# MODELING AND CONTROL OF A WIRE-DRIVEN PARALLEL SUPPORT SYSTEM WITH LARGE ATTACK ANGLES IN LOW SPEED WIND TUNNELS

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## Abstract

*The range of the incidence of modern vehicles in low speed wind tunnel tests is usually very large which can't be carried out by a traditional frame support system. A new wire-driven parallel support system for low-speed wind tunnels to suspend a 1:40 scale model of F-15E is presented. By this design, the ranges of pitch , roll and yaw angles of the scale model at the home pose are all from -90 degree to 90 degree. Such a design has been validated by wind tunnel tests in a wind speed of 28.8 meters per second. And it has been found that there is only very little vibration occurring at the end of the scale model which is less than that in a traditional frame support system. The control law of the wire-driven parallel support system is studied in other parts of the paper. In order to uniquely determine and easily measure the states of the system, the variables of the wire lengths are used for describing the motion of the scale model. Then, the kinematics and statics of the system are studied, and a dynamic model of the system is established. Based on the model, the tracking control of the attitude change of the scale model during a wind tunnel test is studied, and a motion control scheme in the task-oriented coordinates is proposed because it is necessary to obtain accurate attitude angles of the scale model and also it is easy to attain more precise positioning by using external sensors such as cameras to measure the posture of the scale model. The PD controller in the task-oriented coordinates is designed based on a rigid model without considering the elasticity of the wires, and the motion convergence of the scale model to the desired postures is proven and the robustness based Lyapunov stability analysis is discussed. Finally, a simulation is made, and the results show that the proposed control scheme is useful and it is validated that if the estimation errors of the structurematrix of the system is smaller and the feedback gains of the PD controller are larger, the errors of the position and orientation of the scale model during a tracking control will be smaller*

## 1 General Introduction

Wind tunnel test of aircraft model is widely used to investigate the potential flight and aerodynamics characteristics of aircrafts at their early developing stage. The range of attack angle during wind tunnel tests is larger for the modern aricrafts, expecially that for the new generation of fighters is over 90 degree. In such a condition, the support stiffness of the traditional frame support systems is so weak, especailly when the aircraft model is at a posture with a large attack angle, with the result that the viration between the whole system including the aircraft model, balance and support system would occur.On the other hand, the unavoidable frame interference in the streamline flow has significant influence on the force and moment measurement, which can't be compensated completely by the experimental methods [1-3].

Cable mount system presented two decades ago and wire-drivan parallel support system (WDPSS) proposed recently are two alternatives to overcome this problem, in which WDPSS has some obvious advantages to cable mount system in system configuration and motion control [3-6].

The new concept of wire-driven parallel support system in wind tunnels has been presented in recent years with the outcome of parallel manipulators and force control[7,8]. As shown in Fig.1, the scale model is driven by

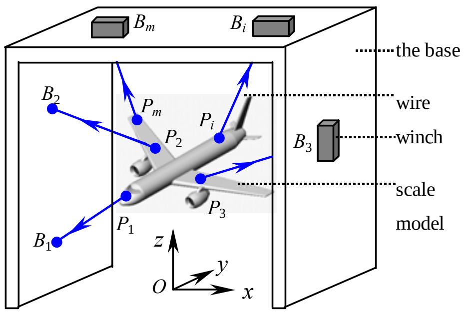



Fig.1. 6-DOF wire-driven parallel support system

more than 7 wires via pointed joints. The other end of each wire is guided by a wrench mounted on the base via pointed joint. The posture of the scale model corresponding to the streamline of airflows can be adjusted by controlling the length of wires to implement the six-degree-of-freedom(DOF) free flight motion. The aerodynamic forces exerted on the scale model can be calculated by measuring the tension of each wire to implement the force control[9].

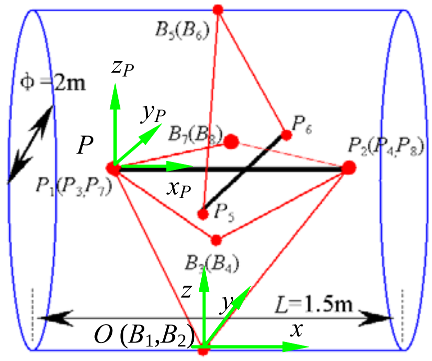
Preliminary achievements have been made in the Suspension ACtive pour SOufflerie (SACSO) project about wire-driven parallel support system in low speed wind tunnels sponsored by Office National d'Études et de Recherches Aérospatiales(ONERA). The SACSO-9 system is suitable for wind tunnels with the diameter of 4 meters, which is under test and adjustment[8,9]. Some researchers in China have done some fundamental theoretical research work in the field , and a prototype is being built with the aid of National Natural Science Foundation of China(NSFC)[8-11].

How to accurately implement the attitude control and force measurement are two key issues for wire-driven parallel support system in wind tunnels. Research on modeling and attitude control of wire-driven parallel support system with large attack angles in wind tunnels will be presented in the paper.

## 2 Modeling of wire-driven parallel support system in low speed wind tunnels

The aircraft model is the 1:40 scale model of F-15E. Suppose that the diameter of the experimental section of the wind tunnel is 2 meters. The aircraft's wingspan is 13.5 meters, its length is 19.45 meters, and its height is 5.64meters.

A six-**DOF WDPSS** is essential for free fight in a 3 dimensional space wind tunnel. Fig. 2(a) shows a 6-**DOF WDPSS** driven by 8 wires with decoupling rotational degrees of freedom.




(a)

(b)

Fig.2. Structure of the wire-driven parallel support system for wind tunnel: **WDPSS**-8

The moving coordinate system (MCS) $Px_Py_Pz_P$ is on the scale model, and the position of the reference point of $P$ is denoted by $\boldsymbol{X}_P$ ($X_P$, $Y_P$,

$Z_P$). The orientation $\boldsymbol{X}_{\text{ang}}$ of the scale model is represented by the roll, pitch and yaw angles ($\varphi_{\text{Y}}, \varphi_{\text{P}}, \varphi_{\text{R}}$) of the MCS $Px_Py_Pz_P$ related to the fixed coordinate system (FCS)$Oxyz$. Here $\varphi_{\text{R}}$ is the roll angle of the scale model around axis $Oz$, $\varphi_{\text{P}}$ is the pitch angle of the scale model around axis $Oy$, and $\varphi_{\text{Y}}$ is the yaw angle around axis $Ox$. The joints of the wires in the FCS $Oxyz$ are denoted by $B_i$ ($X_{B,i}$, $Y_{B,i}$, $Z_{B,i}$) ($i$=1,⋯,8)with $B_1$ ($B_2$)： (0,0,0), $B_3$ ($B_4$)： (0,-1,1), $B_5$ ($B_6$)：(0,0,2), and $B_7$ ($B_8$)： (0,1,1) (unit in meter).The joints of the wires on the scale model in the MCS $Px_Py_Pz_P$ are denoted by $P_i$($x_{P,i}$, $y_{P,i}$, $z_{P,i}$) ($i$=1,⋯,8) with $P_1$ ($P_3$, $P_7$)： (0,0,0), $P_2$ ($P_4$, $P_8$)： (1.535,0,0), $P_5$： (0.7675,-0.6488,0), and $P_6$： (0.7675,-0.6488,0).

The WDPSS has the following features:

(1) When the scale model is in the home pose, i.e., in the middle of the wind tunnel, the range of pitch angle is 90°～90°, the range of yaw angle $\varphi_{\text{Y}}$ is -90°～90°and the range of roll angle $\varphi_{\text{R}}$ is -90°～ 90°.

(2) The solutions to the forward kinematic problem have closed-form expressions.

Such a design has been validated by wind tunnel tests in a wind speed of 28.8 meters per second, shown in Fig. 2(b). And it has been found that th ere is only very little vibration occurring at the e nd of the scale model which is less than that in a traditional frame support system.

## 2.1 Statics and Dynamics

### *2.1.1 Inverse/forward position kinematics*

The inverse kinematics deals with the calculation of the lengths of all wires $l_i\,(i=1,\cdots,8)$ under the assumption of the given posture $P$ of the scale model, $\boldsymbol{X}$=( $\boldsymbol{X}_P$, $\boldsymbol{X}_{\text{ang}}$)$^{\text{T}}$, supposing that $l_i$=||$\boldsymbol{B}_i$-$\boldsymbol{P}_i$||(here $\boldsymbol{P}_i$ denotes the positions of all the joints $P_i$($X_{P,i}$, $Y_{P,i}$, $Z_{P,i}$) ($i$=1,⋯,8) in the FCS $Oxyz$, and $\boldsymbol{B}_i$ denotes the positions of all the joints $B_i$ ($X_{B,i}$, $Y_{B,i}$, $Z_{B,i}$) in the FCS $Oxyz$ ).

For a given posture of the scale model: $\boldsymbol{X}$, the positions of all the joints $P_i$($X_{P,i}$, $Y_{P,i}$, $Z_{P,i}$) ($i$=1,⋯,8) in the FCS $Oxyz$ can be obtained from

$$\begin{bmatrix} X_{P,i} \\ Y_{P,i} \\ Z_{P,i} \end{bmatrix} = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} + T \begin{bmatrix} x_{P,i} \\ y_{P,i} \\ z_{P,i} \end{bmatrix} \tag{1}$$

In which the transformation matrix of the MCS $Px_Py_Pz_P$ with respect to the FCS $Oxyz$ is

$$\begin{aligned} \boldsymbol{T} &= \boldsymbol{T}_{\text{Z}}(\varphi_{\text{Y}})\boldsymbol{T}_{\text{Y}}(\varphi_{\text{P}})\boldsymbol{T}_{\text{X}}(\varphi_{\text{R}}) \\ &= \begin{bmatrix} c_Y & -s_Y & 0 \\ s_Y & c_Y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_P & 0 & s_P \\ 0 & 1 & 0 \\ -s_P & 0 & c_P \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_R & -s_R \\ 0 & s_R & c_R \end{bmatrix} \\ &= \begin{bmatrix} c_P c_Y & c_Y s_P s_R - s_Y c_R & s_Y s_R + c_Y s_P c_R \\ c_P s_Y & c_Y c_R + s_R s_P s_Y & s_P s_Y c_R - c_Y s_R \\ -s_P & s_R c_P & c_P c_R \end{bmatrix} \end{aligned}$$

Where,

$c_R = \cos(\varphi_R)$, $c_P = \cos(\varphi_P)$, $c_Y = \cos(\varphi_Y)$,

$s_R = \sin(\varphi_R)$, $s_P = \sin(\varphi_P), s_Y = \sin(\varphi_Y)$,

$\varphi_R$, $\varphi_P$ and $\varphi_Y$ are the roll, pitch and yaw angles respectively.

The forward kinematics deals with the calculation of the posture of the scale model under the assumption of given the lengths of all wires $l_i\,(i=1,\cdots,8)$.Though the solutions to the forward kinematic problem have closed-form expressions, the expressions of the three attitude angles are not unique and they should be discarded according to the initial assembly mode of the system. The four solutions are as follows:

$$X_P = \frac{\sqrt{l_1^2-(Y_{P_1}+1)^2-Z_{P_1}{}^2}-\sqrt{l_2^2-(Y_{P_2}+1)^2-Z_{P_2}{}^2}}{2}$$

$$Z_P = \frac{l_3^2+l_4^2-l_7^2-l_8^2}{8}$$

$$Y_P = \frac{l_1^2+l_2^2-l_3^2-l_4^2}{4}+Z_P$$

or

$$X_P = \frac{-\sqrt{l_1^2-(Y_{P_1}+1)^2-Z_{P_1}{}^2}+\sqrt{l_2^2-(Y_{P_2}+1)^2-Z_{P_2}{}^2}}{2}$$

$$Z_P = \frac{l_3^2+l_4^2-l_7^2-l_8^2}{8}$$

$$Y_P = \frac{l_1^2+l_2^2-l_3^2-l_4^2}{4}+Z_P$$

or

$$X_P = \frac{\sqrt{l_1^2-(Y_{P_1}+1)^2-Z_{P_1}{}^2}+\sqrt{l_2^2-(Y_{P_2}+1)^2-Z_{P_2}{}^2}}{2}$$

$$Z_P = \frac{l_3^2+l_4^2-l_7^2-l_8^2}{8}$$

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or

$$X_P = \frac{-\sqrt{l_1^2-(Y_{P_1}+1)^2-Z_{P_1}{}^2}-\sqrt{l_2^2-(Y_{P_2}+1)^2-Z_{P_2}{}^2}}{2}$$

$$Z_P = \frac{l_3^2+l_4^2-l_7^2-l_8^2}{8}$$

$$Y_P = \frac{l_1^2+l_2^2-l_3^2-l_4^2}{4}+Z_P$$

Noting that $\boldsymbol{u}_x=(X_{P_1}-X_{P_2}, Y_{P_1}-Y_{P_2}, Z_{P_1}-Z_{P_2})$, $\boldsymbol{u}_z=(X_{P_6}-X_{P_5}, Y_{P_6}-Y_{P_5}, Z_{P_6}-Z_{P_5})$, the three attitude angles can be expressed as follows:

$$\cos(\varphi_R)=\frac{(X_{P_1}-X_{P_2})}{\sqrt{(X_{P_2}-X_{P_1})^2+(Y_{P_2}-Y_{P_1})^2+(Z_{P_2}-Z_{P_1})^2}}$$

$$\cos(\varphi_P)=\frac{(Z_{P_6}-Z_{P_5})}{\sqrt{(X_{P_6}-X_{P_5})^2+(Y_{P_6}-Y_{P_5})^2+(Z_{P_6}-Z_{P_5})^2}}\ .$$

Suppose that $\boldsymbol{u}_y=\boldsymbol{u}_z\times\boldsymbol{u}_x$, then there is $\cos(\varphi_Y)=\frac{(\boldsymbol{u}_y)_z}{|\boldsymbol{u}_y|}$.

### *2.1.2 Statics*

As shown in Fig. 2(a), suppose that $\boldsymbol{L}_i=\boldsymbol{P}_i\boldsymbol{B}_i$, $l_i=\|\boldsymbol{L}_i\|$, $\boldsymbol{u}_i=\boldsymbol{L}_i/l_i$, $t_i$ is the tension of the i$^{th}$ wire, which exerts a wire tension vector $\boldsymbol{T}_i=t_i\,\boldsymbol{u}_i$ on the scale model. Suppose that $\boldsymbol{r}_i=\boldsymbol{PP}_i$, the requirement that the wrench can be exerted on the scale model is that the tension of all wires is greater than zero. Suppose that the scale model sustains the tension of 8 wires and the gravity and keep in the static equilibrium, the following equation is satisfied,

$$\boldsymbol{F}=\boldsymbol{J}^{\mathrm{T}}\boldsymbol{T} \tag{2}$$

Where $\boldsymbol{T}$ is a 8-component vector $(t_1 \ \cdots \ t_8)^{\mathrm{T}}$, the wrench $\boldsymbol{F}=\begin{pmatrix}(m_{\mathrm{P}}.\boldsymbol{g})_{3\times1}\\ \boldsymbol{0}_{3\times1}\end{pmatrix}$ is a 6-component vector, and $\boldsymbol{J}^{\mathrm{T}}$ cab be expressed by the following equation:

$$\boldsymbol{J}^{\mathrm{T}}=\begin{bmatrix}\boldsymbol{u}_1 & \cdots & \boldsymbol{u}_8\\ \boldsymbol{r}_1\times\boldsymbol{u}_1 & \cdots & \boldsymbol{r}_8\times\boldsymbol{u}_8\end{bmatrix}_{6\times8} \tag{3}$$

## 2.2 Dynamics

Dynamic model of the system is the basis of the design of control system, the accuracy of which will influence the characteristic of the control system. In order to simplify the theoretical analysis, the following assumptions are given as follows:

(1) The deformation of wires is so small that it can be neglected.
(2) The mass of the wires can be neglected.
(3) The centroid of the actuator is located at the rotation axis.

### *2.2.1 The actuators dynamics*

The actuators dynamics can be represented by

$$\boldsymbol{M}\ddot{\boldsymbol{l}}+\boldsymbol{B}\dot{\boldsymbol{l}}=\boldsymbol{\tau}-\boldsymbol{T} \tag{4}$$

Where,

$\boldsymbol{l}=(l_1,\cdots,l_8)^{\mathrm{T}}\in\mathrm{R}^8$ :wire-length vector,
$\boldsymbol{M}=\mathrm{diag}(m_1,\cdots,m_8)\in\mathrm{R}^{8\times8}$ :actuator inertia matrix,
$\boldsymbol{B}=\mathrm{diag}(b_1,\cdots,b_8)\in\mathrm{R}^{8\times8}$ :actuator viscous friction coefficient matrix,
$\boldsymbol{\tau}=(\tau_1,\cdots,\tau_8)^{\mathrm{T}}\in\mathrm{R}^8$ :motor torque vector,
$\boldsymbol{T}=(t_1,\cdots,t_8)^{\mathrm{T}}\in\mathrm{R}^8$ :wire tension vector.

### *2.2.2 The dynamics of the scale model*

The dynamics of the scale model is expressed by

$$\frac{d}{dt}(\boldsymbol{M}_0\cdot\dot{\boldsymbol{X}})=\boldsymbol{F}-\boldsymbol{F}_{\mathrm{g}} \tag{5}$$

Where,

$\boldsymbol{M}_0=\begin{bmatrix}(m_{\mathrm{P}}\boldsymbol{I})_{3\times3} & 0_{3\times3}\\ 0_{3\times3} & \boldsymbol{A}_{\mathrm{G}(3\times3)}\end{bmatrix}$ is inertia matrix of the scale model,
$m_{\mathrm{P}}$ : mass of the scale model,
$\boldsymbol{A}_{\mathrm{G}}$ : inertia tensor in the FCS,
$\boldsymbol{X}$ : posture of the given point $P$ of the scale model,
$\boldsymbol{F}$ :wrench vector, satisfying the Equation: $\boldsymbol{F}=\boldsymbol{J}^{\mathrm{T}}\boldsymbol{T}$, where $\boldsymbol{J}$ is the Jacobi matrix which satisfies $\dot{\boldsymbol{l}}=\boldsymbol{J}\dot{\boldsymbol{X}}$,
$\boldsymbol{F}_{\mathrm{g}}=(0,0,m_{\mathrm{P}}.g,0,0,0)^{\mathrm{T}}$ : gravity vector of the scale model,
$g$ :acceleration of gravity.

### *2.2.3 The total dynamics of the system*

From Eqs.(4) and (5), the total dynamics is expressed by

$$\begin{aligned}&(\boldsymbol{M}_0+\boldsymbol{J}^{\mathrm{T}}\boldsymbol{MJ})\ddot{\boldsymbol{X}}+(\dot{\boldsymbol{M}}_0+\boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{J}}\\ &+\boldsymbol{J}^{\mathrm{T}}\boldsymbol{BJ})\dot{\boldsymbol{X}}=\boldsymbol{J}^{\mathrm{T}}\boldsymbol{\tau}-\boldsymbol{F}_{\mathrm{g}}\end{aligned} \tag{6}$$

The dynamic model of wire-driven parallel system is highly-coupled and nonlinear system, and the actuation redundancy makes the system over-restrained. In designing the control scheme, it is necessary to decouple and linearize the dynamic model using constant gravitational compensation and tension calculation algorithm [8].

## 3 The attitude control of the scale model

The attitude control of the scale model is actually a kind of position control, which can be implemented by controlling the length of wires and the posture of the scale model. Because the accurate attitude angles are necessary for the wind tunnel tests, the motion control scheme in task oriented coordinates with strong robustness and stability will be introduced in the paper and some simulation results will be given.

### 3.1 PD feedback control law

As shown in Fig.3, a PD feedback control law in task oriented coordinates id employed, by measuring the position and orientation $\boldsymbol{X}$ in the FCS basing on external sensors, the input vector is given as follows:

$$\boldsymbol{\tau}=(\boldsymbol{J}^{\mathrm{T}})^{+}(\boldsymbol{K}_{\mathrm{p}}(\boldsymbol{X}_{\mathrm{d}}-\boldsymbol{X})+\boldsymbol{K}_{\mathrm{v}}(\dot{\boldsymbol{X}}_{\mathrm{d}}-\dot{\boldsymbol{X}})+\boldsymbol{F}_{\mathrm{g}})+\boldsymbol{v},$$

where $\boldsymbol{J}^{\mathrm{T}}\boldsymbol{v}=\boldsymbol{0}$.

Combining Eq.(7) with the control law, a closed-loop system can be expressed by:

$$(\boldsymbol{M}_0+\boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{J})\ddot{\boldsymbol{X}}+(\dot{\boldsymbol{M}}_0+\boldsymbol{J}^{\mathrm{T}}\boldsymbol{M}\dot{\boldsymbol{J}}$$
$$+\boldsymbol{J}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{J}+\boldsymbol{K}_{\mathrm{v}})\dot{\boldsymbol{X}}-\boldsymbol{K}_{\mathrm{p}}(\boldsymbol{X}_{\mathrm{d}}-\boldsymbol{X})-\boldsymbol{K}_{\mathrm{v}}\dot{\boldsymbol{X}}_{\mathrm{d}}=\boldsymbol{0}$$

In Ref.[12],considering a positive-definite Lyapunov function using the total energy of the system, the stability of the control method can be proven, which shows that the vector $\boldsymbol{X}$ converges to $\boldsymbol{X}_d$ as time t tends to infinity, and at last the actuator torque vector converges to $\boldsymbol{\tau}=(\boldsymbol{J}^{\mathrm{T}})^{+}\boldsymbol{F}_g+\boldsymbol{v}$.

The robustness of the control method is analyzed in Ref.[12], and the conclusion

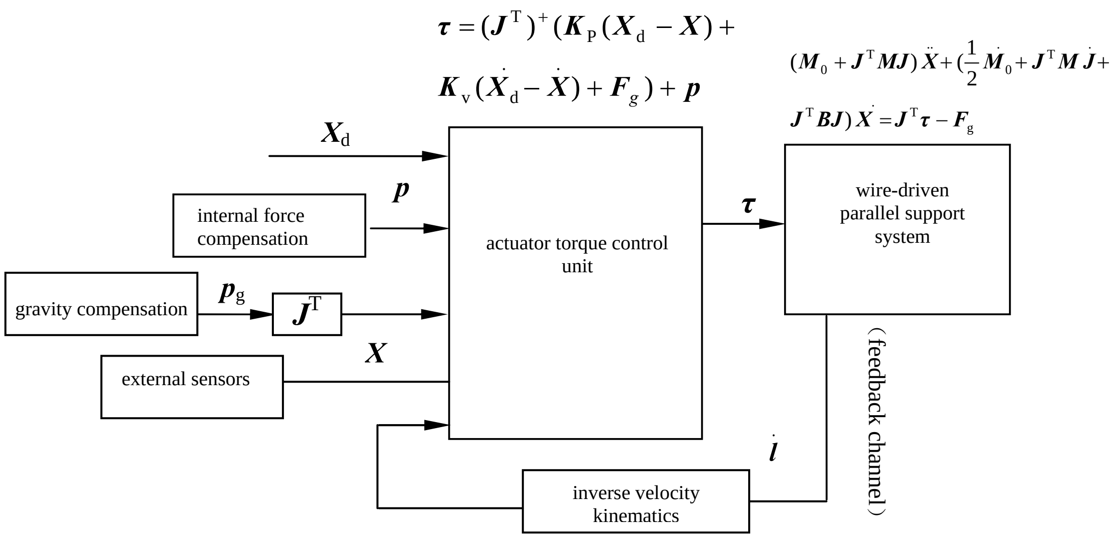


Fig.3. Attitude control

can be drawn: higher measuring accuracy of the posture of the scale model and larger feedback gains makes the errors between the desired and the actual trajectories of the scale model smaller.

### 3.2 Simulation and analysis of results

Based on the control law mentioned in the above, simulation analysis of the system performance is given. The simulation task is to make the centroid of the scale model rotate axis *Oy* at a constant speed to carry out the desired value of attack angle $\beta_d$ to range from -45degree to 45 degree. Suppose that the angular velocity of the scale model $\omega$ is 0.157 (rad /s), the mass of the scale model $m_P$ is 1 *kg*, the mass of all of the actuators, $m_i(i=1,\cdots,8)$, is 5*kg*, and the actuator viscous friction coefficient, $b_i(i=1,\cdots,8)$, is zero. The point to point control is implemented, and 10 points are selected. The actual value of attack angle $\beta$ measured by the external sensors is listed in Table 1.

The results shows that larger feedback gains makes the errors between the desired and the actual trajectories of the scale model smaller

Table 1

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\beta_d$ | −45° | −35° | −25° | −15° | −5° | 5° | 15° | 25° | 35° | 45° |
| $\beta$ | −43° | −36° | −20° | −17° | −2° | 3° | 12° | 23° | 31° | 40° |

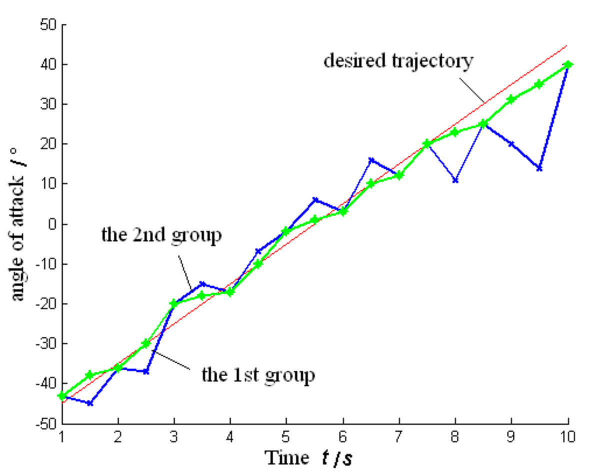


Fig.4.Tacking trajectory

## 4 Conclusions

(1) A 6-**DOF** wire-driven parallel support system with 8 wires with decoupling rotational degrees of freedom has been presented for low speed wind tunnels.

(2) It has been proven that the solutions to the forward position kinematic problem have 4 closed-form expressions.

(3) A motion control scheme in task oriented coordinates with strong robustness and stability has been used to implement the point-to-point attitude control. Simulation results have shown that higher measuring accuracy of the posture of the scale model and larger feedback gains makes the errors between the desired and the actual trajectories of the scale model smaller.

## 5 Acknowledgments

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## References

[1] Gu Y S, Ming X, Forebody vortices control using a fast swirging micro tip-strake at high angles of attack[J]. ActaAeronautica Et Astronautica Sinica, 2003, 24(2):102-106(in Chinese).

[2] Bian Y Z, Li X R, Li L, et al. Development of model cable mount and strain gauge balance measuring system in low speed closed wind tunnel[J]. Experiments and Measurements in Fluid Mechanics, 1999, 13(3): 85-90(in Chinese).

[3] Wu C. Wire suspension system for wind tunnel dynamic testing[J]. International Aviation, 2004, (5):62(in Chinese).

[4] Liu T F,Gao F X,Lu W.Mechanical property calculation of wire-support structure in wind tunnel experiment[J].Mechanics in Engineering, 2001, 23(1): 46-48(in Chinese).

[5] Shen L M,Shen Z H,Huang Y.A wire type-support system for high angle of attack test in low speed wind tunnel[J].Experiments and Measurements in Fluid Mechanics,1988,12(4):15-22(in Chinese).

[6] Yang E X,Diao Y F,Pang Y G.Bracing system of large attack angle in low speed wind tunnel[J].Applied Science and Technology, 2001,28(1):4-5 (in Chinese).

[7] Lafourcade P, Llibre M, Reboulet C. Design of a parallel wire-driven manipulator for wind tunnels[A]. In: Proceedings of the Workshop on Fundamental Issues and Future Directions for Parallel Mechanisms and Manipulators[C]. Quebec City, Quebec, 2002: 187-194.

[8] Liu X W, Zheng Y Q, Lin Q. Overview of wire-driven parallel manipulators for aircraft wind tunnels[J]. Acta Aeronautica Et Astronautica Sinica, 2004, 25(4):393-400 (in Chinese).

[9] Zheng Y Q, Lin Q, Liu X W. Design methodology of wire-driven parallel support systems in the low speed wind tunnels and attitude control scheme of the scale model[J]. Acta Aeronautica Et Astronautica Sinica, 2005, 26(6):774-778 (in Chinese).

[10] Zheng Y Q. Research on key theoretical issues of wire-driven parallel kinematic manipulators and the

application to wind tunnel support systems[D]. Quanzhou: Huaqiao University, 2004:4-104(in Chinese).

[11] Liu X W, Zheng Y Q, Lin Q. Design of a Novel Wire-Driven Parallel Support System in a Low Speed Wind Tunnel and its Calibration Using Two Inclinometers. CD Proceedings of Lamdamap 7th International Conference, Cranfield Management Development Centre, Cranfield, Bedfordshire, UK, 27th~30th June, 2005.

[12] Kino H, Cheah C C, Yabe S, et al. A motion control scheme In task oriented coordinates and its robustness for parallel wire driven systems[A]. In: Proceedings of International Conference on Advanced Robotics[C].Tokyo,1999:545-550.