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Influence Analysis of Input Signal Forms on the Accuracy of Aerodynamic Parameter Identification in Aircraft Longitudinal Motion

Moung Htang Om, Kyaw Zin Latt

Moscow Aviation Institute
Volokolamskoe Highway, 4, Moscow, Russia, 125993

e-mail: mounghtangom50@gmail.com

Abstract. This article deals with the problem of aircraft aerodynamic parameter identification using the flight test data. The influence of forms of input signals on the accuracy of identification is analyzed. All the signals involved into the process of parameter identification are subjects to measurement noises, that is normally distributed random variables with zero means and constant standard deviations. The results, which show the accuracy of parameter identification depending on the forms of input signals are presented.

Key words: system identification, input/output signals, measurement, aerodynamic parameters, measurement noise, accuracy.

1. Introduction

The main purpose of system identification is to build mathematical models of dynamic systems based on measurements of input and output signals. These models can be used for studying the system responses for different inputs, for example, improving the system behavior by adding a control system. For many applications, an aircraft can also be assumed as a rigid body, whose motion is governed by the laws of Newtonian physics. Thus, system identification can be applied to characterize forces and moments which are acting on the aircraft and which arise from aerodynamics and propulsion. Generally, estimates for aerodynamic and thrust forces and moments are obtained from ground tests. Naturally, the errors are present due to the fact that perfect imitation of flight conditions may not be achieved on the ground. That is why the aircraft parameter identification is highly desirable because it is based on flight test data and enables to obtain functional dependence of aerodynamic forces and moments on aircraft motion and control variables as they are in actual flight. The aircraft system identification applications are numerous. Identification of the aerodynamic parameters is essential in flight tests [1] and in simulation for the purposes of dynamics of flight [2–4]. Aerodynamic parameter identification is also used for estimating the systematic errors of aircraft on-board measurement systems [5–7]. The basic approaches to aircraft parameter identification are presented in [8–10], some additional aspects are discussed in [11–13].

The aircraft parameter identification results are influenced by some factors. This paper focuses on input signals formed by the pilots' control since the inputs affect considerably the accuracy of identification [1, 8–10]. Another source of the problems is the measurement noise. In this research for simulation of the measurement noises, normally distributed discrete random variables with zero mean and constant standard deviations are used.

Parameter identification is applied to deal with both linear and non-linear model equations. In this paper the aircraft motion linear model is formulated and also various types of pilot controlled inputs. Since the model is linear and a straightforward optimization procedure — Least Square Method (LSM) is applied to estimate the parameters.

2. Classification of the input signals

Since various types of input signals (φ_t) are formed by the pilot according to various conditions, there are many types of input signals. In this work, only three types of input signals (φ_t) loaded in the elevator module of the airplane model are presented, and they are dipole square wave, multipolar square wave, and frequency sweep. The frequency sweep is regarded as a sum of two sine waves with different frequencies. All types of signals are simulated in many different processing times. In this work the three different processing times (12s, 24s and 48s) in different period of waves have been considered. The input signals (φ_t) in processing time 12s generated by the pilot action, are shown in Fig. 2.1, 2.2, 2.3.

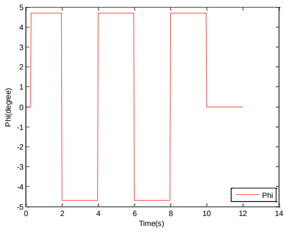


Figure 2.1. Dipole square wave in 12 seconds

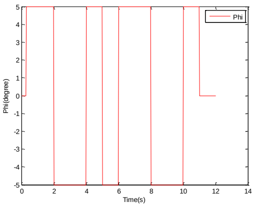


Figure 2.2. Multipolar square wave in 12 seconds

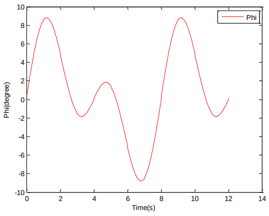


Figure 2.3. Frequency sweep in 12 seconds

For simulation and identification these three forms of input signals are formed into 8 different forms of signals according to the period of wave and frequencies in this works and those signals are listed in table 2.1, 2.2 and 2.3.

In dipole square wave, forming input signals due to the period of wave is done uniformly since the period is uniform.

Table 2.1. Forms of input signals according to the period of dipole square wave and processing time

Signal	**Type of Signal**	**Period** (*s*)	**Processing Time** (*s*)
1st	Dipole square wave	2 / 3 / 6	12 / 24 /48
2nd	Dipole square wave	4 / 6 / 12	12 / 24 /48
3rd	Dipole square wave	6 / 12 / 24	12 / 24 /48

Table 2.2. Forms of input signals according to the period of multipolar square wave and processing time

Signal	**Type of Signal**	**Period 1** (*s*)	**Period** 2 (*s*)	**Processing Time**(*s*)
4th	Multipolar square wave	2 / 3 / 6	1 / 1.5 / 3	12 / 24 /48
5th	Multipolar square wave	4 / 6 / 12	2 / 3 / 6	12 / 24 /48
6th	Multipolar square wave	6 /12 / 24	3 / 6 / 12	12 / 24 /48

In multipolar square wave, forming input signals due to the period of wave is done by a pair of two different periods.

Table 2.3. Forms of input signals according to the frequency value of frequency sweep and processing time

Signal	**Type of Signal**	**Frequencies** (*Hz*)	**Processing Time**
7th	Frequency sweep	0.25; 0.125	12 / 24 /48
8th	Frequency sweep	0.125; 0.65	12 / 24 /48

3. Simulation of the aircraft motion in longitudinal canal

According to the procedure of the system identification, after collecting all the input data, the simulation of the aircraft motion must be performed [7]. For the formation of object model, the angle of attack and angular velocity of pitch of the aircraft in discrete form are used. Since it is more comfortable to do the identification in discrete form, and then the mathematical formulas in discrete form for the angle of attack (1) and angular velocity of pitch (2) are written as follow

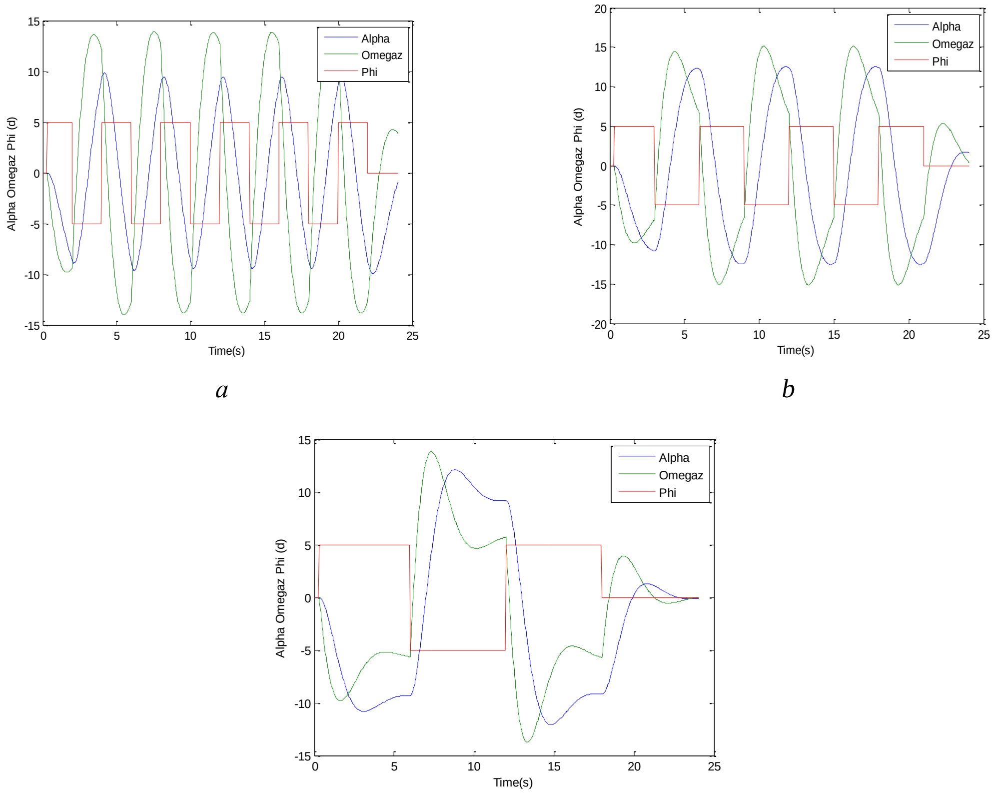
$$\alpha(t_{i+1}) = \alpha(t_i) + \Delta t[-Y^{\alpha}\alpha(t_i) + \omega_z(t_i) - \varphi(t_i)], \tag{1}$$

$$\omega_z(t_{i+1}) = \omega_z(t_i) + \Delta t[M_z^{\alpha}\alpha(t_i) + M_z^{\omega_z}\omega_z(t_i) - M_z^{\varphi}\varphi(t_i)], \tag{2}$$

where, $\alpha(t_{i+1})$ — angle of attack for time instant $(t_{(i+1)})$ (radian), $\omega_z(t_{i+1})$ — angular velocity of pitch for time instant $(t_{(i+1)})$ (radian/s), $\alpha(t_i)$ — angle of attack for time instant (t_i), $\omega_z(t_i)$ — angular velocity of pitch for time instant (t_i), $\Delta t = t_{i+1} - t_i$ — time discretization interval, $Y^{\alpha}, Y^{\varphi}, M_z^{\alpha}, M_z^{\omega_z}, M_z^{\varphi}$ — aerodynamic parameters to be identified.

For simulation, it is assumed that the registration frequency (f-registration) is 32 Hz. This registration frequency (f-registration) also influences the process of estimation and the accuracy of the estimated parameters. Therefore, the time sampling interval is $\Delta t = 1/32\text{s}$.

Firstly, all types of input signals (φ_t) in this work, angles of attack (1) respective to each of input signals, and the angular velocities of pitch (2) respective to each of input signals are simulated without noises, and those simulated signals without measurement noises are shown in Fig. 2.1, 2.2, 2.3.

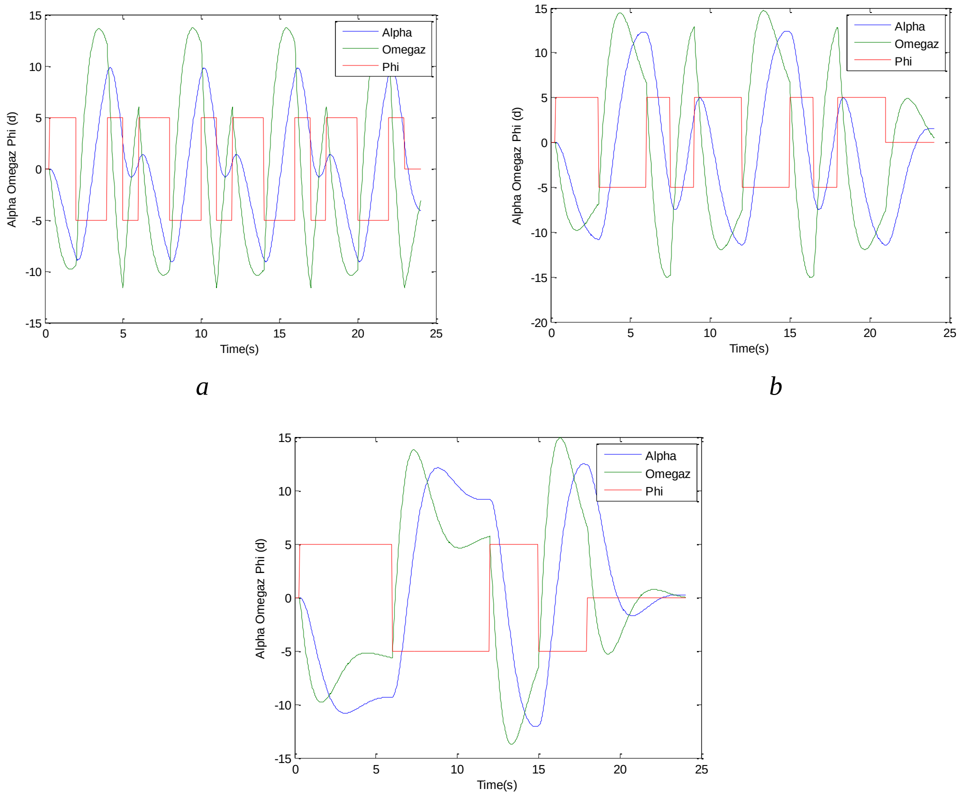


a

b

c

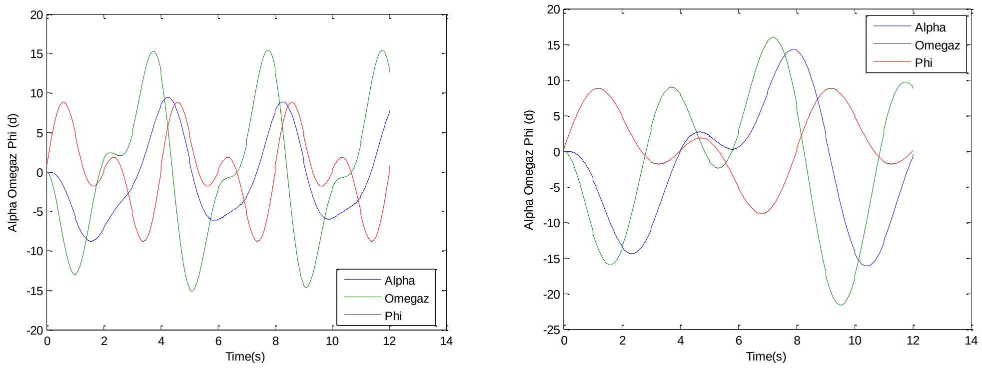
Figure 2.1. Simulation of the signals without any noises with dipole square wave for three different periods for processing time (24 s): a) 1st signal;b) 2nd signal; c) 3rd signal



a　*b*

c

Figure 2.2. Simulation of the signals without any noises with multipolar square wave for three different periods for processing time (24 s): a) 4th signal; b) 5th signal; c) 6th signal

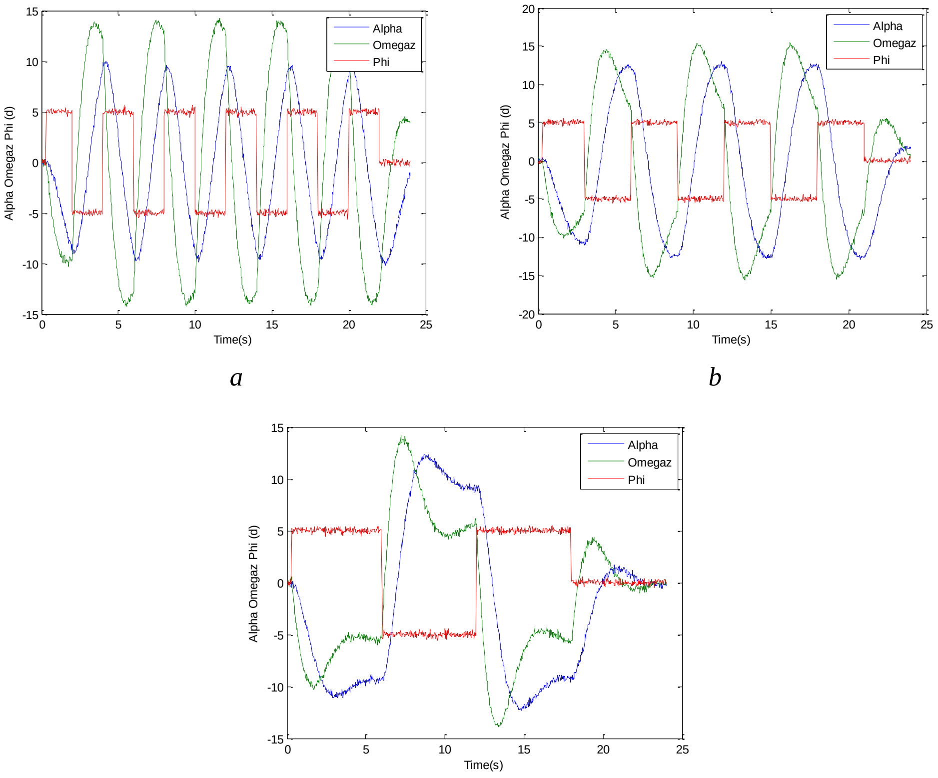


(a)7th signal　*(b) 8th signal*

Figure 2.3. Simulation of the signals without any noises with frequency sweep for two different frequencies for processing time (24 s): a)7th signal; b) 8th signal

4. Measurement of input, output signals with noises

After simulation process, measurement for all input and output signals are performed. In measurement process, the input signals-angle attack (1) and angular velocity of pitch (2) corresponding to each of input signals with measurement noises is performed. The normally distributed random variables are used as the measurement noises. In this work, zero mean and the constant standard deviation is used as the measurement noise. The standard deviation is equal 0.2 degrees for angles and 0.2 degrees/s for angular velocity in this work. The measured input signals-angle of attack and angular velocity of pitch respective to the types of input signals with measurement noises are shown in Fig. 4.1, 4.2, 4.3.

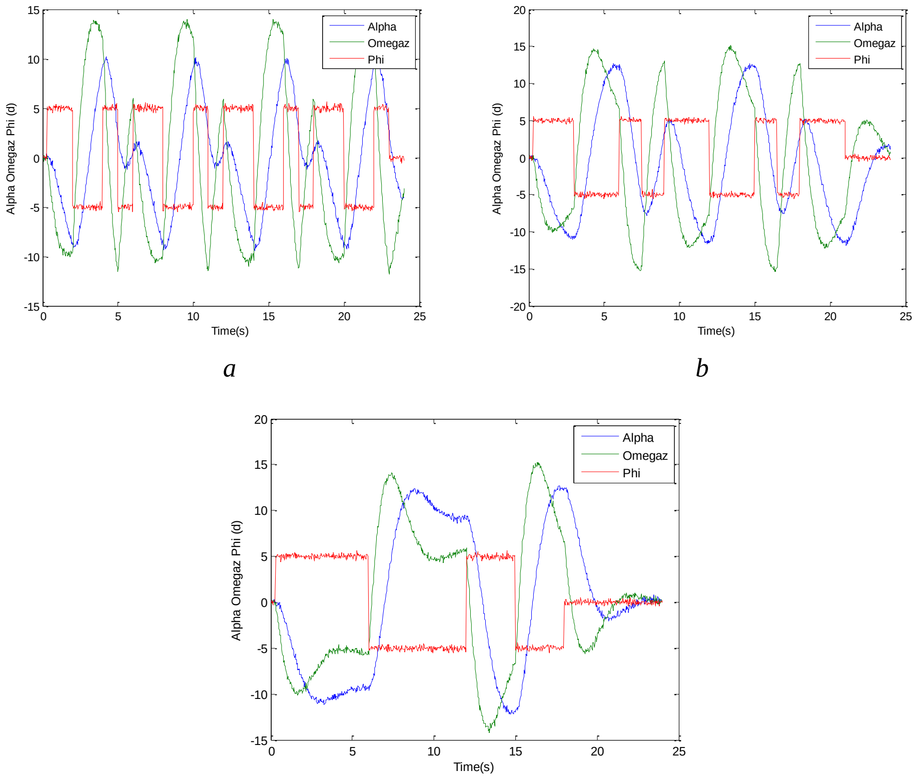


a

b

c

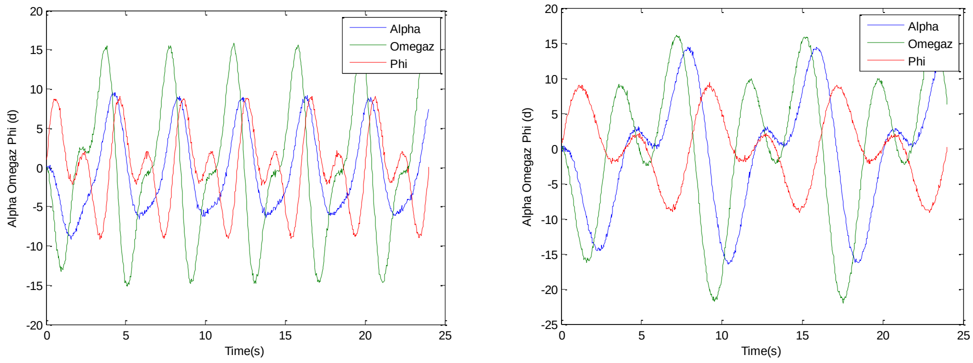
Figure 4.1. Measurement of the signals with dipole square wave for three different periods for processing time 24 s (with measurement noises): a)1st signal; b) 2nd signal; c) 3rd signal



a *b*

c

Figure 4.2. Measurement of the signals with multipolar square wave for three different periods for processing time 24 s (with measurement noises): a) 4th signal; b) 5th signal; c) 6th signal



a *b*

Figure 4.3. Measurement of the signals with frequency sweep for two different frequencies for processing time 24 s (with measurement noises): a) 7th signal; b) 8th signal

5. Identification of aerodynamic parameters

Once an aircraft model is selected, simulated and calculated, what remains is its identification, which is essentially an optimization problem. A typical identification criterion typically has a form of minimization of a function of the prediction errors. The function is usually based on a distance metric. For example, least squares methods minimize the Euclidean distance between the predicted and observed values (squared 2-norm of the prediction errors) [13]. Other factors such as quality of parameter estimates, number of parameters can be factored into the objective function. In order to carry out the identification of the aerodynamic parameter, the least square method (LSM) (5.1) is used. This least square method (LSM) is more effective for the linear systems.

$$\hat{a} = \left(X^T X\right)^{-1} \times X^T \times Y, \tag{5.1}$$

where, $\hat{a}$ — estimates of the parameters, X — matrix for object model, Y — matrix for output signal.

For the identification of parameters, it is necessary to form the object model. Let us consider every equation of the object model separately.

In general form for an arbitrary instant t_i it may be expressed as follows;

$$Y(t_i) = a_0 + a_1 x_1(t_i) + a_2 x_2(t_i) + a_3 x_3(t_i), \quad i = \overline{1, n},$$

where, a_0, a_1, a_2, a_3 — parameters to be identified; N – number of samples.

The object model for identification can be used as a matrix X and a vector Y:

$$X = \begin{bmatrix} 1 & x_{1t_{(1)}} & x_{2t_{(1)}} & x_{3t_{(1)}} \\ 1 & x_{1t_{(2)}} & x_{2t_{(2)}} & x_{3t_{(2)}} \\ & \cdots & \cdots & \cdots \\ 1 & x_{1t_{(N)}} & x_{2t_{(N)}} & x_{3t_{(N)}} \end{bmatrix}, \tag{5.2}$$

$$Y = \begin{bmatrix} Y(t_1) \\ Y(t_2) \\ \cdots \\ Y(t_N) \end{bmatrix}, \tag{5.3}$$

where, X — matrix for object model; Y — vector for output signal.

In order to form the matrix X for the first equation for identifying aerodynamic force coefficients, the input signals (φ_t), angle of attack (1), and angular velocity of pitch (2) are used. For the formation of output matrix Y (5.3), it is better to use the overload, which may be expressed as follow;

$$n_y(t_i) = \left[\frac{V}{g}\left(Y^{\alpha}\alpha(t_i) + Y^{\varphi}\varphi(t_i)\right)\right] + \varepsilon(t_i), \tag{5.4}$$

where, $n_y(t_i)$ — overload with specific noise for time instant (t_i); V — airspeed (m s^{-1}); g — gravitational acceleration (m s^{-2}); $\varepsilon(t_i)$ — normally distributed random error.

For the purposes of identification it is better to present the second equation (for identifying aerodynamic moments) in the form;

$$\frac{d\omega(t_i)}{dt} = M_z^{\alpha}\,\alpha(t_i) + M_z^{\omega_z}\,\omega_z(t_i) - M_z^{\varphi}\varphi(t_i)\,. \tag{5.5}$$

In this case, the matrix X remains same as in the first equation, and the output vector Y consists of the estimates for angular velocity time derivative

$$\frac{d\omega(t_i)}{dt} = \frac{\omega(t_{i+1}) - \omega(t_{i-1})}{2\Delta t}.$$

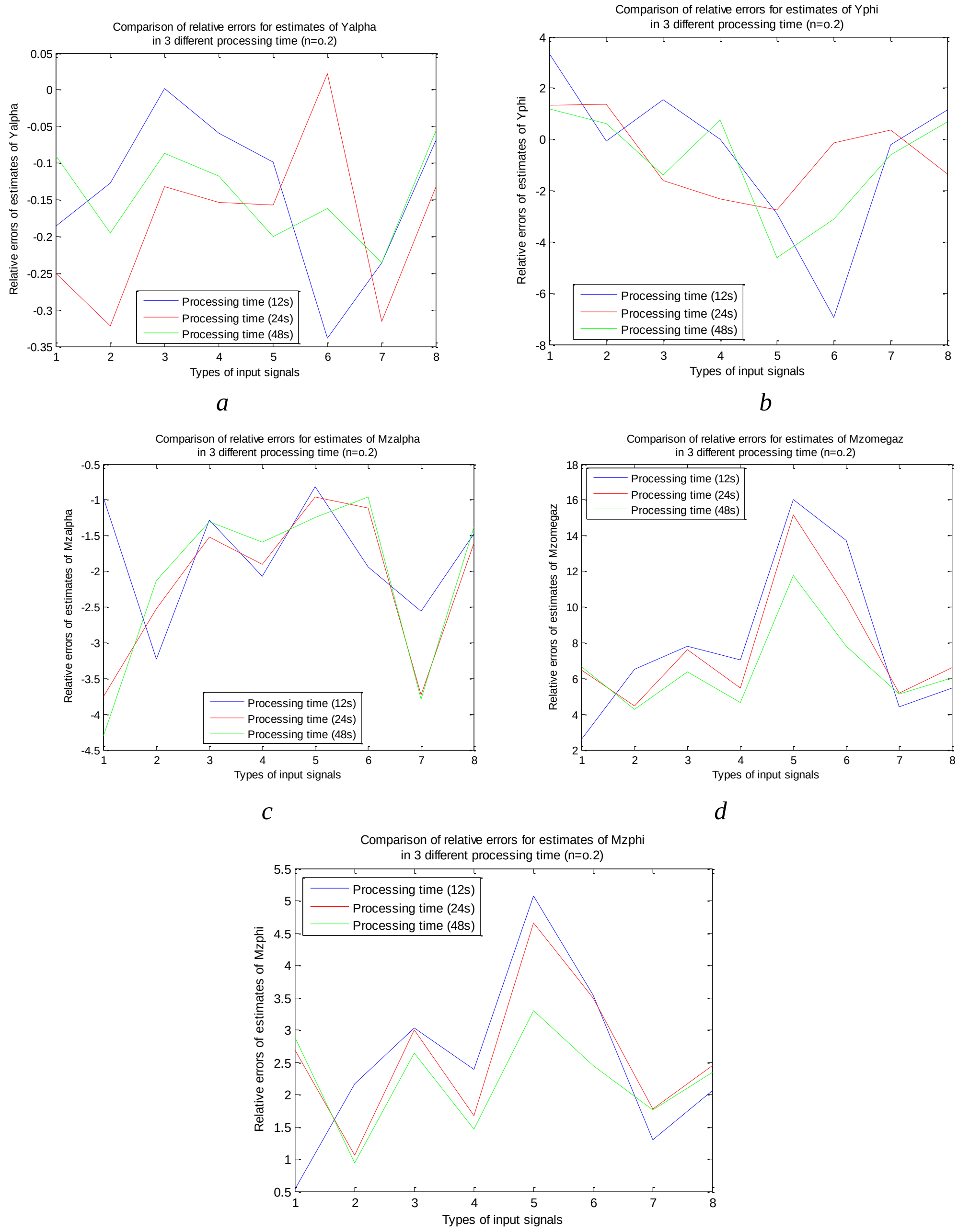
In order to investigate statistically the accuracy of the parameter identification and the influence of measurement noises, the simulation data and the processing of this data by least square method (LSM) must be performed repeatedly. All the signals involved are distorted with simulation noises, which are normally distributed random variables. In this work, the experiments are carried out for 8 different types of the input signals formed by the pilot control with the measurement noise. For every type of input signals, aerodynamic parameters were estimated by the LSM estimator.

It should be explained that a widely known formula [4.1] associated with the matrix $(X^T X)^{-1}$ for the LSM estimates errors dispersion, is valid in the case of output measurements noises only. In this work, we assume that all the signals used for identification, are affected by measurements errors. For this reason we apply the statistical simulation in order to investigate the accuracy of the estimated parameters.

6. Analysis of relative errors of the estimated parameters

After the process of identification, we generally assume that some exact or true value exists based on how we define what is being estimated. While we may never know this true value exactly, we attempt to find this ideal quantity to the best of our ability with the time and resources available.

In this step, the relative errors of the estimated aerodynamic parameters are determined based on different types of input signals. It is obvious, that the standard deviation of the measurement noise, that is normally distributed random errors, can influence the accuracy of the estimated parameters and the accuracy of identification also very much depends on the type of input signal. The relative errors of the estimated parameters are shown in Fig. 6.1.



a *b*

c *d*

e

Figure 6.1. Relative errors of the estimated parameters for 8 types of input signal

In the results graphs, $n = 0.2$ stands for the standard deviation of the normally distributed random variable and is measured in degrees for angles and degrees/s for angular velocity. The numbers 12, 24 and 48 refer to the processing time in which the parameter identification was performed. And the types of input signal have been mentioned above. The relative errors of the estimated parameters show, naturally, that the longer the processing time, the better the accuracy is. Also it shows that, in dipole square waves the broader the period the better the accuracy of estimation is. Besides, the frequency sweep can assure high accuracy of estimation for all parameters, compatible with the best of dipole square waves. The significant increase of relative errors was detected only for multipolar square waves. The most probable reason is the use of rectangular form with «sharp» angles, which are distorted easily by the discretization. In multipolar signal these «corners» are more numerous than in dipole square waves. For the same reason among dipole square waves the broader periods provide better results.

7. Conclusion and discussion

For input signals, dipole square wave and frequency sweep, the parameter identification method can assure the better accuracy rather than the multipolar square waves. Thus it can be said that peaks and corners of every input signal can affect the accuracy of parameter identification and it is needed to use the smoothen forms of input signals. The accuracy of the identification also depends on the length of processing time and the period of the input signal. The longer the processing time, the better the accuracy is. And it must also be noted that the measurement noise also affects the accuracy of the parameter identification.

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Анализ влияния форм входных сигналов на точность идентификации аэродинамических параметров в продольном движении самолета

Моунг Хтанг Ом, Чжо Зин Латт

Московский авиационный институт
(Национальный исследовательский университет)
125993, Москва, Волоколамское шоссе, 4

e-mail: mounghtangom50@gmail.com

Аннотация. Статья посвящена проблеме идентификации аэродинамических параметров самолета по данным летных экспериментов. Исследовано влияние форм входных сигналов на точность идентификации. Все сигналы, используемые в процессе идентификации параметров, содержат шумы измерений, аппроксимируемые нормально распределенными случайными величинами с нулевым средним и постоянной дисперсией. Представлены результаты, показывающие точность идентификации параметров в зависимости от форм входных сигналов.

Ключевые слова: идентификация систем, входные и выходные сигналы, измерение, аэродинамические параметры, шум измерения, точность.

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Авторы:

Моунг Хтанг Ом — аспирант кафедры проектирования самолетов, Московский авиационный институт (Национальный исследовательский университет)

Чжо Зин Латт — аспирант кафедры проектирования самолетов Московского авиационного института (Национального исследовательского университета)