REAL-TIME WAVELET FLIGHT DATA EVALUATOR FOR SYSTEM IDENTIFICATION OF FLIGHT CHARACTERISTICS

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Abstract

Performance of system identification of aircraft flight characteristics quite depends on flight data to be analyzed. In order to make the system identification more useful and reliable, a real-time flight data evaluator which determines appropriate parts of data is proposed. The proposed method is characterized by multi resolution analysis (MRA), a kind of wavelet transform, and validates flight in both time and frequency domains. Results to apply the proposed methods to both simulated and real flight data show that the proposed method has adequate capability to extract desirable parts from flight data.

1 Introduction

Flight tests are important tasks to develop new aircraft. This is because design, production and operation steps are seamlessly connected with the flight tests. Especially, system identification which estimates flight characteristics with flight data obtained by the tests is requisite. The estimated flight characteristics are used for comparisons with wind tunnel test results. If a critical difference is revealed in these comparisons, aircraft must be corrected until the difference is reasonable. Moreover, handling quality checks [1] requested for airworthiness certification, and making a flight simulator for pilot training are also performed with the system identification results.

In addition to the essential roles of the system identification mentioned above, its another usage to improve flight safety is considerable. The system identification generates mathematical models which are composed of parameters to describe flight characteristics. This means whenever the system identification is performed in flight, flight characteristics are monitored quantitatively in real-time. Therefore, sudden changes of the parameters derived from an accident can be captured by the system identification, and will be utilized for pilot or autopilot system to recover from critical situations.

However, the system identification is not applicable easily, because accuracy of its results mostly depends on flight conditions. For example, if there is strong gust, parameters estimated by the system identification will be quite different from wind tunnel test results. Maneuvering is also an important factor to obtain probable results, because the system identification requires adequate excitation of motion in terms of magnitude and frequency. Furthermore, appropriate parts in which the required flight conditions are satisfied have been selected manually, and there is no intelligent method to extract these parts from flight data automatically.

In order to make the system identification more useful and reliable, an intelligent flight data evaluator, which automatically determines whether flight data can be used for the system identification, is required. In addition, if the evaluator works concurrently with flight, we can extend applications of the system identification, such as the flight characteristics monitoring.

Therefore, a real-time flight data evaluator using wavelet transform is proposed.

This paper consists of five sections. Section 2 provides general information of the system identification of aircraft flight characteristics, and defines appropriate flight which is suitable for the system identification. In Sec. 3, the proposed method characterized by wavelet transform is explained and preliminary tests of the proposed method are referred. Then, experimental results obtained by applying the proposed method to real flight data are described and effectiveness of the proposed method is discussed in Sec. 4. Finally, this study is concluded in Sec. 5.

2 Appropriate Flight for System Identification

In this section, general procedures of the system identification of flight characteristics are introduced. Through this introduction, requirements for flight data to perform the identification effectively are summarized. The typical appropriate flight satisfying the requirements is also explained.

2.1 Aircraft System Identification

Although pilot comments are used for acquisition of qualitative flight characteristics, the system identification is mostly utilized for estimation of quantitative ones. In other words, the system identification of flight characteristics is almost equivalent to parameter estimation. This is because the quantitative characteristics are frequently indicated by parameters of a predefined model, for example, coefficients of transfer functions, gains and phase shifts of frequency responses, and stability derivatives consisting of a equation of motion. Each predefined model reflects knowledge of flight dynamics of aircraft, and most of them are depicted with a certain base state and deflections from the base state.

For later explanation, an example predefined model will be referred. The following equation

$$\frac{d}{dt}\begin{bmatrix} u \\ \alpha \\ q \\ \theta \end{bmatrix} = \begin{bmatrix} X_u & X_\alpha & -U_0\alpha_0 & -g\cos\theta_0 \\ \frac{Z_u}{U_0} & \frac{Z_\alpha}{U_0} & \frac{U_0+Z_q}{U_0} & -\frac{g\sin\theta_0}{U_0} \\ M_u & M_\alpha & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ \alpha \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 0 & X_{\delta_t} \\ \frac{Z_{\delta_e}}{U_0} & \frac{Z_{\delta_t}}{U_0} \\ M_{\delta_e} & M_{\delta_t} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_t \end{bmatrix} \tag{1}$$

is the well-known linearized perturbation equation of longitudinal motion of fixed wing aircraft [4], where symbols X, Z, M are longitudinal stability derivatives to be estimated. u, α, q, θ are state values, that is, wind speed deflection, angle of attack, pitch rate, and pitch angle deflection, respectively. δ_e, δ_t are inputs, that is, deflections of elevator and thrust maneuvering. t is time, and g is gravity. U_0, θ_0 are wind speed and pitch angle of a trimmed state.

2.2 Appropriate Flight

Appropriate flight data, which contains sufficient information to make estimation of parameters reliable and accurate as possible, must cover flight envelop assumed in the predefined model. Especially, to acquire the certain base state accurately assumed in the predefined model like shown in U_0 and θ_0 of Eq. (1) is important. For easiness of realization of the basic state in flight, the basic state is frequently chosen from trimmed states, in which no maneuvering is required to maintain flight. This is based on a fact that most of aircraft are designed to have both statical and dynamical stability, that is, aircraft will be recovered to a trimmed state if disturbance such as gust is occurred. If a target aircraft originally has negative stability like fighters, this approach can be still available, because a total system will be stable by using a suitable feedback controller. In addition to the trimmed states, to obtain behavior when inputs are added is also essential. In other words, intentional maneuvering which invokes both instantaneous and transient response adequately is required.

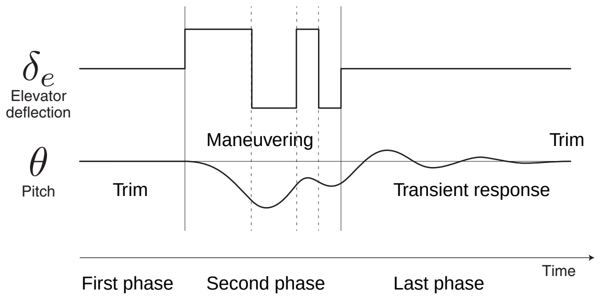


Fig. 1 Concept of appropriate flight for the system identification of flight characteristics

To follow the above mentions, the appropriate flight, with which the system identification estimates flight characteristics accurately, consists of the following three phases like shown in Fig. 1. The first phase is to maintain a trimmed state adequately, that is, significant inputs and state values will not be changed as much as possible among this phase.

In the first phase of Fig. 1, stationary elevator and pitch angle, which are essential inputs and state values of longitudinal motion, respectively, are indicated. Then, in the second phase, suitable maneuvering is performed to excite sufficient motion in terms of magnitude and frequency. As an example, a 3-2-1-1 multi-pulse elevator control pattern recommended by Marchand [5] is depicted in Fig. 1. The pitch angle shown in Fig. 1 is also changed along with the maneuvering. The last phase is returning to the trimmed state through transient responses by stopping the maneuvering and then keeping control inputs at the same positions of the first phase. The last phase of the example shown in Fig. 1 indicates that while the elevator deflection is zero, the pitch angle is still changed.

For automatic flight data evaluation, the above qualitative conditions must be represented quantitatively. Especially, how small changes of the significant state values in the first phase are permitted must be carefully arranged. This is because the second and last phases are evaluated with the deflections from the first phase, which is assumed to be adequately trimmed. Furthermore, to evaluate flight in real-time, it is preferable that required computational power is small. The proposed method explained in the next section considers these problems.

3 Method

The proposed method, which determines the appropriate flight for the system identification, is characterized by MRA, an implementation of wavelet transform. In this section, fundamental information of wavelet transform and MRA will be provided, and then, the proposed method is explained.

3.1 Wavelet Transform and MRA

Generally, wavelet transform decomposes a time variant function $f(t)$ into time-frequency information $\mathfrak{W}(a,b)$ in the following equation:

$$\mathfrak{W}(a,b) \equiv \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{a}} \psi^* \left(\frac{t-b}{a} \right) dt, \quad (2)$$

where t is time, and a and b are called scale and shift parameters, which correspond to frequency band and time, respectively. ψ^* is a mother wavelet function, which is well arranged to express localized oscillation. Equation (2) means that the transform is performed by measuring correlation between the function and a template generated by the mother wavelet function. This implies square of a wavelet transform value $\mathfrak{W}(a,b)^2$ corresponds to signal strength at certain frequency band and time.

In this study, MRA is utilized. MRA is a specialized version of wavelet transform, and converts discrete time series data such as flight data into time-frequency information. Figure 2 shows a linear up-chirp signal, in which frequency increases with time, and its MRA results. The results show that frequency bands in which signal is strong go higher with time, and indicate that MRA is a powerful tool to analyze vibration of discrete data in terms of both time and frequency.

Another MRA suitability for this study is its efficiency of the transform. Figure 3 is a conceptual timing chart showing when MRA transform results are available. The higher frequency band

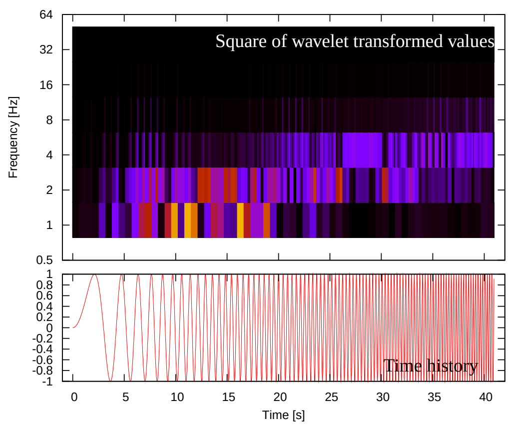


Fig. 2 Time history of a linear chirp signal (bottom) and its MRA results (top). The MRA results are shown with square of transformed values correlated to signal strength.

information of the MRA results is updated more frequently than the lower frequency band. This is quite different from short-time Fourier transform (SFT). SFT is another sophisticated tool to calculate time-frequency information, however, its transform results are obtained after all target data are processed regardless of frequency bands. Moreover, MRA requires $O(N)$ arithmetical operations while SFT with the lowest computational implementation using fast Fourier transform (FFT) is $O(N \log N)$, where N is number of target data samples. Therefore, MRA is superior to SFT for the real-time evaluation of this study in terms of both data instantaneousness and computational cost.

It is noted that choice of the mother wavelet function is still important when MRA is utilized. Including the chirp example shown in Fig. 2, this study utilizes Daubeches wavelet [2].

3.2 Proposed Method

The proposed method analyzes vibration of flight with signal strength obtained by MRA, and determines whether the requirements of the appropriate flight described in Sec. 2.2 are satisfied. In the following, the separation rules of the method are summarized based on the three phases shown in Fig. 1.

The appropriate flight in the first phase, in which the adequate trim flight is supposed, is represented with wavelet transform values as:

$$\sum_{a \in a^*_{z_x}} \mathfrak{W}(a, b_1)^2 [z_x] < \Delta_{\mathrm{trim}, z_x} \tag{3}$$

$$\sum_{a \in a^*_{z_u}} \mathfrak{W}(a, b_1)^2 [z_u] < \Delta_{\mathrm{trim}, z_u}\,, \tag{4}$$

where z_x and z_u are observed values correlated with state values x and inputs u, respectively. There are two parameters Δ and a^*, which should be configured appropriately. a^* is certain frequency bands in which measurement noise is comparatively weak, namely, aircraft motion and maneuvering are sufficiently observable. Δ represents a threshold to determine whether data is not changed and almost settled.

The requirements in the second phase are described in the following equations:

$$\sum_{a \in a^*_{z_x}} \mathfrak{W}(a, b_2)^2 [z_x] \propto \sum_{a \in a^*_{z_u}} \mathfrak{W}(a, b_2)^2 [z_u] \tag{5}$$

$$\sum_{a \in a^*_{z_u}} \mathfrak{W}(a, b_2)^2 [z_u] > \Delta_{\mathrm{trim}, z_u}\,. \tag{6}$$

These two equations mean that strong correlation between aircraft motion and maneuvering is assumed, and maneuvering is intentionally strong enough.

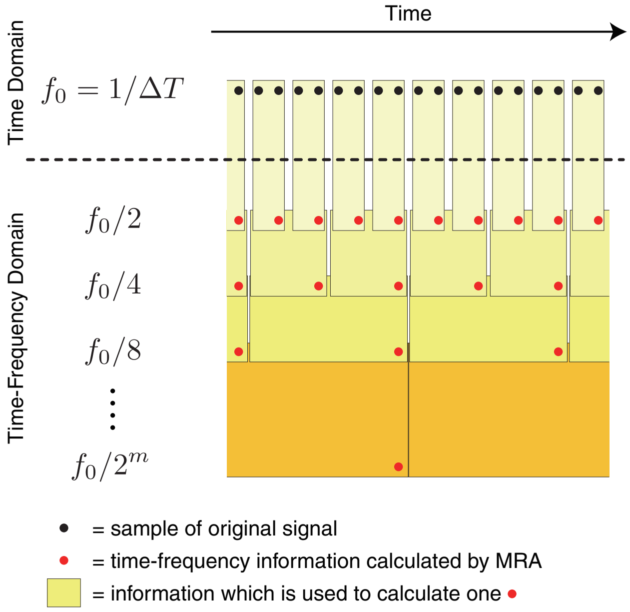


Fig. 3 Conceptual timing chart chart of MRA calculation

The last phase satisfies

$$\sum_{a \in a^*_{z_x}} \mathfrak{W}(a,b)^2 [z_x] < \Delta_{\mathrm{trim},z_x} \quad as \quad b \to b_3 \quad (7)$$

$$\sum_{a \in a^*_{z_u}} \mathfrak{W}(a,b_3)^2 [z_u] < \Delta_{\mathrm{trim},z_u} , \quad (8)$$

where observed values of state values z_x are gradually converged to the initial trimmed state, while observed values of inputs z_u are stationary.

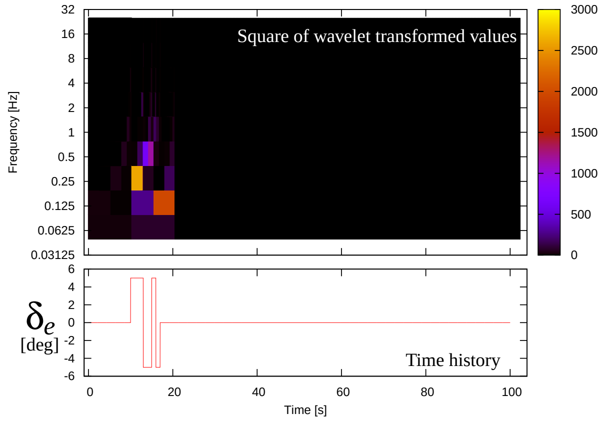
3.3 Preliminary Tests

The proposed method is preliminary examined with simulation data generated with the longitudinal equation of motion represented by Eq. (1). As the stability derivatives of Eq. 1, those of P2V-7 variable flight characteristic research aircraft [3] are used. In the simulation, elevator inputs are trimmed, then 3-2-1-1 from the trimmed position, and finally trimmed, while thrust is always fixed at its trimmed value.

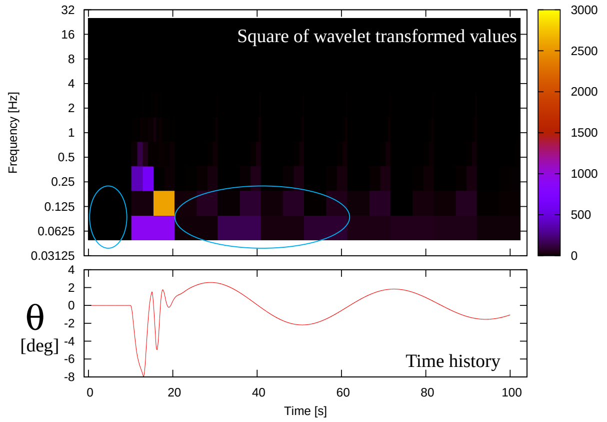
Figure 4 shows an appropriate flight approved by the proposed method. The elevator deflection δ_e and pitch angle θ time histories are represented, and their signal strength obtained by MRA are also indicated by color, same as the chirp example shown in Fig. 2. Figure 5 depicts another pitch angle θ time histories, where strong disturbance which must be avoided for the appropriate flight is introduced besides the same elevator deflection as Fig. 4. In the green circled areas in Fig. 5, the signal strength is weaker than those of their corresponding parts of the appropriate flight, which are surrounded by the cyan circles in Fig. 4. These differences can be used for the rules of Eqs. (3)-(8). Therefore, the preliminary tests reveal that the proposed method has basic capability to evaluate flight.

4 Application to real flight data

The proposed method is evaluated with application to real flight data. The analyzed flight data is so massive that the proposed method adequately demonstrates its convenience. In this section, the method and results of this evaluation are explained.



(a) Elevator deflection



(b) Pitch angle

Fig. 4 Elevator deflection and pitch angle of appropriate flight data

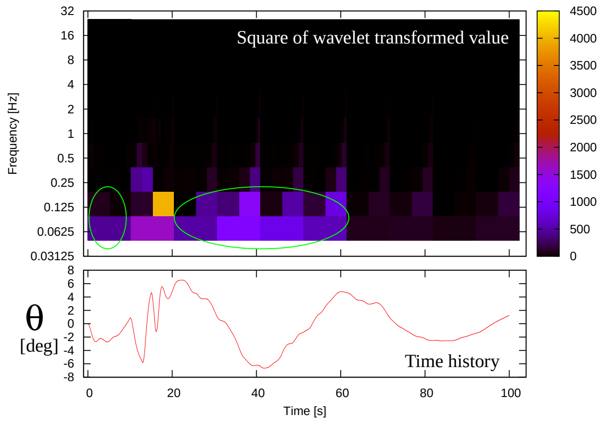


Fig. 5 Pitch angle of not appropriate flight data

4.1 Evaluation Method

The real flight data to which the proposed method is applied is obtained by experimental aircraft MuPAL-α [6] developed by Japan Aerospace Exploration Agency (JAXA). MuPAL-α is modified by adding various measurement devices and fly-by-wire control mechanism to fixed-wing turboprop aircraft Dornier Do228-202. A model of the flight characteristics of MuPAL-α has been already established accurately by using results of wind tunnel and flight tests. For the evaluation, its 271 hours data of 173 flights from year 2000 to 2011 is used. By applying the proposed method, its trim flight is extracted by using Eqs. (3)-(4). Comparing state values in the extracted trim flight with the known characteristics, the proposed method is evaluated.

The flight data obtained with MuPAL-α consists of state values and inputs such as angle of attack, wind speed, pitch angle, pitch rate, and elevator angle. The data is sampled at 50 Hz, that is, the time interval of the discretized data is 0.02 seconds. a^* of Eqs. (3)-(4) is fixed with frequency bands ranging from 10 Hz to approximate 0.05 Hz, which equals to the inverse number of time interval of 1024 samples. The reason why a^* is not ranged from 50 Hz of the sampling rate is to suppress the measurement noise. Table 1 lists thresholds with which the trimmed states are determined by the proposed method. These thresholds are configured based on manual extractions of the trim flight beforehand with this evaluation.

4.2 Results and Discussions

The proposed method determines 12013 cases of 69.6 hours as the trimmed states, and some significant results of the extracted trim will be described. Figures 6-7 show relations between true airspeed and angle of attack, and relations between horizontal stabilizer angle and angle of attack, respectively. These relations are sorted by flap positions and color coded in the figures. Calculated relations by using the established flight characteristics model are also depicted with the lines. The extracted and calculated relations at the trimmed states are well agreed. This means that the proposed method has capability to extract the preferable flight even in the case of real flight.

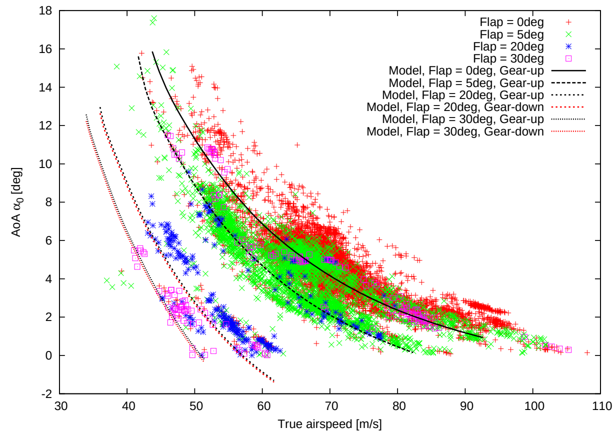


Fig. 6 True airspeed and angle of attack at the trimmed states of real flight and model

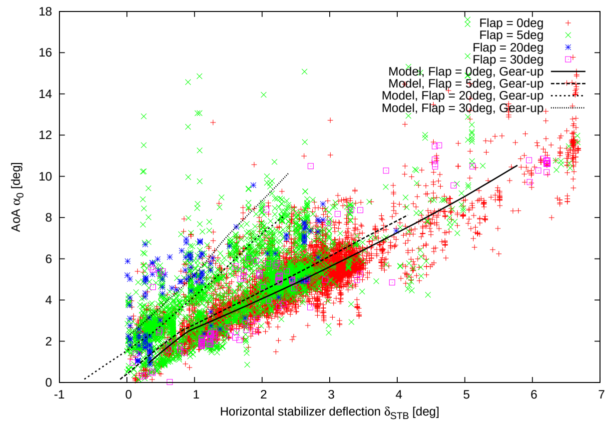


Fig. 7 Horizontal stabilizer angle and angle of attack at the trimmed states of real flight and model

The agreements between the extracted and calculated relations will be improved with further consideration of flight condition differences. Figures 8-9 show the relations corresponding to Fig. 6 with the calculated results under different flight altitude and aircraft weight, respectively. These figures indicate that different flight conditions result in different trimmed states. Therefore, it is important to configure the parameters of the proposed method represented by Table 1 in order to extract the desired parts from flight more accurately.

Table 1 Thresholds for determination of the trimmed states

Item	Symbol	Threshold(Δ_{trim})
True airspeed	U_{TAS}	1×10^5 kt^2
Angle of attack	α	1×10^3 deg^2
Side slip angle	β	1×10^3 deg^2/s^2
Roll rate	p	5×10^2 deg^2/s^2
Pitch rate	q	5×10^2 deg^2/s^2
Heading rate	r	5×10^2 deg^2/s^2
Climb rate	$\frac{dh}{dt}$	5×10^7 ft^2/min^2
Elevator angle	δ_e	1×10^3 deg^2
Aileron angle	δ_a	1×10^3 deg^2
Rudder angle	δ_r	5×10^2 deg^2
Horizontal stabilizer angle	δ_{STB}	1×10^2 deg^2
Left engine power lever angle	$\delta_{\mathrm{PL-L}}$	1×10^3 deg^2
Right engine power lever angle	$\delta_{\mathrm{PL-R}}$	1×10^3 deg^2
Left engine speed lever angle	$\delta_{\mathrm{PS-L}}$	1×10^3 deg^2
Right engine speed lever angle	$\delta_{\mathrm{PS-R}}$	1×10^3 deg^2

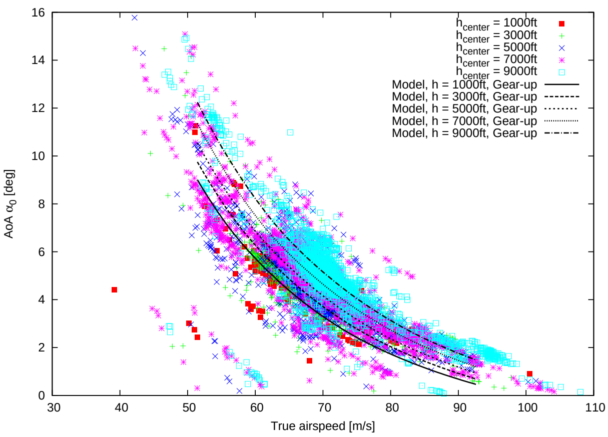


Fig. 8 True airspeed and angle of attack at the trimmed states of real flight and model under 0 degree flap position and different altitude

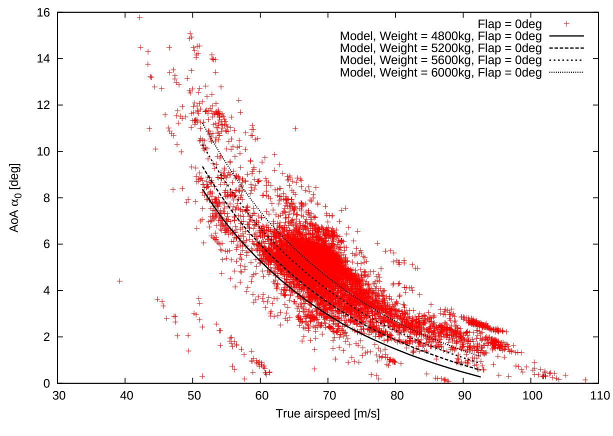


Fig. 9 True airspeed and angle of attack at the trimmed states of real flight and model under 0 degree flap position and different weight

5 Conclusion

In this study, the new real-tine flight data evaluator which determines the appropriate parts for the system identification of aircraft flight characteristics was proposed. The proposed method utilizes MRA, which is an advantageous implementations of wavelet transform in terms of computational cost and instantaneousness, to calculate values corresponding to signal strength in time-frequency domain. By comparisons with the carefully arranged thresholds and the calculated values, the trim, intentional maneuvering, and transient response phases are promptly extracted in flight as the appropriate parts for the system identification. The preliminary tests with simulated flight data indicated that the MRA calculated values were different between the desirable and undesirable cases, and the concept of the proposed method was reasonable. Furthermore, the proposed method was applicable to the real flight data. This was demonstrated by the proposed method extracting the trim flight from the massive real flight data. Therefore, it was concluded that the proposed method effectively evaluated flight and could extract the appropriate flight for the system identification of aircraft flight characteristics.

Copyright Statement

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