Flight Identification Simulation of Performance RX-450

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Received: 24-09-2021. Accepted: 29-11-2021. Published: 31-10-2022

Abstract

The performance of rocket flight can be evaluated from flight test data. The difference between flight prediction simulation and flight test data will indicate the accuracy of the rocket identification model. Several factors cause rocket flight tests to deviate from flight prediction. Atmospheric disturbances and thrust scale are major factors causing the inaccuracy of the rocket model. Another obstacle encountered is the lack of flight data measured from flight tests although there are still several data obtained from an accelerometer, altitude sensors, and GPS. Rocket performance identification can be obtained by conducting a simulation of flight test data. This paper addresses the identification of RX-450 in terms of flight performance. The thrust profile is generated from the accelerometer recording data, and this parameter becomes an input for rocket simulation. The wind data is treated as an atmospheric disturbance. The wind data is augmented by GPS on the air balloon, and further processed become wind speed and wind direction. Comparison of both data can be explained as follow: During the boost phase, flight test data of the rocket shows a maximum acceleration of 14.5g, on the other hand, flight identification simulation gives 13.4g. Rocket flies for 157.36 s in the flight test whereas the result of the fight identification simulation indicates the max flight time is 162.8 s. The rocket has a max range of 86.06 km measured by GPS data whereas flight identification simulation estimates the max range is 82.78 km. The flight identification simulation indicates that the rocket deviated 6.25° from the initial azimuth of the launcher direction. This 6.25° of deviation leads the rocket to fly in Y-direction with a distance of 9.02 km. Flight test data shows that the rocket slides its direction 6° to the right of the initial launch azimuth.

Keywords: *flight performance identification, RX-450.*

1. Introduction

A sounding rocket is an instrument-carrying rocket designed to take a measurement and perform scientific experiments during its flight. A typical sounding rocket is boosted by either a solid-fuel rocket motor, liquid or hybrid rocket engine (Olalekan *et al.*, 2014).

Rocket Technology Center (Pustek Roket) still develops ballistic rockets, in particular sounding rockets. The testing of RX-450 was performed previously, during a flight test of a ballistic rocket, a wobbling motion occurred that is a nonlinear motion forming a conical trajectory (Riyadl, 2015). There are several triggers that cause the phenomenon of the wobbling motion to occur. First, poor design leads to configurational asymmetries. The second is a lateral offset of the center of mass relative to the symmetry axis leads to both pitch or yaw perturbing torques, and to nonlinear roll moments (Hoult and Hien, 2015).

RX-450 launched in December 2020. This rocket has a caliber of 450 mm and a total length of 7162 mm. The designed RX-450 has good stability, so the rocket RX-450 successfully was launched very well without wobbling and there were no structural failures in particular the motor rocket. The applied rocket motor has never been done static test previously. This accomplishment is a history for Rocket Technology Center where the rocket was usually tested before it was launched.

The result of the flight test indicates that there are differences in the trajectory profile between the simulation and flight test of 2.08 %. The range based on flight simulation is 84.30 km whereas the result of the flight test is 86.06 km. Wind disturbances are one of causing of the occurrence of flight path dispersion. The wind factor is involved in the rocket simulation model and the results showed a dependence of the trajectory on wind profile in particular unpowered phase. Considering the defined uncertainties from the wind speed and direction, presented a strong influence on the dispersion of the landing sites (Pinto, 2015). In the case of RX-450, the path of flight occurs a change of flight direction of 6° to the right from the launching pad point.

Previously, several studies have been published concerning the RX-450, in regard to design, simulation, measurement and manufacturing. Riyadl simulated the position of the centre of mass of the rocket which does not lie in the plane of the axis of symmetry causing the moment arm of the aerodynamic force and propulsion force acting on the rocket's centre of mass that causes disturbance in the roll, pitch and yaw moments on the rocket (*Riyadl, 2015*). His paper addressed the effect of dynamic motion as a consequence of the effect of the asymmetry of the centre of mass, while flight performance was not presented. Hakiki *et al.*, in their paper, investigated the initial predictions and the results of the flight test of the RX-450. Initial predictions indicate the rocket had fairly static stability but the flight test indicated behavior of unstable static and thus changing the direction of its flight path. So, some stability parameters rocket unstable static (Hakiki and Riyadl, 2016). Their paper addressed dynamic stability and performance. But, their paper did not involve factor atmospheric disturbances. Whether this factor leads occurrence of instability or not.

Several other papers also have been published concerning rocket trajectory prediction. Andria, N. hypothesized simulation of the model of RX-200 LAPAN-ORARI 2. There were differences in results between the simulation and the flight test. He suggested a hypothesis using correction factor 1.2 for drag coefficient (Cd) and varied several initial velocities based on the flight test in advance. In order that trajectory prediction close to the flight path actually (Andria, 2013). The correction factor of the drag coefficient is still inaccuracy. Because drag coefficient contributes significant accuracy of getting to a predicted trajectory besides scaled thrust. Olalekan *et al.* developed a model of the system in the way compared the result of the real parameters obtained via the onboard data acquisition system, with real experimental data. In order to determine the accuracy of getting to a targeted altitude using a particular rocket. Their paper ignores the effect of atmospheric wind velocity. And the last one, they concluded that the model is affected by the accuracy of the value of the drag coefficient (Olalekan *et al.*, 2014). The value of the drag coefficient indicates that it has an important role in the accurate determination of the sounding rocket trajectory. Chusilp *et al.* carried out a comparative trajectory simulation using different aerodynamic coefficients. The first set of aerodynamic coefficients was estimated using an aerodynamic prediction code, Missile DATCOM. And the second coefficient set was obtained from published experimental data. A significant error was found in the spin rate and angle of attack prediction. The simulated angle of attack, side slip angle, and spin rate are inaccurate. The predicted impact range and Mach numbers are close to the flight test data. (Chusilp *et al.*, 2011). The type of used rocket was the Hydra70. Although a small rocket, their paper gave information that the software Missile DATCOM was recommended for the aerodynamic coefficients predicted, at least range prediction was close to precision.

There are also other papers that addressed in regard to rocket trajectory prediction which involved several disturbances external such as a wind factor. Pinto, addressed test simulation trajectories by taking into account the wind factor. If the wind profile is foreseen under given conditions, it can provide information about the most probable landing region and also perform rocket design optimization using Monte Carlo methods (Pinto, 2015). Besides that, Peng *et al.* (2017) proposed a method of a high-precision dynamic model of a sounding rocket that helps improve performance, where the model includes motion on the launch rail, the free flight phase, parachute deployment, the inflation process, and steady descent, as well from a combination wind compensation method was investigated to rapidly and accurately (Peng *et al.*, 2017). Nowadays, there are various software packages to simulate the trajectories of rockets. The Cambridge Rocketry Simulator can fly rockets under a range of possible flight conditions to obtain expected flight paths and landing locations (Eerland *et al.*, 2017).

Based on the above background, this paper identifies the flight test of RX-450 in terms of performance. One of the used instruments in the rocket is the accelerometer. This device is a means of acquiring a thrust profile. It is used to re-simulate RX-450. Several parameters of the flight identification are compared with preliminary simulation and several instrument data measurements.

2. Methodology

Most rocket trajectory simulations are easily performed using point mass, lift and drag coefficient as well assume that a rocket heads instantly into the relative wind. It means that the variable pitch angle, angle of attack, and flight path angle coincide.

In this case, a trajectory calculation using a 6-DOF model was developed and applied for the RX-450 ballistic rocket (Riyadl, 2012) by using Simulink. During missile flight, the corresponding aerodynamics, such as the lift, drag, and moment that are produced from the airflow against the surface of the rocket body, directly influence its flight attitude, stability, and handling or operational characteristics (Li and Hong, 2017). All aerodynamic characteristics and stability derivatives coefficients are necessary to calculate the aerodynamic forces and moments of flying objects including aerodynamic parameter values estimated by semi-empirical methods of Missile DATCOM (Blake, 1998). Although, there are various methods, such as experimental methods (wind tunnel testing), computational fluid dynamics (CFD) methods, as well semi-empirical and analytical methods.

The mass properties and mass inertia is calculated using SolidWorks considering the rocket mass change during propellant burning till the propellant burn-out. Then the rocket flies as a projectile of fixed mass.

The method of the burning rate of propellant mass is used instead of the thrust profile in the initial simulation as shown in Figure 2-1. Previously, the used thrust profile was based on the static test.

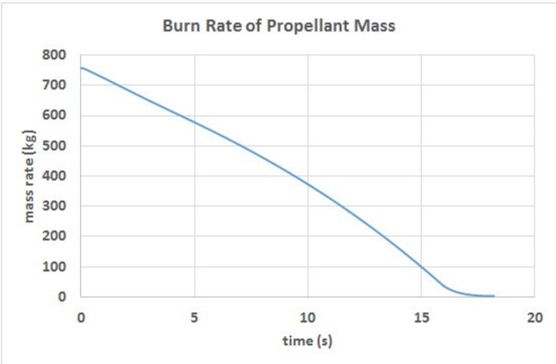

Figure 2-1: Burn rate profile used instead of thrust profile.

The dispersion of trajectory is led by mainly three effects (Khalil, *et al.*, 2009). One of them is the dispersion during the free-flight phase which is due to the fluctuations in wind profile. Lewis has shown that most of the wind response occurs at very low altitudes, then Hoult has made some corrections to the wind response of a 3-DOF point-mass simulation in an attempt to emulate a 6-DOF simulation (Hoult, 2016). The Researchers team of LAPAN (Pussainsa – Pusat Sains Antariksa) have also investigated the wind response by using air balloons in order to receive wind data such as wind speed and wind direction. They took data early morning at 5.30 am in Pameungpeuk, Garut. The results show that the most disturbance wind occurs at 15000 m where the wind speed achieves about 30 m/s as shown in Figure 2-2. Whereas Figure 2-3 presents the wind direction profile where it fluctuates significantly. This simulation involves the inclusion of wind and assumes the absence of vertical wind speed. The equation of the wind velocity vector refers to Stevens *et al.* (Stevens and Lewis, 1992).

An accelerometer is a device to be used in flight recording data. Figure 2-4 indicates that maximum acceleration achieves 14.5g and the rocket flies for 157.4 s. Meanwhile, the burning phase occurs for 15.7 s.

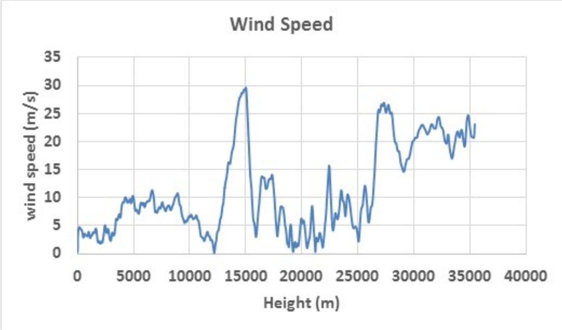

Figure 2-2: Wind speed data

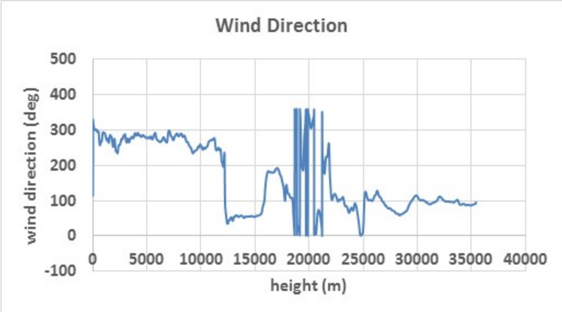

Figure 2-3: Wind direction in North and East axis.

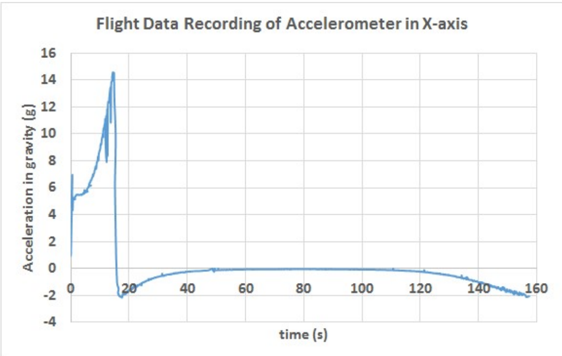

Figure 2-4 : Accelerometer recording data

Accelerometers measure the translational acceleration due to applied force, excluded gravity. In this case, the measured accelerometer is the longitudinal axis of the rocket body. The accelerometer outputs (a) can be related to the applied force. Therefore, thrust profile (F_T) can be calculated according to equation 2-1, where F_A represents aerodynamic force (Klein and Morelli, 2006)

$$a = \frac{1}{m}\,(F_A + F_T) \tag{2-1}$$

The result of accelerometer measurement is calculated by using equation 2-1 to get the thrust profile. Then, it is as input to simulate the rocket. The result was compared by initial simulation and flight test.

3. Result and Analysis

The thrust profile is calculated by applying equation 2-1 to the accelerometer recording data and the result is shown in Figure 3-1. Although there is a bit of ripple, it comes from the inaccuracy of the device as can be seen in the 15th second. Maximum thrust value occurs at the 14.36th second by achieving 16675 kgf. The rocket motor RX-450 has an average thrust of about 91 kilo kg whereas the burning time is 15.6 s. The thrust profile is applied to flight identification simulation instead of the burn rate profile as shown in Figure 2-1.

The initial simulation and the flight identification simulation indicate that the rocket generally flies with good stability as shown in Figure 3-2, Figure 3-3, Figure 3-4, Figure 3-5, Figure 3-6, Figure 3-7, and Figure 3-8, and Figure 3-9. Figure 3-2 and Figure 3-3 illustrate a comparison among flight test measurement, initial simulation and flight performance identification simulation. Figure 3-4 presents the effect of wind disturbance on xxxxxxxx the flight path. And, all of the simulation results are displayed in Table 3-1.

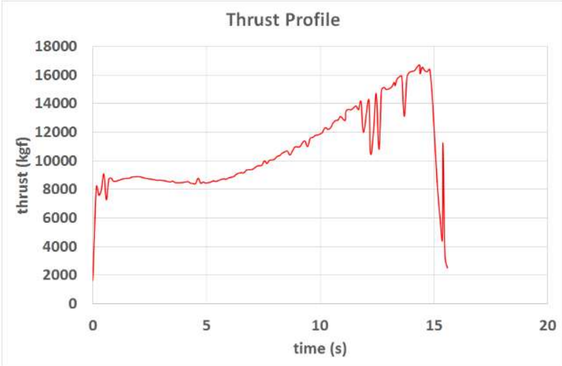

Figure 3-1 : Thrust profile of the result of identification

Several flight data recordings are obtained from flight test measurements such as altitude sensors, GPS and accelerometer in the longitudinal axis of the rocket body. As can be seen in Figure 3-2, altitude sensor 2.4G indicates that the rocket flies for 157.36 s by achieving an apogee point at 26.13 km sea level. And maximum altitude occurs at 75.7th second. Whereas altitude sensor 2.4G shows that endurance is 157.57 s and apogee is 30.44 km at 79.75 s. The GPS indicates 157 s. GPS sensor occurs loss of data from the 58th second to the 149th second. Comparison between the initial simulation and the flight identification simulation indicates the difference in the flight time of 4.8 s where the result of the flight identification simulation is 162.8 s. It means that the initial simulation is faster than the flight identification simulation.

Table 3-1: Comparison of flight performance simulation

Flight Condition	**Flight Identification Simulation**	**Initial Simulation**
Flight time (s)	162.8	158
Range (km)	82.78	84.30
Apogee (km)	28.38	26.45
Deviation (km)	9.02	9.58
Flight path dispersion angle	6.25°	6.52°
Max. Mach	3.34	3.27
G-Load	13.4	11.6

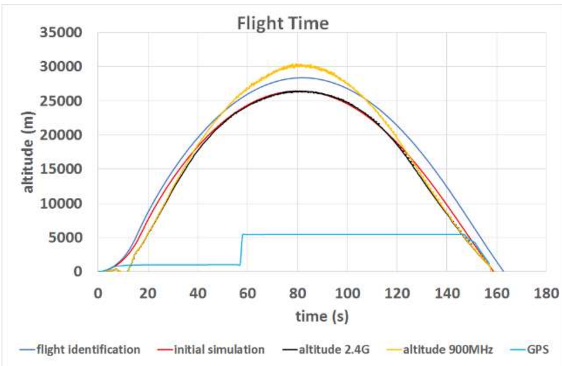

Figure 3-2: Flight time response

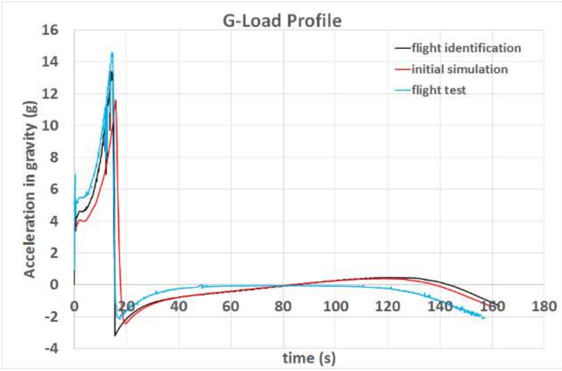

Figure 3-3 : G-load response

G-load, known by the common name G-force, is a measurement of force per unit mass. One "g" equals the value of gravitational acceleration on Earth of about 9.8065 m/s^2. Figure 3-3 shows the acceleration response of the rocket in the g dimension. There are value differences of g-force occur among them. Flight test data indicates that the rocket has a maximum acceleration of 14.5g at 14.82 s. Whereas Initial simulation and flight identification simulation indicate 11.6g and 13.4g, respectively. The value difference between flight test data and flight identification simulation is 8.3%. Meanwhile, the difference between flight test data and initial simulation is 24.78%. Thus, the result of the flight identification simulation is close to flight test data compared to the initial simulation during the boost phase.

The thrust of the rocket motor has an important role in flight performance in particular the boost phase. It is very obvious that the difference in thrust scale affects the flight path of the rocket as can be seen in Figure 3-4. The landing point of the rocket has a distance of 86.06 km whereas the initial simulation is 84.30 km. Flight identification simulation shows a range of 82.78 km as shown in Table 3-1. Table 3-2 shows a comparison flight performance of a rocket at apogee. In the case of the initial simulation, the velocity of the rocket is 1.89 Mach (573.8 m/s) at apogee. s Whereas the range reaches 42.87 km during 80 s. In another case, the rocket flies at a velocity of 1.83 Mach (543.6 m/s). The range reaches 41.58 km during 81 s. Once the rocket has reached apogee, the rocket pitched down. The pitch angle in the initial simulation is smaller than in the second simulation. It means that the second one has a shorter range than the previous simulation. Once the rocket has burned out, there was no power. In this phase, the rocket experiences disturbances of wind so that the trajectory of the rocket is a little bit deviation.

The landing site of the rocket deviates from the assigned azimuth angle from 192° (S12°W) to 198° (S18°W) as shown in Figure 3-5. The fallen site of the rocket diverges to the right side of the alignment of the initial launch azimuth. The result of the flight identification simulation indicates that the rocket diverges 6.25° and has a distance of 9.02 km. While the result of another simulation is 6.52° and the distance of 9.58 km as can be seen in Table 3-1 and Figure 3-6. Whereas Figure 3-9 illustrates the flight path in 3D. The value comparison between flight test data and flight identification simulation data is 4.1%. And, the second comparison is 8.07%.

The rocket velocity response indicates a bit of difference in velocity profile as shown in Figure 3-7. The result of the flight identification simulation indicates that the rocket's maximum velocity is higher than the initial simulation. The difference value is 0.07 Mach as can be seen in Table 3-1. The rocket's maximum velocity in the initial simulation has a speed higher than in another simulation when the rocket has reached apogee.

The flight identification simulation indicates that the pitch angle is a bit higher than another simulation during the boost phase until apogee. But, once the rocket has passed through at apogee, the pitch angles indicated similar responses to each other. As can be seen in Figure 3-8, the result of the flight identification simulation indicates the rocket has a fallen pitch angle of -58.4° whereas the other simulation is -56.5°, in which the rocket is launched at an elevation angle of 70°.

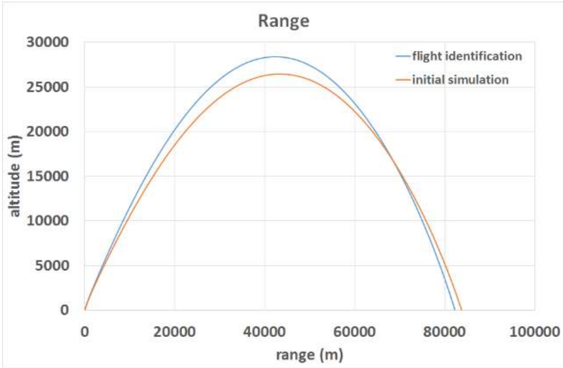

Figure 3-4 : Flight path 2D

Table 3-2 : Comparison at apogee point

Flight Performance	Flight Identification Simulation	Initial Simulation
Range (km)	41.58	42.87
time (s)	81	80
Velocity (Mach)	1.83	1.89
Deviation (km)	4.54	4.9
G-Load	0.05	-0.06
Pitch angle (deg)	1.27	0.56

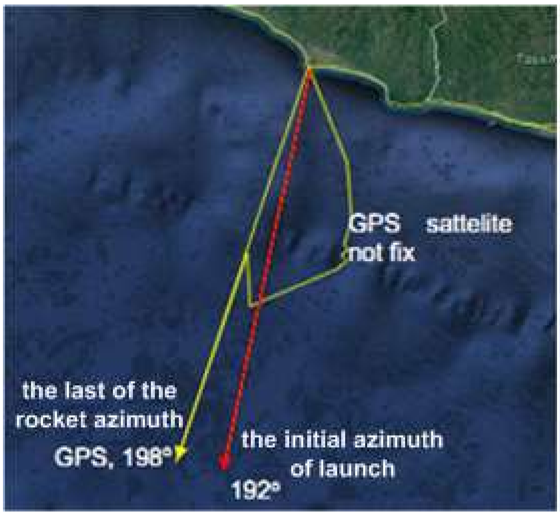

Figure 3-5 : Path of rocket deviates

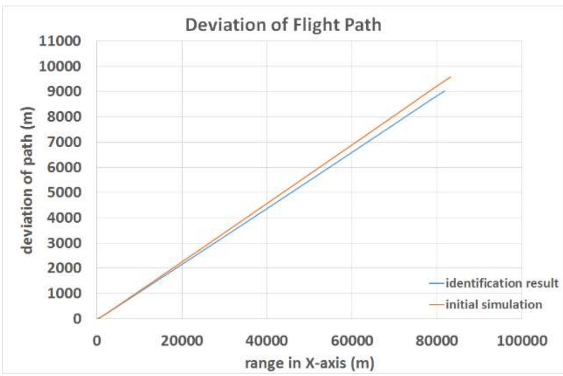

Figure 3-6 : Dispersion of flight path

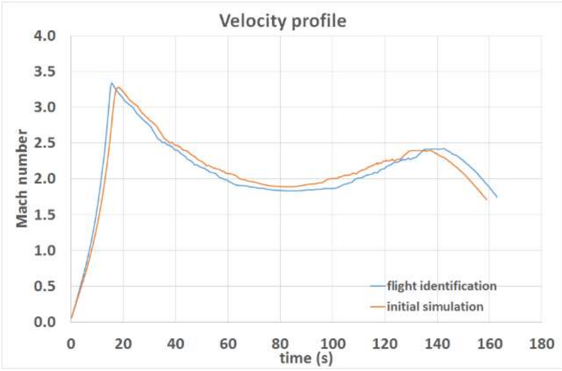

Figure 3-7 : Velocity profile

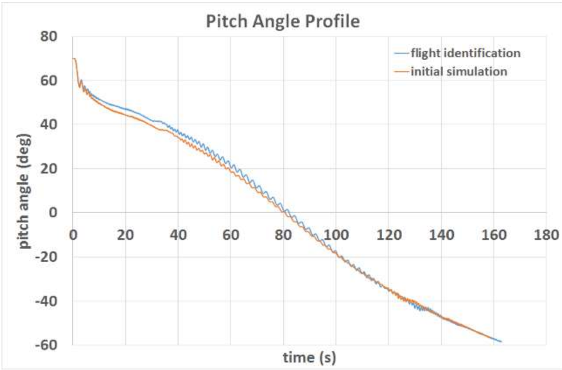

Figure 3-8 : Pitch angle response

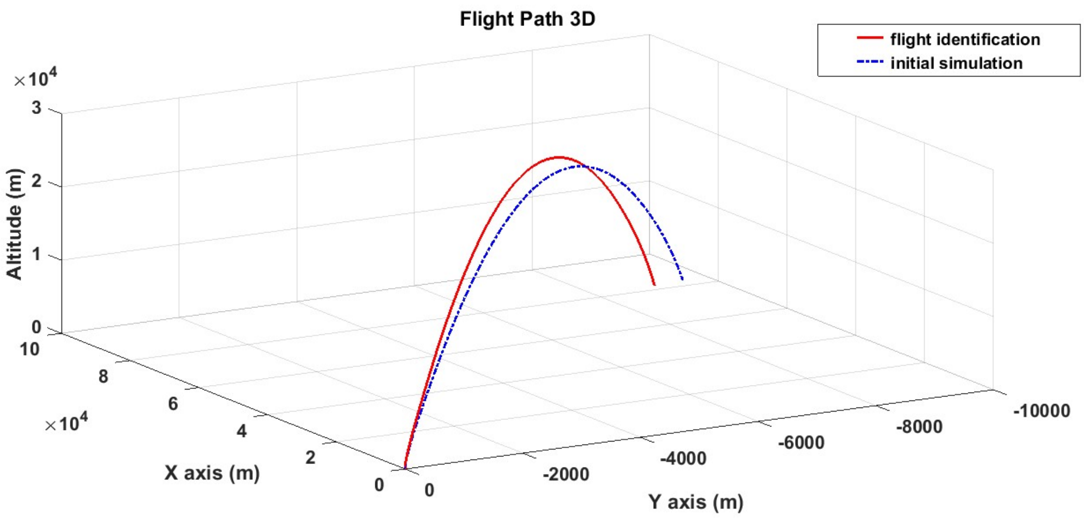

Figure 3-9 : Flight path 3D

4. Conclusions

The identification of rocket performance RX-450 presented in this paper shows that there are still the value difference of the flight test data adequately significant in particular the landing point of the rocket. Where the distance difference between both is 3.82 km whereas its deviation has a difference of 0.25°. On the other hand, the difference in flight time is 4.8 s. The identification of rocket acceleration is close to the flight test data compared to the initial simulation during the boost phase. Its value difference is 8.3%. Although it looks still slightly different it influences adequately the difference of rocket performance. Meanwhile, the difference in rocket maximum velocity between the initial simulation and the flight identification simulation is 0.07 Mach.

A brief overview of the identification of rocket performance indicates that the flight identification simulations have value error well in spite of using one device namely the accelerometer sensor. There were not a lot of flight test data that could be obtained well to identify rocket performance. Hence the flight identification simulation becomes less optimal.

Further research is to get more flight data in order to identify more optimal. And also, several factors causing the inaccuracy of rocket performance are involved such as drag coefficient based on CFD simulation, the effect of initial velocity once the rocket has released from the launcher, the effect of tip-off on the launcher as its guideway system, and the thrust profile scale is applied as an input in simulation.

Acknowledgements

The authors want to express gratitude to the RX-450 all teammates of the Rocket Technology Center (Pustek Roket) and Space Science Center (Pussainsa).

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