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THE ANALYSIS OF TAKEOFF ROTATION OF SUBSCALE FREE-FLIGHT

Kun MA, Li-bo WANG, Huan DU, Wei WANG, Wen-ting GU

AVIC The First Aircraft Institute, Xi'an, Shaanxi, China

Abstract

Subscale free-flight tests of powered aircraft have played an important role in the development of military and civil aircraft development, which could be used in feasibility testing of aerodynamic layout, new technique/instrument validation, and flight exploration outside the flight envelope. In this work, takeoff rotation is taken as the research subject. Takeoff rotation speeds of subscale model and full-scale aircraft are calculated, comparing with free-flight test data, scaling principle and theoretical method of takeoff rotation speed are validated.

Keywords: free-flight test, **subscale**, **takeoff rotation speed**

1. Introduction

In recent years, subscale free-flight tests of powered aircraft have played an important role in the development of military and civil aircraft. Subscale models are designed and constructed in compliance with required scaling laws to ensure that dynamic motions are similar between the model and its full-scale counterpart [1]. Subscale free-flight tests could be used in feasibility testing of aerodynamic layout, new technique/instrument validation, and flight exploration outside the flight envelope. Compared with the full-scale aircraft flight test, the cycle of subscale free-flight is shorter. Moreover, subscale free-flight could reduce the test risk brought by the new aerodynamic layout and new technology validation, and reduce the test cost.

The world's aviation powers attach great importance to subscale free-flight tests, and the United States has carried out a series of flight tests of technical verification aircraft. Among them, X-series technology verification aircraft has been carried out for decades, playing a positive role in promoting the innovation and development of new technology and new aerodynamic layout. The representative X-series technology verification aircraft are X-36 tailless aircraft, X-48 technology demonstrator, X-56A active elastic control technology verifier. The X-36 tailless aircraft, jointly developed by NASA and Boeing, is a 28% scale geometric replica of a full size vehicle [2], which demonstrates the thrust vector control. X-48 technology demonstrator is a series of scaled aircraft developed to investigate the characteristics of Blended Wing Body (BWB) layout [3], which verifies the new layout, high cruise efficiency and handling stability characteristics. X-56A Multi-Utility Technology Testbed (MUTT) mainly demonstrates the feasibility of Active flutter suppression (AFS) and gust load alleviation [4].

In recent years, with the development of autonomous unmanned flight technology, subscale free-flight tests of powered aircraft has been rapidly developed and applied in Chinese aerospace universities, aerospace related enterprises and institutions. Aiming at the future development of civil aircraft, COMAC has successively carried out flight tests of BWB verification aircraft (Figure 1) and truss-braced wing (TBW) scaling verification aircraft (Figure 2) to verify the layout of unconventional civil aircraft.

Figure 1 – BWB verification aircraft of COMAC

Figure 2 – Truss-braced wing (TBW) scaling verification aircraft of COMAC

Through free-flight tests we could obtain firsthand flight data. But by now the free-flight data are mostly used for qualitative analysis rather than quantitative analysis.

In this paper, takeoff rotation is taken as the research subject. By comparing the theoretical results of takeoff rotation speed with free-flight test data, scaling principle and theoretical method of takeoff rotation are validated.

2. Theoretical basis

2.1 Scaling principle

In order to get valuable data for full-scale aircraft, certain scaling principles should be met between subscale model and full-scale aircraft to ensure motion similitude. Geometrically similitude is a fundamental requirement [5-6], such as wingspan, wing area, as well as the angles of attack. Other similitude requirement, including Froude number, Mach number and Reynolds number, could not be satisfied at the same time.

This paper aims at the research of low speed characteristics for a transport airplane. The geometrical dimension ratio of full-scale aircraft to subscale model is K_l, the ratios between full-scale aircraft and subscale model are given in Table 1.

Table 1 – The ratio between full-scale aircraft and subscale model

Parameters	Scale factor
Linear dimension	K_l
Angle of attack	1
Weight, mass	K_l^3

2.2 Takeoff rotation speed calculation

Takeoff rotation ability is an important indicator both for takeoff performance and aircraft's controllability. In the process of ground taxiing, the theoretical calculation method of rotation speed is put forward:

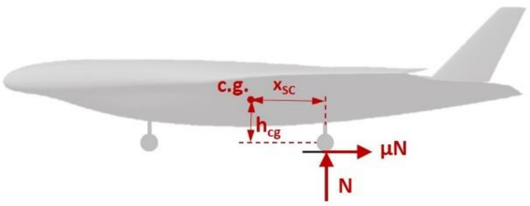

Figure 3 – Force diagram of takeoff rotation

$$Nx_{SC} + \mu N h_{cg} = 0.5\rho V^2 S\bar{c}C_m \quad (1)$$

$$C_L = C_L(\alpha, \delta_e) \quad (2)$$

$$C_m = C_m(\alpha, \delta_e) \tag{3}$$

$$V = \frac{G(x_{SC} + \mu h_{cg})}{0.5\rho S C_L(\alpha, \delta_e)(x_{SC} + \mu h_{cg}) + 0.5\rho S \bar{c} C_m(\alpha, \delta_e)} \tag{4}$$

Where N is the main reacting force of main landing gear, x_{SC} is the horizontal distance between center of gravity and main landing gear, h_{cg} is the height of the center of gravity to the ground, μ is the friction coefficient of runway. $\bar{c}$ is the mean aerodynamic chord, S is the wing reference area, C_L is lift coefficient, C_m denotes pitching moment, α is angle of attack, δ_e is elevator deflection.

According to scaling principle, the relation between subscale model's rotation speed and full-scale aircraft is shown below:

$$V_m = \sqrt{K_l} V_a \tag{5}$$

2.3 Filtering method

Due to the error of model measurement system and the influence of atmospheric environment in real flight, there exists high-frequency noises in flight test data. In this paper, Chebyshev I filter is used to remove high frequency noises. The amplitude square function of Chebyshev I filter can be expressed as:

$$|H(j\omega)|^2 = \frac{1}{1 + \varepsilon^2 C_N^2(\frac{\omega}{\omega_c})} \tag{6}$$

Where ε is the fluctuation of passband amplitude, and the value is between 0 and 1, ω_c is the cut-off frequency, $C_N(x)$ denotes the n-order Chebyshev polynomial and is shown below:

$$C_N(x) = \begin{cases} \cos[N \arccos(x)] & (|x| \le 1) \\ \cosh[N \arccos h(x)] & (|x| > 1) \end{cases} \tag{7}$$

In this paper, the technical parameters of Chebyshev filter is: passband cut-off frequency ω_p=20rad/s, stopband cut-off frequency ω_s =40rad/s, passband ripple δ_p=1dB, stopband attenuation δ_s=30dB.

Figure 4 and Figure 5 show the variation of pitch angle and pitch rate with time before and after low-pass filtering. It can be seen that the low-pass filtering processing of flight test data could improve the data quality and lay a good foundation for data analysis.

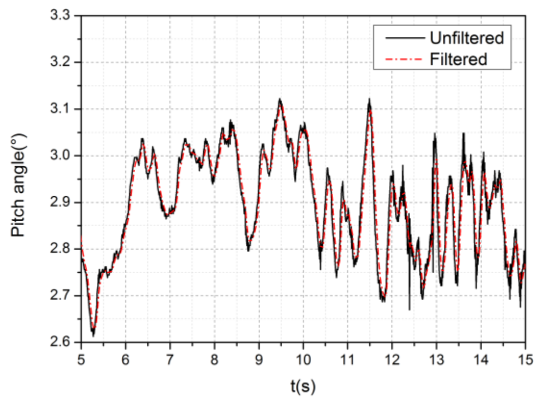

Figure 4 – Unfiltered and filtered pitch angle

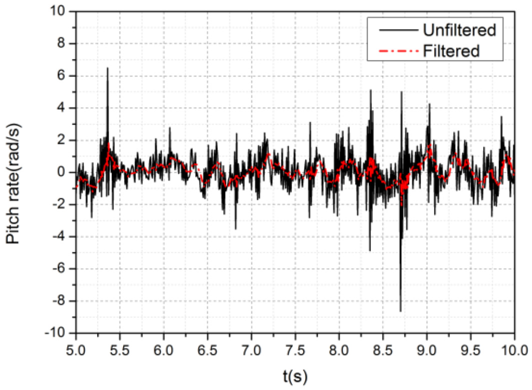

Figure 5 – Unfiltered and filtered pitch rate

3. Subscale model

The main parameters of subscale model and full-scale aircraft are shown in Table 2, where subscale theoretical model is theoretically scaled using scaling principle, and subscale model is the real aircraft used in free-flight test. It is observed that certain difference exists between subscale model and subscale theoretical model, and mainly reflected in the following two aspects:

- The total weight of subscale model is less than theoretical model due to the application of new process.
- In order to satisfy the requirement of inner arrangement, the landing gear installation location of subscale model is different from theoretical model.

- Table 2 – The main parameters of sub-scale model and full-scale aircraft

Parameters	Full-scale aircraft	Subscale theoretical model	Subscale model
$m_{TOW}\,(kg)$	25000	200	176
$x_{SC}\,(m)$	0.92	0.184	0.22
$h_{cg}\,(m)$	2.35	0.47	0.38

4. Results and Discussions

4.1 Theoretical results

According to the parameters of full-scale aircraft, subscale theoretical model and subscale model given in Table 2, and referring to equation (4), the takeoff rotation speed of different models are calculated, and the results are shown in Figure 6. It can be seen that the variation of takeoff rotation speeds of different models with elevator deflection angle is similar, the smaller the elevator deflection angle is, the higher the takeoff rotation speed is required. The results show that there exists distinct difference between the full-scale aircraft and the subscale model, and increases with the increase of the speed which is due to the relation between subscale model's rotation speed and full-scale aircraft, which is given in equation (5).

The differences between the subscale model and subscale theoretical model are mainly reflected in the weight and the location of the landing gear, which leads to the difference of takeoff rotation speed.

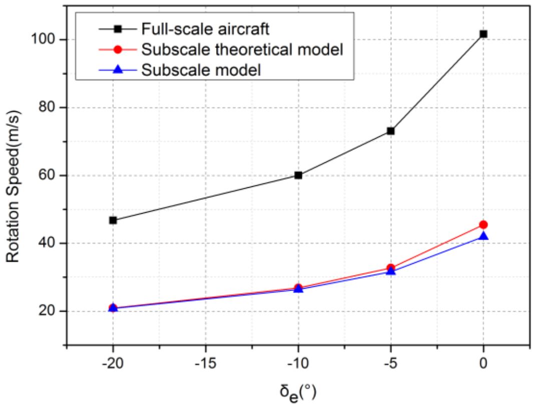

Figure 6 – Theoretical computation results of rotation speed

4.2 Free-flight test result

In this subscale free-flight test, there is a lack of effective means to obtain takeoff rotation speed directly. Therefore, by analyzing the variation of pitch angle and airspeed with time, the time of the front wheel lifting off the ground and related flight parameters is obtained indirectly. Figure 7 shows the variation of airspeed and pitch angle during a ground run of subscale model. At the starting point (t=0s), the initial pitch angle of the subscale model is about 3 degrees. Until t=23s, the pitch angle remains about 3 degrees. After t=23s, the pitch angle increases rapidly and the change of airspeed tends to be smooth.

From the change of pitch angle and airspeed, it can be judged that the time of the front wheel lifting off the ground is t=23s. At this time, the takeoff rotation speed is 40.34m/s, and the corresponding elevator deflection angle is -1.64 degrees.

Figure 8 shows the comparison between the theoretical value of takeoff rotation speed of subscale model and the test result. It can be seen that the relative error between theoretical value and test result is 7% which is influenced by the atmospheric environment, flight parameter measurement accuracy and other factors during the test. From the above analysis, the theoretical calculation is proved to have a high accuracy.

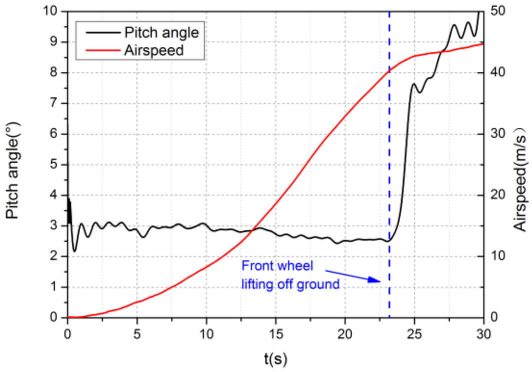

Figure 7 – The variation of pitch angle and airspeed with time

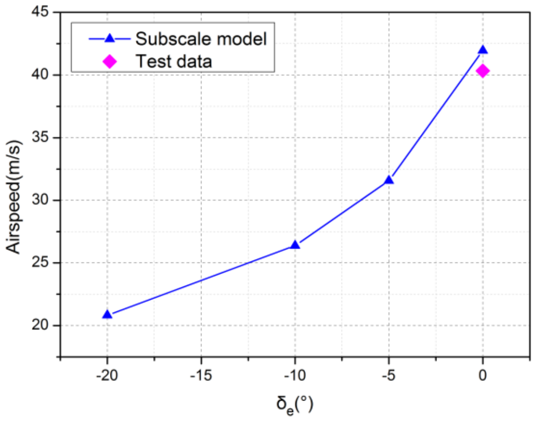

Figure 8 – The comparison of airspeed between theoretical value and test data

5. Summary

In this paper, takeoff rotation speeds of subscale model and full-scale aircraft are calculated, comparing with free-flight test data, theoretical calculation method of takeoff rotation and scale principle are validated.

6. Contact Author Email Address

great_mk@163.com

7. Copyright Statement

References

[1] CHAMBER J R. Modeling flight: The role of dynamically-scaled free-flight models in support of NASA's aerospace programs[M]. Washington, D.C.: NASA, 2010: 5.

[2] Brinker J S , Wise K A . Flight Testing of Reconfigurable Control Law on the X-36 Tailless Aircraft[J]. Journal of Guidance Control and Dynamics, 2001, 24(5):903-909.

[3] Regan C. In-flight stability analysis of the X-48B aircraft[C]//AIAA atmospheric flight mechanics conference and exhibit. 2008: 6571.

[4] Chin A W , Truong S , N Spivey. X-56A Structural Dynamics Ground Testing Overview and Lessons Learned[C]// AIAA Scitech 2020 Forum. 2020.

[5] Wolowicz C H, Bowman J S, Gilbert W P. Similitude requirements and scaling relationships as applied to model testing[R]. NASA TP-1435, 1979.

[6] Zhang S Y. *Model free flight test*[M]. Beijing: National Defense Industry Press, 2002. (in Chinese).