A Wire-Driven Parallel Suspension System with 8 Wires (WDPSS-8) for Low-Speed Wind Tunnels

Yaqing ZHENG[1,2], Qi LIN[1,*] and Xiongwei LIU[3]
1. Department of Aeronautics Xiamen University,Xiamen,361005,China
2. College of Mechanical Engineering and Automation, Huaqiao University, Quanzhou, 362021, China
3. School of Computing, Engineering and Physical Sciences, University of Central Lancashire, Preston, UK

1. Introduction

As a new type of parallel manipulator, the wire-driven parallel manipulator has advantageous characteristics such as simple and reconfiguration structure, large workspace, high load capacity, high load/weight ratio, easy assembly/disassembly, high modularization, low cost and high speed. A new concept has been proposed by using the wire-driven parallel manipulator as aircraft model suspension system in low-speed wind tunnel tests for nearly 9 years. The authors of the context have undertaken over six years research work about a 6-degree-of-freedom (DOF) wire-driven parallel suspension system with 8 wires (WDPSS-8) for low-speed wind tunnels, and achieved some deep understanding. The attitude control and aerodynamic coefficients (static derivatives) of the scale model have been investigated both theoretically and experimentally. Two prototypes (WDPSS-8) have been developed and tested in low-speed wind tunnels. It is also found the possibility to use the prototypes (WDPSS-8) for the experiment of dynamic derivatives by successfully implementing the single-DOF oscillation control to the scale model. In order to investigate the feasibility of using the same wire-driven parallel suspension system for the static and dynamic derivates experiments in low-speed wind tunnels, the research will go on in this direction. The research results, particularly the experiments of the dynamic derivatives, will provide some criterion of experimental data for the free flight and some effective experimental methods， which deal with the controllability capability of post stall maneuvers in the design of great aircrafts and a new generation of vehicles. Concerning the research outcomes, 4 projects including sponsored by NSFC（National Natural Science Foundation of China）have been finished and 21 papers(c.f. Appendix) have been published by our group.

* Corresponding authors: Qi LIN, E-mail: qilin@xmu.edu.cn

2. Background

2.1 The Traditional Rigid Suspension Systems for Wind Tunnels

Wind tunnel test is one important way to obtain the aerodynamic coefficients of the aircrafts. During the wind tunnel tests, it is necessary to support the scale model of the aircraft in the streamline flow of the experimental section of the wind tunnel using some kind of suspension system. The suspension system will have a lot of influences on the reliability of the results of the wind tunnel tests. The traditional rigid suspension systems have some unavoidable drawbacks for the blowing experiments of static and dynamic derivatives such as the serious interference of the strut on the streamline flow [1-6].

2.2 The Cable-Mounted Systems for Low-Speed Wind Tunnels

The cable-mounted systems for wind tunnel tests, developed in the past several decades, deal with the contradiction between the supporting stiffness and the interference on the streamline flow [7-12]. However their mechanism is not robotic and consequently quite different from wire-driven parallel suspension systems in attitude control schemes and force-measuring principle. In addition they can not be used in the dynamic derivatives experiments [12].

2.3 The Wire-Driven Parallel Suspension Systems (WDPSS) for Low-Speed Wind Tunnels

Instead, the free-flight simulation concept in wind tunnels through an active suspension, such as six-DOF wire-driven parallel suspension systems (WDPSS), is suitable to get the aerodynamic coefficients of the aircraft's model [13-16], which comes from the research improvement in wire-driven parallel manipulator and force control. Some successful achievements in this field have been made in the Suspension ACtive pour Soufflerie (SACSO) project supported by French National Aerospace Research Center (ONERA) for nearly 8 years. And they have been applied in vertical wind tunnel tests with a wind speed of 35 m/s for fighters at the first stage of their conceptual design. However the system can not be used in the experiment of dynamic derivatives [13, 14].

The goal of this context is to introduce some contributions in the field of wire-driven parallel suspension systems for static and dynamic derivatives of the aircraft model for low-speed wind tunnels. Under the sponsorship of NSFC (National Natural Science Foundation of China), the research work about a 6-DOF wire-driven parallel suspension system with 8 wires (WDPSS-8) for low-speed wind tunnels has been carried out by the authors over 6 years, and some deep and systematic results have been published [15-26]. The attitude control and aerodynamic coefficients (static derivatives) of the scale model have been investigated in theory and in experiment.

Two prototypes (WDPSS-8) have been built and tested in two different low-speed wind tunnels respectively [21,23,25]. And with the prototype, the single-DOF oscillation control of the scale model has been implemented successfully [23-26]. This shows it is possible to use a WDPSS for the experiment of static and dynamic derivatives in low-speed wind tunnel.

Concerning the possibility of using the same WDPSS to make the static and dynamic derivates experiments in low-speed wind tunnels, a survey of the research work finished about some key issues of WDPSS-8 in wind tunnel experiments will be addressed. The research results, especially in the experiments of the dynamic derivatives, will provide some criterion of experimental data for the free flight and some effective experimental methods about the controllability capability of post stall maneuvers in the design of a new generation of aircrafts and vehicles, which will help to provide a novel support system in the field of wind tunnel tests of aircrafts.

The rest of the Chapter is organized as follows: The key issues of WDPSS-8 for the experiments of static derivatives of the aircraft's model in Low-Speed Wind Tunnels (LSWT) are given in the next Section 3. The research results of WDPSS-8 for the experiments of dynamic derivatives of aircrafts in LSWT are presented in Section 4. Finally, discussions and future works are suggested in Section 5.

3 WDPSS-8 for Experiments of Static Derivatives of Aircrafts for Low-Speed Wind Tunnels

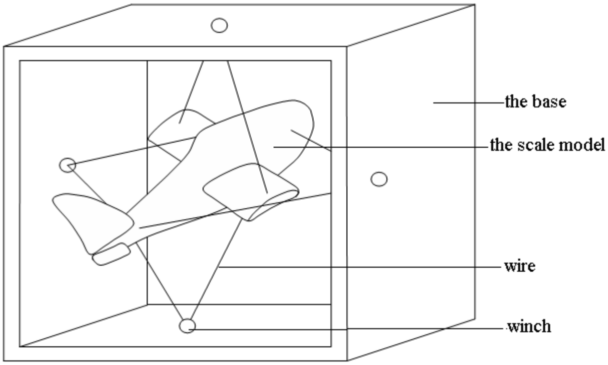
3.1 Two WDPSS-8 prototypes

3.1.1 A Manually operated WDPSS-8 prototype validated in a closed circuit wind tunnel

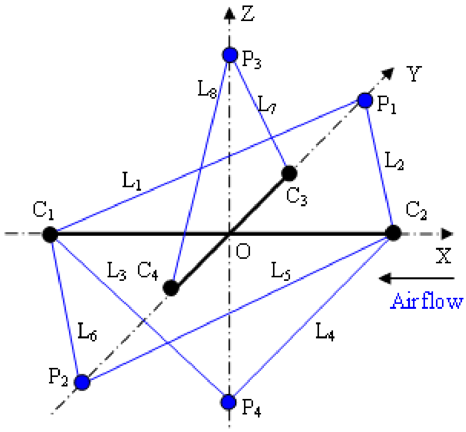
A wire-driven parallel manipulator is a closed-loop mechanism where the moving platform is connected to the base through wires by multitude of independent kinematic chains. The number of moving platform's degree of freedoms (DOFs) is defined as the dimension of linearity space which is positively spanned by all the screws of the structure matrix of the manipulator. So the moving platform of a 6-DOF completely or redundantly restrained wire-driven parallel manipulator is driven by at least 7 or more wires.

Meanwhile, a 6-DOF WDPSS is essential for free fight of the aircraft's model in a 3-dimensional space wind tunnel. Fig. 1(a) shows the concept of a 6-DOF WDPSS driven by 8 wires (WDPSS-8). Its geometric definition is shown in Fig. 1(b). A manually operated prototype of such a design shown in Fig.1 (c) is built and tested in a closed circuit LSWT, the geometric parameters of which are listed in Table 1. To implement the scheme for the attitude adjustment of the aircraft, a driving mechanism adjusted manually has been developed which allows the aircraft model to maneuver, i.e., to permit roll, pitch and yaw motion. For the WDPSS-8, each cable will be attached to a driving unit, which consists of a screw bar and a driving nut, as shown in Fig. 1(d). A commercial load cell interfaced to the cable shown in Fig. 1(e) is used to measure the tension of a cable. To avoid extra interference, the strain gage balance and driving unit are attached to the wind tunnel frame on the outside of the tunnel, as shown in Fig. 1(c) and (d). However, Fig. 1(f) shows the aircraft model mounted on a conventional strut supporter system in the same LSWT.

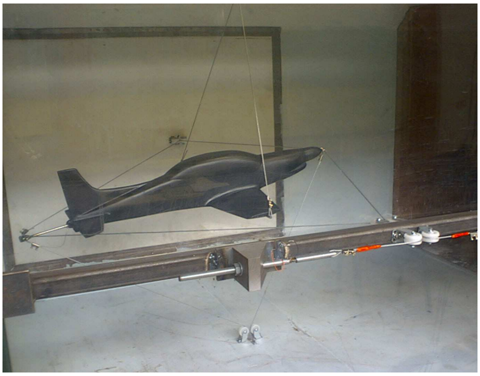
The WDPSS-8 prototype has been validated by wind tunnel tests in a wind speed of 28.8 m/s. It was found in the experiments that there is little vibration occurring at the end of the scale model, which is less than that in the corresponding traditional strut supporter system shown in Fig. 1(f). And it was also been found that the fundamental frequency of WDPPS-8 is smaller than that of the corresponding traditional strut supporter. It shows the rigidity of WDPSS is better than that of traditional strut s supporter. This phenomenon will be more serious when the model is bigger and heavier. Therefore, as a supporter system of scale models in low-speed wind tunnel test, WDPSS is more suitable for researching and developing new great aircraft.



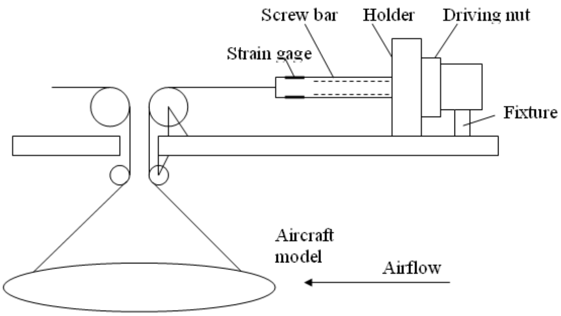
(a) The concept of wire-driven parallel suspension system with 8 wires (WDPSS-8)



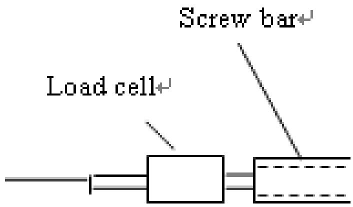
(b) Geometric definition of the WDPSS-8 prototype



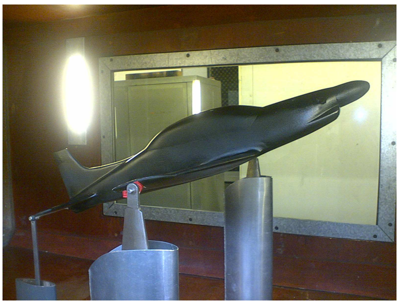
(c) WDPSS-8 tested in closed LSWT with a wind speed of 28.8 m/s



(d) Driving unit of WDPSS-8



(e) Load cell interface



(f) traditional Strut supporter system

Fig. 1. Comparison of 2 different suspension systems

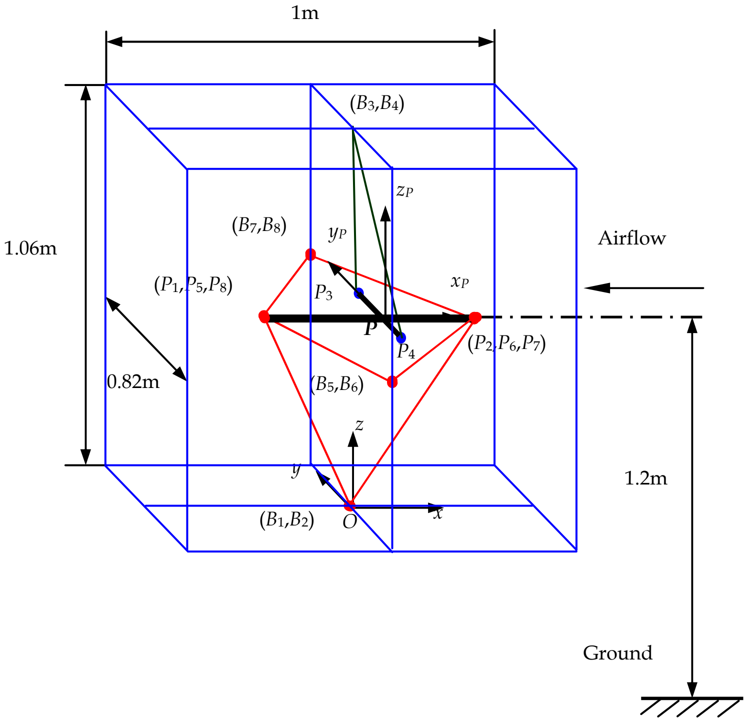
Pitch (°)	C_1 (X,Y,Z)	C_2 (X,Y,Z)	C_3 (X,Y,Z)	C_4 (X,Y,Z)
-6	-300, 0, -32	300, 0, 32	0, 605, -30	0, -605, -30
0	-302, 0, 0	302, 0, 0	0, 605, -30	0, -605, -30
6	-300, 0, 32	300, 0, -32	0, 605, -30	0, -605, -30
12	-295, 0, 63	295, 0, -63	0, 605, -30	0, -605, -30
	P_1 (X,Y,Z)	P_2 (X,Y,Z)	P_3 (X,Y,Z)	P_4 (X,Y,Z)
	0, 0, 420	0, 0, -420	0, 605, 0	0, -605, 0

Table 1. Geometric parameters of the WDPSS-8 prototype (unit :mm)

3.1.2 Another WDPSS-8 prototype tested in an open return circuit wind tunnel

To meet need of open wind tunnels, another kind of WDPSS has to be developed. Second WDPSS-8 presented in the context is one of them. The geometric definition of the WDPSS-8 is shown in Fig. 2(a). And its structural parameters are listed in Table 2.

A test platform about this WDPSS-8 for low-speed wind tunnels realized also is shown in Fig.2 (b) and Fig.2 (c), in which the 3 rotational attitude control of the scale model (yaw, roll and pitch) has been accomplished [27]. The corresponding prototype has been built shown in Fig. 3. During the wind tunnel testing, it is necessary to place the scale model using the suspension system in the experimental section of wind tunnels. And the attitude of the scale model must be adjustable. To give different attitude of the scale model in movement control, the inverse kinematics problem is required to be solved to deals with the calculation of the length of each cable correspond to the attitude wanted of the model. The solution to the problem will provide the data for the movement control experiment. The modeling of inverse pose kinematics of WDPSS-8 can be found in references [18, 22].



(a) Another geometric definition of WDPSS-8 prototype

(b) Prototype of WDPSS-8 (c) Circuit connecting in the control cupboard

Fig. 2. WDPSS-8 prototype for open return circuit wind tunnel

P_1 (x_P,y_P,z_P)	P_2 (x_P,y_P,z_P)	P_3 (x_P,y_P,z_P)	P_4 (x_P,y_P,z_P)
-150, 0, 0	120, 0, 0	0, 142.5,0	0, -142.5, 0
B_1 (X,Y,Z)	B_3 (X,Y,Z)	B_5 (X,Y,Z)	B_7 (X,Y,Z)
0, 0, 0	0, 0, 1060	0, -410, 530	0, 410, 530

Table 2. Structural parameters of the WDPSS-8 prototype (unit: mm)

3.2 Calculation of the static derivatives

Fig. 3. Control experiment of attitude angle

Because the scale model moves in a quasi-static way during the LSWT experiment for the static derivatives, it is reasonable to calculate the aerodynamic force and torque exerted on it using the difference of the force and torque exerted on the scale model between without wind and with wind. As the preliminary research, the assumption that all constraints are perfectly applied with no resistance in pulleys or other mechanisms such as point-shaped joints which are required to maintain the geometry of the wires at the base and the scale model is given for the convenience. Maybe this is not practically the case, but it is reasonable because the attitude of the scale model is controlled and adjusted in a quasi-static way so that the errors about the mechanism configuration between without wind and with wind could easily limited to a range that can be neglected.
The static model of WDPSS-8 without wind can be expressed by:

$$\boldsymbol{J}^{\mathrm{T}}\boldsymbol{T}+\boldsymbol{F}_{\mathrm{G}}=\boldsymbol{0} \tag{1}$$

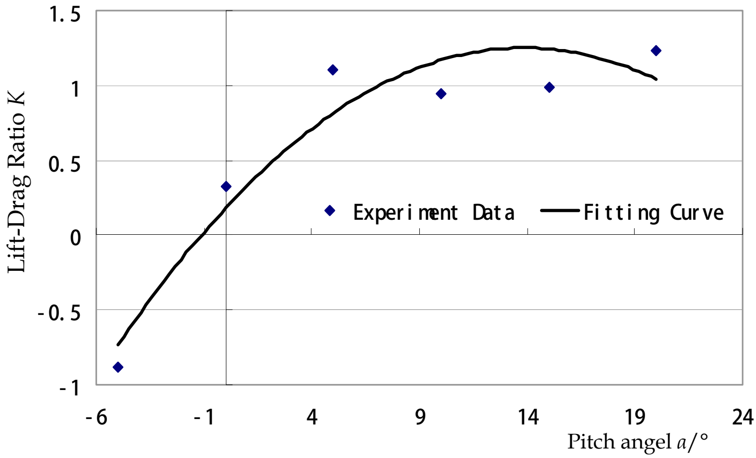
Here, $\boldsymbol{T}$ is a tension vector $(t_1 \ldots t_8)^{\mathrm{T}}$ with 8 components related to 8 wires without wind, $\boldsymbol{0}$ is a null vector with 6 components, $\boldsymbol{J}^{\mathrm{T}}$ is the structural matrix of the manipulator, $\boldsymbol{F}_{\mathrm{G}}$ is the gravity vector with 6 components.
The static model of WDPSS-8 with wind load can be expressed by:

$$J^{\mathrm{T}}T_{\mathrm{W}}+F_{\mathrm{G}}+F_{\mathrm{A}}=0 \tag{2}$$

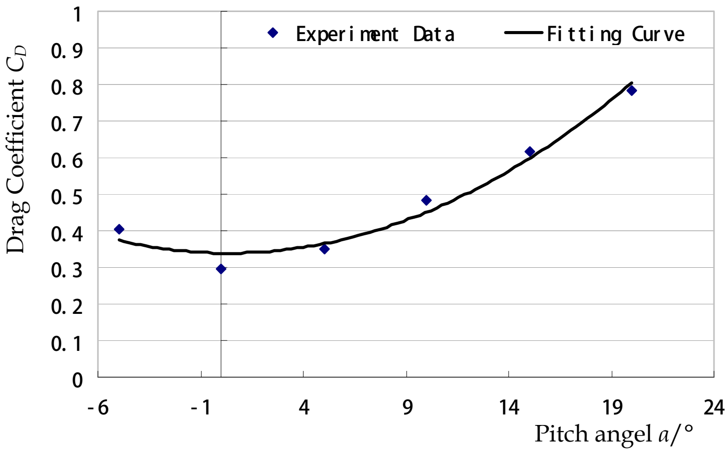
Here, $\boldsymbol{F}_{\mathrm{A}}$ is the vector of aerodynamic force and torque with 6 components, and $\boldsymbol{T}_{\mathrm{W}}$ is the tension vector composed of the tension of 8 wires with wind.
From Eqs.(1) and (2) , it can be found that the equation $\boldsymbol{F}_{\mathrm{A}}=\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{T}-\boldsymbol{T}_{\mathrm{W}})$ is satisfied.
In order to calculate the static derivatives (related to $\boldsymbol{F}_{\mathrm{A}}$), the tension of all wires and the posture of the scale model need to be measured when the position of the scale model is controlled without wind and with wind. The experiment of static derivatives using second WDPSS-8 has been finished in an open return circuit low-speed wind tunnel, which will be stated in the following in detail.
The prototype of second WDPSS-8 has been set in an open return circuit low- speed wind tunnel for blowing test, as shown in Fig.7. The experimental section of the wind tunnel is rectangular with the width of 0.52 meter and the height of 0.50 meter. The space has a length of 1 meter long [26].

Fig. 7. Second WDPSS prototype in open return circuit LSWT for blowing test

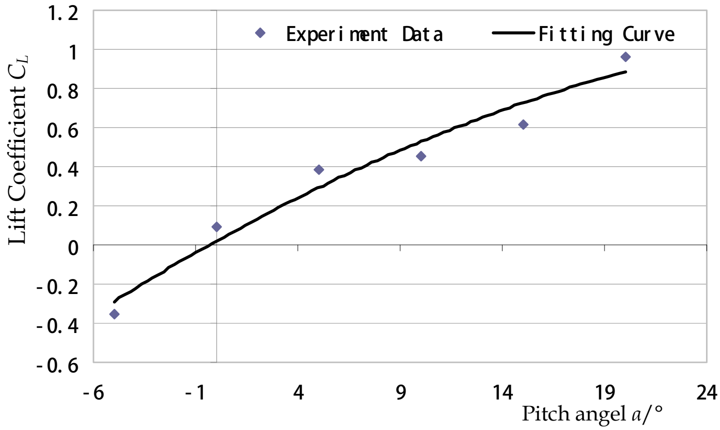
As shown in Fig.7, an airplane model is suspended by second WDPSS-8 in the experimental section of the open return circuit low-speed wind tunnel for tests. And the airflow speed can be adjusted among 0~50m/sec.



(a) Lift-Drag Ratio K *vs*. pitch angel a



(a) Drag coefficient C_D *vs*. pitch angel a



(a) Lift coefficient C_L *vs*. pitch angel α

Fig. 8. Aerodynamic parameter curves from wind tunnel test with WDPSS-8

Because the F_A is determined by $\boldsymbol{T}$ and $\boldsymbol{T}_W$, every components t_i(i=1,2,…,8) of them must be obtained in wind tunnel test. The force-measurement system in the WDPSS-8 consists of the power, force sensors, transducers, interface circuit and data acquisition card.
A group of wind tunnel tests has carried out and a series of experimental curves including lift coefficient C_L, drag coefficient C_D and lift/drag ratio K versus angle of pitch has been acquired by calculating the equation $\boldsymbol{F}_A = \boldsymbol{J}^T(\boldsymbol{T} - \boldsymbol{T}_W)$.
As shown in Fig.8, there are 3 experimental curves for wind tunnel testing of WDPSS-8 with a wind speed of 29.37m/s. Though there is no data about the standard model as a criterion, the curves are reasonable and suitable for expressing the aerodynamic characteristics of the airplane model.

4 WDPSS-8 for the Experiments of Dynamic Derivatives of the Aircraft model for Low-Speed Wind Tunnels

To get dynamic derivatives, the single-DOF oscillation control to the scale model with support system in wind tunnel and the calculation of dynamic derivatives are all very important steps. As a novel attempt, the former has been realized on the prototype of second WDPSS-8. And in theory, the calculating method for dynamic derivatives with WDPSS in low-speed wind tunnel has been also investigated.
In the following, the preliminary oscillation control of the scale model implemented in the test platform of WDPSS-8 will be stated at first, and then the calculation of dynamic derivatives will be given after based on the analysis of the dynamic modeling of the system and oscillation control scheme.

4.1 The preliminary oscillation control of the scale model

With the prototype of second WDPSS-8, the single-DOF oscillation control of the scale model has been implemented successfully [23-26]. This shows it is possible to use WDPSS for the experiment of dynamic derivatives.

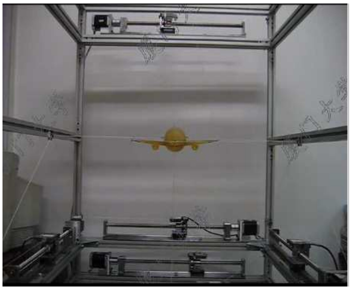


Fig. 9. The single-DOF pitch oscillation control of the scale model

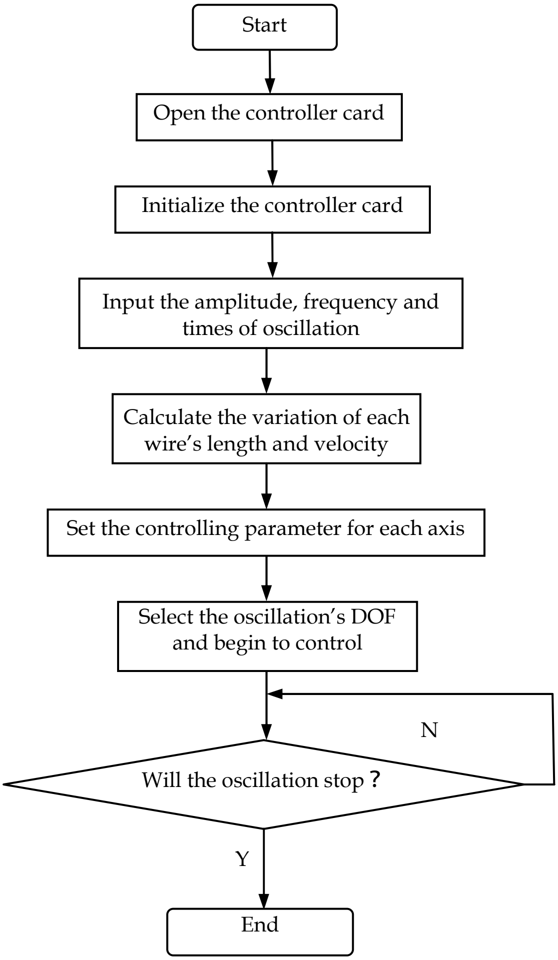


Fig. 10. Flow chart of oscillation control program

Attitude	Amplitude (°)	Frequency (Hz)
Pitch Angle	5	1.5
	10	0.625
Roll Angle	5	2
	10	1.25
Yaw Angle	5	0.625
	10	0.5

As shown in Fig.9, an airplane model suspend by the prototype of WDPSS-8 has been controlled to oscillate in the single-DOF (including pitch, roll and yaw). The amplitude ranges from 0 to 10 degree and the frequency ranges from 0 to 2 Hz for each kind of oscillation. The flow chart of oscillation control program is shown in Fig.10. According to the requirements for the experiments of dynamic derivatives, the oscillation control of the scale model is accomplished according to the suitable selection of the parameters for amplitude and frequency listed in Table 3. More detailed information and video about the experimental results can be found in the URL: http://blog.sina.com.cn/AircraftEngineering [27].

4.2 Dynamic modeling of the system and the scheme of oscillation control

The dynamic modeling to suspension system is necessary to design the control system for the oscillation of the scale model. In building the dynamic model, the assumptions are given as follows:

- The deformation of wires is so small that it may be neglected, and the mass of the wires can be neglected as well.
- The dynamics of the actuators is neglected to simplify the dynamics model of the manipulator.

In references [18, 20], the total dynamic modeling of WDPSS-8 is written as:

$$(\boldsymbol{M}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J})\ddot{\boldsymbol{X}} + (\dot{\boldsymbol{M}}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{J}} + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{J})\dot{\boldsymbol{X}} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{\tau} - \boldsymbol{F}_{\mathrm{g}} \tag{3}$$

Here $\boldsymbol{M}_0 = \begin{bmatrix} (m_{\mathrm{P}}\boldsymbol{I})_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & \boldsymbol{A}_{\mathrm{G}\,(3\times3)} \end{bmatrix}$ is the inertia matrix of the scale model including any attached payload, m_{P} is the mass and $\boldsymbol{A}_{\mathrm{G}}$ is the inertia tensor about the gravity center. $\boldsymbol{M} = \mathrm{diag}(m_1,\cdots,m_8) \in \mathrm{R}^{8\times8}$ is the inertia matrix of the actuators, $\boldsymbol{X}$ is vector of the posture of the scale model, $\boldsymbol{B} = \mathrm{diag}(b_1,\cdots,b_8) \in \mathrm{R}^{8\times8}$ is the matrix of viscous friction of the actuators, $\boldsymbol{\tau} = (\tau_1, \cdots, \tau_8)^{\mathrm{T}} \in \mathrm{R}^8$ is vector of the torque of the actuators, $\boldsymbol{F}_{\mathrm{g}} = (0,0,m_{\mathrm{P}}.g,0,0,0)^{\mathrm{T}}$ is the gravity vector of the scale model, and g=9.8 (m/s^2).

The total dynamic modeling is a highly coupled and redundantly restrained nonlinear system which should be decoupled and linearized.

A control law of actuator vector of motor is designed as follows:

$$\boldsymbol{\tau} = (\boldsymbol{J}^{\mathrm{T}})^{+}(K_{\mathrm{d}}(\boldsymbol{X}_d - \boldsymbol{X})+ K_{\mathrm{v}}(\dot{\boldsymbol{X}}_d - \dot{\boldsymbol{X}})+\boldsymbol{F}_{\mathrm{g}})+\boldsymbol{v} \tag{4}$$

Here, $\boldsymbol{J}^{\mathrm{T}}\ \boldsymbol{v}=\boldsymbol{0}$ is satisfied, moreover K_{d} and K_{v} are the different values of the control feedback gain without wind respectively. It can be proven that the control system is stable and robust with the control law mentioned above.

It is noted that if another control law is used that can ensure the stability of the control system, the values of dynamic derivatives calculated from the control system that will be formulated in detail in the next section will be different. There may occur a question about the correctness of the method for the dynamic derivatives' calculation. However, it is regarded as reasonable after a balance of the analysis of the differences of control schemes and of their robustness is given. Much more work in the aspect will be discussed in the future work. Moreover the required repeatability of the control system will be indicated and investigated using some kind of tools like robustness.

4.3 Dynamic derivatives' calculation

In the test platform of WDPSS-8, the oscillation control of the scale model is controlled without wind and with wind respectively. According to the experimental data, the aerodynamic force and torque can be calculated by the dynamic equations of the system. Also the dynamic derivatives may be calculated by the real torques of motors without wind and with wind, which can be measured by the force sensors mounted on the axis of the motors.

Taking the pitch oscillation as an example, i.e., $X = \boldsymbol{\theta}_P = \{0 \quad 0 \quad 0 \quad 0 \quad \theta_P \quad 0\}^T = \{0 \quad 0 \quad 0 \quad 0 \quad \theta_{\mathrm{P0}} \sin \omega t \quad 0\}^T$, the total dynamic model without wind and with wind can be obtained. In fact, the single-DOF oscillation control of the scale model has been successfully executed on the WDPSS-8 prototype, the frequency of which is from 0~2 Hz and the amplitude of which is 5~10 degree, see Table 3[25]. In addition, the motion versus time tracks that differs by small fractions of a degree should be provided by a motion control system. To obtain accurate measurements of the dynamic derivatives, maybe a time-varying discrete control system should be built and investigated. As the preliminary research, it is only regarded as a time-constant continuous control system. Moreover, the specifications on the path of the single-DOF oscillation of the scale model matching with wind on and wind off should be considered to an extent that target precisions are related to expected accuracies of the measured derivatives, but this issue will not be discussed here. Much more work in the aspect will be discussed in the future work by the tools like the robustness of the control system.

 Under the condition when the scale model has a pure pitch rotation without wind, Eq.(3) can be written as

$$(\boldsymbol{M}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J})\ddot{\boldsymbol{\theta}}_P + (\dot{\boldsymbol{M}}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{J}} + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{J})\dot{\boldsymbol{\theta}}_P = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{\tau} - \boldsymbol{F}_{\mathrm{g}} \tag{5}$$

From Eq.(5), $a\ddot{\theta}_P + b\dot{\theta}_P = c$ can be got. Here, a is the result of adding all the elements of the 5th row of Matrix $(\boldsymbol{M}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J})$,

b is the result of adding all the elements of the 5th row of Matrix $(\dot{\boldsymbol{M}}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{J}} + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{J})$,

$c = K_{\mathrm{d}}(\theta_{Pd} - \theta_P) + K_{\mathrm{v}}(\dot{\theta}_{Pd} - \dot{\theta}_P)$, θ_{Pd} and $\dot{\theta}_{Pd}$ are the desired pitch angle and angular velocity of the scale model.

$M_y(t)_{off}$, defined as the oscillation torque vector of the system without wind when the scale model has a pure pitch rotation, satisfies

$$M_y(t)_{off} = (\bar{M}_y)_{off}\sin(\omega t + \lambda) = a\ddot{\theta}_P + b\dot{\theta}_P = c \tag{6}$$

Under the condition when the scale model has a pure pitch rotation with wind, Eq.(3) can be written as

$$M_y^{\ddot{\theta}_{\mathrm{P}}}\ddot{\boldsymbol{\theta}}_P + M_y^{\dot{\theta}_{\mathrm{P}}}\dot{\boldsymbol{\theta}}_P + M_y^{\theta_{\mathrm{P}}}\boldsymbol{\theta}_P + (\boldsymbol{M}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J})\ddot{\boldsymbol{\theta}}_P +$$

$$(\dot{\boldsymbol{M}}_0 + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{J}} + \boldsymbol{J}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{J})\dot{\boldsymbol{\theta}}_P = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{\tau}' - \boldsymbol{F}_{\mathrm{g}} \tag{7}$$

$M_y(t)_{on}$, defined as the oscillation torque vector of the system with wind when the scale model has a pure pitch rotation, satisfies

$$M_y(t)_{on} = (\overline{M_y})_{on}\sin(\omega t + \lambda) = K_d'(\theta_{Pd} - \theta_P) + K_v'(\dot{\theta}_{Pd} - \dot{\theta}_P) \tag{8}$$

From Eqs. (5) and (7), the following equation can be obtained,

$$M_y^{\ddot{\theta}_{\mathrm{P}}}\ddot{\theta}_{\mathrm{P}} + M_y^{\dot{\theta}_{\mathrm{P}}}\dot{\theta}_{\mathrm{P}} + M_y^{\theta_{\mathrm{P}}}\theta_{\mathrm{P}} = ((\overline{M_y})_{on} - (\overline{M}_y)_{off})\sin(\omega t + \lambda) \tag{9}$$

From Eqs.(6), (8) and (9), the following equation can be obtained,

$$((\overline{M_y})_{on} - (\overline{M}_y)_{off})\sin(\omega t + \lambda) = (K_d' - K_d)(\theta_{Pd} - \theta_P) + (K_v' - K_v)(\dot{\theta}_{Pd} - \dot{\theta}_P) \tag{10}$$

In fact, the 5th element of vector torque $\boldsymbol{\tau}$ and $\boldsymbol{\tau}'$ of the motors, τ_y and τ_y', can be measured by tension sensors, which can be respectively expressed by

$$\tau_y = a_{1\tau_y}\sin\omega t + b_{1\tau_y}\cos\omega t\,;\ \tau_y' = a_{1\tau_y'}'\sin\omega t + b_{1\tau_y'}'\cos\omega t \tag{11}$$

Hence, Eq.(9) can be expressed by

$$((\overline{M}_y)_{on} - (\overline{M}_y)_{off})\sin(\omega t + \lambda) = J_5(a'_{1\tau'_y} - a_{1\tau_y})\sin\omega t + J_5(b'_{1\tau'_y} - b_{1\tau_y})\cos\omega t\,.$$

Here J_5 is the result of adding all the elements of the 5th row of Matrix $\boldsymbol{J}^{\mathrm{T}}$.

Owing to the 3 equations: $\theta_{\mathrm{P}} = \theta_{\mathrm{P0}}\sin\omega t$, $\dot{\theta}_{\mathrm{P}} = \omega\theta_{\mathrm{P0}}\cos\omega t$, $\ddot{\theta}_{\mathrm{P}} = -\omega^2\theta_{\mathrm{P0}}\sin\omega t$, Eq.(9) can be rewritten as

$$M_y^{\theta_{\mathrm{P}}} - \omega^2 M_y^{\ddot{\theta}_{\mathrm{P}}} = \frac{(\overline{M_y})_{on} - (\overline{M_y})_{off}}{\theta_{P0}}\cos\lambda = J_5(a'_{1\tau'_y} - a_{1\tau_y});$$

$$M_y^{\dot{\theta}_{\mathrm{P}}} = \frac{(\overline{M_y})_{on} - (\overline{M_y})_{off}}{\omega\theta_{P0}}\sin\lambda = J_5(b'_{1\tau'_y} - b_{1\tau_y})$$

Owing to the 3 equations: $M_y^{\dot{\theta}_{\mathrm{P}}} = M_y^{\dot{\alpha}} + M_y^{\omega_y}$; $M_y^{\ddot{\theta}_{\mathrm{P}}} = M_y^{\dot{\omega}_y}$; $M_y^{\theta_{\mathrm{P}}} = M_y^{\alpha}$), Eqs.(9) may be rewritten as:

$$M_y^{\alpha} - \omega^2 M_y^{\dot{\omega}_y} = \frac{(\overline{M_y})_{on} - (\overline{M_y})_{off}}{\theta_{P0}}\cos\lambda = J_5(a'_{1\tau'_y} - a_{1\tau_y}) \tag{12}$$

$$M_y^{\dot{\alpha}} + M_y^{\omega_y} = \frac{(\overline{M_y})_{on} - (\overline{M_y})_{off}}{\omega\theta_{P0}}\sin\lambda = J_5(b'_{1\tau'_y} - b_{1\tau_y}) \tag{13}$$

Eqs. (11) and (12) can also be rewritten as Eq.(14) and Eq.(15) respectively, as follows

$$m_y^{\alpha} - K^2 \overline{m_y^{\dot{\omega}_y}} = \frac{(\overline{M_y})_{on} - (\overline{M_y})_{off}}{\theta_{P0}qsb_A}\cos\lambda = \frac{J_5(a'_{1\tau'_y} - a_{1\tau_y})}{\theta_{P0}qsb_A} \tag{14}$$

($m_y^{\alpha} - K^2 \overline{m_y^{\dot{\omega}_y}}$) is called In-Phase Pitch Oscillatory Derivatives. $K = \dfrac{\omega b_A}{V}$ is called reduced frequency, b_A is called mean aerodynamic chord length. V is called free-stream airflow velocity.

$$m_y^{\dot{\alpha}} + m_y^{\omega_y} = \frac{(\overline{M_y})_{on} - (\overline{M_y})_{off}}{\theta_{P0}qsb_A K}\sin\lambda = \frac{J_5(b'_{1\tau'_y} - b_{1\tau_y})}{\theta_{P0}qsb_A K} \tag{15}$$

($m_y^{\dot{\alpha}} + m_y^{\omega_y}$) is called Out-of-Phase Pitch Oscillatory Derivatives.

In the same way, the dynamic derivatives corresponding to the other 2 single-DOF oscillation (roll oscillation and yaw oscillation) also can be obtained.

Surely the analysis is just based on the theoretical aspects. The test platform of WDPSS-8 for the experiment of dynamic derivatives is still to be built and the precise measuring systems of the vibration angular displacement and the real torque of the motors should be designed and implemented.

5. Conclusions and Future Works

Basen on researching into WDPSS-8, after analysing and comparing 3 support systems in wind tunnel including the strut suspension system, cable mounted system and wire-driven parallel suspension system, the following conclusions can be acquired.

(1) Till now the strut support systems and rotary balances can be used in measuring the dynamic derivatives of the aircraft in low-speed wind tunnels successfully, wire-driven parallel suspension system has a great potentiality, but it is still under investigation.

(2) The cable mounted system is one of suitable method for measuring the static derivatives of the aircraft in LSWT. Thoug it allows a large supporting stiffness, small interference of the streamline flow and a high measuring precision for large attack angle, it can not be used in measuring the dynamic derivatives.

(3) Wire-driven parallel suspension system has opened a new horizon for measuring the static and dynamic derivatives of the aircraft in LSWT. Using the same system based on positon control and force control in robotics, it allows to realize the free flight of the aircraft model and to obtain the static and dynamic derivatives. However, the results given in this Chapter can only be considered as a preliminary step in establishing feasibility, although the wire-driven parallel suspension system is a very interesting design, and it may be sufficiently developed into a rountine practical system.

6. Acknowledgements

This research is sponsored by National Natural Science Foundation of China(Grant No. 50475099), the Youth Talents Creation Foundation of Fujian Province (Grant No. 2006F3083). and the Scientific Launch Foundation for the Talents of Huaqiao University (Grant No. 06BS218).

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8. Appendix(the list of the publications of the authors in the field of wire-driven parallel suspension systems for low-speed wind tunnels)

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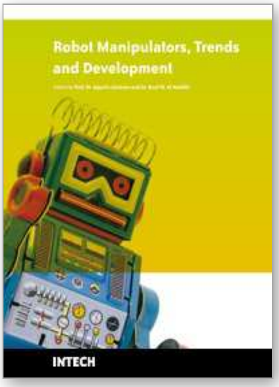

Robot Manipulators Trends and Development

Edited by Agustin Jimenez and Basil M Al Hadithi

ISBN 978-953-307-073-5
Hard cover, 666 pages
Publisher InTech
Published online 01, March, 2010
Published in print edition March, 2010

This book presents the most recent research advances in robot manipulators. It offers a complete survey to the kinematic and dynamic modelling, simulation, computer vision, software engineering, optimization and design of control algorithms applied for robotic systems. It is devoted for a large scale of applications, such as manufacturing, manipulation, medicine and automation. Several control methods are included such as optimal, adaptive, robust, force, fuzzy and neural network control strategies. The trajectory planning is discussed in details for point-to-point and path motions control. The results in obtained in this book are expected to be of great interest for researchers, engineers, scientists and students, in engineering studies and industrial sectors related to robot modelling, design, control, and application. The book also details theoretical, mathematical and practical requirements for mathematicians and control engineers. It surveys recent techniques in modelling, computer simulation and implementation of advanced and intelligent controllers.