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DOCKING OF UAV FOR AIR-TO-AIR REFUELING UNDER THE INFLUENCE OF THE BOW WAVE

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Abstract—*The issues of automating the air-to-air refueling of unmanned aerial vehicle are considered here. The focus is on the contact phase of the "floating-up" drogue with the refueling probe of the refueling unmanned aerial vehicle. The paper discusses affairs of formation of a rendezvous trajectory using a laser beam from a tanker's gyrostabilized optoelectronic system. In this laser beam must keep the refueling unmanned aerial vehicle and the actively controlled refueling drogue. To eliminate the unpredictability of the drogue's "floating-up" direction during the contact phase, the "offset aiming" strategy and algorithms for countering drogue displacement caused by the bow wave effect are proposed. An optimal contact trajectory in terms of approach speed is proposed. The proposed algorithms and their modifications were investigated using mathematical modeling. Studies have shown that the proposed algorithms for compensation of the drogue's "floating-up" effect are quite workable.*

Keywords—Air-to-Air refueling; drogue; refueling probe; bow wave; floating up effect; vertical velocity field; pitch-up; law of control; laser guidance system.

I. INTRODUCTION

Rapid advances in artificial intelligence and unmanned aerial vehicle (UAV) technologies over the past decade have made UAVs affordable and potentially revolutionary air forces. And the introduction of aerial refueling technologies, significantly increasing range and endurance of UAVs, is expanding their potential and making their new missions feasible. This is why unmanned aerial refueling technologies are becoming the focus of numerous studies to improve UAV combat capabilities.

Aerial refueling is divided into two main methods: aerial refueling using a retractable telescopic boom a "flying boom system" and a "probe-and-drogue system" [1], [2]. Compared to the "flying boom system", the "probe-and-drogue system" has several advantages, including a simple design, lower technical complexity, and the ability to simultaneously refuel multiple UAVs. Therefore, it is the basis for most autonomous UAV refueling systems. However, this method also has some disadvantages.

So, for example, at small distances to the drogue, the so-called head wave effect begins to appear, which is an area of increased pressure and and disturbed flow in front of the nose of the aircraft being refueled.The distribution of these disturbances depends on the aerodynamic shape of the nose of the UAV, its configuration and position in the flow. When approaching the drogue, the bow wave creates additional, unevenly distributed aerodynamic forces that act on the drogue. These forces cause unwanted vibrations and displacements (deviations) of the drogue from its established position in the flow (Fig. 1), which determines the essence of the phenomenon of "floating up" or "pushing away" of the drogue from the refueling probe.

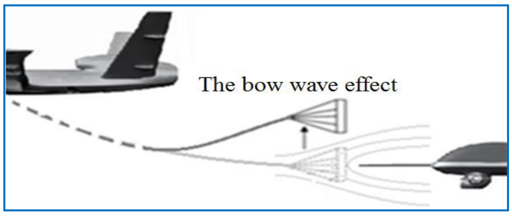

Fig. 1. The the phenomenon of "floating up" of the drogue

Thus, the bow wave is an important factor affecting the success of docking. Studying the dynamic characteristics of the probe-and-drogue system disturbed by the influence of the bow wave and developing automated refueling control algorithms that take this effect into account is an extremely urgent task.

II. PROBLEM STATEMENT

The unmanned autonomous aerial refueling (AAR) process involves three phases:

- the stage of approaching the UAV to the tanker under the influence of atmospheric turbulence and wake turbulence from the tanker aircraft;
- the docking stage, during which the impact of disturbances from the nose of the refueled UAV on the sensor drogueis observed (floating up of drogue);

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- refueling stage (fuel transfer) – a joint flight, during which it is necessary, while maintaining the relative position of the UAV and the tanker within certain limits, to ensure the winding of the hose, preventing it from sagging.

This paper examines the approach and docking stage, where the problem of maneuvering is solved for the purpose of docking the probe with the refueling drogue under conditions of the impact of disturbances from the nose of the refueled UAV on the drogue. The problem statement can be formulated as the development and study of algorithms for autonomous UAV docking for air-to-air refueling in the presence of unstable drogue behavior immediately before contact due to the influence of the bow wave.

III. PROBLEM SOLUTION

The work analyzed the trajectories of approach of a UAV with a tanker. In order to avoid getting into the turbulent wake of the tanker or the exhaust stream of its engines, the trajectory of the recipient UAV approaching the tanker must pass below the wake of the tanker.

For unmanned autonomous air-to-air refueling, the approach trajectory is proposed to be formed by a laser beam from the tanker’s gyrostabilized optical-electronic system (Fig. 2), in which the refueled UAV and the actively controlled droguer of the refueling system should be held. As an option, the approach trajectory may coincide with the continuation of the released hose.

An actively controlled droguer, equipped with avionics, a laser beam guidance system, proximity sensors like parking sensors, and aerodynamic control surfaces (Fig. 3), is a small, controllable UAV.

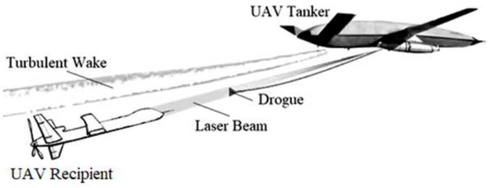

Fig. 2. The approach trajectory which is be formed by a laser beam

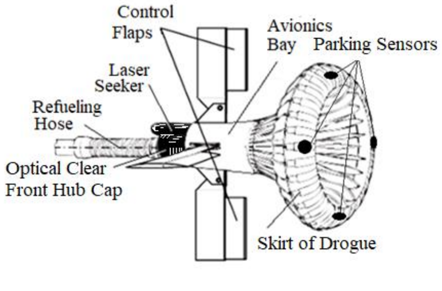

Fig. 3. The actively controlled droguer

The drogue's control system, using aerodynamic control surfaces, stabilizes the drogue, countering turbulent disturbances, and also ensures its guidance over a laser beam to the recipient UAV's refueling probe.

During the docking phase, targeting the probe is complicated by the drogue's oscillation, which appears as the nose of the UAV being refueled approaches it.

The drogue's oscillations, which occur as the nose of the refueled UAV approaches it, are explained by the deformation of the airflow and the creation of a region of variable air velocities and pressures near the surface of the UAV's nose (the creation of a bow wave) resulting in aerodynamic forces. The distribution of these forces depends on the nature of the airflow around the fuselage, its configuration, and its position in the flow. The pattern of airflow around bodies is commonly referred to as the aerodynamic spectrum.

To estimate the bow wave's impact space on the drogue-sensor, it is necessary to know the flow velocity gradients near the drogue as the nose of the receiving UAV approaches. The vertical velocity field in the UAV's symmetry plane, induced by the nose of the fuselage, obtained through wind tunnel testing is shows in (Fig. 4). The UAV's nose of the fuselageis shown in light gray. Linear dimensions along the axes are given in meters.

The velocity field can also be obtained by analytically calculating the flow around a body of revolution.

For example, to estimate velocities near the forward fuselage, which is often approximated by a semi-infinite body or a Rankine body, the velocity potential Φ is used, and the velocity field is determined as the gradient of the potential:

$$\vec{V} = \nabla\Phi.$$

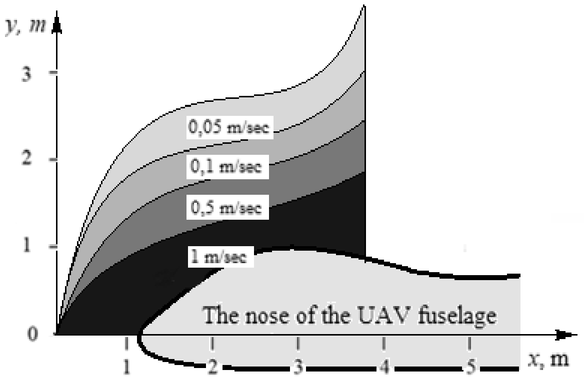

Fig. 4. The vertical velocity field, induced by the nose of the fuselage

For the nose of the UAV, the vertical velocity as a disturbed potential of the flow at the point (x, r) can be expressed in the following form:

$$\frac{\partial \varphi}{\partial r} = \frac{a_0(x)}{r} = \frac{1}{r} R(x) \frac{dR(x)}{dx}.$$

Here (x) is the distribution of radii along the length of the equivalent body of revolution simulating the nose of the UAV.

In modern engineering practice, numerical methods are used to obtain an accurate velocity field.

The dynamics of the interaction of the drogue-sensor with the disturbance field from the nose of the unmanned aerial vehicle is a complex process. As the UAV approaches, the drogue successively crosses zones with varying degrees of aerodynamic disturbance. Initially, at a greater distance, the impact may be insignificant. However, when entering the immediate vicinity of the nose of the fuselage (for example, at a distance of about 1 meter from the drogue location), the drogue is subjected to intense influence of variable pressure and velocity fields. This leads to a sharp change in its trajectory of movement and oscillations.

Therefore, it is quite important to form such a trajectory of convergence that minimizes the negative impact of the bow wave.

When analyzing the approach trajectories, it was taken into account that the deviation in the position of the probe and drogue during refueling in the longitudinal channel are determined by the coordinates of the centers of mass of the tanker X_t and the refueled UAV X_{UAV}:

$$\Delta X = X_{\text{t}} - X_{\text{UAV}},$$

and in the vertical channel, also the coordinates of the refueling devices.:

$$\Delta Y = Y_t + Y_d - Y_{\text{UAV}} - X_{\text{probe}}\vartheta,$$

where Y_d is the position of the drogue relative to the tanker's center of mass; X_{probe} is the coordinate of the probe tip relative to the UAV's center of mass; ϑ is UAV pitch angle.

As the probe approaches the drogue, the $X_{\text{probe}}\vartheta$ component increasingly influences the elimination of deviation in the probe and drogue positions ΔY. Since the angular motion is faster than the center-of-mass movement, it's easier to compensate for small ΔY misalignments at short distances from the drogue with a pitch maneuver.

To improve the reliability of the approach process and prevent the negative impact of aerodynamic disturbances from the bow wave, a strategy is proposed for targeting not the geometric center of the drogue, but a point offset downwards from the center, i.e., its lower part.

Targeting the bottom of the drogue is a proactive strategy that takes into account known aerodynamic effects and instabilities, rather than just reactively responding to them. However, this strategy implicitly assumes that the vertical size (diameter) of the drogue mast be large enough so that when targeting the bottom of the drogue, a successful docking is still guaranteed after the UAV has performed its final maneuver – pitch-up (Fig. 5), eliminating the deviation ΔY – of the probe position from the position of the drogue center. This strategy is the following rationale.

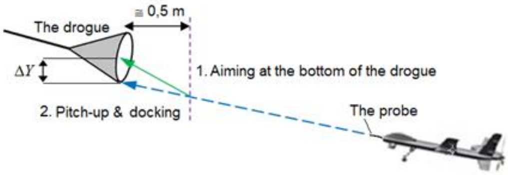

Fig. 5. The actively controlled droguer

Firstly, it further reduces the effect of turbulence on the receiving UAV. By positioning the recipient UAV slightly lower, it can be removed from the zone of the most intense vortex flows, thereby reducing random fluctuations and facilitating the task of stabilization and precise guidance.

Secondly, this approach eliminates uncertainty regarding the direction of the drogue's floating-up. As noted, the drogue tends to shift under the influence of the vortex field of receiving UAV, particularly under the influence of the bow wave of the nose of the fuselage. The bow wave creates a region of high pressure ahead of the receiving UAV, which pushes the drogue away, and the direction of this push is unpredictable. However, if the receiving UAV approaches the drogue from below, this push becomes predictable, directed upward.

The "offset aiming" strategy is used by experienced pilots during aerial refueling to counteract the vertical cone shift caused by the bow wave effect.

Table I show that the choice of "offset aiming" strategy is a reasonable compromise between ease of implementation and effectiveness in countering key destabilizing factors.

By directing the UAV's probe toward the bottom of the cone, the system "predicts" its floating-up. When the receiver – UAV approaches the drogue and its bow wave begins to act on it, the drogue, rising, moves precisely in the direction of the probe axis, which is located above the longitudinal axis, so its upward displacement does not result in a miss.

This creates a certain "go margin" for the drogue's vertical movement.

The study of the "floating-up "effect of the cone was carried out with different speed of approach and different initial data.

TABLE I ANALYSIS OF THE GUIDANCE STRATEGY AT THE BOTTOM OF THE DROGUE

Guidance strategy	**Advantages**	**Disadvantages**	**Impact on the "floating up" effect**
Guidance on the geometric center of the drogue	• Simplicity of implementation of the control law; • Intuitively understandable goal.	• Random direction of drogue deflection under the action of the bow wave; • The risk of appearancea “hunting” effect for the drogue.	***Negative*** – the system is forced to eliminate the influence bow wave using the deviation information, and this can lead to a miss.
Guidance at the bottom of the drogue	• Reducing the influence of turbulence; • It is possible to prevent the drogue from floating up under the influence of the bow wave.	• Final maneuver required; • Efficiency depends on drogue size; • Requires precise know-ledge of the drogue's bottom position.	***Positive*** – the flo-ating up of the drogue may even facilitate reaching the docking line before the final maneuver of the UAV.

The results of the studies showed that at a low approach speed of about 0.2 m/s, the deviation of the cone from the initial position is much larger than at speeds of 1.5...2 m/s and is about 1 meter. This shift is caused by long-term airflow around the nose of the receiving UAV and has a significant impact on the docking process itself.

Guidance errors lead not only to failed connections but also to accidents during maneuvers. Furthermore, a slow approach speed can cause to fail the lock of drogue.

Possible meeting trajectories and the docking result are shown in Fig. 6. The most effective approach is a uniform approach aiming at the bottom of the drogue at a speed of 1.5…2 m/s, ending with a pitching maneuver to enter the cone's skirt at a distance of 0.5 m from the drogue (option *A* in Fig. 6).

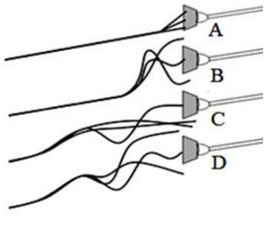

Fig. 6. Trajectories of the approach and docking results

The advantage of this approach is the high probability of docking and the ease of performing the maneuver; the disadvantage is the short time allotted for maneuvering.

Approaches at medium (option *B*), low and ultra-low speeds lead to an increased influence of the bow wave, causing the cone to deviate from a stable position and sway Oscillations of the drogue cause corresponding oscillations in the system of guiding the probe to the drogue, which leads to an unsuccessful docking The most dangerous and unsuitable approach and docking trajectories are low approach speeds – option *C* (0.2…0.5 m/s) and ultra-low approach speeds – option *D* (0.1 m/s).

The danger of such contacts lies in the reaction of the drogue, the fluctuations of which force the system to begin to correct the trajectory too early, which leads to the cone moving out of the equilibrium position and, as a consequence, to an unsuccessful docking.

Active control system of drogue at the approach stage provides drogue stabilization in the laser beam of the guidance system, parrying turbulent disturbances. In particular, in the vertical channel control is formed through the loop of normal overload according to the PID controller law:

$$\delta_h = K_{ny}(n_y - n_{y_{\text{des}}}),$$
$$n_{y_{\text{des}}} = \frac{-1}{K_{ny}}\left(K_{\phi_{vert}} + K_{\dot{\phi}_{vert}}\,p + \frac{K_{\tilde{\phi}_{vert}}}{p}\right)\Delta\phi_{vert}. \qquad (1)$$

Here δ_h is displacement of the aerodynamic control rudder of the drogue in the vertical channel; n_y is excess vertical acceleration, measured by the accelerometer; $\Delta\phi_{vert}$ is the the vertical laser guidance system error, accounting for the downward shift of the targeting point.

Starting from a certain distance, the active control system of drogue, "sensing" the approach of the UAV by the signal of ultrasonic sensors, must actively generate a control effect aimed at compensating for the repulsive force of the bow wave. Taking into account the fact that the aerodynamic layout of the recipient UAV, in particular the shape of the nose of its fuselage, as well as the height and speed of the stage of refueling are known in advance, the nose wave floating-up effect depends only [3] on the distance ΔD between the drogue and the nose of the UAV and on the speed of approach V_{app}.

The control law in the vertical channel of the system of active control of drogue is transformed to the form:

$$\delta_h = K_{ny}(n_y - n_{y_{\text{des}}}) + u(\Delta D, V_{\text{app}}), \qquad (2)$$

The compensation component $u(\Delta D, V_{\text{app}})$ is formed based on the results of blowing the nose of the UAV fuselage in a wind tunnel. The key feature of this approach is the smoothly modulated nature of the control effect $u(\Delta D, V_{\text{app}})$. This is not just a binary activation of the maximum counterforce, but its gradual increase as the UAV approaches and the effect of the bow wave increases. The control effect of the drogue should gradually increase to the level of the bow wave. This means that the drogue control system must be able to estimate (directly or indirectly) the intensity of the bowe wave or the distance to the UAV that correlates with it, and scale its response accordingly.

Research results show (Fig. 7) that the active drogue control system is able to parry the floating-up effect even without a compensatory component. However, the resulting overshoot can contribute to a miss when the probe enters the drogue skirt.

When contacting, information about the distance between the fuel drogue lock and the probe tip is formed by ultrasonic sensors. Sensors installed in a circle in the rear part of the drogue skirt (Fig. 8) measure d_{probe} – the distance to the probe tip, and the distance ΔD from the drogue lock to the probe tip additionally takes into account the value dlock – the distance from the sensors to the drogue lock:

$$\Delta D = d_{\text{lock}} + d_{\text{probe}}.$$

When the cone approaches the nose of the recipient UAV, the velocity field around it does not change in a jump-like manner. Therefore, and in the control law of the longitudinal channel of the drogue control system, the component of compensation for the “floating up” effect $u(\Delta D, V_{\text{app}})$ should be added gradually increasing:

$$\delta_h = K_{ny}(n_y - n_{y_{\text{des}}}) + \frac{u(\Delta D, V_{\text{app}})}{T_f p + 1},$$

$$\delta_z = K_{n_z}(n_z - n_{z_{\text{des}}}),$$

here T_f is the time constant of the aperiodic link, which ensures a gradual increase in the component of compensation for the “float-up” effect to the level $u(\Delta D, V_{\text{app}})$. In the horizontal channel, δ_z control is implemented according to the same laws as in the vertical channel.

If the component of the compensation for the "floating-up" effect $u(\Delta D, V_{\text{app}})$ does not exactly correspond to the field of vertical speeds created by the nose of the fuselage, then overcompensation or, conversely, undercompensation of the float effect may occur. To prevent such a situation, it is proposed that the compensation for the "floating-up" effect be carried out only in dynamic mode, by including the component $u(\Delta D, V_{\text{app}})$ of the isodromic link in the circle.

The control law in the vertical channel of the drogue, which implements such a compensation option, has the form:

$$\delta_h = K_{ny}(n_y - n_{y_{\text{des}}}) + \frac{T_f p}{T_f p + 1} u(\Delta D, V_{\text{app}}).$$

The research results show (Fig. 9) that knowing the precise value of the compensation $u(\Delta D, V_{\text{app}})$ signal obtained from blowing the nose of the UAV fuselage in a wind tunnel for different approach speeds is not necessary.

There is no need and for error-free compensation for the floatsng-up effect, since the final precise guidance of the probe to the center of the cone is achieved during the final pitchsng maneuver of the recipient UAV.

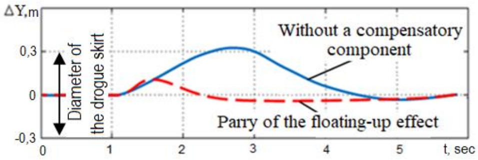

Fig. 7. Research results on compensation for the floating-up effect

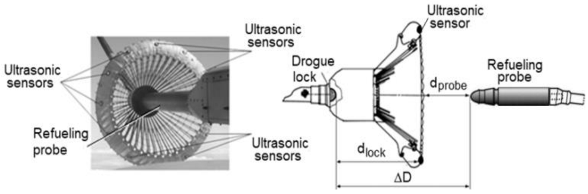

Fig. 8. Distance from the drogue lock to the probe tip

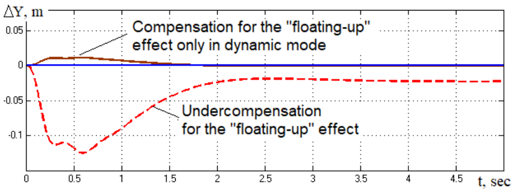

Fig. 9. Research results on compensation for the floating-up effect only in dynamic mode

The error of the static control loop is compensated at the final stage of the approach by a high-speed pitch angle change loop (see Fig. 5) based on information from the parking sensors.

IV. CONCLUSIONS

Simulation results showed that during docking, the bow wave disrupts the equilibrium of the hose-cone system, causing the cone to deflect unforeseen from its equilibrium position.

The proposed "offset aiming" guidance strategy eliminates uncertainty regarding the braking drogue's rise direction, enabling the design of a docking control loop operating on the disturbance-based control principle.

It measures the bow wave's disturbing effect before it affects the drogue's movement and adjusts the control action to compensate for this disturbance's impact on the system.

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М. К. Філяшкін. Стикування БПЛА для дозаправки в повітрі під впливом головної хвилі

Розглянуто питання автоматизації заправки безпілотних літальних апаратів у повітрі. Основну увагу приділено фазі контактування «спливаючого» конуса із заправним зондом безпілотного літального апарату, що заправляється. У статті розглядаються питання формування траєкторії зближення за допомогою лазерного променя від гіростабілізованої оптоелектронної системи танкера. У цьому лазерному промені повинен утримуватися безпілотний літальний апарат, що заправляється, та активно керований конус системи дозаправки. Для усунення непередбачуваності напрямку «спливання» конусу під час фази контакту запропоновано стратегію «зміщеного прицілювання» та алгоритми протидії зміщенню конусу, спричиненому ефектом головної хвилі. Запропоновано оптимальну траєкторію контакту з точки зору швидкості зближення. Запропоновані алгоритми та їх модифікації досліджено за допомогою математичного моделювання. Дослідження показали, що запропоновані алгоритми компенсації ефекту «спливання» конусу є цілком працездатними.

Ключові слова: дозаправка в повітрі; конус; штанга системи дозаправки; головна хвиля; ефект спливання; вертикальне поле швидкості; кабрирування; закон керування; лазерна система наведення.

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Освіта: Київське вище військове інженерно-авіаційне училище Військово-Повітряних Сил, Київ, СРСР, (1970).
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