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STUDY ABOUT THE STABILITY AND CONTROL OF A ROTOR AIRPLANE

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Abstract. *On this paper is studied the stability and control of a Rotor Airplane, more specifically a MAV (Micro Air Vehicle) and how works the dynamics of flight of this unusual configuration of aircraft. It's discussed the impact of the gyroscopic effect on stability (mainly lateral and directional stability) and was found the best feasible configuration of the stability surface, but the project of the stabilizers was limited to lifting surfaces that use airfoil sections, the possibility of a very unconventional stabilizer like other rotating cylinders or a very complex geometry wasn't tested.*

The principal motivation of this study is that are few references and studies about the stability and control of this type of aircraft, and knowing that the use of rotating cylinder instead of a wing makes great modifications on the dynamic system, it's very important to know how the system works in order to certify the MAV can complete its mission.

Keywords: *Stability, Rotor Airplane, Magnus Effect, Aeronautics*

1 INTRODUCTION

On this paper a research was done on a specific rotor airplane configuration, the principal objective of this research is to understand how the flight mechanics of an unusual aircraft like that works. The principal challenges are the mix of aerodynamic characteristics and the lack of references.

The mix of the aerodynamic characteristics puts on one side, the dependence of the angle of attack of the control surfaces and on the other side the almost independence of the angle of attack of the spinning cylinder. This strange characteristic drives to some problems on how stability of the aircraft would be evaluated. For example, the main problem of the longitudinal static stability could be to trim the airplane that can has a very big value of $\boldsymbol{C_{M0}}$ depending on the location of the CG. The lack of references of researchers and engineers that already faced the same problem is another fact that makes this study more difficult.

Frequently strange values of stability derivates are necessary to meet good flight modes of the airplane, the standards of flight qualities like the [MIL-F-8785-C] just don't represent the reality of flight like that. Even for the new on mini UAV's projects this type of aircraft is strange. So it's important to analyze this project and find a model that represents well the dynamics of this system and can preview the stability and control characteristics of this aircraft.

2 THE MAGNUS EFFECT

The Magnus effect is a phenomenon that occurs on cylinders, spheres and even on fluid structures, that are on rotation. The physics concept behind it is very simple, the body that is rotating creates a pressure gradient between the flow up and down, a cylinder for example, if it's rotating on its longitudinal axis, in clockwise direction and the flow its immersed in, is dislocating from left to the right, the velocity on the upper part of the cylinder is bigger than the velocity on the lower part of the cylinder, so the dynamic pressure is different in low and upper part of the body and that creates a pressure gradient (inertial effect) that conduct the flow downwards, and as the 3º Law of Newton states, the cylinder suffer an up force, the Lift.

One advantage of the lift generated by the Magnus effect (a spinning cylinder for example) in comparison with that generated by an airfoil is its very high $\boldsymbol{C_L}$ that for some Reynolds numbers can be bigger than 20, an impressive value comparing with the conventional wings used on the major of airplanes. The type of force generated by the rotating body, the Lift or Downforce, is defined by the direction of rotation.

The Magnus effect was used in the past as a propeller on ships in place of vessels and many rotor planes were projected, but the most failed. Nowadays the Magnus effect still has a big importance to industry processes.

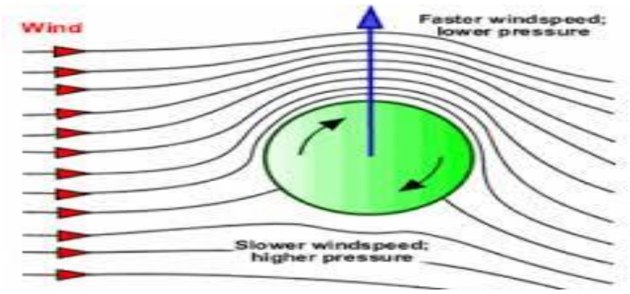

Figure 1. Representation of how the Magnus effect works

3 ROTOR PLANES

The rotor planes were first tested on the decade of 1920, but they have many problems principally due to the lack of knowledge about aerodynamics comparing with the today's knowledge, in past almost all the non-linear, viscous and tridimensional influences on the theoretical solution were discovered experimentally.

Other enormous problem was the big drag that this kind of airplane generate and consequentially the big thrust power it required. The fact that it's necessary another engine just to generate lift, instead of generating it without need of energy consumption specifically for that purpose, like other aircraft as airplanes and helicopters. Although the last is also lifted by the rotation movement, it has the very important help of the autorotation effect that just doesn't works for a rotor plane.

In addition to those disadvantages makes difficult and not feasible the project and construction of an aircraft like that, there is still other problem, the big influence of the gyroscopic effect generated by the rotors on the stability and control of the plane.

All this makes impossible the progress of this configuration of aircraft, but with the increasing interest on mini UAV's project, and with the possible advantage this kind of configuration can offer (very High C_L) to mini UAV's, again becomes important to know the Dynamic characteristics of this weird plane.

Bellow, a figure of Plymouth A-A-200, still today, the unique known successfully medium sized rotor-plane flight in history of aviation.

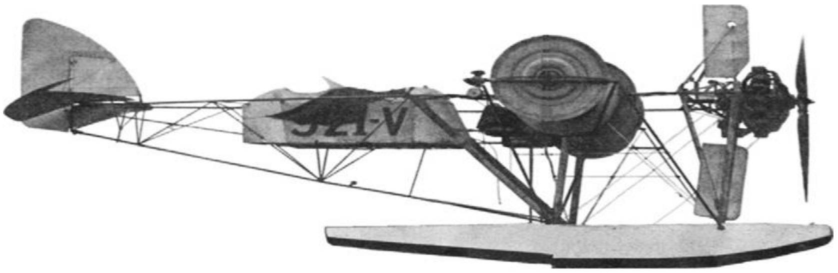

Figure 2. Photo of the Plymouth A-A-200 flight

4 GYROSCOPIC EFFECT

The gyroscopic effect occurs as a result of rotation coupling, every time a body on rotation in a determinate axis suffers a rotation on another axis it will suffer a force moment on the third axis. In this case, for a cylinder rotating on the pitch axis an angular velocity on the yaw axis will result in an angular velocity on the roll axis, and vice versa. The relation is described by the Eq. (1). So it's possible to infer that if the airplane suffers a positive yaw moment it will respond with a positive rolling moment, and if it suffers a positive roll moment it will respond with a positive yaw moment. The same case repeat if a negative moment is imposed to the MAV, the response moment will have the same sign.

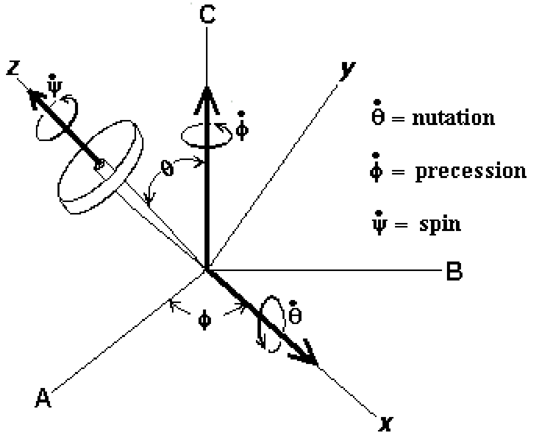

Figure 3. Representation of the gyroscopic effect with the euler angle

$$\boldsymbol{M_1 = I_2 \omega_2 \omega_3} \tag{1}$$

5 THE ROTOR-PLANE OF THIS PROJECT

As said before the Rotor-Plane investigated in this study is a MAV which have two cylinders as lifting surfaces, they are 300 mm long and have a diameter of 60 mm, the cylinders have one end-plate on each tip, which have 120 mm of diameter. The MAV has a fuselage of 80 mm of height, 100 mm wide and a length of 500 mm. The aircraft make use of a tail boom in order to maximize the horizontal and vertical tail volume ratios.

The conditions of flight simulated were an angular velocity of $900\ rad/s$ to the cylinder and a varying velocity ratio of the cylinder that ranges from 1 to 6, so simulations were done with different velocities. The principal outputs of the simulation were the drag and lift force of the cylinders that are the basis to obtain the contribution of the cylinder to the value of the stability derivates. On Fig.3 are presented the Drag and Lift coefficients variation with the velocity ratio.

The simulations done with the cylinder have been already validated with experimental data of Badalamenti (2010).

For the project of the tail, the conventional configuration was chosen. The horizontal stabilizer projected is rectangular and have 100 mm of chord and 350 mm of span. The vertical stabilizer is rectangular and have 100 mm of chord and 300 mm of span. Both horizontal and vertical tail are all-moving stabilizers.

The engine used on the projected and that will be used on a possible prototype is the Emax CF2822.

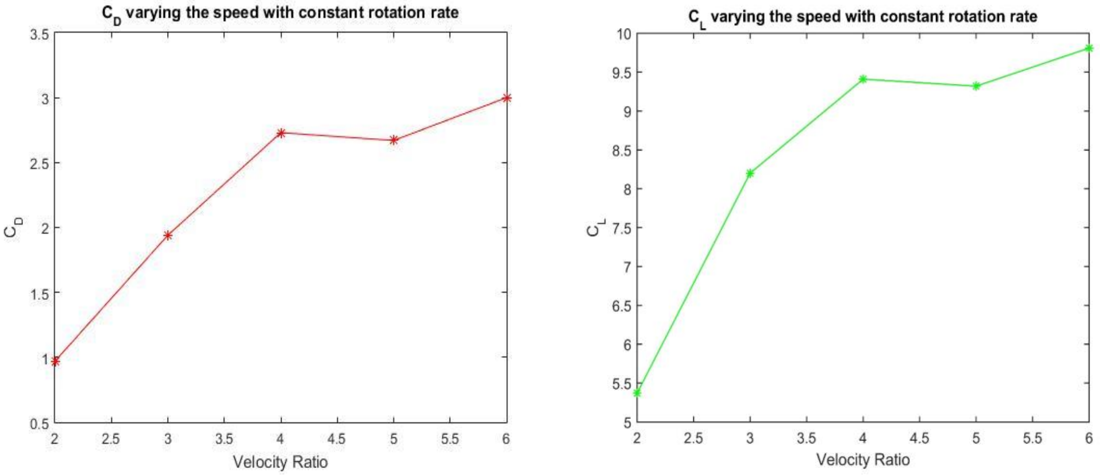

Figure 3. Drag and Lift coefficient of three different configurations of cylinder, obtained by CFD simulation with STAR-CCM+$^{®}$

6 MODELING THE DYNAMIC SYSTEM

For an initial analysis of the system a linear model approach was done using the state-space representation, derived by the equations of rigid motion. The way of analyzing the aircraft stability and control is equal to the way would be analyzed a conventional aircraft, just with the difference that's necessary to consider the gyroscopic effect contribution to the aircraft stability due the cylinder rotation, this is done simply adding the moment generated by the spinning cylinder when the aircraft suffers a determinate angular velocity.

The lateral and longitudinal modes are decoupled, analyzing lateral-directional and longitudinal stability and control separately, what is possible to do with a very small loss of precision on the results, because there will be only one elevator and the gyroscopic effect has a big influence only on lateral-directional modes. The lateral-directional and longitudinal matrix used on the calculations are the same of Badalamenti (2010).

Some of the values used to calculate the stability and control derivates were obtained by CFD simulation using the software STAR-CCM+$^{®}$, principally the ones that are more influenced by the cylinder and fuselage, the part of the derivates that are related to stabilizers were obtained principally by analytical methods due to the know reliability of them for lifting surfaces that use airfoil section.

So for the solution of the model a mix of analytical and numerical data was used. On further studies all the stability derivates values, for the entire plane, will be obtained by CFD simulation, in order to compare with the first results and simulate the system response with more precision.

The mass and inertia of the aircraft were just estimated with simple calculations, in order to find an approximated result, that's enough for the objectives of this research.

7 RESULTS AND ANALYSIS

Beginning the analysis of the system, first the static stability and control were estimated. After this the dynamic analysis was made, making use of all stability derivates found, then the longitudinal and lateral modes of the aircraft were calculated and its response to input commands of the pilot and to wind gusts.

The stabilizers were projected during the static and dynamic analysis, and the best one was presented on the previous section. In order to obtain the most optimized stabilizers, the principal objective of their project was to provide the aircraft the biggest range of velocity ratio during the flight.

The non-dimensionalization of the derivates were done just by dividing them by the product of the cylinder total area (the reference area), the dynamic pressure and the cylinder span, for lateral-directional derivates, or the cylinder diameter for longitudinal derivates.

7.1 Simulations of the aircraft rotation on the three axis

Three simulations were performed in addition to those done in order to have the drag and lift variation with α, the first had the objective to find the change on drag and lift values on the cylinder when the aircraft is rolling, the second and third analysis were done to find also the drag and lift variation but respectively for yaw and pitch rotation of the aircraft. These simulations were done with a velocity ratio of 3.

The results of the last three simulations were very important to discover the influence of the bank angle (Φ), the angle of attack (α) and the sideslip angle (β) to the stability derivates. Which have a big influence on the most important stability derivates.

The simulation consisted in compute the C_L and C_D variation with the rate of variation of those angles that were set to $1\ rad/s$. With those results, a regression was done for each data of C_L and C_D variation, adjusting the function that makes the best fit. Was possible to find simple functions that described the coefficients changes with those angles for a large range, principally due to the symmetry behavior of the changes in those angles and the linear variation of C_L with those angles for a relatively big range.

Five regressions were done, the unique exception was α x C_L, because C_L almost doesn't varies with α. The expressions found are presented below.

$$C_D = -7.165\alpha^2 - 2.127\alpha + 1.857 \tag{2.a}$$

$$C_D = -1819.4\Phi^5 + 5986.1\Phi^4 - 2874.2\Phi^3 + 465.9\Phi^2 - 24.8\Phi + 1.857 \tag{2.b}$$

$$C_D = -2327.2\beta^5 + 8015.3\beta^4 - 2274.2\beta^3 + 475.1\beta^2 - 28.6\beta + 1.857 \tag{2.c}$$

$$C_L = 561.5\Phi^3 - 75.5\Phi^2 - 46.1\Phi + 8.26 \tag{2.d}$$

$$C_L = 543.2\beta^3 - 83.2\beta^2 - 54.3\beta + 8.26 \tag{2.e}$$

One conclusion that can be taken by the result is that the aircraft, if flying with a load near its maximum take-off weight (MTOW) can't stand with significant roll angle for a long period because it will lose altitude with great chances of falling on the ground.

Other important conclusions that can be taken from the regressions is that the angle of attack have almost no influence to the cylinders lift but have a significantly influence on drag. So from this simulation a particular characteristic of this configuration rises, the independence of angle of attack to generate lift and so to the contribution of the cylinder to the C_{m_α} value of the aircraft tends to be smaller than for other configurations. On the other hand the C_D of the cylinder decreases with almost a constant ratio with the angle of attack, principally due to the reduction of the velocity component normal to the cylinder. From this is possible infer that the elevator doesn't need to be projected to meet take-off requirements because the angle of attack wouldn't help the aircraft have a bigger MTOW.

The static margin will be dominated by the stabilizer effects with almost no cylinder influence, but the trim requirements by the other side can be hard to meet if the center of pressure of the cylinder is too distant from the center of gravity of the aircraft, so the aircraft was projected to have the center of pressure of the cylinder aligned with the longitudinal position of the CG.

The yaw affects lift on a similar way the roll did, but less intensively in case of C_L and more in case of C_D. The drag suffers a big increase what means the airplane would suffer a reduction on its velocity, considering the thrust of the engine is loaded 100%. For a significant yaw rotation, would be an increase in the cylinder velocity ratio and as it's shown later in this paper, the phugoid mode is very sensitivity to velocity ratio changes so this situation could lead the airplane to instability.

7.2 LONGITUDINAL STATIC STABILITY

For the longitudinal stability were added the effect of the engine, the horizontal tail, the spinning cylinder and the fuselage to C_{M_α}, the coefficient of pitching moment due to the angle of attack. The effects of the engine and the horizontal tail were calculated analytically using the same methods of calculation of Etkins (1996) and Roskam(2007). The contribution of the fuselage was directly obtained by the CFD simulations. The contribution of the cylinder was obtained by the Eq. (3) from Badalamenti (2010), using the values acquired on the simulations. The C_{M_0} is calculated by analogous method.

To guarantee the trimmed aircraft if the CG moves behind the cylinder CP, an all-moving tail was projected. The equations used to obtain the pitching moment derivate in relation to the angle of attack are shown below.

$$\frac{\partial \Omega}{\partial \alpha} = \frac{V_r}{w} \tag{3.a}$$

$$\frac{\partial C_M}{\partial \Omega} = \frac{\partial C_L (X_{cg} - X_{ac})}{\partial \Omega} \tag{3.b}$$

$$\frac{\partial C_M}{\partial \alpha} = \frac{\partial C_m}{\partial \Omega} \frac{\partial \Omega}{\partial \alpha} \tag{3.c}$$

Where α is the angle of attack, Ω is the velocity ratio, V_r is the tangential velocity of the cylinder.

The projected static margin of this aircraft is very big principally because the almost no influence of the cylinder to it due to its low sensitivity to angle of attack variation. The aircraft can easily be trimmed for different velocities and payloads, but can't change its weight during the flight (letting payload off) without a big change on the force needed on the elevator to conduct a steady flight, it just doesn't occur if the CG of the empty aircraft is very close to the CG of the full aircraft, so the unique possible thing could be done to remain the plane under control is to decrease very rapidly the rotation rate (in the case of loss of weight).

7.3 Lateral Static stability and control

For the static lateral stability, the need of $C_{l_\beta} \leq 0$ and $C_{n_\beta} \geq 0$ were attended and then to be certain about the stability, the dynamic analysis. The principal lateral control issue for this aircraft is to overcome the gyroscopic effect adverse force when the aircraft is yawing or rolling.

The force moment that acts on the aircraft when the it suffers the gyroscopic effect can be calculated by the Eq. (1), so $C_{l_{\delta_r}}$ needs to have a higher absolute value than the dimensionless rolling moment on the aircraft when it's yawing. The same thing needs to occur for $C_{n_{\delta_r}}$ when the plane is rolling and suffering a yawing moment.

The project of rudder was done with a limit of yawing and rolling rate the aircraft would be capable to support, was thought that $1°/s$ of roll rate and $2°/s$ of yaw rate would be sufficient, due to the gyroscopic effect it would be necessary a very big rudder to support slightly bigger roll and yaw rates, so the maneuvers taken with the plane needs to be done a little slow with no abrupt commands.

7.4 Dynamic stability and control

From analytical calculations and the simulations data, the 5 modes of the aircraft and its response to control inputs were calculated and are shown below. The command simulated for the lateral-directional response of the aircraft was a step input of $10°$ of the rudder, and for the longitudinal response $-10°$ of the elevator. Was simulated also the response of the aircraft to a lateral and vertical gusts of $6\ m/s$ and $3\ m/s$ respectively.

The stability analysis was done for 5 velocities, corresponding to the 5 velocities ratios of the cylinder simulations that were validated with experimental data. Was assumed no angle of attack or maneuvers tacking place, the plane was on steady flight condition.

All the control analysis was done for a velocity of 15 m/s due to the conclusions about the stability analysis of phugoid mode, as detailed further in this paper, that makes reasonless analysis for lower velocities. For higher velocities the drag would be bigger than the traction of the used engine, and the results of the CFD simulation weren't validated for that velocity ratio.

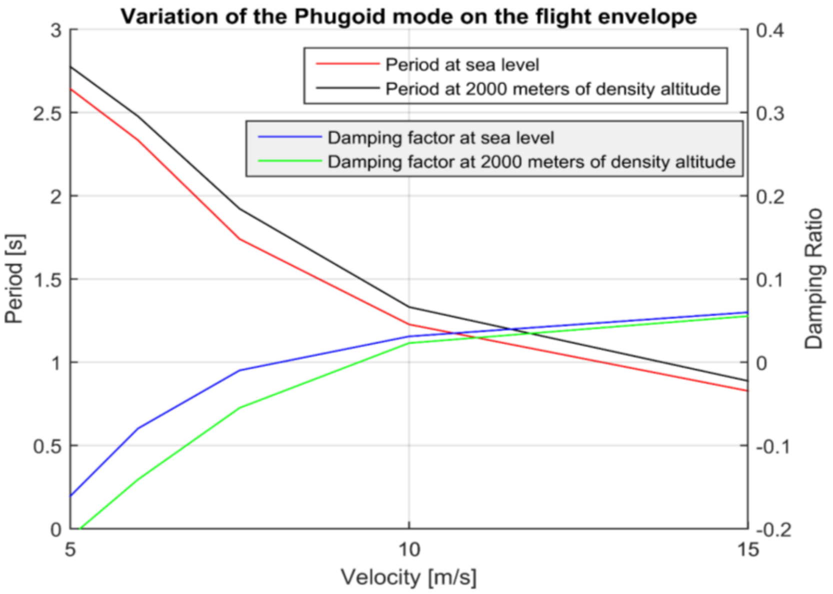

Figure 4. Variation of Phugoid mode on the flight envelope

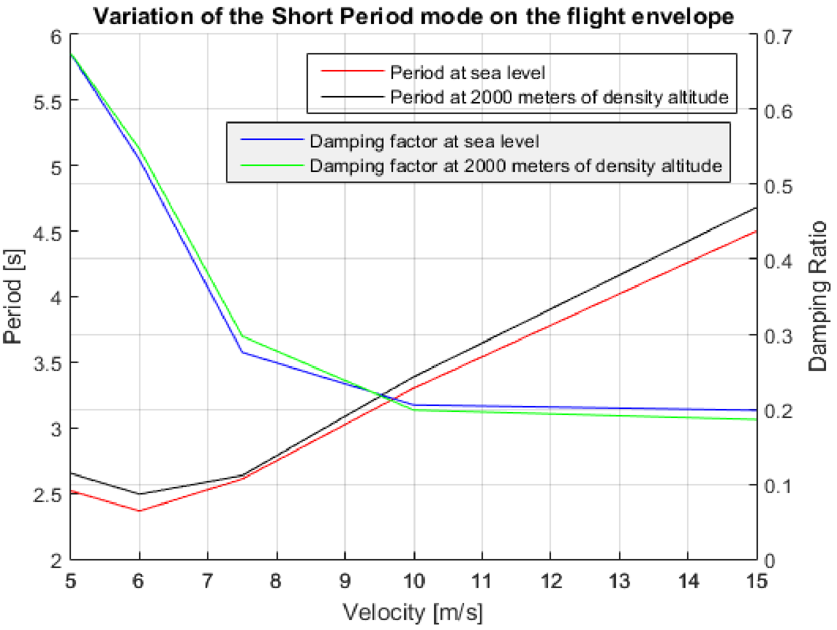

Figure 5. Variation of Short Period mode on the flight envelope

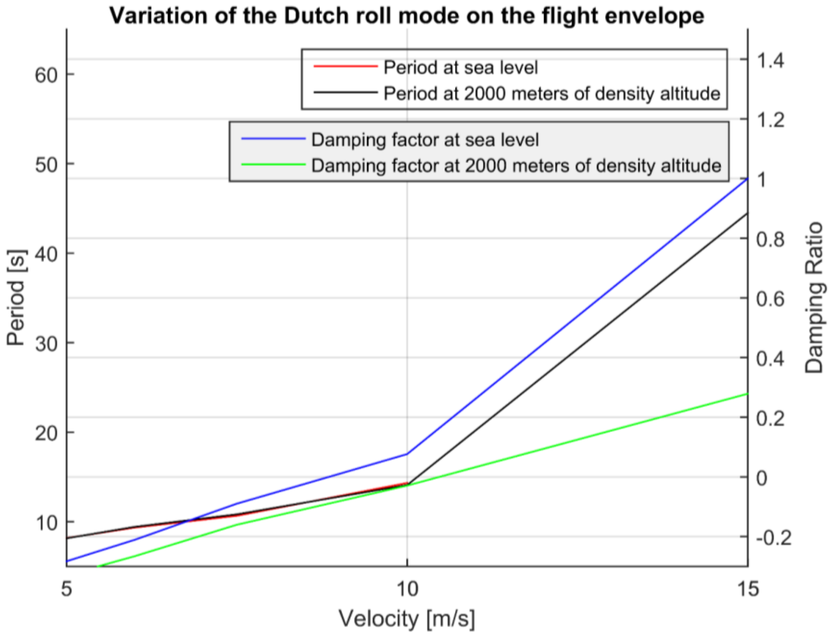

Figure 6. Variation of Dutch roll mode on the flight envelope

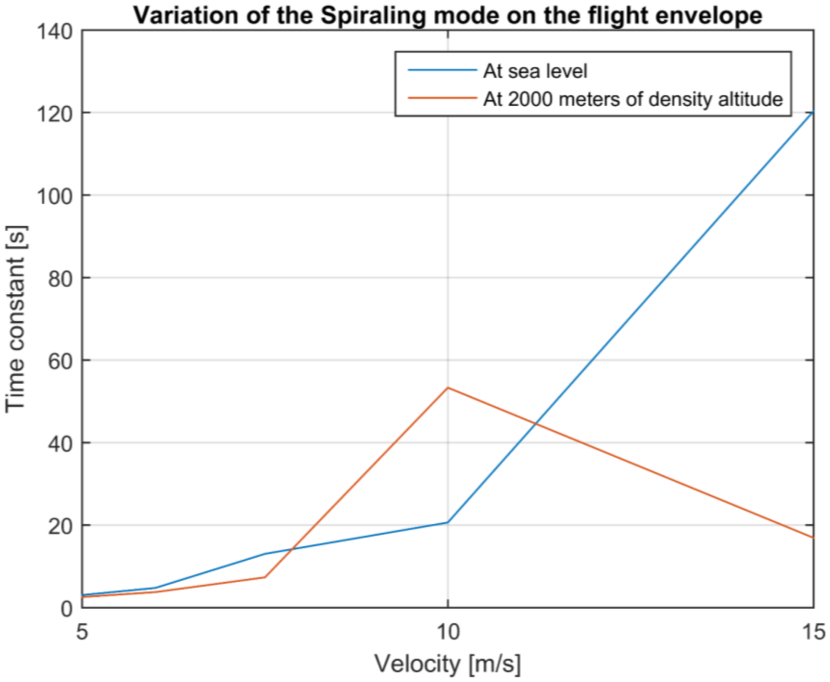

Figure 7. Variation of Spiraling mode on the flight envelope

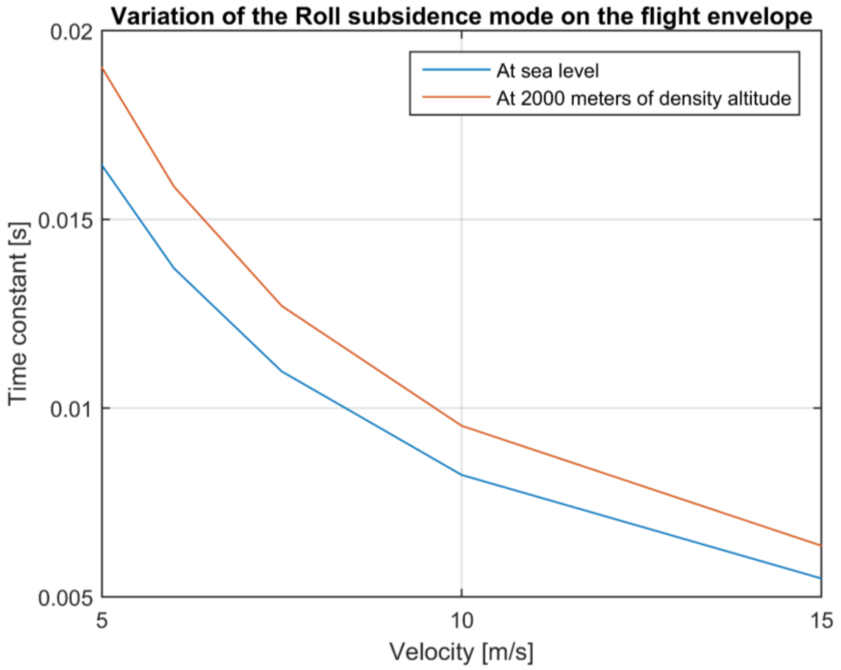

Figure 8. Variation of Roll subsidence mode on the flight envelope

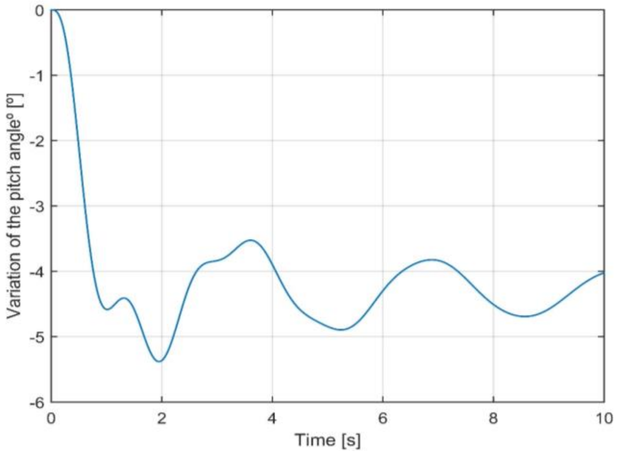

Figure 9. Variation of Pitch angle with the elevator input command

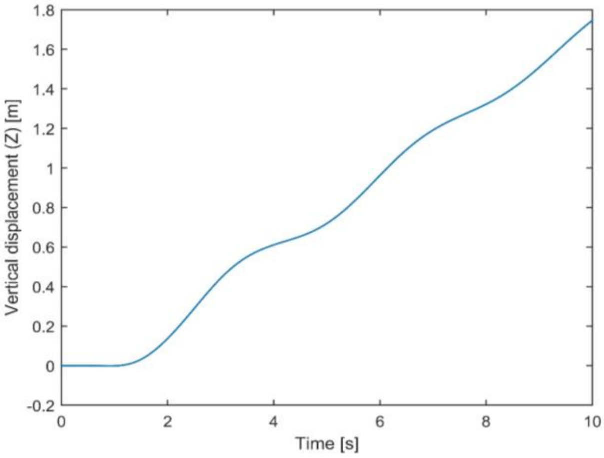

Figure 10. Variation of vertical displacement with the elevator input command

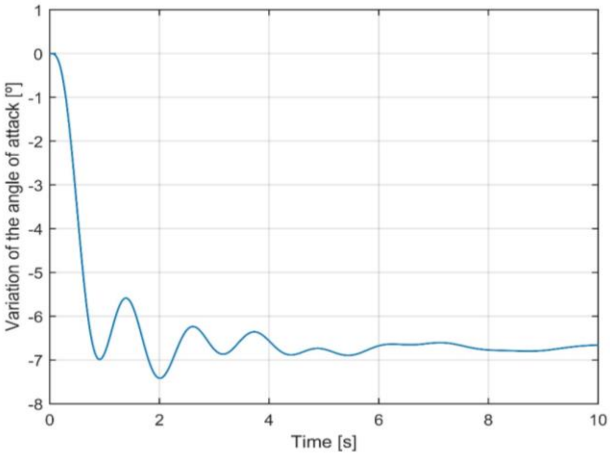

Figure 11. Variation of the angle of attack with the elevator input command

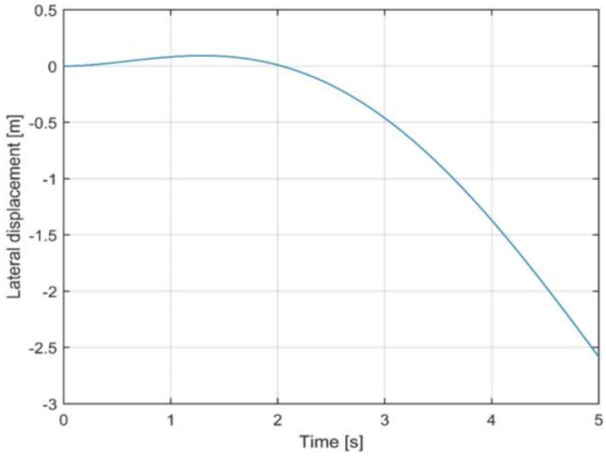

Figure 12. Variation of the lateral displacement with the rudder input command

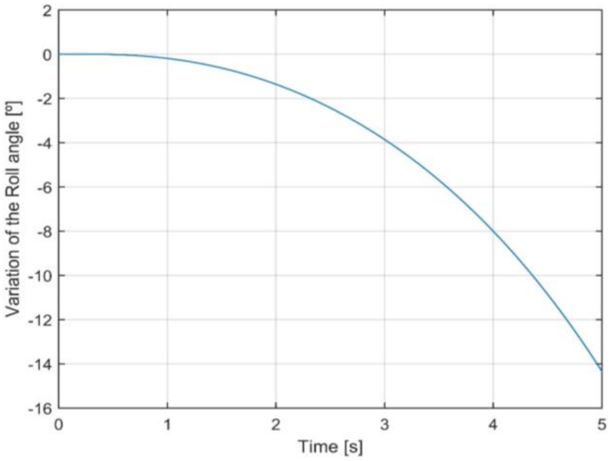

Figure 13. Variation of the Bank angle with the rudder input command

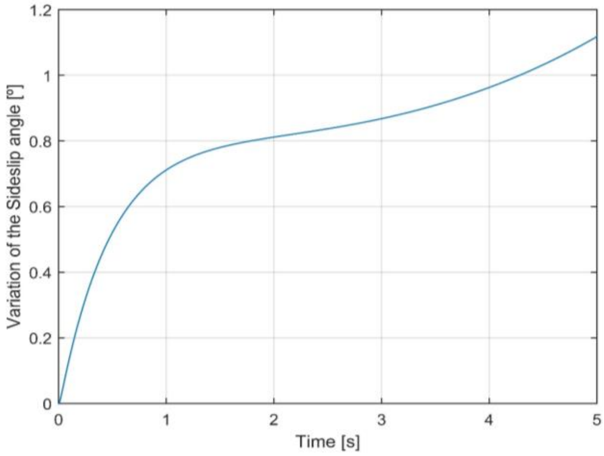

Figure 14. Variation of the Sideslip angle with the rudder input command

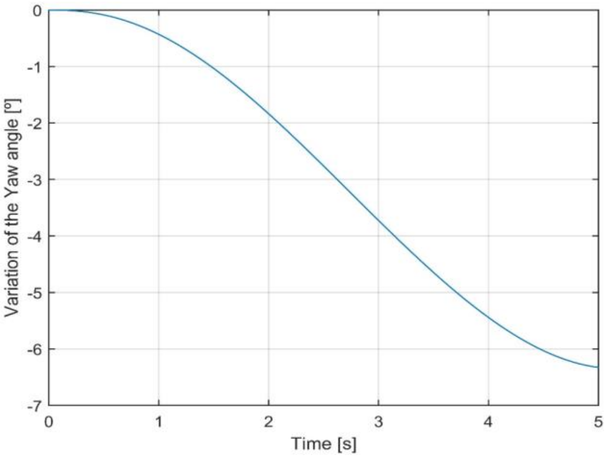

Figure 15. Variation of the Yaw angle with the rudder input command

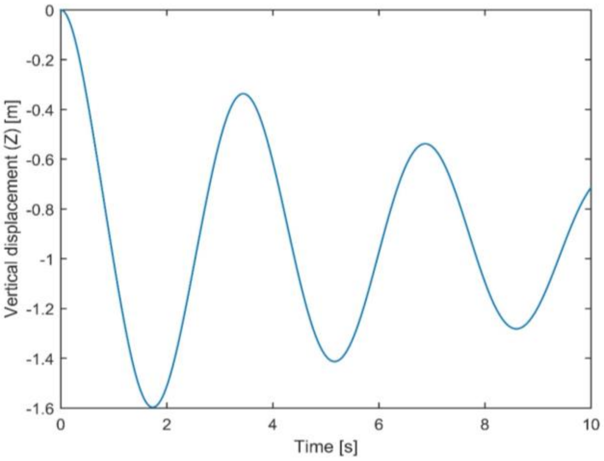

Figure 16. Response of the vertical displacement with the vertical gust input

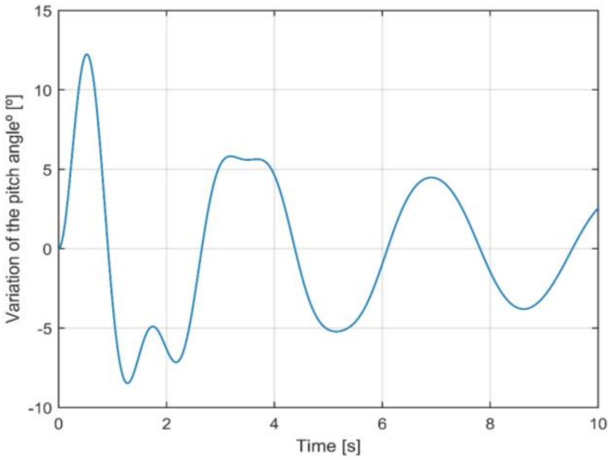

Figure 17. Response of the pitch angle with the vertical gust input

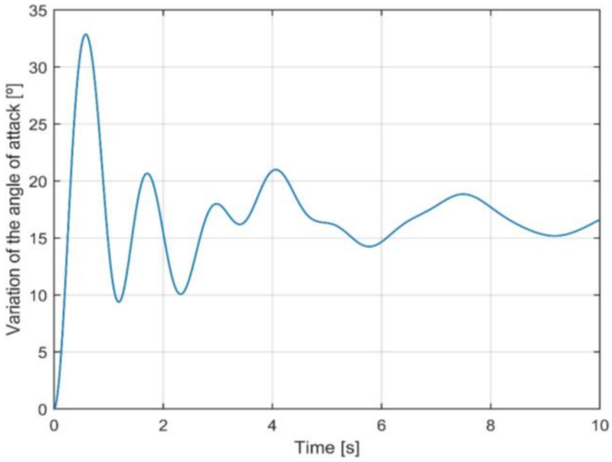

Figure 18. Response of the angle of attack with the vertical gust input

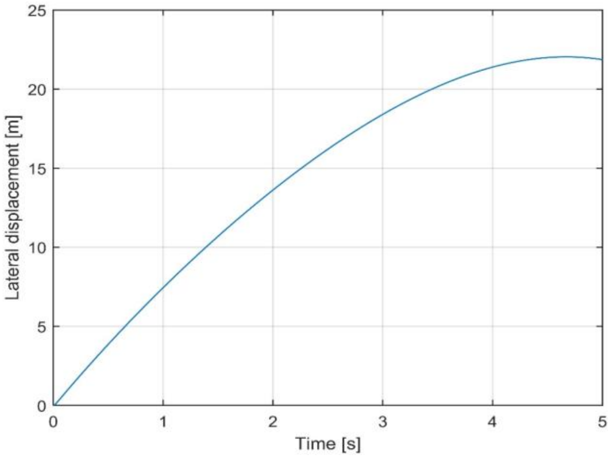

Figure 19. Response of the lateral displacement with the lateral gust input

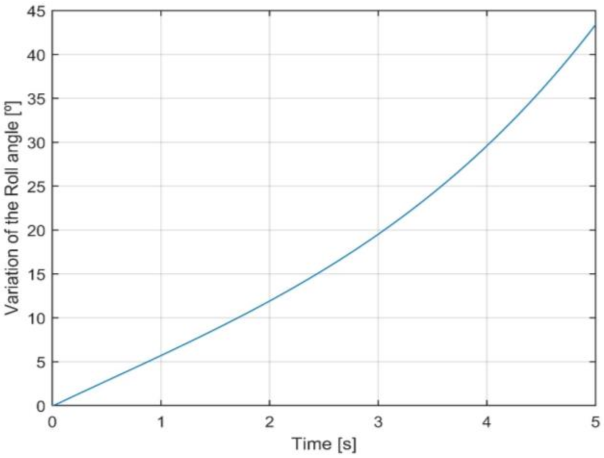

Figure 20. Response of the Bank angle with the lateral gust input

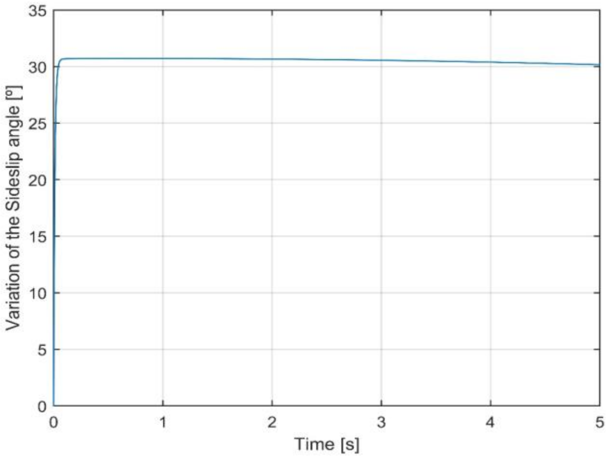

Figure 21. Response of the Sideslip angle with the lateral gust input

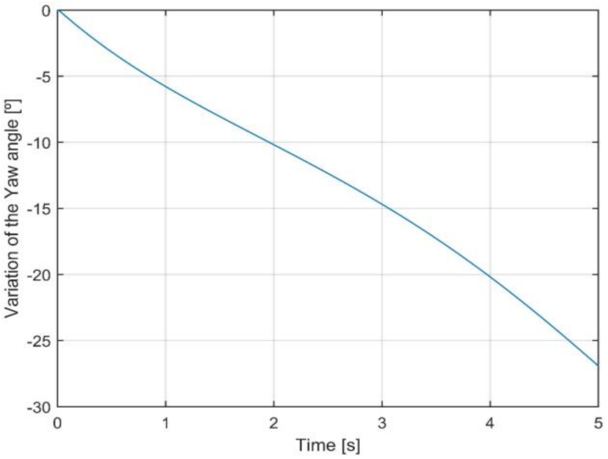

Figure 22. Response of the Yaw angle with the lateral gust input

From the results it's possible conclude that this aircraft has satisfactory stability characteristics just for a velocity ratio lower than 3, for a higher velocity ratio the phugoid mode turns unstable. This is the most critical mode of this kind of aircraft and limits the higher payloads because of the limited range of velocity ratio the aircraft can fly safely. The cause of this instability are the great changes that are made to the dynamics of the system when the Ω is varied, principally caused by the great gain of lift to the cylinder when its tangential velocity increase, an effect very pronounced for $\Omega \leq 3$.

So the stabilizer, even with a huge tail volume ratio isn't capable to stabilize the plane, for a high velocity ratio it would be necessary an augmentation system that damps phugoid mode that will be projected on further studies.

The short-period damping factor decrease with the velocity for $\Omega \geq 3$ then the mode tends to have a constant damping factor as the velocity increases and the damped frequency of the body remains almost constant during the entire flight envelope. This mode isn't a big trouble for this aircraft.

The lateral-directional modes can have satisfactory flying qualities with a good vertical stabilizer project. The roll subsidence mode wasn't too much affected by the gyroscopic effect, and was little affected by the velocity ratio, the reduction of the time constant is caused principally by the growth of the airplane velocity.

The Spiraling mode have a low time constant for low velocities (high Ω) but nothing too serious, it rises as the velocity increase. The time constant suffers a reduction for the highest velocity analyzed on an altitude-density of $2000\ m$, probably because C_L increases faster with Ω (C_{L_Ω} is high) for those conditions, so the time constant difference between the two conditions analyzed are amplified.

The Dutch roll mode is the most critical lateral-directional mode, the damping factor increases as the velocity decreases, it's possible fly safe just for $\Omega \leq 3$. Dutch-roll is highly affected by Ω and the variations of C_L the cylinder, these are the principal reasons for the big changes on damping factor with changes on velocity.

The response of the aircraft to the commands are according to what was expected, after the analysis of the rigid modes. The most critical axis is the roll axis, that reacts rapidly with the rudder command and lateral gust, so the aircraft is vulnerable to strong lateral gusts, and it can't be easily avoided.

8. CONCLUSIONS

On this study was analyzed just the basic dynamic responses of an aircraft with a spinning cylinder. Although the analysis was done just with a simplified model and without a very precise data about the stability derivates, that would take some CFD simulations and experimental tests to be an actual precise data, some important conclusions about the principal characteristics of stability and control can be taken of the results.

First, the instabilities caused by the unstable phugoid mode can only be solved by the use of an augmentation system. The short-period isn't a critical for this configuration of airplane.

The control force input on the airplane as shown on the results needs to be powerful, principally due to two problems. The first one is to trim the pitch axis of the airplane, if the CG position is a little wrong, what would make a big difference on the forces balance due to the big lift force of the cylinder, a robust elevator would be needed to solve this problem. The second problem is that to overcome wind gusts, a lateral wind gust particularly, would be hazardous due to the gyroscopic effect, so that another reason for a robust rudder.

The absence of ailerons doesn't make impossible to do a roll motion with success, but turns really hard to make a trimmed flight just with the rudder deflection, as if the other component that has influence on the roll axis control, the cylinder, can't has its rolling moment changed with a simple command of the pilot, without changing significantly its lift, what can cause the plane to lose altitude or even fall. Ailerons would help control the gyroscopic effect adverse moments too.

So it's possible to fly this kind of configuration of aircraft safely, doing a careful project of the stabilizers. Without an augmentation system there will be a maximum velocity ratio the vehicle can fly that will be limited by Phugoid and Dutch roll instabilities.

To have a more detailed knowledge about the dynamics of this system a non-linear model of the aircraft with longitudinal and lateral-directional modes solved together would be very helpful, and it would make clear what kind of simplification could be done.

The acquisition of all the stability derivates data by CFD simulations, would be very important too, the model can only give great results with the right values of the derivates, many of the literature ways of calculate some of the stability derivates can't be applied to this configuration, for some derivates the approach is good but the coupled effects due to the iteration of the aircraft components, can make a significantly difference on the results. So for more precise results a more general way to get this values would be needed.

All the results obtained needs validation that can be made with a data acquisition system, with it would be possible compare the airplane response of project with the response of the prototype. Adjusting an experimental model to the aircraft with these data, would make possible a comparison with the theoretical model validating it and discovering the possible simplifications, that would be interesting principally if a more complete model is used.

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