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HIGH-SPEED UNDERWINDING OF FUEL HOSE OF UAV AERIAL REFUELING SYSTEM

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Abstract*—The paper is devoted to the issues of automation of refueling of unmanned aerial vehicles in the air. The problems of the docking stage are considered, in particular, the sagging of the fuel hose with its subsequent beating, which occurs immediately after contact. The main attention is paid to the stage of winding the sagging fuel hose after the drogue is docked with the probe of the refueled unmanned aerial vehicle. Options for improving the fuel hose winding drive are proposed. The emergency braking programs of the refueled unmanned aerial vehicle to equalize its speed with the speed of the tanker are studied. Options for changing the speed of reeling the fuel hose depending on the emergency braking parameters are proposed. The procedure for laying the fuel hose on the underwinding drum and its effect on changing the reeling speed are analyzed. Options are offered to prevent the drogue and probe from disengaging due to excessive hose tension.*

Keywords—Refueled UAV; air-to-air refueling; probe-and-drogue system; fuel hose; sagging of the fuel hose; hose whipping; drive underwinding drum; spring-loading system; slip clutch.

I. INTRODUCTION

Since their inception, unmanned aerial vehicles (UAVs), particularly military ones, have evolved from the original semi-aircraft to a multifunctional system that combines reconnaissance and surveillance, battlefield assessment and target identification, radio relay communications, ground attack, etc. UAVs are used in various military operations. Artificial intelligence technologies, low cost, high mobility, stealth make UAVs a potentially revolutionary new type of air force that is becoming the backbone of the air combat system.

However, existing UAV models are usually limited in terms of payload and fuel capacity, which, as highlighted in the US Defense Advanced Planning Agency's Joint Unmanned Aerial Vehicle project, often results in insufficient safe flight time to perform their assigned air support missions. Therefore, the procedure for autonomous in-flight refueling of UAVs is becoming a key component in air support technologies (Fig. 1).

Autonomous refueling, increasing the time UAVs are in flight, for example, detecting forest fires, greatly increases the efficiency of their use.

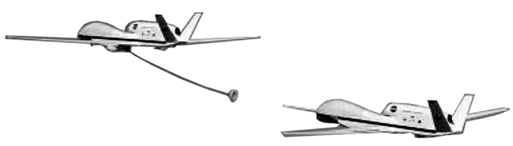
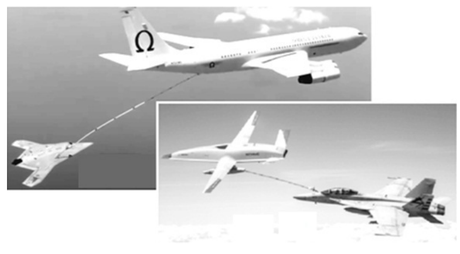


Fig. 1. Aerial refueling of UAVs

Leading research institutes in the US and Europe are developing autonomous refueling systems for UAVs. The first tests of such systems were conducted in 2013. During the tests, an unmanned aircraft of the US Navy, the X-47B, was refueled in flight (Fig. 2a). The UAV docked with the Omega K-707 tanker during a flight over the coast of Maryland and received more than 4,000 pounds of fuel from it. And in 2015, the American company Boeing transferred a pre-production model of the MQ-25 Stingray tanker drone to the US Navy for testing (Fig. 2b).



a) b)

Fig. 2. Testing autonomous refueling systems: (a) the UAV X-47B is refueled in flight; (b) the MQ-25 Stingray tanker drone to the US Navy

According to the assessment of UAV capabilities conducted by the NASA Flight Research Center, in-flight refueling of UAVs can increase their effective flight duration by 50–80%, which will simultaneously increase the capabilities of solving the combat missions assigned to them and improve flight safety.

That is why the study of in-flight refueling technologies for UAVs is of great practical importance.

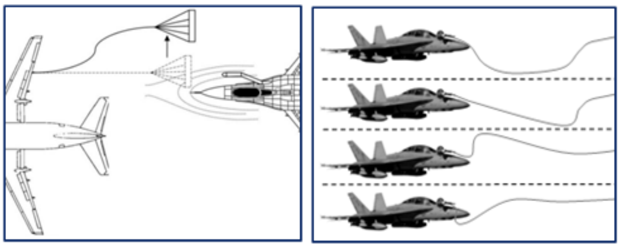
II. Problem Statement

An analysis of existing refueling systems shows that the probe-and-drogue system has a number of advantages: small size, compactness and simplicity of design, low production cost – which predetermines its choice for an automated refueling system for medium and large UAVs.

In addition, it is proposed to automate not only the UAV control, but also the control of the refueling system drogue by equipping it with aerodynamic rudders and thereby turning it into a controlled object.

The drogue control system, using its own controls, can stabilize the docking device in the air, parrying turbulent disturbances, and also automatically direct the drogue to the boom of the refueled UAV.

However, the disadvantages of this system are also obvious. The movement of the refueling system drogue is sensitive to atmospheric turbulence, the wake of the tanker, as well as to the compaction wave in front of the nose of the refueled aircraft (Fig. 3a). A significant problem at the docking stage is the sagging of the hose with its subsequent vibrations (hose whipping) (Fig. 3b), which occur immediately after contact.



a) b)

Fig. 3. Problems at the docking stage: (a) sensitive of the drogue to compression waves before the aircraft-receiver nose; (b) sagging of the hose with its subsequent vibrations (hose whipping)

It is reported that NASA's Dryden Research Center (DFRC) has succeeded in only two of six docking attempts in its UAV autonomous refueling test program, and the US Marine Corps' KC-130 tanker aircraft had a 2.5% failure rate for mid-air refueling. And the main reason for failures after successful docking is precisely the strong whipping of the fuel hose (Fig. 4), the length of which after the drogue engages with the probe of the UAV being refueled becomes greater than the decreasing distance between the UAVs.

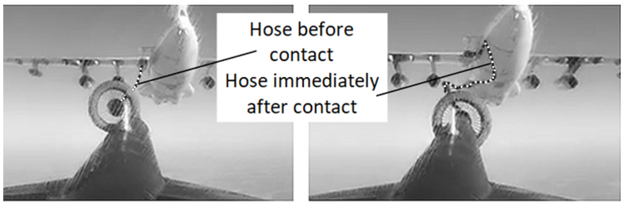


Fig. 4. Fuel hose whipping effect

The whipping that occurs after a strong impact of the probe on the drogue during docking at high approach speeds creates, firstly, a strong sag of the hose due to a significant reduction in the distance during the braking stage and the equalization of the speeds of the refueled aircraft and the tanker. Secondly, the whipping of the sagging hose creates extreme tension loads in the hose, which can disengage the drogue and the probe, and even rupture the hose – the famous "whip effect".

To suppress the effect of whipping, a fuel hose winding system with an underwinding drum (UWD) is used, restoring the required tension of the hose, the length of which should correspond to the distance between the UAV being refueled and the tanker.

The UWD (Fig. 5), which is controlled by the turbine of the suspended fueling unit, rotated by the oncoming air flow, carries out the release and retraction of the hose with a drogue.

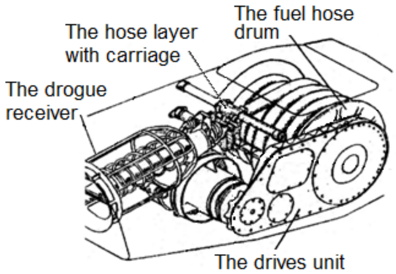


Fig. 5. The fuel hose underwinding drum

The results of the studies of the "whip effect" with a faulty fuel hose drum winding system conducted in [1] are shown in Fig. 6. At the moment of contact, the hose has a static shape (Fig. 6a) and moving at the speed of horizontal flight of the tanker.

During contact, the drogue is pushed forward with certain acceleration, depending on the speed of approach, after which the drogue lock is triggered and the probe-drogue connection is fixed. The greater the approach speed at the moment of contact, the greater the distance between the UAVs being refueled will decrease and the excess length of the already released hose will increase, creating a sagging effect.

Due to the interaction of gravity and the updraft flow, a sinusoidal wave is created at the rear of the tanker fuselage that moves towards the probe-drogue junction (Fig. 6b), (Fig. 6c), eventually creating "whip" of the hose just ahead of the drogue (Fig. 6d). This phenomenon is consistent with a number of reported observations.

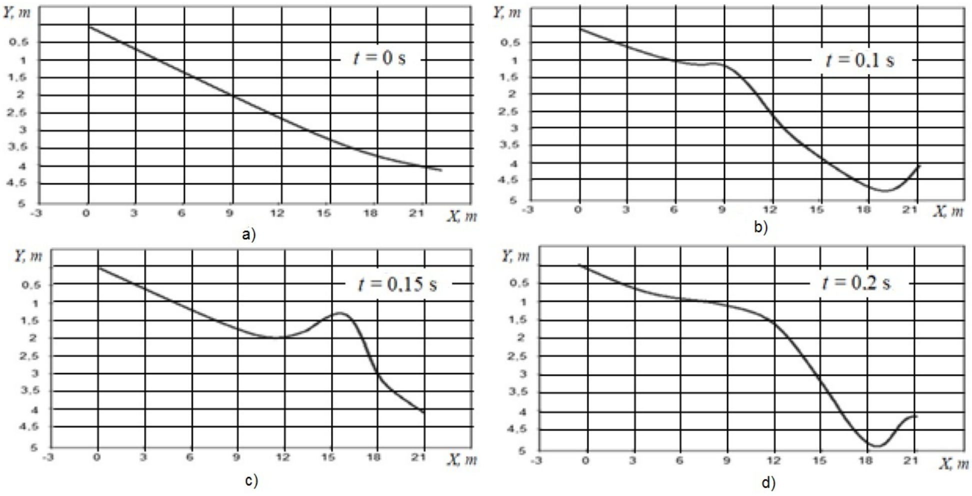


Fig. 6. Fuel hose “Whiplash Effect” research: (a) static shape of the hose at the moment of contact; (b), (c) a wave moves towards the probe-drogue junction; (d) “whips” the hose just in front of the drogue

To suppress the whiplash effect and hose flutter, a fast-acting UWD control system with variable rotation speed is required to restore the required tension in the hose, the length of which must correspond to the distance between the UAV being refueled and the tanker.

In the existing system, the UWD rotation speed is regulated by changing the position of the air turbine blades of the drive. Their pitch automatically increases in the release-retraction mode and decreases in the stabilization mode of the released hose position, pulling the hose in cases of its sagging. However, the significant inertia of such a system is not able to timely wind up the fuel hose and smooth out its beating.

Therefore, the problem statement can be formulated as follows: propose options for improving the design of the fuel hose winding system and analyze its operation.

III. Problem Solution

To increase the adjustable speed of hose reeling, it is proposed to first improve the UWD drive system by replacing the air turbine with an electric drive and supplementing the drive with a spring-loaded system (Fig. 6). The UWD spring-loaded system is relatively simple, but it cannot regulate the reeling acceleration. In contrast, the electric drive can control the reel winding acceleration.

Secondly, it is necessary to implement such speed control at the approach stage so that at the moment of docking it exceeds the speed of the refueling drone by 1.5...2 m/s. At a lower approach speed at short distances to the cone, the so-called "floating" of the docking device caused by the compaction wave of the UAV nose increases significantly, which significantly affects the docking process. In addition, at a lower docking speed, the docking lock may not work.

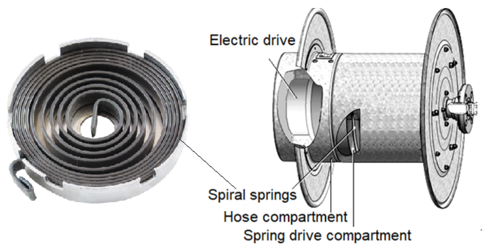


Fig. 6. Modification of the UWD drive

As mentioned, high approach speeds cause hose thrashing.

The issues of controlling the speed of approach at the docking stage were considered in the works [2], [3], but much less attention was paid to the issues of emergency braking of the refueled drone after successful docking with simultaneous winding of the fuel hose.

First of all, it is necessary to determine the length of the fuel hose that must be wound immediately after docking and obtain the dependence of this length on the braking methods and inertial-mass characteristics of the refueled UAV.

Secondly, it is necessary to obtain the dependence of the change in the approach speed on time during emergency alignment of the speeds of the tanker and the refueled UAV.

The mathematical model for speed control can be obtained from the force equation in projection onto the *OX* axis of the trajectory coordinate system, which, taking into account wind disturbances (longitudinal wind component W_x) has the form:

$$m(\dot{V}+\dot{W}_x)=P\cos\alpha-X_a-G\sin\theta,$$

where V the UAV flight speed; P is the engine thrust, X_a is the drag force, G is the weight force, α is the angle of attack, θ is the trajectory angle.

After linearization, taking into account that $X_a = X_a(V, \alpha, \delta_{flap})$, $P = P(V)$, we obtain:

$$\Delta\dot{V}+\left(a_x^V+\Delta\delta_{flap}\right)\Delta V+a_x^{\theta}\Delta\theta+a_x^{\alpha}\Delta\alpha=a_x^{\delta_p}\Delta\delta_p+\Delta\dot{W}_x \quad (1)$$

where δ_p is control handle of the engine thrust, δ_{flap} is the angle of release of the brake flaps.

Considering that refueling occurs in horizontal flight, the components $\Delta\theta$, $\Delta\alpha$ in equation (1) can be neglected, and when forming the coefficient a_x^V, the possibility of its change when releasing the brake flaps δ_{flap} should be taken into account, which increases the drag by about four times.

When modeling the emergency braking process with the release of brake flaps, the dynamics of the release of the flaps, as well as the dynamics and throttling limitations of the UAV engine were taken into account.

The simulation results (Fig. 7) show that after contact at a closing speed of 1.4 m/s, the distance L between the tanker and the refueled UAV decreases by 4.3 m during the speed equalization time. When contacting at a speed of 2.2 m/s, the distance is reduced by almost half. This is the exact length of the hose that must be wound to avoid excessive whipping due to hose sagging. In this case, the speed of approach, and therefore the speed of retracting the hose, decreases almost linearly, and the time required to equalize the speeds of the tanker and the UAV being refueled also increases linearly.

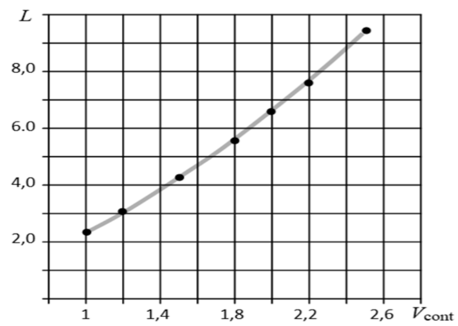


Fig. 7. Results of emergency braking simulation

Taking into account the identity of the thrust and aerodynamic characteristics of the refueled UAVs, as well as the invariance of the standard altitude and refueling speed, it is possible to obtain a dependence (Fig. 8) of the sag value of the fuel hose L on the speed at which contact occurred V_{cont}. Minor variations in the mass of the refueled UAVs practically do not change the emergency braking distance.

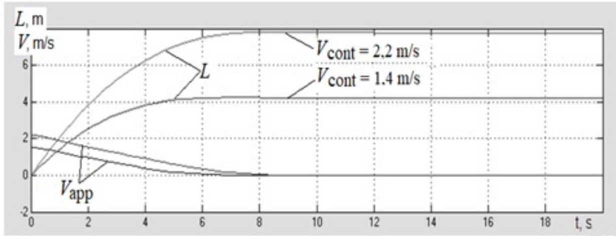


Fig. 8. Fuel hose sag dependence on contact speed

Control of flight speed at the emergency braking stage $V(t)$ using two control actions (release of brake flaps, increasing drag $u_1 = f(\delta_{flap})$ and throttling of the engine $u_2 = f(\delta_p)$) in the presence of control restrictions

$$0 \le u_1(t) \le u_{1_{max}},\quad u_{2_{min}} \le u_2(t) \le u_{2_{max}} \quad (2)$$

refers to the problems of optimal control in terms of speed using the Pontryagin maximum principle.

At the end of the control process T, it is necessary to ensure a given accuracy ε of the approach of the flight speed of the refueled drone $V(t)$ to the refueling speed V_{ref}:

$$\max\left|V(T)-V_{ref}\right| \le \varepsilon \quad (3)$$

The overall braking time T in the form of the following integral quality functional serves as the optimality criterion:

$$I=\int_0^T dt = T \to \min_{u_1(t),u_2(t)} \quad (4)$$

Based on the procedure of Pontryagin's maximum principle, the optimal controls in terms of response time are established in the form of relay time functions $u_1(t)$ & $u_2(t)$, alternately taking only their maximum permissible values (2) with duration DT_{1_i} and DT_{2_i}, which transfer the control object (1) from the specified initial state V_{cont} to the required final state V_{ref} with the minimum value of the optimality criterion (4).

If stow the brake flaps δ_{flap} is carried out already after switching to the V_{ref} stabilization mode, then the optimal speed control is simplified and reduced to the search for the duration of the maximum permissible values of the throttle deflection of the drone engine $\delta_{p_{opt}}$.

However, the simulation results (Fig. 9) show that the distance between the tanker and the UAV being refueled during the speed equalization time with optimal control remains the same as with deviation control. Accordingly, the dependence of the fuel hose sag on the contact speed does alsow not change. Therefore, the feasibility of implementing optimal control in terms of response time during emergency braking remains highly questionable.

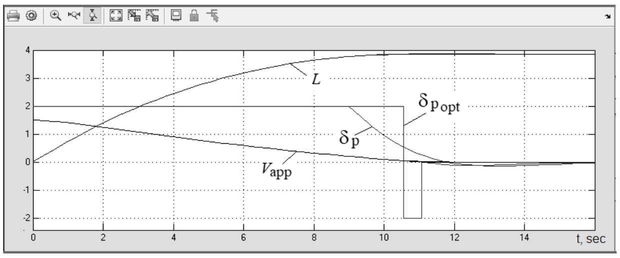


Fig. 9. Results of emergency braking with different control options

The contact velocity V_{cont} is determined by the magnitude of the overload that occurs at the moment of impact of theprobe into the drogue. The overload is recorded by the MEMS accelerometer of the active drogue control system, installed in the avionics bay. The contact velocity can also be defined as the rate of the decreasing distance between the aircraft at the moment of contact.

According to the characteristic $L = f(V_{\text{cont}})$ (Fig. 8), the amount of sagging of the fuel hose L is determined, and knowing the length of the released hose and the contact speed, the initial rotation speed of the UWD can be calculated.

When winding a hose on a UWD, the diameter onto which the winding is performed gradually increases. The law of change in the diameter of the hose winding is expressed by the following equation:

$$D_N = D_0 + 2Nd, \quad \text{or} \quad R_N = R_0 + Nd \qquad (5)$$

$$D'_N = D_N - d = D_0 + 2Nd - d = D_0 + (2N-1)d \qquad (6)$$

or

$$R'_N = R_N - \frac{d}{2} = R_0 + Nd - \frac{d}{2} = r_0 + \left(N - \frac{1}{2}\right)d \qquad (7)$$

where D_0 is the initial winding diameter; d is the hose diameter; N is the number of layers laid on the UWD; D_N is the outer diameter of the Nth layer; D'N is the average diameter of the Nth layer; R_0, R_N and R'_N are the corresponding winding radii.

The angular velocity of rotation of the UWD is determined by the circumferential velocity of the upper layer of the hose on the UWD, equal to the approach speed of the UAV. The rotation speed of the UWD also depends on the number of layers laid on the take-up drum:

$$\omega_N = \frac{V_{\text{app}}}{R'_N}; \qquad n_N = \frac{V_{\text{app}}}{2\pi R'_N},$$

where $\omega = 2\pi n$.

With an approach speed of 2.5 m/s and a fully released hose ($R'_N = R_0 = 10$ cm), the initial rotation speed of the UWD n_N should be maximum, equal to 720°/s (2 rev/s).

If the peripheral speed on the UWD exceeds the approach speed, this can cause stretching or rupture of the hose in this section. If the peripheral speed on the UWD is less than the approach speed, then the latter sags. Therefore, the receiving UWD must rotate with a variable decreasing angular velocity as it fills and the approach speed decreases. The approach speed V_{app} is continuously measured as the rate of change of the decreasing distance during the emergency braking phase.

The process of winding a hose on UWD consists of forming the N-th layer and transitioning from this layer to the (N + 1)th. When laying the turns of one layer, the rotation frequency UWD decreases only as the approach velocity V_{app} decreases. When the next layer is formed, the rotation frequency decreases abruptly, i.e. $n_N = f(N)$:

$$n_1 = \frac{V_{\text{app}}}{\pi(D_0 + d)}, \quad n_2 = \frac{V_{\text{app}}}{\pi(D_0 + 3d)}, \quad n_3 = \frac{V_{\text{app}}}{\pi(D_0 + 5d)}.$$

etc.

The hose is laid on the underwinding drum at two components: around the circumference of the underwinding drum and along its generatrix with a step approximately equal to the diameter of the hose.

To ensure uniform row laying of the hose, the speed of movement of the hose layer carriage (Fig. 5) along the underwinding drum axis is inversely proportional to the current laying diameter, which is ensured by the design of the existing hose layer of the refueling unit and does not require modification.

The start of the rewinding mode should occur immediately after contact of the refueling devices. In this case, using both underwinding drum winding drives (electric drive and spring system), the hose sag that arose after the probe hit in the drogue is eliminated as quickly as possible, then the drive is switched to the "Tracking" mode, controlling the required winding speed depending on the approach speed.

To prevent the drogue and probe from becoming disconnected due to excessive hose tension that occurs when the winding speed exceeds the approach speed, it is advisable to include a slip clutch in the underwinding drum drive design that disconnects the electric drive from the underwinding drum gearbox at certain hose tensions.

IV. Conclusions

Analysis of the UAV capabilities for implementing the missions assigned to them showed that in-flight refueling technology will increase their effective flight duration by 50...80%, which will simultaneously increase the ability to solve air support tasks and improve flight safety.

As the test results showed, a significant problem with in-flight refueling of UAVs is hose beating, which occurs immediately after successful contact, which can disengage the drogue and the probe, and even rupture the hose.

Research has shown that the cause of the beating is the length of the unwound hose, which after the drogue adhesions with the probe of UAV which approaching the tanker, becomes greater than the decreasing distance between them.

The proposed high-speed fuel hose winding system, which restores the required hose tension immediately after the drogue engages with the probe, will reduce or even eliminate the beating effect.

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М. К. Філяшкін. Високошвидкісне підмотування паливного шлангу системи дозаправки БПЛА у повітрі

Роботу присвячено питанням автоматизації дозаправки безпілотних літальних апаратів у повітрі. Розглянуто проблеми етапа стикування, зокрема провисання паливного шланга з подальшим його биттям, що виникає відразу після контакту. Основну увагу приділено етапу підмотування провислого паливного шлангу після стикування конуса-датчика зі штангою системи дозаправки БПЛА, що заправляється. Запропоновано варіанти покращення привода підмотування паливного шлангу. Досліджено програми екстренного гальмування БПЛА, що заправляється, для вирівнювання своєї швидкості зі швидкістю танкера. Запропоновано варіанти зміни швидкості підмотування паливного шлангу залежно від параметрів екстренного гальмування БПЛА, що заправляється. Проаналізовано процедуру укладання паливного шланга на барабан підмотування та її вплив на зміну швидкості підмотування. Запропоновано варіанти попередження розчеплення конуса та штанги через надмірне натягування шланга.

Ключові слова: БПЛА, що заправляється у повітрі; система штанга-конус; провисання та биття паливного шланга; привід підмотувального барабана; пружинна система; муфта ковзання.

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Освіта: Київське вище військове інженерно-авіаційне училище Військово-Повітряних Сил, Київ, СРСР, (1970).
Напрям наукової діяльності: комплексна обробка інформації в пілотажно-навігаційних комплексах, автоматизація та оптимізація керування повітряними суднами на різних етапах польоту.
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