Influence of the receiver aircraft’s bow wave on the motion characteristics of the drogue in hose-drogue refueling system

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Abstract. In the docking process of hose-drogue aerial refueling 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 docking. This paper presents a 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 a probe-drogue aerial refueling dynamic simulation system, which combined with the hose-drogue dynamic model and tanker wake dynamic model. The motion characteristics of the drogue under different flight altitude, flight velocity and docking velocity are calculated and analyzed. The results show that when the other conditions are certain, when the flight altitude increases, the bow wave effect decreases the vertical and longitudinal influence on the drogue, increases the lateral influence. When the flight velocity increases, the bow wave effect increases the vertical and longitudinal influence on the drogue, decreases the lateral influence. When the docking velocity increases, the drogue’s swing displacement and the swing velocity are all increased.

1. Introduction
The aerial refueling is a power multiplier in modern naval and air force. The hose-drogue aerial refueling system is simple and widely used [1, 2]. But the hose-drogue system of flexible structure which is highly sensitive to external factors such as atmospheric turbulence, tanker wake and the receiver-aircraft’s bow wave. In the actual docking process, there is the problem of the hose-drogue swing, 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 [3, 4]. 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 [5]. 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 wake is relatively mature. However, there is less research on the bow wave effect modeling. Most of people use half Rankine body [6] to simulate the bow wave effect. This method has a small amount of calculation, but also has the problem of accuracy is poor. A CFD simulation was carried out by Wang and Dong [7]. They used the
FLUENT software to analyze the variation of bow wave with Mach number and Angle of attack. Khan and Masud [8] 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 [5, 9].

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. The motion characteristics of the drogue at different flight altitude, flight velocity and docking velocity are calculated and analyzed.

2. Frame definitions and modeling assumptions.

2.1. Reference frames
As shown in Fig. 1. This paper defines the ground coordinate system OgXgYgZg. The body frame of the receiver aircraft ObXbYbZb and the body frame of the tanker aircraft OaXaYaZa. Ob is fixed on the top of the receiver aircraft. Oa is fixed on the refueling pod.

\[
\begin{align*}
\mathbf{V}_{\text{bow}} &= \mathbf{V}_{\text{body}} + \mathbf{V}_{\text{cockpit}} + \mathbf{V}_{\text{mainwing}} + \mathbf{V}_{\text{strakewing}}
\end{align*}
\]

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.

2.2. Modeling assumption
To simplify the modeling of the head 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 head wave effect can be expressed as:

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

(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 modeling

3.1. Receiver aircraft’s fuselage and cockpit modelling method
To simplify the receiver aircraft model establishing, seem the fuselage as Rankine body [10], 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:

\[
\varphi = -UX + \frac{m}{\sqrt{(x+a)^2 + y^2}} - \frac{m}{\sqrt{(x-a)^2 + y^2}}
\]

(2)

\[
\psi = -\frac{1}{2} Uy^2 + \frac{m(x+a)}{\sqrt{(x+a)^2 + y^2}} - \frac{m(x-a)}{\sqrt{(x-a)^2 + y^2}}
\]

(3)

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

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

(4)

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

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

(5)

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

(6)

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.

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

(7)

Cause the geometric relationship shown as in Fig. 2

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

(8)

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

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

(9)

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

(10)

Combine the two equations

\[
h^2 l \sqrt{h^2 + a^2} = (l^2 - a^2)^2
\]

(11)
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

$$v_{body} = \frac{m}{r_s} - \frac{m}{r_{-s}}$$  \hspace{1cm} (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

$$x' = x, \quad y' = \frac{a}{b} y, \quad z' = z$$  \hspace{1cm} (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 $v_{body} = [v_{x}', v_{y}', v_{z}']^T$ by Eq. (12). After that, the ellipse transformation is applied again to transform $v_{body}'$ back to the original scale as

$$v_x = v_x', \quad v_y = \frac{b}{a} v_y', \quad v_z = v_z'$$  \hspace{1cm} (14)

Modified fuselage induced velocity shown as

$$v_{body} = [v_{x}', v_{y}', v_{z}']^T$$  \hspace{1cm} (15)

**Figure 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 [11]. 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×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 ith control point’s velocity induced by M×N horseshoe vortexes is obtained. According to the boundary conditions of control points, a set of equations of M×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 Gohtert Rule is used for compressibility modification too. The corresponding induced velocity is obtained in the compressible flow.

4. The simulation process
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 [12].
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 [13].

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 span              | 0.808m |
| root chord                 |        |
| wing sweep                 | 11.43m |
| Drogue                     |        |
| Weight                     | 200N   |
| Diameter                   | 0.6m   |

5. Simulation results and analysis of the motion characteristics of the hose-drogue.

5.1. Influence of the flight altitude on the drogue.
The flying velocity is 120m/s, the docking velocity is 1.0m/s. The flight altitude is 3000m, 5000m and 7000m respectively. The simulation results are as follows:

In the process of docking, the deviation of the offset in the vertical and lateral of the drogue is shown in the Fig. 4. The drogue begins to float to the right and upward. And then swings back to the connected position from the maximum offset position until the drogue is connected with the probe,
after that the displacement is no longer changed. The other conditions remain unchanged, when the flight altitude increases, the vertical maximum deviation of the drogue from the equilibrium position will decrease, and the lateral maximum of the drogue from the equilibrium position deviation will increase. The drogue begins to deviate from the equilibrium position at a later time point, which means that the influence area of the bow wave effect on the longitudinal axis (X-axis) decreases with the increase of altitude.

When the flight velocity is constant, the circulation of the tanker and receiver aircraft’s wing attached vortex and free vortex increase with the increase of altitude. The downwash and sidewash velocity of the tanker put on the hose-drogue system is increased, and the upwash and sidewash velocity of the receiver aircraft is increased. Combined with the bow wave effect, the flight altitude increases, the vertical deviation of the drogue decreases, the lateral deviation increases, and the longitudinal influence range decreases.

![Figure 4](image-url)  
**Figure 4.** Deviation of drogue in Y and X direction with different flight altitude.

5.2. **Influence of the flight velocity on the drogue.**

The flying altitude is 3000m, the docking velocity is 1.0m/s. The flight velocity is 120m/s, 150m/s and 180m/s respectively. The simulation results are as follows:

In the process of docking, the deviation of the offset in the vertical and lateral of the drogue is shown in the Fig. 5. The other conditions remain unchanged, when the flight velocity increases, the vertical maximum deviation of the drogue from the equilibrium position will decrease, and the lateral maximum of the drogue from the equilibrium position deviation will increase. The drogue begins to deviate from the equilibrium position at a later time point, which means that the influence area of the bow wave effect on the longitudinal axis (X-axis) decreases with the increase of velocity.

![Figure 5](image-url)  
**Figure 5.** Deviation of drogue in Y and X direction with different flight velocity.
When the flight altitude is constant, the circulation of the tanker and receiver aircraft’s wing attached vortex and free vortex decrease with the increase of velocity. The downwash and sidewash velocity of the tanker put on the hose-drogue system is decreased, and the upwash and sidewash velocity of the receiver aircraft is decreased. Combined with the bow wave effect, the flight velocity increases, the vertical deviation of the drogue increases. The lateral deviation decreases and the longitudinal influence range increases.

5.3. Influence of the docking velocity on the drogue.
The flying altitude is 3000m, the flight velocity is 150m/s, the docking velocity is 0.5m/s, 1.0m/s and 1.5m/s respectively. The simulation results are as follows:

![Graphs showing deviation of drogue in Y and Z direction with different docking velocity.](image)

**Figure 6.** Deviation of drogue in Y and Z direction with different docking velocity.

The deviation of the lateral and vertical deviation of the drogue during the docking process is shown as Fig. 6. The larger the docking velocity is, the larger the deviation of the drogue will be, and the larger the slope of the offset curve will be, which means the larger the swing rate is. It is indicated that the larger the docking velocity will increase the swing displacement and the swing velocity of the drogue which affected by the bow wave effect and increase the difficulty of the docking.

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 refueling docking process was carried out. The motion characteristics of drogue under different docking state are analyzed. The results show that when the other conditions are certain, when the flight altitude increases, the bow wave effect decreases the vertical and longitudinal influence on the drogue, increases the lateral influence. When the flight velocity increases, the bow wave effect increases the vertical and longitudinal influence on the drogue, decreases the lateral influence. When the docking velocity increases, the drogue’s swing displacement and the swing velocity are all increased.

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