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Numerical Simulation of Hose Whip Phenomenon in Hose-Drogue Aerial Refueling

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Abstract. The study of hose whip phenomenon is a significant part for further researching dynamic characteristics of hose-drogue system during the aerial refueling operation. The hose whip phenomenon in hose-drogue aerial refueling is simulated based on a high-efficiency neighbor-to-neighbor algorithm. The Osher scheme and S-A turbulence model are employed to solve the compressible Navier-Stokes equations, and the hose is discretized into a series of ball hinges linked by massless rigid links which form a multi-body system, the kinematical and dynamic equations are then derived for the system. The numerical model is used to simulate the hose-drogue system dynamics in multiple conditions, the results show a good correlation with previously reported flight-test data in open literature and the application of neighbor-to-neighbor algorithm saves a lot of computational cost. Results of this study may have certain guiding significance for the probe-and-drogue aerial refueling.

AMS subject classifications: 76G25, 76M12

Key words: Aerial refueling, hose-drogue, whip phenomenon, multi-body system, numerical simulations.

1 Introduction

The "probe-and-drogue" is a method of aerial refueling whereby a probe from the receiver aircraft fits into a trailing hose with a drogue attachment from the tanker aircraft. The hose-drogue aerial refueling system is the most universal refueling equipment, there

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have been a growing number of researches and flight tests on the flowfield of the "probe-and-drogue" at home and abroad, and some results have been achieved. Eichler [1] presented the derivation and solution of the nonlinear partial differential equation in closed form for sine-wave gust disturbances and numerically for both sine wave and pulse-type vertical gusts and wing vibration and calculated the anticipated effect of vortex from the wingtip on the hose-drogue system. Venkataramanan et al. [2–4] investigated an improved and more natural method of incorporating the trailing vortex effect associated with aircraft flying in close proximities, including the effect of time-varying mass and inertia properties associated with the fuel transfer, the tanker's vortex induced wind effect and atmospheric turbulence. Zhu and Meguid [5] developed an accurate and computationally efficient three-noded, locking-free curved beam element to model an aerial refueling hose, the large deformations and rotations of curved beams were formulated in terms of an updated Lagrangian framework with consistently coupled quintic polynomial displacement fields to satisfy the membrane locking-free condition. Ro and Kamman [6–8] developed a dynamic model of a hose-paradrogue assembly for aerial refueling using the finite-segment approach and studied the effects of atmospheric turbulence on paradrogue motion by incorporating the Dryden turbulence model into the hose-paradrogue dynamic model. Hu et al. [9, 10] modeled the trailing refueling hose-drogue by using an array of discrete point mass nodes that represents the physical properties of the hose-drogue, and analyzed the influence of air turbulence on hose-drogue's motion following the simulation of the motion in the cloudless air turbulence. In addition, some literature [11–13] analysed the effects of a bow wave on the drogue during a probe-and-drogue refueling, which suggested that a solution to the bow wave effect was not only desirable but essential for a successful aerial refueling.

In the probe-and-drogue aerial refueling process, the hose-drogue system has proven very reliable except when excessive forces on a receiver aircraft's probe are induced during a hose whip. The hose whip phenomenon is created by the angle of attack increase in the forward to mid hose section which is caused by gravity pulling down the hose slack after the probe-drogue contact. The study of hose whip phenomenon is a significant part for further researching dynamic characteristics during the aerial refueling operation. A thorough understanding of hose whip phenomenon is a key to work out strategies for the successful design of hose-drogue system and saving aerial refueling. In the current study, the hose-drogue system is discretized into a number of nodes which represent physical properties of the system, an initial configuration of the hose-drogue is obtained by searching host cells of theses discrete points in flowfield using an efficient neighbor-to-neighbor algorithm, and the accurate configuration of the hose-drogue is achieved by CFD methods. The simulation of hose dynamic characteristics is then carried out in case of reel malfunction and working properly in the refueling stage.

2 Numerical methods