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# EVALUATIONS OF PROBLEM AREAS ON CAUSES OF EXCESSIVE FUEL CONSUMPTION FOR TURBOFAN ENGINES

**Ray C. Chang* and Szuying Tan***
* Dept. of Aviation Mechanical Engineering, China University of Science and Technology, Taiwan, R.O.C

*Keywords*：*lift-to-drag ratio (L/D); exhaust gas temperature (EGT); fuzzy-logic modeling (FLM); quick access recorder (QAR); excessive fuel consumption*

## Abstract

*The fuel economy of a jet transport is closely related to aircraft performance and engine health. The assess factors of fuel wastage for turbojet transports are quite complicate to estimate due to too many influencing variables in the system. The present study is to use a model-based method to examine the possible influencing variables in aircraft performance deficiencies first, and then to detect the engine faults for the purpose to examine the possible reasons on causes of excessive fuel consumption. The fuzzy-logic modeling (FLM) technique is employed to establish the standard lift-to-drag ratio (L/D) and exhaust gas temperature (EGT) models based on flight data from quick access recorder (QAR). The deviations and abnormal conditions can be diagnosed after the comparative analysis with the standard models. The deficiencies in operational L/D and engine faults can be examined by the sensitivity derivatives of model-predicted results to determine the relative contributions from influencing flight variables. If all the deficiencies related to the excessive fuel consumption could be improved or removed, the fuel efficiency enhancement would be achieved. The developments of judgments of engine-defect database (knowledge-based database) for the specific flight fleets will be the further tasks for this study. The present method can be used in the future to assist airlines to monitor the engine health as a complementary tool to improve aviation safety, operation and operational efficiency.*

## 1 Introduction

The aviation fuel consumption has always been the key factor for the airline's operating cost. Since the amount of worldwide fuel usage for the transport aircraft is huge and the fuel cost is up surging, how to reduce the fuel consumption and the carbon emission is an urgent problem in aviation industrial circles.

The Flight Operations Division of some airlines use tools like the APM (Aircraft Performance Monitoring) [1] 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. The relative contribution values for the fuel saving are quite complicated to estimate due to too many influencing variables. 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 in the original design after a certain period of services. It may be the reason for the APM system to estimate only the deviations.

The present study is to use a model-based method to examine the possible influencing variables in aircraft performance deficiencies and engine health. The fuzzy-logic modeling (FLM) technique is employed to establish the standard lift-to-drag ratio (L/D) and exhaust gas temperature (EGT) models based on the flight data. The deviations and abnormal conditions can be diagnosed after the comparative analysis with the standard models. The deficiencies in operational L/D and engine faults can be examined by the sensitivity derivatives of model-predicted results to determine the relative contributions from influencing flight variables.

The technique of FLM has been applied successfully to a large number of non-linear, complex systems. The present paper is based on the modeling technique suggested by Tan & Xie. [2]. In order to obtain all the corresponding output, the present technique uses internal functions instead of fuzzy sets to generate the output of the model. It is most useful when analyzing the abnormal conditions of a system's performance. A detailed description of the modeling procedure is available in Lan and Chang [3].

The technique used here has been applied to model identification of a fighter aircraft from flight test data [4], aerodynamic estimation of transport aircraft for the simulator database establishments [5] & [6], accident investigations [7] & [8], diagnosis of engine health [9], and diagnosis of structural integrity [10]. The present paper is a new application on aviation fuel saving.

## 2 Present Method of Analysis

### 2.1 Lift-to-Drag Model

Modeling means to establish the numerical relationship among certain variables of interest. In the fuzzy-logic model, more complete necessary influencing flight variables can be included to capture all possible effects on L/D, which is an indicator of aircraft performance. In order to maximize the efficiency of the model setup, the lift-to-drag ratio, L/D, in general is assumed to depend on the following 11 influencing variables for this twin-jet transport:

$$L/D = f(\alpha, \beta, \delta_e, M, \delta_s, V, \delta_a, \delta_r, V_w, h, \bar{q}) \quad (1)$$

In Eq.(1), the monitoring parameters of flight control surfaces in cruise flight are stabilizer angle ($\delta_s$) in pitch trim, elevator angles ($\delta_e$) in pitch control, and rudder angles ($\delta_r$) in lateral-directional control; those deflected angles of flight control surfaces are similar to the angles of attack ($\alpha$) and sideslip angles ($\beta$) being the fast-varying variables; the angle of symmetrical ailerons can be zero or very small in cruise phase; wind speed ($V_w$, + for tail wind), dynamic pressure ($\bar{q}$), airspeed ($V$), Mach number ($M$), symmetrical ailerons ($\delta_a$), and flight altitude ($h$), belong to slow-varying influence variables.

In the present paper, the fast-varying influence variable is defined as the magnitude of the variable that can be quickly adjusted by the flight operation. The slow-varying influence variables are those that do not change too much within the chosen period for analysis.

The lift (L) and drag (D) based on the stability axes are always defined as the component of aerodynamic forces perpendicular and parallel to the relative wind, respectively. The lift and drag can be calculated based on $C_x$ and $C_z$ as follows

$$C_L = -C_z \cos\alpha + C_x \sin\alpha$$

$$C_D = -C_x \cos\alpha - C_z \sin\alpha$$

where $C_x$ and $C_z$ are the force coefficients along the $x$ and $z$-body axes of aircraft, which can be calculated through the axial and normal force coefficients of flight dynamic equations along the airplane body axes.

Then, the L/D can be obtained by the equation as follows:

$$L/D = C_L \bar{q} S / C_D \bar{q} S = C_L / C_D \quad (2)$$

The L/D model has the capability to generate continuous derivatives, which can be used to analyze the effects of influencing variables on L/D in flight. As an example, consider the derivative with $\alpha$. The derivative $(L/D)_\alpha$ is extracted from the model of L/D. It is evaluated with the central difference approach as follows:

$$(L/D)_1 = f_1(\alpha+\Delta\alpha, \beta, \delta_e, M, \delta_s, V, \delta_a, \delta_r, V_w, h, \bar{q})$$

$$(L/D)_2 = f_2(\alpha-\Delta\alpha, \beta, \delta_e, M, \delta_s, V, \delta_a, \delta_r, V_w, h, \bar{q})$$

$$(L/D)_\alpha = \frac{(L/D)_1 - (L/D)_2}{2\Delta\alpha} \quad (3)$$

where $\Delta\alpha$ =0.1 degree represents that $\alpha$ is perturbed by 0.1 degree while keeping all other variables unchanged. Usually, $\Delta\alpha$ may be larger depending on the variation of α in the model data. Similarly, all other L/D derivatives, such as the derivatives with elevator angle ($\delta_e$), aileron angle ($\delta_a$), or stabilizer angle ($\delta_s$), are calculated by using the same method.

## 2.2 Deficiency of Lift-to-Drag Ratio

For convenience of formulation, the influencing variables will be denoted by $x_1$, $x_2$, …, and so on. Assume that L/D predicted by the design model at the flight conditions $(\cdots, \beta, \alpha)$ is

$$(L/D)_{std} = f(x_1, x_2, \cdots)$$

where $f$ represents the standard model. The indicated L/D of a monitored flight is

$$(L/D)_{ind} = f(x_1+\Delta x_1, x_2+\Delta x_2, \cdots)$$

Therefore, the difference between the monitored flight and design model at the $i^{th}$ data point is

$$\Delta(\frac{L}{D})_i = (\frac{L}{D})_{ind} - (\frac{L}{D})_{std} = \Delta f \tag{4}$$

Eq. (4) in Taylor series expansion with only the linear terms becomes:

$$\Delta(\frac{L}{D})_i = \Delta f_0 + \frac{\partial f_i}{\partial x_1}\Delta x_1 + \frac{\partial f_i}{\partial x_2}\Delta x_2 + \frac{\partial f_i}{\partial x_3}\Delta x_3 + \ldots + \frac{\partial f_i}{\partial x_m}\Delta x_m \tag{5}$$

All the terms after $\Delta f_0$ on the right hand side of Eq. (5) are the individual contributions of influencing variables to the deficiency. $\Delta f_0$ represents all other factors, not in the model of L/D, contributing to the deficiency. The difference at the $i^{th}$ data point can be rewritten as:

$$\Delta(\frac{L}{D})_i = \Delta f_0 + \sum_{k=1}^{m}(\frac{\partial f_i}{\partial x_k}\Delta x_k) \tag{6}$$

where $m$ on the right hand side of Eq. (6) is the total number of influencing variables to affect L/D.

In ideal conditions, the left and right hand sides of Eq. (6) could be equal. However, because of the possible errors in data samplings and nonlinearity effect in Eq. (5), equality in Eq. (6) at every data point is revised by requiring that the sum of squared differences over all sample points is minimized:

$$\sum_{i=1}^{n}\left[(\Delta f_0 + \sum_{k=1}^{m}\frac{\partial f_i}{\partial x_k}\Delta x_k) - \Delta(\frac{L}{D})_i\right]^2 = \text{min.} \tag{7}$$

where $n$ is the number of samples and $m$= 11 in the present paper. Let $\Delta f_0 = (\partial f_i/\partial x_0)\Delta x_o$, with $\partial f_i/\partial x_0 = 1$. Then Eq. (7) becomes

$$\sum_{i=1}^{n}\left[\sum_{k=0}^{m}\frac{\partial f_i}{\partial x_k}\Delta x_k - \Delta(\frac{L}{D})_i\right]^2 = \text{min.} \tag{8}$$

To minimize the sum of the squared differences, the derivatives of Eq. (8) with respect to $\Delta x_j$ should be zero

$$\sum_{i=1}^{n}\frac{\partial\left[\sum_{k=0}^{m}\frac{\partial f_i}{\partial x_k}\Delta x_k - \Delta(\frac{L}{D})_i\right]^2}{\partial \Delta x_j} = 0, \text{ and}$$

$$2\sum_{i=1}^{n}\left[\sum_{k=0}^{m}\frac{\partial f_i}{\partial x_k}\Delta x_k - \Delta(\frac{L}{D})_i\right]\frac{\partial f_i}{\partial x_j} = 0, \; j=1,\ldots, m$$

It follows that

$$\sum_{i=1}^{n}\sum_{k=0}^{m}\frac{\partial f_i}{\partial x_j}\frac{\partial f_i}{\partial x_k}\Delta x_k = \sum_{i=1}^{n}\Delta(\frac{L}{D})_i\frac{\partial f_i}{\partial x_j}, \; j= 1,\ldots, m \tag{9}$$

In Eq. (9), one can form a matrix S such that

$$S_{jk} = \sum_{i=1}^{n}\frac{\partial f_i}{\partial x_j}\frac{\partial f_i}{\partial x_k} \tag{10}$$

Therefore, Eq. (9) is the matrix equation to be solved for $\Delta x_k$. It is found that the diagonal terms in Eq. (10) can be very different by one order of magnitude. The sensitivity derivatives for the 6 slow-varying variables are usually different in order of magnitude compared with the others. The solution process is divided into two parts: the first part consists of solving the whole equation, and the second part consists of two separate equations involving 6 slow-varying variables and 5 other variables (fast-varying variables). If the solutions for Mach number, symmetrical ailerons, and rudder deflections do not differ too much, the solution based on the full equations is used; otherwise, the solution based on the second part is chosen.

## 2.3 Exhaust Gas Temperature Model

In the standard model of **e**ngine performance, more complete necessary influencing flight variables can be included to capture all possible effects on EGT. The standard model of **e**ngine performance diagnosis is set to be of the form as follows:

$$EGT = f(h, M, TAT, CAS, EPR, N_1, N_2) \tag{11}$$

The variables on the right hand side of Eq. (11) denote the pressure altitude (*h*), flight Mach number (*M*), outside air temperature (*TAT*), calibrated airspeed (*CAS*), engine pressure ratio (EPR), rpm of low and high rotor speeds ($N_1$) and ($N_2$). In the present paper, the engines of this twin-jet passenger transport are Pratt & Whitney. Engine pressure ratio (EPR) is used to set the level of thrust for the Pratt & Whitney turbofan engines [8] by the engine manufactures.

The first four variables of Eq. (11) for all engines on the same aircraft in the same flight are the same; but the last three variables may differ. To avoid too much similar data being used in modelling to slow down the numerical convergence, typically the data are thinned by keeping one record in every two. This process can be repeated as many times as needed, in particular for the cruise flight where there are no significant changes in the flight parameters. Typically, small part of the climbing flight should be included to improve the ranges of variables.

When the preliminary standard model of engine performance is established, the model-based filtering will be carried out. The predicted EGT values of preliminary standard model are compared with the sensor values of the original input data. According to the reference [9], the deviations of EGT is defined as

$$\Delta(\text{EGT}) = \text{standard EGT} - \text{sensed EGT} \qquad (12)$$

where the standard EGT is the predicted EGT by standard model of **e**ngine performance and the sensed EGT is the reading value from post flight data.

In a study of turboshaft engines of a military helicopter, the accuracy of TGT (turbine gas temperature) sensing was assumed to be ±3 deg. C based on the manufacturer [9]. A more liberal value for transport's old engines is assumed in present study. The value of Δ(EGT) cannot be larger than 10 deg. C or less than -5 deg. C. in normal operation condition in the present study. If the values of Δ(EGT) are large at certain points, the reading of the sensors may be influenced by some unknown factors. The unknown biases and noise should be removed through "model-based filtering" during the model refining process. In order to avoid the important features in the signal being removed, firstly, the model structure is determined with all data included. The original data is replaced with the filtered data after $R^2$ remains unchanged and change in SSE is small ($<10^{-7}$), the original data is replaced with the filtered data. This process continues until the filtered data remains unchanged.

## 2.4 Evaluation Methodology of Engine Defects

The engine performance models can be used to do the required derivative analyses with respect to any input parameter. Once the resulting data has been predicted, correct judgment of engine health is essential. Certain kinds of engine failures or degradation would result in specific changes in the parameters being monitored. The following engine failure modes for judgments are sorted in order from reference [11] as follows:

#1. Failures due to air leakage from compressor cage will result in drop of EPR, and to regain EPR, fuel flow, EGT and $N_2$ would be increased.

#2. Compressor contamination from salt water and oil leaks will change the aerodynamic shape of airfoils and hence will increase EGT and $N_2$.

#3. Mechanical failures, involving a few blades or vanes, will increase $N_1$ and $N_2$ at a given power setting, and hence EGT is in high power setting.

#4. Failures in the combustion section, such as blocked fuel nozzles, fuel line leaks, burner, are difficult to detect, except when it is severe enough.

#5. Failures in high-pressure turbines, such as broken blades, seal erosion, etc. will cause the turbines to absorb less than the desired work and result in drop in $N_2$, increase in fuel flow and EGT at a given EPR. $N_1$ is relatively unchanged.

#6. Failures in low-pressure turbines will results in drop in $N_1$ and increase in EGT and fuel flow at a given EPR. $N_2$ is relatively unchanged.

#7. Vibration: broken turbine blades will result in a sudden change in vibration level; while a progressive change in vibration level indicates bearing malfunction.

#8. Instrumentation error: trend in only one parameter is indicated. Note that a malfunction affecting the gas path will cause trends in at least 2 parameters.

#9. Foreign-object damage (FOD): in case of extensive damage, it will be indicated by vibration and changes in the engine's normal operating parameters, such as a decrease in EPR and an increase in EGT.

## 3 Numerical Results and Discussions

### 3.1 Flight Data

In the present study, a twin-jet transport with two Pratt & Whitney turbofan engines are employed to examine the factors contributing to the degradation of L/D and EGT in operations. The service age of this transport aircraft is 14 years, 10 months and 14 days, which almost reaches the boundaries of service years for an aging aircraft. The datasets of this transport used for the modeling are flight data of a revenue flight.

The main aircraft geometric and inertial characteristics are taken to be:

$W$ (take-off) = 1,431,800 N (321,900 lb)

$S$ = 260 m$^2$ (2798.7 ft$^2$), $\bar{c}$ = 6.608 m (21.68 ft),

$b$= 44.827 m (147.08 ft)

$I_{xx}$ = 10,710,000 kg-m$^2$ (7,899,900 slugs-ft$^2$), $I_{yy}$ = 14,883,800 kg-m$^2$ (10,978,000 slugs-ft$^2$)

$I_{zz}$ = 25,283,271 kg-m$^2$ (18,648,470 slugs-ft$^2$),

$I_{xz}$ = 0.0 kg-m$^2$

The flight data of climb and cruise phases are used for L/D model and the excursion flight is taken within 0 to 1500 seconds after take-off for EGT model in modeling. The factors of fuel wastage are assessed in cruise flight condition around 10,058 m (33,000 ft). The required thrust of climbing flight is larger than that of other flight conditions; the abnormal engine health is diagnosed easily in this stage. The model-predicted L/D and EGT of transport aircraft are compared with flight data as shown in Fig. 1 and Fig. 2, respectively. The model-predicted L/D and EGT have acceptable agreement with the flight data.

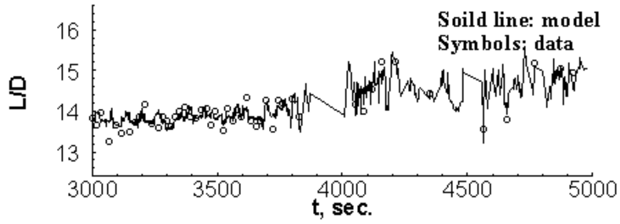


Fig. 1 Comparison of data in L/D with model prediction

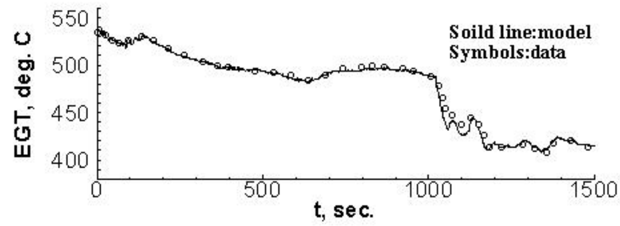


Fig. 2 Comparison of data in EGT with model prediction

### 3.2 Aircraft Performance Evaluation

Lift and drag are equivalent to weight and thrust, respectively, in cruise flight condition of a transport aircraft. To estimate drag and hence the thrust magnitude in cruise, the assumption of a design lift-to-drag ratio (*L/D*) of 17.5 is made [12]. This value of lift-to-drag in cruise is assumed based on the past design experience for twin-jet transports.

To determine how the influence variables affect L/D, the least-squared average through Eq. (9) is obtained. The deficiencies in operational L/D can be examined by the sensitivity analyses of model-predicted results to determine the relative contributions from influencing flight variables. The assessable factors of fuel wastage through the evaluations of L/D derivatives with slow-varying and fast-varying influence variables can be estimated. The results are listed in Table 1. $\Delta x_o$ = -2.637 in Table 1 is the first term in Eq. (5), represents contributions of all other factors not in the model of L/D to the deficiency.

The magnitudes of $\Delta\alpha$ is 0.143 deg in positive values in Table 1. It implies that decreasing $\alpha$ can improve L/D, at least in the cruise phase. The contribution of $\alpha$ to the L/D-deficiency is by a magnitude of about 0.143 deg. For $\delta_e$, the contribution is mostly negative and the contribution to the L/D-deficiency is by a magnitude of -0.081 deg. In other words, $\alpha$ should be more negative and $\delta_e$ should be more positive to improve L/D. The average value of L/D (i.e. $(L/D)_{average}$) in cruise is about 14.177 and the total deficiency (i.e. $D_x$) in L/D is 3.362. It implies that the design value of L/D can be achieved, if the contributing values of all 11 influencing variables to the L/D-deficiency are improved by a magnitude of about 3.362.

Table 1 Potential fuel saving amount after the deficiency of $x_k$ being improved

| Variable ($x_k$) | $\partial$ (L/D)/$\partial x_k$ | $\Delta x_k$ | $\Delta(L/D)x_k$ | Potential fuel saving (%) | Potential fuel saving amount (kg/h) |
|---|---|---|---|---|---|
| $x_o$ | --- | 2.637 | --- | 18.602 | 482.50 |
| $\alpha$ | 0.634 | 0.143 | 0.091 | 0.642 | 16.60 |
| $\beta$ | 0.275 | 0.493 | 0.135 | 0.955 | 24.77 |
| $\delta_e$ | 3.823 | -0.081 | -0.309 | 2.181 | 56.57 |
| $\delta_r$ | -0.021 | 0.006 | -0.001 | 0.001 | 0.023 |
| $\delta_s$ | -2.422 | 0.003 | -0.001 | 0.004 | 0.114 |
| $\delta_a$ | 0.058 | 0.119 | 0.007 | 0.049 | 1.261 |
| M | 149.318 | -0.001 | -0.037 | 0.263 | 6.825 |
| V | -0.087 | 5.523 | -0.481 | 3.392 | 87.99 |
| $V_W$ | -0.001 | -0.001 | 1.66 E-06 | 1.17 E-05 | 3.03 E-04 |
| h | -0.003 | -0.001 | 1.356E-07 | 9.565E-07 | 2.481E-05 |
| $\bar{q}$ | 0.535 | -0.203 | -0.109 | 0.766 | 19.87 |

The contribution values for potential fuel saving per each influencing variable can be estimated, if the contribution of variable $x_k$ to L/D is defined as

$$\Delta(L/D)x_k = \partial(L/D)/\partial x_k \times \Delta x_k \qquad (13)$$

where k= 1, m in Eq. (13), m=11 for the present study; $\partial(L/D)/\partial x_k$ is the average value in cruise phase of modeling points. All the values of $\Delta(L/D)x_k$ can be calculated through Eq. (13) and are also shown in Table 1.

To take an influencing variable as an example, the contribution of $\alpha$ to L/D can be expressed as:

$$\Delta(L/D)_\alpha = \partial\,(L/D)/\partial\alpha \times \Delta\alpha \qquad (14)$$

$\Delta(L/D)_\alpha$ = 0.091 in Table 1 represents that the incremental L/D after $\alpha$ deficiency is improved. Similarly, all other, $\Delta(L/D)_\beta$, $\Delta(L/D)_{\delta e}$, $\Delta(L/D)_{\delta a}$,…, etc. are defined by using the same concept.

In the flight manual of the transport aircraft [13], various weights, altitudes, Mach numbers, CAS, EPR, and fuel flow rates in cruise are tabulated. The fuel flow rate decreases from 2,689.39 kg/h (5,929 pph) to 2,601.85 kg/h (5,736 pph), while thrust decreases from the 39,372.47 N (8,857.1 lb) to 38,102.44 N (8,571.4 lb) at Mach 0.8 and flight altitude of 10,058 m (33,000 ft). The fuel flow rate decreases 3.23% as the thrust decreases by the same value. In other words, the drag decreases 1% as the fuel flow rate decreases by the same value. The percentage of $\Delta(L/D)$ can be calculated as:

$$\Delta(L/D)\% = \left(\frac{1}{(1-0.01)}\right)\% = \left(\frac{1}{0.99}\right)\% = 1.01\%$$

The fuel flow rate is about 2,595.04 kg/h (5,721 pph) at Mach 0.8 and flight altitude of 10,058 m in cruise condition. The fuel flow rate is decreased by about 26.2 kg/h (57.78 pph), if *L/D* is increased by 1.01%. The change in fuel flow rate can be estimated based on the relations of -26.2 kg/h (-57.78 pph), if $\Delta(L/D)\%$= 1.01% (i.e. increasing in *L/D* would decrease the fuel flow rate).

For the given values as an example, the fuel flow rate is decreased about 26.2 kg/h (57.78 pph), if L/D is increased 1.01% at Mach 0.8 and flight altitude of 10,058 m in cruise condition. The average value of L/D in cruise is about

14.177 for the present study. The potential fuel saving (%) of $x_o$ is equivalent to:

$\Delta x_o/14.177 = 2.637/14.177 = 18.6$ %, so as the potential fuel saving (%) of $\alpha$ is equivalent to:

$\Delta(L/D)_\alpha /14.177 = 0.091/14.177 = 0.64$ %

The fuel consumption for contribution can be calculated by:

Potential fuel saving (kg/h) of $\Delta x_o$ = $26.2 \left(\frac{18.6\%}{1.01\%}\right) = 482.50$, and

$$\Delta(L/D)_\alpha = 26.2 \left(\frac{0.64\%}{1.01\%}\right) = 16.60$$

The potential fuel saving of other variables can be obtained by the similar method. The potential fuel saving amount (kg/h) of all variables are shown in Table 1. Note that all values indicating contributions to excessive fuel consumption are positive.

### 3.3 Engine Performance Evaluation

Table 1 indicates that potential fuel saving % and amount after the deficiency of $x_o$, and all influencing variables in L/D model are improved. The largest value of potential fuel saving is $x_o$. In most cases, this would point to high fuel flow rates to the engines, or high required thrust. In other words, $x_o$ is the largest amount of excessive fuel consumption and the deficiencies of engine performance are required to have further study.

The excursion flight is taken within 0 to 1500 seconds after take-off for the establishment of EGT models. After the standard models of engine performance are established, it is then used to predict the EGT for two engines under the flight conditions without thinning.

The predicted engine performance is presented in Fig. 3. The comparative results in Figs. 3(a) and 3(b) show that $N_1$ and $N_2$ values of ENG#2 are slightly higher than those of ENG#1. The values of $N_1$ and $N_2$ are increased at a given power setting; the health condition of ENG#2 is similar to the engine failure mode #3 described in Section 2.4; but EGT is in normal condition. The excursion flight is taken within 0 to 1,500 seconds.

The time-averaged EGT excursion, integrating Δ(EGT) with time and then dividing by the total time, is the numerical values to represent the overall performance in the segment flight indicated in Fig. 2. The Averaged Δ(EGT) excursion of ENG#1 and ENG#2 are presented in Table 2. According to the definitions of normal operation condition in Section 2.3, the value of Δ(EGT) cannot be larger than 10 deg. C or less than -5 deg. C. It can be judged from Table 2 that ENG#1 and ENG#2 are in normal conditions. In Fig. 3(d), Δ(EGT) has a larger negative values after t=1,000 sec. The larger negative values of Δ(EGT) occur at the flying stage from climbing to the cruise conditions due to the $N_1$ and $N_2$ decrease in cruise flight. The required thrust of climbing flight is larger than that of other flight conditions; the abnormal engine health is diagnosed easily in this stage.

Table 2 Predicted time-averaged EGT excursion

| ENG | Averaged Δ(EGT) excursion, deg. C |
|---|---|
| #1 | 3.185 |
| #2 | -1.153 |

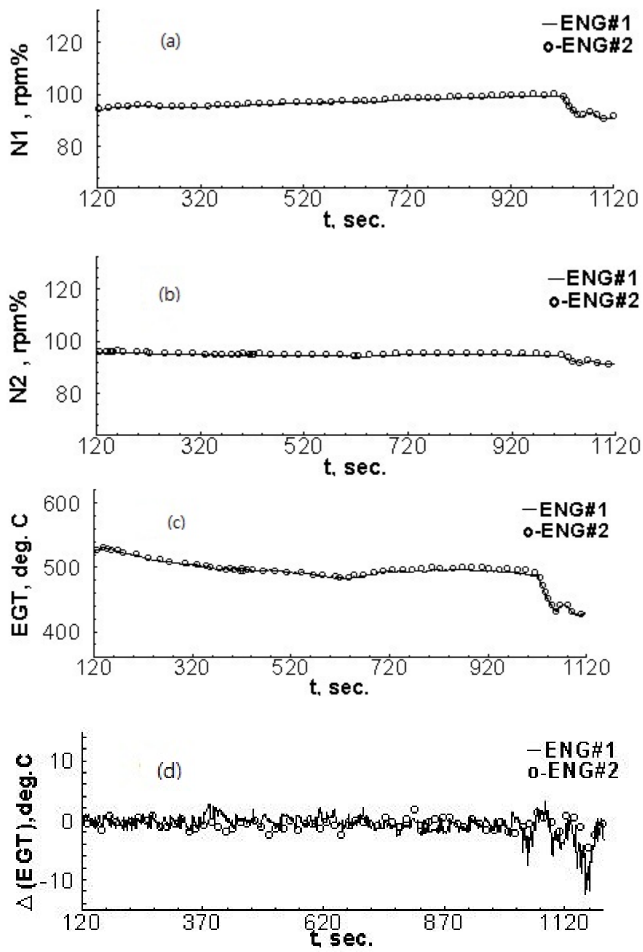


Fig. 3 Predicted engine performance of two engines

The relative efficiencies for compressors and turbines can be obtained through sensitivity derivatives [14] as follows:

$$\text{deriv1} = \frac{\partial(EGT)}{\partial(N_1)}\text{; deriv2} = \frac{\partial(EGT)}{\partial(N_2)} \qquad (15)$$

Fig. 4 shows the relative efficiencies of compressors and turbines. The values of relative efficiencies for these two engines are quite low and even some parts of relative efficiencies are in negative values. The sensitivity derivatives of EGT with respect to the operational variables indicate that the performance of these two engines has been declining due to aging. The amount of excessive fuel consumption of $x_0$ is 18.6% in table 1. If the relative efficiency of these two engines could be improved, the potential fuel saving would be a big amount.

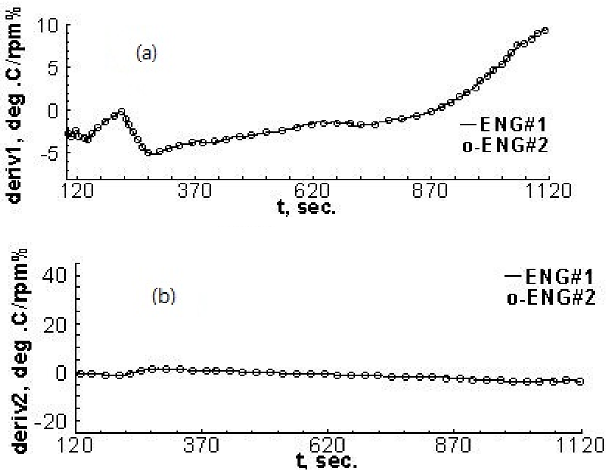


Fig. 4 Sensitivity derivatives of two engines

## 4 Concluding Remarks

The main objective in this paper was to detect the engine faults for the purpose to find the possible reasons of excessive fuel consumption. The standard models of L/D and EGT of a twin-jet passenger transport were established by using the techniques of FLM and model-based filtering. The predicted results of L/D model could produce not only L/D-deficiency, but also continuous derivatives for the assessment of operational controls and flight operations with the amount of excessive fuel consumption. The non-aerodynamic sources contributing to the L/D-deficiency ( i. e. $x_0$) was the largest amount of excessive fuel consumption in the present study case. The model-predicted results of EGT models could be examined for engine abnormality based on the previously established malfunction modes. Although the two engines did not have abnormal conditions, the relative efficiencies of compressors and turbines had been declining. If the relative efficiency of these two engines could be improved, the potential fuel saving would be significant.

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## Contact Author Email Address

Ray C. Chang.
E-mail address: raychang@cc.hc.cust.edu.tw

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