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Investigation of lateral-directional aerodynamic parameters identification method for fly-by-wire passenger airliners

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Identification;
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Abstract A new identification method is proposed to solve the problem of the influence on the loaded excitation signals brought by high feedback gain augmentation in lateral-directional aerodynamic parameters identification of fly-by-wire (FBW) passenger airliners. Taking for example an FBW passenger airliner model with directional relaxed-static-stability, through analysis of its signal energy distribution and airframe frequency response, a new method is proposed for signal type selection, signal parameters design, and the appropriate frequency relationship between the aileron and rudder excitation signals. A simulation validation is presented of the FBW passenger airliner's lateral-directional aerodynamic parameters identification. The validation result demonstrates that the designed signal can excite the lateral-directional motion mode of the FBW passenger airliner adequately and persistently. Meanwhile, the relative errors of aerodynamic parameters are less than 5%.

1. Introduction

Aerodynamic parameter identification is to obtain an airframe's aerodynamic parameters from flight test data, based on the principle of dynamic system identification. This technology is widely used in flight dynamic model modification, flight envelope expansion, flight simulator development, flight control law design, and so on.[1,2] Currently, research in China in this field mostly focuses on airplanes with an open-loop control system or a simple closed-loop control system,[2] lacking large-scale fly-by-wire (FBW) passenger airliners with a complex system and a high feedback gain augmentation. As a safety precaution, the flight control system cannot be turned off actively during flight tests. So the aerodynamic parameters identification for this category of airplanes is a problem of closed-loop identification. For this issue, there are two conventional solutions.[3–6] One approach is to identify the flight control parameters and the airframe's aerodynamic parameters in two steps, which is the so-called closed-loop identification method. The other one is to identify the airframe's aerodynamic parameters only by using the airplane's flight status data and control surface deflections directly, which is the open-loop identification method. Since the former approach requires

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more rigorous information on the flight control system and flight data, it is hardly adopted, and the latter one is more frequently applied in aircraft engineering.

The precision of aerodynamic parameter identification is dependent on not only the identification model and parameter estimation method, but more importantly also on the excitation signal in the identification test. To a large FBW passenger airliner, for one thing the high feedback gain augmentation changes the loaded excitation signal, causing the airliner's control surfaces to deflect differently from anticipation and suppressing the excitation of the airliner's motion mode.[7–9] For another thing, the lateral control and the directional control are crossed to eliminate the sideslip angle when coordinating a turn, which increases the relevancy between rudder deflection and aileron deflection and finally creates difficulties in aerodynamic parameter identification.

With regard to the FBW passenger airliner model with directional relaxed-static-stability,[10–12] comparing the different influences on excitation signals brought by the simple closed-loop control system and the complex closed-loop control system, this paper emphasizes the excitation signal design for lateral-directional aerodynamic parameter identification, proposes a new method of signal type selection and signal parameter design, and suggests a signal relationship between the aileron signal and the rudder signal. The validation of the lateral-directional parameter identification for a FBW passenger airliner is performed, which can be applied in engineering.

2. Problem analysis and investigation method

2.1. Problem analysis

The flight control system of an FBW passenger airliner cannot be turned off during flight tests for aerodynamic parameter identification. Therefore, the externally loaded excitation signal is continually influenced by the feedback signal generated by the high feedback gain augmentation.

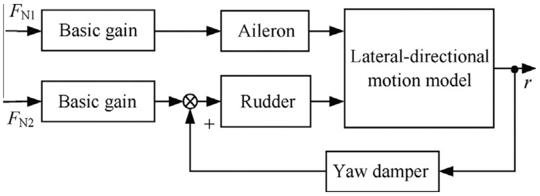


Fig. 1 Simple closed-loop control framework.

Compared with a simple closed-loop controlled airliner, an FBW passenger airliner has a crossed flight control framework and high feedback gain. Fig. 1 shows the simple control framework with a yaw damper. The normal lateral-directional flight control framework of an FBW passenger airliner is presented in Fig. 2. In the figures, r is the yaw rate, p is the roll rate, ϕ is the roll angle, β is the sideslip angle, F_{N1} and F_{N2} are control stick force and pedal force, respectively.

The difference between these two categories of flight control systems will cause different changes of a loaded signal, and finally result in different deflections of the airliner's control surface.

The signal 3211, which is commonly used as the excitation signal in airliner aerodynamic parameters identification, is loaded onto both of the two airliner's aileron modules. The comparison of deflection signals and originally loaded signal is presented in Fig. 3. In the figure, A is the amplitude of the signal, T is the time.

The comparison results in Fig. 3 demonstrate that: (A) for the simple closed-loop controlled airliner, the excitation signal loaded is less influenced by the flight control system and therefore the aileron deflection signal is almost the same as the excitation signal, the rudder deflects slightly due to the yaw damper only; (B) for the FBW airliner, the flight control system affects the excitation signal greatly, and the change of the aileron signal is significant, the rudder deflects obviously as a result of the yaw damper and the aileron's interference.

Consequently, in the excitation signal design for an FBW passenger airliner, the influence on excitation signal by the high feedback gain augmentation and the impact between the aileron and rudder should be considered to guarantee that the actual deflection excites the airliner's lateral-directional motion adequately.

2.2. Investigation method

For the research object of an FBW passenger airliner which is preliminarily established based on the wind tunnel test data, the simulation result of this model (see Fig. 2) is used as the virtual flight data, whose functions are the following: (A) as the input data in lateral-directional aerodynamic parameters identification; (B) as the reference flight data in validation,

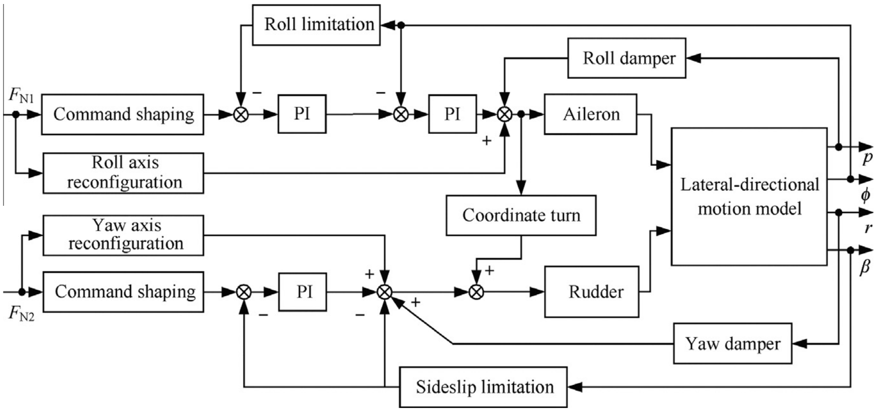
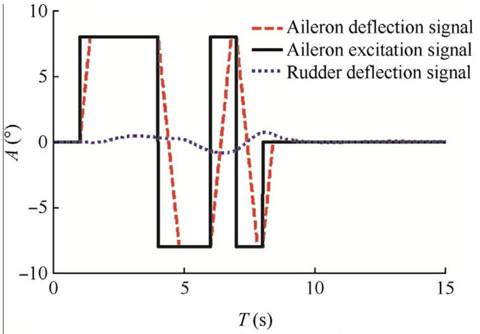
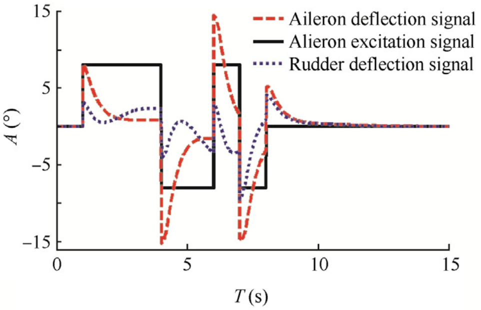


Fig. 2 Normal lateral-directional flight control framework of an FBW passenger airliner.



(a) Simple closed-loop control airliner



(b) FBW passenger airliner

Fig. 3 Comparison of deflection signals and originally loaded signals.

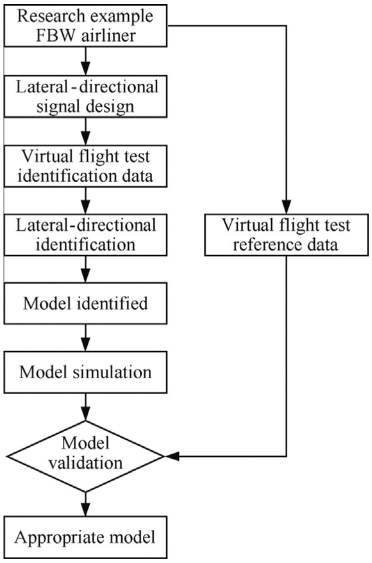


Fig. 4 The investigation scheme.

which is to be compared with the simulation of the identified model. The investigation in this paper is illustrated in Fig. 4.

3. Identification model and method

According to the fundamental principle of an airliner's aerodynamic parameters identification[13] presented in Fig. 5, the four techniques—identification model, parameter estimation method, excitation signal, and model validation are confirmed.

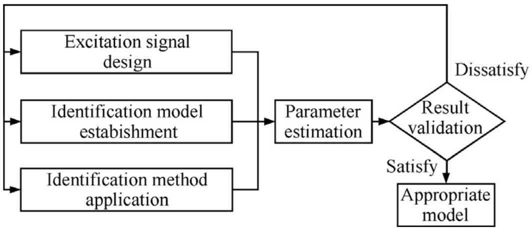


Fig. 5 Fundamental principle of airliner's aerodynamic parameters identification.

3.1. Identification model

Since a passenger airliner usually flies in a small angle of attack, the linear identification model is adopted as follows[14]:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{Ax} + \boldsymbol{Bu} \\ \boldsymbol{y} &= \boldsymbol{Cx} + \boldsymbol{Du} \end{aligned} \tag{1}$$

Given that the velocity of an airliner hardly varies and the sideslip angle is small, then the relationship is,

$$\Delta\dot{\beta} \approx \dot{V}_{y\mathrm{b}}/V \approx a_{y\mathrm{b}}/V \tag{2}$$

where $a_{y\mathrm{b}}$ is the airplane acceleration along the Y axis of the fuselage coordinate system, and $V_{y\mathrm{b}}$ is the airplane velocity along the Y axis of the fuselage coordinate system.

Therefore Eq. (1) can be rewritten as:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \tilde{\boldsymbol{A}}\boldsymbol{x} + \tilde{\boldsymbol{B}}\boldsymbol{u} \\ \boldsymbol{y} &= \tilde{\boldsymbol{C}}\boldsymbol{x} + \tilde{\boldsymbol{D}}\boldsymbol{u} \end{aligned} \tag{3}$$

where the control input, status and observation are:

$$\begin{cases} \boldsymbol{u} = [\Delta\delta_\mathrm{a}\ \Delta\delta_\mathrm{r}]^\mathrm{T} \\ \boldsymbol{x} = [\Delta\beta\ \Delta p\ \Delta r\ \Delta\phi]^\mathrm{T} \\ \boldsymbol{y} = [a_{y\mathrm{b}}\ \Delta p\ \Delta r]^\mathrm{T} \end{cases} \tag{4}$$

and matrices $\tilde{\boldsymbol{A}}$, $\tilde{\boldsymbol{B}}$, $\tilde{\boldsymbol{C}}$, and $\tilde{\boldsymbol{D}}$ are:

$$\begin{cases} \tilde{\boldsymbol{A}} = \begin{bmatrix} \overline{Y}_\beta & \alpha_0 + \overline{Y}_p & \overline{Y}_r - 1 & g\cdot\cos\theta_0/V_0 \\ \overline{L}_\beta & \overline{L}_p & \overline{L}_r & 0 \\ \overline{N}_\beta & \overline{N}_p & \overline{N}_r & 0 \end{bmatrix} \\ \tilde{\boldsymbol{B}} = \begin{bmatrix} 0 & \overline{Y}_{\delta_\mathrm{r}} \\ \overline{L}_{\delta_\mathrm{a}} & \overline{L}_{\delta_\mathrm{r}} \\ \overline{N}_{\delta_\mathrm{a}} & \overline{N}_{\delta_\mathrm{r}} \end{bmatrix} \\ \tilde{\boldsymbol{C}} = \begin{bmatrix} V_0\cdot\overline{Y}_\beta & V_0\cdot(\alpha_0 + \overline{Y}_p) & V_0\cdot(\overline{Y}_r - 1) & g\cdot\cos\theta_0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \\ \tilde{\boldsymbol{D}} = \begin{bmatrix} 0 & V_0\cdot\overline{Y}_{\delta_\mathrm{r}} \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \end{cases} \tag{5}$$

where V_0, θ_0 and α_0 are the fiducial flight velocity, pitch angle and attack angle respectively; δ_a and δ_r are respectively, the deflection of the aileron and the rudder; $\overline{Y}_i$, $\overline{L}_i$, $\overline{N}_i$ ($i = \beta, p, r, \delta_\mathrm{a}, \delta_\mathrm{r}$) are the model parameters to be identified.

3.2. Identification method

The least square estimation principle is proposed to estimate the identification model parameters. The main idea of the least square principle is to search the values of those parameters which determine the lateral-directional flight observation closest to the measured flight data in terms of squared difference for a given excitation signal. The arithmetic of generic least square is applied to accomplish the parameter estimation in the least square principle.[15]

The identification model can be described by:

$$z = \boldsymbol{H}\boldsymbol{\theta} + \boldsymbol{v} \tag{6}$$

where $\boldsymbol{z}$, $\boldsymbol{H}$, $\boldsymbol{\theta}$ and $\boldsymbol{v}$ are respectively the observation parameter, observation matrix, parameter to be estimated and observation noise. To get the least square value $\hat{\boldsymbol{\theta}}_{\text{LS}}$, the value of the following principle function should be minimum:

$$J = \boldsymbol{v}^{\text{T}}\boldsymbol{v} = (\boldsymbol{z} - \boldsymbol{H}\boldsymbol{\theta})^{\text{T}}(\boldsymbol{z} - \boldsymbol{H}\boldsymbol{\theta}) \tag{7}$$

The expression of $\hat{\boldsymbol{\theta}}_{\text{LS}}$ can be solved by,

$$\hat{\boldsymbol{\theta}}_{\text{LS}} = (\boldsymbol{H}^{\text{T}}\boldsymbol{H})^{-1}\boldsymbol{H}^{\text{T}}\boldsymbol{z} \tag{8}$$

4. Excitation signal design

An excitation signal's function is to drive an airliner's control surfaces as expected, which will enable the pertinent airplane motion response to appear and ultimately ensure the lateral-directional motion characteristic be fully reflected in the flight data. Consequently, the chief principle of the lateral-directional excitation signal design is to ensure that the deflection signal, which is influenced by the high feedback gain augmentation, can adequately and persistently excite the lateral-directional motion mode in the concerned frequency range.

Typically, a pilot cannot manually produce maneuvers that satisfy the requirement of identification. In some flight tests,[16–18] a signal generation device is installed on airliners, which is controlled by a pilot or a remote ground computer.

Since the elevator is the sole longitudinal main control surface, it is only necessary to design its excitation signal in longitudinal aerodynamic identification.[19] In contrast, there are two main lateral-directional control surfaces, which control the airliner's lateral-directional motion jointly. Consequently, the relationship between the aileron and rudder signals has to be considered in lateral-directional identification. From the above, the lateral-directional excitation signal design comprises signal type selection, parameter design and consideration of the relationship between these two signals.

Currently, square wave, dipole square wave, 3211 multipolar square wave, sine wave, and frequency sweep[20] are studied most. Due to the unitary deflection of square wave and single frequency of sine wave, they are relatively less suitable for excitation signals.

In the selection of signal type, considering the different influences on the loaded signal by the high feedback gain augmentation, the type of signal which is minimally impacted is fit to excite the airliner's lateral-directional motion mode, and this can be found through spectral analysis of the signal before and after the change. Simultaneously, the loaded signal should persistently excite the airliner's lateral-directional motion and decrease the oscillatory suppression of the flight control system, which will drastically reduce the information contents required for estimating the parameters.

In the design of signal parameters, the preliminary airplane lateral-directional dynamic linear state equation should be established first through known data. Secondly, the relevant frequency ranges of the aileron and rudder signals can be found respectively, through frequency response analysis of the side force, roll, and yaw motion equations.[9] Thirdly, the signal parameters can be designed using the fast Fourier transform technique, with the precondition of the relevant frequency range being satisfied.

With regard to the relationship between the aileron and rudder excitation signals, both of these two control surfaces are used synchronously to excite the lateral-directional motion modes adequately. Through loading different groups of excitation signals, simulation and calculation, the impact of the relationship between aileron and rudder excitation signals on the identification results is discussed.

As described above, the design procedure of excitation signals is presented in Fig. 6.

4.1. Selection of signal type

As mentioned before, the three types of signals loaded in the rudder module of the research airliner are dipole square wave, 3211 multipolar square wave, and frequency sweep. The shape variations of the three signal types in the time domain are presented in Fig. 7, demonstrating: (A) the 3211 multipolar square wave and the dipole square wave of the rudder channel change their signal shapes distinctly, while the frequency sweep changes less, with its amplitude decreasing and frequency varying little; (B) though there is no excitation signal loaded in the aileron channel, the aileron is also deflected obviously due to the roll damper.

The spectral analysis of the original signals loaded as excitation signals, and final signals influenced by the high feedback gain augmentation can be obtained through fast Fourier transform, presenting the signal energy distribution variation in the frequency domain, see Fig. 8, in the figure, ω is the signal frequency, and $|F|$ is the power spectrum of the signal.

Fig. 8 shows that (A) due to the bandwidth limit of a flight control system, the power spectrums of the three final signals

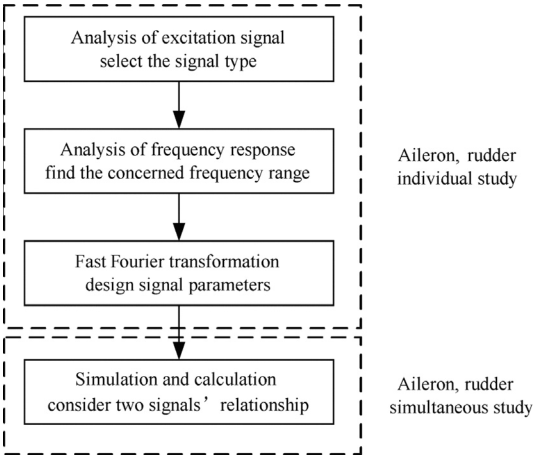
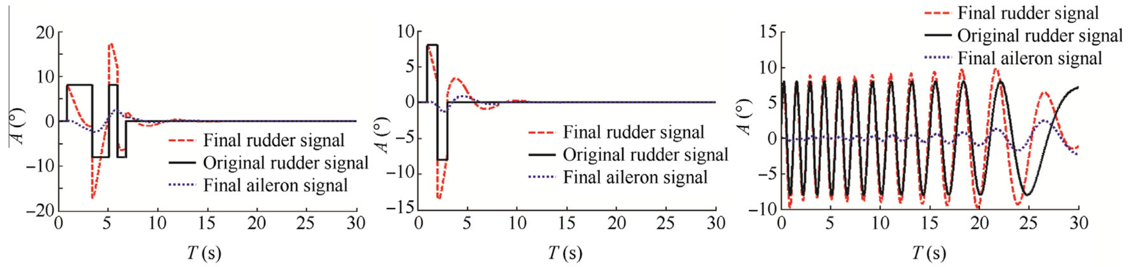
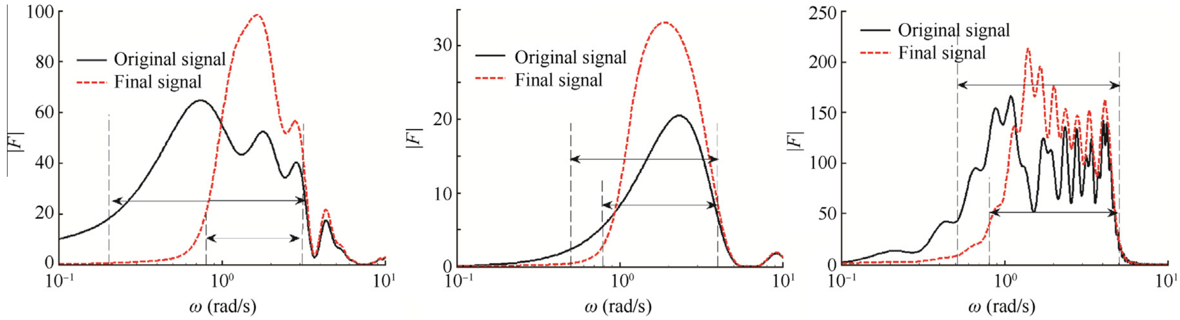


Fig. 6 Design procedure of excitation signals.



(a) 3211 multipolar square wave (b) Dipole square wave (c) Frequency sweep

Fig. 7 Shape changes of three signal types in time domain.



(a) 3211 multipolar square wave (b) Dipole square wave (c) Frequency sweep

Fig. 8 Energy distribution of three types of signal in frequency domain.

become distinctly higher when above 0.8 rad/s, which will be the lower limit of the bandwidth. When the frequency is high, the power spectrums of the final signals depend mostly on the original signals; (B) the variation degree of spectral shapes of all the three signal types is close and the frequency wave has relatively smaller change than the other signal types.

As analyzed, the high feedback gain augmentation of the FBW passenger airliner will distinctly change the shapes of the dipole square wave and 3211 multipolar square wave, while the frequency sweep signal does not change obviously. In flight tests, an unpredictable deflection of the control surface may threat flight safety. Essentially, the high feedback gain augmentation changes the power spectrum shapes of those former two signal types distinctly, but not that of the third signal type.

Simultaneously, the oscillatory suppression of the flight control system will rapidly reduce the control input of the 3211 multipolar square wave and dipole square wave, while the frequency sweep can persistently excite the airliner's motion, which is helpful for parameters estimation.

From the above, considering the requirement of the excitation signal design principle, the frequency sweep is fit to be the excitation signal of lateral-directional aerodynamic parameters identification for an FBW passenger airliner.

4.2. Design of signal parameters

The signal parameters of linear frequency sweep are: high frequency ending ω_{high}, low frequency ending ω_{low}, amplitude $|A|$, and duration T. The first two signal parameters are the most important elements, which determine the frequency range of signal energy distribution. Actually, the point of frequency sweep design is to obtain these four signal parameters. Taking the rudder excitation signal for example, the design of signal parameters is as follows.

(1) The high frequency ending ω_{high}

For the research example, the airliner's lateral-directional linear state matrix is preliminarily established based on the wind tunnel test data. Using Bode diagram, the frequency response analysis of side force, roll, and yaw motion equations is carried out to observe the aerodynamic parameters' frequency responses along with the frequency variation of the elevator deflection signal. The frequency range with large amplitude responses is the concerned frequency range. The appropriate excitation signal will have a relatively high level of energy in that range.

Taking the roll motion for example to demonstrate the computation method of the concerned frequency range's high frequency ending ω_{high} the amplitude response curves of $\overline{L}_\beta$, $\overline{L}_p$, $\overline{L}_r$, $\overline{L}_{\delta\mathrm{r}}$, and $\dot{p}$ in the frequency domain – $|\overline{L}_\beta/\Delta\delta_\mathrm{r}|$, $|\overline{L}_p/\Delta\delta_\mathrm{r}|$, $|\overline{L}_r/\Delta\delta_\mathrm{r}|$, $|\overline{L}_{\delta\mathrm{r}}/\Delta\delta_\mathrm{r}|$, and $|\Delta\dot{p}/\Delta\delta_\mathrm{r}|$ are presented in Fig. 9.

Fig. 9 shows that when the signal frequency of rudder deflection exceeds a specific range, most of the amplitude responses of roll moment parameters descend, demonstrating that the accuracy of these parameters identification becomes distinctly low. To get large amplitude response and accurate identification results of aerodynamic parameters, the excitation signal should be in a specific frequency range.

Generally, the rigid motion mode frequency of an airplane varies from 0.1 to 10 rad/s[13]. As seen in Fig. 9, in that frequency range, $|A_1|$ is the descent extent of the frequency response corresponding to $\omega_{\mathrm{high}.i}$, which is determined by L_i

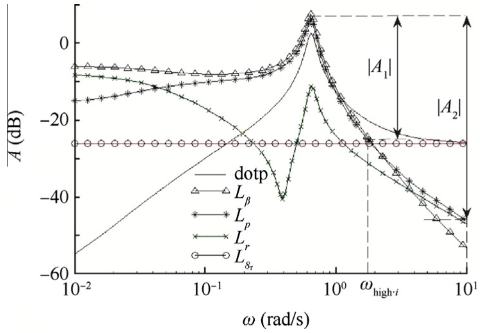


Fig. 9 Amplitude response of roll moment parameters in the frequency domain.

($i = \beta, p, r, \delta_r$), and $|A_2|$ is the maximal descent extent of the frequency response of the roll moment parameter L_i. To obtain a large amplitude response of L_i, $|A_1|$ should not exceed 60%–70% of $|A_2|$, which can be expressed as:

$$|A_1| \leqslant (0.6 \sim 0.7)|A_2| \tag{9}$$

According to Eq. (9), the highest frequencies $\omega_{\text{high}\cdot\beta}$, $\omega_{\text{high}\cdot p}$, and $\omega_{\text{high}\cdot r}$, which are determined by L_i, are respectively 2.18, 1.68, and 2.04 rad/s. For all of the roll moment parameters, L_i should be identified accurately, and the highest frequency $\omega_{\delta\text{r}\cdot\text{high}\cdot L}$ of the rudder excitation signal can be gotten by

$$\begin{aligned}\omega_{\delta\text{r}\cdot\text{high}\cdot L} &= \min(\omega_{\text{high}\cdot\beta},\ \omega_{\text{high}\cdot p},\ \omega_{\text{high}\cdot r})\\ &= \min(2.18, 1.68, 2.04)\\ &= 1.68\ \text{rad/s}\end{aligned} \tag{10}$$

The side force and yaw moment equations of the airliner's lateral-directional linear state matrix can be analyzed in the same way. The highest frequencies $\omega_{\delta_r\cdot\text{high}\cdot Y}$ and $\omega_{\delta_r\cdot\text{high}\cdot N}$ of the rudder excitation signal, which is determined by the side force and yaw moment parameters, can be gotten by

$$\begin{cases}\omega_{\delta_r\cdot\text{high}\cdot Y} = 2.41\ \text{rad/s}\\ \omega_{\delta_r\cdot\text{high}\cdot N} = 1.68\ \text{rad/s}\end{cases} \tag{11}$$

For all the aerodynamic parameters ω should be identified accurately, and the highest frequency $\omega_{\delta\text{r}\cdot\text{high}}$ in the concerned frequency range can be gotten by

$$\begin{aligned}\omega_{\delta\text{r}\cdot\text{high}} &= \min(\omega_{\delta\text{r}\cdot\text{high}\cdot Y}, \omega_{\delta\text{r}\cdot\text{high}\cdot L}, \omega_{\delta\text{r}\cdot\text{high}\cdot N})\\ &= \min(2.41, 1.68, 1.68)\\ &= 1.68\ \text{rad/s}\end{aligned} \tag{12}$$

Similarly, the highest frequency $\omega_{\delta\text{a}\cdot\text{high}}$ of the aileron excitation signal in the concerned frequency range can be gotten by

$$\begin{aligned}\omega_{\delta\text{a}\cdot\text{high}} &= \min(\omega_{\delta\text{a}\cdot\text{high}\cdot Y}, \omega_{\delta\text{a}\cdot\text{high}\cdot L}, \omega_{\delta\text{a}\cdot\text{high}\cdot N})\\ &= \min(2.48, 1.75, 1.73)\\ &= 1.73\ \text{rad/s}\end{aligned} \tag{13}$$

According to the wind tunnel test data, the Dutch roll mode frequency of the research airliner ω_{dutch} is 0.64 rad/s. Therefore, the highest frequency ω_{high} in the concerned frequency range is approximately 3 times the Dutch roll mode frequency ω_{dutch}, which means, when the excitation signal frequency exceeds this range, the identification result will become relatively poor.

(2) The low frequency ending ω_{low}

As seen in Fig. 10, when the frequency of the deflection signal is low, the amplitude of the frequency response is still high, which means the identification result is good. For the frequency range to includes many as possible the frequencies of the lateral-directional motion mode, the low frequency ending ω_{low} can be set at the spiral mode frequency or the lower limit frequency of the rigid motion mode. In this paper, the low frequency ending ω_{low} is set at the latter one.

(3) The amplitude $|A|$

The amplitude of the excitation signal should be appropriate, to ensure the final deflection signal influenced by the high feedback gain augmentation is neither too large nor too tiny. If the excitation signal's amplitude is inadequate, the excitation of the airliner's pertinent motion mode will not be obvious and the flight status will be more easily influenced by measure noise.[21] If the excitation signal's amplitude is too large, the flight status range will be too wide, which may introduce nonlinear aerodynamic influence. Meanwhile, the signal amplitude is also constrained by the division of the identification status range.[22,23] Consequently, the amplitude of the excitation signal can be ascertained by the requirement of the aerodynamic angle range, considering the high feedback gain augmentation. In this paper, the amplitude of the aileron and rudder excitation signal is set at 8°.

(4) The duration T

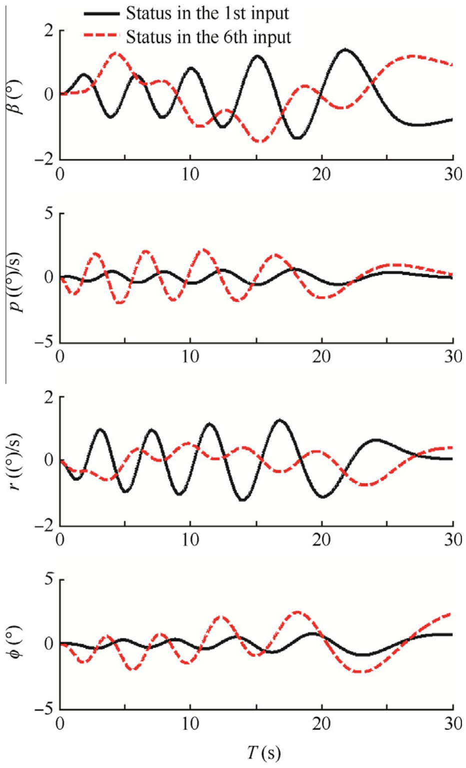


Fig. 10 Response comparison between the 1st and 6th control inputs.

The duration T of the frequency sweep cannot change the frequency range of signal energy distribution. However, it can make the energy density grow greater when it becomes longer, demonstrating that the excitation signal has more energy to excite the airliner's motion mode.

From the above, for the research airliner model, a suitable frequency sweep signal can be set as:

$$\begin{aligned} \omega_{\text{low}\cdot\delta\text{a}} &= \omega_{\text{low}\cdot\delta\text{r}} \approx 0.1\ \text{rad/s} \\ \omega_{\text{high}\cdot\delta\text{a}} &= \omega_{\text{high}\cdot\delta\text{r}} \approx 3\omega_{\text{dutch}} = 1.92\ \text{rad/s} \end{aligned} \tag{14}$$

4.3. Relationship between aileron and rudder signals

As mentioned before, through the Bode diagram analysis of the airliner's lateral-directional linear state matrix, the aileron and rudder excitation signal parameters can be obtained, under the premise of single signal excitation. As the simultaneous deflection of these two control surfaces can excite the lateral-directional motion modes adequately, the aileron and rudder excitation signals are loaded synchronously to discuss the impact of the relationship between aileron and rudder excitation signals on the identification results.

After the different groups of excitation signals are loaded onto the research airliner model, the identification results using the identification model in Section 4.1 and the parameter estimation method in Section 4.2 are presented in Table 1.

In Table 1, ω = 2.0–5.0 rad/s means the initial frequency of sweep is 5.0 rad/s and the ending frequency is 2.0 rad/s. $|A|$ means the signal amplitude, and T = 30 s means the signal duration and simulation time are both 30 s.

The results in Table 1 show that:

(1) The single deflection of either the aileron or rudder cannot excite the lateral-directional motion models adequately and the identification result is obviously poor, while the identification result is better in the synchronous excitation of two control surfaces.

(2) When the excitation signals are in the designed concerned frequency range, the precision of identification result is relatively high and the amplitude has little influence on the estimation results in the suitable status range. In Fig. 10, the flight status is in a similar range, but the estimation results of the 1st and 6th control inputs are clearly different.

Table 1 Comparison of identification results in different groups of excitation signals.

No.	Signal parameter	Relativeerror of identification parameter (%)/reference value of identification parameter								
		$\overline{Y}_\beta/-0.07$	$\overline{L}_\beta/-1.16$	$\overline{N}_\beta/0.09$	$\overline{L}_p/-0.97$	$\overline{N}_p/-0.15$	$\overline{L}_r/0.35$	$\overline{N}_r/-0.17$	$\overline{L}_{\delta_a}/-0.58$	$\overline{N}_{\delta_r}/-0.13$
1	ω_{δ_a} = 0 rad/s, ω_{δ_r} = 0.1–1.9 rad/s, $\|A\|$ = 8°, T = 30 s	−30.0	−6.3	−206.9	−74.6	1092.5	20.7	92.4	35.4	−5.6
2	ω_{δ_a} = 0 rad/s, ω_{δ_r} = 0.1–1.9 rad/s, $\|A\|$ = 3°, T = 30 s	−27.7	−6.3	206.9	−74.6	1092.5	20.7	92.4	35.4	−5.6
3	ω_{δ_a} = 0.1–1.9 rad/s, ω_{δ_r} = 0 rad/s, $\|A\|$ = 8°, T = 30 s	−6.8	26.9	−51.9	−5.1	−4.3	61.8	−22.9	−5.9	9.2
4	ω_{δ_a} = 2.0–5.0 rad/s, ω_{δ_r} = 2.0–4.0 rad/s, $\|A\|$ = 8°, T = 30 s	−0.6	−5.8	13.1	−5.7	−2.3	11.5	−27.0	−0.1	−0.2
5	ω_{δ_a} = 5.0–0.1 rad/s, ω_{δ_a} = 0.1–4.0 rad/s, $\|A\|$ = 8°, T = 30 s	−1.1	2.4	4.0	−4.3	−2.5	−1.6	−11.5	0.1	−0.2
6	ω_{δ_a} = 0.1–1.9 rad/s, ω_{δ_r} = 0.1–0.4 rad/s, $\|A\|$ = 8°, T = 30 s	−1.8	−0.1	−0.3	−1.0	0.4	1.6	−1.7	−0.1	−0.1
7	ω_{δ_a} = 0.1–1.9 rad/s, ω_{δ_r} = 0.1–0.4 rad/s, $\|A\|$ = 20°, T = 30 s	−2.3	−0.1	−0.4	−1.1	0.5	1.6	−1.7	−0.1	−0.1
8	ω_{δ_a} = 0.1–1.9 rad/s, ω_{δ_r} = 0.1–1.9 rad/s, $\|A\|$ = 8°, T = 30 s	6.9	−9.8	50.9	−5.6	−14.3	−12.9	7.5	1.9	−2.7
9	ω_{δ_a} = 0.5–1.9 rad/s, ω_{δ_r} = 0.1–0.4 rad/s, $\|A\|$ = 8°, T = 30 s	−1.7	−0.2	−0.1	−0.9	0.6	3.1	−2.3	0.1	−0.3
10	ω_{δ_a} = 0.1–0.4 rad/s, ω_{δ_r} = 0.1–1.9 rad/s, $\|A\|$ = 8°, T = 30 s	−2.9	−0.1	−12.8	−0.2	6.5	0.4	−3.2	−0.1	−0.5
11	ω_{δ_a} = 0.1–1.9 rad/s, ω_{δ_r} = 0.1–0.4 rad/s, $\|A\|$ = 8°, T = 5 s	1.8	−11.6	30.1	−6.4	−7.1	42.6	−19.8	−6.4	7.5

(3) The identification result is better when the initial frequency of the aileron signal is higher than that of the rudder signal. Conversely, the result precision is lower. Especially when the aileron excitation signal is exactly the same as the rudder one, the result is worse than either of the former case.
(4) Whether or not there is an overlapping frequency range between the aileron and rudder excitation signals, it has little influence on the identification results, as long as the initial frequency of the aileron signal is higher than that of the rudder signal.
(5) When the duration of flight data decreases, the identification result precision decreases, too. It suggests that the appropriate duration of flight data should at least be twice the period of the airframe's Dutch motion mode (the period of the example airframe's Dutch motion mode is 9.8 s).

For the above conclusions, the physical explanation is given as follows:

(1) There are three modes in lateral-directional motion, which are jointly controlled by the aileron and the rudder. Any single control surface cannot excite the airliner's lateral-directional motion.
(2) For a regular aerodynamically configured airliner, inertia moment I_{xx} is usually smaller than inertia moment I_{zz}, and the frequency of the roll motion is typically higher than that of the yaw motion. Consequently, the identification result is good when the initial frequency of the aileron is higher than that of the rudder. An airliner's lateral motion and directional motion are not synchronized with different motion phases, which implies that the aileron and rudder signals should not be the same. Consequently, when the aileron excitation signal is exactly the same as the rudder one, it will result in low identification precision.
(3) The flight data contains the airliner's motion characteristics. In general, the longer is the duration of the flight data, the more characteristic is the information, and the better the identification result will be.

5. Identification result validation

The identification result should be validated before being applied to aircraft engineering. The common validation of aerodynamic parameter identification is by loading a specific deflection signal onto the identified model and comparing response histories between the identified model and the research airliner model. In engineering, the validation of identification result is loading a deflection signal in the flight data onto the identified model and comparing its response with real flight status data.

Usually, one set of the flight data in the same flight status and similar control inputs is used to validate the identified model, while the other flight data is used to estimate the model parameters. Therefore, the first step of model validation is to load signals that are similar to the excitation signals onto the identified model and the research airliner model and then compare the two models' flight state.

It is noted that in this validation, the actual deflection signal of the research airliner model should be input to the identified model. Moreover, the flight control system of the identified model should be cut off. Otherwise, the actual deflection signals of these two models are not the same, which means it is improper to validate the estimation results through comparing the flight state parameters (see Fig. 11).

The identification results of the loaded signals and the actual deflection signals in the validation of No. 6 are presented in Fig. 12, and the flight state comparison of these two airliner models can be seen in Fig. 13. Table 2 shows the response comparison between two models.

Table 2, Figs. 12 and 13 demonstrate that the identification result in that excitation signal is accurate, and the errors of contrast parameters are small. Consequently, the lateral-directional characteristic of the identified model is almost the same as that of the research airliner. The following items should be noted when applying this validation method to engineering:

(1) The virtual flight test validation data is displaced by the actual flight test data as the reference data in the response comparison.
(2) The actual airliner's deflection data is input to the model identified in the simulation. Meanwhile, the flight control system of this simulation model should be cut off, because the actual deflection signal in the flight data is the addition of the loaded excitation signal and the signal fed back by the flight control system. In the model simulation validation, if the actual deflection is input to the airliner model and its flight control system is not cut off, then the feedback influence on the excitation signal is considered repeatedly and the deflection signal in the simulation model is different from the actual

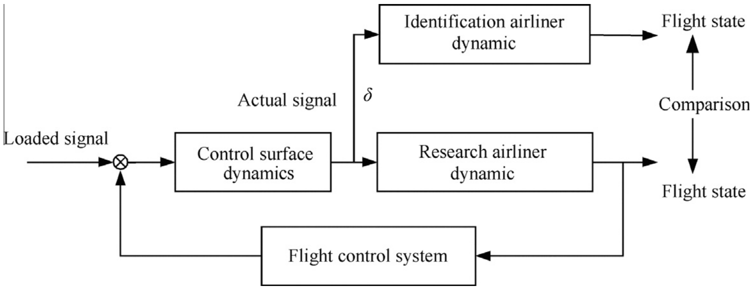


Fig. 11 Schematic of identification result validation.

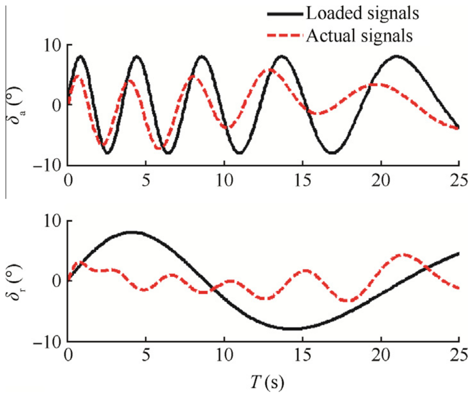


Fig. 12 Loaded signals and actual deflection signals in validation.

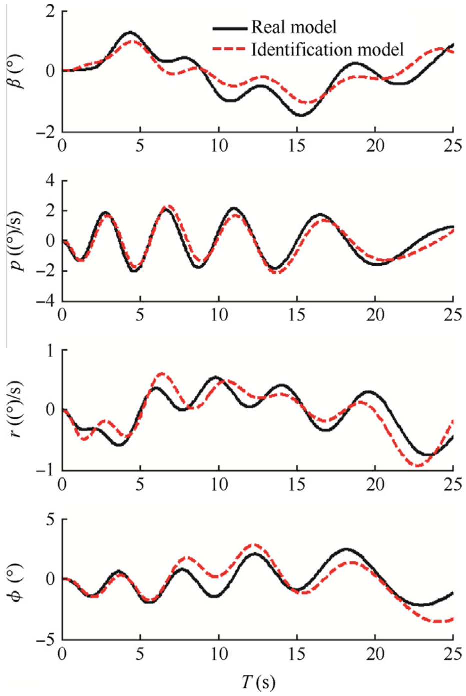


Fig. 13 Flight status comparison in validation.

Table 2 Response comparison between two models.

Contrast parameter	Maximum absolute error
Bank angle (°)	0.44
Roll rate ((°)/s)	−0.72
Yaw rate ((°)/s)	0.30
Roll angle (°)	−1.67

deflection signal in flight test data. Therefore, the simulation validation for the airliner's lateral-directional aerodynamic model cannot be accomplished.

6. Conclusion

(1) For the high feedback gain augmentation of an FBW passenger airliner, a method of type selection of lateral-directional excitation signal is advanced. Through the spectral analysis of signals before and after the change, the frequency sweep signal is adopted to be the excitation signal.

(2) Through the frequency response analysis of the lateral-directional motion equations, the design principle of frequency sweep is given as follows: the low frequency ending ω_{low} can be set at the spiral mode frequency or lower limit frequency of the rigid motion mode; the high frequency ending ω_{high} can be set at three times the Dutch roll mode frequency.

(3) The aileron and rudder should deflect together to excite the lateral-directional motion adequately, and the initial frequency of the aileron excitation signal should be higher than that of the rudder signal.

(4) It is suggested that the appropriate duration of flight data is at least twice the airframe's Dutch roll mode period, and that the amplitude of excitation signals should guarantee that the airliner's sideslip angle will not exceed a specific value such as ±3°.

(5) The validation of lateral-directional aerodynamic parameter identification for an FBW passenger airliner is given, which proves the excitation signal design method in this paper is valid and feasible.

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