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Introduction of full flight dynamic stability constraints in aircraft multidisciplinary optimization

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ABSTRACT

Obtaining satisfactory flight dynamic characteristics for an aircraft within the design process is a mandatory task required by the flight law regulations. In the classical approach dynamic stability analyses are done at the end of the design process, when most aircraft properties are already known. Possible changes of the dynamic properties can influence the whole project and force a redesign. This reason has caused a number of researchers and industry representatives to try to incorporate the dynamic analysis earlier in the design process. This demanding task has often been executed with a number of simplifications, limited to a single wing or analysis of only the longitudinal flight dynamic stability modes. The new presented approach goes much further. The article presents a successful attempt to include all dynamic modes of motion (longitudinal and lateral) into the analysis taking stability criteria as constraints. The numerical optimization process is fully automated and based on parallel processing, making the computations very efficient. Moreover, a complete aircraft in an innovative boxwing configuration is optimized with the dynamic stability constraints, which has not been achieved ever before.

1. Introduction

Thanks to the constantly increasing computational power, numerical optimization has become more and more common in research and industrial practices. Coupling aerodynamics and structural analyses in a multidisciplinary optimization framework is a well known practice [1]. In addition to the aerodynamics and structural analyses, the analysis of flight dynamics properties of an aircraft are one of the most important ones. Although flight dynamic analyses are crucial, they are often implemented at the end of the design process because of the computational cost and complexity. Advancing towards more competitive aerospace products, comprehensive knowledge about the most important airplane characteristics is essential.

It means, that also flight dynamics characteristics should also be predicted in the early stage of design. The problem was considered among others within the SimSAC project [2]. The claim is also recognized by industry. Bazile et al. from the Airbus company describe the analytical method for Dutch Roll prediction [3]. However, more competitive designs also mean innovative, unconventional configurations, which are not well known and the classical methods of analysis could be insufficient, especially when the configuration is strongly aerodynamically coupled. For example, Bras et al. computed flight dynamic characteristics for different configurations of an aircraft without a vertical tail [4]. The problems with flying qualities of other unconventional configurations, three surface aircraft (TSA) and tandem wing configuration, are presented also in [5,6]. Numerical optimization is proposed here to predict the properties of flight dynamics and impose stability constraints during the design process. Morris et al. presents an optimization framework for multidisciplinary optimization of supersonic tailless aircraft [7]. Static stability, as well as dynamic stability is analyzed in that work, but only for the longitudinal modes. Moreover, aerodynamic coefficients for the dynamic analyses are derived from the Digital DATCOM [8] method. Mader and Martins wrote a number of articles (e.g. [9]) about using stability constraints in aerodynamic shape optimization of a flying wing configuration. They utilized the Euler method to compute aerodynamic properties of the wing and solved the dynamic stability eigenvalue problem. These results were compared with and evaluated against, MIL-F-8787c handling qualities limits [10] and flight regulations [11].

Work presented in this paper is a development of the presented concepts. All of the examples from literature that considered dynamic stability constraints are focused only on one type of oscillation: longitudinal or lateral. In reference [7] the whole aircraft has been considered, but authors used simple DATCOM methods

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Nomenclature

ρ	air density	kg/m^3
CD	aerodynamic drag coefficient	
CL	aerodynamic lift coefficient	
CM	aerodynamic moment coefficient	
g	gravity acceleration, 9.81	m/s^2
m	mass	kg
V	flight velocity	m/s
S	reference area	m^2
D	aerodynamic drag	N
P	power	W
σ	stress	Pa
ε	nodes structure displacement	
ν	safety factor	
ζ	damping ratio	
ω	frequency of oscillations	Hz

T_2	time to double	s
V_k	particles velocity (displacement) vector in optimization	
w	relaxation parameter for particles' global velocity vector from previous iteration in PSO optimization	
$s1$, $s2$	relaxation parameters for particles' components of velocity vector in PSO optimization	
$r1$, $r2$	random variables in optimization to improve PSO algorithm robustness	
F	objective function	
x	optimization design variables	
μ	optimization constraints parameter	
q	optimization constraint value	
k	iteration index in the optimization	

to derive the aerodynamic derivatives that cannot be used for untypical and innovative aircraft configurations. On the other hand, in reference [9] CFD computations have been used to obtain the aerodynamic derivatives but only a single wing was considered.

The boxwing concept was first introduced by Prandtl [12]. The configuration promises benefits in terms of induced drag reduction, decreased mass and higher stiffness [13,14]. These advantages come at a certain price. Joining surfaces of the front and rear wing increase wet area and may introduce additional interference drag. Stiffer, closed loop structure can produce stress concentrations where the wings join [15] and demand precise manufacturing tolerances to avoid problems during structural assembly. Moreover, the configuration has different dynamic stability characteristics than conventional aircraft and like all aircraft, it has to be trimmed and stable. Nevertheless, the boxwing configuration has the potential to outperform classical airplane configurations in certain missions. Researchers today still investigate the potential boxwing designs [16,17] to exploit the advantages of this configuration. Present work was performed during the Polish project MOSUPS (Dynamically Scalable Airplane Demonstrator in Boxwing Configuration) [18,19]. The project was initialized by a preliminary investigation of a boxwing configuration with inverted vertical position of the wings, which caused the positive interference effect of increased lift and reduced drag [20]. The objective of the project was to develop tools and methods for the design of a boxwing aircraft configuration and to build a flying demonstrator as proof of the concept – Fig. 1.

The paper describes multidisciplinary numerical optimization of a whole aircraft, which incorporates automated numerical analysis of aerodynamics, strength, and flight dynamic stability. Many of the simplifications, assumed in the previous research work, were dropped. Numerical computations were made for a complete aircraft. Stability constraints included both longitudinal and lateral stability modes. Additionally, an innovative aircraft boxwing configuration was considered as a demanding task. The presented method of optimization with the flight dynamic stability constraints turned out to be feasible also in this case.

Aerodynamic analyses were conducted with the use of an inviscid 3D panel method and supplemented with a viscous analysis of the wings' airfoils. Geometry of the wings with structural loads was exported to a FEM solver, and the structure was sized by changing the panels' thickness. Having aerodynamic properties and the mass of the aircraft structure from the FEM model, dynamic stability analysis was possible. A full (6 DoF) flight dynamics model [21–24] was used to compute both longitudinal and lateral modes of motion. Constraints on the dynamic properties were imposed based on the requirements from the MIL-F-8787c handling qualities limits [10].

Fig. 1. Boxwing flying demonstrator.

2. Multidisciplinary optimization framework

The authors have been involved in the creation and development of the computational framework called MADO – Multidisciplinary Aircraft Design and Optimization, which was developed to link existing methods of analysis within an optimization process. Initially only the aerodynamic characteristics of an aircraft were optimized [25]. Later on more sophisticated optimization algorithms were developed [26] and more types of analysis were incorporated during the optimization process [27,28]. Inclusion of the full flight dynamic stability analysis is the latest achievement and is described in this paper.

The general idea of the optimization framework is shown in Fig. 2 according to the convention presented in [29]. Analyses performed during the optimization include aerodynamics, structural analysis and flight dynamic stability analysis. A detailed list of optimization design variables is given in the appendix. There are 24 variables concerning the geometry of the wings and 183 variables which define the thickness of panel sets. The vector of variables x is common to all analyzed disciplines and the disciplines are analyzed sequentially. To maintain the PSO algorithm with a high computational efficiency the particles, which represent different aircraft configurations during a particular iteration, are computed in parallel. Sequence of computations of the particular disciplines is important since results from earlier analyses are used by the subsequent analyses. From the aerodynamic analysis the computational grid of the airplane and aerodynamic loads are transferred to the structural analysis, which is represented by the state variable y_1 in Fig. 2. The grid is modified by adding the primary internal structure of the wings. From the structural analysis, masses of the