Available online at www.sciencedirect.com

ScienceDirect

Fuzzy Sets and Systems 269 (2015) 115–134

FUZZY sets and systems

www.elsevier.com/locate/fss

Examination of excessive fuel consumption for transport jet aircraft based on fuzzy-logic models of flight data

Ray C. Chang

Dept. of Aviation Mechanical Engineering, China University of Science and Technology, Hsinchu County (31241), Taiwan, ROC

Received 23 February 2012; received in revised form 22 April 2014; accepted 23 April 2014

Available online 10 May 2014

Abstract

Because the amount of fuel usage is huge, and exhaust emissions of commercial transports is regulated under the Kyoto Protocol, how to reduce fuel consumption is an urgent problem for all airlines. The airlines urgently need a practical method to reduce fuel consumptions within constraints to accomplish the mission. The objective for the present paper is to use a model-based method and flight data to enhance fuel efficiency for commercial transports. The fuzzy-logic modeling (FLM) technique will be employed to establish the reference lift-to-drag (L/D) model. The model is utilized to predict the deficiencies of lift-to-drag ratio through sensitivity analysis to determine the relative contributions from influencing flight variables for the excessive fuel consumption. This method is based on the flight data in quick access recorder (QAR) available in the Flight Operations Quality Assurance (FOQA) program. The process of identifying how flight variables reduce the lift-to-drag ratio of a twin-jet transport aircraft in cruise flight will be presented. The sensitivity derivatives for slow-varying and fast-varying influence variables are analyzed. The factors contributing to the degradation of aerodynamic efficiency (i.e. L/D) in operations are evaluated. The excessive fuel consumption due to the effects of deficiencies will be estimated in the present paper. If all the deficiencies can be improved, the fuel efficiency enhancement will be achieved.

Keywords: Fuzzy sets; Membership functions; Parameter identification; Structure identification; Fuzzy-logic modeling (FLM)

1. Introduction

Recent surging of oil price is due to the petrochemical fuel resources being limited and gradually exhausted. How to develop the energy resources and to reduce the waste of fuel, and at the same time reduce the carbon emission, is one of the global popular subjects of research. Since the amount of worldwide fuel usage for the transport aircraft is huge, and exhaust emissions of commercial transports is regulated under the Kyoto Protocol [1], aviation industrial circles have an urgent problem to save the fuel consumption and reduce the carbon emission. The fuel economy of a jet transport is dependent on the lift-drag ratio (L/D) and engine health. Boeing provided a training program of fuel conservation for the performance engineers of airlines [2]. The training program of fuel conservation included flight operations in optimal aerodynamic performance and excrescence drag reductions based on cleanliness of aerodynamic components.

http://dx.doi.org/10.1016/j.fss.2014.04.021

Traditionally, the flight operations are executed for optimal aerodynamic performance; while flight plans are arranged in according to the optimal efficiency of engine performance. Regarding to the enhancements of fuel efficiency, the flight plan should be arranged in an optimum altitude with maximum ground miles per unit of fuel burned. In other words, the optimal altitude exists at a given weight and Mach number such that the aerodynamic performance can match the engine performance with a minimum fuel flow rate. The optimum altitudes depend on Mach number, airspeed, and weight [3]. The calculated rates of change will predict how these three slow-varying variables should be modified. The maximum ground miles per unit of fuel burned depends on wind speed, direction, and altitudes. A head wind typically reduces it and a tail wind increases it. The monitoring parameters of maximum ground miles per unit of fuel burned in cruise flight are the wind speed along the trajectory and altitude. The wind speed, dynamic pressure, airspeed, Mach number, and flight altitude, belong to slow-varying influence variables in this paper.

In general, the excrescence drag is caused by miss-rigged angular positions of flight control surfaces, and mismatched surfaces of steps and gaps at skin joints, around windows, doors and access panels. If the angular positions of flight control surfaces are not set properly, drag will be increased and L/D reduced. The excrescence drag for a not-so-clean aircraft may reach 4% of the aircraft total drag. But if the rigging and adjustment of flight control surfaces are careless, the irregular deviations of flight control surface deflected angles may account for more than 80% of the entire excrescence drag [2]. The monitoring parameters of flight control surfaces in cruise flight are stabilizer deflections in pitch trim, elevator angles in pitch control, aileron and rudder angles in lateral-directional control. Those deflected angles of flight control surfaces are similar to the angles of attack and sideslip angles belong to fast-varying variables in the present paper.

The Flight Operations Division of airlines uses tools like the APM (Aircraft Performance Monitoring) [4] to monitor the performance changes and provide assessment of fuel efficiency. However, contemporary analytic software of the airlines does not indicate a definite solution to improve fuel efficiency and the tools like the APM are available on-line under restriction of registering. From the point view of mathematics, the relative contribution value at a single point can be estimated by a Taylor series in several variables from the values of the function's derivatives. However the values of the function's derivatives are not the same as those in the original design after a certain period of services. It may be the reason for the APM system to estimate only the deviations. This kind contemporary analytic software does not indicate the causes of deviations and cannot provide a definite solution for fuel saving neither.

In the present study, the fuzzy-logic modeling (FLM) will be employed to establish the reference L/D models based on flight data in quick access recorder (QAR) available in the Flight Operations Quality Assurance (FOQA) program. The QAR is an airborne flight data recorder designed to provide raw flight data, through means "quick and easy access", such as USB or cellular network connections and/or the use of standard flash memory cards. QARs are typically used by airlines to improve flight safety and operational efficiency [5], usually in the scope of FOQA program. In general, QAR has 88 operational parameters and the recorded values must meet the designated range, resolution, and accuracy requirements during dynamic and static conditions [6].

In setting up the models of aerodynamic or flight dynamics to predict the required derivatives, the traditional approaches of flight data analysis, such as the maximum likelihood method (MMLE) [7], the least-square or the regression method [8], have not been shown to be capable of handling nonlinear and unsteady (i.e. dynamic) aerodynamic environments. Those traditional approaches are very difficult to correlate complex functional relations among numerous parameters.

The FLM technique is to set up a relation between an outcome variable (e.g. L/D) and its influencing variables. It is most useful when analyzing the abnormal conditions of a system's performance [9] and [10]. The deficiencies of L/D can be examined by the sensitivity analyzes of model-predicted results to determine the relative contributions from influencing flight variables for the excessive fuel consumption. The assessable factors of fuel wastage through the evaluations of L/D derivatives with slow-varying and fast-varying influence variables will be illustrated in this paper.

2. Fuzzy logic modeling

Since the reference L/D model is established by using flight data, modeling technique is important and need to be carefully considered. Factors that affect the modeling procedures include the mathematical tool to set up system model and the method to identify parameters of model structure. Modeling procedures start from separating the input data into many groups, and nonlinear relations are set up between each input–output data space. In order to obtain all