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RESEARCH ON BARYCENTER MEASUREMENT METHOD IN LAUNCH OF ROCKET-BOOSTED UNMANNED AERIAL VEHICLES

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Abstract

The rocket assisted take-off (RATO) is an important way for heavy lift unmanned aerial vehicles (UAV) to launch. A successful RATO requires a good match between the actual center of gravity (CG) of the drone and its thrust line. CG measurement methods and the vertical lifting methods commonly used in engineering, due to large cumulative errors and difficulties in operation, are unable to meet launch requirements of the aerial target. In this paper, a heavy lift UAV launched by a certain type of rocket is taken as the research object, and a new method of single-point lift on the back is proposed. A cylinder device for measuring the distance between CG and the thrust line is developed.

In the method of single-point lift on the back, there’s no need to flip the prototype of the drone, and the distance between the thrust line and CG of the target can be directly measured; the overload direction and the position of the fuel CG of the UAV are close to that while launching; the measurement errors are small, the position and angle installation errors of the thrust cone are reduced, the technical requirements of RATO of the drone are met, and thus the safe take-off of the drone is ensured.

Keywords: Unmanned Aerial Vehicle (UAV); Rocket Assisted Take-off (RATO); Thrust Line; the Method of Single-point Lift on the Back; Measurement Error

1. General Introduction

In recent years, with the development of aerospace technology, drones have been widely used in civil and military fields, replacing manned aircraft to perform tasks in high-risk areas, such as detecting disasters in forest fires and poisoned areas, and investigating enemy situation in battlefields, etc. [1]. There are many ways for drones to take-off, one of which is RATO, namely zero-length launch, referring to accelerating the drone to the initial speed required for the flight control by boosting the thrust provided by the rocket in a short time [2]. With the development of drones, RATO methods have been widely studied and applied. The drones studied in this paper use rocket-assisted launches.

There are many safety problems with RATO of drones. Most of them occur during the take-off phase, where the control efficiency could be low due to the relatively low flight speed and the small aerodynamic impact. Once there is an accident, the drone may crash if the umbrella on it doesn’t open in time. There are many factors in the safe launch of the drone, such as the actual CG of the drone not on the thrust line of the rocket, large errors of the match between the launching cradle and the aircraft interface, and the influence of ambient winds. Shi Lin et al. use ADAMS to establish an UAV take-off dynamics simulation model and find that the eccentricity of the center of mass and the booster rocket thrust have more effects on the launch attitude and thrust line eccentricity. Tao Yujin research on the parameters of zero-length launching safety boundary of small size fixed-wing UAV and find that the installation angle of the booster rocket will affect the launch safety of the drone, and determining the safety boundary of the rocket installation angle offset is the basis of the actual thrust line lifting work, which can ensure the safety of the launch [4]; Liu Fuping et al. have studied the effect of booster rocket installation deviations on the launch safety of small UAVs. Simulation and test results show that when the longitudinal deviation of the booster rocket’s installation angle is controlled within -0.5 ° ~ 0 ° and the lateral deviation within -0.5 ° ~ 0.5 °, the UAV take-off is safe [5].

This paper studies CG measurement and the match between CG and thrust line of drones, introduces a CG measurement method-parallel lift measurement method, and proposes a single-point lift method on the back for match check. The error analysis is performed separately and verified by experiments.

2. Parallel Lift Method

2.1 Parallel Lift Measurement Method

CG of the drone is measured by parallel lift on the back. As shown in Figure 1, there are four lift points of equal height on the back of the aircraft, which form a rectangle when viewed from the top. The front point are marked as point A, and the measured force is expressed as P11, Pl2 (expressed as P13, P14 when there's an angle α) and the back point marked as point B, and the measured force expressed as P21, P22 (expressed as P23, P24 when there's an angle α). The distance between the front and back points is l, and the distance between the left and right points is b.

The four lifting points on the lifting device are consistent with those on the aircraft. The device is equipped with angle sensors and can adjust the inclination angle α. Steel cables and load cells are applied to connect the lifting device to the corresponding lifting points on the aircraft.

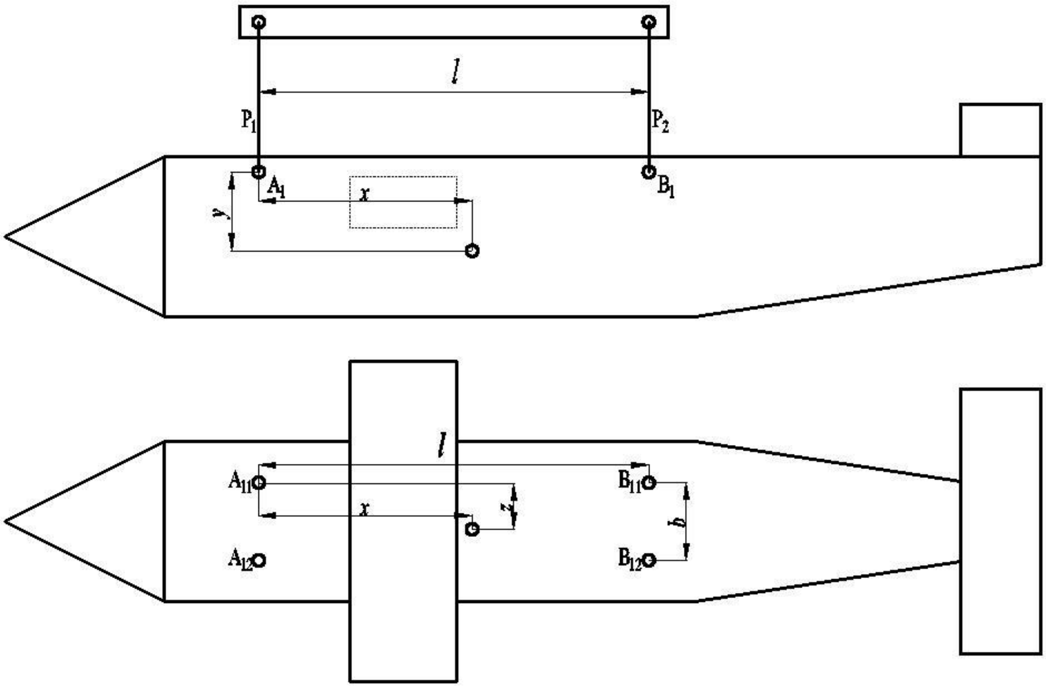


Figure 1 – Parallel lift measurement (α=0°)

2.2 Measurement Procedure

Horizontal measurement: keep the lifting device horizontal (Figure 1), and the inclination angle α is 0 The weights measured by the four load cells are P11, P12, P21, P22, P1 = P11 + P12, P2 = P21 + P22. Equations (1) and (2) can be obtained from the moment balance.

$$P_2 \cdot l \cdot cos(\alpha) = (P_1 + P_2) \cdot [x \cdot cos(\alpha) - y \cdot sin(\alpha)] \tag{1}$$

$$(P_1 + P_2) \cdot z = (P_{12} + P_{22}) \cdot b \tag{2}$$

Inclination measurement: adjust the inclination angle of the lifting device (see Figure 2), and the inclination angle α'is adjusted to 45°. The weights measured by the four load cells are P13, P14, P23, and P24. P_1'= P13+P14， P_2'= P23+P24. Equation (3) can be obtained from the moment balance.

$$P_2' \cdot l \cdot \cos(\alpha') = \left(P_1' + P_2'\right) \cdot [x \cdot \cos(\alpha') - y \cdot \sin(\alpha')] \tag{3}$$

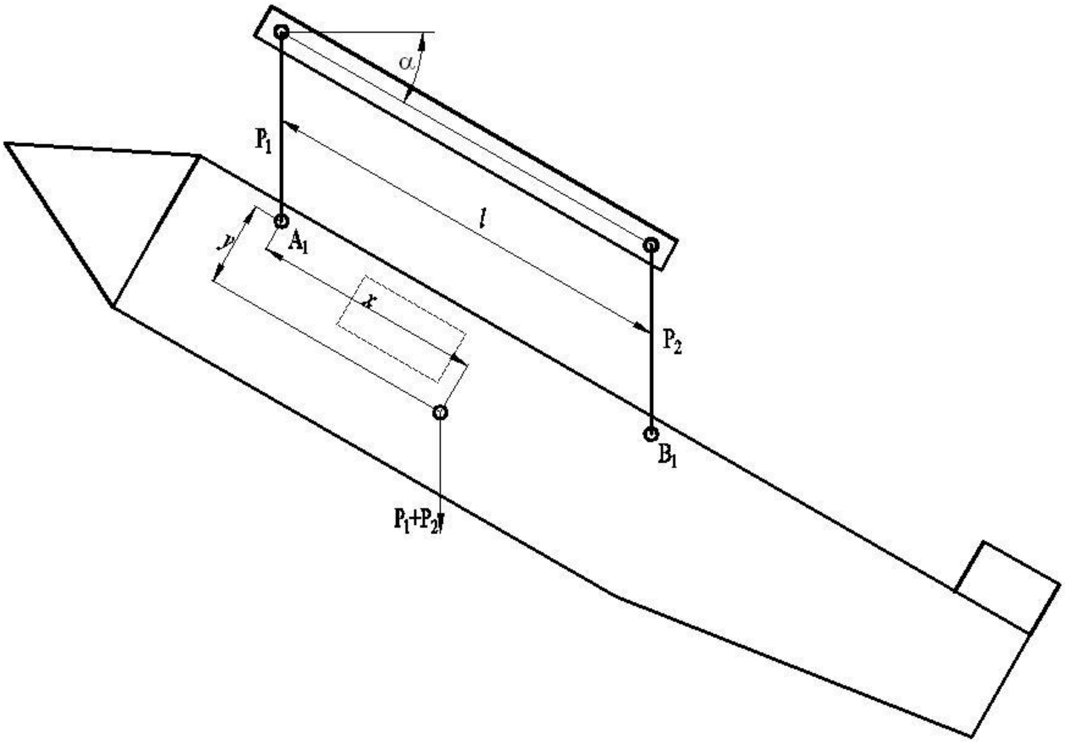


Figure 2 – Parallel lift measurement (α′=45°)

2.3 Gravity Calculation

From the equation (1), (2), and (3), the x, y, and z values of CG relative to A can be worked out.

$$x = \frac{P_2 \cdot l}{P_1 + P_2} + y \cdot tan(\alpha) \tag{4}$$

$$y = (x - \frac{P_2' \cdot l}{P_1' + P_2'}) \cdot cot(\alpha') \tag{5}$$

$$z = \frac{(P_{12} + P_{22}) \cdot b}{P_1 + P_2} \tag{6}$$

applying x to equation (5) yields:

$$y = (\frac{P_2}{P_1 + P_2} - \frac{P_2{}'}{P_1{}' + P_2{}'}) \times l \times \frac{1}{tan(\alpha') - tan(\alpha)} \tag{7}$$

Therefore, the coordinates of CG are:

$$\begin{cases} x = \frac{P_2 \cdot l}{P_1 + P_2} + y \cdot tan(\alpha) \\ y = (\frac{P_2}{P_1 + P_2} - \frac{P_2{}'}{P_1{}' + P_2{}'}) \cdot l \cdot \frac{1}{tan(\alpha') - tan(\alpha)} \\ z = \frac{(P_{12} + P_{22}) \cdot b}{P_1 + P_2} \end{cases}$$

2.4 Error Analysis

According to the theory of error transfer and synthesis, the function of the measured value:

y=f(x1,x2……xn)

In the equation, x1, x2……xn are values measured directly; y is an indirect measurement value.

The increment can be expressed by total differential of the function, and then the function increment of the above equation is:

$$dy = \frac{\partial y}{\partial x_1}dx_1 + \frac{\partial y}{\partial x_2}dx_2 + \cdots + \frac{\partial y}{\partial x_n}dx_n$$

Therefore, the systematic error of the function is:

$$dy = \frac{\partial y}{\partial x_1}dx_1 + \frac{\partial y}{\partial x_2}dx_2 + \cdots + \frac{\partial y}{\partial x_n}dx_n$$

Due to the symmetry of the drone, the values of x and y have significant impact on the RATO. Therefore, only these two values are analyzed. Equations (4) and (7) are respectively expressed in total differentials. The errors of x and y are expressed as follows:

$$\Delta x = -\frac{P_2 \cdot l}{(P_1+P_2)^2} \cdot \Delta P_1 + \left(\frac{l}{P_1+P_2} - \frac{P_2 \cdot l}{(P_1+P_2)^2}\right) \cdot \Delta P_2 + \frac{P_2}{P_1+P_2} \cdot \Delta l + tan(\alpha) \cdot \Delta y + \frac{y}{cos^2(\alpha)} \cdot \Delta\alpha \tag{8}$$

$$\Delta y = \frac{l}{tan(\alpha') - tan(\alpha)} \cdot \left\{-\frac{P_2}{(P_1+P_2)^2} \cdot \Delta P_1 + \left[\frac{1}{P_1+P_2} - \frac{P_2}{(P_1+P_2)^2}\right] \cdot \Delta P_2 + \frac{P_2'}{\left(P_1'+P_2'\right)^2} \cdot \Delta P_1' - \left[\frac{1}{P_1'+P_2'} - \frac{P_2'}{\left(P_1'+P_2'\right)^2}\right] \cdot \Delta P_2'\right\} + \left(\frac{P_2}{P_1+P_2} - \frac{{P_2}'}{{P_1}'+{P_2}'}\right) \cdot \frac{1}{tan(\alpha') - tan(\alpha)} \cdot \Delta l - \left(\frac{P_2}{P_1+P_2} - \frac{{P_2}'}{{P_1}'+{P_2}'}\right) \cdot \frac{l}{(tan(\alpha') - tan(\alpha))^2} \cdot \{[tan^2(\alpha)+1] \cdot \Delta\alpha - [tan^2(\alpha')+1] \cdot \Delta\alpha'\} \tag{9}$$

$$\Delta z = -\frac{(P_{12}+P_{22}) \cdot b}{(P_1+P_2)^2} \cdot (\Delta P_1 + \Delta P_2) + \frac{P_{12}+P_{22}}{P_1+P_2} \cdot \Delta b + \frac{b}{P_1+P_2} \cdot (\Delta P_{12} + \Delta P_{22}) \tag{10}$$

For a certain type of drones, the origin of coordinates is the zero point of the drone head, the X direction is backward along the drone axis, the Y direction is perpendicular to the horizontal direction of the drone, and the Z direction is on the right side of and perpendicular to the drone symmetry axis. The designed CG of the target is (2148, -34, 0), front lifting points (835, 75, ± 350), rear lifting points (3280, 75, ± 350). The horizontal distance of CG from the front points is 1313mm, and 1132mm from the rear points. Therefore, it can be worked out that l=2445mm，b=700mm. The inclination angle α of is 0 degree at the first weighing and the inclination angle α' is 45 degrees at the second weighing. Therefore, in theory, P1 = 231.493kg, P2 = 268.507kg, and P2' = 246.217kg.

The error of the load cell is 0.5 ‰ FS, the full scale is 200kg, and the absolute error is about 0.1kg. Therefore, ΔP1 = 0.2kg, ΔP2 = 0.2kg, ΔP1'= 0.2kg, ΔP2' = 0.2kg, Δ P = 0.2kg. The position is guaranteed by the tooling, the error can be controlled within ±1mm, the angle sensor error is 0.005° (8.726646e-5 radians), the installation error is 0.01 °, and the total angle error is 0.015 ° (2.617994e-4 radians).

In equation (8) and (9), the errors of each factor are replaced with the sum of absolute values and the maximum errors are obtained: $\Delta x = 1.544\text{mm}$，$\Delta y = 2.087\text{mm}$，$\Delta z = 1.840\text{mm}$.

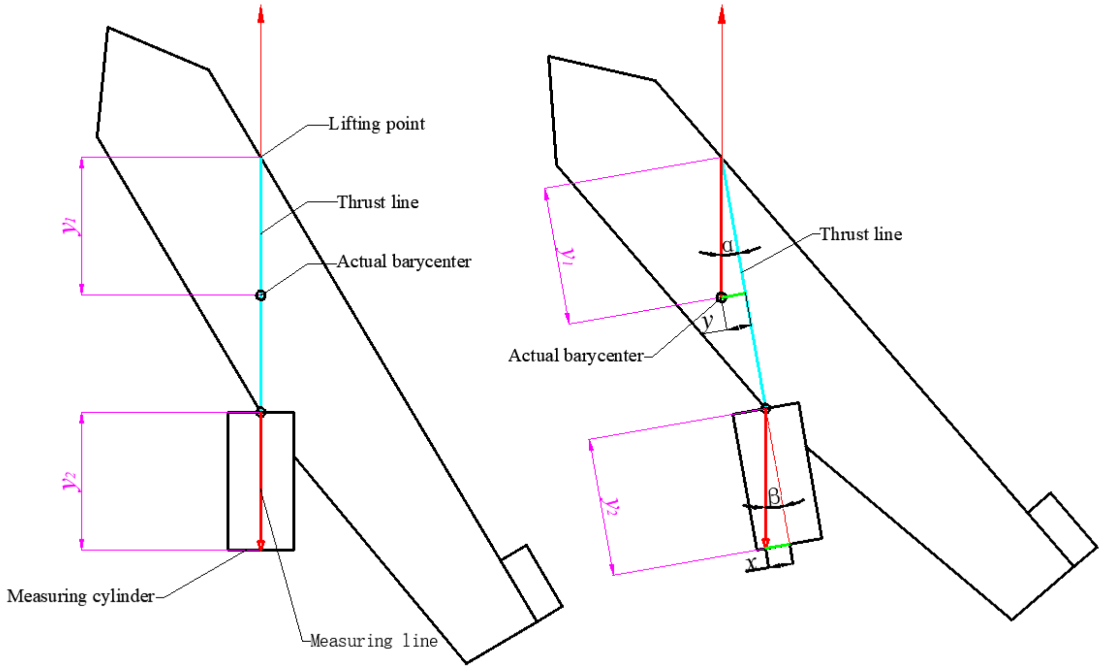
Δx and Δy are measurement and calculation errors relative to the front lifting points. Generally, the position error of the front lifting point itself is about 1mm. The comprehensive measurement error of CG in the method is 2.544mm in heading, 2.840mm in wingspan, and 3.087mm in height. It can be found from the error values that the influence of the lifting point’s position error on the measurement accuracy accounts for about half of the total error. Therefore, the lifting point’s position error needs to be controlled.

3. General Style Preferences the Method of Single-point Lift on the Back

From the error analysis of the parallel lifting method, it can be seen that there are many factors in the measurement of the drone’s CG, causing large comprehensive error in the heading and altitude directions. If the installation error of the booster rocket is taken into consideration, the distance between the thrust line and CG is likely to be too large, increasing the risk of launch failure [5]. Therefore, more accurate measurement methods are needed to check the measurement results. In this paper, the thrust line refers to the axis of the rocket. In theory, the thrust line passes through the designed CG of the drone.

3.1 The Method of Single-point Lift on the Back

In this measurement method, there’s no need to flip the drone, and the distance between the thrust line and CG of the drone can be directly reflected. In this state, the overload direction of the drone is close to that during launch, and the position of the fuel’s CG is close to that in the launch state. The measuring principle of the method of single-point lift on the back is shown in Figure 3. The lifting point is set at the intersection of the back of the drone and the thrust line to ensure that the lifting point is on the thrust line. The measuring cylinder device is installed on the interface between the UAV and the booster rocket, and thus its axis coincides with the thrust line and the length of the measuring line (y2) is equal to the distance (y1) between the lifting point and CG. Therefore, when the drone is lifted through the single point on the back, the actual CG is certain to be on a vertical line. If the actual CGcoincides with the thrust line, which is also a vertical line, the measuring line in the measuring cylinder points to the center of its end face, as shown in Fig. 3(a); otherwise, there will be an angle α between the vertical line passing through the actual CG and the thrust line. The angle between the axis of the measuring cylinder and the measuring line is β. β and α should be equal based on the principle of similar triangle, and then the measuring cylinder reading x is equal to y, the distance between the actual CG and the thrust line, namely x=y, as shown in Fig. 3(b). It is available to replace the measuring cylinder with a sensor and convert the measuring angles (β and α) into the distance between the thrust line and the actual CG， therefore, $y = y_1 \cdot \tan\beta$



a

b

Figure 3 – Measurement of y, the distance between CG and the thrust line, by the method of single-point lift on the back

3.2 Error Analysis

According to the principle of similar triangles, α = β, yielding:

$$\tan\alpha = \frac{y}{y_1} = \tan\beta = \frac{x}{y_2} \tag{11}$$

From Equation (11), it yields:

$$y = y_1 \cdot \frac{x}{y_2} \tag{12}$$

$$y = y_1 \cdot tan\,\beta \tag{13}$$

Expressed errors in fully differential:

$$\Delta y = -\frac{x \cdot y_1}{{y_2}^2} \times \Delta y_2 + \frac{x}{y_2} \times \Delta y_1 + \frac{y_1}{y_2} \times \Delta x \tag{14}$$

$$or \quad \Delta y = y_1 \cdot [(\tan\beta)^2 + 1] \times \Delta\beta + \tan\beta \times \Delta y_1 \tag{15}$$

For a certain type of drones, the value of y_1 is 760mm ± 10mm because of the processing and assembly errors of the aircraft parts; $y_{2,}$the effective length of the measuring cylinder, is set as 760mm ± 0.5mm, due to processing and assembly errors; x, the measurement value of the measuring cylinder, is taken as 10mm ± 0.5mm because there’s visual error with its reading; the measured value of the angle sensor is 0.8 ° ± 0.01 ° (1.75e-4); when measuring, the deviation caused by the measuring device is ignored because its weight is relatively small compared with that of the aircraft.

In equation (14) and (15), the errors of each influencing factor are replaced with the sum of absolute values, and the maximum error of the distance between the thrust line and CG measured by the cylinder is $\Delta y = 1.28\mathrm{mm}$; with a sensor, the maximum error is $\Delta y = 0.55mm$.

4. Application

For a certain type of drones, due to the large measurement error in the height direction, in this paper, only the horizontal CG is measured in the method of parallel lifting measurement and then the method of single point lift on the back is applied to check the match between CG and the thrust line.

4.1 Actual CG Measurement

The drone weighs about 500kg, with a designed CG (2148, -34, 0). With the rocket installation angle set as 14 °, the distance within 5.50mm between the thrust line and CG can meet the launch requirements. The position of CG allows deviations to be decomposed into the coordinate system, with front-back ± 22.73mm, left-right: ± 5.50mm, up-down: ± 5.67mm. The actual weights obtained are $P_{11} = 81.008\mathrm{kg}$，$P_{12} = 150.287\mathrm{kg}$，$P_{21} = 168.814\mathrm{kg}$，$P_{22} = 99.381\mathrm{kg}$，$P_1 = 231.295\mathrm{kg}$，$P_2 = 268.195\mathrm{kg}$, after respectively applying these weights to equation (4) and equation (6), it can be found that x = 1312.813mm, z = 349.892mm, and thus the deviation of CG in the X direction is -0.813mm ± 2.544mm, in the Z direction is 0.108mm ± 2.840mm, which are both acceptable to launch requirements.

4.2 The Check on the Match between CG and the Thrust Line

In the method of single-point lift on the back, when using a measuring cylinder, it is found that the actual CG of the aircraft is below the thrust line, and the deviation value is 2.4mm, and thus the deviation distance of CG from the thrust line on the Y direction is -2.4/cos（14°）±1.28mm, that is -2.47mm ± 1.28mm; when a sensor is used, the negative value obtained indicates that the actual CG of the aircraft is also below the thrust line. The sensor has measured the angle value: -0.149 °, when the value is substituted into the equation (13), it can be obtained: y=-1.98mm, and the deviation distance of CG from the thrust line on the Y direction:-2.04mm±0.55mm. Therefore, it can be concluded that both the measurement results of the measuring cylinder and of the sensor are within 5.50mm, which meets the launch requirements.

4.3 Ejection Test

The certain type of drone launches at a pitch angle of 25 °, and the booster rocket works for 2s. The rocket thrust reaches a maximum value at 0.2s, when the drone is separated from the launcher. Figure 4 shows the change of the elevation angle α of the drone, the roll angle β, the ground speed v, and the flight height (h) with the rocket boost time during the launch process. It can be seen from Figure 4 that during the rocket boost phase, because CG is below the thrust line, the nose-down pitching moment brought by the rocket thrust causes the pitch angle to decrease slightly, and the minimum pitch angle is 23.26 °. When the boost ends, the nose-down pitching moment is overcome by aerodynamic force, and thus the pitch angle gradually increases; as CG in the wingspan direction deviates to the right, therefore, the roll angle also gradually deviates to the right and the rocket deflects 15 ° at the end of the thrust. The roll angle increases over time, but the deflection can be controlled by the rudder surface; the changes in flight altitude and ground speed are relatively gentle, and both have basically stabilized.

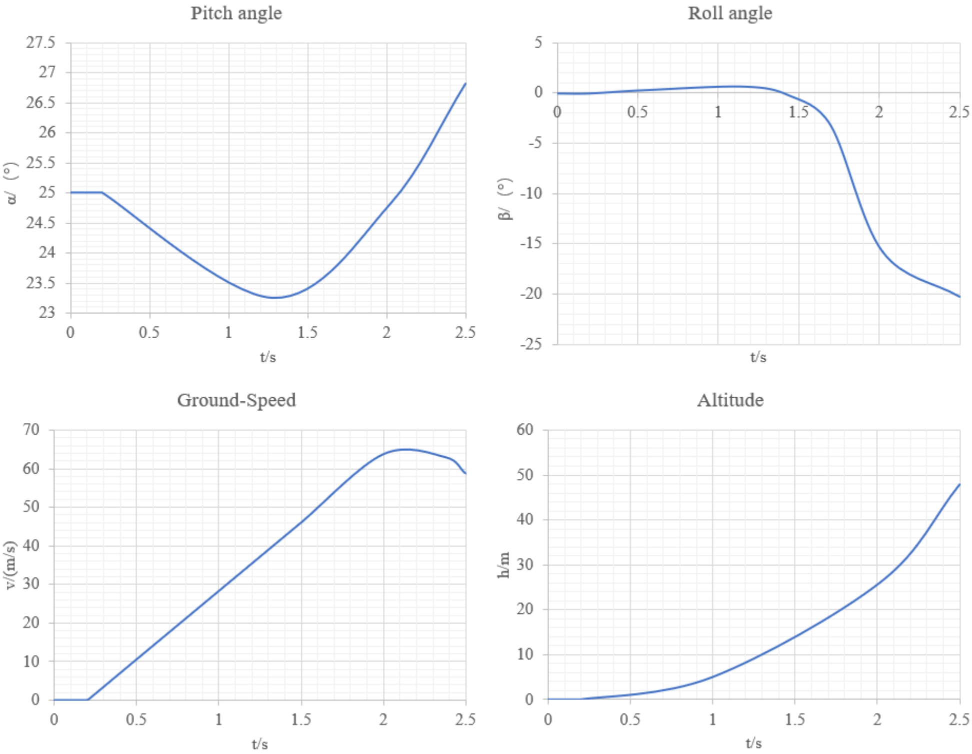


Figure 4 – State-change curves of the target during the launch process

5. Conclusion

This paper introduces CG measurement method of the UAV, and proposes a new thrust line matching check method. The corresponding error analysis based on the error transfer equation is performed, and both methods are tested and verified.

1) The parallel lift measurement method requires a high accuracy of the position of the lifting point, otherwise the comprehensive error could be large, the error in the height direction in particular, which has a large influence on the emission, has exceeded half of the allowable deviation of the position of CG.

2) A new checking method for the match of CG and thrust line, namely, the method of single-point lift on the back, is proposed in this paper. This checking method is easy to operate and does not require the aircraft to be flipped and can better simulate the launch state. By comparing the measurement errors between the measuring cylinder and the sensor, it is found that the measurement error of the sensor is relatively small and thus the result is more accurate.

3) The actual CG is measured in the parallel lift method, and then the match between CG and thrust lines are checked in the method of single-point lift on the back. The measurement results meet the launch requirements. The ejection test shows that the two measurement methods meet the actual needs, further verifying the accuracy of CG measurement and the check of match between CG and the thrust line.

References

[1] CUI Xiumin，WANG Weijun，FANG Zhenping． Present situation and analysis of related issues of small size unmanned air vehicles． *Flight Dynamics*，Vol.23, No. 2, pp14-18, 2005．

[2] EYMANN Timothy, MARTEL John. Numerical investigation of launch dynamics for subscale aerial drone with rocket assisted Take-Off (RATO). 2008.

[3] SHI Lin，MA Wei，YANG Longjun． Dynamic simulation and analysis of UAV zero length launch based on ADAMS． *Journal of Projectiles，Rockets，Missiles and Guidance*, vol.37, No.2, pp 37-39, 2017．

[4] TAO Yu-jin. Research on parameters safety boundary during zero-length launchs of small fixed-wing UAV. *Journal of Naval Aeronautical and Astronautical University*,. Vol.1 No. 5, pp 447-451, 2017.

[5] LIU Fuping, ZHENG Yao, XIE Fang-fang, et al. Effects of installation deviation of a booster rocket on launch safety of a small unmanned aerial vehicle. *Journal of Harbin Engineering University*, Vol. 39, No.8, pp 52-53, 2018.

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