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Dynamic Flight Simulation of aircraft and its comparison to Flight tests

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Abstract

Nowadays obtaining data for air vehicles researches and analyses is very expensive and risky through the flight tests. Therefore using flight simulation is usually used for the mentioned researches by aerospace science researchers. In this paper, dynamic flight simulation has been performed by airplane nonlinear equations modelling. In these equations, aerodynamic coefficients and stability derivatives have an important role. Therefore, the stability derivatives for typical aircraft are calculated on various flight conditions by analytical and numerical methods. Flight conditions include of Mach number, altitude, angle of attack, control surfaces and CG position variations. The obtained derivatives are used in the form of look up table for dynamic flight simulation and virtual flight. In order to validate the simulation results, the under investigation maneuvres parameters are recorded during many real flights. The obtained data from flight tests are compared with the outputs of flight simulations. The results indicate that less than 13% differences are found in different parts of the maneuvres.

Keywords

Flight simulation, Loop maneuvre, Chandelle maneuvre, Flight test, Stability derivatives.

1. Introduction

Since 1970 the case of virtual reality has been put forth; manufacturing virtual flight systems has been taken into consideration and aircraft flight simulation by modelling flight equations has become very important.

Nowadays, it is really necessary and inevitable to have a simulated model of an aircraft for manufacturing a simulator [1].

With the progress of aerospace science, many researches have been conducted about using simulations in stability mode and aircraft control studies [2]. Utilizing simulations stability mode and aircraft control studies was put forth by Nelson in 1976 [3].

In 1991, Black Lock wrote a book about the application of simulations in stability mode and aircraft control as well as aircraft dynamic flight studies [4]. In his book, Black Lock has explained the calculations of aerodynamic coefficients, aerodynamic forces, and torques and Euler angles for dynamic aircraft flight simulation.

In 1992, a research was released by Hogg et al about total flight simulation [5]. In the mentioned survey, the researchers have explained the transmission of aerodynamic torques and forces required for dynamic flight simulation of aircraft in different coordinates.
In 2003, Stevens et al wrote a book about the application of flight simulation in stability mode and aircraft control studies [6].

In 2003, NASA could simulate aircraft F-4, F-16, F-14 and F-106 to be used by PCs. For this purpose, aerodynamic features and inertia characteristics/mass of aircrafts were obtained through wind tunnels and flight tests [7]. The paper on the subject of Real time flight simulation of highly maneuvrable unmanned aerial vehicles was presented by selig [8]. He focused on full six degree of freedom aerodynamic modelling of small unmanned aerial vehicles at high angle of attacks and high sideslip in maneuvers performed using large control surfaces at large deflections for aircraft with high thrust to weight ratios in his paper.

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The implementation and evaluation of a real time Six Degree Of Freedom (6DOF) flight simulation model for a Skid-To-Turn (STT) Infra-Red (IR) rolling missile with a single plane of control was conducted by Wang and Awad in 2014 [9]. They applied the true proportional navigation (TPN) instead of Classical proportional navigation (CPN) guidance law that is used in guidance system of real missile.

In 2015, the study about the real-time cloud modeling and rendering approach based on L-system for flight simulation was presented by kang et al. [10].

In 2015, Xing et al. [11] elaborated the composition and function of the flight simulation system according to characteristics of UAV flight simulation in simulation training device. They designed the flight control model and navigation model based on the Matlab/Simulink to solve mode switch and other key technical difficulties in software.

Precise dynamic flight simulation is a way to acquire suitable flight information during different aircraft maneuvres. The mentioned information is really desirable for many researches. If flight simulation is not carry on, some of the mentioned information is not achieved. In such cases, it results to too much cost.

In this paper, a method for producing a dynamic flight simulation of aircraft has been presented. For this purpose, firstly, nonlinear equations governing aircraft movement have been presented. Then, nonlinear and dynamic flight simulation of aircraft has been performed. Sustainability derivations of aircraft training for calculation of aerodynamic coefficients in different flight conditions have been given accordingly.

One of the most important stages of simulation is validation of the obtained results by using real aircraft experimental test results [12]. For this purpose, Loop and Chandelle maneuvres which are among the most important maneuvres of an aircraft have been performed by an expert and skilful pilot by using the simulated model. The obtained information during the maneuvres is compared to the information obtained from flight tests. The simulation results show that the difference among the parameters obtained from simulation and experimental method is less than 13%.

2. Aircraft mathematical model

For modelling the aircraft, equations of motion have been used assuming that the aircraft is a rigid body. Decrease of mass has been neglected because the consumption of petrol during the maneuvre is low. Moreover, change in the position of the gravity center has also been discarded.

Climate conditions such as density and temperature have been considered according to the standard atmospheric conditions. Furthermore, changes in conditions due to the change of height have been regarded as standard.

3. Aircraft nonlinear equations

Aircraft nonlinear equations that have been coupled and connected with each other are used for flight simulation are namely force, momentum and kinematic equations [2, 4, and 6]. Further to these equations, for dynamic flight simulation, it is necessary to taken navigation equations into account as well [5].

According to the aforesaid equations, in order to obtain moments and forces implied to an aircraft flight simulation, the calculation of aerodynamic coefficients such as CL, CD, CY, Cm, Cl and Cn is necessary. These coefficients are achieved by using sustainability derivations through the following formulas [4]:

$$C_L = C_{L0} + C_{L\alpha}.\alpha + \left(\frac{C}{2V_T}\right)C_{Lq}.Q + C_{L\delta e}.\delta e, \quad (1)$$

$$C_D = C_{D0} + C_{D\alpha}.\alpha + C_{DiH}.iH + C_{D\partial e}.\partial e, \quad (2)$$

$$C_m = C_{m0} + C_{m\alpha}.\alpha + \left(\frac{C}{2V_T}\right)C_{mq}.Q + C_{m\delta e}.\delta e, \quad (3)$$

$$C_Y = \left(\frac{b}{2V_T}\right)\left(C_{yp}.P_s + C_{yr}.R_s\right) + C_{y\beta}.\beta + C_{y\delta a}.\delta a + C_{y\delta r}.\delta r, \quad (4)$$

$$C_l = \left(\frac{b}{2V_T}\right)\left(C_{lp}.P_s + C_{lr}.R_s\right) + C_{l\beta}.\beta + C_{l\delta a}.\delta a + C_{l\delta r}.\delta r, \quad (5)$$

$$C_n = \left(\frac{b}{2V_T}\right)\left(C_{np}.P_s + C_{nr}.R_s\right) + C_{n\beta}.\beta \qquad (6)$$

$$+ C_{n\delta a}.\delta a + C_{n\delta r}.\delta r,$$

$$K = \frac{1}{\pi Ae}. \qquad (7)$$

In order to fulfill simulation stages, it is required to calculate aerodynamic coefficients and sustainability derivations. In this research, by using analytical-experimental methods and use of AAA and DATCOM software, the derivations have been calculated.

Then, the model of aircraft was prepared in the computational fluid dynamic (CFD) Software for the numerical solutions. The numerical solutions have been performed in different conditions of flight such as different conditions of Mach number, attack angle, control surfaces angle and the ones. For assurance about the preciseness of aerodynamic derivations obtained through the above methods, some of the mentioned derivations have been compared to the numerical solution outputs.

For example, the values of $C_{m\alpha}$ derivation that have been calculated in different conditions are presented in two situations of center of gravity in Tables 1 and 2.

4. Simulation Stages

For dynamic flight simulation or flight with simulator, it is required that after modeling the aircraft nonlinear equations, sustainability derivations are calculated promptly and under different flight conditions.

For this purpose, the derivations calculated through the aforesaid methods, have been drawn up in the software in form of Look-up Table. Using the said table, software may calculate the respective derivation in different flight situations and conditions by using interpolation.

After the derivations are calculated, coefficients and eventually forces and aerodynamic torques are obtained through simulation equations.

The resulted forces and torques have been used to obtain linear and angular speeds, Euler angles, angles of attack and side slip angles.

In order to make simulation conditions become closer to real conditions of corresponding inputs, the respective changes of propulsion force and transfer of control surfaces is applied by the pilot through use of Joy Stick to simulation program. The blocks prepared for any of calculation stages, corresponding blocks to inputs and schematic indicators have been shown in Figure 1.

Table 1: Changes of $C_{m\alpha}$ at the height of 10000 feet and $x_{cg} = 10\%$ of MAC

Altitude 10000ft	Mach Number			
Angle of Attack	0.3	0.5	0.7	0.85
-4	-0.6689	-0.6728	-0.6697	-0.6469
0	-0.7355	-0.7476	-0.7667	-0.7591
5	-1.07	-1.083	-1.073	-1.029
10	-1.391	-1.414	-1.429	-1.44
15	-1.477	-1.438	-1.498	-1.595
20	-0.9959	-0.9494	-1.065	-1.253
24	-0.2138	-0.2704	-0.4454	-0.6972

Table 2: Changes of $C_{m\alpha}$ at the height of 10000 feet and $x_{cg} = 15\%$ of MAC

Altitude 10000ft	Mach Number			
Angle of Attack	0.3	0.5	0.7	0.85
-4	-0.4598	-0.4613	-0.4502	-0.4186
0	-0.5264	-0.5367	-0.5437	-0.5225
5	-0.854	-0.8661	-0.8457	-0.7868
10	-1.2	-1.226	-1.227	-1.215
15	-1.337	-1.296	-1.335	-1.407
20	-0.8881	-0.8159	-0.9073	-1.069
24	-0.1242	-0.1299	-0.2747	-0.4884

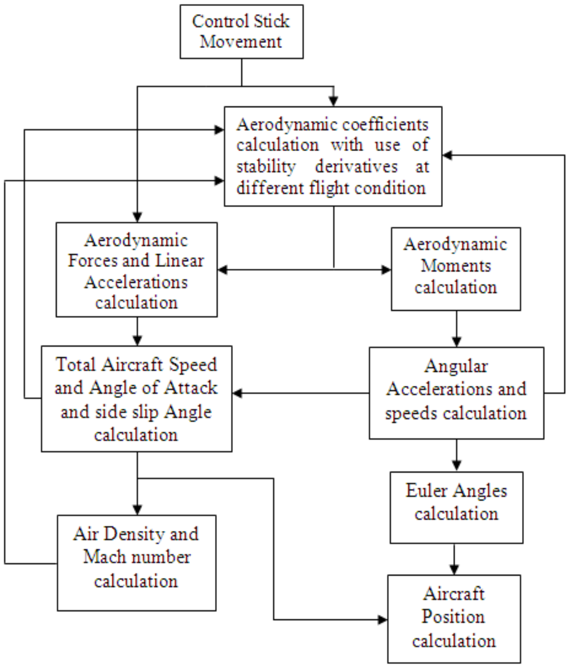

Figure 1: Functional Scheme of flight Simulation

5. Introducing the typical aircraft

The typical aircraft in this research is a training fighter jet. The mentioned aircraft is 556.41 inches in length with a wing area of 173.82 feet square. The distance of tip of wings is 24.855 feet and its weight is 13881 Pound with internal petrol and serial tanks with two passengers. The power of the engines of the mentioned aircraft is 4160 Pound force in maximum mode and 6020 Pound force in after burner.

6. Execution of loop and chandelle maneuvres with simulation

The aforesaid maneuvers have been performed by using the simulated model by an expert pilot and by using of airspeed indicator, altitude indicator, "G" meter indicator, heading indicator and attitude indicator that were installed on the model. The flight started with the simulated model in such a manner that at the starting time, primary conditions for the maneuvers have met.

Performing of the maneuvers are started and terminated by flight simulation like a real aircraft and according to the respective instructions. Corresponding information obtained from the flight simulation during the performance of Loop maneuver as well as Chandelle maneuver in different aircraft positions are given in Table 3 and Table 4, respectively.

Table 3: Parameters of Loop Maneuver obtained by flight simulation

Position	Airspeed (Knot)	Pitch Angle (Deg)	Mach. No	VLF or Nz ("g")
1(Start)	501.51	1.95	0.88	0.99
2	445.49	45.02	0.796	4.45
3	347.86	89.5	0.661	3.47
4	225.64	(Invert) 0.027	0.451	1.22
5	251.52	-45.01	0.5	1.82
6	328.92	-89.67	0.64	3.22
7	442.74	-45	0.79	3.87
8(Final)	499.92	-1.06	0.859	0.98

Table 4: Parameters of Chandelle Maneuver obtained by flight simulation

Position	Airspeed (Knot)	Turn Angle (Deg)	Mach. No	VLF or Nz ("g")
1(Start)	400	0	0.71	1
2	363.9	45	0.68	3.51
3	310.9	90	0.61	2.88
4	271.7	135	0.52	1.9
5(Final)	200.9	180	0.39	1

7. Execution of maneuvers with real aircrafts (experimental)

Loop Maneuver started according to the corresponding instructions on horizon and in the straight and the level mode of aircraft with a speed of 500 KNOT and a vertical acceleration given as 4.5 times as gravity acceleration (4.5 "g"). Power of engines from starting through termination of the maneuver was at their maximum level. During the performance of the maneuver, the pilot did not use rudders by any means and tries to keep ailerons without movement during it.

Execution method of Loop maneuver is shown in Figure 2.

The experimental parameters of this maneuver that were recorded during deferent flights by the pilot instructors of aircraft are given in Table 5.

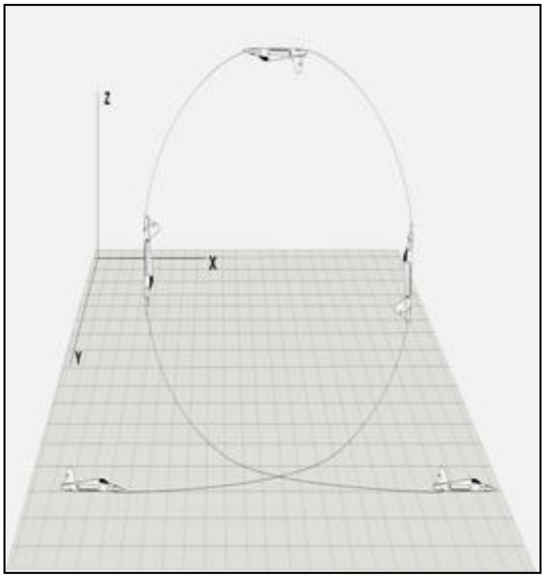

Figure 2: Performance method of Loop Maneuver

For performance of Chandelle Maneuver, the rotation of engines must be 95% and the speed of aircraft must be 400 KNOT. The mentioned maneuver started and ended according to the respective instructions.

Schematic performance of Chandelle Maneuver is given in Figure 3. The obtained experimental information, i.e. information that is recorded during different flights, is given in Table 6.

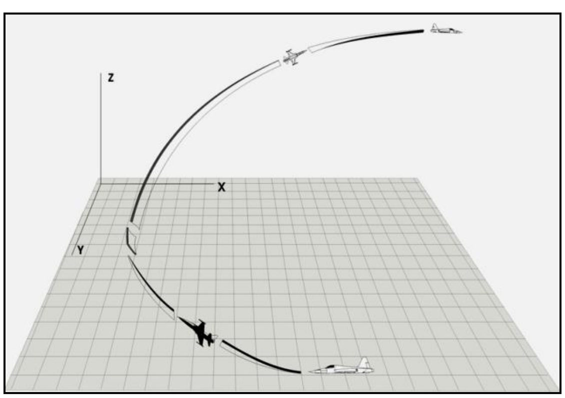

Figure 3: Performance Schematic Figure of Chandelle Maneuver

Table 5: Information of Loop Maneuver obtained by experiment

Position	Air Speed (Knot)	Pitch Angle (Deg)	VLF or Nz ("g")
1(Start)	500	0	1
2	450	45	4.5
3	350	90	3.5
4	200	(Invert) 0	1.2
5	250	-45	2
6	300	-90	3
7	440	-45	3.5
8(Final)	500	0	1

Table 6: Information of Chandelle Maneuver based on experiment

Position	Air Speed (Knot)	Turn Angle (Deg)	VLF or Nz ("g")
1(Start)	400	0	1
2	360	45	3.5
3	300	90	3
4	250	135	2
5(Final)	200	180	1

8. Results and Discussion

As it has been mentioned, the information obtained from simulation during performance of Loop Maneuver is given in Table 3 and corresponding results are given in Table 5. Considering the aforesaid two tables, the difference between airspeed and vertical load factor (VLF) in flight simulations and experiments have been calculated in different positions of Loop Maneuver and are given in Table 7. The speeds obtained from simulation and flight in different pitch angles have been compared according to Figure 4.

Based on Figure 4 and Table 7, difference of speed in all points except for points 4 and 6 is trivial (about 1%). At point 4 where the aircraft is in reverse condition, the airspeed difference reaches 12.8%. Moreover, at point 6 where the aircraft moves toward earth with a pitch angle of minus 90 degrees to the horizon, the airspeed difference reaches about 9.6%.

Table 7: Difference and percentage of error between airspeed and vertical load factor obtained from simulation and on experimental basis during Loop Maneuver

Position	Sim. and Exp. VLF diff. ("g")	Error of Sim and Exp VLF (%)	Sim. and Exp. A/S diff. (Knot)	Error of Sim. and Exp. A/S (%)
1(Start)	0.01	1%	1.51	0.3%
2	0.05	1.1%	4.51	1%
3	0.03	0.8%	2.14	0.61%
4	0.02	1.6%	25.64	12.8%
5	0.18	9%	1.52	0.6%
6	0.22	7.3%	28.93	9.6%
7	0.37	10.5%	2.74	0.62%
8(Final)	0.02	2%	0.08	0.01%

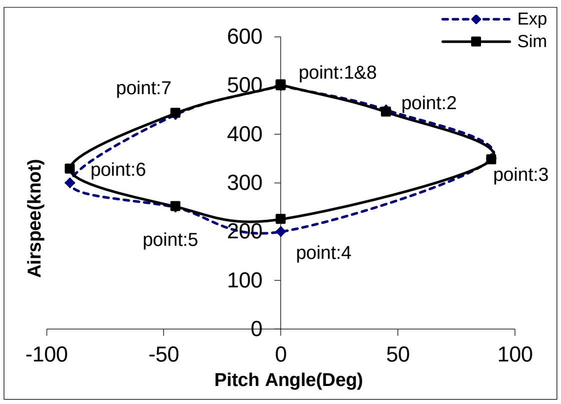

Figure 4: Comparing airspeeds of simulation and on experimental basis in different pitch angles during performance of Loop Maneuver

In figure 5, comparison of vertical load factors (VLF) obtained from flight simulation and on experimental basis in different pitch angles have been shown. According to Figure 5 and Table 7, difference of vertical load factor in most points of the maneuver is trivial. At points 5, 6 and 7, the values of vertical load factor obtained from flight simulation and on experimental basis show more difference. At point 5, the mentioned difference reaches 9% and at point 6, it reaches about 7.3%. At point 7, the mentioned difference reaches to the highest value i.e. 10.5%.

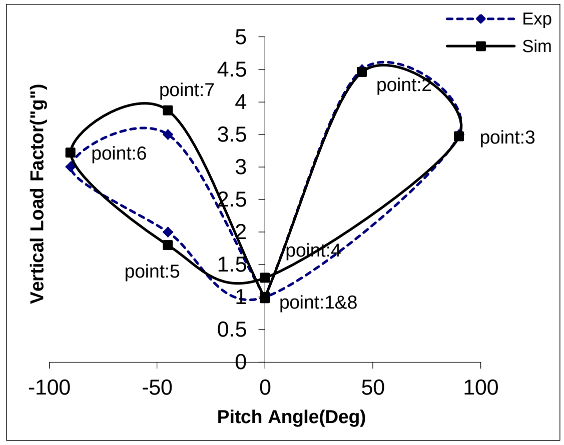

Figure 5: Comparing vertical charge factors of simulation and on experimental basis in different pitch angles during performance of Loop Maneuver

According to Table 4 and Table 6 which show the parameters obtained from flight simulation and on experimental basis during performance of Chandelle Maneuver. The difference between airspeed and vertical load factor obtained from flight simulation and on experimental basis have been calculated in different conditions of Chandelle Maneuver and presented in Table 8.

Table 8: Difference and percentage of error between airspeed and vertical load factor obtained from flight simulation and on experimental basis in Chandelle Maneuver

Position	Sim. and Exp. VLF diff. ("g")	Error of Sim. and Exp. VLF (%)	Sim. and Exp. A/S diff. (Knot)	Error of Sim. and Exp. A/S (%)
1(Start)	0	0%	0	0%
2	0.01	0.2%	3.9	1%
3	0.12	4%	0.9	3.63%
4	0.1	5%	21.7	8.68%
5(Final)	0	0%	0.9	0.45%

The airspeeds obtained from flight simulations and tests in different positions of turn have been compared according to Figure 6.

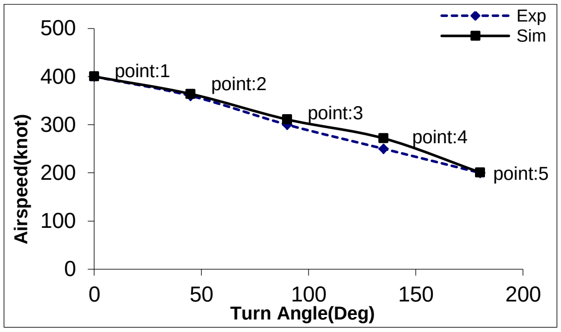

Figure 6: Comparing airspeeds obtained from flight simulation and on experimental basis in different positions of turn angles during performance of Chandelle Maneuver

As it is shown in Table 8 and Figure 6, difference of speed in most points of the Maneuver is trivial (about 0-4%) and only at point 4 where the pilot starts roll-out the aircraft, the difference reaches about 9%. By comparing the vertical load factors obtained from flight simulation and on experimental basis in different conditions shown in Figure 7 and Table 8. It is found that the difference of vertical load factors is trivial at most points. Only at points 3 and 4, this difference reaches about 4-5 percent.

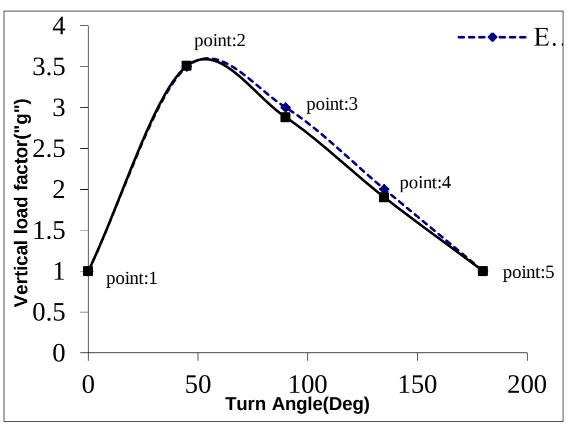

Figure 7: Comparing vertical load factors obtained from flight simulation and on experimental basis in different turn angles during performance of Chandelle Maneuver

Flight execution by using the simulated model by the pilot caused that the pilot corrects applied inputs by receiving feedback from the aircraft behavior. This phenomenon has led to decrease of some errors in many cases because of the study of the aircraft behavior.

Generally, the difference among the obtained parameters from flight simulations and tests of both maneuvers rises from such cases as described as follows:

1. Error in calculation of sustainability derivations by analytical-numerical methods.
2. Standardization of changes in temperature and atmospheric pressure in flight simulation that affect Mach Number, Airspeed, height and eventually calculation of all derivations and coefficients.
3. Assuming that weight of simulated of aircraft is constant from starting through termination of the maneuver that have a slight effect on vertical and horizontal accelerations, inertia momentums and torques.
4. The error in registration of parameters by the pilot in a real aircraft due to sensitiveness and difficulty of the duty of the pilot especially during the conditions of Loop Maneuver where the aircraft is in reverse and vertical position toward the earth and in certain condition of Chandelle Maneuver where the aircraft rolls out. Thus, in the mentioned conditions, the difference between airspeeds and vertical load factors in simulation and flight tests is more than that of other conditions.
5. The error of indicators of real aircrafts because these indicators are not graded on the basis of display of small numbers. It quite clear that in the case that these indicators are digital, the pilot may increase the preciseness of speed recording up to one knot and the preciseness of vertical charge factor up to 0.1, respectively.
6. Ideal propulsion force of engines in flight simulation concerning the fact that the engine of a real aircraft is not able to generate real propulsion force due to high service life.

9. Conclusion

Comparing the results of flight simulation with the recorded parameters in similar modes to real flight indicate low error of the simulation results. One of the reasons for low error is execution of the flight by an experienced pilot using the simulated model because this has caused that the pilot corrects applicable inputs through feedback from the behavior of the aircraft. The value of error in most parts of the maneuvers was between 1% and 4% and it reached 12.8% at most in the limited parts. This error is not exclusively related to the simulation and parts of such errors correspond to problems with recording the information during the experimental flights.

Standard changes in temperature, changes in atmospheric pressure and assuming that the weight of the aircraft is not changed during the maneuver performance and error in calculating stability derivations causes error in flight simulation.

Imprecise information recorded by the pilot of a real aircraft and low preciseness of indicators of a real aircraft result in the error during an experimental flight. Thus, in such conditions as the pilot requires more preciseness for control of the aircraft, the percentage of error has been increased. The obtained results reveal that aircraft dynamic flight simulation by the use of calculation of sustainability derivations in different flight conditions and development of a Look-Up table has the ability to perform a maneuver with high preciseness.

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