeroelastic effects.

FSI is relative new and complex method which is very demanding, because it forces the user to master several software systems with different point of view.

For the purpose of aeroelastic effects on wing there is no tutorial describing the way how to do it, and there is lack of even other two way fluid structure interactions examples.

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