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Integrated optimization on aerodynamics-structure coupling and flight stability of a large airplane in preliminary design

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Abstract The preliminary phase is significant during the whole design process of a large airplane because of its enormous potential in enhancing the overall performance. However, classical sequential designs can hardly adapt to modern airplanes, due to their repeated iterations, long periods, and massive computational burdens. Multidisciplinary analysis and optimization demonstrates the capability to tackle such complex design issues. In this paper, an integrated optimization method for the preliminary design of a large airplane is proposed, accounting for aerodynamics, structure, and stability. Aeroelastic responses are computed by a rapid three-dimensional flight load analysis method combining the high-order panel method and the structural elasticity correction. The flow field is determined by the viscous/inviscid iteration method, and the cruise stability is evaluated by the linear small-disturbance theory. Parametric optimization is carried out using genetic algorithm to seek the minimal weight of a simplified plate-beam wing structure in the cruise trim condition subject to aeroelastic, aerodynamic, and stability constraints, and the optimal wing geometry shape, front/rear spar positions, and structural sizes are obtained simultaneously. To reduce the computational burden of the static aeroelasticity analysis in the optimization process, the Kriging method is employed to predict aerodynamic influence coefficient matrices of different aerodynamic shapes. The multidisciplinary analyses guarantee computational accuracy and efficiency, and the integrated optimization considers the coupling effect sufficiently between different disciplines to improve the overall performance, avoiding the limitations of sequential approaches utilized currently.

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1. Introduction

Taking into account increasing environmental problems and economic requirements, the airline industry and airplane designers are seeking more efficient and comfortable airplanes.[1,2] Research on airplane designs is therefore focused more on increasing the lift-to-drag ratio, reducing the structural weight, and improving the stability. The airplane design process is in general divided into three phases, i.e., the conceptual design phase, the preliminary design phase, and the detailed design phase. In the conceptual phase, main parameters, such as airfoil, planform shape, structural layout and stiffness distribution, are initially determined by empirical formulas and engineering estimation formulas,[3] and it is guaranteed that the overall performance of the airplane can reach the design targets. In the preliminary phase, the aerodynamic shape, structural layout, and structural sizes are further refined and optimized, and the aerodynamic shape is finally determined. Highly accurate methods, such as Computational Fluid Dynamics (CFD), Finite Element Method (FEM), and so forth, are employed in this phase to ensure that the scheme can meet the design requirements. The detailed design phase contains structural size design, strength checks, various types of tests, and detailed design drawings of components used for manufacturing.[4]

Though every design phase is very important, the preliminary design phase has a special place since it is the continuation of the conceptual design phase and the base of the detailed design phase. The earlier the appropriate aerodynamic shape, structural layout, and sizes can be determined, the more economical the whole design process will be, avoiding costly redesigns and corrections later, so the preliminary design has enormous potential in enhancing the overall performance.[5]

Conventional methods perform the aerodynamic, structural, and stability designs in a specific sequence. The aerodynamic shape, which has the maximum lift-to-drag ratio and a reasonable geometric shape,[6,7] is designed first. Given the aerodynamic shape, the structural layout[5,8] and structural sizes[9,10] are designed to minimize the structural weight subjected to multiple constraints. Following that, a jig shape will be obtained referring to the predefined aerodynamic shape and structure.[11] However, airplane design is a complex process requiring a detailed consideration of the coupling effects between different disciplines. Conventional designs excessively depend on engineering experience, which will lead to repeated iterations and low efficiency, so it can hardly adapt to the designs of modern airplanes, especially the preliminary phase with an enormous potential. Multidisciplinary Analysis and Optimization (MAO) could take disciplines containing aerodynamics, structure, flight dynamics, etc. into consideration simultaneously and has the capability to overcome the limitations of conventional methods, so it has been applied widely in modern airplane designs.[12–14]

A crucial challenge of MAO is the tradeoff between analytical accuracy and computational burden. Many engineering software systems contain modules for aeroelastic analyses. Doublet-Lattice theory for static aeroelasticity and flutter analyses adopted in MSC.Nastran is a type of low-order panel methodology,[15] and the modal approach adopted in ZONAIR formulates a reduced-order trim system combining a unified high-order panel methodology and structural modes.[16] Although these methods can be employed with much less computer time than that of direct methods, the analytical accuracy of aerodynamics or structures cannot satisfy the requirements of MAO for airplane designs in the preliminary phase. A three-dimensional flight load method for static aeroelasticity analysis is applied.[17] Aerodynamic analysis and elastic correction are based on Aerodynamic Influence Coefficient (AIC) matrices generated by a high-order panel method, which can guarantee both the accuracy and efficiency. Though CFD simulations based on Reynolds-averaged Navier-Stokes (RANS) equations can simulate intricate flow, its massive computational burden is unacceptable. Steady flight conditions make up most of the flight time of a large airplane, so some viscous/inviscid iteration methods[18,19] are more suitable for a large airplane under cruise conditions with moderate flow separation. The disturbance in cruise conditions is weak compared with that in the steady state, and therefore, the small-disturbance theory is valid for cruise stability analysis. To further reduce the computational burden, the Kriging method has found widespread use owing to its promising potential.[20,21] As a Response Surface Method (RSM), the Kriging model[22] is developed in the field of spatial statistics and geostatistics, which is the most widely used RSM compared with the polynomial-based model.

A gradient-based algorithm, which is the major method in some commercial structural optimization software systems,[23] has the advantage of rapidity, but it is apt to converge to a local optimum solution, and sometimes the derivatives are impossible to calculate. On the contrary, evolutionary algorithms are suitable to seek the optimal solution for these MAO problems, and Genetic Algorithm (GA) is the most widely used global algorithm.[24]

To exploit the immense potential of a large airplane in the preliminary design phase and avoid the design limitations of conventional methods, an integrated optimization method accounting for aerodynamics, structure, and stability is proposed, and the optimal wing geometry shape, front/rear spar positions, and structural sizes are obtained simultaneously. The three-dimensional flight load method is used for static aeroelasticity analysis, and the *p-k* method provided by MSC.Nastran is used for flutter analysis. The lift-to-drag ratio is estimated by the viscous/inviscid iteration method provided by the commercial CFD solver MGAERO. The stability and control analyses of flight dynamics are performed using the linear small-disturbance theory. To further reduce the computational burden of static aeroelasticity analysis in the optimization process, the Kriging method based on Latin hypercube Design of Experiment (DoE) is used to predict AIC matrices of different aerodynamic shapes. Parametric optimization is performed using GA for the minimum wing structure weight subject to aerodynamic, aeroelastic, and stability constraints in the cruise trim condition. Sensitivity analysis is conducted to study the response trends to the variation of each design variable aiming at the optimal design, and the obtained results provide designers with a wealth of information for airplane design in the preliminary phase.

2. Methodology

2.1. Static aeroelasticity

Static aeroelasticity is performed by the three-dimensional flight load method.[17] It combines the high-order panel method