ARTICLE IN PRESS
Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics
cja@buaa.edu.cn
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FULL LENGTH ARTICLE

Multipoint optimization on fuel efficiency in conceptual design of wide-body aircraft

Xiao CHAI, Xiongqing YU *, Yu WANG

College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Received 16 March 2017; revised 12 June 2017; accepted 28 August 2017

KEYWORDS

Aircraft conceptual design;
Fuel efficiency;
Multiple missions;
Optimization;
Wide-body aircraft

Abstract Aircraft conceptual design optimizations that maximize the performance at a design condition (single-point) may result in designs with unsatisfying off-design performance. To further improve aircraft efficiency under actual flight operations, there is a need to consider multiple flight conditions (multipoint) in aircraft conceptual design and optimization. A new strategy for multipoint optimizations in aircraft conceptual design is proposed in this paper. A wide-body aircraft is taken as an example for both single-point and multipoint optimizations with the objective of maximizing the specific hourly productivity. Boeing 787-8 flight data was used in the multipoint optimization to reflect the true objective function. The results show that the optimal design from the multipoint optimization has a 7.72% total specific hourly productivity increase of entire flight missions compared with that of the baseline aircraft, while the increase in the total specific hourly productivity from the single-point optimal design is only 5.73%. The differences between the results of single-point and multipoint optimizations indicate that there is a good option to further improve aircraft efficiency by considering actual flight conditions in aircraft conceptual design and optimization.

1. Introduction

The continued growth of air traffic has caused increasing demands to improve aircraft fuel efficiency for minimizing aviation's environmental impact and for counteracting fuel prices. According to the Intergovernmental Panel on Climate Change (IPCC), the civil air transport is expected to continue increasing at a rate of 4.8% by 2036.[1] The contribution to global anthropogenic carbon emissions by the continued growth in aviation may increase to 15% by 2050.[1] Ambitious research goals of the reduction of fuel burned have been set by NASA's Environmentally Responsible Aviation (ERA) Project[2] and European "Clean Sky 2" Program.[3]

Traditionally, aircraft conceptual design optimizations have been generally performed to maximize the aircraft fuel efficiency at a design flight condition,[4,5] which is referred to as single-point optimizations and may result in designs with unsatisfying performance under off-design flight conditions.

* Corresponding author.
E-mail addresses: chaixiao@nuaa.edu.cn (X. CHAI), yxq@nuaa.edu.cn (X. YU), wangyu@nuaa.edu.cn (Y. WANG).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2017.10.006
1000-9361

Please cite this article in press as: CHAI X et al. Multipoint optimization on fuel efficiency in conceptual design of wide-body aircraft, *Chin J Aeronaut* (2017), https://doi.org/10.1016/j.cja.2017.10.006

To improve the robustness of the designs and increase the aircraft fuel efficiency under actual flight operations, there is a need to consider multiple flight conditions in aircraft conceptual design optimization. The multipoint optimization in this paper means that the objective function in the aircraft conceptual design optimization involves multiple flight conditions.

Early work with a consideration of multiple conditions has been focused on the aerodynamic shape optimizations of airfoils and wings. Buckley et al.[6] performed an airfoil design optimization under 18 flight conditions. Lyu and Martins[7] investigated the impact of multipoint design optimization on a Navier-Stokes-based aerodynamic shape and planform optimization of a blended-wing-body aircraft. Liem et al.[8] performed a multipoint aerostructural optimization of a long-rang twin-aisle aircraft, in which high-fidelity aerodynamic and structural analysis models were used. Recently, more studies, which couple aircraft designs and air transport networks, have been conducted with the application of the concept of system of systems oriented design.[9] Lammering and Schneider[10] presented an approach focused on single-aisle market requirements. Their results showed that an increase in fuel efficiency and economics of up to 25% was feasible under the consideration of the entire mix of daily operations of single-aisle aircraft. An integrated design and optimization of aircraft families and air transport networks were performed by Jansen and Perez.[11] Liu et al.[12] proposed a design index sets evaluation method combining airliner market analysis with aircraft conceptual design.

However, there was few effort made in rapid aircraft conceptual design and optimization with a consideration of the actual uses of these aircraft in an operator's route networks. In this paper, a new strategy to formulate multipoint design optimization problems is developed to maximize the aircraft fuel efficiency over a large number of different missions. The remainder of the paper is organized as follows: The actual flight operations of a wide-body aircraft are presented in Section 2, in which a civil jet Boeing 787-8 is chosen as the representative of wide-body aircraft based on market analysis, and its flight missions are analyzed in terms of payloads and ranges. A multipoint optimization problem considering the actual flight missions is formulated in Section 3. A framework to solve both the single-point and multipoint optimization problems is presented in Section 4. The differences between the results from the single-point and multipoint optimizations are discussed in Section 5, followed by conclusions in Section 6.

2. Wide-body aircraft market analysis and flight mission data

Based on the operation capacity of an aircraft, wide-body aircraft can be generally divided into three categories: small wide-body, medium wide-body, and large wide-body. According to the Boeing Current Market Outlook[13], the design payloads of small wide-body, medium wide-body, and large wide-body aircraft are 200–280, 280–400, and more than 400 passengers, respectively. They mainly operate for international flights and partially domestic flights. The Boeing current market outlook[13] predicted that 39620 new commercial aircraft will be delivered over the next 20 years, as shown in Fig. 1.

Although the predicted total number of wide-body aircraft to be delivered in the next 20 years is only about one-third of

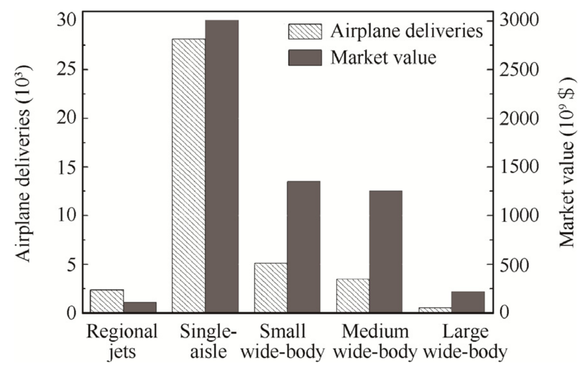

Fig. 1 Boeing current market outlook 2016 to 2035[13].

that of single-aisle aircraft, the total market value of wide-body aircraft is about the same as that of single-aisle aircraft, as illustrated in Fig. 1. The majority of wide-body aircraft is small and medium wide-body aircraft, and Boeing 787-8 is the latest widely operational small wide-body aircraft now. Also considering that China and Russia are co-developing wide-body aircraft[14], a wide-body aircraft similar to Boeing 787-8 is chosen as the baseline aircraft in the following optimizations.

To obtain a set of missions that is representative of the actual operations of the baseline aircraft, we referred to the American Research and Innovative Technology Administration (RITA)'s Bureau of Transportation Statistics flight database.[15] The payload and range data for all Boeing 787-8 flights that took off from the United States, landed in the United States, or both was extracted. Since such data is only available for the United States market, we assume that the data can also be used to reflect other markets. These data consists of 60453 flights, of which the payload and range distribution (surface) in reference to the design payload-range envelope (solid line) of Boeing 787-8[16] is shown in Fig. 2. This distribution is plotted using a 26×42 grid of bins. Each bin is 500 km in range by 1000 kg in payload. We chose the midpoint to represent the range and payload of a bin that contains at least one flight mission. The color map shown in Fig. 2 represents the number of flight missions contained within each bin. There are 426 representative flight missions in our analysis. A more detailed analysis is provided in Fig. 3. The white circle in Fig. 2 represents the design point of Boeing 787-8. It can be seen that the majority of all flights were operated within a range of around 8000 km and a 30000 kg payload, respectively.

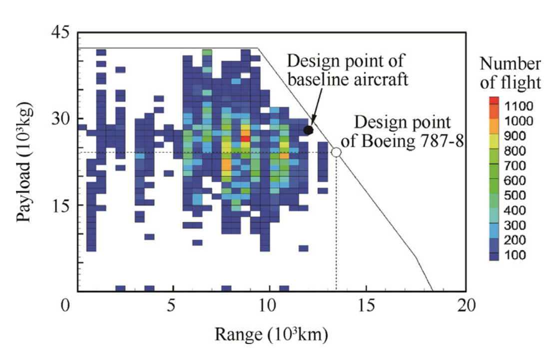

Fig. 2 Distribution of 60453 flights for Boeing 787-8 and its payload-range envelope.