Chinese Journal of Aeronautics, (2014),27(5): 1062–1069

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Safety modeling and simulation of multi-factor coupling heavy-equipment airdrop

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Received 5 December 2013; revised 22 April 2014; accepted 9 June 2014
Available online 6 September 2014

KEYWORDS

Heavy-equipment airdrop;
Modeling and simulation;
Multi-body system;
Multi-factor coupling;
Safety

Abstract Heavy-equipment airdrop is a highly risky procedure that has a complicated system due to the secluded and complex nature of factors' coupling. As a result, it is difficult to study the modeling and safety simulation of this system. The dynamic model of the heavy-equipment airdrop is based on the Lagrange analytical mechanics, which has all the degrees of freedom and can accurately pinpoint the real-time coordinates and attitude of the carrier with its cargo. Unfavorable conditions accounted in the factors' models, including aircraft malfunctions and adverse environments, are established from a man-machine-environment perspective. Subsequently, a virtual simulation system for the safety research of the multi-factor coupling heavy-equipment airdrop is developed through MATLAB/Simulink, C language and Flightgear software. To verify the veracity of the theory, the verification model is built based on dynamic software ADAMS. Finally, the emulation is put to the test with the input of realistic accident variables to ascertain its feasibility and validity of this method.

1. Introduction

So far, the research on the heavy-equipment airdrop at home and abroad mainly concentrates on the modeling and simulation,[1–5] the design of control laws,[6,7] the airdrop experiments,[8,9] the analysis of stability and maneuverability, the flight quality of the airdrop, and the development of precision airdrop technology.[10–13] Little literature can be found on the correlation between safety analysis and airdrop. However, flight safety is an eternal theme of aviation, which not only seriously affects military aircraft combat effectiveness of the play, but also is an important evaluation criterion in terms of overall design. As a critical means of rapid reaction and long-range maneuverability, as well as facilitating logistics support and ongoing assistance, heavy-equipment airdrop plays a pertinent role, thus, safety problem becomes an even more important factor to be considered. The research of heavy-equipment airdrop safety has a very important military implication as well as application values.

The heavy-equipment airdrop system is a representative man-machine-environment system. Any link malfunction may bring adverse effect on the entire system, which may lead to single or multiple failures, subsequently crashing the system. The quantitative research methods of flight safety fall into

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2014.08.014

three categories: the mathematic analytical method, the test statistical method and the expert evaluation method. The test statistical method falls into the flight test, the hardware-in-the-loop simulation and the mathematic modeling and simulation. The modeling and simulation method is an important method for the complex system research, in which not only the cost can be greatly reduced, but also retrieve data that would otherwise be difficult to obtain, especially the data of the system's dynamic characteristic in multi-factor complex flight situations. This paper first builds the multi-body system dynamic model of the heavy-equipment airdrop system, along with contingency variables, which include aircraft malfunctions and unfavorable environments. To achieve this, a virtual simulation system for the safety research of the heavy-equipment airdrop in the multi-factor complex scenarios is developed through MATLAB/Simulink, C language and Flightgear (a system used to study the dynamic characteristic of the heavy-equipment airdrop in the multi-factor complex flight situations). Data is then extracted. This model serves as the foundation for the subsequent quantitative safety research.

2. Modeling of heavy-equipment airdrop system

The heavy-equipment airdrop system consists of the carrier, the cargo and the parachute. In order to simplify the derivation and avoid the solution of the constraining force, a model was built using the Lagrange analytical mechanics. The schematic diagram of the heavy-equipment airdrop system is shown in Fig. 1, where $Ox_gy_gz_g$ is the earth's fixed axis coordinate, $Ox_by_bz_b$ the carrier body axis coordinate, θ the pitch angle of the carrier, c_1 the carrier's barycenter, c_2 the cargo's barycenter. Several assumptions can be made to simplify the calculation: (A) the cargo's barycenter and the carrier's are parallel with the cargo's floor, and the distance between them is l; (B) the potential energy on ground is zero; (C) the parachute model is simplified as drag, which runs opposite of the airflow axis; (D) the cargo goes along the slide rail with no lateral movements and the work of the friction is ignored; (E) negative or positive of the variables are subject to up pitches, right yaws and right rolls of the carrier, for example.

The second kind Lagrange equation is written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_j}\right)-\frac{\partial L}{\partial q_j}=Q_j\ (j=1,2,\ldots,n) \tag{1}$$

where L is Lagrange function, q_j the generalized coordinates, t the time, and Q_j the generalized force.

Select the position coordinates (x,y,z) and attitude angles (ϕ,θ,ψ) of the carrier, the distance between the cargo's barycenter and the carrier's (l) as the generalized coordinates, the vector form of the generalized coordinates is written as

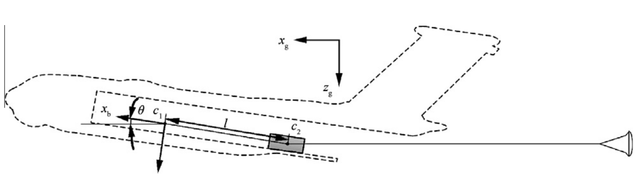

Fig. 1 Schematic diagram of heavy-equipment airdrop system.

$$\boldsymbol{q}=[x \quad y \quad z \quad \phi \quad \theta \quad \psi \quad l]^{\mathrm{T}} \tag{2}$$

The velocity of the carrier's barycenter is represented by

$$\boldsymbol{v}_1=[\dot{x} \quad \dot{y} \quad \dot{z}]^{\mathrm{T}} \tag{3}$$

The angular velocity of the carrier is represented by

$$\boldsymbol{\omega}_1=[\dot{\phi} \quad \dot{\theta} \quad \dot{\psi}]^{\mathrm{T}} \tag{4}$$

The kinetic energy of the carrier is represented as

$$E_{k1}=\frac{1}{2}m_1\boldsymbol{v}_1^{\mathrm{T}}\boldsymbol{v}_1+\frac{1}{2}\boldsymbol{J}^{\mathrm{T}}[\dot{\phi}^2 \quad \dot{\theta}^2 \quad \dot{\psi}^2]^{\mathrm{T}} \tag{5}$$

where m_1 is the mass of the carrier and $\boldsymbol{J}$ the rotational inertia moment of the carrier.

The position of the cargo's barycenter in the earth's fixed axis is written as

$$\boldsymbol{r}_2=[x-lc_\theta c_\psi \quad y-lc_\theta s_\psi \quad z+ls_\theta]^{\mathrm{T}} \tag{6}$$

The logograms of the trigonometric functions in the Eq. (6) are shown as

$$\begin{cases} s_\psi=\sin\psi, & c_\psi=\cos\psi \\ s_\theta=\sin\theta, & c_\theta=\cos\theta \end{cases} \tag{7}$$

The velocity of the cargo is represented as

$$\boldsymbol{v}_2=\begin{bmatrix} \dot{x}+s_\theta c_\psi l\dot{\theta}+c_\theta s_\psi l\dot{\psi}-c_\theta c_\psi \dot{l} \\ \dot{y}+s_\theta s_\psi l\dot{\theta}-c_\theta c_\psi l\dot{\psi}-c_\theta s_\psi \dot{l} \\ \dot{z}+c_\theta l\dot{\theta}+s_\theta \dot{l} \end{bmatrix} \tag{8}$$

The kinetic energy of the cargo can be represented as

$$E_{k2}=\frac{1}{2}m_2\boldsymbol{v}_2^{\mathrm{T}}\boldsymbol{v}_2 \tag{9}$$

where m_2 is the mass of the cargo.

The total kinetic energy of the heavy-equipment airdrop system can be represented as follow

$$E_k=E_{k1}+E_{k2} \tag{10}$$

The potential energy of the heavy-equipment airdrop system can be deduced as

$$E_p=m_1gz+m_2g(z+ls_\theta) \tag{11}$$

Then, the Lagrange function can be written as

$$L=E_k+E_p \tag{12}$$

The external forces acting on the airdrop system consist of the engine thrust (P), the aerodynamic forces along the air path axis system (X,Y,Z), the drag of the parachute (N), the gravities of the carrier and the cargo (G_1,G_2).

The following text shows how the engine's thrust is projected onto the earth's fixed axis:

$$[P_{xg} \quad P_{yg} \quad P_{zg}]^{\mathrm{T}}=\boldsymbol{L}_{gb}[P \quad 0 \quad 0]^{\mathrm{T}} \tag{13}$$

where $\boldsymbol{L}_{gb}$ is the transformation matrix from the carrier body axis coordinate to the earth's fixed axis coordinate.

Assuming that the carrier has no sideslip, and then project the aerodynamic forces to the earth fixed axis system, that is

$$[R_{xg} \quad R_{yg} \quad R_{zg}]^{\mathrm{T}}=\boldsymbol{L}_{ga}[X \quad Y \quad Z]^{\mathrm{T}} \tag{14}$$

where $\boldsymbol{L}_{ga}$ is the transformation matrix from the airflow axis coordinate to the earth's fixed axis coordinate.