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MODELING Of VSTOL AIRCRAFT LIFT LOSS In HOVER BASED On WIRE SUSPENSION BALANCE

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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 sucktion pressure which leads to lift loss. The past 50 years investagations 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 phenomenons at Fig.1, and pointed out that assessing VSTOL aircraft lift loss accurately was a crucial reseach to determine the performance of aircraft [5].

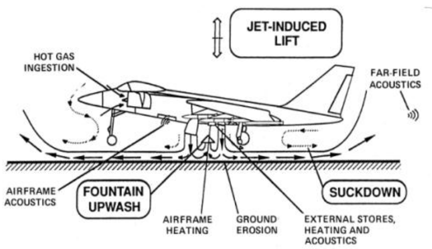


Fig.1 Ground effect of VSTOL aircraft in hover

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.

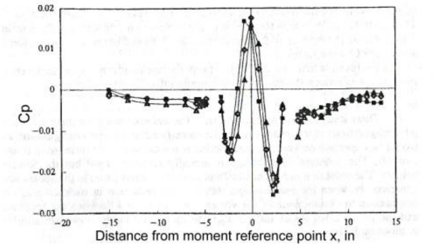


Fig.2 Effect of thrust on centerline pressure

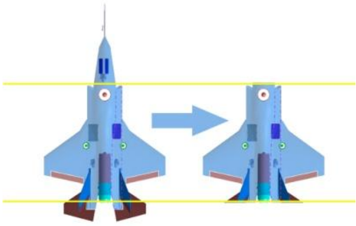


Fig.3 Equivalent airframe

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.

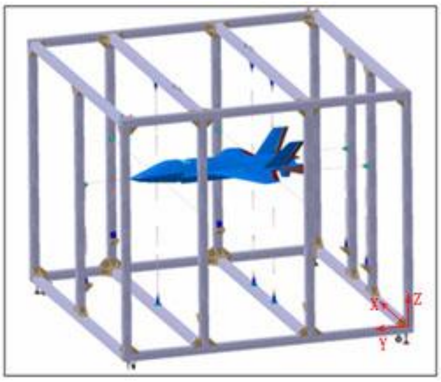
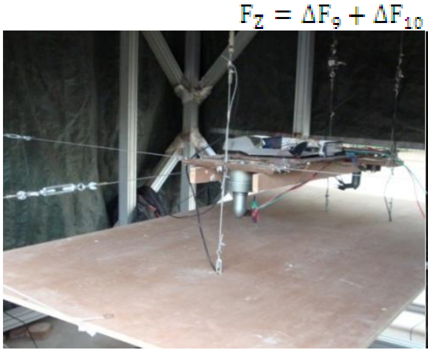


Fig.4 The schematic diagram of wire suspension balance

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:

$$F_Z = \Delta F_9 + \Delta F_{10} + \Delta F_{11} - \Delta F_6 - \Delta F_7 - \Delta F_8$$



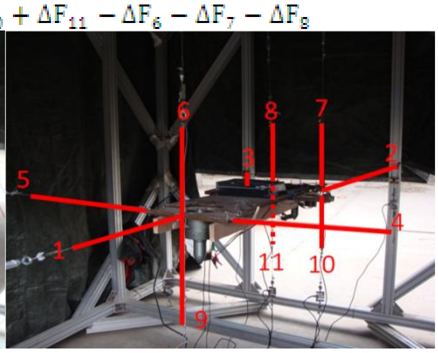


Fig.5 Ground effect test

Fig.6 Wires number

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:

$$y(k)+a_1 y(k-1)+\cdots+a_n y(k-n)=b_0 u(k)+ b_1 u(k-1)+\cdots+b_m u(k-m)$$

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

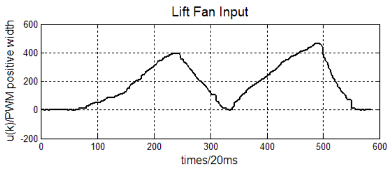


Fig.7 Balance system input

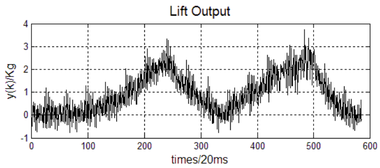


Fig.8 Balance system output

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

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

Transfer function turns to:

$$G(z)=\frac{B(Z^{-1})}{A(Z^{-1})}=\frac{b_0+b_1 Z^{-1}+\cdots+b_m Z^{-m}}{1+a_1 Z^{-1}+\cdots+a_n Z^{-n}}.$$

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

$$A(Z^{-1}) = 1+0.5884Z^{-1}+0.4631Z^{-2}$$

$$B(Z^{-1}) = -0.0164+0.027Z^{-1}.$$

Identification result is shown in Fig.9.

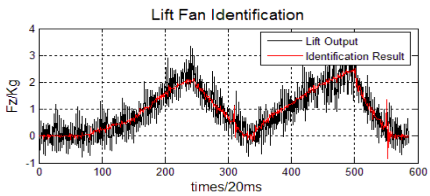


Fig.9 Lift fan identification result

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

$A(Z^{-1}) = 1+0.6305Z^{-1}+0.5352Z^{-2}$

$B(Z^{-1}) = -0.0069+0.0152Z^{-1}$.

The corresponding identification result is in Fig.10.

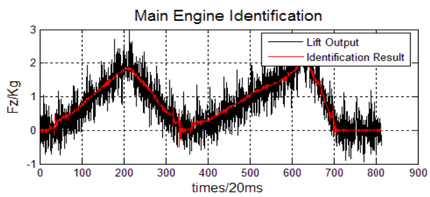


Fig.10 Main engine identification result

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 emprical formulas[5]:

$$\frac{h_f}{e} = 3.7(NPR)^{-0.5}\left(\frac{e}{d}\right)^{-0.2}\left(\frac{w}{e}\right)^{0.6(NPR)^{-0.6}},\ \frac{h_{tv}}{d} = \frac{0.2(D_p - d)}{d},$$

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=0.55m, w=0.1255m, D_p=0.5299m, d=0.125m.

Calculation results: h_f=1.4988m, h_{tv}=0.1206m.

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

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

Tab.1 identification results of different heights in hover

Height	**0.12m**	**0.22m**	**0.32m**	**0.42m**
a_1	-1.697	-1.795	-1.763	-1.721
a_2	0.73	0.819	0.7903	0.744
b_0	3.923×10^{-4}	-2.805×10^{-5}	4.061×10^{-4}	7.088×10^{-4}
b_1	-7.748×10^{-5}	2.483×10^{-4}	-1.551×10^{-4}	-4.774×10^{-4}

Identification results：

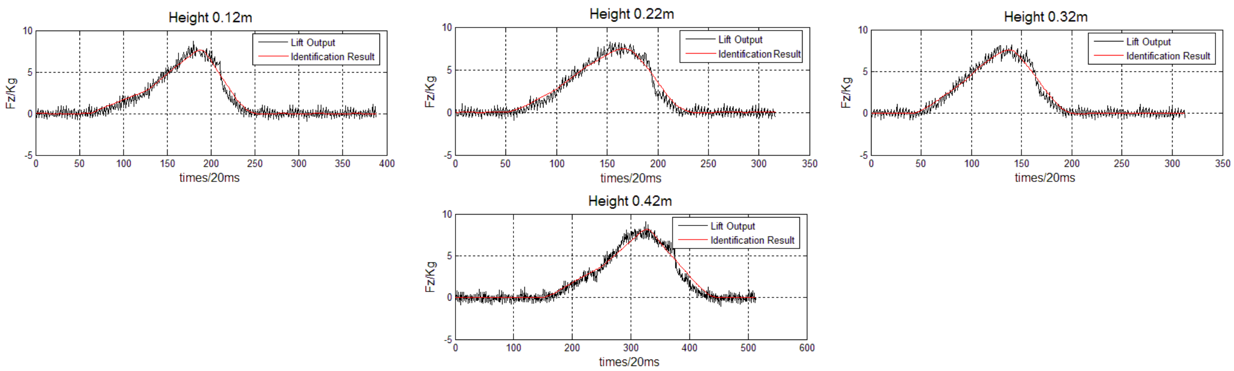


Fig.11 Identification results of different heights in hover

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

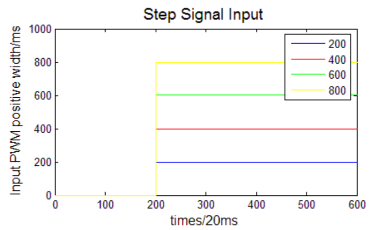


Fig.12 Step signal input

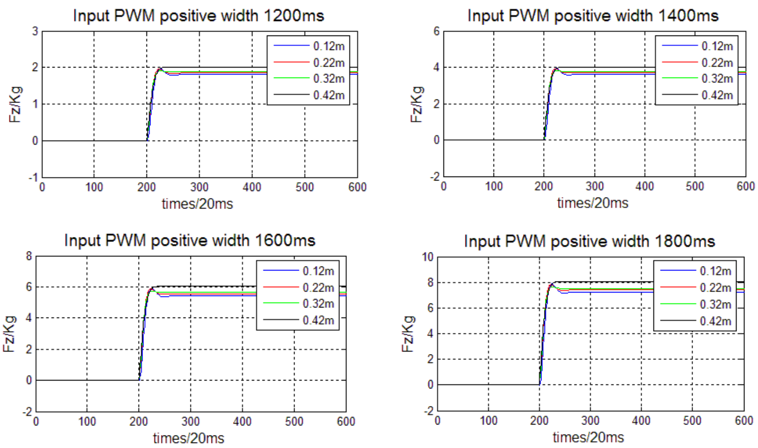


Fig.13 Static responses of lift loss model

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

Tab.2 lift loss in different heights

Height	**0.12m**	**0.22m**	**0.32m**	**0.42m**
Lift loss	**6.68%**	**5.83%**	**3.33%**	**0**

4. MODELing result CHECK

In this section, check the modeling result by using the method of empriacal formula calculation.

From section 2, fuselage is divided as Fig.14:

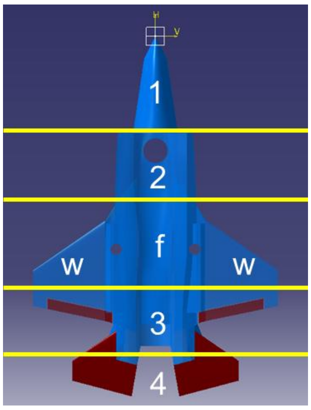


Fig.14 Divide fuselage

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

$$\frac{\Delta L}{T} = \frac{\Delta L_{S1}}{T} + \frac{\Delta L_{S2}}{T} + \frac{\Delta L_{f}}{T} + \frac{\Delta L_{S3}}{T} + \frac{\Delta L_{S4}}{T},$$

where $\Delta L_{S1}/T = \Delta L_{S4}/T = 0.$

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

$$\left(\frac{\Delta L_{\infty}}{T}\right)_b = -0.00022\sqrt{\frac{S}{A_J}}\left(\frac{per}{d_e}\right)^{1.58}(NPR)^{-0.5},$$

where S is the platform area, A_J is the total jet exit area, per is the total perimeter of the jet nozzle, and $d_e = \sqrt{2d^2} = 0.1768m$. For the equivalent airframe, S2=S3=0.144m^2:

$$\left(\frac{\Delta L_{S2}}{T}\right) = \left(\frac{\Delta L_{S3}}{T}\right) = -0.00022\sqrt{\frac{S_2}{A_J}}\left(\frac{per}{d_e}\right)^{1.58}(NPR)^{-0.5} = -0.0078.$$

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

$$\frac{\Delta L_f}{T} = C_{p,ave,f}\frac{S_f}{2A_J}K_{n,f}K_r,$$

$C_{p,ave,f}$, $K_{n,f}$ and K_r denote the average pressure presented later, nozzle shape factor and the body shape factor separately. For the equivalent airframe Sf=0.128m^2, fountain effect in different heights are listed in Tab.3.

Tab.3 fountain effect

Height	**0.12m**	**0.22m**	**0.32m**	**0.42m**
Lift improvement	6.68%	3.96%	2.81%	2.19%

Empirical formula of suckdown effect is[5]:

$$\frac{\Delta L_S}{T} = C_{p,ave,s}\frac{S_x}{2A_J}\frac{T_l}{T/2}$$

where S_x is S-Sf/2=0.352m^2, T is lift force, $C_{p,ave,s}$ has relationship with the hovering height.

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

Tab.4 suckdown effect

Height	**0.12m**	**0.22m**	**0.32m**	**0.42m**
Lift loss	13.42%	9.62%	6.56%	2.48%

Compare the modeling result and empirical formula calculation:

Tab.5 results compare

Height	0.12m	0.22m	0.32m	0.42m
Modeling result	6.68%	5.38%	3.33%	0
Empirical formula calculation	7.33%	6.44%	4.53%	1.47%

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.

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