ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Chinese Journal of Aeronautics 21(2008) 71-78
Chinese Journal of Aeronautics
www.elsevier.com/locate/cja

Dynamics Analysis of Close-coupling Multiple Helicopters System

Zhao Zhigang*, **Lu Tiansheng**

School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200230, China

Received 8 June 2007; accepted 26 October 2007

Abstract

The particularity and practicality of harmony operations of close-coupling multiple helicopters indicate that the researches on it are urgent and necessary. Using the model that describes two hovering helicopters carrying one heavy load, an inertia coordinate system and body coordinate systems of each sub-system are established. A nonlinear force model is established too. The equilibrium computation results can be regarded as the reference control inputs of the flight control system under hovering or low-speed flight condition. After the establishment of a translation kinematics model and a posture kinematics model, a coupling dynamics model of the multiple helicopter system is set up. The results can also be regarded as the base to analyze stabilization and design a controller for a close-coupling multiple helicopters harmony operation system.

Keywords: close-coupling; multiple helicopters; harmony operation; equilibrium computation; kinematics analysis; dynamics analysis

1 Introduction

As an automatic aircraft can be considered a flying robot, many universities and research organizations in the last year have fulfilled researches on flying robots. Helicopters have high practicality because they can take off and land vertically, hover on one point, and have larger load capability than other forms of aircraft. Moreover, complexity and particularity of helicopter's dynamics characteristics have made it an ideal object in studying the dynamics characteristics of aircraft. Therefore, helicopters are often chosen to be the preferential object to study the practices and theory of aircraft[1-4]. This paper is also dedicated to helicopters[5-8].

At present, many countries and their military organizations are doing research work on the flight theory and military uses of multiple aircraft, also could be found a lot of publications in this field[9-12]. Using multiple aircrafts, more kinds of missions could be performed than using only one aircraft. During the operation with multiple aircrafts, a great deal of message has to be exchanged between each craft, which, still, is dealt with in a loose-coupling way[13-14]. Still exist some cases, in which harmony operation of multiple helicopters with stronger and closer coupling is needed, for example, in transporting large equipment and emergency rescuing. In these cases, because the mass of the load exceeds the load capacity of a large-scale helicopter or a large crane, harmony operation between two or more helicopters with close-coupling becomes the first choice. Even if the mass of the load does not exceed a large helicopter's capacity, stronger coupling and harmony operation is still needed when a fixed posture is required to be maintained. Fig.1 shows a suspending and carrying model of a close-coupling multiple helicopters system (CCMHS).

*Corresponding author. Tel.: +86-21-54742932-819.
E-mail address: flapping@21cn.com
Foundation item: National Natural Science Foundation of China (60475039)

This is a very complex operation system. In order to analyze the working process of the proposed system, a system model must be established. It is well known that to model a helicopter is a difficult problem. The model of helicopter in common use is a 6-DOF rigid model that includes a rotor model. The dynamics and mathematic modeling of a soft object, such as a thick rope, also is a difficult problem. There are some kinds of models such as line spring model, rigid soft large rope model, rigid soft object model and spring soft object model etc[15]. From the above discussion, it is clear that the operation of a CCMHS presents a new challenge, which is abundant in practical and theoretical meanings.

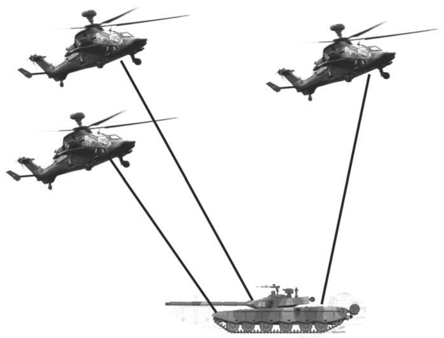

Fig.1 Suspending and carrying model of close-coupling multiple helicopters system.

The research work in connection with the multiple helicopter system includes force equilibrium computation, kinematics and dynamics analyses. The remainder of this paper is organized as follows: Section 2 introduces a kind of SSMHS. Section 3 defines the coordinates of the system. In Section 4, the translation kinematics model and the posture kinematics model are established. Subsequently, the coupling dynamics model of the multiple helicopter system is established in Section 5. In Section 6, using the kinematics model proposed above, the relative velocity can be simulated and the results are given.

2 Model of Close-coupling Multiple Helicopters Harmony Operation

The close-coupling helicopters are joined with the load by a soft thick rope, which causes forces and kinematics restrains between the sub-systems. These systems can be regarded as a single one, but each sub-system is independent of others. Supposing helicopters are rigid bodies, the proposed system is a multiple rigid soft rope structure. The rope provides drag force only. There is a drag force of the rope besides the air force, air resistance and gravitational force. Regarding the helicopters and the load as particles and support points of the rope, CCMHS is a mass-damp system. Fig.2 defines a kind of system, which includes a model of two helicopters, and the model of a load. It can be seen that the motion and the position of the helicopters determine the motion and the position of the load through the cable, i.e., there is dynamics coupling between subsystems.

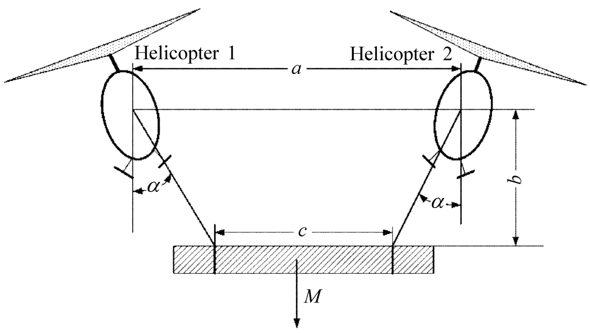

Fig.2 A space structure of two helicopters suspending and carrying an object.

In order to avoid influences on the airfield around the helicopters and ensure system safety in space, the distance between sub-systems must be kept large enough. Suppose two helicopters suspend and carry one rectangle load, Fig.2 shows this system's space structure. If a, b, c and M are given, the pull force of cable, F, can be calculated by

$$F = M/(2\cos\alpha) \tag{1}$$

where M is the gravity of the load, α the angle between F and the vertical direction.

3 Coordinate System Definitions

In CCMHS, every sub-system can translate and/or rotation not only relative to the fixed coordinate system, but also relative to the other subject (a moving coordinate). In order to define relative positions, velocities and accelerations, multiple coordinate systems must be used. Because there are many variables, such as forces, moments and motion variables, which obey complex laws, many coordinates and the relations between the coordinates are needed. The coordinate systems and the relevant motion variables are defined as follows.

As shown in Fig.3, two kinds of frames should be considered: the reference inertial grand frame fixed to the globe, and the body frames attached to the helicopters. In the grand frame $O_g x_g y_g z_g$ (represented by S_g), the origin O_g is an arbitrary point close to the helicopter on the globe. Because the helicopter's flying velocities is small relative to the self-rotating velocity of the globe, the globe gravitation field can be regarded as a simple parallel force field in which the force is a constant. z_g points downward vertically while x_g points northward in the horizontal plane, so y_g can be fixed by the Right Hand Rule. The grand frame is mainly used to determine the positions and postures of helicopters. In the body frame $O_b x_b y_b z_b$ (represented by S_b), the origin O_b is located at the center of mass of a model-scale helicopter, x_b points to the frontage along the structure longitudinal axis, z_b points downward and is perpendicular to the longitudinal axis in the symmetrical plane, the lateral axis y_b is perpendicular to the symmetrical plane and points to the right. The body coordinate systems of helicopter 1, helicopter 2 and the load are defined as $O_{b1}x_{b1}y_{b1}z_{b1}$ (represented by S_{b1}), $O_{b2}x_{b2}y_{b2}z_{b2}$ (represented by S_{b2}), $O_{b3}x_{b3}y_{b3}z_{b3}$ (represented by S_{b3}) respectively.

The relation between the body frame S_b and the grand frame S_g can be defined by three Ruler angles, i.e. posture angles (ψ, θ, ϕ). ψ is named a yaw angle, the one between the projections of x_b on the $x_g y_g$ plane, and if the projection is on the right of x_g, it is positive. θ is named a pitch angle, the one between the x_b and the horizontal plane $x_g y_g$, and if the direction of the x_b is above $x_g y_g$, it is positive. ϕ is named a roll angle, the one between the structure symmetrical plane $x_b z_b$ and the plumb plane across the longitudinal axis, and if the plumb plane can rotate to the symmetrical plane deasil when seen along x_b, it is positive.

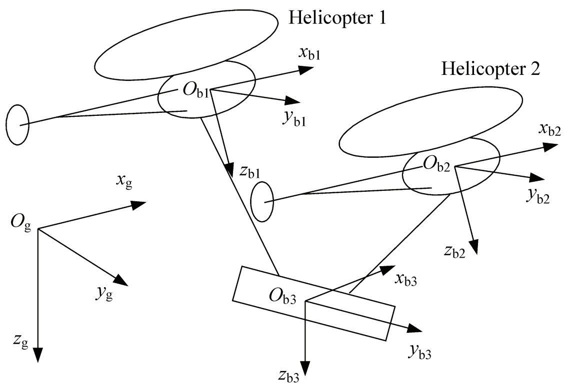

Fig.3 Coordinates of suspending and carrying system of close-coupling multiple helicopters.

ψ, θ, ϕ determine the posture of a model helicopter, where ψ and θ determine the direction of the x_b, ϕ the rotating motion of a helicopter around the x_b. The posture angles of helicopter 1, helicopter 2 and the load are denoted by (ψ_1, θ_1, ϕ_1), (ψ_2, θ_2, ϕ_2) and (ψ_3, θ_3, ϕ_3), respectively, as follows:

$$S_g \xrightarrow{\psi_1,\theta_1,\phi_1} S_{b1} \tag{2}$$

$$S_g \xrightarrow{\psi_2,\theta_2,\phi_2} S_{b2} \tag{3}$$

$$S_g \xrightarrow{\psi_3,\theta_3,\phi_3} S_{b3} \tag{4}$$

4 Kinematics Analysis

No matter what maneuvered flight do the model-scale helicopter perform, the computation of its velocity and acceleration must be fulfilled before that of the posture angles, manipulate variables and over-loading. In order to ensure the system safety of two helicopters suspending and carrying a load, every sub-system must be safe in work, and enough information about relative velocities, relative accelerations, relative postures must be provided for multiple helicopter harmony operation[15]. Before the kinematics analysis, the helicopter 1 is supposed to be the main object, and the helicopter 2 the reference object, which means the movement characteristics of the helicopter 2 relative to the helicopter 1 is to be studied.

The motion equations of the sub-systems are

$$\mathrm{d}\boldsymbol{r}_1/\mathrm{d}t=\boldsymbol{V}_1 \tag{5}$$

$$\mathrm{d}\boldsymbol{r}_2/\mathrm{d}t=\boldsymbol{V}_2 \tag{6}$$

$$\mathrm{d}\boldsymbol{r}_3/\mathrm{d}t=\boldsymbol{V}_3 \tag{7}$$

where $\boldsymbol{r}_1$, $\boldsymbol{r}_2$, $\boldsymbol{r}_3$ and $\boldsymbol{V}_1$, $\boldsymbol{V}_2$, $\boldsymbol{V}_3$ are position and velocity vectors of the helicopter 1, the helicopter 2, and the load. The relative position vector $\boldsymbol{r}_{21}$ and the relative velocity $\boldsymbol{V}_{21}$ can be expressed by

$$\left.\begin{aligned}\boldsymbol{r}_{21}&=\boldsymbol{r}_2-\boldsymbol{r}_1\\ \boldsymbol{V}_{21}&=\boldsymbol{V}_2-\boldsymbol{V}_1\end{aligned}\right\} \tag{8}$$

The distributive variables are

$$\left.\begin{aligned}(\boldsymbol{r}_{21})_i&=(\boldsymbol{r}_2)_i-(\boldsymbol{r}_1)_i\\ (\boldsymbol{V}_{21})_i&=(\boldsymbol{V}_2)_i-(\boldsymbol{V}_1)_i\end{aligned}\right\} \tag{9}$$

The other relative velocities and relative positions are similar to those in Eqs.(8)-(9).

The rotation kinematics equations of the sub-systems are

$$\begin{bmatrix}\mathrm{d}\phi_i/\mathrm{d}t\\ \mathrm{d}\theta_i/\mathrm{d}t\\ \mathrm{d}\psi_i/\mathrm{d}t\end{bmatrix}=$$

$$\begin{bmatrix}\omega_{x\mathrm{b}i}+\tan\theta_i\left(\omega_{y\mathrm{b}i}\sin\phi_i+\omega_{z\mathrm{b}i}\cos\phi_i\right)\\ \omega_{y\mathrm{b}i}\cos\phi_i-\omega_{z\mathrm{b}i}\sin\phi_i\\ \left(\omega_{y\mathrm{b}i}\sin\phi_i+\omega_{z\mathrm{b}i}\cos\phi_i\right)/\cos\theta_i\end{bmatrix} \tag{10}$$

where $\omega_{x\mathrm{b}i}$, $\omega_{y\mathrm{b}i}$, $\omega_{z\mathrm{b}i}$ (i=1,2,3) denote roll, pitch and yaw angle velocities of the helicopter 1, the helicopter 2, and the load respectively. It can be seen that the angle velocities are not equal to the change rates of the Ruler angles: $\mathrm{d}\phi_i/\mathrm{d}t$, $\mathrm{d}\theta_i/\mathrm{d}t$, $\mathrm{d}\psi_i/\mathrm{d}t$. If the angle ϕ_i, θ_i, ψ_i are small enough, the angle velocities will approximate to the change rates. Let the relative Ruler angles ϕ_{21}, θ_{21}, ψ_{21} express the relative posture of the helicopter 2 relative to the helicopter 1:

$$\boldsymbol{L}_{21}=\boldsymbol{L}_{\mathrm{b2g}}\boldsymbol{L}_{\mathrm{b1g}} \tag{11}$$

$$S_{\mathrm{b1}}\xrightarrow{\phi_{21},\theta_{21},\psi_{21}}S_{\mathrm{b2}} \tag{12}$$

In order to calculate the relative Ruler angles ϕ_{21}, θ_{21}, ψ_{21}, the rotation dynamics equations of sub-systems are established as follows:

$$\mathrm{d}\left(\boldsymbol{\omega}_1\right)_{\mathrm{b1}}/\mathrm{d}t=$$

$$\left(\boldsymbol{I}_1\right)_{\mathrm{b1}}^{-1}\left[\left(\boldsymbol{M}_1\right)_{\mathrm{b1}}-\left(\boldsymbol{\omega}_1\right)_{\mathrm{b1}}^{\times}\left(\boldsymbol{I}_1\right)_{\mathrm{b1}}\left(\boldsymbol{\omega}_1\right)_{\mathrm{b1}}\right] \tag{13}$$

$$\mathrm{d}\left(\boldsymbol{\omega}_2\right)_{\mathrm{b2}}/\mathrm{d}t=$$

$$\left(\boldsymbol{I}_2\right)_{\mathrm{b2}}^{-1}\left[\left(\boldsymbol{M}_2\right)_{\mathrm{b2}}-\left(\boldsymbol{\omega}_2\right)_{\mathrm{b2}}^{\times}\left(\boldsymbol{I}_2\right)_{\mathrm{b2}}\left(\boldsymbol{\omega}_2\right)_{\mathrm{b2}}\right] \tag{14}$$

$$\mathrm{d}\left(\boldsymbol{\omega}_3\right)_{\mathrm{b3}}/\mathrm{d}t=$$

$$\left(\boldsymbol{I}_3\right)_{\mathrm{b3}}^{-1}\left[\left(\boldsymbol{M}_3\right)_{\mathrm{b3}}-\left(\boldsymbol{\omega}_3\right)_{\mathrm{b3}}^{\times}\left(\boldsymbol{I}_3\right)_{\mathrm{b3}}\left(\boldsymbol{\omega}_3\right)_{\mathrm{b3}}\right] \tag{15}$$

Because vectors could not express postures, relative postures are not the difference between absolute postures. Thus the following method is used to compute the relative posture.

At first, an absolute posture matrix is set up with absolute posture angle variables

$$\boldsymbol{L}_{\mathrm{b1g}}=\boldsymbol{L}_{\mathrm{b1g}}\left(\phi_1,\theta_1,\psi_1\right) \tag{16}$$

$$\boldsymbol{L}_{\mathrm{b2g}}=\boldsymbol{L}_{\mathrm{b2g}}\left(\phi_2,\theta_2,\psi_2\right) \tag{17}$$

then the relative posture matrix is

$$\boldsymbol{L}_{21}=\boldsymbol{L}_{\mathrm{b2g}}\boldsymbol{L}_{\mathrm{b1g}} \tag{18}$$

The relative Ruler angles can be calculated using the unit l_{jk} of relative posture matrix:

$$\left.\begin{aligned}\sin\theta_{21}&=-l_{13}\\ \tan\phi_{21}&=l_{23}/l_{33}\\ \tan\psi_{21}&=l_{12}/l_{11}\end{aligned}\right\} \tag{19}$$

The calculation of other relative Ruler angles are also completed using Eq.(19).

5 Dynamics Analysis

In order to accomplish the given missions, the dynamics characteristics of each sub-system and their dynamics constrains must be computed. Adjusting the manipulate variables of two helicopters can change the aerodynamic forces and moments acting on the helicopters resulting in changes of their positions and postures. The load can also be adjusted to assume the expected position and posture.

The translation dynamics equations of the sub-system's centers of mass in the grand frame S_{g} can be expressed by

$$\left.\begin{aligned}\mathrm{d}\boldsymbol{V}_1/\mathrm{d}t&=\boldsymbol{F}_1/m_1\\ \mathrm{d}\boldsymbol{V}_2/\mathrm{d}t&=\boldsymbol{F}_2/m_2\\ \mathrm{d}\boldsymbol{V}_3/\mathrm{d}t&=\boldsymbol{F}_3/m_3\end{aligned}\right\} \tag{20}$$

where $\boldsymbol{F}_i$ (i=1,2,3) is the resultant force acting on the sub-systems. The rotation dynamics equations of the sub-systems are expressed by Eqs.(13)-(15).

From the format of the equations, the dynamics equations of any sub-system are semblable, but because of the presence of force restriction between the helicopters and the load, the dynamics coupling exists in the system.

When two helicopters are hovering in the sky, their flying velocity is so small that it can be considered zero and, meantime, the aero-force produced by fuselage and flat tail are also small, so the equilibrium computation of a helicopter under hovering condition mainly is about the balance between the aero-force, gravity force and rope pull force. The forces and moments acting on the helicopter 1 under the hovering condition are expressed in Fig.4. T, H, S, M_k, M_{zg}, M_{xg} denote the rotor drag force, backward force, lateral force, converse moment, pitch hub torque and roll hub torque respectively. F_{yF}, M_{zF}, M_{xF} denote the fuselage resistance force, fuselage pitch torque and fuselage roll torque respectively. F_{yH} denotes flat tail resistance force, T_T tail rotor drag force, and M_{kT} tail rotor converse moment. G and F are the helicopter gravity and rope pull force[16]. Supposing the coordinate of a rotor center is (x_M, y_M, z_M), the pitch angle of rotor shaft is β, the coordinate of tail-rotor center is (x_T, y_T, z_T), the upward oblique angle of tail-rotor center is β_T, the distance between the y_b axis and the center of the flat tail is x_H.

Using Fig.4, the distributive forces acting on the helicopter 1 in the grand frame S_g and the distributive moments acting on the helicopter 1 in the body frame S_b are

$$\left.\begin{aligned} F_{1xg} &= T\cos\beta\sin\theta + T\sin\beta\cos\theta - H\cos\theta \\ F_{1yg} &= T\sin\beta\sin\theta - T\cos\beta\cos\theta + G_1 + F_{zF} + \\ &\quad F_{zH} + F_1\cos\alpha - T_T\sin(\beta_T + \phi) \\ F_{1zg} &= T\cos\beta\sin\phi - F_1\sin\alpha - T_T\cos(\beta_T + \phi) + S \end{aligned}\right\} \tag{21}$$

$$\left.\begin{aligned} M_{1xb} &= M_{xg} + M_{xF} - Tz_M + Sy_M + T_T\cos\beta_T \cdot y_T \\ M_{1yb} &= M_{kT} - M_{yg} - M_{yF} - T(x_M\cos\beta - z_M\sin\beta) - \\ &\quad Hz_M\cos\beta - F_{zH}x_H + T_T\sin\beta_T \cdot (-x_T) \\ M_{1zb} &= M_k + Sx_M - T_T\cos\beta_T \cdot x_T \end{aligned}\right\} \tag{22}$$

Similarly, in the case of the load, they are

$$\left.\begin{aligned} F_{3xg} &= 0 \\ F_{3yg} &= F_1\sin\alpha - F_2\sin\alpha \\ F_{3zg} &= G_3 - F_1\cos\alpha - F_2\cos\alpha \end{aligned}\right\} \tag{23}$$

$$\left.\begin{aligned} M_{3xb} &= \frac{b}{2}(F_2 - F_1)\cos\alpha \\ M_{3yb} &= 0 \\ M_{3zb} &= 0 \end{aligned}\right\} \tag{24}$$

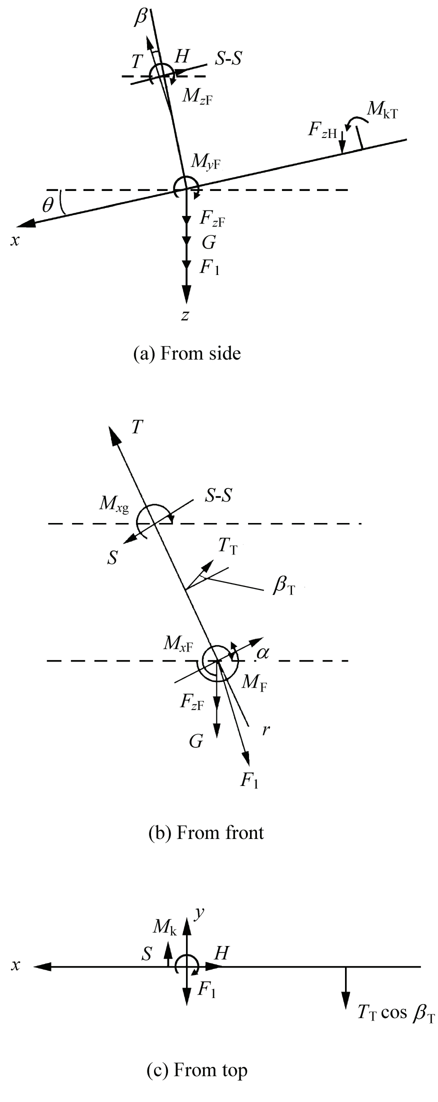

Fig.4 Forces and torques acting on helicopter 1.

Because the dynamics coupling between the helicopter 2 and the load resembles that between the helicopter 1 and the load, there is no need for further detailed discussion. In the following the relative posture dynamics equation between the helicopter 1 and the helicopter 2 will be discussed.

The relative angle velocities can be computed using the absolute angle velocities

$$\left(\boldsymbol{\omega}_{21}\right)_{\mathrm{b}2}=\left(\boldsymbol{\omega}_{2}\right)_{\mathrm{b}2}-\boldsymbol{L}_{21}\left(\boldsymbol{\omega}_{1}\right)_{\mathrm{b}1} \tag{25}$$

The differential of the above equation is

$$\frac{\mathrm{d}\left(\boldsymbol{\omega}_{21}\right)_{\mathrm{b}2}}{\mathrm{d}t}=\frac{\mathrm{d}\left(\boldsymbol{\omega}_{2}\right)_{\mathrm{b}2}}{\mathrm{d}t}-\boldsymbol{L}_{21}\frac{\mathrm{d}\left(\boldsymbol{\omega}_{1}\right)_{\mathrm{b}1}}{\mathrm{d}t}-\dot{\boldsymbol{L}}_{21}\left(\boldsymbol{\omega}_{1}\right)_{\mathrm{b}1} \tag{26}$$

There is a transfer matrix equation

$$\dot{\boldsymbol{L}}_{21}=-\left(\boldsymbol{\omega}_{21}\right)_{\mathrm{b}2}^{\times}\boldsymbol{L}_{21} \tag{27}$$

By inserting $\dot{\boldsymbol{L}}_{21}$ into Eq.(26), the relative angle acceleration can be obtained

$$\frac{\mathrm{d}\left(\boldsymbol{\omega}_{21}\right)_{\mathrm{b}2}}{\mathrm{d}t}=\frac{\mathrm{d}\left(\boldsymbol{\omega}_{2}\right)_{\mathrm{b}2}}{\mathrm{d}t}-\boldsymbol{L}_{21}\frac{\mathrm{d}\left(\boldsymbol{\omega}_{1}\right)_{\mathrm{b}1}}{\mathrm{d}t}+\left(\boldsymbol{\omega}_{21}\right)_{\mathrm{b}2}^{\times}\boldsymbol{L}_{21}\left(\boldsymbol{\omega}_{1}\right)_{\mathrm{b}1} \tag{28}$$

Combining Eq.(28) with the rotation dynamics Eqs.(13)-(15) results in the relative posture dynamics equations.

6 Simulations and Results

Taking one kind of helicopter as an example, its gravity G is 2 000 kg, the pitch angle of rotor shaft β is 2°, and the up oblique angle of tail-rotor center β_{T} is 2°. It is supposed that the load M weighs 4 000 kg and a, b and c amount to 200 m, 100 m, 100 m respectively.

Using the dynamics model proposed above, the postures and relative postures can be computed. In order to adjust the relative position instantaneously to avoid accidents, the relative velocity must be small enough to prevent the reasonable relative position from change. Therefore, the relative velocity must be measured and maintained within an enough small range.

Fig.5 and Fig.6 illustrate the velocity of helicopter 1, v_{yg1}, and the velocity of helicopter 2, v_{yg2}, along the axis y_{g} respectively. The relative velocity v_{yg12} shown in Fig.7 can be calculated on the base of the results mentioned above.

Based on the simulation results, it follows that once the motion parameters of subsystems are fixed, the positions of subsystems can be attained which can be regarded as the referenced position of the controller.

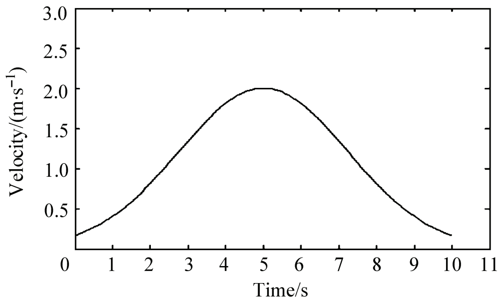

Fig.5 Motion velocity of helicopter 1.

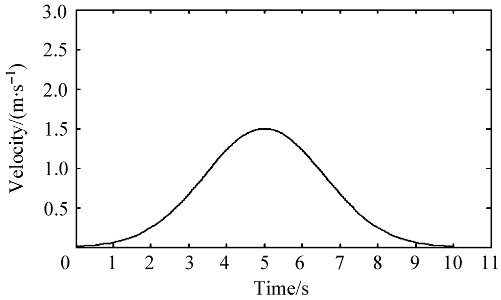

Fig.6 Motion velocity of helicopter 2.

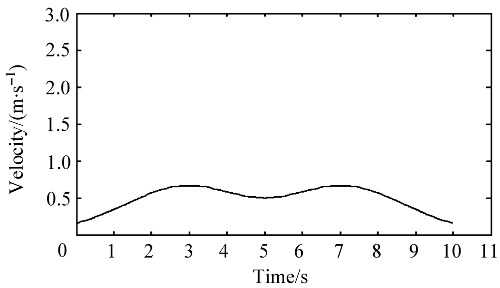

Fig.7 Motion velocity of helicopter 2 relative to helicopter 1.

Because of existence of a linkage between the translation and the posture of a helicopter, a change in the helicopter's position and/or velocity must induce a change in the posture of a helicopter. In order to ensure system safety, the relative posture must be kept as constant as possible. When the posture and the position of each sub-system are measured, using kinematics model the relative position and posture can be attained, and, subsequently, using the dynamics model, the load can be controlled to sustain the expected position and posture by adjusting the position of helicopters.

7 Conclusions

The particularity and practicality of harmony operation of close-coupling multiple helicopters indicate that the researches on it are urgent and necessary. Taking the model that describes two helicopters suspending and carrying one heavy load as an example, the inertia coordinate system and the body coordinate systems of each sub-system are established. A nonlinear force model is also established. The equilibrium computation results can be regarded as the reference control inputs of the flight control system under hovering condition. The translation kinematics model and the posture kinematics model are established. Subsequently, the coupling dynamics model of the multiple helicopter system is established. The above-mentioned results also can be regarded as a base of stabilization analysis and controller design for a close-coupling multiple helicopter harmony operation system.

In the equilibrium analysis and dynamics modeling process, it is supposed that two identical helicopters are used with rope pull forces passing through their centers of gravity. In order to make two helicopters assume good posture and have dynamics characteristics, the reasonable load distribution on different helicopters should be taken into account. Besides, the center of gravity of each helicopter, the join points between the helicopters and the load, the positions of helicopters in the air can also have effects on the system performance. In addition to the dynamics analysis, the control strategies and the communication between the sub-systems etc. are also considered. These problems are expected to be the future research direction.

Two identical helicopters are used in the example. The rotation of the rotors and the pull force of tail-rotors are supposed in the same direction, while the pull force of ropes in the opposite. Therefore, it is surmised that between two helicopters exists a large difference of cyclic lateral inputs and the roll angles.

Acknowledgments

The authors are grateful to the members of Shanghai Jiaotong University's Autonomous Small-Scale Model Helicopter Project for their helpful advice and constructive comments.

References

[1] Vilchis J C A, Brogliato B, Dzul A, et al. Nonlinear modeling and control of helicopters. Automatica 2003; 39(7): 1583-1596.

[2] Hu G C, Xiang J W, Zhang X G. An analytical model of coupled rotor/airframe helicopter dynamic stability in forward flight. Acta Aeronautica et Astronautica Sinica 2004; 25(5): 451-455. [in Chinese]

[3] Zeng Q F, Xie G H, Li T. Integrated simulation model of a helicopter. Acta Aeronautica et Astronautica Sinica 1997; 18(5): 563-566. [in Chinese]

[4] Li J B, Gao Z. Aerodynamic modeling and experiment for simulation of helicopter maneuver flight. Acta Aeronautica et Astronautica Sinica 2003; 24(2): 116-118. [in Chinese]

[5] Aldebrez F M, Mat Dams I Z, Tokhi M O. Dynamic modeling of a twin rotor system in hovering position. First International Symposium on Control, Communication and Signal Processing. 2004.

[6] Sugiura R, Fukagawa T, Noguchl N. Field information system using an agricultural helicopter towards precision farming. Proceeding of the 2003 IEEE/ASME International Conference on Advanced Intelligent Mechatronics. 2003.

[7] Johnscn T, Olscn K E, Gundersen R. Hovering helicopter measured by bi-/multistatic CW radar. IEEE Radar Conference. 2003; 165-171.

[8] Liu X D, Zhang H, Cheng X. Research and simulation on separating multi-target with anti-helicopter mine. Proceeding of the Third International Conference on Machine Learning and Cybernetics. 2004.

[9] Wang Y, Tan M, Jing F S, et al. Kinematic analysis and application of a huge workpiece handling system based on multi-robot coordination. Robot 2002; 24(5): 451-455. [in Chinese]

[10] Wang Z L, Huaglory T, Jiang P. A framework for coordination in multi-robot systems. Proceedings of IEEE International Conference on Industrial Informatics. 2003.

[11] Brumitt B L. A mission planning system for multiple mobile robots in unknown, unstructured, and changing environments. PhD thesis, Carnegie Mellon University, 1999.

[12] Chien Y P, Xue Q, Chen Y B. Configuration space model of tightly coordinated two robot manipulators operating in 3-dimensional workspace. IEEE Transactions on Systems, Man, and Cybernetics 1995; 25(4): 246-257.

[13] Li B, Li Y H, Yin X G. Dynamic modeling and simulation of flexible cable with large sag. Applied Mathematics and Mechanics 2000; 21(6): 640-646. [in Chinese]

[14] Gao Z, Chen R L. The flight dynamics analyzing of helicopter. Beijing: Science Press, 2003. [in Chinese]

[15] Zhao Z G, Lu T S. Equilibrium computation of close-coupling multiple helicopters in hover condition. Journal of System Simulation 2007; 19(1): 153-155. [in Chinese]

[16] Xiao Y L. Modeling of aeronautics and astronautics crafts motion: the theory base of flight dynamics. Beijing: Beijing University of Aeronautics and Astronautics Press, 2003. [in Chinese]

Biography:

Zhao Zhigang Born in Gansu province, China in 1975. He received the M.S. degree in mechanical engineering in 2000 from Xi'an Jiaotong University. He is an instructor at the department of mechanical and electrical engineering. He is a Ph.D. candidate in School of Mechanical Engineering, Shanghai Jiaotong University. His main research interests are complex system identification and special robot etc.
E-mail: flapping@21cn.com