Dynamic Models Based Virtual Reality Flight Simulator

Kelvin Valentino, Kevin Christian, Singgih S. Wibowo, and Endra Joelianto

***Abstract*—Flying has become a lifestyle for numerous people, everywhere human's mobility has become very high. Now, a lot of people has gone flying with airplane. However, only a few people have flown airplane personally. In the digital era, the emerging of mobile virtual reality that are cheap and more portable gives a great chance to build low cost flight simulator that can give any user a good flying experience. In this paper, it is presented an application of virtual reality to build a flight simulator which is based on flight dynamics of an airplane. A simple flight dynamic model in Unity 3D (game engine that supports physics and virtual reality technology) is developed in order to create an almost real flight simulator prototype with high fidelity.**

***Index Terms*— flight simulator, aircraft model, mobile VR, virtual reality, Cessna 182.**

I. INTRODUCTION

NOWADAYS, virtual reality (VR) has been known and spreaded out all over the world, People are exciting to embark a new world where they can discover freely in virtual world. At first, Oculus introduced their desktop VR, following that Google and Samsung are introducing mobile VR that are cheaper and more portable. This technology is widely used for video games, virtual worlds, education, productivity, tourism, architectural or real estate, live events, web browsing and many more [1]. Moreover, the technology has been used in enterprise applications used for simulation and training [2]. Simulators are very useful and effective for learning of almost many jobs functions or workings of a tool, particularly for apprentice.

By means of the simulator, the apprentice is able to practice tools or original units much better than only theory. Hence, the virtual reality is a perfect fit for enhancing their experience by using a simulator. One of the most common simulators is the driving simulators that have been developed for these purposes: safe driving trainings in diverse situations (ice, rain, overcrowdings) or assessment of new cars.

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As in a virtual situation, it is probable to alter any of the characteristics both aesthetic and functional of cars and afterward to examine how real drivers counter to the variations. The simulator also permits planned cars to be trialed before really making a prototype [3]. Similar in area of aviation, specifically in pilot schooling, a pilot requires to thoroughly comprehend the right procedures to control an aircraft, the use of tools or panels. By using simulator, the pilot has gained an improved knowledge when doing a real flight accordingly the pilot is able to take better approaches and to do the best procedure that can be used in these conditions [4]. If the simulator is operative, then an hour of exercise in a simulator could substitute an hour, or even a number of hours exercise in an airplane.

Using a simulator will present economic benefits, in which, the expense is much lower than a real flight [5]. As a result, the flight simulator has ordinarily used to become a fraction of programs in flight institutes [6]. Therefore, the paper is aimed to build a flight simulator incorporating a simple dynamic model to achieve an actual flying experience in virtual reality environment. It is intended to build low cost simulator where everyone can have flying experiences.

A. Flight Dynamic Model

To build a high fidelity simulator, it is required an accurate mathematical model of the system to be simulated. Models have to be matched with the system behaviour. It is commonly based on the understanding of the physics of the real system or developed from data gathered [7]. The principles of flight modelling are based on mechanics and fluid dynamic. First, it is important to know about the acting forces in an aircraft.

a) Lift Force

Lift force is generated by the remarkable design of wing especially aerofoil, where air flow passing over the wing and some passing under the wing which has different path. These result in pressure differential which later on producing lift force to the airplane. The equation is given by [5]:

$$L_F = \frac{C_L.\rho.V^2.s}{2} \tag{1}$$

where L_F is lift force, C_L is coefficient of lift, V is airspeed, s is aerofoil area, ρ is air density respectively.

b) Drag Force

Drag is the force that counterattacks movement of an aircraft throughout the air. This force is generated by the particles in atmosphere that produce backward direction acting force on the whole body of an aircraft. The equation is given by [5]:

$$D_F = \frac{C_D . \rho . V^2 . s}{2} \tag{2}$$

where D_F is drag force, C_D is coefficient of drag.

c) Side Force

This force is generated when there are lateral forces working on the fuselage of aircraft, in case the fuselage is not aligned with the path of flight. The equation is [5]:

$$S_F = \frac{C_y . \rho . V^2 . s}{2} \tag{3}$$

where S_F is side force, C_y is factor of drag normally delivered as a function of β and rudder input.

d) Propulsive Force

This force generated by engine and consequences of the movement of the aircraft. The equations are as follow [5]

$$F_x = L_F . \sin\alpha - D_F . \cos\alpha - W . \sin\theta + E_x + G_x \tag{4}$$

$$F_y = S_F + W . \sin\phi . \cos\theta + E_y + G_y \tag{5}$$

$$F_z = -L_F . \cos\alpha - D_F . \sin\alpha + W . \cos\theta . \cos\phi + E_z + G_z \tag{6}$$

where F_x, F_y, F_z are forces along the aircraft body axes. α is angle of attack, θ pitch angle and ϕ is heading angle, W is weight of the aircraft, E_x, E_y, E_z are engine forces along body axes and G_x, G_y, G_z are gear forces along the body axes.

Second, it is needed to learn about axes of an aircraft, as it is shown in Fig 1, the motion about its longitudinal axis (x-axis) is roll, the movement around its lateral axis (y axis) is pitch and the movement around its vertical axis (z axis) is yaw/heading. Also, the Fig. 1. shows the forces are *X*, *Y* and *Z* ; the moments are *L*, *M* and *N*; the linear velocities are *u*, *v* and *w*; the angular velocities are *p*, *q* and *r* related to *x*, *y* and *z* axes.

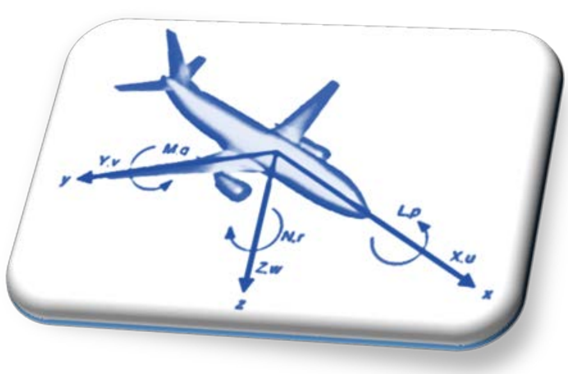

Fig. 1. Aircraft body axes [3]

On this body axis, there are two crucial angles to understanding many aspects of airplane performance, stability, and control. First is angle of attack (α) and second is angle of sideslip (β). Angle of attack is described as the acute angle among the chord line of the airfoil and the path of the relative wind (as we can see in Fig. 2). When the fuselage is not aligned with the flight path, this leads to an incident angle with the wind called angle of sideslip (as shown see in Fig. 3).

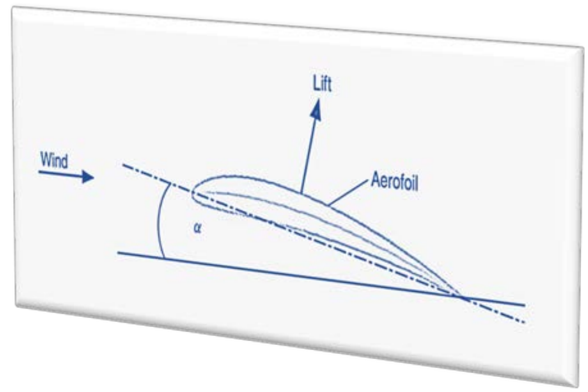

Fig. 2. Angle of Attack [5]

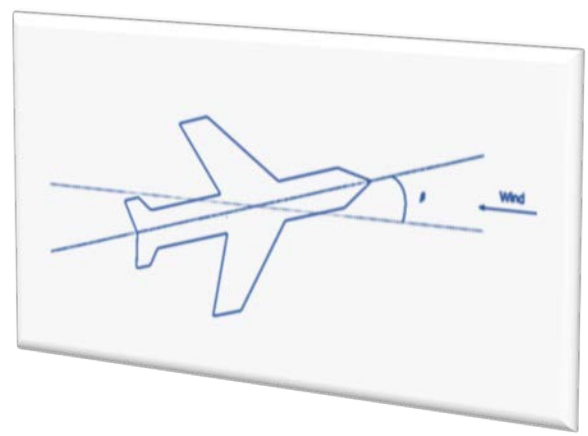

Fig. 3. Angle of Sideslip [5]

Third, it is to learn about moments that are acting on the body axes aircraft. In Fig. 1, there are L, M, N that represent moment acting in each axis on the aircraft. Moment L will generate roll motion, moment M will generate pitch motion and moment N will generate yaw motion. In order to compute those moments that are acting on body axis, first, it is required to compute the moments in stability axes. The equations are as follow [5]

$$L_{stab} = \frac{1}{2}\rho . V_c^2 . s . b\left(C_{l\beta} . \beta + C_{l\delta\alpha} . \delta\alpha + C_{l\delta r} . \delta r\right) + \frac{1}{4} . \rho . V . s . b^2\left(C_{lp} . p_{stab} + C_{lr} . r_{stab}\right) \tag{7}$$

$$M_{stab} = \frac{1}{2}\rho . V_c^2 . s . c\ (C_{m0} + C_{m\alpha} . \alpha_w + C_{m\delta e} . \delta e) + \frac{1}{4}\rho . V_c . s . c^2\left(C_{mq} . q + C_{m\dot{\alpha}} . \dot{\alpha}\right) \tag{8}$$

$$N_{stab} = \frac{1}{2}\rho.V_c^2.s.b\left(C_{n\beta}.\beta + C_{n\delta a}.\delta a + C_{n\delta r}.\delta r\right) + \frac{1}{4}\rho.V_c.s.b^2\left(C_{np}.p_{stab} + C_{nr}.r_{stab}\right) \quad (9)$$

$$M = M_{stab} + L_F.(cg - 0.25).\bar{c}.\cos\alpha + D_F.(cg - 0.25).c.\sin\alpha + E_M + G_M \quad (10)$$

$$L = L_{stab}.\cos\alpha - R_{stab}.\sin\alpha + E_L + G_L \quad (11)$$

$$N = N_{stab}.\cos\alpha + L_{stab}.\sin\alpha + S_F.(cg - 0.25).c + E_N + G_N \quad (12)$$

where Vc is airspeed, s, b and c represent the wing area, the wing span and the wing mean chord correspondingly, δa, δe and δr are the aileron deflection, the elevator deflection and the rudder deflection, and cg is center of gravity. The coefficient C_{ab} is recognized as the *aerodynamic derivative*, where the subscript a represents the axis and the subscript b indicates the source of the moment part.

After getting all the forces and moments, it can then be computed angular accelerations and linear accelerations. The equations are as follow [5]

$$\dot{u} = \frac{F_x}{m} - q.w + r.v \quad (13)$$

$$\dot{v} = \frac{F_y}{m} - r.u + p.w \quad (14)$$

$$\dot{w} = \frac{F_z}{m} - p.v + q.u \quad (15)$$

$$\dot{p} = \frac{L + \left(I_{yy} - I_{zz}\right)q.r + I_{xy}(\dot{r}.p + p.q)}{I_{xx}} \quad (16)$$

$$\dot{q} = \frac{M + (I_{zz} - I_{xx})r.p + I_{xz}(r^2 - p^2)}{I_{yy}} \quad (17)$$

$$\dot{r} = \frac{R + \left(I_{zz} - I_{yy}\right)p.q + I_{xz}(\dot{p} - qr)}{I_{zz}} \quad (18)$$

where m is mass of aircraft, I_{ab} is moment inertia of the aircraft, $\dot{u}, \dot{v}, \dot{w}$ are linear acceleration in the body axes and $\dot{p}, \dot{q}, \dot{r}$ are angular acceleration in the body axes. The expressions $\dot{u}, \dot{v}, \dot{w}$ and $\dot{p}, \dot{q}, \dot{r}$ are then incorporated to present the linear velocities u,v,w and the angular body rates p, q, r in body axes.

B. *Virtual Reality*

Virtual reality (VR) is a recent technology being fostered which incorporates softwares that give graphics and also realistic sound as close as possible if it was in the world performed. The virtual reality furnishes importance to the visual sensitivity of users, consequently in generating strong vision of moving pictures and sound created by the softwares. It can be said a window or a gate to explore a new world called a virtual world. Virtual reality is utilized by employing a distinctive tool fastened to the head, and then it can be viewed a show presented by a special device. Such devices typically have particularly adapted vision screen field with eyes so users can see it visibly.

In this virtual reality, one is able to look around in cyberspace, can also interact with the surroundings, support the use of headphones to create an atmosphere like he is entering a virtual world. This support is obtained because sensors are needed in the world of virtual reality such as gyroscope sensors, proximity, and accelerometers, so the ability to interact with cyberspace can be even more exciting [2]. Based on the type of VR display mounted on the head, there is a desktop VR, most likely the headset is connected to a computer with cable and cellular VR, which uses your cellphone processor to display the display on the phone's display screen which makes limited image complexity. Although the quality of the VR experience with a mobile VR device is limited and it is probably a "starter" device that will just be a couple of years, Cardboard is new for the small projects and it will be revisited its limitations from time to time [8].

The VR technology has led to a lot of research and development, such as education: to assist teachers in teaching students about optical waves [7] [9], to teach in medical classes that provide great benefits for medical internships to enter the medical field [10]], to teach anatomy for students so that they can find out, which saves huge costs in experimental material [11], to teach more effectively about sign language because students are in the 3D domain [12], to educate and train hydrogen station staff by building various scenarios that can occur on the 3D VR platform so that staff can better understand the standard handling and problem solving processes in accidents [13]. It has also been used in a learning vehicle simulation platform, which is used to develop driver skills for security verification test platforms [13] [14] [15] [16].

C. *Unity*

Unity is software for making games that will be distributed to the public. Unity has also been widely used by developers to create games based on Android, Windows, Apple, etc. The free version of Unity is fully displayed. The free version of Unity is fully featured. For commercial use, the company offers reasonable licensing terms that include an affordable monthly fee and a modest royalty. Unity can be used by anyone because of their rich ecosystem on their Asset Store that featuring countless 3D models, animations, code packages and utilities, which make Unity one of the most vibrant developer communities on the planet [1]. This software is very supportive of making virtual platform in three dimensions so that the game that are have a real taste. And for realistic purpose, Unity has physics element such as center of gravity in object. Inside the Unity, a programming language, namely C#, is used. The language is usual to somebody previously comprehends the programming language C or C ++ programming languages.

II. Stages of Preparation

The components of the hardware and the software of the virtual reality flight simulator comprise:

- Samsung smartphone (Galaxy S7)

a. Android Marshmallow v6.0.1
b. Chipset Exynos 8890 Octacore (4x2.3 GHz Mongoose & 4x1.6 GHz Cortex-A53)
c. 4 GB RAM
d. 32 Internal Memory
e. Virtual reality aid

Fig. 4. Samsung Galaxy S7 (samsung.com)

- Samsung Gear VR

Fig. 5. Samsung Gear VR (samsung.com)

- Gamepad

Fig. 6. Gamepad (lazada.com)

- Notebook with descriptions:
  a. i3 INTEL Processor
  b. 4 GB RAM
  c. 500 GB Hard disk

- Software:
  Unity 3D Personal Edition

Note that the developed virtual reality flight simulator in this paper is limited due to the limitations of the computer which has lower specifications compared to the computer for game development.

III. Stage of Construction

First, it is made the scenario for flight simulator (i.e. terrain, airplane model, etc.) in Unity3D. Here in the flight simulator, Cessna 182 is used as an airplane model. After the process concluded, it is created a script for flight dynamic of the airplane.

In making the script, it is mined all the parameters that are needed in the flight dynamic. After getting all the parameters needed, it is computed the aerodynamic factors of the aircraft, for instance the angle of attack and sideslip.

Then, with the result of computation of aerodynamic coefficients, it is acted forces at the aircraft (Fig. 7). After it, it is scripted codes to compute the aircraft propulsive forces (Fig. 8) and moments. With these propulsive forces, it can be computed the aircraft linear accelerations (Fig. 9). With the moments, it can be computed the angular accelerations. These accelerations are combined to develop the body frame linear velocities and the body frame rates. The steps to make the script shown in subsequent diagram (Fig 10).

```
lift = 0.5F * rho * Vc * Vc * s * CL; //lift
drag = 0.5F * rho * Vc * Vc * s * CD; //drag
side = 0.5F * rho * Vc * Vc * s * (C_ydr * dr + C_ybeta * beta);
//sideforce
```

Fig. 7. Code for Acting Forces in C#

```
//Body frame forces
Fx = lift * Mathf.Sin(alp) - drag * Mathf.Cos(alp) - W *
Mathf.Sin(theta) + Ex;
Fy = side + W * Mathf.Sin(phi) * Mathf.Cos(theta);
Fz = W * Mathf.Cos(theta) * Mathf.Cos(phi) - lift * Mathf.Cos(alp) -
drag * Mathf.Sin(alp);
```

Fig. 8. Code for Propulsive Forces in C#

```
//body frame accelerations
u_1 = Fx / 1338F - q * w + r * v;
v_1 = Fy / 1338F - r * u + p * w;
w_1 = Fz / 1338F - p * v + q * u;
```

Fig. 9. Code for Body Accelerations in C#

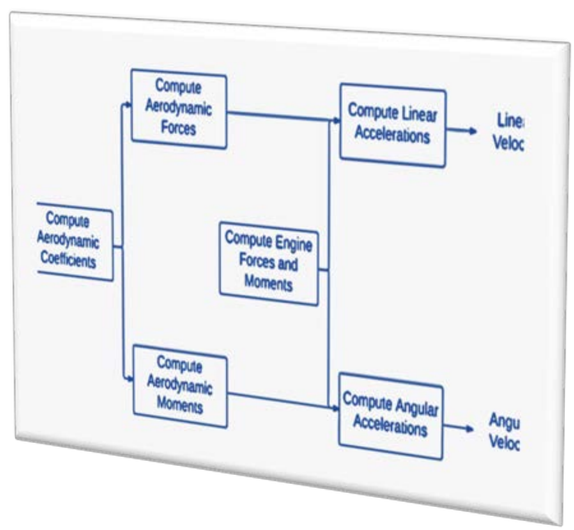

Fig. 10. Workflow of Computing Equation of Motions [2]

After the process of building the terrain and movement, then the game is rendered. The rendering process of the simulator takes a long time, it takes up to 25 hours to complete the rendering simulator. This rendering time depends on the compatibility of the computer used and how much space the flight model is used. The results of the simulation can be seen in Fig. 11.

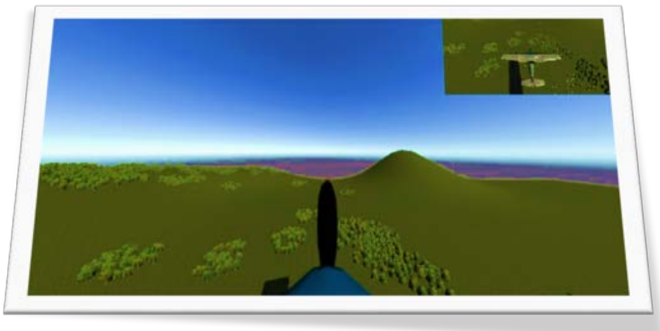

Figure 11. Display at Unity 3D Simulation [2]

After rendering, it will create an *.apk* file which is the elementary function of Android. Afterward, the *apk* file is set to be put in the proposed gadget and ready to be exercised to play in place of a flight simulator. Overall, the steps of creation are shown in Fig. 12 that illustrates the workflow of creating a virtual reality flight simulator.

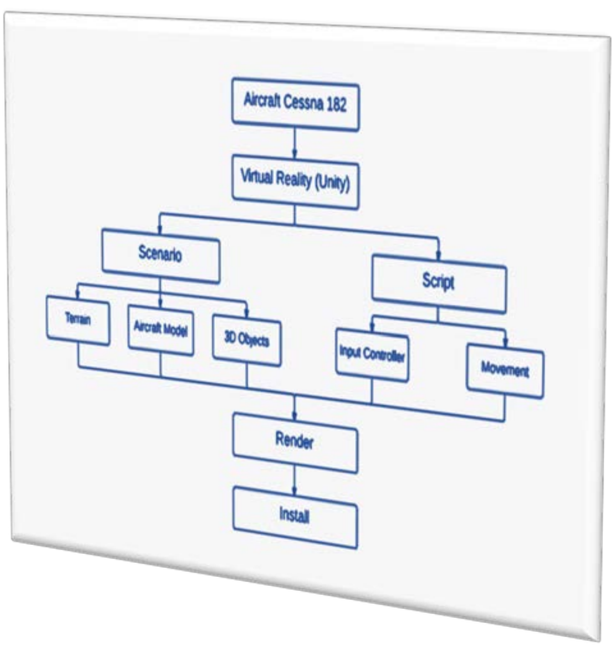

Figure 12. Workflow of the Construction [2]

IV. Results

As comparison, it is used Microsoft Flight Simulator X (FSX) to compare the Cessna 182 model. Fig. 6 shows track record of the used model, which has maximum height at 500 m, while in Fig. 14 it can be seen track record of the airplane in FSX model has maximum height in 1200 m. With peak velocity in the model is 62.98 m/s and FSX model is 67.78 m/s.

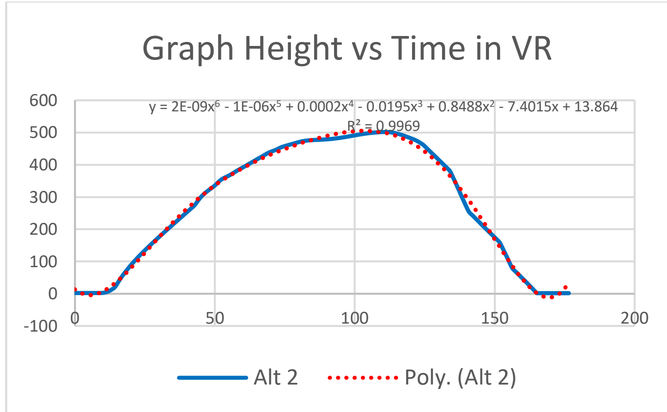

Figure 13. Graph Height vs Time in Unity

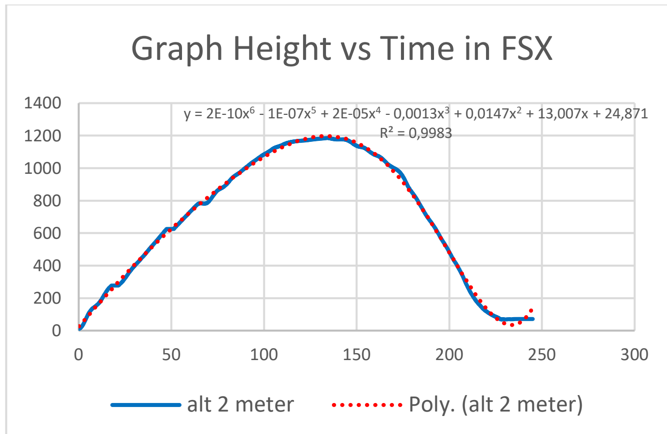

Figure 14. Graph Height vs Time in FSX

V. Conclusion

In this paper, it was build a flight simulator in the virtual world based upon an actual simple dynamic model of Cessna 182. The model was fully developed using C# programming language in Unity3D. Although this flight simulator can successfully simulate the flying of the airplane, there are still many limitations that caused by limited information in the developing the model. However, users of this flight simulator can experience flying as a pilot in small airplane. For the next stage, the dynamics of complex aircraft flights will be included with better terrain and more realistic aircraft objects. And to make this flight simulator more realistic, providing it with feedback (i.e. haptic feedback) will be very useful. There are still many rooms to develop and to improve the virtual reality flight simulator in near future.

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APPENDIX

Parameters used for Cessna 182 [17]:

- Wing area (m^2), s = 16.16
- Wing span (m), b = 10.912
- Wing mean chord (m), $\bar{c}$ = 1.49
- Mass (kg), mass = 1338
- Airplane moment of inertia about X axis (kg m^2), I_{xx} = 1285.31
- Airplane moment of inertia about Y axis (kg m^2), I_{yy} = 1824.93
- Airplane moment of inertia about Z axis (kg m^2), I_{zz} = 2666.89
- Airplane product of inertia XY axis (kg m^2), I_{xy} = 0
- Airplane product of inertia XZ (kg m^2), I_{xz} = 0

Aerodynamic Derivatives / Coefficients Variants of an Aircraft [17]:

- Lift coefficient, C_L = 0.719
- Drag coefficient, C_D = 0.057
- Variation of airplane side force coefficient with angle of sideslip, $C_{y\beta}$ = -0.404
- Variation of airplane side force coefficient with rudder angle, C_{ydr} = 0.187
- Pitching moment coefficient for zero lift, C_{m0} = 0.04
- Variation of airplane pitching moment coefficient with angle of attack, $C_{m\alpha}$ = -0.65
- Variation of airplane pitching moment coefficient with elevator deflection angle, C_{mde} = -1.369
- Variation of airplane pitching moment coefficient with pitch rate, C_{mq} = -15.2
- Variation of airplane pitching moment coefficient with dimensionless rate of change of angle of attack, $C_{m\dot{\alpha}}$ = -5.57
- Variation of airplane rolling moment coefficient with angle of sideslip, $C_{l\beta}$ = -0.0895
- Variation of airplane rolling moment coefficient with aileron deflection angle, C_{lda} = 0.229
- Variation of airplane rolling moment coefficient with rudder deflection angle, C_{ldr} = 0.0147
- Variation of airplane rolling moment coefficient with dimensionless rate of change of roll rate, C_{lp} = -0.487
- Variation of airplane rolling moment coefficient with dimensionless rate of change of yaw rate, C_{lr} = 0.1869
- Variation of airplane yawing moment coefficient with angle of sideslip, $C_{n\beta}$ = 0.0907
- Variation of airplane yawing moment coefficient with aileron deflection angle, C_{nda} = -0.0504
- Variation of airplane yawing moment coefficient with rudder deflection angle, C_{ndr} = -0.0805
- Variation of airplane yawing moment coefficient with dimensionless rate of change of roll rate, C_{np} = -0.0649
- Variation of airplane yawing moment coefficient with dimensionless rate of change of yaw rate, C_{nr} = -0.1199