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Multi-objective optimization of aircraft design for emission and cost reductions

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Abstract Pollutant gases emitted from the civil jet are doing more and more harm to the environment with the rapid development of the global commercial aviation transport. Low environmental impact has become a new requirement for aircraft design. In this paper, estimation method for emission in aircraft conceptual design stage is improved based on the International Civil Aviation Organization (ICAO) aircraft engine emissions databank and the polynomial curve fitting methods. The greenhouse gas emission (CO_2 equivalent) per seat per kilometer is proposed to measure the emissions. An approximate sensitive analysis and a multi-objective optimization of aircraft design for tradeoff between greenhouse effect and direct operating cost (DOC) are performed with five geometry variables of wing configuration and two flight operational parameters. The results indicate that reducing the cruise altitude and Mach number may result in a decrease of the greenhouse effect but an increase of DOC. And the two flight operational parameters have more effects on the emissions than the wing configuration. The Pareto-optimal front shows that a decrease of 29.8% in DOC is attained at the expense of an increase of 10.8% in greenhouse gases.

1. Introduction

In these decades, with the rapid development of the global commercial aviation transport as well as the raise of people's environmental protection consciousness, the emissions of aircraft have increasingly become a very important issue. And in accordance with the European Union Emissions Trading Scheme, starting on January 1, 2012, all airlines flying to and from EU airports will be charged for carbon emissions. If carbon emissions exceed what is permitted by its credits, they have to purchase trading credits from other airlines or countries.[1] Even though many countries oppose this rule nowadays, not only do the pollution gas emissions have harmful effect on environment, but they maybe indirectly increase the operating costs of the aircraft as well in future.

The emissions from aircraft engine include not only carbon dioxide (CO_2), but also nitrogen oxides (NO_x), water vapor (H_2O), Hydrocarbons (HC), soot, and other gases.[2,3] These emitted gases impact on the environment mainly including two aspects: pollution around the airport and atmosphere

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greenhouse effect. In the past, only the emissions in the vicinity of airport are considered.[4–6] The International Civil Aviation (ICAO) proposed the limitation on emissions of HC, NO_x, smoke, and some other gases during standardized landing and takeoff (LTO) cycle at sea-level. In recent years, the awareness of the greenhouse effect caused by the emissions especially during the cruise flight has grown.[7–10] The contribution of aircraft to the greenhouse effect is mainly caused by CO_2, H_2O and NO_x. According to Intergovernmental Panel on Climate Change (IPCC) report 1999, the total radiative forcing may be about a factor of 2–4 larger than the radiative forcing due to CO_2 alone.[11] The greenhouse effect of NO_x is indirect and complicated. The cruise altitude of subsonic airplane is usually between the upper troposphere and the lower stratosphere. When transmitted to or emitted directly into the stratosphere, NO_x acts as catalysts in chemical reactions that contribute to the depletion of the ozone layer.[12,13] When emitted into the upper troposphere, NO_x may change the formation of tropospheric ozone and methane. The impact of H_2O in the form of contrails and cirrus are also sensitive to the flight altitude. Hence, the relationship between cruise altitude and greenhouse effect caused by the aircraft is complex.

Recently, another important issue for commercial airplane design is the cost. For the economic reason, all the airframe/engine manufacturers and the airliners endeavor to reduce the cost, especially the Direct Operating Cost (DOC), to keep ahead of competition. Volders and Slingerland[10] researched on the minimum environmental harm and the minimum DOC of long range aircraft during cruise flight, by varying the ratio of thrust to weight and the ratio of weight to wing area. Schwartz and Kroo[14] presented a time- and altitude- varying climate model and optimized the aircraft for minimum cost, fuel burn and NO_x emissions, separately. Whereas the climate impact model is not prone to be used for comparison between different designs.

This study aims to improve the emission estimation method at aircraft conceptual design stage, and proposes a measure parameter used for comparison of greenhouse effect caused by the emissions from various types of civil jets. Then an approximate sensitive analysis and a multi-objective optimization of aircraft design for minimizing greenhouse effect and minimizing DOC are performed with five geometry variables of wing configuration and two flight operational parameters.

2. Analysis models for civil jet

The multidisciplinary analysis code is a pre-requisite for the multi-objective optimization in civil jet conceptual design. In this section, the framework of multidisciplinary analysis is briefly described, and the analysis models for two disciplines (emissions and costs) are presented with the detail for the emission prediction method.

2.1. Multidisciplinary analysis framework

The multidisciplinary analysis code includes several disciplines: propulsion, geometry, aerodynamic, structure, weight, performance, emission and DOCs, as shown in Fig. 1. The disciplines analysis models are mainly based on empirical formulations with various statistical data, semi-empirical equations and the simplified numerical methods.[15,16] In this framework, the geometric model provides a unified and comprehensive geometry data for the other models. The models for propulsion, aerodynamic and weight are the core analysis ones, whose output data are used as the input data in the performance, stability and control (SAC), emission and DOC analysis. For the detail on the multidisciplinary analysis code, refer to Ref.[17]

2.2. Emissions

2.2.1. Estimation method

The ICAO provides a prediction model for emissions of civil jet with turbofan engines.[4] Emission quantities are computed using the emission index (EI), which is the mass ratio of emitted gases to fuel burned in units of g/kg, given by

$$E = \mathrm{EI} \cdot W_{\mathrm{fuel}} \tag{1}$$

where E is the mass of some emitted gas per mission, and W_{fuel} the mass of fuel burned.

The primary greenhouse-effect emissions are CO_2, NO_x and H_2O. The EIs of CO_2 and H_2O are determined by the composition of the fuel and can be considered as constant,

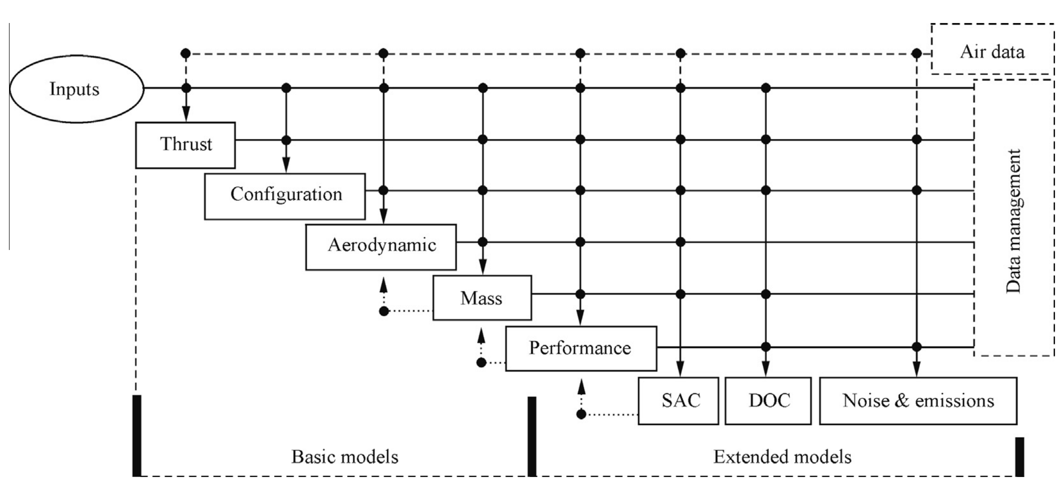

Fig. 1 Framework of multidisciplinary analysis code.