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AUTOMATION OF DOCKING OF REMOTELY CONTROLLED REFUELING DEVICES IN THE AIR

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Abstract—*The issues of automating the air-to-air refueling of civilian aircraft are considered here. The main attention is paid to the stage of contacting of the "floating up" drogue with of the probe of refueling of the tanker aircraft. The options for implementing this technology are discussed, based on the automatic control loop of the tanker thrust in the mode of change according to the exponential law of approach speed as a function of the range between the refueling devices. To implement an exponential speed change program, it is proposed to use predictive control based on a dynamic process model. An alternative approach to automating the process of approaching the fueling devices involves using remote control of the unwinding of the fuel hose drum of the outboard fueling unit to control of the speed of approach of refueling devices. Such control is less inertial than controlling the flight speed of a multi-ton tanker.*

Index Terms—Air-to-air refueling; refueling probe; floating up of drogue; aircraft which refueling; tanker aircraft; law of control; remote-controlled drogue.

I. INTRODUCTION

Reducing the specific resource intensity of air transport services requires new ideas to improve the efficiency of transport services. One such idea is air-to-air refueling of regional civil aviation aircraft. This idea is currently being developed by leading European aviation research organizations within the framework of the Recreate project [3], as well as research institutes in the United States, Great Britain and Russia [2]. Air-to-air refueling technology can significantly increase the flight range of regional aircraft when organizing non-stop flights, reduce fuel consumption by 35–40% when flying in a fan pattern with landing at a hub, will increase the commercial load of the aircraft several times and reduce CO^2 emissions, as well as the cost of the fleet. All this emphasizes the relevance of developing technologies for air-to-air refueling of civil aviation aircraft.

When implementing air-to-air refueling in civil aerial transport, the long-term experience of military aviation can be used. However, this is true only in terms of technical feasibility, but nothing more. Ensuring the safety of a civil aviation aircraft in this stage should be at the top of the list of requirements for such technologies. In particular, in order to ensure the safety and comfort of passengers, as well as to reduce the workload on pilots of scheduled aircraft, a "reverse air-to-air refueling" technology is proposed for hose-drogue refueling systems, in which the tanker aircraft (TA) is approaching the commercial aircraft from behind and, maneuvering, docks its refueling system with it, that is, the main piloting tasks at the air-to-air refueling stage are transferred to trained TA crews. Due to this, the refueling process can be performed during a standard straight-and-line flight of a civil aircraft, its crew does not experience additional workload, except for performing the procedures for releasing and retracting the hose with the sensor drogue (SD) of the refueling system, and passengers of the commercial aircraft (the the receiver aircraft (RA)) may not notice anything at all.

In addition, the refueling process can be automated to reduce the burden on the crew of the refueling aircraft. At the same time, must be automated not only the control of aircraft, but also the control of the drogue of refueling system. The drogue must be equipped with aerodynamic rudders (Fig. 1) and thereby turned it into a remotely controlled unmanned aerial vehicle (UAV. The drogue control system, using aerodynamic rudders, will stabilize the drogue in the air, parrying turbulent disturbances, and also provide remote guidance of the drogue on the refueling probe of the tanker [1].

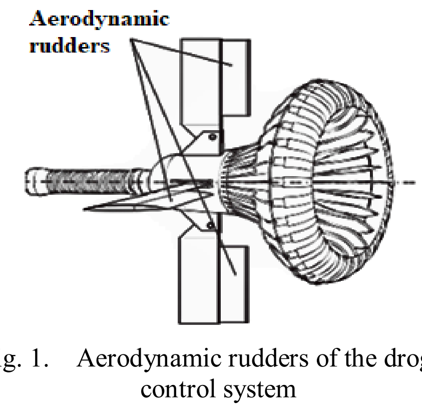

Fig. 1. Aerodynamic rudders of the drogue control system

The presence of two pilots on the heavy aircraft tanker allows the control process to be divided at the approach and docking stages. In particular, the right pilot is assigned the task of remote control of the sensor drogue, and the left pilot – the crew commander – is assigned the task of controlling the approach speed. At the same time, the speed of the TA at the docking stage should exceed the speed of the RA by 1.5…2 m/s. At a lower approach speed at short distances to the cone, the so-called "floating" of the drogue, caused by the flow around the nose of the tanker aircraft, increases significantly, which significantly affects the docking process. In addition, at a lower speed of docking, the drogue lock may not work.

At a speed of approach of more than 1.5 ... 2 m/s, at the moment of contact, a strong impact on the drogue occurs, which leads to an oscillatory movement of the hose ("effect of whip") and swinging of the drogue in the vertical plane, as a result of which the refueling probe is usually destroyed (broken) or the hose is torn.

Naturally, the creation of remote control systems for the SD significantly simplifies the process of docking refueling devices, but the problem of controlling the speed of approach and docking is not removed.

II. Problem Statement

The paper proposes to automate the control of the approach speed so that at the moment of docking its value does not go beyond the specified range.

At the stage of approaching, an ultrasonic distance sensor such as a parking radar can be used as an information sensor. Ultrasonic sensors must be installed in a circle in the rear part of the brake skirt (Fig. 2.) to measure the distance to the probe d_{probe}, and then, taking into account the distance d_{lock} from the sensors to the brake lock, calculate the distance ΔD from the lock to the refueling probe:

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

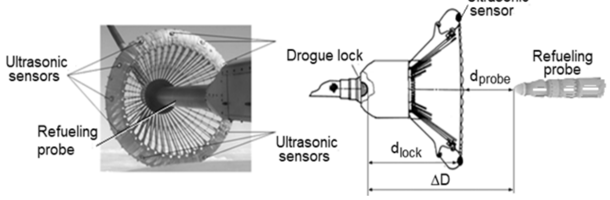

Fig. 2. Placement of distance measuring sensors from the drogue lock to the probe

As an option, this distance can be zeroize by controlling the flight speed of the tanker aircraft through the autothrottle, implementing the control law:

$$\delta_p = K_V(\Delta V_{\text{set}} - \Delta V),$$

where $\Delta V = V_{\text{RA}} - V$, $\Delta V_{\text{set}} = \dfrac{K_D}{K_V}\Delta D$,

Here V_{RA} is the speed of the receiver aircraft; δ_P is the deflection of the thrust control lever; ΔV_{set} is the set deviation of the tanker's flight speed from the refueling speed (the speed of the receiver aircraft).

However, with such control at the moment of contact the approach speed ΔV_{dok} (Fig. 3) may exceed the permissible contact speed (V_{cont} = 1.5...2 m/sec), which will inevitably lead to the so-called effect of whip.

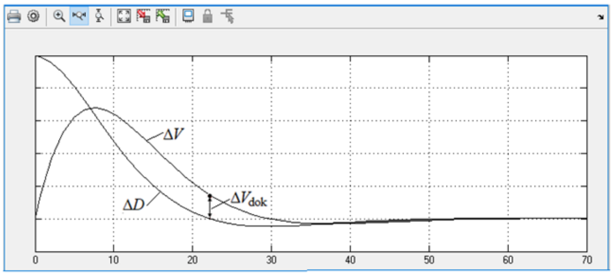

Fig. 3. Results of modeling the approach and contact stage

Therefore, in the work it is proposed to form a program for changing the speed ΔV of approach according to the exponential law (Fig. 4) depending on ΔD, i.e. based on information from the distance between the refueling devices.

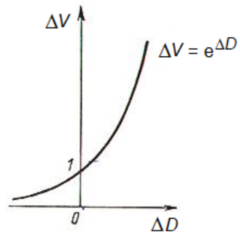

Fig. 4. The program for changing the speed of approach depending on th distance between the refueling deevices

But the probe touches the drogue's lock (the asymptote of the exponent) when using the exponential law of the formation the approach trajectory theoretically only in infinity. To avoid this, the asymptote of the exponential must be located beyond the drogue's lock.

III. Problem Solution

To implement an exponential program for changing the approach speed, we will use the model predictive control method (MPC), that is, control with predictive models. In the case when the tanker violates the specified approach trajectory, this control method will form another exponential trajectory from the new approach parameter values, according to which the engine thrust control will bring the tanker's speed to the specified level. A necessary condition for such control is the prediction of the tanker's movement.

Typically, the motion of the aircraft's center of mass is modeled using a system of nonlinear differential equations, which have the form:

$$\dot{\mathbf{x}} + f(\dot{\mathbf{x}}, \mathbf{u}) = 0. \quad (1)$$

In our case, this is a mathematical model of the longitudinal motion of an aircraft.

$$\begin{aligned}
&m\dot{V} = P\cos\alpha - X_a - mg\sin\Theta - m(\dot{w}_x\cos\Theta + \dot{w}_y\sin\Theta),\\
&mV\dot{\theta} = P\sin\alpha + Y_a - mg\cos\Theta + m(\dot{w}_x\sin\Theta + \dot{w}_y\cos\Theta),\\
&I_z\dot{\omega}_z = M_z,\\
&\dot{\vartheta} = \omega_z,\\
&\alpha = \vartheta - \Theta + \alpha_w,\\
&\dot{H} = V_y = V\sin(\Theta + \alpha_w) + w_y,\\
&\dot{D}_{\mathrm{TA}} = \dot{d}_{\mathrm{prob}} = V\cos(\Theta + \alpha_w) + w_x,\\
&\dot{D}_{\mathrm{RA}} = \dot{d}_{\mathrm{lock}} = V_{\mathrm{RA}} + w_x,\\
&\Delta D = D_{\mathrm{RA}} - D_{\mathrm{TA}}.
\end{aligned}$$

where m is the aircraft mass; M_z, J_z are the aerodynamic moment and the axial moment of inertia of the tanker relative to the transverse z-axis; P is the engine thrust; X_a, Y_a is the drag force and the lift force; ϑ, Θ is the pitch angle and the trajectory inclination angle; ω_z is the angular velocity relative to the z-axis; w_x, w_y are horizontal components of the wind speed; α, α_w are angle of attack and vertical disturbance from wind; D_{TA} is the distance flown by the tanker; D_{RA} is the distance flown by the receiver aircraft; V_{RA} is the specified refueling speed; ΔD is the distance between the refueling devices.

As a predictive model, a simplified linear model of the change in the tanker speed is selected with coefficients corresponding to the flight mode at the refueling stage:

$$\dot{\bar{\mathbf{x}}}(\tau) + \bar{f}(\tau, \bar{\mathbf{x}}(\tau), \bar{\mathbf{u}}(\tau)) = 0, \qquad \bar{\mathbf{x}}\big|_{\tau=t} = \mathbf{x}(t). \quad (2)$$

In equations (1), (2) $\mathbf{x}$ is the state vector, $\mathbf{u}$ is the control.

For the refueling mode, as a predictive mathematical model of the tanker's movement, one can choose a simplified linear model of the change in aircraft speed, which for a given mode in form of operational variables has the form:

$$\begin{aligned}
&\left(p + a_x^V\right)V(p) = a_x^{\delta_p}\delta_p,\\
&pD_{\mathrm{TA}} = V(p),\\
&pD_{\mathrm{RA}} = V_{\mathrm{RA}},\\
&\Delta D(p) = D_{\mathrm{RA}}(p) - D_{\mathrm{TA}}(p).
\end{aligned}$$

The coefficients of the linear model a_x^V, $a_x^{\delta_p}$ correspond to the refueling mode.

By setting the initial parameters of the predictive model equal to the current state of the object and some control, the equations of this model are integrated in accelerated time, which gives a forecast of the object's movement over a given time interval (over the forecasting interval). By changing the control according to a certain program $\bar{\mathbf{u}} = \mathbf{u}(\tau)$ and again integrating the system (2) over a given interval with the initial conditions $\bar{\mathbf{x}}\big|_{\tau=t} = \bar{\mathbf{x}}(t)$, the optimal value of control is sought, which is interpreted as a forecast of the control object reaching a given level.

All tasks of optimal control are based on a search the control which provides a solution to a given problem with a given quality functional:

$$\lim_{t\to\infty}\left\|\mathbf{x}(t) - \mathbf{r}_x(t)\right\| = 0, \quad \lim_{t\to\infty}\left\|\mathbf{u}(t) - \mathbf{r}_u(t)\right\| = 0. \quad (3)$$

Here $\mathbf{r}_x(t)$ and $\mathbf{r}_u(t)$ are objective vector functions that determine the desired movement of the object taking into account the restrictions:

$$\mathbf{x}(t) \in X \;\; \forall \;\; t \in [0, \infty].$$

We define some functionality for the controlled movement of the object:

$$J = J(\mathbf{x}(t) - \mathbf{u}(t)). \quad (4)$$

Then the problem of optimal control consists of finding a control that ensures (3) and delivers a minimum to the functional (4). Naturally, the same functional is sought for optimal control for the predictive mathematical model of the tanker's movement.

At the stage of approaching, the set speed of the aircraft is formed by the autothrottle according to the exponential law:

$$\begin{aligned}
&\delta_{\mathrm{p}} = K_V(V_{\mathrm{set}} - V), \; V_{\mathrm{set}} = V_{\mathrm{RA}} + V_{\Delta D},\\
&V_{\Delta D} = \left(\Delta D + D_{\mathrm{as}}\right)/T_{\mathrm{exp}}.
\end{aligned} \quad (5)$$

Here V_{set} is the set speed, which differs from the refueling speed V_{RA} by the value $V_{\Delta D}$, which changes exponentially depending on the distance ΔD between the refueling devices; T_{exp} is the time constant of the exponential; D_{as} is the depth of placement of the asymptote of the exponent behind the drogue's lock $D_{\mathrm{as}} = T_{\mathrm{exp}}/V_{\mathrm{RA}}$

By means of multiple integration of predictive model on an accelerated time scale with different control actions, The optimal value of control is sought, which brings the controlled variables closer to the corresponding parameters on the forecast horizon. Optimization is carried out taking into account the entire complex of restrictions imposed on the control and controlled variables.

The optimal control found is implemented on the real object during the same period of time and at the end of this step its actual state is measured again in order to use it in the predictive model in the next step.

The forecasting horizon shifts one step forward (the forecast interval decreases), and the search for a new optimal control is repeated. As the forecast interval decreases, control accuracy gradually increases.

The study of the control with predictive models at the stage of contacting of the refueling devices was carried using the Simulink program of mathematical modeling, which is a part of the MATLAB mathematical package (Fig. 5).

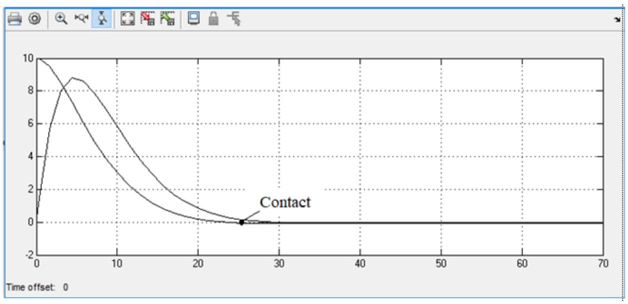

Fig. 5. Simulation results of the control of the contact's stage of the refueling devices

The simulation demonstrated the efficiency of the proposed control with a predictive model. The time of approaching with the sensor drogue from a distance of 10 m is approximately 25 s. The contact speed may be changed by changing the value of the D_{as} parameter.

Another approach to automation of the process of approaching and docking refueling devices assumes that at the last stage of the approach process, remote control of the unwinding of the fuel hose drum of the outboard refueling unit is used, thus controlling the approach speed and, accordingly, the position of the drogue relative to the refueling probe. The process of remote control of the approach speed of the drogue to the refueling probe by unwinding the fuel hose drum is significantly less inertial than controlling the flight speed of a multi-ton tanker.

During aerial refueling, about 2 meters of fuel hose must be let out from the suspension refueling aggregate before contact. In this case, the drogue, under the pressure of air, straightens out from the folded position into its working configuration.

The tanker aircraft approaches the cone at a distance of about 15…20 m using the inter-aircraft navigation system and conventional approach control algorithms, after which the refueling speed stabilization mode is activated and the docking stage of the refueling devices begins.

The fuel hose let out control system is switched on, which includes the fuel hose underwinding drum (Fig. 6). The fuel hose underwinding drum control mechanism has an auto-matic or manual mode of operation. It is proposed to supplement the automatic mode with a remote control mode for the unwinding speed of the fuel hose.

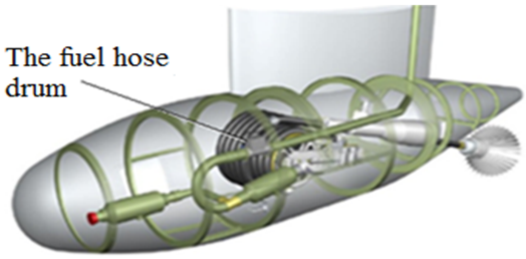

Fig. 6. The fuel hose let out control system

After the tanker aircraft has taken its place in the formation of refueling, pilot of the tanker issues a command to let out the drogue. There are two possible options for let out.

In the first option, the drogue to let out at a constant speed not exceeding 2 m/s in order to avoid the whip effect at the moment of contact. At the same time, the right pilot uses remote control to aim the drogue at the refueling probe, and the control system of drogue improves the guidance process, stabilizing the drogue in space and parrying turbulent disturbances. When the lock of drogue lock is triggered, the fuel hose underwinding drum is braked.

Thus, in the first variant, practically relay control of the rotation speed of the fuel hose underwinding drum is implemented:

$$\dot{\varphi} = \begin{cases} \frac{V_{cont}}{R} = \text{const} & \text{if} \quad K_{lock} = 0 \\ 0 & \text{if} \quad K_{lock} = 1 \end{cases}$$

where (V_{cont} = 1.5…2 m/s) is the contact speed; K_{lock} is sign of the drogue lock triggering; R is radius of hose winding on the underwinding drum.

Some inertia of the drogue let out stoppage processes leads to hose sagging (the length of the hose L is greater (Fig. 7) than the distance D between the probe and the suspension aggregate of refueling). This effect is recorded by the hose tension sensor.

Based on the information from the tension sensor, the standard mode of the fuel hose underwinding control system is activated, which maintains the required tension of the hose and eliminates it sagging.

The duration of the docking process depends on the distance to the tanker aircraft (10 ... 15m), that is, on the length of the let out hose L, and at a drogue let out speed V of 2 m/s it is 7.5 ... 10 s. (Fig. 7)

Another option for bringing the refueling devices closer together involves starting to let out the hose at the maximum possible speed, decreasing it as the distance decreases between refueling devices.

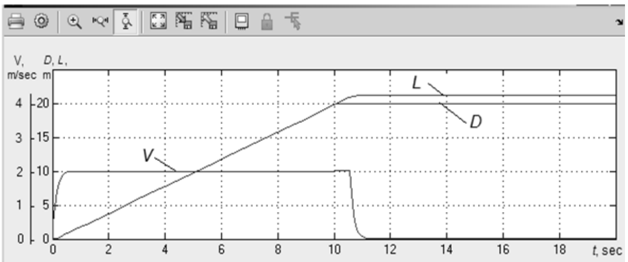

Fig. 7. Simulation results of the docking process with a cone which is released at a constant speed

As in the tanker aircraft speed control mode during the rendezvous phase, an exponential law of the reduction let out speed of the hose is proposed for remote control of the fuel hose drum rotation speed.

$$\dot{\varphi} = K_V (V_{\text{set}} - V),$$

where the current approach speed V is formed by differentiating the distance d_{probe} between the filling devices, which is measured by ultrasonic sensors or calculated by the rotation speed of the fuel hose underwinding drum, and the set speed is in formed as:

$$V_{\text{set}} = \left(\Delta D + D_{\text{ac}} \right) / T_{\text{exp}}.$$

After the tanker rod is engaged with the cone, the tanker's position in the formation is maintained. The crews receive the "Contact" command, which is generated by the cone lock limit switches, and the "Contact" indicator lights up on the aircraft instrument panels.

IV. CONCLUSIONS

The technology of refueling regional jet aircraft in flight will allow: to increase their commercial payload; to significantly save fuel and reduce CO2 emissions into the atmosphere.

The proposed system of automation of docking of refueling devices in the air significantly reduces the psychophysical stress of pilots of tanker aircraft, increases both the reliability and simplicity of refueling even in turbulent atmosphere.

Automatic and remote control of the speed of unwinding of the fuel hose drum significantly reduces refueling time, facilitates the technique of piloting a tanker aircraft and increases the safety of contact at the docking stage.

Equipped with the proposed system of refueling in the air, regional aircraft of the An-158, An-170 type may become out of competition on the routes Europe – Southeast Asia.

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М. К. Філяшкін. Автоматизація стикування дистанційно керованих заправних пристроїв у повітрі
Розглядаються питання автоматизації дозаправки цивільних літаків у повітрі. Основна увага приділяється етапу стикування конуса-датчика зі штангою системи дозаправки літака-заправника. Розглядаються варіанти реалізації даної технології на основі контуру автоматичного керування тягою танкера в режимі зміни за експоненціальним законом швидкості наближення в залежності від дальності між заправними пристроями. Для реалізації програми експоненціальної зміни швидкості пропонується використовувати прогнозне управління на основі моделі динамічного процесу. Альтернативний підхід до автоматизації процесу підходу до заправних пристроїв передбачає використання дистанційного керування розмотуванням барабана паливного шланга підвісної паливної системи літака, що заправляється для керування швидкістю підходу до заправних пристроїв. Таке керування менш інерційне, ніж керування швидкістю польоту багатотонного танкера.
Ключові слова: дозаправка у повітрі; заправна штанга; конус-датчик палива; літак, що заправляється; літак-заправник; закон керування; дистанційно керований конус.

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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.
Кількість публікацій: більше 200 наукових робіт.
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