Hose-drum-unit Modeling and Control for Probe-and-drogue Autonomous Aerial Refueling

Xunhua Dai, Zi-Bo Wei, Quan Quan, and Kai-Yuan Cai.

Abstract—Probe-and-drogue aerial refueling is widely adopted because of its flexibility, but the drogue is susceptible to wind disturbances, especially the receiver forebody bow wave disturbance and the excessive contact on the drogue. The docking process is an accurate task, and a sub-meter error may result in a failure docking. Thus, it is important for the docking task to understand the dynamics of the drogue under wind disturbances and improve safety after excessive contact happens. In this paper, based on the previous work of the drogue dynamic modeling, an improved integrated model is proposed by adding the hose-drum unit to describe more accurately the behavior of the drogue under wind disturbances. For the convenience of docking controller design of the receiver aircraft, the simplified drogue dynamic model with the hose-drum unit is obtained through system identification. Finally, to avoid the hose whipping phenomenon after excessive contact on the drogue, a control method is proposed to monitor the state of the hose and control the hose length to stabilize the drogue movement. Simulations and comparisons indicate that the motion of the drogue generated by the proposed modeling method is in good agreement with the real experimental results, and the proposed control method can significantly reduce the effect of hose whipping phenomenon and improve the safety of probe-and-drogue aerial refueling systems.

Index Terms—Autonomous aerial refueling, hose-drum unit (HDU), probe-and-drogue, bow wave effect, hose whipping phenomenon (HWP).

I. INTRODUCTION

Autonomous Aerial Refueling (AAR) is an effective method of increasing the endurance and range of Unmanned Aerial Vehicles (UAVs) [1], [2], [3] by refueling them in flight [4]. The Probe-and-Drogue Refueling (PDR) is widely adopted in AAR owing to its simple requirement of equipment and flexibility. In a PDR system, there is a hose payout and reel-in device which is called Hose-Drum Unit (HDU) [5] (also known as the reel take-up system [6], [7]). It consists of a hose-drum motor and a motor control unit, and determines the motion of the upper end of the hose [5]. It is an important device to suppress the hose whipping phenomenon (HWP), which can result in severe damage to the probe or the drogue [8].

The HWP is caused by the excessive contact between the probe and the drogue. The existing literature focused on how to design an HDU controller to maintain the tension of the hose and suppress HWP, such as [6], [8]. In practice, the drogue will remain relatively static if the hose-drogue system is not affected by wind disturbances. In this situation, the “excessive contact” is hard to happen because tracking a static target is a relatively easy and simple task. However, when affected by wind disturbances, the drogue is always moving, so the receiver has to speed up to chase the drogue which may result in excessive contact and HWP. In addition to suppressing the HWP after the contact, this paper tries to reveal that the HDU can also be applied as a feedback damper to reduce the frequency and amplitude of the drogue position fluctuation under wind disturbances, which has not attracted enough attention in the previous research. Fortunately, the basic models were established by the existing literature, which can be employed to analyze the dynamics of the drogue with HDU controller. The hose-drogue dynamic model is established and the behavior of the drogue in the docking stage is analyzed by references [5], [6], [7], [9], [10].

In the whole refueling process, the motion of the drogue is influenced by many types of wind dis-
turbances, such as the aerodynamic influence of the tanker [11], atmospheric turbulence [12], the bow wave effect [13], and so on. According to the NASA flight test results [13] as shown in Fig. 1(a), the drogue fluctuates with the amplitude about 0.1∼0.2m (mainly caused by atmospheric turbulence, and the amplitude depends on the weather condition) in a low frequency when the receiver is far away. When the receiver comes close to the drogue, the drogue is quickly pushed away by the bow wave flow field with offset about 0.4m (dotted ellipse region in Fig. 1(a)), and this docking attempt is failed because the probe is too slow to chase the drogue. As a result, in the docking stage, the bow wave of the receiver is the most substantial one. Thus, the hose-drogue model under the bow wave is simplified by reference [14], [15], which is called the drogue dynamic model. Moreover, the motion of the drogue under the bow wave and its control methods are studied in [16], [17], [18]. However, there were some differences (the dotted ellipse regions in Fig. 1) between the simulation results generated by the drogue dynamic model (see Fig. 1(b)) and the flight test experiment (see Fig. 1(a)) [13], where the simulation results are about 40% larger than the experimental results, especially for the vertical position. One of the main reasons is that the effects of HDU were not considered by the drogue dynamic model. Thus, the results of reference [14] are improved in this paper by considering the effects of HDU. Meanwhile, the traditional HDU control methods mainly feedback the hose tension to reduce the drogue fluctuation and suppress HWP to some extent, but it cannot avoid HWP essentially because it cannot detect whether the HWP is happening and its degree. Since the HWP is essentially caused by the over-slack of the hose due to excessive contact on the drogue, this paper proposed an anti-HWP control method to monitor the state of the hose and control the hose length to stabilize the drogue movement.

In summary, the main contributions of this paper are: (i) a more precise modeling method for hose-and-drogue system is proposed based on the previous study; (ii) by considering the effects of HDU controller, an improved integrated model is proposed to describe more accurately the behavior of the drogue under wind disturbances, and a simplified drogue dynamic model is obtained through system identification for the convenience of docking controller design of the receiver aircraft; (iii) improvements are proposed for the traditional HDU controllers to realize a better performance to stabilize the drogue position under disturbances before the contact happens; (iv) for the excessive contact situations, an anti-HWP control method is proposed to significantly reduce the effect of hose whipping phenomenon and improve the safety of aerial refueling systems.

This paper is organized as follows. Section II reviews the drogue dynamic model without HDU controller, and analyzes the deficiency of it. Section III describes the models used in the simulation and demonstrates the procedure of researching the effects of HDU. Section IV compares two types of controllers for HDU, and the corresponding drogue dynamic models with HDU controllers are obtained by following the procedure of the simulation as mentioned in Section III. Their performances are also compared in this section. The anti-HWP control method is proposed and verified in Section V. Finally, the conclusions are given in Section VI.

II. THE DYNAMICS OF THE DROGUE WITHOUT HDU CONTROLLER

A drogue dynamic model without HDU is proposed by reference [14]. In order to make this paper self-contained, this model is introduced briefly in this section. Then, the problem of this model is analyzed in the rest of this section.

A. Drogue Dynamic Model without HDU Controller

A flexible hose-drogue dynamic model is often expressed by a series of rigid links according to
the finite element method, which is called the link-connected model [19]. As shown in Fig. 2, the orientation of each link \( L_j \) with the length \( l_j \) is described by its orientation angles \( \alpha_j, \beta_j \in \mathbb{R}, j = 1, 2, ..., N \), where \( N \in \mathbb{Z}^+ \) is the number of rigid links. If a hose-drogue dynamic model with fixed length hose (fixed length hose-drogue model for short) is considered, then each lumped mass position \( p_{L_j} \in \mathbb{R}^3 \) and velocity \( \dot{p}_{L_j} \in \mathbb{R}^3 \) are expressed by \( \alpha_j, \beta_j, \alpha_j, \beta_j, l_j \). Moreover, for a hose-drogue dynamic model with variable length hose (variable length hose-drogue model for short), \( p_{L_j} \) and \( \dot{p}_{L_j} \) are expressed by \( \alpha_j, \beta_j, \alpha_j, \beta_j, l_j \).

All of these variables are measured in the tanker frame \((o-xyz)\). The origin of this frame \(o\) is set to the conjunctive point between the tanker and the hose, and the frame axes \((x, y, z)\) are aligned with the wind frame forward-right-down directions of the tanker; namely, the direction of \(ox\) is identical with the velocity of the tanker. Under this frame, a fixed length hose-drogue model without HDU controller is established by reference [14]. Then, it was linearized when \( h = 3000m \) and \( v_T = 120m/s \). The simplified system is the drogue dynamic model for the drogue offset position \( \Delta p_d = p_d - p_d(0) \), where \( p_d = [p_{dz}, p_{dy}, p_{dx}]^T \in \mathbb{R}^3 \) is the position of the drogue. The transfer function for the drogue dynamic is as shown in the following equation [14]

\[
\Delta p_d(s) = \begin{bmatrix}
G_{xx}(s) & 0 & G_{xz}(s) \\
0 & G_{yy}(s) & 0 \\
G_{zx}(s) & 0 & G_{zz}(s)
\end{bmatrix}
\begin{bmatrix}
f_b(s)
\end{bmatrix}
\]

where \( f_b = [f_{bx}, f_{by}, f_{bz}]^T \in \mathbb{R}^3 \) is the disturbance force input acting on the drogue. Moreover, under a fixed flight condition (the height \( h \) and the airspeed \( v_T \) of the refueling), if the hose-drogue device is not influenced by any disturbance, the drogue will reach a steady position which is noted by \( p_d(0) \). The detailed expressions for (1) can be found in our previous work [14].

**B. The Deficiency of the Drogue Dynamic Model without HDU Controller**

According to reference [14], the vertical motions of the drogue in the simulation and the experiment are somewhat different as shown in Fig. 1. An important reason causing this phenomenon is that the gains of \( G_{zx} \) and \( G_{zz} \) are much larger than \( G_{xx} \) and \( G_{yy} \), respectively. It means that both \( f_{bx} \) and \( f_{by} \) influence \( p_{dz} \) much more than \( p_{dx} \). This phenomenon can be explained by an intuitive example as follows. When the drogue reaches the steady position, the hose is tight. The hose-drogue device is similar to a pendulum in this situation [20], as shown in Fig. 3(a). Thus, with a small range, the motion of the drogue is close to a circular arc around the upper end of the hose, no matter the force on which direction acts on it. Because the length of the hose cannot be changed, the vertical motion and the longitudinal motion of the drogue are coupled tightly, and the corresponding drogue dynamic model cannot describe the behavior of the drogue in practice accurately. On the other hand, HDU modifies the dynamics of the drogue by changing the length of the hose, as shown in Fig. 3(b). Thus, it is important to research the effects of HDU acting on the dynamics of the drogue.

**III. HOSE-DROGUE MODEL WITH HDU CONTROLLER UNDER THE BOW WAVE EFFECT**

According to the previous section, the fixed length hose-drogue model under the bow wave has been analyzed by reference [14]. However, this model needs to be replaced by a variable length hose-drogue model and an HDU model to obtain the dynamics of the drogue more accurately. Thus, the bow wave model and these two models are introduced first. Then, the procedure of the simulation is illustrated.
A. Three Models Used in the Simulation

1) Bow wave model: The bow wave is a complex disturbance caused by the receiver forebody flow field. Based on the modeling and simulation methods [5], [6], [7], [21] of the hose-drogue dynamics, reference [22] established the bow wave effect model as a lookup table, and then references [14][15] modeled it as explicit equations. In order to compare the results of this paper with reference [14], the bow wave model in this reference is employed.

2) Variable length hose-drogue model: The variable length hose-drogue model also bases on the link-connected model. There are two kinds of variable length hose-drogue model: (i) only the length of the first link $l_1$ is variable [5] and (ii) the variation of the hose assigns to every link equally [8]. Since the variation of the hose is not remarkable before the impact happens, the former model is adopted for simulations without the requirement to consider the intense contact on the drogue to reduce the computational cost. Please refer to reference [5] for details.

3) HDU model: The HDU system for hose payout and reel-in is modeled as a drum (or reel) [5][6]. The dynamical motion of the drum can be described as,

$$(T_{reel} - T_{hose}) r_{reel} = I_{reel} \alpha_{reel},$$

where $r_{reel}$ is the drum radius of the reel system, $I_{reel}$ is the moment of inertia of the drum, and $\alpha_{reel}$ is the angular acceleration. The tension of $L_1$ is $T_{hose}$ because the tension of the whole hose acts on it, and $T_{reel}$ is the tension of the reel. Letting $l$ present the total length of the hose as

$$l = \sum_{i=1}^{N} l_i$$

where $N$ is the number of the links, $l_i$ is the length of the $i^{th}$ link. If the reel is modeled as a thin circular cylindrical shell, then $I_{reel} = m_{reel} r_{reel}^2$, where $m_{reel}$ is the weight of the reel. On the other hand, the angular acceleration $\alpha_{reel}$ can be expressed regarding the linear acceleration, that means $\alpha_{reel} = \frac{\dot{l}}{r_{reel}}$. Thus, Eq. (2) becomes

$$\dot{l} = \frac{T_{reel} - T_{hose}}{m_{reel}}.$$  

Note that, if only the first link has variable length, then there are $\dot{l} = \dot{l}_1$ and $\dot{l} = \dot{l}_1$; if all the links have variable length, then $\dot{l}/N = \dot{l}_1$ and $\dot{l}/N = \dot{l}_i$.

The relation of the bow wave model, the variable length hose-drogue model and the HDU model is shown in Fig. 4(b), while the relation of the models used in reference [22] is shown in Fig. 4(a).

B. The Procedure for Researching the Effects of HDU

The controller in HDU can adjust the tension $T_{reel}$ in Eq. (4), and consequently, influences the dynamics of the drogue through changing the length of the hose. How the controller influences the dynamics of the drogue is the main issue in the rest of the paper. This issue is analyzed by two simulations: Simulation 1 is used in system identification, and Simulation 2 is used to compare the effects of the drogue dynamic models with and without HDU controller. These simulations are organized by the following procedure, and the procedure is realized in the next section.

First, Simulation 1 is established, which contains the variable length hose-drogue model and HDU model. The structure of the simulation is illustrated as shown in Fig. 5, which is the same as the models between $f_b$ and $p_d$ in Fig. 4(b).

Second, two types of controllers are set into the “Controller” block, and step signals are employed to

![The motion of the drogue without HDU controller](image1)

![The motion of the drogue with HDU controller](image2)

Fig. 3. The motion of the drogue with and without HDU controller
stimulate the system in Simulation 1. The response data of the system are used to analyze the effects of the different controller with different parameters preliminary.

Third, based on Simulation 1, the system identification method is employed to obtain the linearized models, which are the drogue dynamic models with HDU controller. These models can express the dynamics of the drogue with HDU controllers, which are controlled by different controllers. The input of the system identification method is the force acting on the drogue, which is equivalent to the bow wave force $f_b$, and the output is the position of the drogue $p_d$. The procedure of the system identification method is the same as reference [14]. Through the linearized models, the different effects caused by the different controllers are further analyzed.

Finally, Simulation 2 is established. The structure of this simulation is the same as the final simulation of reference [14], as shown in Fig. 6(a). However, in this paper, the drogue dynamic model without HDU controller is replaced by the drogue dynamic models with HDU controllers, as shown in Fig. 6(b). The simulation results of Simulation 2 are the motions of the drogue generated by the drogue dynamic model with and without HDU controller. They are compared in the next section. It should be noted that, unlike the complex nonlinear models used in Fig. 4, the models of Fig. 6 are simple linearized models.

IV. THE CONTROLLERS OF HDU AND THE CORRESPONDING DROGUE DYNAMIC MODELS

In this section, two types of controllers are designed for HDU, and the corresponding drogue dynamic models with HDU controllers are obtained. This section is introduced by following the procedure introduced in Section III.B.

A. Parameters of the Simulations

The parameters of Simulation 1 and 2 are the same as reference [14]. However, the new parameters used in the HDU model and the variable length hose-drogue model are listed in Table I. Here, the
length of the first link is variable, and the length of the rest hose is divided into the other links which are constants. The initial tension of the hose $T_0$ means the hose tension without disturbance when the whole hose is released. Then, Simulation 1 and Simulation 2 are established according to Fig. 5 and 6.

**TABLE I**
The parameters of the simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of the links, $N$</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Full length of the hose, $L_h$</td>
<td>15</td>
<td>m</td>
</tr>
<tr>
<td>Initial length of $L_1$, $l_1(0)$</td>
<td>2</td>
<td>m</td>
</tr>
<tr>
<td>Length of other links, $L_j$, $j = 2, 3, \ldots, N$</td>
<td>13/9</td>
<td>m</td>
</tr>
<tr>
<td>Weight of the reel, $m_{reel}$</td>
<td>68</td>
<td>kg</td>
</tr>
<tr>
<td>Initial tension of the hose, $T_{hose}(0)$</td>
<td>1610</td>
<td>N</td>
</tr>
</tbody>
</table>

**B. Two Types of Controllers**

*Simulation 1* is employed in this section, and two types of controllers are considered. First, one type of controllers for HDU is proposed by references [5] and [6],

$$T_{reel}(t) = T_{hose}(0) \cdot \left[ \frac{l_1(t)}{l_1(0)} \right]^k, \quad 0 < l_1(t) \leq l_1(0).$$  \hfill (5)

Under this controller, HDU responds by reeling in the hose as the drogue is influenced by disturbances. The parameter of the controller is set as $k = \{0.3, 0.5, 1, 3\}$, and the simulation results are shown in Fig. 7(a1)∼(a4) where the responses of $T_{hose}(t), l_1(t), p_d(t)$ are illustrated respectively. For the convenience of observing the dynamic response of the HDU controller, a step disturbance force $f_b$ (from $[0, 0, 0]$ to $[75, 0, 0]$) is injected into the hose-drogue system at $t = 100$. In order to simulate the disturbance intensity in real condition, the amplitude of the step disturbance is selected according to the average amplitude of the bow wave effect obtained by CFD methods. The reason of using this input is that at the beginning part of the docking stage, only $f_{bx} > 0$ while $f_{by} = f_{bz} = 0$. Moreover, in this part, the differences (as shown in Fig. 1) between reference [14] and the experiment in reference [13] begin to emerge, and a 40% modeling error is observed in the vertical position.

According to Fig. 7(a1)∼(a4), the transient processes of the responses oscillate initially, although the tension recovers its balance again at last. Thus, in order to improve the transient processes, the damping is introduced to the controller, and the new type of controllers is

$$T_{reel}(t) = T_{hose}(0) \cdot \left[ \frac{l_1(t)}{l_1(0)} \right]^k + k_d l_1'(t)$$  \hfill (6)

where $0 < l_1(t) \leq l_1(0)$ and $k_d \in \mathbb{R}_+$. The variable $l_1(t)$ can be measured directly or through the rotational speed of the reel indirectly, so the controller is realizable. By employing controller (6), the simulation results are shown in Fig. 7(b1)∼(b4), when $k_d = 500$. It is obvious that the transient processes are much better than before.

![Fig. 7. The responses under the two types of controllers (the output $p_d$ is omitted because its response is always 0 in this situation)](image-url)
if the hose length needs to be changed as small as possible, then a large $k$ can be chosen.

(iii) A larger $k$ will bring negative effects, which will make the system tend to be unstable, according to Fig. 7(a1)(a2). Actually, for controller (5) and $k = 4$, the outputs are divergent. Controller (6) can improve this situation significantly.

(iv) The parameter $k$ influences the dynamics of the drogue indirectly through the variation of the hose length, according to Fig. 7(a3)(a4)(b3)(b4). This property will be analyzed further in the next subsection.

### C. Drogue Dynamic Model with Different HDU Controllers

Based on Simulation 1, the system identification is employed to obtain the linearized models, which are known as the drogue dynamic model with HDU controller. The procedure of the system identification method is the same as reference [14]. System Identification Toolbox [23] of Matlab is employed to identify the system, and the simulation used in the identification is as shown in Fig. 5. Then, the two identified systems are shown in Table II, which demonstrate the dynamics of the drogue under controller (5) and controller (6) with $k = 0.5$. The quantitative performance assessment of estimation is shown by Fitness $F$ in Table II, which is calculated by $F = 1 - \frac{\|y - \hat{y}\|}{\|y - \bar{y}\|}$, where $y$, $\hat{y}$, $\bar{y}$ are the real output, the estimation of the output, and the mean of the real output, respectively.

Unlike the drogue dynamic model without HDU controller, 4th-order transfer functions are employed to identify the drogue dynamic model with HDU controller. The reason is that besides the 2nd-order dynamics of the drogue without HDU controller, additional 2nd-order transfer functions are needed to describe the dynamics of HDU, according to Eq. (4). Thus, the 4th-order-identification results are much better than the 2nd-order ones, and the 4th-order transfer functions are adopted. Then, according to Table II, the following conclusions about the dynamics of the drogue are obtained:

(i) The transient process of the dynamics of the drogue under controller (6) is much better than that under controller (5). The reason is that controller (6) makes the poles far away from the imaginary axis.

(ii) According to Fitness in Table II, the effect of identification for controller (5) is worse than that under controller (6). The reason is the behavior of the drogue under controller (6) is closer to outputs of linear systems than that under controller (5) as shown in Fig. 7(a3)(a4). Thus, if a linear model is used to express the dynamics of the drogue with HDU controller, the system under controller (6) is more appropriate.

(iii) By comparing the gains of the transfer functions in Table II and that of Equation (1), it is obvious that the dynamics of the drogue is very different when the system with or without HDU controller. In order to demonstrate the differences in detail and analyze the influences of different $k$, the Direct Current (DC) gains [24, p. 94] under the two controllers with $k = \{0.3, 0.5, 1, 3\}$ are shown in Table III.

According to Table III, the following conclusions about the dynamics of the drogue are obtained:

(i) The gains of the transfer functions under controllers (5) and (6) are similar, which means that the controller (6) does not change the final value of the system.

(ii) When $k$ is small, the influences acting on the gains, which are caused by HDU, are remarkable, especially for $G_{xx}(s)$, $G_{zz}(s)$. The $x$ channel and the $z$ channel are decoupled perfectly, which means the gains of $G_{xx}(s)$, $G_{zz}(s)$ are much smaller than

### TABLE II

<table>
<thead>
<tr>
<th>Controller (4)</th>
<th>Transfer Function</th>
<th>Fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{xx}$</td>
<td>$s^4 + 2.158s^3 + 9.17s^2 + 7.54s + 18.21$</td>
<td>84.9%</td>
</tr>
<tr>
<td>$G_{zz}$</td>
<td>$0.0010s + 0.0057s + 0.046$</td>
<td>79.09%</td>
</tr>
<tr>
<td>$G_{yy}$</td>
<td>$0.026s^2 + 0.0634s + 0.42$</td>
<td>99.5%</td>
</tr>
<tr>
<td>$G_{xz}$</td>
<td>$s^4 + 0.39s^3 + 24.02s^2 + 5.76s + 49.66$</td>
<td>85.1%</td>
</tr>
<tr>
<td>$G_{zy}$</td>
<td>$0.0026s + 0.010s + 0.032$</td>
<td>94.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Controller (5)</th>
<th>Transfer Function</th>
<th>Fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{xx}$</td>
<td>$s^4 + 0.56s^3 + 24.22s^2 + 7.06s + 53.95$</td>
<td>98.3%</td>
</tr>
<tr>
<td>$G_{zz}$</td>
<td>$s^4 + 0.090s^3 + 0.011s + 0.021$</td>
<td>98.5%</td>
</tr>
<tr>
<td>$G_{yy}$</td>
<td>$s^4 + 4.01s^3 + 6.61s^2 + 10.48s + 7.382$</td>
<td>99.6%</td>
</tr>
<tr>
<td>$G_{xz}$</td>
<td>$s^4 + 0.0048s^3 + 0.019s + 0.0085$</td>
<td>93.2%</td>
</tr>
<tr>
<td>$G_{zy}$</td>
<td>$s^4 + 0.40s^3 + 24.01s^2 + 5.75s + 49.62$</td>
<td>96.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Controller (6)</th>
<th>Transfer Function</th>
<th>Fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{xx}$</td>
<td>$s^4 + 0.61s^3 + 24.05s^2 + 7.71s + 55.76$</td>
<td>95.9%</td>
</tr>
<tr>
<td>$G_{zz}$</td>
<td>$s^4 + 0.027s + 0.0046s + 0.39$</td>
<td>96.3%</td>
</tr>
<tr>
<td>$G_{yy}$</td>
<td>$s^4 + 0.0051s^3 + 0.0091s + 0.0051$</td>
<td>96.3%</td>
</tr>
</tbody>
</table>

| Fitness | 84.9% | 79.09% | 99.5% | 85.1% | 94.5% | 98.3% | 98.5% | 99.6% | 93.2% | 96.3% |
TABLE III
THE DC GAINS OF THE DROGUE DYNAMIC MODEL WITH DIFFERENT HDU CONTROLLERS AND WITHOUT HDU CONTROLLER (THE MAGNITUDE OF THE VALUES IN THE TABLE IS $10^{-3}$)

<table>
<thead>
<tr>
<th></th>
<th>With HDU Controller</th>
<th>No HDU Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k = 0.3</td>
<td>k = 0.5</td>
</tr>
<tr>
<td>$G_{xz}$</td>
<td>(5)</td>
<td>41.60</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>42.04</td>
</tr>
<tr>
<td>$G_{yz}$</td>
<td>(5)</td>
<td>8.08</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>7.42</td>
</tr>
<tr>
<td>$G_{yy}$</td>
<td>(5)</td>
<td>84.65</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>84.65</td>
</tr>
<tr>
<td>$G_{zz}$</td>
<td>(5)</td>
<td>11.81</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>11.48</td>
</tr>
<tr>
<td>$G_{xx}$</td>
<td>(5)</td>
<td>72.42</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>72.02</td>
</tr>
</tbody>
</table>

$G_{xz}(s), G_{zz}(s)$ respectively. Conversely, when $k$ is large, the $x$ channel and the $z$ channel are coupled seriously. When $k$ is large enough, such as $k = 3$, the gains with HDU controller approaches the gains without HDU controller.

(iii) The influences acting on the gains of the $y$ channel by HDU are not remarkable.

Above all, if the purpose of HDU is to suppress HWP, then $k$ should be chosen as a large number. On the other hand, if the purpose of HDU is to decouple the dynamics of the drogue, then $k$ should be chosen as a small number. Thus, $k$ should be chosen to balance these two properties. Moreover, regardless of the value of $k$, it is necessary to choose controller (6) for HDU to obtain a better transient process.

**Remark 1:** The results in Table II are obtained without crosswind. If the crosswind in the refueling environment is remarkable, the $y$ channel will be coupled with $x, z$ channels. That means $G_{yx}, G_{xy}, G_{zy}, G_{yz}$ will not be zero. However, they can also be identified. Moreover, in general situations, the crosswind is not remarkable, and the $y$ channel is decoupled with $x, z$ channels according to reference [14].

**D. The Comparison of Dynamics of Drogue with and without HDU controller**

According to Simulation 2, in order to demonstrate the influence acting on the dynamics of the drogue by HDU, the corresponding parts of models used in reference [14] are replaced by the drogue dynamic models with HDU controllers which are shown in Table II. The motions of the drogue under different situations are illustrated in Fig. 8. The corresponding video is available at https://youtu.be/zcm6D1Gfcbg and the screenshot is shown in Fig. 9.

![Fig. 8. Comparison of motions of the drogue under the following situation:](image-url)

(i) the simulation results without HDU controller; (ii) the simulation results with the HDU controller (5) as $k = 0.5$; (iii) the simulation results with the HDU controller (6) as $k = 0.5$

According to Fig. 8, HDU influences the dynamics of the drogue slightly. However, the docking process is an accurate task, and a sub-meter error may result in a failure docking. Thus, the slight influence is important. The subplots of Fig. 8 (b)(c) show the detailed changes in the vertical position. Moreover, as shown in the bow wave region of Fig. 9, the drop in the vertical position is decreased, and the length of the hose is adjusted by HDU remarkably. Compared with our previous results in [14], the motion of the drogue with HDU controller (5) is closer to the motion in the experiment than the motion without HDU controller. That means the drogue...
dynamic model under controller (5), which is a commonly used controller, is approximate to the actual situation. On the other hand, because HDU under controller (6), which is a new controller, adjusts the hose faster than controller (5), the dynamics of the drogue are different from those under the commonly used controller. However, controller (6) is supposed to be adopted in the future HDU controller design, because its smooth transient process is helpful to suppress HWP and linearize the hose-drogue model.

E. The Effect of HWP Suppression of Traditional HDU control methods

In order to estimate the effect that the traditional HDU control methods suppress the HWP after the excessive contact between the probe and the drogue, comparison simulations are performed and the results are shown in Fig. 10, where an impulse disturbance (500N·s) is injected into the hose-drogue system at 5s to simulate the excessive contact on the drogue. It can be observed from Fig. 10 that the hose-drogue system with HDU controller has a larger longitudinal offset and a smaller vertical offset than those of the hose-drogue system without HDU controller, where the larger longitudinal offset is caused by the hose being reeled up by the HDU controller to avoid vertical offset. The vertical offset indicates that the current HDU control methods can suppress the HWP to some extent, but the effect is very limited and it cannot avoid the HWP essentially. In the next section, a new HDU controller is proposed to avoid the HWP and improve the safety of probe-and-drogue systems.

V. Anti-HWP Control Method for HDU

The traditional HDU control methods mainly feedback the hose tension to reduce the drogue fluctuation and suppress HWP to some extent, but it cannot avoid HWP essentially because it cannot detect whether the HWP happens. For example, when the probe is docked into the drogue, it may drive the drogue to continue to move forward a distance, which may cause the hose slack and reach to a new equilibrium state as shown in Fig. 11(b). In this situation, the hose tension remains unchanged so the traditional HDU control methods cannot work correctly, but HWP will happen if the probe accidentally breaks away from the drogue. Therefore, the HWP is essentially caused by the over-slack of the hose due to excessive contact on the drogue. In order to avoid HWP, the HDU controller must be able to observe the hose slack degree and roll up the hose with an appropriate control method. This section will present an anti-HWP control method from three aspects: HWP observation, control method, and simulation verification.

A. HWP observation

1) Drogue Position Estimation: The most direct way to detect HWP is to observe the shape of the hose through computer vision methods, but it is impractical and unreliable for real aerial refueling systems. Observing the position of the drogue \( \mathbf{p}_d \) to estimate the hose slack degree indirectly for HWP is a more feasible way, which is adopted in this paper.
The drogue position \( p_d \) is essential for the docking control of autonomous aerial refueling system to estimate the relative position between the probe and the drogue. There are many mature methods to estimate the drogue position, among which the vision-based methods [13], [25] are the most convenient and widely used one. These methods can be applied to estimate the drogue position for the following HDU control method.

2) Hose Slack Degree: With the drogue position \( p_d \) and the total hose length \( l \), how to define the hose slack degree and how to estimate it are presented in this subsection. First of all, the normal situation with no hose slack is presented as shown in Fig. 11(a), which is the equilibrium state of the hose when the desired hose length \( \hat{l} \) is defined to equal to the hose length \( l \), i.e., \( l = \hat{l} \). Second, when the hose is over-slack as presented in Fig. 11(b), the hose length should be larger than its desired value, i.e., \( l > \hat{l} \). Consequently, the hose slack degree \( \mu_{\text{slack}} \) can be defined as

\[
\mu_{\text{slack}} \triangleq \left| \frac{l - \hat{l}}{\hat{l}} \right|
\]  

which can be used to describe the hose state and predict the degree of HWP. The slack degree \( \mu_{\text{slack}} = 0 \) indicates that the hose is in the desired state with no over-slack. The more the slack degree \( \mu_{\text{slack}} \) increases, the more the hose is bent which indicates a more serious HWP is ready to happen.

In order to obtain \( \mu_{\text{slack}} \), the method to obtain the desired hose length \( \hat{l} \) should be given first. As shown in Fig. 11(a), the desired hose shape is a smooth curve, whose length \( \hat{l} \) can be written as a function that depends on the drogue position \( p_d \) as

\[
\hat{l} = f_\hat{l}(p_d)
\]  

where \( f_\hat{l}(\cdot) \) can be obtained by hose modeling methods [5], [8] or look-up table methods. However, in practice, the precise expressions of \( \hat{l} \) for different flight conditions (altitude and speed) are very complicated and unobtainable. Alternatively, an approximate estimation method for \( \hat{l} \) is developed in this paper. Based on the simulation results with the hose model [5], [8], the estimation expression for the desired length \( \hat{l} \) is approximate to a function of the straight-line distance of the drogue \( \|p_d\| \) as

\[
\hat{l} \approx f_\hat{l}^{\prime}(\|p_d\|) \approx \frac{\|p_d\|}{\|p_{d0}\|} \cdot l_0
\]  

where \( p_{d0} \) and \( l_0 \) are the initial equilibrium drogue position and hose length. The maximum estimated error \( \varepsilon_\hat{l} \) for (9) is given by

\[
\varepsilon_\hat{l} = \max_{p_d \in \Omega} \left| \frac{\hat{l} - \frac{\|p_d\|}{\|p_{d0}\|} \cdot l_0}{\hat{l}} \right|
\]  

where \( \Omega \) denotes a safe region for the normal drogue movement. According to the simulation results, \( \varepsilon_\hat{l} \) is very small but still the following anti-HWP control method will well consider this error and hand it for robustness requirements.

3) HWP Detection: Safety is always the most fundamental requirement for any aerial refueling system. To avoid the damage of HWP after excessive or abnormal impact on the drogue, this subsection presents a method to detect the hose state and classify it into three situations based on its hazardous degree.

(i) Normal Situation. Ideally, the normal situation should be \( \mu_{\text{slack}} = 0 \); namely, the hose coincides exactly with the desired hose curve as shown in Fig. 11(A). However, it is unreachable in practice due to the estimated error of (9) and other uncertain errors, such as the small fluctuation of the hose under atmospheric turbulence. Therefore, a minimum slack threshold \( \varepsilon_{\text{min}} \) is defined as shown in Fig. 12. The normal situation of the hose is defined by the criterion

\[
\mu_{\text{slack}} \leq \varepsilon_{\text{min}} \quad \text{and} \quad p_d \in \Omega
\]  

where the threshold \( \varepsilon_{\text{min}} \) should cover the estimation error \( (\varepsilon_{\text{min}} > \varepsilon_\hat{l}) \) and other uncertain errors for
robustness requirements. For simplicity, it can be select as $\varepsilon_{\text{min}} = 2\varepsilon_1$ for a 100% safe margin. In (11), the safe region $p_d \in \Omega$ is presented as the meshed region in 12. If the drogue is out of this region ($p_d \notin \Omega$), it indicates that an abnormal big swing is already appearing and emergency measures should be taken immediately.

(ii) **Over-slack Situation.** The over-slack situation is defined as that the hose slack degree $\mu_{\text{slack}}$ is out of “normal range” in (11) and it is within the controllable region for the HDU controller to safely reduce the slack degree $\mu_{\text{slack}}$ to the normal situation. Similar to (11), the over-slack situation can be defined by the following criterion

$$\varepsilon_{\text{min}} < \mu_{\text{slack}} \leq \varepsilon_{\text{max}} \text{ and } p_d \in \Omega \quad (12)$$

where $\varepsilon_{\text{max}}$ is the maximum slack threshold as shown in Fig. 12, which is selected based on the safety requirement and controller performance.

(iii) **Unsafe Situation.** The unsafe situation is defined as the complementary set of (11)(12)

$$\mu_{\text{slack}} > \varepsilon_{\text{max}} \text{ or } p_d \notin \Omega. \quad (13)$$

When the drogue-drogue system reaches this situation, it means that a serious HWP is happening or ready to happen. To ensure the safety of the hose-and-drogue system, emergency measures should be applied immediately. For example, rolling up the hose with maximum speed to avoid a collision on the receiver aircraft.

For the above three situations, different control strategies will be adopted to avoid the HWP and ensure the safety of the drogue-hose system. When the hose is in the normal situation, it indicates that no impact or abnormal oscillation is happening on the drogue, so the traditional HDU control methods as presented in Section IV can be applied to reduce the drogue position fluctuation for improving the docking success rate. When the hose is in the unsafe situation, emergency control measures should be carried out to avoid further damage on the receiver aircraft or equipment. For example, HDU controller rolls up the hose with the maximum speed to leave a safe distance between the hose and the receiver aircraft. Since the over-slack situation is the most important stage to handle impact on the drogue and avoid HWP, the next subsection will focus on the anti-HWP controller design in this situation.

![Fig. 12. Safety criteria for the hose-drogue system.](image)

**B. Anti-HWP Control**

The objective of the anti-HWP controller for HDU is to smoothly control the hose length to change the hose state from the over-slack situation ($\varepsilon_{\text{min}} < \mu_{\text{slack}} \leq \varepsilon_{\text{max}}$) to the normal situation ($\mu_{\text{slack}} \leq \varepsilon_{\text{min}}$). Then, the traditional HDU controller is capable of stabilizing the hose-and-drogue system to an equilibrium state in the normal situation.

First of all, a speed feedback control is given by

$$T_{\text{reel}} = T_{\text{hose}} - m_{\text{reel}} \cdot k_d \cdot (\hat{l} - \hat{i}) \quad (14)$$

where $\hat{l}$ is an indirect control input signal that indicates the desired increasing speed of the hose length, and $k_d > 0$ is a controller parameter. Substituting (14) into the HDU model (4) gives

$$\hat{i} = \frac{T_{\text{reel}} - T_{\text{hose}}}{m_{\text{reel}}} = -k_d \cdot (\hat{l} - \hat{i}) \quad (15)$$

which is an exponentially convergent system that ensures the HDU track the given speed as $\hat{i} \rightarrow \hat{i}$. Second, the desired speed input $\hat{i}$ is further given by

$$\hat{i} = -k_p \cdot (l - \hat{i}) \quad (16)$$

where $k_p > 0$ is a controller parameter. Note that, in practice, a saturation function can be added to (16) to prevent the drogue from pulling out the probe if the hose rolls up too fast. Finally, by combining
(9)(14)(16), the anti-HWP controller can be written as

\[ T_{reel} = T_{hose} + m_{reel}k_dk_p\|p_{d0}\|l_0 - m_{reel}k_d\cdot l - m_{reel}k_dp\cdot l. \]  

(17)

The following theorem provides the convergence condition under which one can conclude the convergence property of the designed TILC controller in (17).

**Theorem 1.** Consider a hose-and-drogue system with the HDU structure described by (2)(4). Suppose (i) the hose state is in over-slack situation (12); (ii) the anti-HWP controller is designed as (17) with its parameters satisfy

\[ k_p > 0, k_d > 0 \]  

(18)

Then, the hose slack degree \( \mu_{slack} \) can converge to zero, i.e., \( \mu_{slack} (t) \to 0 \).

**Proof.** Combining (15)(16) gives

\[ \dot{l} + k_d\dot{l} + k_dp\left(l - \hat{l}\right) = 0. \]  

(19)

By letting \( \Delta l \triangleq l - \hat{l} \), for constant value \( \hat{l} \), (19) can be rewritten as

\[ \Delta \ddot{l} + k_d\Delta \dot{l} + k_dp\Delta l = 0. \]  

(20)

It can be observed from (20) that controller (17) is essentially a PD (Proportion Differentiation) controller with proportion coefficient \( k_p \) and differentiation coefficient \( k_d \). Therefore, (20) is a stable second-order linear system when \( k_d > 0 \) and \( k_d > 0 \), which will converge exponentially to zero

\[ \lim_{t \to \infty} \left| l(t) - \hat{l} \right| = \lim_{t \to \infty} \left| \Delta l(t) \right| = 0. \]  

(21)

Then, according to the definition of \( \mu_{slack} \) in (7), it can be derived from (21) that

\[ \mu_{slack} (t) \triangleq \left| \frac{l(t) - \hat{l}}{l} \right| = \left| \frac{\Delta l(t)}{l} \right| \to 0 \]  

(22)

which indicates that the hose slack degree \( \mu_{slack} \) can converge to zero under controller (17). \( \Box \)

According to **Theorem 1**, when the hose slack degree is in the range \( \varepsilon_{min} < \mu_{slack} \leq \varepsilon_{max} \), it will always converge to zero, which means the slack degree can eventually be reduced into region \( \mu_{slack} \leq \varepsilon_{min} \). Then, the traditional HDU controller will take over the control privilege. According to research in [16], the hose-and-drogue system is a self-stabilizing system, and it will be stabilized to an equilibrium state under the effect of gravity, air drag and air viscous.

### C. Simulation Verification

A series of simulations are performed to verify the effect of the proposed anti-HWP controller. The basic parameters are listed in Table I, and additional parameters are given below

\[ \varepsilon_{min} = 0.004, \varepsilon_{max} = 0.05, k_d = 10, k_p = 3. \]

The variable length hose-drogue model [8] with the link number \( N = 20 \) is used in these simulations for better simulation accuracy and display effect. A video has also been released to introduce the simulation environment and demonstrate the control effect of the proposed anti-HWP controller method. The URL of the video is https://youtu.be/s9XgGICqKtA.
safely. The above three simulations all contain the following stages: (i) the receiver flies close to the drogue from time $0 \leq t_1$; (ii) the contact between the probe and the drogue happens at $t_1$; (iii) the probe drives the drogue fly forward a distance from time $t_1 \leq t_2$; (iv) the probe holds the drogue and remains relatively static from time $t_2 \leq t_3$; (v) the receiver suddenly breaks away from drogue at time $t_3$ and flies backward from time $t_3 \sim 35\,\text{s}$.

It can be observed from Fig. 13(a): 1) the hose slack degree increase to a large for simulation curve with no HDU controller, which indicates a serious HWP is happening; 2) the hose slack degree increase to a medium value for simulation curve with an HDU controller but its slack degree is much smaller than the simulation curve with no HDU controller, which indicates that the existing HDU control methods can suppress HWP but cannot completely avoid it; 3) there is almost no hose slack for simulation curve with anti-HWP controller, which indicates the HWP is successfully avoided. Figs. 14(a)(b) show the slack states of the hose with no HDU controller and with the proposed anti-HWP controller. Due to the over-slack state of the hose, a significant HWP is observed in the simulation without the anti-HWP controller, which is reflected in the drastic position fluctuation along Y and Z directions in Fig. 13(b)(c). By contrast, the hose and drogue states are both very steady with the proposed anti-HWP controller, and no HWP happens as expected. The above results indicate that, compared with the existing HDU control methods, the proposed anti-HWP control method can effectively avoid the HWP and ensure the safety of hose-and-drogue systems.

VI. CONCLUSION

It is critical to analyze the dynamics of the drogue under the bow wave, for designing docking controllers and docking simulations. However, this problem is not considered comprehensively in the existing literature. This paper integrates the HDU model, the bow wave model and the variable length hose-drogue model into an integrated model. Then, two types of controllers are designed for HDU. One type is the commonly used controller used in the real PDR, and the other one is an improved one based on the commonly used controller. Based on the integrated model, the drogue dynamic models under different HDU controllers are obtained through system identification, and the performance of them are analyzed. By considering the effects of HDU, the dynamics of the proposed method is in better agreement with the real experiment than our previous study. Meanwhile, the traditional HDU control methods mainly feedback the hose tension to reduce the drogue fluctuation and suppress HWP to some extent, but it cannot avoid HWP essentially. An anti-HWP control method is proposed to significantly reduce the effect of the hose whipping phenomenon and improve the safety of aerial refueling systems. Finally, the effectiveness of the proposed modeling method and the anti-HWP control method are well verified by simulations and comparisons.

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