Study on the affecting factors of bow wave effect modeling in hose-drogue refueling system

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Abstract. In the docking process of aerial refueling hose-drogue system, the bow wave effect of an approaching receiver aircraft will produce a strong aerodynamic effect on the drogue which intensify the deviation of drogue and increase the difficulty of the coupling. This paper presents a receiver aircraft’s bow wave effect modeling method previously developed by the authors is continued to study, which based on potential flow theory and considers the major shape characteristics of the receiver aircraft. This method is used in a simulation system, which combined with the hose-drogue dynamic model and tanker downwash model. The model of the receiver aircraft, which includes the fuselage, cockpit, main wing and other structural factors, is simulated respectively. The motion law of drogue under different bow wave model is analyzed. The results show that the fuselage, cockpit and main wing structure have significant influence on the bow wave effect.

1.  Introduction
The hose-drogue aerial refueling system is simply and widely used and is a power multiplier in modern air force. [1]. But the hose-drogue system used flexible hose which is highly sensitive to external factors such as atmospheric turbulence, tanker downwash and the receiver aircraft’s bow wave effect. In the actual docking process, there is the problem of the hose-drogue transient motion, which increased the difficulty of the docking and security risks.

In the docking process, when the receiver aircraft is close to the drogue, the drogue will deviate from the balance position and then quickly return back. This phenomenon is called as the bow wave effect or the forebody effect [2]. The drogue movement caused by the bow wave brings great uncertainty to the success of the docking. The rise of unmanned aircraft vehicle (UAV) in recent years has opened up new areas for aerial refueling [3]. Therefore, it is required to conduct more in-depth studies on the hose-drogue aerial refueling to ensure the safety of the docking process, whether manned or unmanned.

So far, the research on atmospheric turbulence and tanker downwash is relatively mature. However, there is less research on the bow wave effect modeling. Most of researchers use half Rankine body [4] to simulate the bow wave effect. This method has a small amount of calculation, but also has the problem of accuracy is poor. Dai and Wei use a series of line doublets to simulate the nose and cockpit of the receiver aircraft and use the CFD result to correct the analytical results. [5] A CFD simulation was carried out by Wang and Dong [6]. They used the FLUENT software to analyze the variation of bow wave with Mach number and Angle of attack. Khan and Masud [7] used CFD to simulate the
aerial refueling of the "Thunder" fighter and analyze the docking strategy of reducing bow wave effect. The CFD simulation results are more reliable. However, due to different receiver aircrafts have different complex configuration structure, the CFD simulation requires a large amount of computing resources and time. Moreover, the CFD results are inconvenient for the controller design. NASA Dryden Flight Research Center tested the bow wave effect by F/A-18 receiver-aircraft and estimated the range of the bow wave effect [4, 8].

In view of the current shortage of modeling of bow wave effect, this paper proposes a fast and efficient receiver aircraft’s bow wave effect modeling method based on potential flow theory and considers the major shape characteristics of the receiver aircraft. This method is used in aerial refueling docking simulation system. On the basis of this, the bow wave effect model is simulated respectively with different shape structure. The importance of different structure of the receiver aircrafts in the modeling of bow wave effect is analyzed.

2. Frame definitions and modelling assumptions.

2.1. Reference frames
As shown in Fig. 1. This paper defines the ground coordinate system O_\text{g}X_\text{g}Y_\text{g}Z_\text{g}. The body frame of the receiver aircraft O_bX_bY_bZ_b and the body frame of the tanker aircraft O_aX_aY_aZ_a. O_b is fixed on the top of the receiver aircraft. O_a is fixed on the refueling pod.

![Fig 1. Overview of the reference frames](image)

2.2. Modelling assumption
To simplify the modeling of the bow wave effect, the following assumptions are made.

(1) In the shape structure of the receiver aircraft, there is a large influence on the flow field near the nose, fuselage, cockpit, main wing and strake wing. Suppose the aerodynamic effects of each structure are independent to each other. According to the superposition principle, the induced velocity of the bow wave effect can be expressed as:

\[ \mathbf{v}_{\text{bow}} = \mathbf{v}_{\text{body}} + \mathbf{v}_{\text{cockpit}} + \mathbf{v}_{\text{mainwing}} + \mathbf{v}_{\text{strakewing}} \]  

Where \( \mathbf{v}_{\text{bow}} \) denotes the induced velocity produced by the bow wave, \( \mathbf{v}_{\text{body}} \), \( \mathbf{v}_{\text{cockpit}} \), \( \mathbf{v}_{\text{mainwing}} \) and \( \mathbf{v}_{\text{strakewing}} \) denotes the induced velocity produced by the fuselage, cockpit, main wing and strake wing.

(2) Considering the angle of attack of the receiver aircraft is small. So, it can be assumed that the fuselage is axisymmetric.

3. Bow wave effect modelling

3.1. Receiver aircraft’s fuselage and cockpit modelling method
To simplify the receiver aircraft model establishing, seem the fuselage as Rankine body [9], whose flow field is superposition by the three-dimensional point source, the three-dimensional point sink and
three-dimensional straight uniform stream. Finally, the fuselage flow field model is obtained by elliptical transformation. The cockpit is modeled in the same way as the fuselage.

Assumption that the three-dimensional point source strength of Rankin body is \( m \) and was placed in \( A (-a, 0) \) as shown in Fig. 2. The three-dimensional point sink strength of Rankin body is \( m \) and was placed in \( B (a, 0) \). Straight uniform stream \( U \) is going along the x axis. The velocity potential and stream function can be expressed as:

\[
\begin{align*}
\varphi &= -Ux + \frac{m}{\sqrt{(x + a)^2 + y^2}} - \frac{m}{\sqrt{(x - a)^2 + y^2}} \\
\psi &= -\frac{1}{2} Uy^2 + \frac{m(x + a)}{\sqrt{(x + a)^2 + y^2}} - \frac{m(x - a)}{\sqrt{(x - a)^2 + y^2}}
\end{align*}
\]

Eq. (3) can be transformed to the form as:

\[
\varphi = -\frac{1}{2} U r^2 \sin^2 \theta + m(\cos \theta_2 - \cos \theta_1)
\]

Causing the boundary condition rules that \( \varphi = 0 \). The function can be rewritten as

\[
y^2 + b^2 (\cos \theta_1 - \cos \theta_2) = 0
\]

\[
b^2 = \frac{2m}{U}
\]

Assuming that \( OC=OD=l \), \( OE=h \). Because of point \( C \) is the stationary point. The velocity of the free stream is offset by the velocity induced by source and sink.

\[
-\frac{m}{(1 + a)^2} + \frac{m}{(1 - a)^2} = U
\]

Causing the geometric relationship shown as in Fig. 2

\[
(l^2 - a^2) = 2ab^2 l
\]

Where \( 2b^2 \cos \alpha = h^2 \), Eq (8) can be rewritten as

\[
\frac{2a}{\sqrt{h^2 + a^2}} = \frac{h^2}{b^2}
\]

\[
h^2 l \sqrt{h^2 + a^2} = 2ab^2 l
\]

Combine the two equations
Based on the receiver aircraft’s parameters. Setting the length of the fuselage is 2l, and the maximum radial width is h. The three-dimensional coordinates and strength m of point source and point sink are calculated. The induced velocity $v_{body}$ at any point in space can be calculated as

$$v_{body} = \frac{m}{r_s} - \frac{m}{r_{-s}}$$

(12)

Where $r_s$ is the vector from the source to the point. $r_{-s}$ is the vector from the sink to the point.

During refueling process, the aircraft keeps the subsonic flight. Based on the fuselage model in the incompressible flow. The Gothert Rule is used for compressibility modification. The corresponding induced velocity is obtained in the compressible flow.

While for some receiver aircraft like F/A-18, the cross section of the nose is like an ellipse. In order to obtain more accurate simulation results, the ellipse transformation is necessary.

As is shown in Fig. 3, the scale transformation is presented as

$$x' = x, \quad y' = \frac{a}{b} y, \quad z' = z$$

(13)

Where a and b are the short axis and long axis of the ellipse. The coordinates of the desired point are converted by Eq. (13) and obtain the $v_{body}' = [v_x', v_y', v_z']$ by Eq. (12). After that, the ellipse transformation is applied again to transform $v_{body}'$ back to the original scale as:

$$v_x = v_x', \quad v_y = \frac{b}{a} v_y', \quad v_z = v_z'$$

(14)

Modified fuselage induced velocity shown as

$$v_{body} = [v_x, v_y, v_z]^T$$

(15)

Fig 3. Illustration of the ellipse transformation

3.2. Receiver aircraft’s aerofoil modelling method
In the process of aerial refueling, the flight velocity is low. In this case, compared with the general CFD method, the vortex lattice method (VLM) has a small precision and high computational
efficiency [10]. Under the assumption of the inviscid flow, the VLM can be used to find the flow field of the aerofoil easily and efficiently.

The VLM is a practical numerical method based on lifting surface. The VLM considers the wing as a network with a horseshoe vortex superimposed on the aerofoil. First, the aerofoil is divided into $M \times N$ grids, and each grid is equipped with a horseshoe vortex, and the induced velocity generated by each horseshoe vortex is obtained by the Biot-Savart Law. The $i$th control point’s velocity induced by $M \times N$ horseshoe vortexes is obtained. According to the boundary conditions of control points, a set of equations of $M \times N$ control points can be obtained to solve the vortex strength of each horseshoe vortex, so as to obtain the induced velocity of the finite discrete horseshoe vortex on any point in space. The Gothert Rule is used for compressibility modification too. The corresponding induced velocity is obtained in the compressible flow.

4. The simulation processes
In the aerial refueling, the receiver aircraft and tanker in the same flight altitude and velocity. The receiver aircraft is close to the drogue with a stable docking velocity behind the tanker, until the connection is successful, and the relative position of the drogue is no more changes. In the process of receiver aircraft slowly close to the drogue, the bow wave effect caused by the receiver aircraft destroys the original force balance state of the drogue and produces swing. The relative position and velocity between the receiver aircraft and drogue is constantly changing. To simulate this process accurately. The digital simulation process is as follows.
(1) Calculate the equilibrium position of the hose under the no turbulence condition [11].
(2) Calculate the tension of each hose element, relative airflow velocity, external force and equivalent hose restoring force.
(3) Calculate the fuselage and cockpit’s strength and coordinates of the source and sink. After that, calculate the induced velocity at the point in space.
(4) Calculate the velocity induced by the main wing on the drogue by VLM.
(5) Calculate the bow wave induced velocity at the point of the drogue by Eq. (1).
(6) The acceleration of the drogue is calculated by the induced velocity, and the acceleration of the drogue is obtained by using the fourth-order Runge-Kutta method [12].

Repeat the above steps to obtain the real-time motion of the drogue. The receiver aircraft is subject to the F/A-18. The simulation is conducted under the condition without turbulence. The simulation parameters used in this paper are illustrated in Table 1. The parameters of the tanker and hose-drogue system are with the same parameters in Ref. 13

| Table 1. Parameters of the simulation. |
|----------------------------------------|
| Parameter                             | Value   |
| Tanker                                |         |
| The length of the fuselage             | 17.07m  |
| The maximum radius of the fuselage     | 0.808m  |
| span                                  | 11.43m  |
| root chord                            | 4.04m   |
| wing sweep                            | 25.82°  |
| Drogue                                |         |
| Weight                                | 200N    |
| Diameter                              | 0.6m    |

5. Simulation results and analysis.
In order to verify the accuracy of the bow wave model established in this paper, the simulation results are compared with the experimental data of the Autonomous Airborne Refueling Demonstration (AARD) project in 2006 by NASA Dryden Flight Research Center [5].
NASA conducted six experiments using the F/A-18 as the receiver aircraft, but only the third and sixth experiments were successful. In the third docking simulation process, the deviation of the maximum deviation in the vertical and lateral of the drogue is shown in Table 2. The table shows the simulation values the experimental value has a certain deviation, this is because the simulation ignores the influence of atmospheric turbulence. In the actual flight test, the faint atmospheric turbulence causes the drogue to swing, and the random oscillation will have a certain effect on the result.

**Table 2.** Experiment and simulation results.

| Case | The lateral maximum deviation | The vertical maximum deviation | Remarks   |
|------|--------------------------------|--------------------------------|-----------|
| 1    | 0.213 m                        | 0.366 m                        | experimental value |
| 2    | 0.266 m                        | 0.348 m                        | simulation value  |

In the process of docking, the deviation of the deviation in the vertical (Y-axis) and lateral (Z-axis) of the drogue which include experiment and simulation results are shown in the Fig. 4. Before the receiver aircraft approached, drogue affected by turbulent flow swings near the equilibrium position, give the experimental results a lot of randomness, but we can still observe that the bow wave effect has some common features: (1) The drogue begins to float to the right and upward. And then swings back to the connected position from the maximum deviation position until the drogue is connected with the probe. (2) The maximum value of drogue deviation in simulation is similar to the experimental value. (3) The swing velocity of the drogue which affected by the bow wave effect in simulation is similar to the experimental. To sum up, the simulation results and the actual behaviour deviation are small, meeting the expectation.

![Fig 4. Deviation of drogue in simulation and experimental](image)

5.1. **Simulation and analysis of the affecting factors of bow wave effect modelling.**

Use the model established above, a numerical docking simulation for different configurations of the receiver is carried out. The configuration contained in the receiver bow wave effect model is shown in the Table 3. Under different flight conditions, the deviation of the deviation in the vertical and lateral of the drogue is shown in the Fig. 5, Fig. 6 and Fig. 7.

**Table 3.** Different configuration for receiver bow wave effect modeling.

| Case 1 | Case 2 | Case 3 | Case 4 |
|--------|--------|--------|--------|
| Fuselage | Fuselage + cockpit | Fuselage + cockpit + main wing | Fuselage + cockpit + main wing + canard |
As shown in the Fig. 5. In the case of high dynamic pressure, compared with the simple model of Rankine body model (including only the fuselage), the cockpit and the main wing would have a larger impact on the result of the simulation. The maximum deviation would be nearly 30 percents higher than only the fuselage. However, the simulation results of the canard are small and negligible. By comparison of the Fig. 5, Fig. 6 and Fig. 7, the maximum deviation of the simulation of the bow wave effect generated by the bow wave model with different receiver structure factors tends to approach with the decrease of dynamic pressure. Under the condition of low dynamic pressure, the cockpit and the main wing would have a lower impact on the result of the simulation results.
6. Conclusion

(1) In this paper, a simple and efficient modeling method is proposed based on potential flow theory, and a mathematical model of fuselage, cockpit and aerofoil is established by means of source, sink and finite discrete horseshoe vortex. Through the compressibility modification and elliptical modification, the model is as accurate as possible to simulate the aerodynamic characteristics of the bow wave effect.

(2) Based on the shape features and parameters of F/A-18, a model of bow wave effect was established. The numerical simulation of the aerial refuelling docking process was carried out. The results are compared with the experimental results of NASA, which proves the validity of the modelling method.

(3) The bow wave effects induced by the receiver model with different structural factors were simulated and analysed. It is concluded that the fuselage, cockpit and main wing have significant influence on the bow wave effect, and the larger the dynamic pressure of the oil machine, the more significant the bow wave effect.

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