Abstract. The traditional method to assess VSTOL aircraft lift loss in hover is based on empirical formula. However, for a complete airframe, it is hard to determine mechanism parameters of empirical formula and ensure calculation accurately. In this paper, we propose a new method to assess complete airframe lift loss: identifying the lift loss dynamic model based on wire suspension balance test. Compared with empirical formula calculation, this approach avoids the problem of determining mechanism parameters. Modeling result fits the result of empirical formula in a same aircraft.

Keywords: VSTOL aircraft, Modeling of lift loss, Equivalent airframe, Wire suspension balance

1. Introduction

Jet and fan powered VSTOL aircraft has ground effect in hover. It causes suction pressure which leads to lift loss. The past 50 years investigations have showed that, VSTOL aircraft lift loss included the following aspects: out-of -ground effect, suckdown effect and fountain effect[1-6]. NASA and Lockheed Martin researchers illustrated these phenomena at Fig.1, and pointed out that assessing VSTOL aircraft lift loss accurately was a crucial research to determine the performance of aircraft [5].

Fig.1 Ground effect of VSTOL aircraft in hover

A.J.Saddington provided a review of VSTOL aircraft ground effect research in hover and transition flight regimes. The review pointed out that the traditional method to assess lift loss is by using empirical formula, however, a complete airframe was difficult to predict and must therefore be assessed through experiments [6].

In aeronautical experiments, six-component balance (test aircraft three-axis force and three-axis moment) is conventionally used for aircraft dynamic modeling. In paper we choose a wire suspension six-component balance to assess VSTOL aircraft lift loss. Since the setting position affects jet-induced test significantly, leveraged-balance and box-balance are therefore not chosen.

Modeling of VSTOL aircraft lift loss in paper is based on a wire suspension balance test. Hang a complete airframe model in balance and get the output signals, the lift loss model will then be identified. Modeling result is consistent with the result of empirical formula calculation in a same aircraft.
2. Equivalent airframe and test on wire suspension balance

Ground effects on different parts of a complete airframe are not equal [5], see Fig. 2. Considering that there is little pressure on head and tail, we can omit the two parts and make an equivalent airframe as Fig. 3, whose engine, control system and equivalent area are the same as the complete aircraft.

The size of the equivalent airframe is 1.3m in length and 0.32m in width, with span 0.64m. The type of lift fan is Lander 120mm Special Metal EDF.

The schematic diagram of wire suspension balance is as Fig. 4. This test system includes balance bracket, wires, force sensor and data collection system.

To study ground effect, fix a board under the airframe (Fig. 5), and use laser level equipment to adjust. Before test, calibrate sensor and number wires as Fig. 6, with the first line pointing to the head direction. Studies of lift loss focus on Z axis lift $F_Z$. From Fig. 6:

$$F_Z = \Delta F_1 + \Delta F_{10} + \Delta F_{11} - \Delta F_9 - \Delta F_7 - \Delta F_8$$
3. MODELING OF THE EQUIVALENT AIRFRAME LIFT LOSS

3.1. Modeling of Lift Fan

The equivalent airframe is a two lift fan configuration, the front fan is regarded as lift fan and the other as main engine. When it is hovering, two fans flow vertically. In hover without ground effect, these two fans’ model can be identified separately [2].

For the balance system, input $u(k)$ is lift fan control signal, and output $y(k)$ is lift force $F_z$. It is a dynamic discrete-time system, described as an n-order linear differential equation:

$$y(k) + a_1 y(k-1) + \cdots + a_n y(k-n) = b_1 u(k) + b_2 u(k-1) + \cdots + b_m u(k-m)$$

Input and output signals are as Fig.7 and Fig.8 shown.

![Fig.7 Balance system input](image1)
![Fig.8 Balance system output](image2)

Use the Auto-Regressive Moving Average (ARMA) models:

$$A(Z^{-1}) y(k) = B(Z^{-1}) u(k).$$

Transfer function turns to:

$$G(z) = \frac{B(Z^{-1})}{A(Z^{-1})} = \frac{b_1 + b_2 z^{-1} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_n z^{-n}}.$$

Using the least-squares method, get the lift fan model as:

$$A(Z^{-1}) = 1 + 0.5884Z^{-1} + 0.4631Z^{-2} \quad B(Z^{-1}) = -0.0164 + 0.027Z^{-1}.$$

Identification result is shown in Fig.9.

![Fig.9 Lift fan identification result](image3)

From the same modeling method, the main engine model is:

$$A(Z^{-1}) = 1 + 0.6305Z^{-1} + 0.5352Z^{-2} \quad B(Z^{-1}) = -0.0069 + 0.0152Z^{-1}.$$

The corresponding identification result is in Fig.10.

![Fig.10 Main engine identification result](image4)

3.2. THE EQUIVALENT AIRFRAME LIFT LOSS UNDER GROUND EFFECT

Fix a board under the airframe, then the airframe has ground effect which leads to lift loss. With the board set in different heights, the equivalent airframe lift model could be identified based on section 3.1. Notice that choosing height must refer to some typical value.

From section 1, ground effect in hover contains fountain and suckdown effects causing lift change. Their typical heights can be calculated by empirical formulas[5]:

$$\text{Fountain Effect} = 12.2m$$

$$\text{Suckdown Effect} = 0.4m$$
\[
\frac{h_f}{e} = 3.7(NPR)^{-0.5} \left( \frac{e}{d} \right)^{-2.2} \left( \frac{\theta}{\theta_0} \right)^{3.6(NPR)^{-1.6}}, \quad \frac{h_{TV}}{d} = \frac{0.2(D_p - d)}{d},
\]

where \(h_f\) and \(h_{TV}\) are the fountain and suckdown effect typical heights, NPR is nozzle pressure ratio, \(e\) is half of the distance between the two nozzles, \(w\) is half of the wing root chord, \(D_p\) is the equivalent diameter of the platform, and \(d\) is the nozzle out-diameter.

For the equivalent airframe in paper, these parameters are: NPR=1.024, \(e=0.55\) m, \(w=0.1255\) m, \(D_p=0.5299\) m, \(d=0.125\) m.

Calculation results: \(h_f=1.4988\) m, \(h_{TV}=0.1206\) m.

Then based on the calculation results, four heights are selected: 0.12 m, 0.22 m, 0.32 m, 0.42 m.

Modeling method is the same as section 3.1. Results are shown in Tab.1:

<table>
<thead>
<tr>
<th>Height</th>
<th>0.12m</th>
<th>0.22m</th>
<th>0.32m</th>
<th>0.42m</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_1)</td>
<td>-1.697</td>
<td>-1.795</td>
<td>-1.763</td>
<td>-1.721</td>
</tr>
<tr>
<td>(a_2)</td>
<td>0.73</td>
<td>0.819</td>
<td>0.7903</td>
<td>0.744</td>
</tr>
<tr>
<td>(b_1)</td>
<td>3.923 \times 10^{-4}</td>
<td>-2.805 \times 10^{-1}</td>
<td>4.061 \times 10^{-4}</td>
<td>7.088 \times 10^{-4}</td>
</tr>
<tr>
<td>(b_2)</td>
<td>-7.748 \times 10^{-1}</td>
<td>2.483 \times 10^{-1}</td>
<td>-1.551 \times 10^{-4}</td>
<td>-4.774 \times 10^{-1}</td>
</tr>
</tbody>
</table>

Identification results:

![Fig.11 Identification results of different heights in hover](image)

Input step signals to the identification results and observe static responses:

![Fig.12 Step signal input](image)

From Fig.13, the following table of lift loss in different heights is given:
### Tab.2 lift loss in different heights

<table>
<thead>
<tr>
<th>Height</th>
<th>0.12m</th>
<th>0.22m</th>
<th>0.32m</th>
<th>0.42m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift loss</td>
<td>6.68%</td>
<td>5.83%</td>
<td>3.33%</td>
<td>0</td>
</tr>
</tbody>
</table>

### 4. MODELing result CHECK

In this section, check the modeling result by using the method of empirical formula calculation. From section 2, fuselage is divided as Fig.14:

![Fig.14 Divide fuselage](image)

For whole craft, the lift loss empirical formula is [6]:

\[
\frac{\Delta L}{T} = \frac{\Delta L_{S1}}{T} + \frac{\Delta L_{S2}}{T} + \frac{\Delta L_f}{T} + \frac{\Delta L_{Sf}}{T}.
\]

where

First calculate out-of-ground-effect [6]:

\[
\left(\frac{\Delta L_{S1}}{T}\right)_b = -0.00022 \frac{S}{A_1} \left(\frac{\text{Per}_{e}}{d_e}\right)^{1.56} (\text{NPR})^{-0.5},
\]

where \(S\) is the platform area, \(A_1\) is the total jet exit area, \(\text{Per}_{e}\) is the total perimeter of the jet nozzle, and \(d_e = \sqrt{2d^2} = 0.1768\) m. For the equivalent airframe, \(S_2 = S_3 = 0.144\) m²:

\[
\left(\frac{\Delta L_{S2}}{T}\right) = \left(\frac{\Delta L_{S2}}{T}\right)_b = -0.00022 \frac{S}{A_1} \left(\frac{\text{Per}_{e}}{d_e}\right)^{1.56} (\text{NPR})^{-0.5} = -0.0078.
\]

Fountain effect occurs on area \(f\), which can be written as [5]:

\[
\frac{\Delta L_f}{T} = C_{f, \text{ave}, f} \frac{S_f}{2A_1} K_{n,f} K_f
\]

\(C_{f, \text{ave}, f}, K_{n,f}\) and \(K_f\) denote the average pressure presented later, nozzle shape factor and the body shape factor separately. For the equivalent airframe \(S_f = 0.128\) m², fountain effect in different heights are listed in Tab.3.

### Tab.3 fountain effect

<table>
<thead>
<tr>
<th>Height</th>
<th>0.12m</th>
<th>0.22m</th>
<th>0.32m</th>
<th>0.42m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift improvement</td>
<td>6.68%</td>
<td>3.96%</td>
<td>2.81%</td>
<td>2.19%</td>
</tr>
</tbody>
</table>

Empirical formula of suckdown effect is [5]:

\[
\frac{\Delta L_S}{T} = C_{p, \text{ave}, S} \frac{S_s}{2A_1} \frac{T_1}{T/2}
\]

where \(S_s\) is \(S - S_f = 0.352\) m², \(T\) is lift force, \(C_{p, \text{ave}, S}\) has relationship with the hovering height.

The calculation results of suckdown effect are shown in Tab.4:

### Tab.4 suckdown effect

<table>
<thead>
<tr>
<th>Height</th>
<th>0.12m</th>
<th>0.22m</th>
<th>0.32m</th>
<th>0.42m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift loss</td>
<td>13.42%</td>
<td>9.62%</td>
<td>6.56%</td>
<td>2.48%</td>
</tr>
</tbody>
</table>
Compare the modeling result and empirical formula calculation:

<table>
<thead>
<tr>
<th>Height</th>
<th>Modeling result</th>
<th>Empirical formula calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12m</td>
<td>6.68%</td>
<td>7.33%</td>
</tr>
<tr>
<td>0.22m</td>
<td>5.38%</td>
<td>6.44%</td>
</tr>
<tr>
<td>0.32m</td>
<td>3.33%</td>
<td>4.53%</td>
</tr>
<tr>
<td>0.42m</td>
<td>0%</td>
<td>1.47%</td>
</tr>
</tbody>
</table>

The data of Tab.5 shows that modeling result fits the empirical formula calculation result in a same aircraft. The differences occur because the calculation of empirical formula does not include the lift loss of wings area.

5. Conclusion

This paper provides a new modeling method to assess the VSTOL aircraft lift loss in hover. This method does not rely on mechanism parameters of aircraft which are always difficult to determine, therefore is a practical way to assess the lift loss of complete aircraft especially the one with complex configuration.

6. References