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Common computational model for coupling panel method with finite element method

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Abstract

Purpose – Conceptual and preliminary aircraft concepts are getting mature earlier in the design process, than ever before. To achieve that advanced level of maturity, multiple multidisciplinary analyses have to be done, often with usage of numerical optimization algorithms. This calls for right tools that can handle such a demanding task. Often the toughest part of a modern design is handling an aircraft's computational models used for different analysis. Transferring geometry and loads from one program to another, or modifying internal structure, takes time and is not productive. Authors defined the concept of a common computational model (CCM), which couples programs from different aerospace scientific disciplines. Data exchange between the software components is compatible, and multidisciplinary analysis can be automated to high degree, including numerical optimization.

Design/methodology/approach – The panel method was applied to aerodynamic analysis and was coupled with open-source FEM code within one computational process.

Findings – The numerical results proved the effectiveness of developed methodology.

Practical implications – Developed software can be used within the design process of a new aircraft.

Originality/value – This paper presents an original approach for advanced numerical analysis, as well as for multidisciplinary optimization of an aircraft. The presented results show possible applications.

Keywords Optimization, Finite element method, Panel method

Paper type Research paper

Introduction

The common computational model (CCM) is somehow similar to the already well-known concept of common parametric aircraft configuration schema (CPACS, 2013), as well as to other common languages: AMDL (Deshpande, 2013) or OpenVSP (McDonald, 2016). The difference is that, in CPACS, all data needed for analysis for different programs are gathered in one huge structured file. Adding a new program to the analysis procedures, with usage of CPACS, may introduce a problem of unique parameters used by the new software. A new class can be built, which inherits the old structure and adds new parameters, but the updated structure cannot be exchanged back with users who utilize only the original structure. The problem will become even more apparent when many users extend the original structure for their unique software. In the CCM, the data are distributed in multiple files, but output from one program is automatically a viable input for the other program. This creates a natural data flow from one software component to another. The problem of extending the network of numerical analyses requires only building appropriate wrapper for the new program, with compatible input and output. Moreover, the CCM is not only limited to pure data management. While passing the results from one program to the other, the data can be extended for

new essential components. For example, modifying and extending computational grid with internal structure for strength analysis.

The paper presents procedures for efficient coupling of panel method (PANUKL software by Goetzendorf-Grabowski, 2012) for aerodynamic analysis, with finite element method (CalculiX, 2016) for strength analysis. The results obtained from the aerodynamic and strength analysis can be further used for static (Błaszczuk *et al.*, 1997) and dynamic stability analysis in SDSA program (Goetzendorf-Grabowski *et al.*, 2011) (Figure 1). As the data passing becomes automated, implementation of applied numerical optimization is straightforward, and an example is shown.

The architecture of presented approach is open and exchanging, or adding other software components, e.g. for dynamic analysis is relatively easy. The only requirement is compatibility between input and output data passed from one program to another. Similar approach is presented in well-known commercial package ANSYS Workbench (ANSYS, 2016) or in freeware system CEASIOM (2016).

Panel method

The development of CFD methods and big increase of the computers' power caused that Euler or Navier-Stokes models are used more often, and potential methods could be seen as obsolete. However, despite many simplifications, potential

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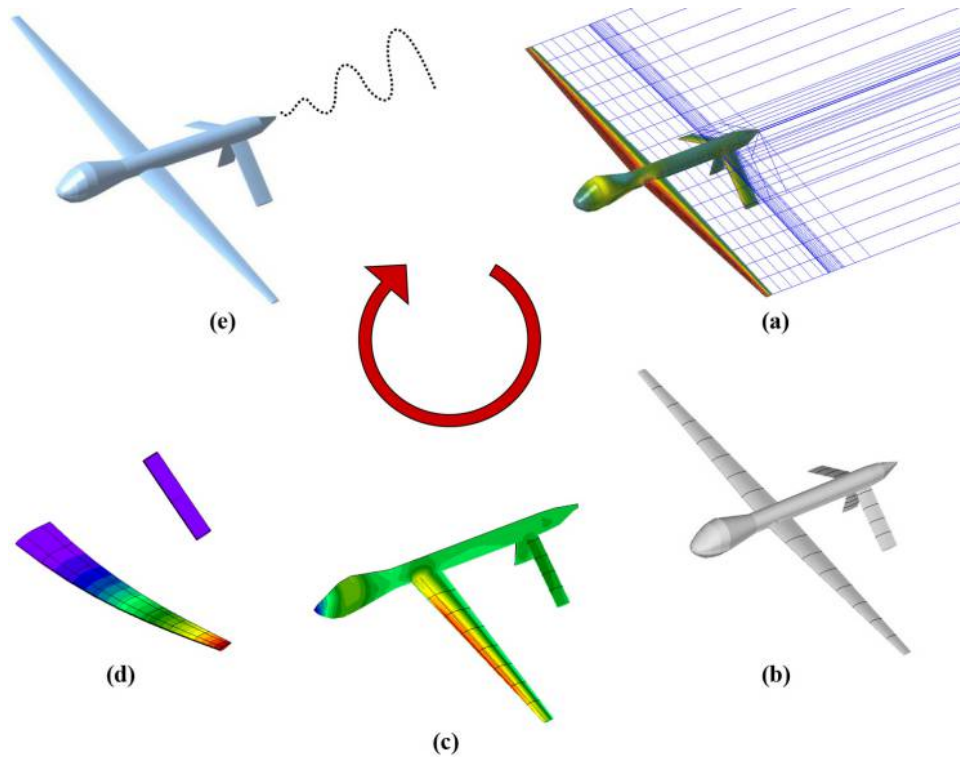


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Figure 1 Utilizing the CCM concept

Notes: (a) Aerodynamic analysis; (b) geometry exchange for FEM analysis; (c) geometry modification for FEM analysis and applying loads from pressure distribution; (d) FEM analysis; (e) dynamic stability analysis

methods are still an attractive tool (Hess, 1985; Yates, 1985; Goraj and Pietrucha, 1995). Low cost and the fact that they are relatively easy to apply compensate for their disadvantages and lower accuracy.

Physical and mathematical model

The most important assumptions made for physical model definition are that fluid is inviscid and irrotational (except vortex wake). The viscosity effect is simulated by the Kutta-Joukowski boundary condition, which could be interpreted, that circulation on the trailing edge is equal to zero.

The mathematical model is as follows:

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \mathbf{V}) = 0 \quad (1)$$

- Euler equation:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \text{grad}) \mathbf{V} = \frac{1}{\rho} \text{grad } p \quad (2)$$

- State equation:

$$p = p_\infty \left(\frac{\rho}{\rho_\infty} \right)^\kappa \quad (3)$$

Because fluid is irrotational ($\text{rot } \mathbf{V} = 0$), the scalar function, called velocity potential, can be defined and the following condition is satisfied:

$$\text{grad } \phi(x, y, z, t) = \mathbf{V} \quad (4)$$

If we assume, that $\Phi = \Phi_\infty + \varphi$ and $\text{mod } \nabla \varphi \ll U_\infty$, $\text{mod } \nabla \varphi \ll a_\infty$ and $\text{mod } \nabla \varphi \ll (U_\infty - a_\infty)$, then we obtain:

$$\frac{1}{a_\infty} \left(\frac{\partial}{\partial t} + \mathbf{V}_\infty \frac{\partial}{\partial x} \right)^2 \varphi = \nabla^2 \varphi \quad (5)$$

assuming additionally that flow is steady and incompressible, we have:

$$\nabla^2 \varphi = 0 \quad (6)$$

Computational method

The computational method strongly depends on the way of aircraft body modeling. The model defined in previous section concerns only flow and does not define the object. Generally, two methods are in use. In the first method, the body of aircraft is modeled using thin surfaces. The second method uses a three-dimensional model of the aircraft body. The presented method bases on the low-order panel method, where the internal Dirichlet problem is solved (Hess method – Hess and Smith, 1967; Hess, 1972). The quadrangle panels

are used. The flat vortex wake, parallel to the free stream velocity or parallel to chord, is assumed.

The base of the method is solution of the Laplace equation for the full velocity potential.

$$\nabla^2 \Phi = 0; \quad (7)$$

The velocity potential can be written in form (Katz and Plotkin, 2001):

$$\Phi(x, y, z) = \frac{1}{4\pi} \cdot \int_{BODY+WAKE} \mu \frac{\partial}{\partial n} \cdot \left(\frac{1}{r} \right) dS - \frac{1}{4\pi} \cdot \int_{BODY} \sigma \left(\frac{1}{r} \right) dS + \Phi_{\infty} \quad (8)$$

Assuming the following boundary conditions:

- Internal Dirichlet boundary condition on the body surface:

$$\frac{1}{4\pi} \cdot \int_{BODY+WAKE} \mu \frac{\partial}{\partial n} \left(\frac{1}{r} \right) dS - \frac{1}{4\pi} \cdot \int_{BODY} \sigma \frac{1}{r} dS = 0 \quad (9)$$

where:

$$\text{doublet strength: } \mu = -(\Phi - \Phi_i), \quad (10)$$

$$\text{source strength: } \sigma = \partial \mu / \partial n. \quad (11)$$

- Kutta-Joukowski conditions on the trailing edge:

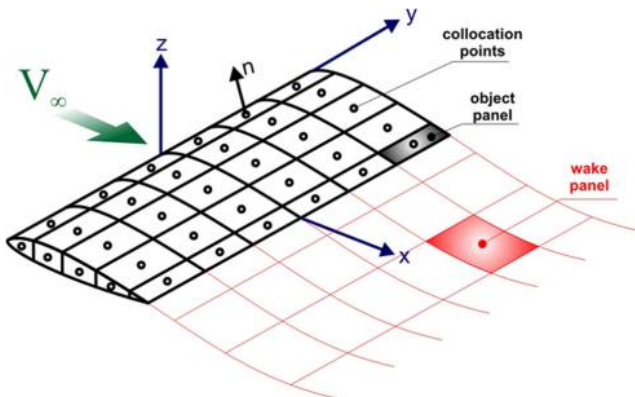
$$\Delta p(x, y)_{TE} = 0 \quad (12)$$

- On the vortex wake:

$$\frac{\partial \varphi(x, y)}{\partial x} = 0; \quad (13)$$

and assuming that the velocity potential inside the body Φ_i is equal to velocity potential in infinity Φ_{∞} , the integral equation is derived in form (9) (Figure 2). The approximation of the aircraft body surface by flat panels allows to approximate equation (9) with a set of linear algebraic equations with unknown doublet strength (constant for panel):

Figure 2 Approximation of the body surface by panel elements



$$\sum_{k=1}^N C_k \mu_k + \sum_{l=1}^{N_w} C_l \mu_l + \sum_{k=1}^N B_k \sigma_k = 0 \quad (14)$$

where C_k , C_l and B_k denote influence coefficients:

$$C_k = \frac{1}{4\pi} \cdot \int_{S_{1234}} \frac{\partial}{\partial n} \left(\frac{1}{r_k} \right) dS_k; \quad B_k = -\frac{1}{4\pi} \cdot \int_{S_{1234}} \frac{1}{r_k} dS_k \quad (15)$$

N = numbers of panels on the aircraft surface;

N_w = number of panels on the wake; and

S_{1234} = area of the k^{th} panel (Figure 3).

The source strength σ (constant for panel), can be defined [using definitions (10)], (11), and the boundary condition of the closed body $\partial \Phi_i / \partial n = 0$ as follows:

$$\sigma = -n \cdot \nabla_{\infty} \quad (16)$$

It will result in a set of equations with the doublet strength as the unknown. To determine the doublet strength on the vortex wake, the Kutta-Joukowski condition is used:

$$\mu_{TE} = \mu_w = \text{const} \quad (17)$$

The doublet strength on the wake is equal to difference between doublet strength on the upper and lower surface close to the trailing edge. Using equation (17), the doublet strength on the wake can be obtained from formula (Figure 4):

$$\mu_w = \mu_U - \mu_L \quad (18)$$

The formula (18) completes the set of equations (14). Only integrals (15) have to be determined. An effective method of determination of these integrals is shown by Hess and Smith (1967) and Katz and Plotkin (2001). The solution of set (14) gives the potential distribution on the body surface. To obtain the pressure distribution, necessary to obtain the global aerodynamic coefficients, the velocity distribution must be found. It can be done by differentiation of the potential with respect to defined tangential coordinates. Next, using Bernoulli's theorem, the pressure can be computed. The numerical differentiation in general case is not easy and can be the source of errors, especially in places where the grid is not

Figure 3 Influence of K^{th} panel on point P

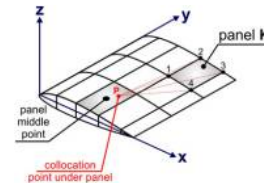
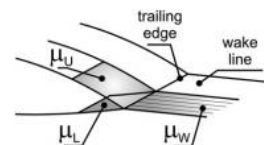


Figure 4 Relation between doublet strength on trailing edge and wake



regular. Pressure distribution allows to calculate the loads acting on the aircraft, components of force and moment of force, their dimensionless coefficients, by integrating by all panels.

Grid model

The panel method has some strict requirements related to the mesh. The panels should be flat and should create the closed polyhedral solid, while the panels are quadrangles or they are reduced to triangles. To create the grid of the whole aircraft, two types of objects are defined: wings and fuselages (Figure 5). Moreover, two types of so-called virtual objects can be added: connections and wakes. The surface of the whole aircraft is created by mesh generator basing on the data included in the script-data file. The structure of this script file is similar to CPACS (Rizzi *et al.*, 2012) common language; however, some differences do not allow to apply the CPACS idea at this stage of the project (Goetzendorf-Grabowski *et al.*, 2014).

The main object can be defined sequentially using cross-sections geometry (airfoils, ribs, etc.) or by using a semi-analytical definition of geometry (Mieloszyk *et al.*, 2016). The main coordinates system is defined as follows: X axis backwards, Z axis upwards, Y axis on the right wing. The origin is usually located in the nose of fuselage; however, it is not obligatory.

Wing geometry

The geometry of a wing can be defined in two ways: sequential or modular. The second method allows faster and easier definition; however, it is internally translated into sequential definition, which is next used for grid generation and to export data to FEM analysis. The sequential definition of a wing is presented in Figure 6.

Figure 5 The division into objects

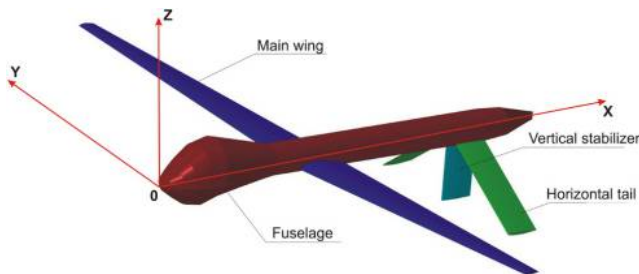
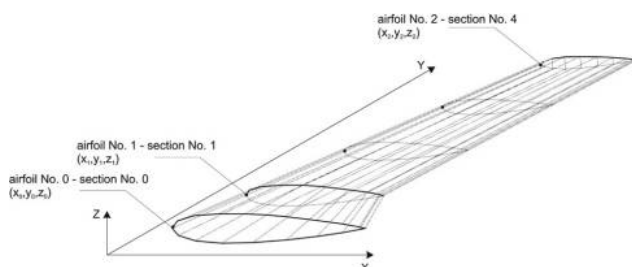


Figure 6 Sequential definition of the wing



Fuselage geometry

The geometry of fuselage is described by geometry of sections as it is shown in Figure 7. The mesh is created by ribs and longerons basing on the section definition. The intersection geometry between the wing and fuselage is computed automatically.

Virtual objects – connections

Virtual objects are used to add the information about connection of two wings to obtain regular mesh without gaps. The possible cases are presented in Figures 8 and 9.

“Vertical” connection is used to connect vertical wing (e.g. winglet) to horizontal wing – Figure 8 (left). Horizontal connections are used to connect horizontal wing with vertical one, for example, in case of T-tail (Figure 8 (right)). The third type of connection “parallel” is used to connect two wings in case of discontinuous change of chord, e.g. in case of slotted flap – Figure 9.

Virtual objects – wake information

The presented method assumes flat vortex wake, which sometimes has to intersect the aircraft body (wings, fuselage). The wake from the wing trailing edge is automatically attached

Figure 7 Fuselage geometry definition

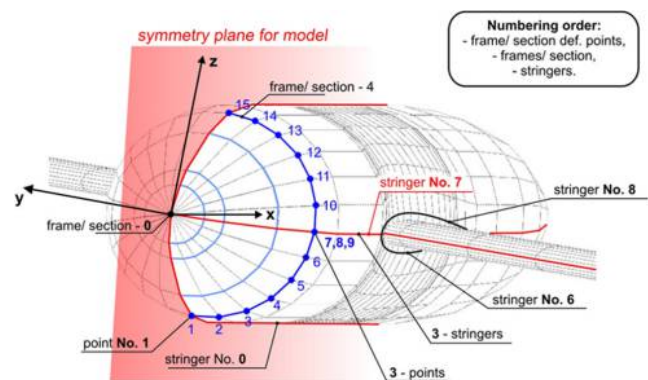


Figure 8 Connections: vertical (left), horizontal (right)

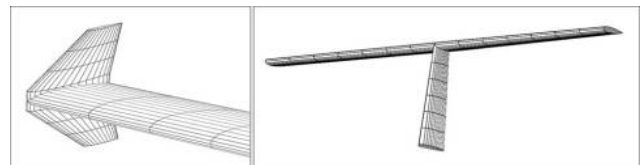
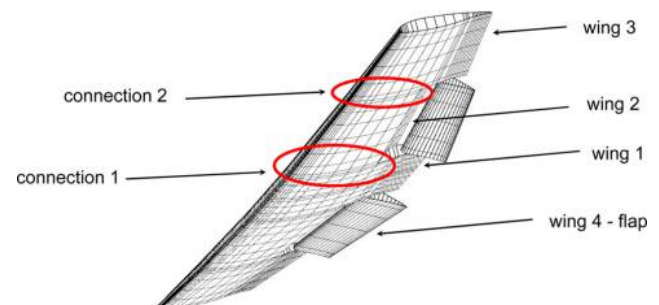


Figure 9 Slotted flaps – modeled using parallel connection



to fuselage, to the appropriate stringer. However, sometimes, it crosses other wings as it is presented in Figure 10. In this case, the additional information is necessary to correctly attach the wake to the wing surface.

Rapid definition of geometry

New concepts of building the geometry by modular wing definition is introduced in the software. Usually, wings are defined by airfoil sections properly placed in three-dimensional space. It is a quite natural way to define geometry for an aerospace engineer, but with complicated geometry requires definition of many parameters. To make the process more efficient, geometry modules are defined. Building geometry from modules is similar to building with different blocks (line, arc, etc.) by adding one to another. This approach has many advantages, such as: group of cross-sections are defined at once in a single module, less parameters are required to setup the geometry, connectivity and modules tangency can be achieved to maintain geometry smoothness.

To visualize it better, an example definition of wing with winglet by geometry modules is presented in Figure 11. The basic geometry consists of horizontal linear part, arc and winglet, which is a vertical linear part. The arc module automatically computes tangency constraints. After making a few more adjustments and adding the fuselage with stabilizers, the airplane is created. The definition of the wing geometry requires setting only a few parameters. Building wings with modules is easy, fast and flexible. More details about the method of geometry definition of wings, fuselage and nacelles are described in the paper by Mieloszyk *et al.* (2016).

Modifications for FEM analysis

A numerical tool called FEMexport is able to export airplane's computational grid with aerodynamic loads for the strength

Figure 10 Wake information necessary to compute wing-wake intersection

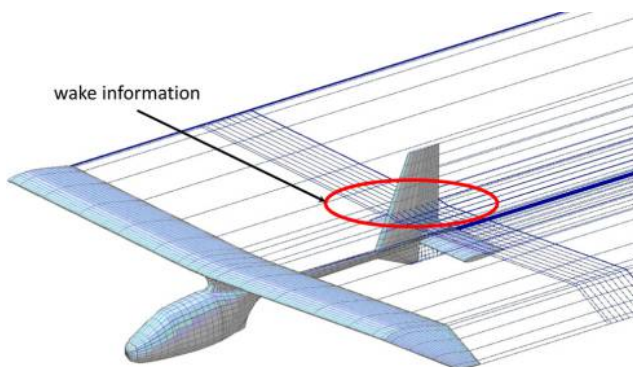
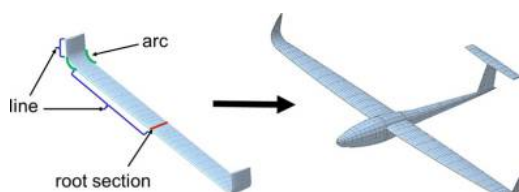


Figure 11 Modular wing geometry with winglets



analysis in CalculiX (2016) software. The grid may be efficiently adjusted by modifying and adding internal structure. Spars and ribs can be added by setting a few flags. The same rule applies when part of the wings' skin has to be removed. After setting the computational geometry, boundary conditions, material properties and other parameters can be assigned to specified panel sets. Complete configuration is written to a file compatible with the CalculiX format (Figure 12). Most of the tool's features are described in detail in the following paragraphs.

Spar wall addition and skin trim

Spar walls can be easily added to the wing's grid for FEM analysis. Additionally, a wing's skin can be cut on the leading edge, and trailing edge forming a wing box, which will transfer loads. It is done by setting only four parameters for each wing:

- Flag to cut, or not leading edge panels.
- Flag to cut, or not trailing edge panels.
- Number of panels to cut from the leading edge.
- Number of panels to cut from the trailing edge.

Depending on the parameters set, different effects can be achieved, which is shown in Figure 13. For example, only wing box transferring loads can be modeled, or wing without flaps, and ailerons part. The effect presented on a real geometry example is shown in Figure 14.

The grid of wings for structure analysis also needs ribs, which are not present in the grid for the aerodynamic analysis.

Figure 12 Scheme of exporting geometry and results from PANUKL to CalculiX

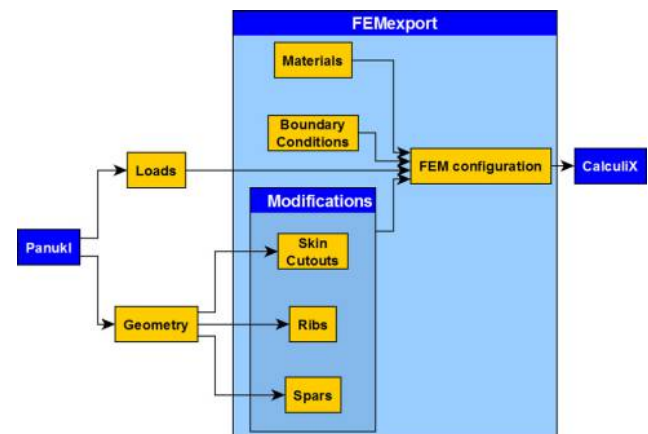
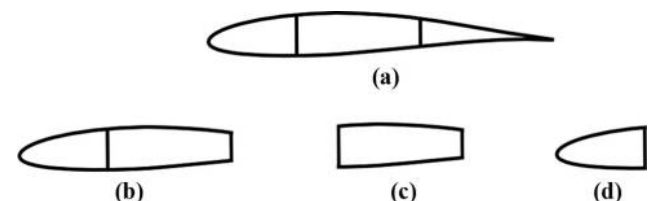
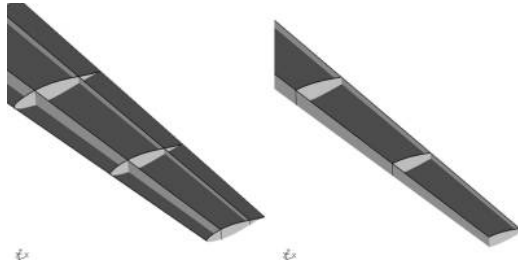


Figure 13 Different wings' structure configurations



Notes: (a) Complete wing with front and rear spar; (b) trailing edge cut-off; (c) leading edge and trailing edge cut off; (d) trailing edge cut off with the leading edge wall position offset set on 0

Figure 14 Example of geometry with the wing's skin cut flags on leading edge and trailing edge turned on



FEMexport, by default, automatically creates panel elements for ribs on every span-wise division of the wing's grid. Additionally, the number of panel layers, on the height of ribs direction, has to be specified.

Assigning properties to grid panel sets

Every wing with shell elements will contain common structure parts like: wall LE, wall TE, ribs, upper skin, lower skin. Chord-wise panels of the structure parts are organized in sets, for which parameters can be assigned: material properties (also composites), local coordinate system for material, panel set's thickness, or removing the panel set. This way, properties of a wing's structure span-wise can be easily controlled and adjusted (Figure 15).

The elements of structure, like ribs, parts of spar, or skin, which are not needed can be easily removed by setting the panels' thickness variable to zero, or giving the name of the material "0" (Figure 15).

Computing structure mass properties from FEM model

Mass properties of the analyzed structure are crucial, especially in aerospace. During the conceptual phases of design, it is often a problem to accurately estimate the mass of an aircraft. Designers may try to use statistical data, but the method is not applicable to unconventional aircraft configurations. Obtaining data of inertia moments, which are needed for example for dynamic stability analysis, is even more difficult. As creation of the numerical model with material properties for FEM analysis is easy with help of the CCM, mass of the structure can also be easily obtained. In the FEMexport tool, user can define material properties, including mass properties, even for composites. These materials are assigned to parts of the structure which is represented after export by FEM mesh. Knowing volume and material density of every mesh element, one can get an element's mass. Mass properties of the whole structure can be

Figure 15 Setting properties for the wing's structure parts

CUT/LE/TE	BOUNDARY	MATERIAL	ORIENTATION	SHELL_SEC	OUTPUT
WallLE	WallTE	Ribs	Skin		
*SEC_WallLE_Simpling		6			
y	ELSET	MAT	OR	TH	
0	WallLE_0	Mat	0	0.001	
1	WallLE_1	Mat	0	0.001	
2	WallLE_2	Mat	0	0.001	
3	WallLE_3	Mat	0	0.001	
4	WallLE_4	Mat	0	0.001	
5	WallLE_5	Mat	0	0.001	

derived by integration of masses of all elements. FEMexport includes a built-in tool to generate short report (Table I) with mass properties of the structure based on the described method.

There is also a possibility to build volume grid of the wings. In practice, a wing's structure with volume filled with foam is sometimes used in small UAV platforms. This feature might also be useful for preparation of the FEM model for topology optimization of the structure.

Examples of practical usage

The process begins with the definition of even advanced geometry, with usage of a graphical user interface (GUI). Next natural step is obtaining aerodynamic pressures on the airplane. From the aerodynamic analysis, performance, coefficients for dynamic stability and control and loads for strength analysis can be obtained. After the airplane's structure is defined, it is easy to obtain structure mass properties needed for flight dynamics stability and control analysis.

Advanced analysis

A practical example of advanced analysis of vertical stabilizer is shown in Figure 16. The process includes generation of computational model for aerodynamic analysis, export of the vertical stabilizer structure, which has automatically added ribs, spar walls, assigned materials, panel set's thickness. Fittings and stringers are added manually. Finally, static and frequency strength analyses are done.

Multidisciplinary optimization

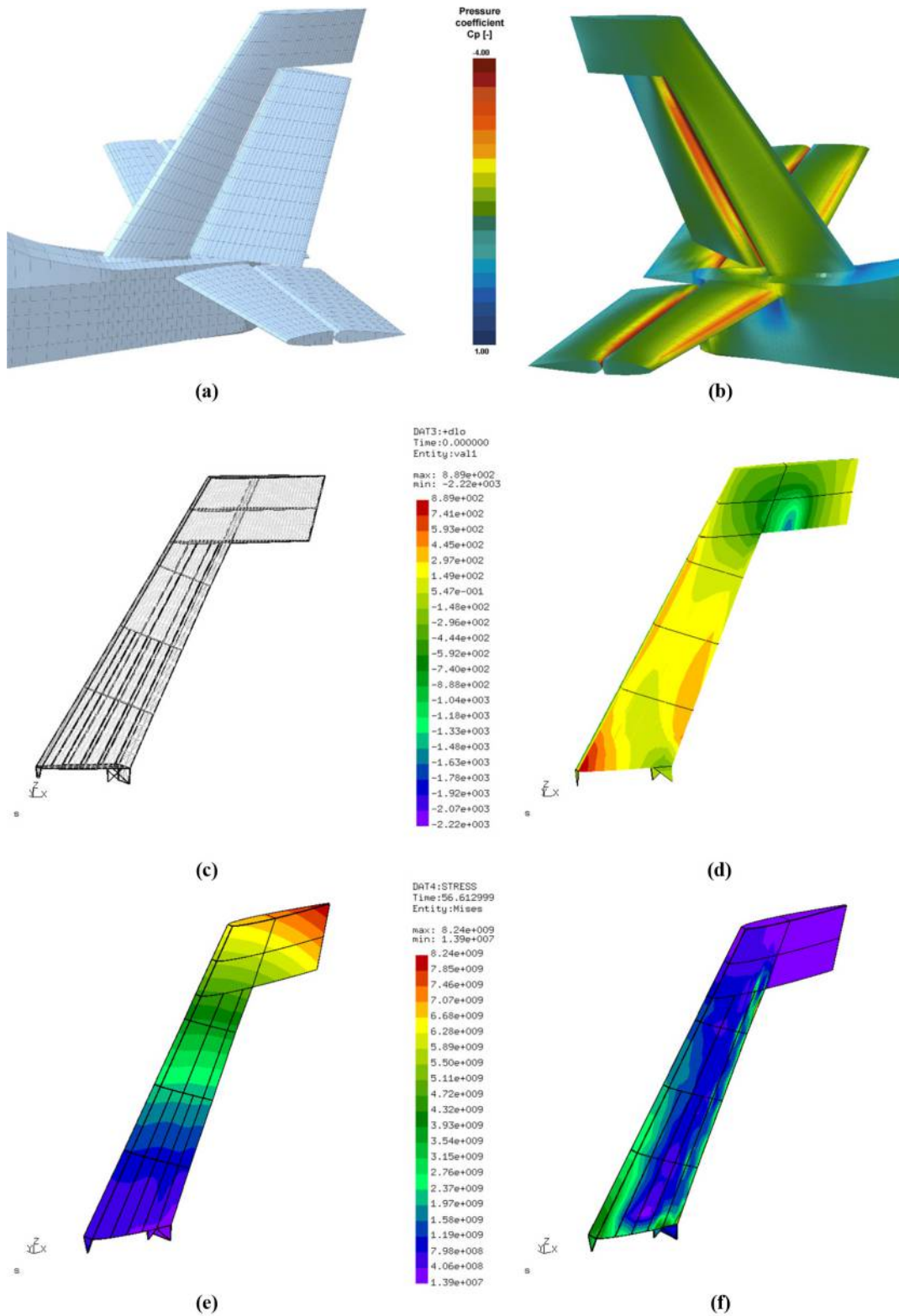
Thanks to the CCM concept and automatic data exchange between programs, implementation of numerical optimization is possible. The presented example (Figure 17) is a multidisciplinary optimization of an aircraft's advanced conceptual design (Mieloszyk and Goetzendorf-Grabowski, 2017). Considered innovative aircraft configuration was box-wing. The algorithm used to drive the optimization process was particle swarm optimization. The process included aerodynamic analysis, strength analysis and dynamic stability analysis. The objective function was defined as the minimum power needed for level flight. Over 200 design variables were set, and over 10 various constraints were imposed and satisfied in the optimization.

Conclusions

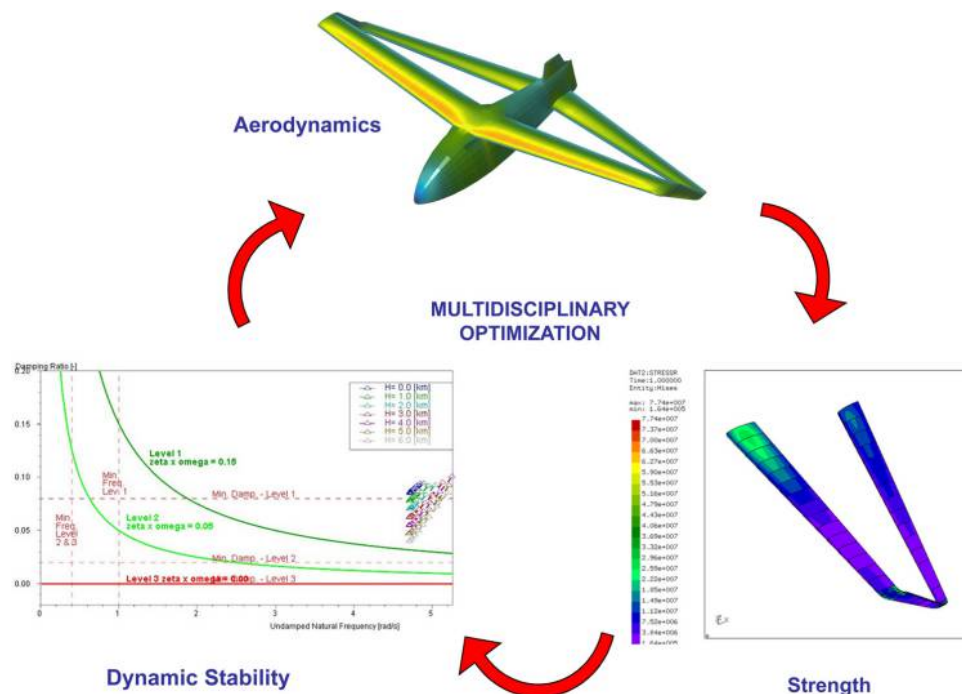
The approach proposed in the CCM shows new possibilities in aircraft design. Thanks to the modular structure of the CCM, exchanging or adding the numerical tools is not a

Table I Mass properties obtained from FEMexport, on an example of small UAV.

CG coordinate [m]	Moment of inertia [kg m ²]	Product of inertia [kg m ²]
mass = 10.0568 kg		
Xcg = 0.6927	Jxx = 3.8512	Jxy = 0.0000
Ycg = 0.0000	Jyy = 0.8696	Jxz = 0.0464
Zcg = 0.0105	Jzz = 4.6096	Jyz = 0.0000

Figure 16 Utilization of the common computational model by Deak (2016)

Notes: (a) Grid for aerodynamic analysis; (b) pressure coefficient distribution; (c) FEM model with internal structure and fittings; (d) loads from pressures and rudder; (e) displacements from the second frequency mode; (f) reduced stress from the second frequency mode

Figure 17 Multidisciplinary optimization of the aircraft's advanced conceptual design

problem. As a consequence of the approach, natural data flow occurs from one simulation tool to another. Strong coupling between the tools gives new possibilities, like deriving mass properties from the aircraft's FEM model after structure sizing, which is useful for flight dynamics and other simulations. More and more complicated, realistic scenarios of simulations can be realized. For instance, we are able to close the design loop and do numerical optimization, which might not be possible otherwise (Figure 17).

Practical application was shown on two examples of advanced multidisciplinary analysis and multidisciplinary optimization, which utilizes simulation tools of medium and high fidelity.

Due to the amount of time needed to set computational case, it is still a conceptual design phase, but big amount of data of high fidelity brings the design automatically to the level of early preliminary design.

Further work

The open character of the presented approach allows to add other disciplines software, e.g. dynamic analysis, performance analysis, etc., giving almost complete information about the new designed aircraft. The authors are going to develop such approach, extend it using other modules and test it within new projects.

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