https://dx.doi.org/10.22161/ijaers.5.7.10 ISSN: 2349-6495(P) | 2456-1908(O)

Analytical Calculation of the Drives of a Flight Simulator Platform with 2 Degrees of Freedom

Weslei Patrick Teodósio Sousa[1], Túlio Pinheiro Duarte[2], Bruno Rodrigues Castro[3], Tarcísio Flávio Umbelino Rego[4], Pedro Américo Almeida Magalhães Júnior[5]

[1]Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: wesleisousa94@gmail.com
[2]Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: tulio-p.duarte@outlook.com
[3]Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: brunurc@gmail.com
[4]Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: tarcisiopuc@gmail.com
[5]Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: paamjr@gmail.com

Abstract**—*****With constant technological advances, flight simulation has increasingly resembled a real flight. The use of motion platforms together with a virtual simulation is what is most recent in this field, due to its global approach to a flight. However, these flight simulators generate a great added value, so that for trivial trainings and entertainment their use becomes impracticable. With this in mind, in this work was presented a low cost project of a new model of flight simulator containing both simulations, visual and motion. More specifically, this work aims to demonstrate an analytical method for calculating the drives of the designed simulator, so that it supports the loads of the structure and user, in addition to the dynamic torque required by the simulation platform. Furthermore, it was shown how to obtain the inertia of a complex structure as designed using SolidWorks software and also how to acquire magnitudes such as acceleration and angular velocities using Flight Simulator X and Link2FS Multi software. Finally, with the torque and power values required to perform the pitch and roll movements, a commercial selection of the motors was made for platform so that these drives would supply the demand of both torque and power.*
Keywords—Analytical Calculation.Flight Simulation. Links2FS Multi. Power. Torque.

I. INTRODUCTION

Since the dawn of aviation, pilots training has been the subject of many studies seeing that they should achieve a high level of efficiency without risk being taken during the training phase. In military aviation, for example, pilot skill was of paramount importance, as precision in combat maneuvers could ensure the success of the mission [1].

Flight simulators have been developed for more than a century, seeking to achieve the highest possible realism and safety for the user. Currently, flight simulators have been widely used for both professional training and entertainment. Generally, the use of a simulator is always superior to the use of real equipment in three aspects: safety, cost of equipment and experimental control [1][2][3].

According to Dourado [1], when used for training, the flight simulator should have a reduction in the time between land training and real flight due to mistakes made by beginners, the simulation must be safe, cost and pollution must also be smaller.

Many authors have discussed themes or subsystems related to the simulation of a flight, but few have discussed this as a whole, that is, from virtual simulation to simulation of aircraft movements. For example, Shahal treated only the influence of visual parameters such as brightness and contrast on the visual simulation of a fixed-base simulator, while Pool presented a cybernetic approach to evaluate the flight simulator's motion fidelity [4][5].

Due to that reason, the authors elaborated a project considering the required subsystems in order that a simulation with a global fidelity of a real flight can be acquired[6]. These subsystems are a view of the environment outside the cockpit of an airplane, a motion system which supports the movements done by an

https://dx.doi.org/10.22161/ijaers.5.7.10 *ISSN: 2349-6495(P) | 2456-1908(O)*

aircraft, and the main controllers of an airplane, in this case the joystick, the rudder pedals and the accelerators. A flight simulator with 2 degrees of freedom (2DOF) containing both the visual and control simulation made by Flight Simulator X (FSX) software and controller replicas of an aircraft, as well as simulation of airplane movements, made through a motion platform composed of structural parts and electrical drives.

However, owing to the complexity of the platform and the calculations involved, in addition to all programmatic control, this work aims to present the final design of the flight simulator and the analytical procedure to calculate the power and torque of the electric motors of the simulator and also the computational method used to obtain the moment of inertia of the simulation platform. In addition, an effort has been done to select the appropriate commercial electric motors for each movement.

II. METHODS

2.1 Project of the Flight Simulation Platform

During the initial phase of the project several factors were defined in order to delimit the peripherals and drives to be used. The relevant factors for this project were the final cost, the interaction of the user with the simulator and, the most relevant, the fidelity of the simulation provided by the precision of the movements. For the platform modeling, SolidWorks 2016 software was used.

2.2 Determination of the Drive type

Before determining the type of drive to be used on the platform, the initial factors were again considered on the choosing. The main types of drives are hydraulic, pneumatic and electric. Pneumatic drives were the first to be discarded because they can achieve low power and torque, which would not match the demand of this project. The hydraulic drive would be the one that would present greater precision of the movements, besides high powers that could be reached, but the needed cost would be very high compared to the electric drives, for this reason the hydraulic drive was also discarded [7]. Amongst the electric drives, stand out the conventional motors AC and DC, besides the servomotors. Of these types of electric motors, the one that fit better was the AC motor, although this one needs an inverter of frequency for the control of the speed, would still be a cheaper option than the others. However, this motor has less control accuracy when compared to the servomotor, but by establishing a certain precision tolerance, the AC motor would comply with the demand.

2.3 Torque Analytical Calculation

The motion platform was designed to describe the pitch and roll movements of an aircraft, each movement being described by an electric motor. Thus, the calculation procedure was done using the Euler equations of motion for the dynamic torque, where each component of the torque represents one of the movements of the aircraft. However, if this analytical method were not used, the computation could be done by systematic computation using a generic technique such as Euler-Newton [8].

So, the minimum torque required by the motors can be calculated as proposed, analytically, by equation 1:

$$M_{min} = M_{dynamic} + M_{static} \quad (1)$$

Where $M_{dynamic}$ can be calculated by Euler equations from 2 to 4[9]:

$$M_x = I_{xx}\alpha_x + \omega_y\omega_z(I_{zz} - I_{yy}) \quad (2)$$

$$M_y = I_{yy}\alpha_y + \omega_z\omega_x(I_{xx} - I_{zz}) \quad (3)$$

$$M_z = I_{zz}\alpha_z + \omega_x\omega_y(I_{yy} - I_{xx}) \quad (4)$$

Where I is the inertia for the part of the motion platform and α and ω are respectively the maximum angular acceleration and velocity described by the structure.

Using the parallel-axis theorem, also called the Steiner's theorem, the rotational inertia of a body with respect to an axis parallel to the center of mass axis can be calculated by equation 5 [10]:

$$I = I_o + Md^2 \quad (5)$$

Where I_o is the inertia about to the center of mass and d is the distance between the parallel axes.

However, this inertia calculation is usually done manually for bodies with simple geometry as shown by Abdulghany [10]. Therefore, to calculate the inertia of three-dimensional bodies and complexes, software is commonly used to this calculation and it express the result as an inertia tensor as shown in equation 6 [10]:

$$I = \begin{pmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{pmatrix} (6)$$

Where the elements of the diagonal refer to the moments of inertia on the three orthogonal axes x, y and z.

In order to obtain this tensor a tool of the software SolidWorks 2016 was used, which shows the mass properties of the selected bodies in the project, so that inertia can be obtained for both pitch and roll.

The angular acceleration was obtained empirically using two programs, Flight Simulator X (FSX) and Link2FS Multi. A flight simulation was done using the FSX with Cessna 172 model as aircraft, one of the most used aircraft for pilot training. During the simulation,

https://dx.doi.org/10.22161/ijaers.5.7.10 **ISSN: 2349-6495(P) | 2456-1908(O)**

forced maneuvers were made to simulate extreme flight situations, where critical accelerations would be imposed on the aircraft. Using the Link2FS Multi software, the critical accelerations imposed on the aircraft were collected and the maximum acceleration obtained was used for the calculation, as this would be the situation where a higher torque would be required. Then, the dynamic torque was calculated using the Euler equations.

As well as the minimum torque, the dynamic torque could have been computationally calculated according to the dynamic analysis done by Herrero [11] for a mechanism with 3DOF. But, as a simplification to calculate the static torque, the equation 5 [12] was used.

$$M_{static} = r \times F = \begin{vmatrix} i & j & k \\ r_x & r_y & r_z \\ F_x & F_y & F_z \end{vmatrix} \quad (7)$$

Where r_x, r_y and r_z represent the orthogonal distances, according to the coordinate system, up to the axis of rotation and F_x, F_y e F_z represent the force vectors according to the coordinate system.

However, for this calculation both mass and distance were obtained using SolidWorks 2016 software to evaluate these quantities, where m would be the mass of the selected platform part added to an arbitrary mass given to the user which multiplied by gravity would promote the force weight would generate the static torque considering a r that would be the orthogonal distance from the center of mass to the axis of rotation of the motors. Then, the static torque was calculated, disregarding its sense since at times the torque would be favorable to the movement and now would be contrary. Finally, the minimum torque required for each of the motors can be calculated.

2.4 Power Analytical Calculation

The motors are commercially found according to their power and in their datasheet can be found the value of the nominal torque. The electric motor must suplly both the required power and torque. Thus, the analytical power calculation was done using equation 8[13]]:

$$P = M_{min} * \omega \quad (8)$$

Where M_{min} was previously calculated and ω is the maximum angular velocity achieved by the Cessna 172 aircraft during the simulated flight in FSX. As well as the angular acceleration, the maximum angular velocity was obtained using Link2FS Multi.

2.5 Selection of motors and gear units

The selection of suitable motors was consulted catalogs from one of the largest electric motor companies, the WEG [14]. In addition, catalogs of gears were also consulted, so that the drives meet the required torque[15].

Another necessity was that the drive presented irreversibility, something that only the AC motors are not able to guarantee, being thus in analyzing the reducers this factor was also considered for choice.

III. RESULTS

3.1 Flight Simulator Platform

Fig.1: Motion Flight Simulator Platformshows the isometric view of the finished and rendered project. The platform was designed in an attempt to obtain the maximum possible structural symmetry. As seen in Fig.1: Motion Flight Simulator Platform, the roll is described by the internal structure, the gear and motor assembly being located on a support in the outer ring, where movement would be imposed on the structure by a coupling. In the meantime, the pitch movement would be imposed on the structure as a whole by means of the gear and motor assembly arranged in one of the support tripods of the structure. The platform is designed to describe angles of maximum 40°, and in commercial flights the maximum pitch and roll values are 15 °. In this way, the platform would attend both for pilot training and entertainment.

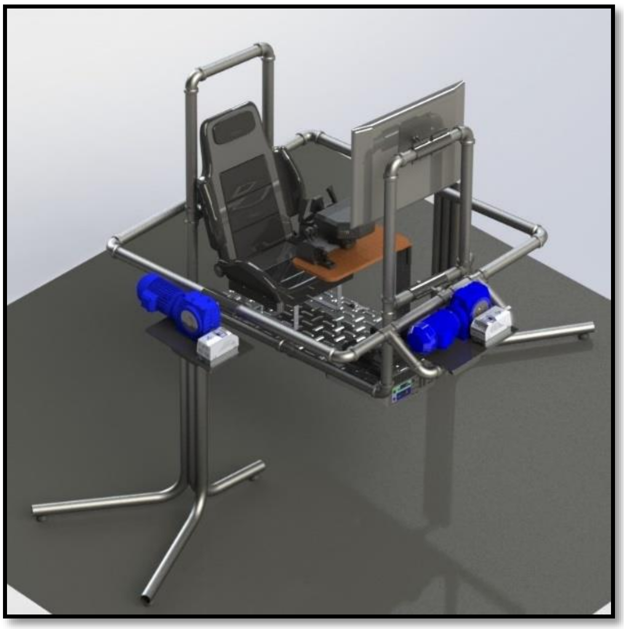

Fig.1: Motion Flight Simulator Platform

Fig.2: Other view of the Fligh Simulator shows another view of the simulation platform, which can be seen interface devices with a replica of the joystick used in the Cessna 172 as well as accelerators, in addition to a 32 "TV for visual simulation.

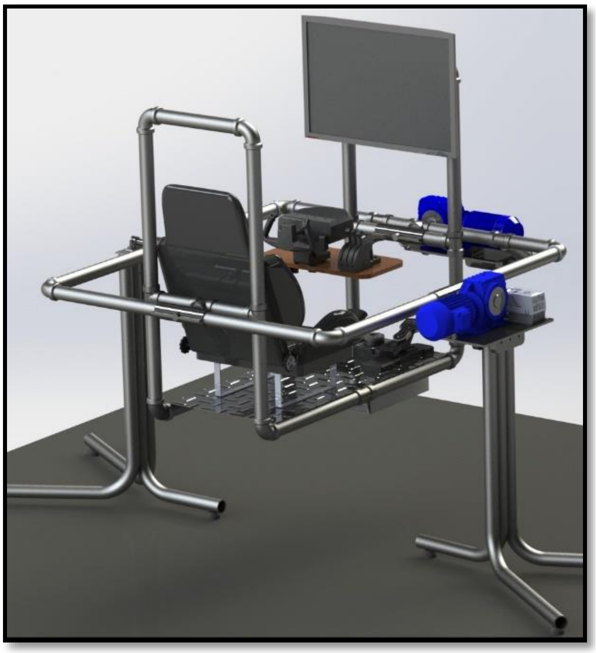

Fig.2: Other view of the Fligh Simulator

3.2 Torque Analytical Calculation

Fig.3: Internal Structure and its Mass Centershows an image of the selected platform parts to obtain their mass properties, and with the inertial tensor calculated by the software, the inertia for the roll was obtained. The mass of the user was simulated by a thin plate positioned on the seat with a mass of 100kg.

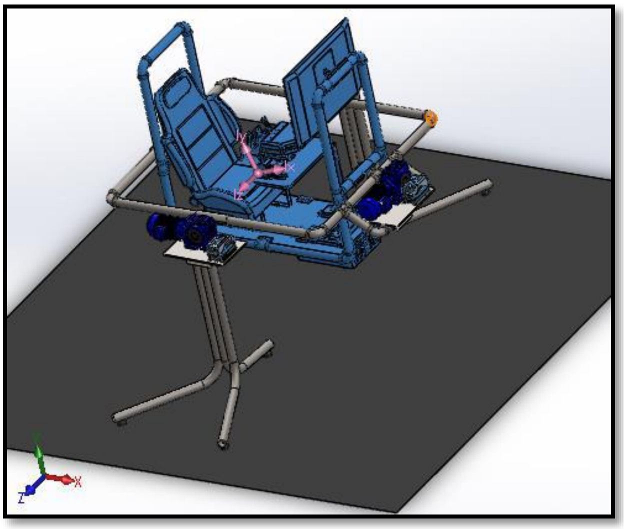

Fig.3: Internal Structure and its Mass Center

The relevant properties for the torque calculation are the distance from the center of mass to the center of rotation of the roll motor and the inertia of the structure relative to the axis of rotation. Equation 9 shows the inertia tensor of the selected bodies and shown in Fig. 3:

$$I = \begin{pmatrix} 51.55 & 5.25 & -0{,}59 \\ 5.25 & 73.27 & -0.47 \\ -0.59 & -0.47 & 106.95 \end{pmatrix} \quad (9)$$

The units of the inertias shown in equation 9 are in kg.m^2. Fig.3: Internal Structure and its Mass Centershows that the dynamic torque for the roll is the M_x, so the inertia to be considered for the calculation should be the I_{xx} which is equal to 51.55 kg.m^2. The acceleration obtained using the software FSX and Link2FS was 0.5 rad/s^2. From this data can be calculated the dynamic torque using the equation 2 and considering that there is no initial velocity, because the motor would have interrupted cycles, that is, with each movement that was carried out, soon after if it was not necessary to continue the movement, the motor would stop the movement. In this way, the second part of equation 2 would be null. Thus, the dynamic torque obtained was 17.44 N.m.

The orthogonal distances from the center of mass to the axis of rotation were also obtained through the mass properties in order to calculate the static torque. Table.1: Mass Center from Internal Structure shows the data from the center of mass to the internal structure.

Table.1: Mass Center from Internal Structure

Mass Center (m)	
X	-0.08
Y	-0.13
Z	0.01

Therefore, the distance considered for the calculation of the torque was the distance in Z, since this is perpendicular both the force weight (Fy) and the axis X, already the distance ry although it is orthogonal to the X axis at the same time is parallel the force weight, for this reason does not generate a static torque. Using equation 7, the static torque was calculated. The mass of the internal structure considering the mass of a user of 100 kg was 284 kg. The static torque for distance Z was 27.8604 N.m. Thus, using equation 1, the minimum torque for the motor running the roll was 45.3 N.m.

The same procedure was used to calculate static and dynamic torques for pitch motion. Equation 10 below shows the inertial tensor for the platform considering the internal and external structures.

$$I = \begin{pmatrix} 55.05 & 4.59 & 1.16 \\ 4.59 & 93.25 & -0.55 \\ 1.16 & -0.55 & 123.62 \end{pmatrix} \quad (10)$$

The coordinate axis was maintained for this calculation, so the pitch motion is executed around the Z axis. In this way, the inertia used to calculate the dynamic torque (M_z) was the I_{zz} which is equivalent to 123.62 kg.m^2. Using the equation 4 and the same consideration which was done for roll, the dynamic torque for the pitch was realized and this obtained a value of 61.81 N.m.

Another time, the displacement of the center of mass in relation to the axis of rotation was considered to calculated the static torque. Table.2: Mass Center from the Whole Motion Structureshows the values of the displacements of the center of mass on the axis of rotation about to the orthogonal axes.

Table.2: Mass Center from the Whole Motion Structure

Mass Center (m)	
X	-0.03
Y	-0.12
Z	0.01

From these values were made the same calculations as previously performed for the roll. But for the pitch we considered the distance r_x as this is orthogonal to the force weight and the Z axis. This time, the mass found for the whole structure was 305 kg. From these values, the static torque found was 89.76 N.m. Therefore, the minimum torque for pitch execution was 151.57 N.m.

3.3 Power Analytical Calculation

Once the pitch and roll torques have been determined, the power calculation becomes trivial. Using equation 6 and a maximum angular velocity for a structure of 0.42 rad/s, the powers for pitch and roll were respectively 63.66 W and 19.03 W.

Table.3: General Results for Torque and Powershows the final results obtained for torque and power.

Table.3: General Results for Torque and Power

	Pitch	Roll
Torque (N.m)	151.57	45.3
Power (W)	63.66	19.03

3.4 Selection of motor and gear units

As seen in Table 3, the powers found were very low, but in other hand the required torque was very high. Therefore, it was proposed to use motors with low power with high reductions to withstand the torques at the output. Table.4: Reducer and its output propertiesshows the selected gear units and their respective output torques and powers. The values shown in the table refer to reductions rates in 1 stage and motors with 1750 rpm of nominal speed.

Table.4: Reducer and its output properties

	Reduction	Power (hp)	Torque (N.m)
Pitch	1:80	0.65	208
Roll	1:60	0.40	96

For the selected reduction and to obtain these values of torque and output power, the electric motors required for pitch and roll were respectively 2 hp and 1 hp. According to the gearbox catalog of WEG-Cestari, MAGMA type gear units for pitch and roll were size 7 and 5 respectively.

IV. CONCLUSION

From the analysis of the results, it can be concluded that the flight simulation platform, despite having a high torque demand, at the same time showed a low power requirement due to the low displacement velocity. It may also be noted that as proposed, the analytical method of calculating dynamic quantities was very simple, even for a complex structure as projected.

Finally, it is possible to simply specify the torque and power calculation to specify commercial devices that would support with a certain safety factor the torque and power values found.

In future works, this article will be compared an another approach calculation which will be done using an assistance of software like Adams and Ansys.

V. ACKNOWLEDGEMENTS

The authors are verygratefultothe PUC/MG (Pontifícia Universidade Católica de Minas Gerais), CNPQ (Conselho Nacional de Desenvolvimento Científico e Tecnológico)and FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais).

REFERENCES

[1] Dourado, A.O; Martin, C.A. New concept ofdynamicflightsimulator,PartI. Aerospace Science and Technology, v.30, i.1, pp.79-82, 2013.https://doi.org/10.1016/j.ast.2013.07.005

[2] Eryilmaz, U; Tokmak, H.S;Cagiltay, K; Isler, V; Eryilmaz, N.O. A novel classification method for driving simulators based on existing flight simulator classification standards.Transportation Research Part C, v.42, pp.132-146, 2014.https://doi.org/10.1016/j.trc.2014.02.011.

[3] Reed, M.P., Green, P., 1995. Validation of a Low-cost Driving Simulator using a Telephone Dialling Task. Final Report, No: UMTRI-95-19. Retrieved from

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.895.5939&rep=rep1&type=pdf.

[4] Shahal, A; Hemmerich, W; Hecht, H. Brightness and contrast do not affect visually induced motion sicknessin a passively-flown fixed-base flight simulator, Displays, v.44, pp.5-14, 2016. https://doi.org/10.1016/j.displa.2016.05.007.

[5] Pool, D.M; Zall, P.M.T. A Cybernetic Approach to Assess the Training of Manual Control Skills. IFAC-PapersOnLine, v.49, i.49, pp.343-348, 2016.https://doi.org/10.1016/j.ifacol.2016.10.588.

[6] Baarspul, M. A review of flight simulation techniques. Progress in Aerospace Sciences, v.27, i.1, pp. 1-120, 1990. https://doi.org/10.1016/0376-0421(90)90006-6.

[7] Benyonga, W;Yanliang, D;Kedingb, Z.Compound Control for Hydraulic Flight Motion Simulator. Chinese Journal of Aeronautics, v.23, i.2, pp.240-245, 2010.https://doi.org/10.1016/S1000-9361(09)60211-9.

[8] Jain, A. Robot and Multibody Dynamics. Springer, 2011.

[9] Shames, I.H. Engineering Mechanics (Statics and Dynamics). Prentice Hall (ISBN: 0133569241), 1996.

[10] Abdulghany, A.R. Generalization of parallel axis theorem for rotational inertia. American Journal of Physics, v.85, i.10, 2017. https://doi.org/10.1119/1.4994835.

[11] Herrero, S; Pinto, C; Altuzarra, O; Diez, M. Analysis of the 2PRU-1PRS 3DOF parallel manipulator: kinematics, singularities and dynamics. Robotics and Computer-Integrated Manufacturing, v. 51, pp. 63-72, 2018. https://doi.org/10.1016/j.rcim.2017.11.018.

[12] Hibbeler, R.C. Engineering Mechanics: Statics, 12th Edition. Prentice Hall (ISBN: 0136077900), 2009.

[13] Colins, J.A; Busby, H; Staab, G. Mechanical Design of Machine Elements and Machines: A Failure Prevention Perspective, 2nd Edition. Wiley (ISBN: 0470413034), 2009.

[14] WEG. Motores elétricos assíncronos e síncronos de média tensão – Especificação, características e manutenção. Retrieved from http://ecatalog.weg.net/files/wegnet/WEG-curso-dt-6-motores-eletricos-assincrono-de-alta-tensao-artigo-tecnico-portugues-br.pdf.

[15] WEG-CESTARI; MAGMA-M. Redutores e Motorredutores de Coroa e Rosca Sem-fim.Retrieved from http://www.transmitechredutores.com.br/admin/docs_upload/Cat.magmam_2013.pdf.