

PAPER • OPEN ACCESS

Dynamic Characteristics Analysis and Flight Test of Free Flight Model with Four Propellers

To cite this article: Yalong Wang *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **887** 012035

View the [article online](#) for updates and enhancements.

You may also like

- [Quasi-steady aerodynamic model of clap-and-fling flapping MAV and validation using free-flight data](#)
S F Armanini, J V Caetano, G C H E de Croon et al.
- [Indeterminacy of drag exerted on an arrow in free flight: arrow attitude and laminar-turbulent transition](#)
T Miyazaki, T Matsumoto, R Ando et al.
- [The Comparison Of In-Flight Pitot Static Calibration Method By Using Radio Altimeter As Reference with GPS and Tower Fly By Methods On CN235-100 MPA](#)
Derajat and Hindawan Hariowibowo



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Dynamic Characteristics Analysis and Flight Test of Free Flight Model with Four Propellers

Yalong Wang*, Wenqiang Yin and Shenjun Qi

Chinese Flight Test Establishment, Xi'an, China

*E-mail address: yalong2015@163.com

Abstract. Flight mode characteristics of free flight model with four propellers are analyzed, based on the results and flight test requirement, the control law is designed, then the simulation model is established and analyzed, finally, the control law is applied to free flight model test. The flight test results show: the propeller promoted the velocity stability and Dutch mode characteristic; level and turn flight stall test subjects were effectively accomplished based on the control law; the dynamic model built can simulate the free flight model test process and initially predict the stall characteristics; level stall angle is 10-12°, turn stall angle is 8-10°.

1. Introduction

According to the requirements of the stall demonstration of the CCAR 25 Stall Test Flight Clause 25.201, the stall flight test should be made under zero thrust and thrust required to maintain 1.5VSR1 level flight [1], and the thrust characteristics will affect the stall characteristics, therefore, stall flight test must be conducted under similar dynamic conditions to explore the stall characteristics of a full-size aircraft. However, in the free flight test, the model is dropped from a height of more than 1km. The flight operator has limited field of view when operating on the ground and cannot intuitively feel the motion state of the model. Therefore, there exists error in maneuvering, and at the same time, carrier' airflow and model processing error will also affect the stability of the model, which will have an impact on the test. Therefore, the corresponding control law must be designed before the test to ensure the success of the flight test.

Scholars have carried out a lot of research on flight simulation and test of free flight model. Zheng Hao et al. designed control law of the free flight model and effectively completed the free flight test [2]. Liu Shangmin et al. studied the control law of the fly-by-wire model [3], and gave the flight test method of the static unstable aircraft. Liu Chaojun et al. used a free flight test as an example [4], Through simulation, the deflection law of the control surface during the stall test of the free flight model was studied. Jiao Wencheng et al. studied the propeller's dynamic characteristics of free flight model and simulated the propeller's pull force using similarity criteria. However, the model used did not have a self-driving system and did not simulate the test process [5]. Luo Wumei used the free flight model to study the stability of K8 aircraft, he designed the control stabilization system and carried out simulation experiments, and achieved good results [6]. However, most of these studies are based on flight test data, and there is no calculation and analysis of the dynamic characteristics of the model.

Taking a free flight model with four propellers as an example, the influence of the propeller's pull force on the dynamic characteristics of the free flight model is considered. The control logic and control law suitable for the free flight test are designed. The free flight model test process is carried out through



simulation. The simulation and prediction of the stall characteristics were carried out. Finally, the design scheme was applied to the flight test of the free flight model, and the level and turn flight stall subjects were accomplished, and desirable results were obtained.

2. Analysis of propellers' influence on dynamic characteristics

2.1. Theoretical Analysis

In order to ensure the dynamic similarity between the free flight model and the prototype aircraft, it is necessary to simulate the propeller's pull force. In this test, the propeller's pitch is fixed and the forward ratio of the free flight model is the same as the prototype aircraft, which in turn ensure the dynamic similarity of the free flight model to the prototype aircraft at the stall point.

However, during the test, the propeller's pull force can affect the dynamic characteristics of the free flight model due to the fixed pitch and the changing force of the propeller with the incoming flow velocity.

The free flight model has four propellers, according to the formula for calculating the single propeller pull force and forward ratio

$$T = T_c \rho n_s^2 D^4 \tag{1}$$

$$\lambda = \frac{V}{n_s D} \tag{2}$$

Then, the pull force can be obtained as a function of the speed

$$T_v = \frac{4\Delta T}{\Delta V} = \frac{4\Delta T_c \rho n_s^2 D^4}{\Delta \lambda n_s D} = \frac{4\Delta T_c}{\Delta \lambda} \rho n_s D^3 \tag{3}$$

Where,

T_c	Pull force coefficient
T	Pull force
ρ	Air density
n	Speed of the propeller's rotation
V	Air velocity
D	Diameter of the propeller

The wind tunnel test data of the propeller used to obtain the relation between the propeller's pull coefficient and the forward ratio under the thrust required to simulate unpowered and 1.5VSR level flight state, as shown in Figure 1.

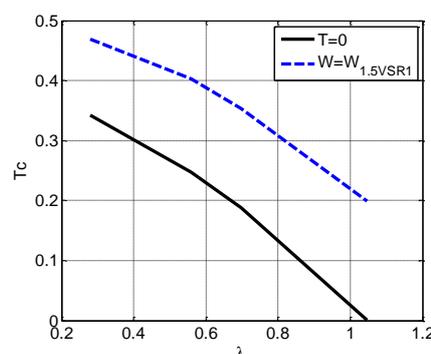


Figure 1. Pull coefficient curve of different state

$\frac{\Delta T_c}{\Delta \lambda}$ can be calculated by linearizing the curves above, and the T_v can be calculated by the equation(3), the results are shown in table1.

Table 1. T_v of different condition

Flight condition	T_v
Tc=0	-4.1
1.5VSR1	-2.67
Without propeller	0

Furthermore, the influence of the distributed propeller’s pull force on the directional damping characteristics of the free flight model can be obtained, as shown in Equation 4.

$$\Delta C_{nr} = \frac{\Delta C_n}{\Delta r} = \frac{\frac{1}{2} T_v \Delta r (L_1 + L_2) / (\frac{1}{2} \rho V^2 S b)}{\Delta r} = \frac{T_v (L_1 + L_2)}{\rho V^2 S b} \tag{4}$$

Where, L1 and L2 are the distances of one side of the engine from the symmetry plane.

It can be seen that the four-propeller can improve the velocity stability of the free flight model and the directional damp, which in turn affects the dynamic characteristics. Therefore, the influence of the propeller’s pull force needs to be considered in the subsequent dynamic analysis, flight simulation, and control law design.

2.2. longitudinal flight mode

When the flight quality is calculated by the small disturbance equation, it is generally considered that $T_v = 0$, in this test $T_v \neq 0$, the longitudinal flight quality calculation results are shown in Table 2. It can be seen that the dynamic characteristics of the propeller significantly improve the long period damping and have no effect on the short period characteristics.

Table 2. longitudinal flight quality

Flight condition	Phugoid		Short period		CAP
	frequency	damp	frequency	damp	
Tc=0	0.37	0.19	6.4	0.47	5.06
V=1.5VSR	0.33	0.15	6.4	0.47	5.06
Without propeller	0.38	0.05	6.4	0.474	5.06

2.3. lateral and directional flight mode

The results of the lateral and directional flight quality are shown in Table 3. It can be seen that the free flight model Dutch mode and the Roll mode flight quality is improved by the propeller. The spiral mode is unstable, so it need to be stabilized in the free flight test.

Table 3. lateral and directional flight quality

Flight Condition	Dutch mode		Roll mode		Spiral mode	
	frequency(rad/s)	damp	eigenvalue	T_r (s)	eigenvalue	$T_{1/2}/T_2$ (s)
Tc=0	5.39	0.153	-5.43	0.1842	0.0469	14.78
V=1.5VSR	5.84	0.159	-5.52	0.1810	0.0430	16.12
Without propeller	5.78	0.141	5.72	0.1746	0.0540	12.84

3 Design of control law

3.1 Flight Control Strategy

As shown in Figure 2, Three control modes are designed for flight test.

- Drop control mode
Drop control mode is designed to achieve the safe separation of the model from the carrier, the lateral trimming after the drop and the desirable attitude maintenance when the umbrella is to be opened. In the test, the pitch angle and the roll angle control law are designed to make the model stable after it's dropped.
- Stall control mode
The role is to achieve automatic control of the model. In the process of entering the stall, the roll angle control law is used to ensure lateral and directional stability before the model enters the stall.
- Direct control mode
The main control method is to use the full rod to control the full rudder. The model is rectified after stalling.

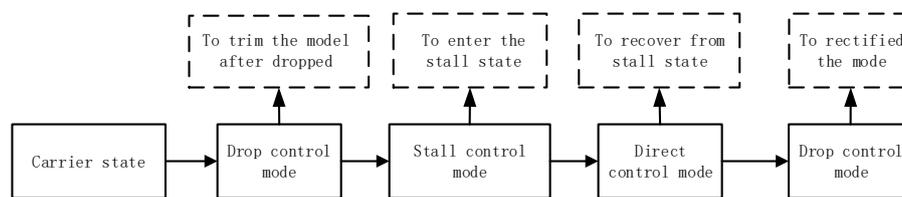


Figure 2. Flight control scheme and process of the free flight test

3.2 Control law

a) Longitudinal control law

The longitudinal control loop circuit input is the pitch angle command, and the feedback is the pitch angle and the pitch rate. The output is the elevator deflection command.

$$\delta_e = k_q q + k_\theta \Delta\theta + k_{\theta i} \int \Delta\theta dt + \delta_{e0} \tag{5}$$

$$\Delta\theta = \theta - \theta_c$$

b) Lateral & directional control law

$$\delta_l = I_p p + I_\phi (\phi - \phi_c) \tag{6}$$

$$\delta_r = K_r r$$

4 Flight test

4.1 Design of the flight process

Step1: The model is taken to 1500m by the carrier aircraft. After the carrier reaches the scheduled drop point, it will be confirmed by the tower, then the model will be dropped by the pilot of the carrier aircraft.

At the same time, the operator manipulates the flight control into the delivery control mode, at which time the longitudinal bar corresponds to the pitch angle control command, and the transverse bar corresponds to the roll angle control command;

Step2: After the model is dropped, the ground operator manually pushes the push rod, the model subducts, and the roll angle remains at zero. At the same time, the carrier pilot pulls the pole and exits the test area.

Step3: The operator switches to the stall control mode, then the model enters the stall. During the flight test of the level flight, the roll angle is controlled to -30° during this process, and the roll angle is controlled to -30° during the test.

Step4: After the model stalls, it enters the direct control mode, and the simulated pilot changes out of stall.

4.2 Analysis of the flight data

The results of the level-flight stall test are shown in Figure.3, and the results of the turn-flight stall test are shown in Figure.4.

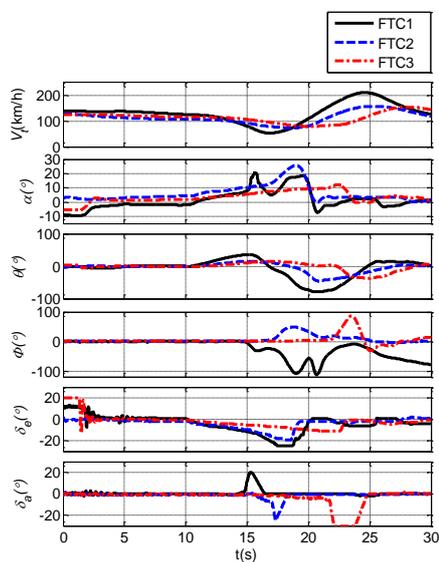


Figure 3. Flight test result of level flight stall

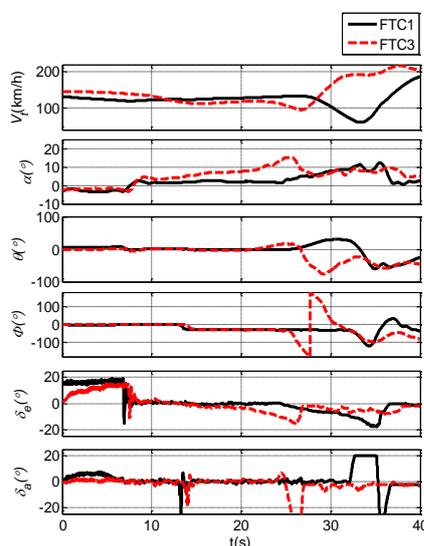


Figure 4. Flight test result of turn flight stall

The following conclusions can be drawn:

- 1) Under different test conditions, the switch of control mode is stable and there is no control surface jump;
- 2) The angle of attack of the level flight stall is 10-12°, and the angle of attack of the turn flight stall is 8-10°, which is consistent with the simulation results;
- 3) Operator evaluation: The propeller improved the stability of the free flight model, which is consistent with the analysis and simulation results.

5 Conclusion

- 1) The dynamic characteristics of the propeller can improve the speed stability and the directional stability of the free-flying model, which is beneficial to the flight operator's control;
- 2) The established dynamic model can achieve the simulation of the flight test process of the propeller powered free flight model;
- 3) The designed control scheme effectively implements the level and turn stall tests;
- 4) The research procedure is applicable to the stall flight test of the propeller powered free flight model.

References

- [1] Chinese Civil Aviation Regulations. *CCAR-25-R4*.
- [2] Zheng Hao Zhao Zhijun Zhang Jiaqi. Design of control law for unpowered free flight model [J]. *Flight Mechanics*, 2016.
- [3] Liu Shangmin, Zhao Lei. Research on flight control technology of free flight test of teletype aircraft model[J].*Flight Mechanics*,2012,2.
- [4] Liu Chaojun, Sun Yingfei, Wu Xinlong. Simulation Research on Free Flight Test Process of Unpowered Model[J]. *China Science and Technology Information*, 2016, 9.
- [5] Jiao Wencheng. Experimental study on free flight with dynamic model [J]. *Flight Mechanics*, 1994, 3.
- [6] Luo Wumei. Research on Relaxation and Static Stability of K8 Aircraft Free Flight Model[J].*Flight Mechanics*,1995,9.