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DEVELOPMENT AND VERIFICATION OF OSCILLATING BLADE GUST GENERATOR IN LOW-SPEED WIND TUNNEL

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Abstract

The composition and development process of the oscillating blade gust generator in FL-10 wind tunnel were discussed. The parameters were selected by numerical simulation method. The independent drive form of hydraulic servo oscillating cylinder was reduced the installation parts and the coupling vibration between the generator and the wind tunnel. The test and flow field calibration results show that the generator can simulate the combined motion of sine wave, triangular wave and random wave with different amplitudes and frequencies. The generator can work normally under the incoming wind speed of 70 m/s. The blade swing angle is 0~40 ° and the swing frequency is 0~16 Hz. The maximum gust amplitude in the center of the model is higher than 12 m/s, and the flow field covers a large range. The successful completion of the gust load alleviation test of the whole aircraft model indicates that the FL-10 wind tunnel has the ability to study the gust effect.

Keywords: low peed wind tunnel; oscillating blades; gust generator; gust field measurement; gust load alleviation

1. Introduction

It is almost inevitable that the aircraft will encounter gusts in various degrees during flight, which will bring additional structural dynamic load and wing elastic modal vibration, making it difficult for pilots to operate, reducing passenger comfort, and even causing aircraft bumps, resulting in fatigue dama ge or damage[1-2]. In order to predict the impact of gust on aircraft, numerical simulation and wind t unnel test are usually used. In the aspect of numerical calculation, it mainly includes frequency dom ain calculation and time domain calculation. The frequency domain calculation method is mainly use d to calculate the unsteady aerodynamic force of several discrete frequencies in the frequency dom ain[3]. However, this aerodynamic model is often difficult to take into account the influence of nonlin earity. With the development of CFD technology, the method of directly simulating gust response in t ime domain is gradually emerging[4]. However, gust-related wind tunnel tests can not only accuratel y simulate the gust characteristics of aircraft, but also verify the accuracy and reliability of the numer ical simulation results, which have attracted more attention.

The gust generator is an important equipment for gust response and load alleviation test. Since the 1960s, various forms of gust generators have emerged. Dowell E H et al[5]. designed a rotary slotte d cylinder / movable wing gust generator, which can produce sinusoidal gust profiles with strong win d speed, and gave the estimation formula of gust angle of attack. Buell et al[6]. studied the problem of velocity fluctuation in the downstream flow field of oscillating blade. When the array blade deflects in sinusoidal form, a sinusoidal-like gust is formed in the downstream. The amplitude of blade oscill ation is proportional to the amplitude of gust, which lays a foundation for the gust generator form tha t produces gust through blade deflection. Greenblatt configures blades at downstream exit of the tes t section to adjust gust amplitude by changing blade angle[7]. Two oscillating blades are arranged at the exit of the opening test section of the T-104 low speed wind tunnel with a diameter of 7 m by th e Russian Central Aerodynamic Research Institute [8-9]. In order to improve the stiffness of the blad e, three vertical steel cables are used to divide the blade into three sections. The 6-blade gust gener ator driven by motor was designed by Milan Institute of Technology in 4m × 3.84m low-speed wind t unnel[10]. The generator can produce transverse gust field. The blade adopts NACA0012 airfoil, the span is 3.56m, the chord length is 0.4m, and the single blade weight is about 15kg. Tang of Duke U niversity uses rotary slotted cylinder to match a fixed airfoil to generate lift and transfer airflow[11]. After more than ten years of accumulation, China has made great progress in the development and application of gust generator in low speed wind tunnel. Representative is the gust generator developed by China Aerodynamics Research and Development Center in 4m × 3m and 8m × 6m low speed wind tunnels[12-13]. and the corresponding supporting equipment is established[14], and the multi-stage gust correlation test is carried out.

2. Generator system design

The gust generator is installed in the closed test section of FL-10 wind tunnel with the size of 8m (width) × 6m (height). The generator is mainly composed of blades, hydraulic swing cylinder, swing cylinder support and vertical support, as shown in Figure 1. The transmission form of the generator is: servo hydraulic swing cylinder - elastic coupling - blade drive shaft - vertical support bearing - blade driven end. In order to reduce the overlap between the working frequency of the generator and the vibration frequency of the transmission structure, each blade is driven independently. In addition, the blade support structure is installed on the pillar of the wind tunnel, which does not contact with the tunnel wall, and reduces the coupling vibration between the support structure and the tunnel body.

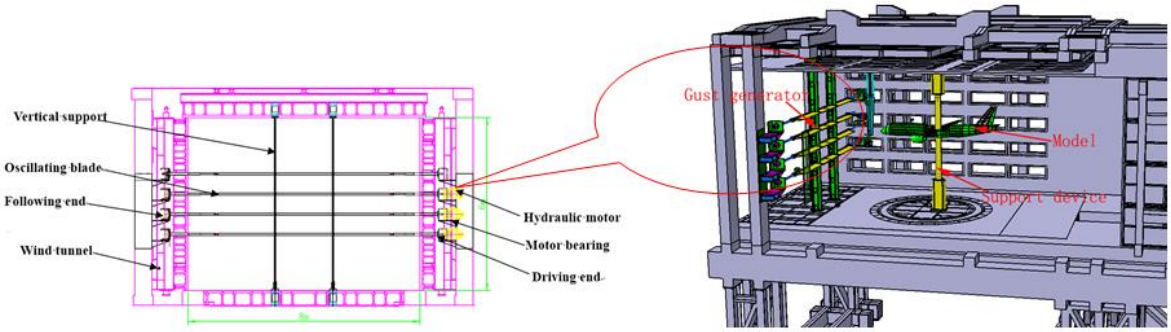


Figure 1 – Layout scheme of gust generator

The shape, number, spacing, chord length and span of the blade section of the gust generator are the influencing parameters of its performance index. Therefore, the aerodynamic design of the generator is a multi-parameter optimization process. In this paper, numerical simulation is used. According to the design requirements, through multi-round iteration and optimization selection, the NACA0015 airfoil is selected as the generator blade, the span is 6 m, the chord length is 0.5 m, and the blade spacing is 0.7 m.

2.1 Structure design

2.1.1 Blade structure design

The papers should be prepared, if possible, using the format like this document. The blade structure is a single-wing structure, which is divided into two parts, including the main blade spar, front skin, front partition, posterior margin skin and form. The leading edge is aluminum alloy structure, composed of leading edge skin and diaphragm; the latter part is a composite sandwich structure consisting of carbon fiber skin and full height foam filling, as shown in Figure 2.

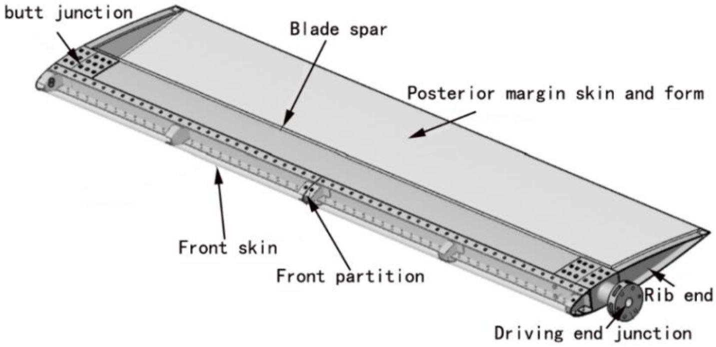


Figure 2 – Blade structure

2.1.2 Vertical support design

Since the spanwise length of the blade is too long, in order to ensure the blade stiffness, the blade s upport is set at the spans of 2 m and 4 m. In order to ensure that the vertical support has sufficient s trength and stiffness and is convenient for rapid assembly, two steel beams are used as the skeleto n, and the auxiliary strengthening component connection is used between the two steel beams to en hance the overall stiffness. In order to ensure the gust flow field quality, the glass fiber reinforced pla stic shell is used to rectify the support frame, and the thickness of the rectification shell is 2 mm. The schematic diagram of intermediate support structure is shown in Figure 3.

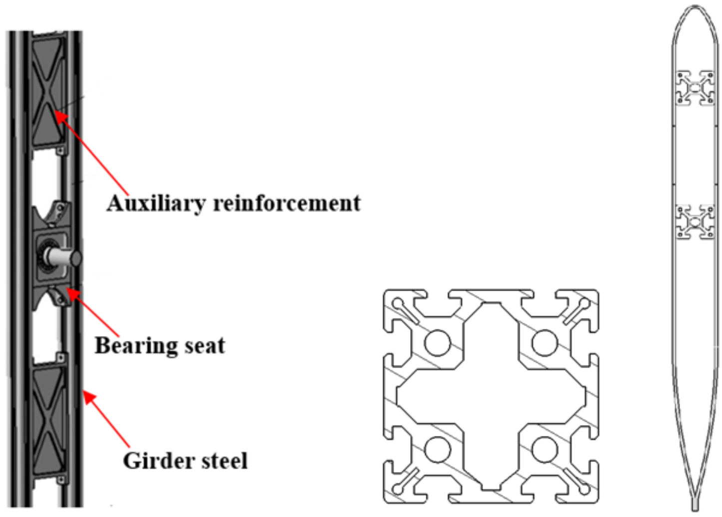


Figure 3 –Schematic diagram of vertical support structure

2.1.3 Rotary shaft mechanism design

The motion of gust generator adopts the single-drive mode of a single set of blades. There are four bearing points on each blade. There is a bearing at the driving end, driven end and vertical support of the blade. The joint of shaft and blade is in the form of key connection, as shown in Figure 4.

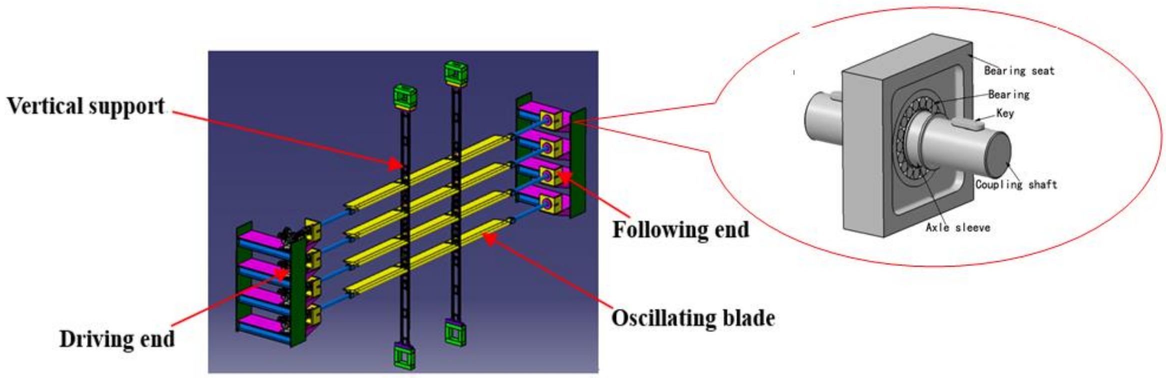


Figure 4 – Schematic diagram of the structure of the rotating shaft

2.1.4 Modal analysis

The finite element model generally includes the gust generator ' s drive mechanism, transmission m echanism, blade, supporting structure and so on. The natural nodes are basically used in meshing, and the analysis is not merged. The analysis node is taken on the theoretical shape, and the interna l structure is taken on the intersection point constructed by the longitudinal and transverse main bea ring forces. After analyzing the force characteristics of gust generator structure, it is necessary to de termine the element selection of finite element model in the discrete process of structure, because t he selection of model element type needs to reflect the force characteristics of actual structural com ponents, and the connection between elements also needs to correctly reflect the force transmission path of the structure. The finite element model of gust generator including vertical support and four groups of blades is established, as shown in Figure 5.

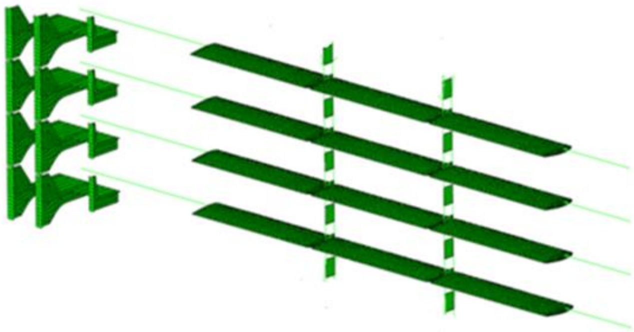


Figure 5 – Finite element model of generator

Based on the established finite element model, the modal solution of gust generator is carried out. The first three modes (vertical support) of the generator are shown in Figure 6. It can be seen that the lowest order frequency of the vertical support is higher than the blade deflection frequency of 16 Hz, so the blade deflection does not produce coupling vibration with the vertical support.

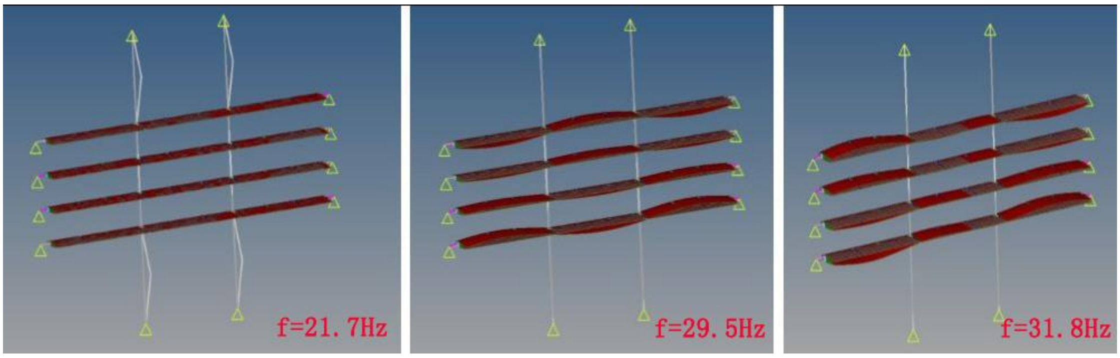


Figure 6 –Structural Modal Diagram

2.2 Design of drive and control system

Due to the high requirements of generator indicators (the maximum angular acceleration is 59217° / S2, and the maximum torque is 2400 N·m), the existing motor is difficult to meet the requirements. Therefore, this paper uses the hydraulic servo swing cylinder to drive. The drive and control system mainly includes oil source pump station, servo swing motor, transfer computer, sensor and control system, as shown in Figure.7.

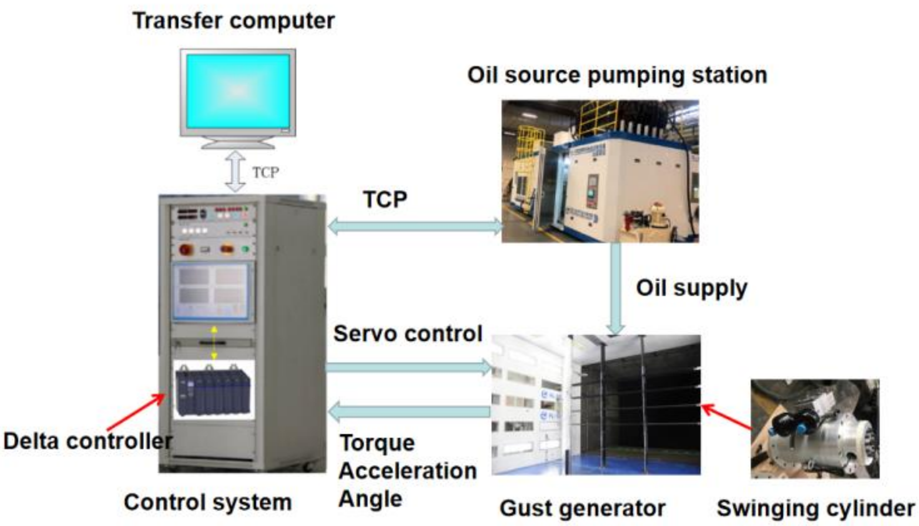


Figure 7 – Drive and control system of gust generator

2.2.1 Oil source pumping station design

This project adopts movable oil source pumping station to provide power for generator. Through the analysis of hydraulic swing cylinder index requirements, when the hydraulic swing cylinder meets the corresponding technical requirements such as torque and swing frequency, the parameters required by the oil source pumping station are shown in Table 1.

Table1 Design parameters of oil pumping station

Serial number	Item	Requireme
1	Rated pressure	21MPa
2	Rated flow	180L/min
3	Pressure fluctuation	≤5MPa
4	Temperature	Controllable

The designed oil-source pumping station includes control cabinet, pumping station and oil cooler. The power distribution cabinet and control cabinet of the oil-source pumping station are equipped with safety protection such as leakage, anti-interference and accidental collision (misoperation). The structural layout of oil source pumping station is shown in Figure 8.

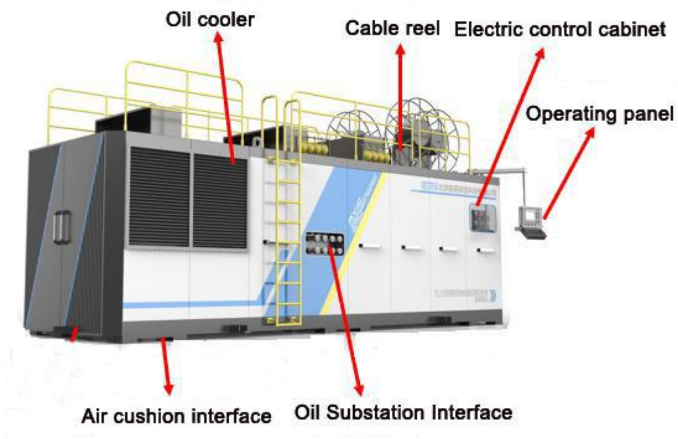


Figure 8 –Structure layout of oil source pumping station

2.2.2 Design of multi-channel control strategy

The four blades of gust generator are independently and equally controlled, but there are certain differences in the load and interference of each channel. Therefore, on the basis of adopting the same synchronous control, the connection of each branch is strengthened, the motion difference of each branch is reduced, and the displacement of the four hydraulic motors is compensated for each other. The control strategy adopted is shown in Figure 9.

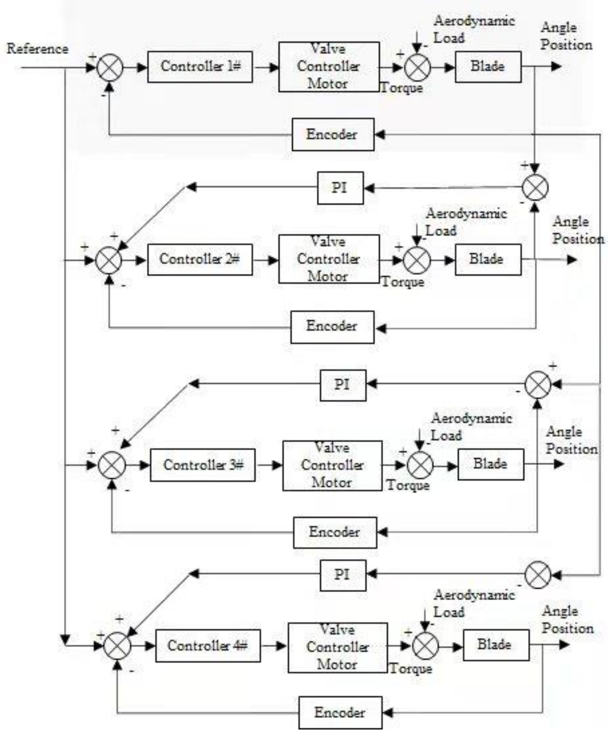


Figure 9 –The principle of synchronous control

3. Generator test and verification

3.1 Test of different motion waveforms of blade

The independent hydraulic swing cylinder is used to drive the blade movement, and the device can realize the combined movement of sine wave, triangular wave and random wave. Figure 10 shows the waveforms of four groups of blades swinging at the same time and different movements. The generator can more realistically simulate the disturbance current of different motion forms and different frequency components in the atmosphere, especially the generation of random wave, which makes the device have the simulation ability of continuous gust.

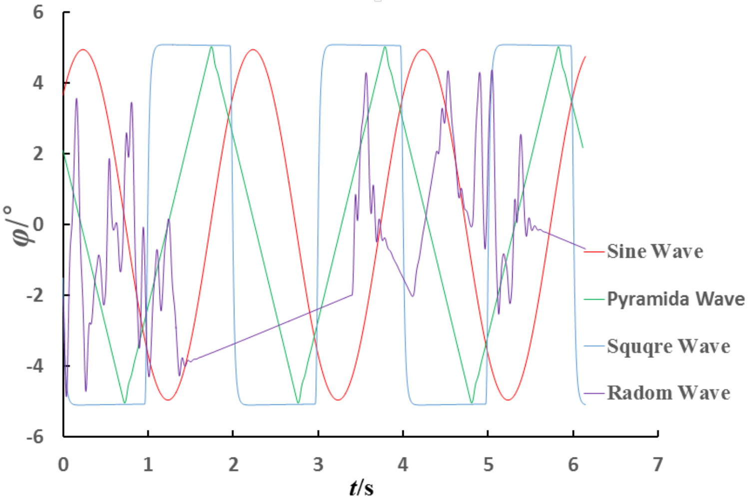


Figure 10 – Waveforms of t four groups of blades with different motions

3.2 Calibration test of gust flow field

The flow field calibration test was carried out on the developed gust generator. The preset points were calibrated by moving the calibration device, and the gust generator and flow field calibration device installed in the wind tunnel (Figure 11).

Figure 11 –Gust generator and flow field calibration device

This experiment used Streamline Pro multi-channel hotline anemometer of Danish DANTEC company to measure gust field. The measuring range of hot wire anemometer is 0 ~ 300m /s. The system consists of hot wire probe, L-shaped strut, calibration equipment, acquisition equipment and data processing equipment. This test uses 55P61 two-dimensional probe, strut is 55H22 strut. As shown in Figure 12.

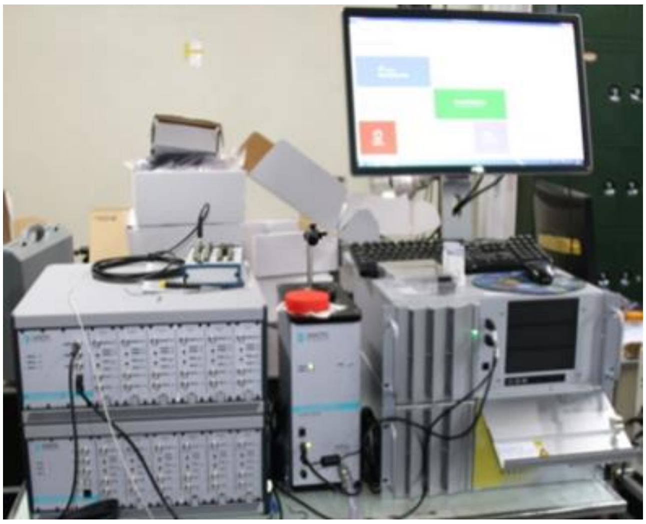


Figure 12 – Hotline anemometer

Figure 13 shows the gust flow field curves at different wind speeds when the blade oscillation frequency is 8 Hz and the blade oscillation angle is 8°. It can be seen from the figure that the gust amplitude increases with the increase of the flow velocity. At the flow velocity of 70 m / s, the maximum gust velocity amplitude is 12.6 m/s. When the incoming flow velocity is fixed at 40m / s and the blade swing angle amplitude is 4 °, the gust velocity amplitude increases with the increase of swing frequency, and the maximum working frequency is 16Hz. These indicators show that the gust generator studied can well meet the requirements of gust simulation.

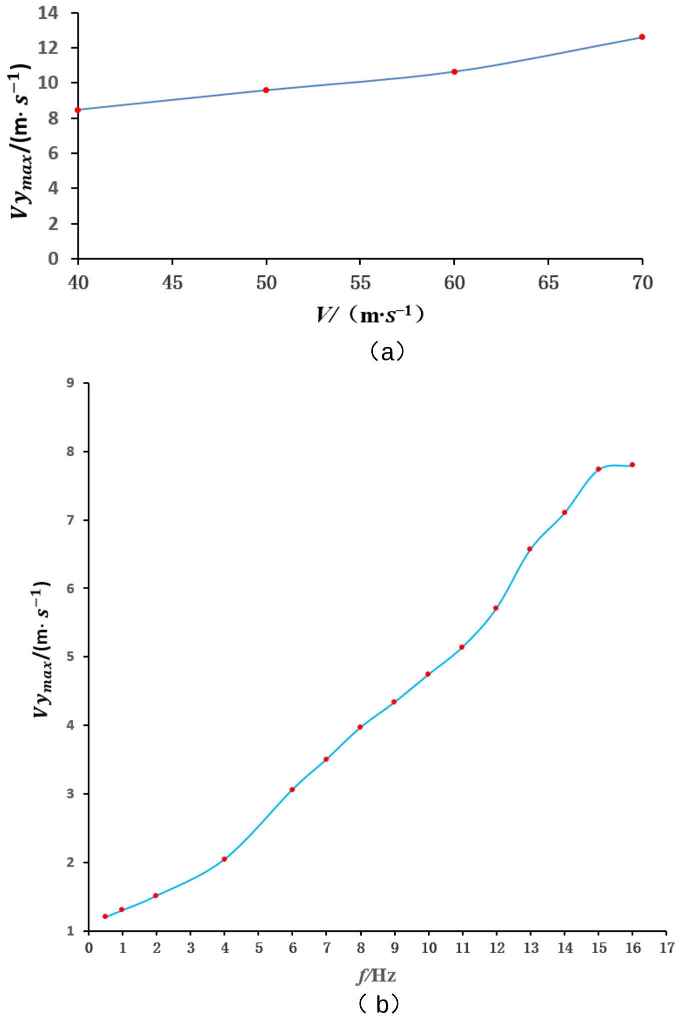


Figure 13 – Gust flow field curve （a） Variation of gust amplitude with incoming wind speed （b） Variation of gust amplitude with blade swing frequency

3.3 Test of gust load alleviation

Civil aircraft model was used in the test. The wingspan of the model was 4.4 m, the fuselage length was 4.8 m, the aspect ratio was 9.6, and the weight was 78 kg. The stiffness of each component of the test model is simulated by a variable cross-section aluminum alloy beam. The wing surface and the body are divided into several sections, and the wood structure is adopted for dimension. Each section is connected with the metal beam at a single point. The sliding block and turntable bearing are installed on the fuselage to realize the up-down and up-down movements of the test piece. There are six control surfaces of the model, including the left / right aileron, the left / right elevator and the left / right fast flap. Each rudder surface is driven by a separate servo motor. Install vibration accelerometer along vertical direction near wing tip. The strain gauge is pasted along the wing beam direction at the wing root, and the strain is measured and then converted into the bending moment of the point. The conversion coefficient is given by the load calibration test. An inclination sensor is installed near the fuselage pitch shaft to measure the body pitch angle ; a displacement sensor is installed on the slider to measure the body ' s heave and floating displacement. The model is installed in a wind tunnel with a two-degree-of-freedom support that can realize both heave and pitch motion, as shown in Figure 14.

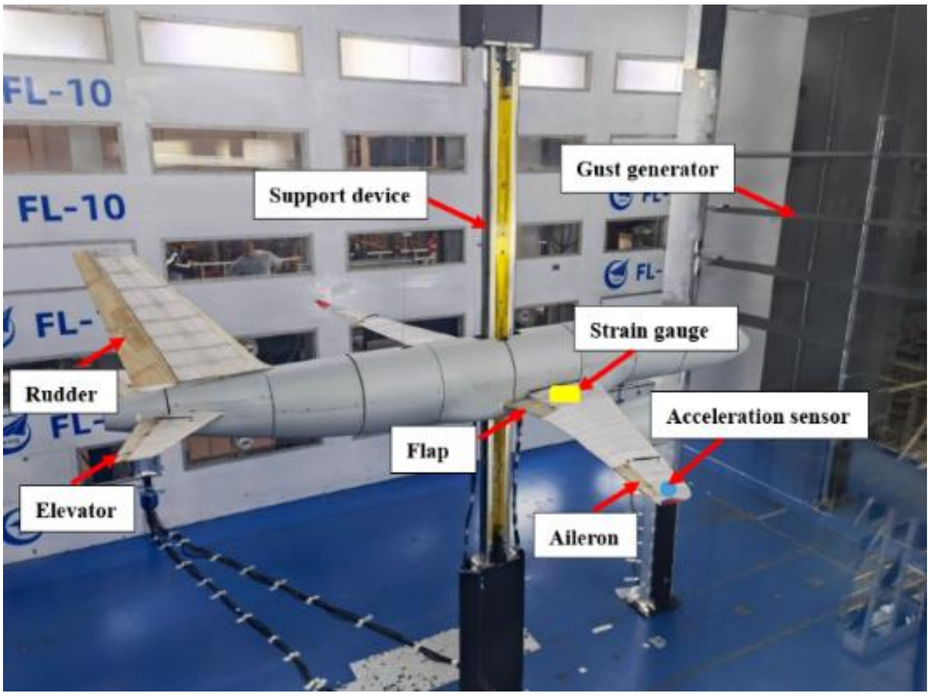
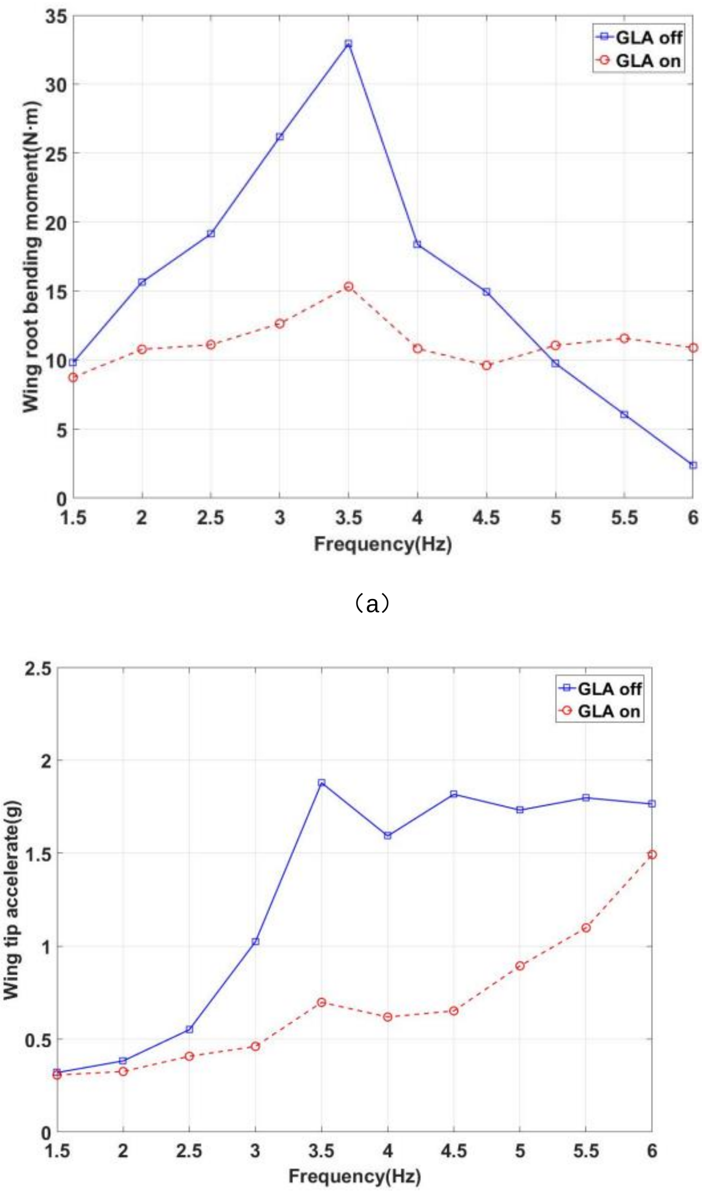


Figure 14 – Photo of gust load alleviation test

In the test, the gust load alleviation control (GLA) test was carried out by controlling the rudder deflection of the rudder combination such as elevator, aileron and flap. Figure 15 shows the test results when the wind speed is 20 m / s, the generator swing frequency is 1～6 Hz, and the swing angle is 2°. It can be seen from the figure that the rigid body movement of the model and the wing root bending moment are reduced significantly after the controller is opened. Especially for the wing symmetrical bending mode frequency (3.177Hz) of the wing root bending moment and wing tip normal overload alleviation effect is very obvious, the maximum alleviation is more than 50 %.



(a)

(b)

Figure 15 – Gust load alleviation results for full scale model （a） Wing root benging moment alleviation effect （b） Wing tip acceleration alleviation effect

4. Conclusions

Through the FL-10 wind tunnel gust generator test and experimental verification, the following conclusions can be drawn :

(1) The design of FL-10 wind tunnel gust generator is reasonable, and the unique design method of hydraulic servo swing cylinder driving blades alone is adopted to reduce the coupling vibration between gust generator and supporting structure.

(2) The generator blade swing frequency, swing angle, gust amplitude is high, with a wide frequency range.

(3) The generator can simulate different forms of gust, which greatly meets the test requirements.

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