Mechanical Systems and Signal Processing 104 (2018) 87–105

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Anti-disturbance rapid vibration suppression of the flexible aerial refueling hose

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ARTICLE INFO

Article history:
Received 6 June 2017
Received in revised form 31 August 2017
Accepted 24 October 2017

Keywords:
Aerial refueling
Vibration suppression
Tracking control
Anti-disturbance control
Sliding mode control

ABSTRACT

As an extremely dangerous phenomenon in autonomous aerial refueling (AAR), the flexible refueling hose vibration caused by the receiver aircraft's excessive closure speed should be suppressed once it appears. This paper proposed a permanent magnet synchronous motor (PMSM) based refueling hose servo take-up system for the vibration suppression of the flexible refueling hose. A rapid back-stepping based anti-disturbance nonsingular fast terminal sliding mode (NFTSM) control scheme with a specially established finite-time convergence NFTSM observer is proposed for the PMSM based hose servo take-up system under uncertainties and disturbances. The unmeasured load torque and other disturbances in the PMSM system are reconstituted by the NFTSM observer and to be compensated during the controller design. Then, with the back-stepping technique, a rapid anti-disturbance NFTSM controller is proposed for the PMSM angular tracking to improve the tracking error convergence speed and tracking precision. The proposed vibration suppression scheme is then applied to PMSM based hose servo take-up system for the refueling hose vibration suppression in AAR. Simulation results show the proposed scheme can suppress the hose vibration rapidly and accurately even the system is exposed to strong uncertainties and probe position disturbances, it is more competitive in tracking accuracy, tracking error convergence speed and robustness.

1. Introduction

In recent years, unmanned aerial vehicles (UAVs) have been widely used in civilian or military fields which include but are not limited to target tracking, increasing the combat radius, extending the flight range, and improving battle operational efficiency [1]. Autonomous aerial refueling (AAR) is an effective method of increasing the endurance and the range of aircraft by refueling them in flight [2]. An increasing interest over the last decades has prompted research into methods for AAR processes, from the theoretical and practical aspects [3-12]. There are two ways of refueling [3]: flying boom method [3,4] and probe-drogue refueling (PDR) [8–10]. The PDR, where the flexible refueling hose is dragged like a flexible string in the air by the tanker aircraft, has gathered substantial attention with the rapid development of the autonomous aerial refueling (AAR)

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https://doi.org/10.1016/j.ymssp.2017.10.034
0888-3270/

[7,10]. Due to its low cost and wide operational aspects, the PDR system has been a very important device to effectively increase the endurance and range.

However, a significant drawback is that the PDR requires a skillful piloting technique of maneuvering a probe into the moving drogue with an acceptable closure speed [10,13–15]. The closure rate of the receiver aircraft must typically be within a required range; the refueling coupling flight will fail to latch below the minimum speed, whereas a violent reverberation through the flexible refueling hose (namely the hose vibration, as Fig. 1 shows) can result in equipment severe damage at higher closure rate [10,13]. When the receiver aircraft probe couple the drogue at a higher closure rate, it definitely will cause excessive slack of the refueling flexible hose as the probe pushes the drogue forward. Then, the internal hose tension will rapidly decrease, and the hose will violently vibrate under the action of the aerodynamic forces. Finally, tremendous high load torque on the hose and the probe arise, and equipment damage occurs. The vibration on the flexible refueling hose greatly constraints the AAR's success rates and security.

The flexible hose vibration caused by the excessive closure speed represents a typical case of the vibration phenomena of a flexible string-like system. As the vibration along this flexible hose may quickly lead serious refueling accident in a very short time, this vibration must be immediately suppressed once it occurs via a specially designed refueling hose take-up control system.

Although some experiments and model analysis are conducted to further research dynamic characteristics of the hose vibration [12–15], the conventional suppression methods for the flexible hose vibration don't show satisfactory performance in a more adverse condition. The Boeing Company confirmed that the reel take-up speed lagging behind the closure speed is responsible for the failure by numerical simulation [13,15]. That means, although the conventional pod is equipped with a tensator to suppress the hose vibration at present, the tensator may not be the sufficient effective strategy.

Like the elevator flexible string vibration suppression strategy via a permanent magnet synchronous motor (PMSM) in [16,17], Alden and Vennero [18] invented a new refueling pod with a refueling hose take-up reel driven by a PMSM, and it provides another choice for high-performance suppression methods for the hose vibration by integrating the high-precision position sensors and the excellent performance of PMSM in servo control systems [19–21]. Wang and Dong [15] designed an integral sliding mode back-stepping control strategy for the PMSM to suppress the hose vibration on the basis of the relative position between the tanker and the receiver. That strategy achieves the good performance on the condition that the PMSM model is precise enough and the equipment's working environment is ideal enough. However, the actual acquisition of the PMSM's load torque which is needed in their designed controller as well as the system uncertainties are all not taken into consideration. Actually, uncertainties always exist especially in the rigorous AAR work environment, and load torque information of the motor is generally tough to be directly acquired. Given this, when the control strategy for the flexible hose vibration suppression is designed, the following abilities must be considered: (i) rapid speed of the vibration suppression; (ii) strong ability of anti-disturbance; (iii) observation ability for the unmeasured load torque and other uncertainties from the available system states. These considerations pose a challenge to the hose vibration suppression methods.

In recent decades, the sliding-mode control (SMC) [22] has been successfully applied to many uncertain systems and areas [19,23–26], due to its superiorities such as strong robustness, order reduction, easier implementation and design simplification. Among the SMC methods, the terminal sliding mode (TSM) controller has drawn much attention [27]. It has been further developed to the nonsingular faster terminal sliding mode (NTSM) [27] and has been applied to many plants [19,28–31]. It has shown the fast finite time convergence, strong robustness and nice ability to handle the uncertainties and disturbances. And these capacities provide a preferable solution for the vibration suppression of the flexible hose vibration as it requires the rapid speed of the vibration suppression and strong anti-disturbance ability mentioned above.

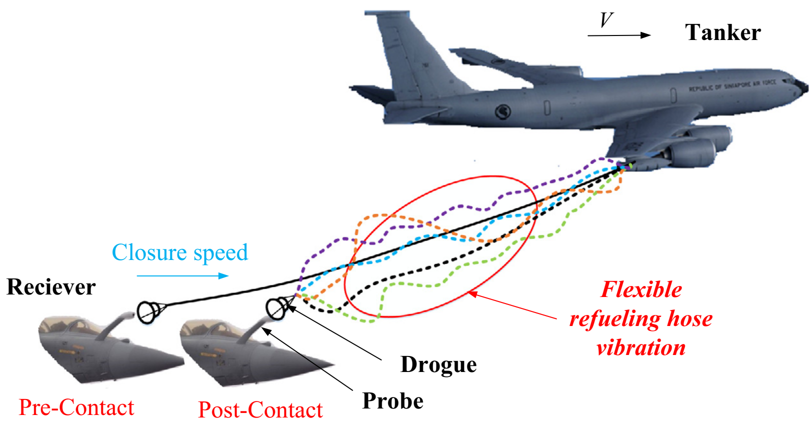

Fig. 1. Flexible aerial refueling hose vibration due to excessive closure speed.