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# Dynamic modeling of a hose-drogue aerial refueling system and integral sliding mode backstepping control for the hose whipping phenomenon

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**Abstract** Dynamic modeling of a hose-drogue aerial refueling system (HDARS) and an integral sliding mode backstepping controller design for the hose whipping phenomenon (HWP) during probe-drogue coupling are studied. Firstly, a dynamic model of the variable-length hose-drogue assembly is built for the sake of exploiting suppression methods for the whipping phenomenon. Based on the lumped parameter method, the hose is modeled by a series of variable-length links connected with frictionless joints. A set of iterative equations of the hose's three-dimensional motion is derived subject to hose reeling in/out, tanker motion, gravity, and aerodynamic loads accounting for the effects of steady wind, atmospheric turbulence, and tanker wake. Secondly, relying on a permanent magnet synchronous motor and high-precision position sensors, a new active control strategy for the HWP on the basis of the relative position between the tanker and the receiver is proposed. Considering the strict-feedback configuration of the permanent magnet synchronous motor, a rotor position control law based on the backstepping method is designed to insure global stability. An integral of the rotor position error and an exponential sliding mode reaching law of the current errors are applied to enhance control accuracy and robustness. Finally, the simulation results show the effectiveness of the proposed model and control laws.



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## 1. Introduction

Autonomous aerial refueling (AAR) has received substantial attention from countries of the world spurred by a rapid integration of unmanned aerial vehicles (UAVs) into modern military missions.[1] Hose-drogue aerial refueling systems (HDARSs) are the most universal refueling equipment, and some outstanding progress has been made to automate the

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refueling process using vision-based control and navigation techniques recently.[2,3] Consequently, automation of hose-drogue-based refueling methods will have greater development potential in military and economic aspects.

It is also important to note that not all achievements of AAR are the result of improvement of UAV control and navigation, but the result of effective hose rewind control. As reported, if the reel is disabled during coupling, it is impossible for a receiver to couple without experiencing the so-called hose whipping phenomenon (HWP).[4] During coupling, the current pod is equipped with a tensator (spring-loaded take-up device)[5] to retract any slack in the hose as the probe pushes the drogue forward. If the tensator malfunctions or is subjected to an excessive closure speed during coupling, slack in the hose can form. When excessive slack occurs, the internal hose tension will rapidly decrease, and then the hose will violently whip due to aerodynamic forces. This phenomenon generates high loads on the hose and the probe, even damages them.[5] The HWP has been a serious constraint to AAR's success rates and security. Unfortunately, only a limited number of research on dynamic characteristics and control methods of the HWP can be found.

In order to further research dynamic characteristics of the HWP, many scholars and research institutions have conducted a lot of experiments and modeling analysis. NASA Dryden Flight Research Center[6,7] obtained abundant aerodynamic data specifically required in hose-drogue dynamic modeling by wind tunnel and flight tests. The Boeing Company[4,5] investigated dynamic characteristics of the KC-10 HWP by numerical simulation. Zhu and Meguid[8,9] proposed a new curved beam finite element formulation based on mechanics of materials to depict the dynamics of the hose-drogue assembly. Ro et al. tested the aerodynamic characteristics of the drogue by wind tunnel and computational fluid dynamics,[10] moreover gave a link-connected dynamic model of the hose-drogue assembly.[11,12] Although the models as mentioned above can reflect dynamics of the hose-drogue assembly, they cannot support exploiting HWP suppression methods due to the limitation of a constant hose length.

To keep the hose tension stable and suppress the HWP, every pod is equipped with a tensator at present. However, a hose-drogue system suffered a 2.5% failure rate when the hose slackened and lost the stability.[8] The Boeing Company[4] confirmed that the reel take-up speed lagging behind the closure speed was responsible for the failure by numerical simulation. Ro et al.[13] tried to improve the control law of the tensator ignoring the difficulty of mechanism rebuilding. Recently, the integration of a permanent magnet synchronous motor (PMSM) and high-precision position sensors into the refueling pod provides another chance for high-performance suppression methods for the HWP. Alden and Vennero[14] invented a new refueling pod with a reel driven by a PMSM. Liu and Sun[15] achieved position tracking for nominal model-based through sliding mode control with backstepping. Yang et al.[16] proposed an integral sliding mode backstepping speed control for high-altitude electric propulsion systems. Zhang et al.[17] designed a PMSM nonlinear speed control method using sliding-mode control and disturbance compensation techniques. Bartov[18] achieved relative position communion by three position sensors installed in the tanker, receiver, and drogue, respectively.

In this paper, a link-connected dynamic model of the hose-drogue assembly with a variable length is built. Then reeling in/out of the hose is converted into a PMSM's rotor angular position control, and a nonlinear controller based on backstepping with integral and sliding mode action for the HWP is derived. Finally, characteristics of the HWP are analyzed, while the model and the controller are validated by numerical simulation.

## 2. Dynamic modeling of an HDARS

### 2.1. Equation of motion of the hose-drogue assembly

#### 2.1.1. Modeling assumptions and definition of coordinate systems

The reel, hose, and drogue are the key parts of an HDARS for suppressing the HWP, transferring fuel, and assisting hookup. The PMSM drives the reel to deploy and retrieve the hose through a reducer.

Based on the lumped parameter method, the variable-length hose-drogue assembly is discretized as a link-connected system, where the hose consists of a finite number of variable-length links connected with frictionless joints. The masses and forces associated with each link are concentrated at the joints. The drogue is treated as a mass point at the end of the hose.[11,12] The twist around the hose central axis and the property of elasticity and damping of the hose are neglected here. The configuration, modeling assumptions, and definition of coordinates of the HDARS are illustrated in Fig. 1.

As shown in Fig. 1, $O_gX_gY_gZ_g$ represents an inertial reference coordinate system. The equation of motion of the hose-drogue assembly is deduced in the towing point coordinate system $O_WX_WY_WZ_W$. The axes of $O_WX_WY_WZ_W$ are parallel to the trajectory coordinate of the tanker $O_TX_TY_TZ_T$. The orientations of the $K$th link are described relative to $O_WX_WY_WZ_W$ using the angles $\theta_{K1}$ and $\theta_{K2}$ respectively relative to the planes $O_WX_WY_W$ and $O_WX_WZ_W$.

#### 2.1.2. Kinematics analysis

As shown in Fig. 1, the position vector $\boldsymbol{r}_K$ of joint $K$ relative to $O_WX_WY_WZ_W$ is expressed as

$$\boldsymbol{r}_K = \boldsymbol{r}_{K-1} + \boldsymbol{p}_K \tag{1}$$

where $\boldsymbol{p}_K$ is the position vector from joint $K-1$ to joint $K$. The coordinates of $\boldsymbol{p}_K$ in $O_WX_WY_WZ_W$ can be written as

$$\boldsymbol{p}_K = -l_K[C_1C_2 \quad S_2 \quad -S_1C_2]^{\mathrm{T}} \tag{2}$$

where $C_i = \cos\theta_{Ki}$ and $S_i = \sin\theta_{Ki}$ $(i = 1, 2)$; $l_K$ is the length of the $K$th link. To describe the hose reeling in/out, $l_K$ is regarded as a variable.

The velocity $\boldsymbol{v}_K$ and acceleration $\boldsymbol{a}_K$ of the $K$th joint can be found by differentiating Eq. (1):

$$\begin{cases} \boldsymbol{v}_K = \boldsymbol{v}_{K-1} + \dot{\boldsymbol{p}}_K \\ \boldsymbol{a}_K = \boldsymbol{a}_{K-1} + \ddot{\boldsymbol{p}}_K \end{cases} \tag{3}$$

Considering the transport motion as the plane motion of $O_WX_WY_WZ_W$ relative to $O_gX_gY_gZ_g$, namely the attitude variation of the tanker, the first and second derivatives of $\boldsymbol{p}_K$ by differentiating Eq. (3) can be expressed as

$$\dot{\boldsymbol{p}}_K = \sum_{i=1}^{2}(\boldsymbol{p}_{K,\theta_{Ki}}\dot{\theta}_{Ki}) + \boldsymbol{p}_{K,l_K}\dot{l}_K + (\boldsymbol{\omega}_W \times \boldsymbol{p}_K) \tag{4}$$