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INFLUENCE OF ASPECT RATIO ON THE WING ROCK PHENOMENON

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Abstract. *The Wing Rock phenomenon is characterized by unstable roll oscillations that occur in airplanes when they are at relatively low flying speeds and high angle of attack. The present work intends to study the behavior of this phenomenon in aluminum rectangular plates, for two distinct aspect ratios (AR) using a wind tunnel. Rectangular aluminum plates with thickness of 0.5 mm and ARs of 2 and 4 are tested. The oscillations were measured using an Arduino Uno board and an MPU-6050 accelerometer that can measure acceleration angles around the x, y, z axis of the sensor. Variation of the rolling angle due to Wing Rock phenomenon was studied. According to the results obtained, the roll angle amplitude increases with AR, which is in agreement with data published in the literature. Thus, the increase in AR leads to an intensification of the swing amplitude of the wing roll angle.*

Keywords: *Wing rock, Wind tunnel , Arduino.*

1. INTRODUCTION

Wing rock is characterized by an undesirable rotational oscillation about the aircraft's roll axis, which occurs in airplanes when they are in relatively low attack velocities (α) (Go and Maqsood, 2015).

The onset of this phenomenon is usually associated with a reduction in the roll angle damping of the aircraft when it is at a high angle of attack (Orlik-Ruckemann, 1983), *i.e.*, due to nonuniform loading along the wing, because of the irregular detachment of vortices, the aircraft will have a tendency to oscillate around the roll axis, as the forces on the wing will be distinct and unbalanced between wings. Thus, after oscillations start, they will increase gradually, if the pilot does not change some parameter (e.g. angle of attack) that decreases this loading difference in order to dampen the loads that will produce a moment around the roll axis of the airplane.

The present work aims at analyzing the wing rock phenomenon in samples of rectangular shape, due to the complexity and cost of building a small-scale model of an airplane. A wind tunnel that reaches the velocity of 6 m/s was used.

Figure 1 shows the autorotation around the longitudinal axis (Wing rock) that can occur in an aircraft, where this undesirable oscillation can be caused by the displacement of the tip vortices associated with a wing with low aspect ratio (Katz, 1999).

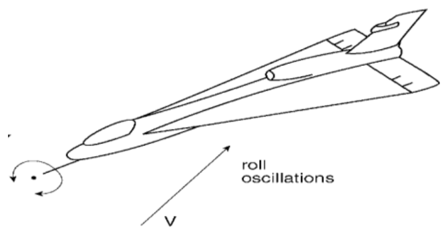


Figure 1. Aircraft rotation due to Wing Rock.
Source: Katz, 1999.

Nelson and Pelletier (2003) studied aerodynamic instability in flight mechanics and identified the main adverse ffects on aircraft wings in maneuvers: Wing Rock; Wing Drop; Heavy Wing; Nose Slice and Buffet. According to ese authors, these adverse effects are discovered during the flight test phase. The present work will be directed to the study of Wing Rock, in order to evaluate its influence on the performance, quality and safety in aircrafts, since flight instabilities caused by the rotational oscillations can make the control of the airplane more difficult for the pilot.

The maneuvers performed by the aircraft during flight, which increases pitch motion, can intensify the instability due the wing rock phenomenon, since this phenomenon is associated with a non-linear damping along the wing and the combination of these factors produces changes in the stability of the flight (Guglieri and Quagliotti, 1997).

According to Nelson and Pelletier (2003) a wing with a triangular shape, that has an unstable movement, presents a change in the field of flow due to a maneuver performed, generating delays in the flow separations and formation of vortices at low angles of attack. In addition, at high angles of attack a vortex breaking process may occur. This process alters the aerodynamic loads on the wing and the stability of the aircraft (Lan and Hsu, 1982).

Thus, the study of these undesirable oscillations is important for the understanding of the factors that cause instabilities in the airplane that, depending on the intensity of oscillation, can affect the performance of the flight and its safety. According to Katz (1999), the growing interest in improving maneuverability and safety of both combat aircraft and space planes has led to studies for the understanding of the Wing Rock phenomenon.

Figure 2 shows the airplane movement with a high angle of attack. The vortices formed can be modified due a process of interaction between them along the aircraft because the aerodynamic forces generated due to vortex flow are non-linearly related to the angles of attack and lateral slope (Nelson and Pelletier, 2003).

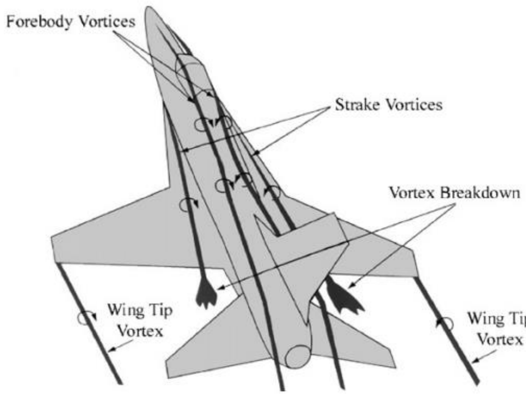
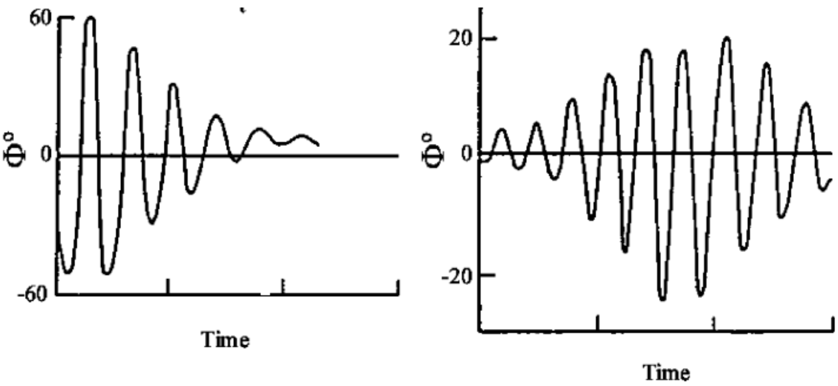


Figure 2. Wind flow and formation of vortexes in military aircraft. Source: Nelson e Pelletier, 2003.

The Handley aircraft was designed to study the maneuverability and aerodynamics of airplanes at low flight speeds (Thompson et al., 1969 and Ross, 1972). This study showed that the Wing Rock phenomenon arose when the aircraft had an angle of attack greater than 20°, according to Fig. 3, which shows the variation of the inclination / rolling angle (Φ °) with time. A reduction in amplitude Φ ° can be observed. This was because the pilot reduced the oscillatory movement around the aircraft's rolling axis by means of the ailerons, Fig. 3 a), while in the graph of Fig. 3 b) it decreased the angle of attack to attenuate the Wing Rock effect. Thus, it is possible to suppress the Wing Rock phenomenon by using ailerons or by reducing the angle of attack of an airplane. This study showed that the maximum angle of inclination was 40° when α increased to 30°. It must be remembered that this phenomenon can occur in any type of aircraft.

It can be seen in Fig. 3 that the left chart decreased Φ ° faster than the right chart. This was because the pilot reduced the oscillatory movement through the ailerons of the aircraft, while in the right chart he decreased the angle of attack.



a) b)

Figure 3. Behavior of the angle of inclination (Φ °) during Wing Rock. Figure 3. a) shows the reduction of the oscillations by the ailerons and Figure 3. b) shows the reduction of the oscillation when the angle of attack decreases. Source: Ross, 1972.

Thus, the formation of vortices is the main responsible for the Wing Rock phenomenon and it is necessary to analyze their formation on the wing. These studies can be conducted in wind tunnels that produce an airflow that affects a certain speed on a small-scale model of an airplane or on a wing in rectangular or triangular format. The present work aims at analyzing the wing rock phenomenon in samples of rectangular shape, due to the complexity and cost of building a small scale model of an airplane. It was used a wind tunnel that achieves the speed of 6 m/s.

2. METODOLOGY

The study of the Wing Rock phenomenon was performed through the results obtained using a custom-made device called free-to-roll that consists of an axis supported in lubricated bearings so that the axis is free to oscillate with minimum friction (Hu *et. al*, 2013). Figure 4 shows the test bench, where air in the horizontal direction is incident on the aluminum sample that is at a certain angle of attack. Fig. 4 a) shows the side of the wind tunnel, where the angle of attack (20 degrees) was measured by means of an analog goniometer. In Fig. 4 b) it is shown the blue wire that will transmit the measured oscillation values of the axis to the computer. Fig. 4 c) shows the inside of the wind tunnel test section and the location of the oscillation sensor.

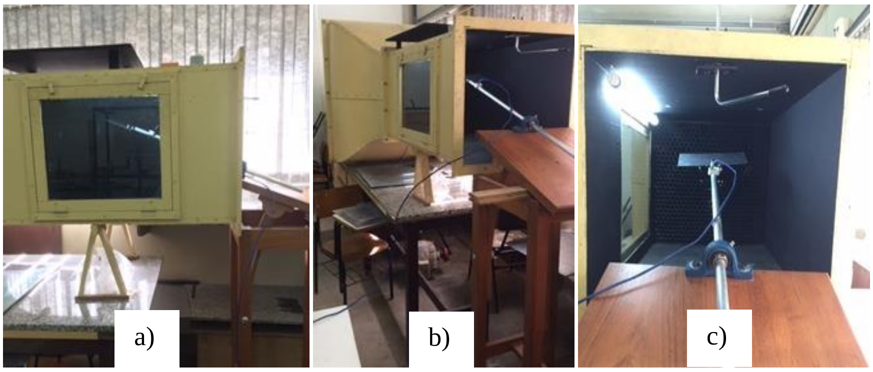


Figure 4. Schematic of the device to be used in the experiment.

An aerodynamic tunnel was used to simulate the airflow, over free-to-roll instruments (Fig. 5). It is an open circuit, blower type, with the following characteristics: total length of 4.5m; testing cross section with dimensions of 0.50m x 0.50m, with an area of $0.25m^2$; maximum speed of approximately 6 m/s, obtained using a single-phase electric motor with a maximum power of 5HP (3.7kW); diffuser with contraction ratio of 2: 1 (according to Catalano (1998), increases the velocity of the fluid due to pressure decrease).

Figure 5. Wind tunnel apparatus

Bearings with good lubrication were used to minimize friction. The study was performed for α equal to 20° for two aluminum plates with an aspect ratios (AR) of 2 and 4, respectively. Plates were 25470 mm^2 in area with 0.5 mm thickness. The AR of the samples, that were fixed in the free-to-roll, is defined by Eq. (1) where b is the wingspan and S the wing surface area (S). The location of b and S is shown in Fig. 6. The present work intends to evaluate the oscillation of the axis, due to the air flow in the aluminum plates, and to compare the results obtained in order to study the influence of the aspect ratio on the phenomenon of Wing Rock.

$$AR = \frac{b^2}{S} \tag{1}$$

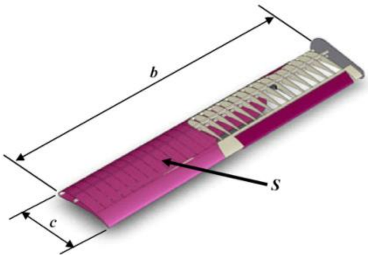


Figure 6. Dimensions of a rectangular wing. Source: Rodrigues, 2014

Arduino Uno was used in addition to an MPU 6050 plate, which is an accelerometer that measures the linear displacement in the x, y and z axes, besides measuring the angular acceleration around these axes. About 1630 angular velocity data were stored for 60 seconds and 1024 of them were used to apply the Fast Fourier Transform (FFT) in order to obtain the frequency distribution during the experiment and to evaluate what would be the maximum oscillation frequency of the Aluminum plates.

3. RESUTS AND DISCUSSION

The preliminary results in the wind tunnel are presented in this section. Figure 7 shows the roll angle oscillation of the aluminum plate fixed to the free-to-roll axis that has an AR of 2 and α = 20°. The test lasted for about 1 minute. It is observed that the highest angular velocity (in absolute value) was approximately 14º/s in 17.7 seconds of the test. In 22.5 seconds the angular velocity measured by the accelerometer was 12 º/s and the oscillation achieved certain stability at around 10 º/s.

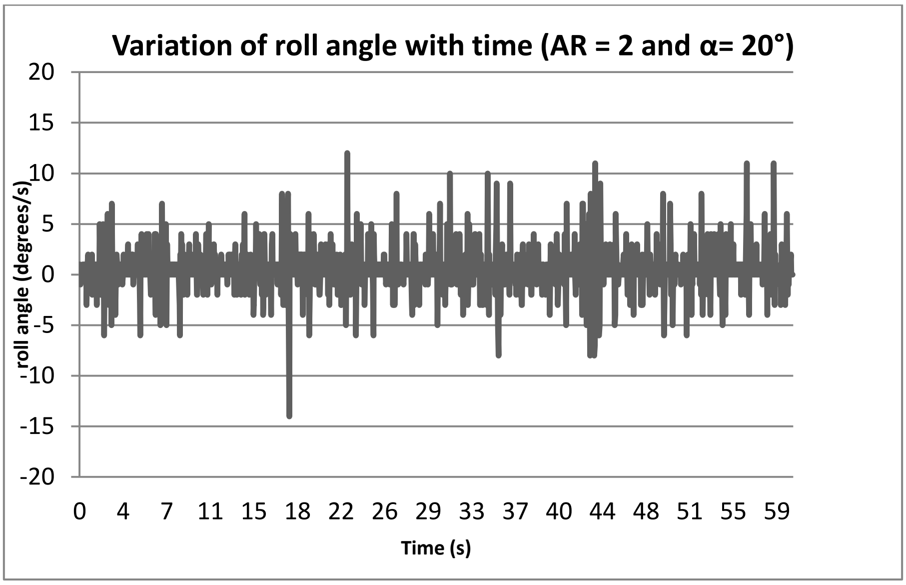


Figure 7. Variation of the roll angle of the aluminum plate with AR = 2 for α = 20 °

In Figure 8, the result of the oscillation for a plate with AR = 4 with same α of the plate with AR = 2 is presented. It is observed that the accelerometer fixed to the axis of the free-to-roll indicated that the highest angular velocity measured was of 42 °/s in 36.6 seconds of the test. In this case, greater angular velocity variations occurred throughout the test, in which a slightly uniform oscillation between 15 and 30 seconds and several oscillation peaks between 30 and 45 seconds could be observed. It is possible that the higher AR has influenced the vortex detachment in such a way that the amplitude of the roll angle has increased compared to the plate with AR = 2.

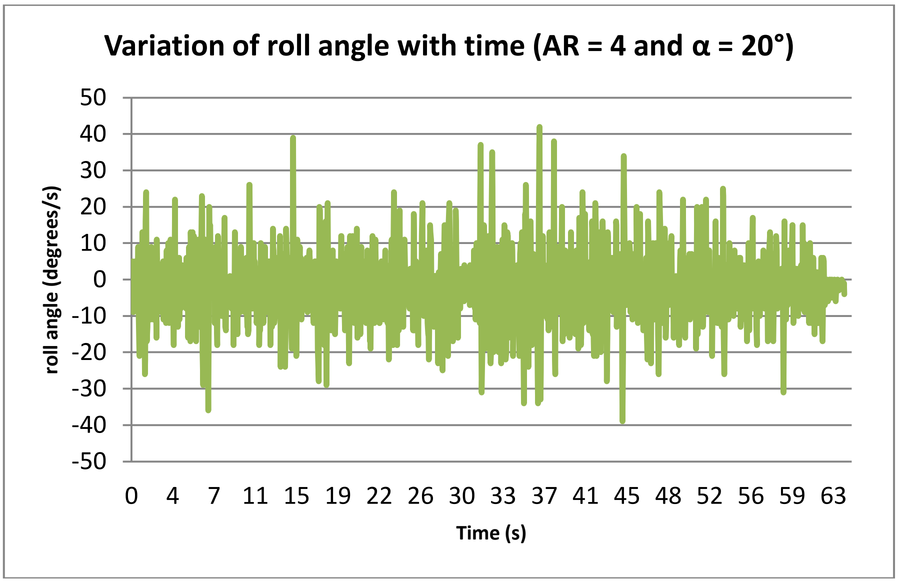


Figure 8. Variation of the roll angle of the aluminum plate with AR = 4 for α = 20°

Figure 9 compares the roll angle obtained in the tests performed with the AR = 2 plate (red chart) and AR = 4 (blue chart) both with α = 2°. It is observed that the plate with AR = 4 presented higher angular velocities with respect to the plate with AR = 2. This result was expected according to data published in the literature (Go and Maqsood 2015), that reported that the amplitude of the roll angle increases when AR increases in wings of rectangular format.

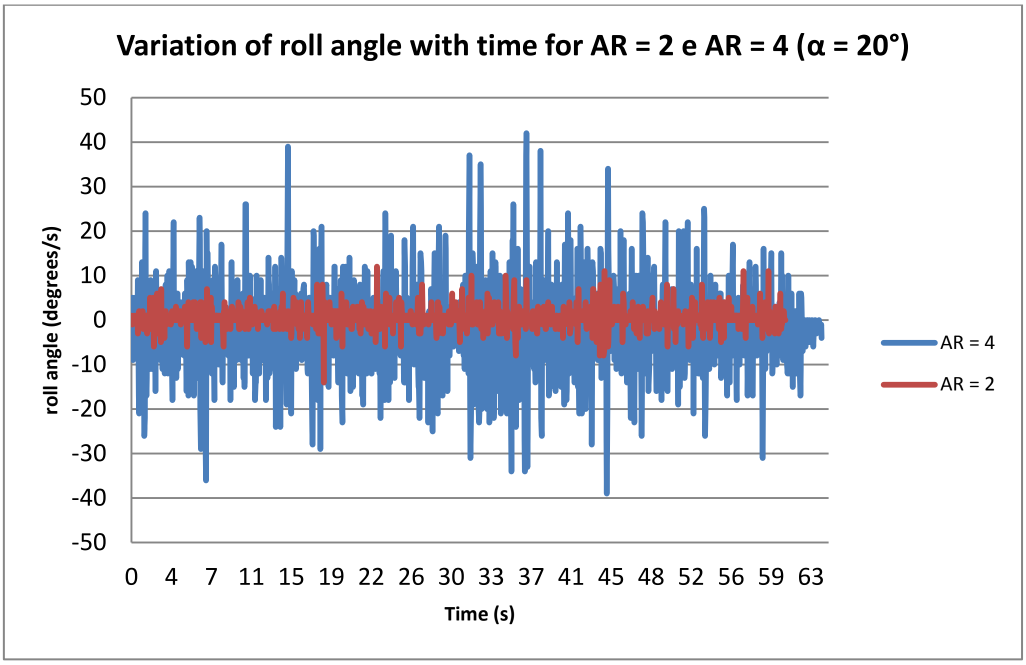


Figure 9. Comparison of the angular velocity for the aluminum plate with AR = 2 and AR = 4 (both with α = 20 °)

From the data obtained in Fig. 9 the FFT was applied in order to obtain the results in the frequency domain and to evaluate the oscillation frequencies that were present in the tests with AR = 2 and AR = 4. Figure 10 shows the results after the application of the FFT to the case where α = 20 °. It is noticed that two peaks of greater intensity of approximately 205.06 appeared. The frequencies associated to them were 6.8 Hz and 20.2 Hz and, therefore, these were the main frequencies that affected the system.

It was verified by analytical calculations that the frequency of 20.2 Hz would be related to the frequency of oscillation of the axis. The frequency of 6.8 Hz could have arisen due to the vortex detachment, because to the formation of vortices created a non-uniform loading distribution that results in an oscillatory movement. This movement is called Wing Rock, so the frequency of 6.8 Hz may be the frequency at which Wing Rock occurs with greater intensity for the case of rectangular aluminum plate.

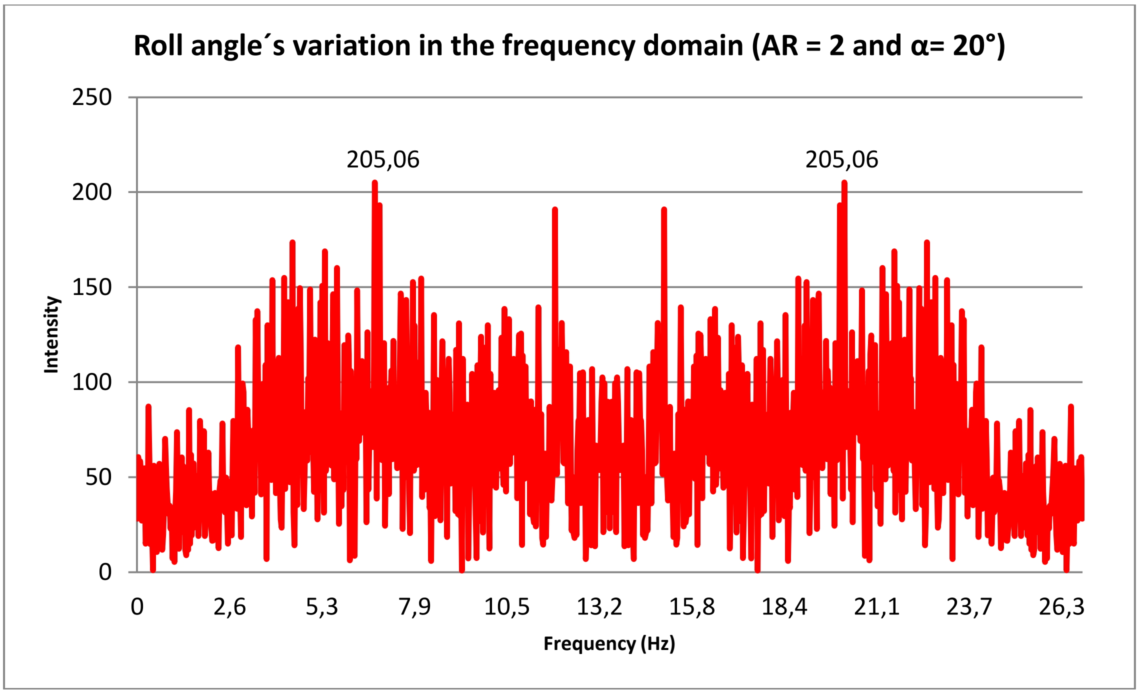


Figure 10. Frequency for the aluminum plate with AR = 2 and α = 20 °

The graph in the frequency domain for the plate with AR = 4 and α = 20 ° is shown in Fig. 11. It can be seen that the highest intensity was 630.61 at 4.7 Hz and 22.2 Hz. Again the frequency of 22.2 Hz would be associated with the oscillation of the axis and 4.7 Hz would be the frequency related to Wing Rock. In addition, it was possible to observe that the frequency due to vortex detachment decreased when AR increased from 2 to 4. This shows that increasing the wingspan of the plate reduces the frequency of oscillation, vortex formation. Thus, Wing Rock will have less oscillation frequency when AR is increased.

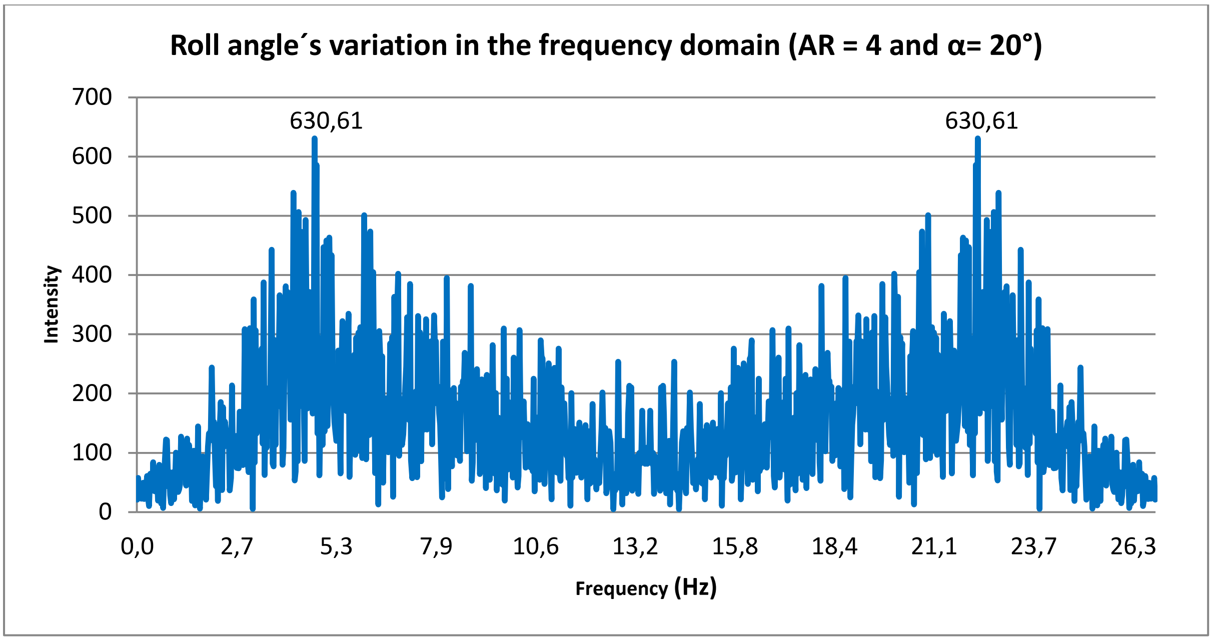


Figure 11. Frequency for the aluminum plate with AR = 4 and α = 20 °

Figure 12 compares the variation of the angular oscillation frequency showed above for the plates with AR = 2 and AR = 4, both with α = 20 °. Analyzing the highest peaks, which represent the main frequencies prevailing in the tests, it is observed that the intensity of the oscillation frequency for the case in which AR = 4 is higher in comparison to the result presented for AR = 2, however the oscillation frequency tends to decrease with increasing AR. Thus, the higher the AR lowed the frequency of oscillation, *i.e.*, the lower the frequency of vortex formation. In addition, the wing-tip vortices formed along the string of a wing with higher AR, will have less influence on the distribution of load along the plate, compared to a plate with lower AR.

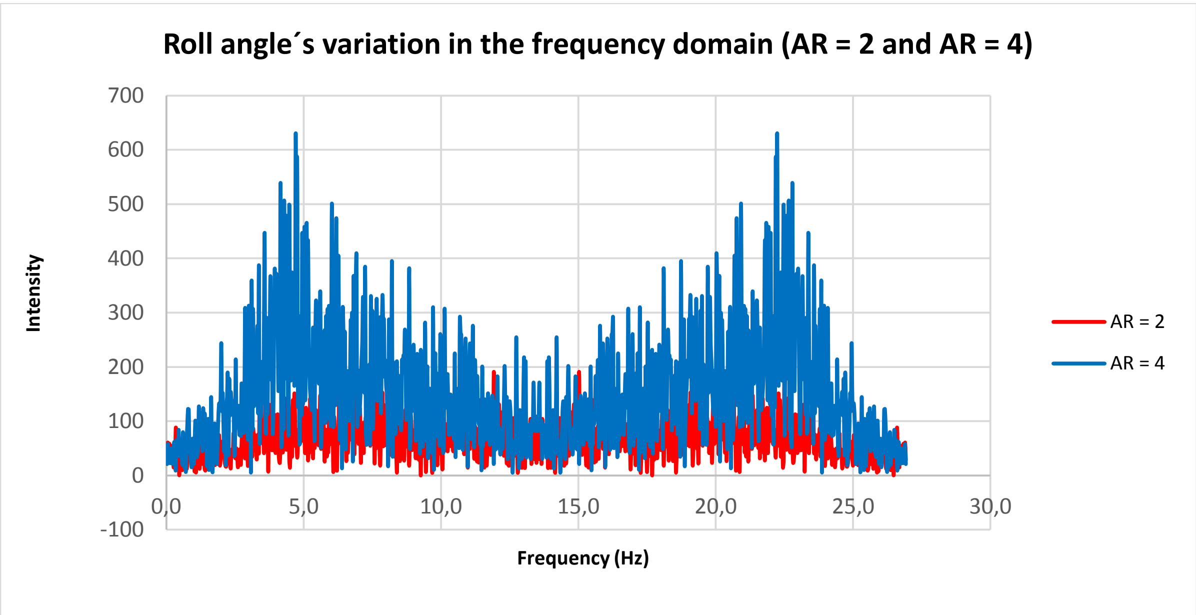


Figure 12. Comparison of frequency for the aluminum plate with AR = 2 and AR = 4 (both with α = 20 °)

Figure 13 shows the variation of the angular velocity versus time for the plate with AR = 2 when α is equal to 0 °, 10 °, 15 °, 20 ° and 25 °. It is observed that as α increased the angular velocity it raises. The maximum angular velocity for α equal to 25 ° was approximately 22 °/s and for the 20° was 12 °/s. When the α reduces, the angular velocity also decreases. Thus, it is possible to observe that an increase of 5 ° in the α results in a significant difference in the angular velocity of oscillation of the aluminum plate, *i.e.*, the wing rock phenomenon presents a greater oscillation amplitude.

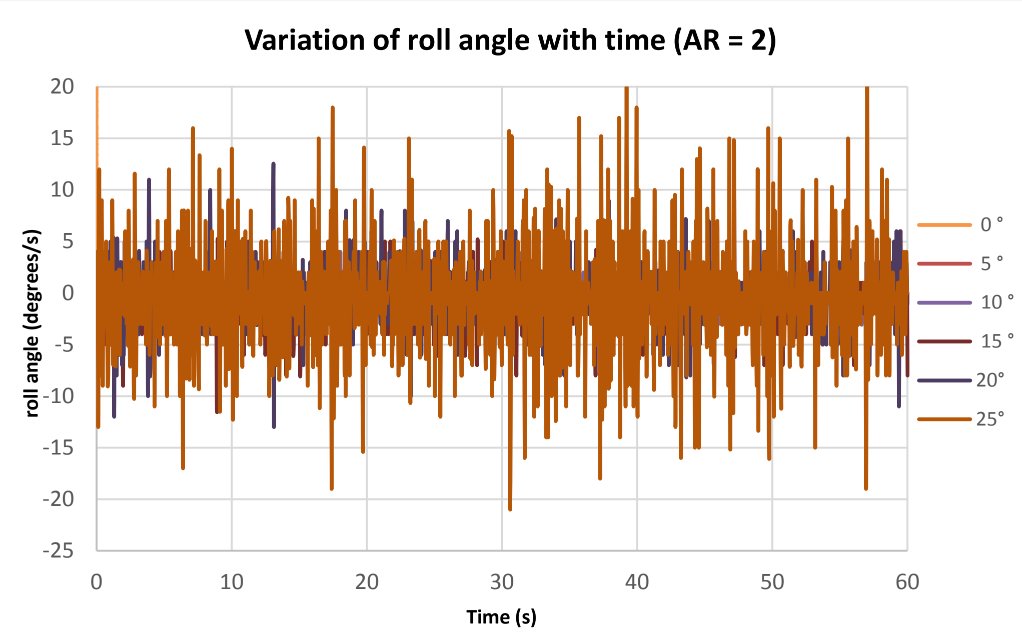


Figure 13. Angular velocity for the aluminum plate with AR = 2 when α = 0°,5°,10°,15°,20° and 25°.

Based on Fig. 14, the variation of the angular oscillation frequency for the aluminum plate with AR = 2 when α is equal to 0 °, 5 °, 10 °, 15 °, 20 ° and 25 ° can be evaluated. In this case, the frequency when α = 25 ° presented the values 6.6 Hz and 20.26 Hz. Comparing the frequency for the situation where α = 20 °, there was no significant change in frequency related to vortex detachment. When α = 15 ° and α = 10 °, the oscillation frequencies due to the vortices were 9.4 Hz and 13.5, respectively. Thus, in the interval between 10 ° to 20 °, the frequency showed a tendency to reduce its value, thus, the greater the α less the oscillation frequency due to the vortex detachment and the greater of angular velocity amplitude, according to Fig. 13. This indicates that the Wing Rock phenomenon will occur at smaller angular frequencies with greater amplitudes, if α increases.

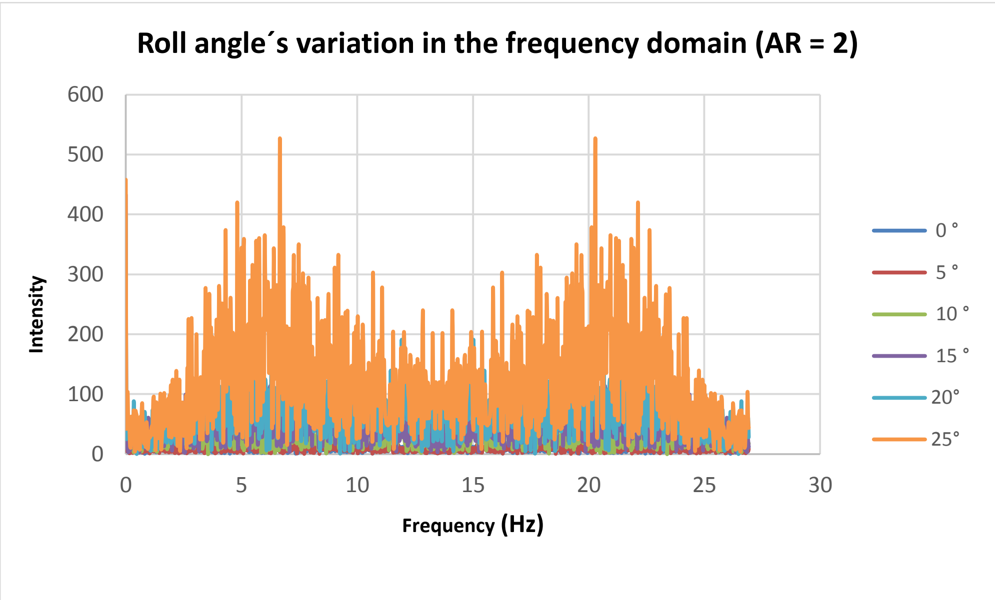


Figure 14. Frequency for the aluminum plate with AR = 2 when α = 0°,5°,10°,15°,20° and 25°

Figure 15 shows the variation of the angular velocity as a function of time when the plate with AR = 4 was α equal to 0°, 10°, 15°, 20° and 25°. In this situation, it is observed that there is not an intense variation of the angular velocity when α = 25 °, α = 20 ° and 15 °, where the maximum angular velocity for these three cases were 32 °/s, 38 °/s and 32 °/s, respectively. This shows that the increase of the AR can increase the speed of oscillation of the aluminum plate at certain moments, *i.e.*, the Wing Rock phenomenon will have a greater amplitude and a lower oscillation frequency, when α or AR to increase.

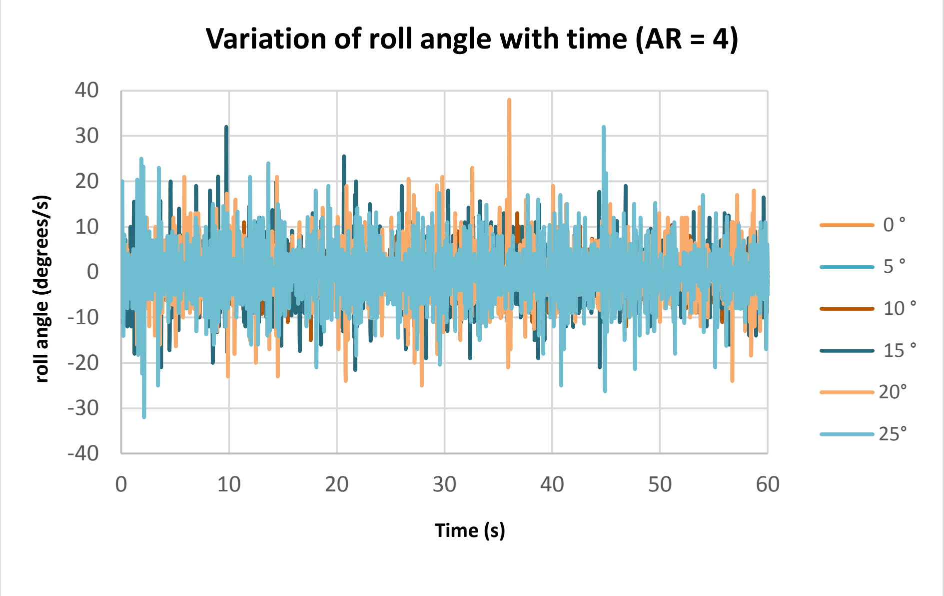


Figure 15. Angular velocity for the aluminum plate with AR = 4 when α = 0°,5°,10°,15°,20° and 25°

In Figure. 16, it is shown the variation of the angular oscillation frequency for the aluminum plate with AR = 4 when α is equal to 0°, 5°, 10°, 15°, 20° and 25°. The plate oscillation frequency, due to vortexing, for α equal to 25°, 20°, 15°, 10° was 5.1 Hz, 4.7 Hz, 7.7 Hz and 8.8 Hz , respectively. In comparison with AR = 2, again the frequency tends to decrease as α increases between 10° and 20°. In addition, the increase of AR resulted in lower values of those presented for AR = 2, this shows that α and AR influence the Wing Rock phenomenon. Thus, the increased the α or the AR reduced the oscillation frequency of the aluminum plate and, consequently, smaller the influence of the vortex detachment on the angular oscillation frequency.

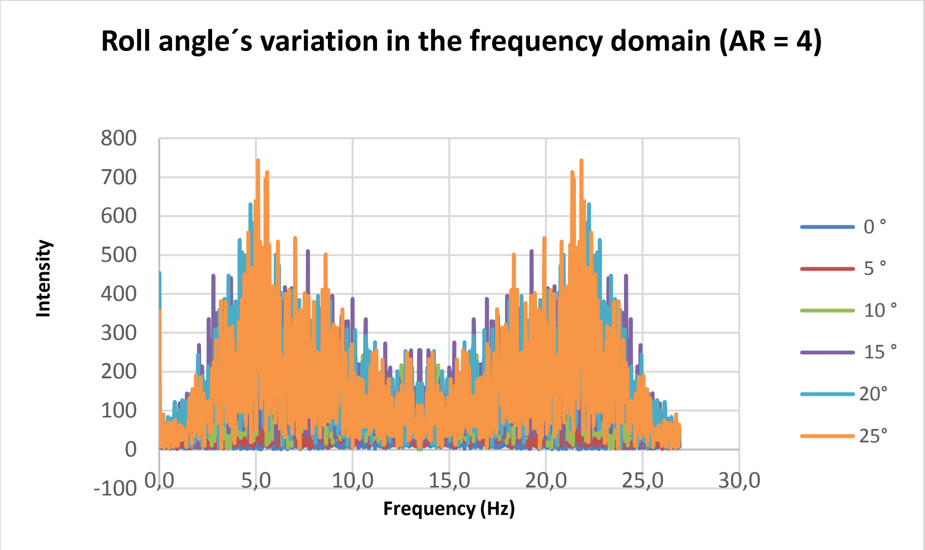


Figure 16. Frequency for the aluminum plate with AR = 4 when α = 0°,5°,10°,15°,20° and 25°

4. CONCLUSIONS

Thus, the results showed that in the case of rectangular wings the roll angle increases with increasing AR. The new tests with different ARs showed that the vortex detachment is the main reason of increase or decrease Wing Rock due it changes the load on the plate, resulting in an oscillation. It was concluded that a higher AR causes greater intensity oscillations during the tests, in which non-uniform angular velocity peaks arise. This may have occurred due to irregular flow in the wind tunnel. In addition, the influence of the increase of AR on the amplitude of roll angle oscillation was further investigated and the vortex detachment on the aluminum plates showed less oscillation frequency and more amplitude when α or AR increased.

The tip vortices decrease their intensity when the AR increases, because the increase of AR increases the wingspan of the plate, this way, the vortices are formed further away from the surface area of the aluminum plate. As a result, the increase of the AR lowed the oscillation frequency. However, this study showed that the angular velocity intensity increases with increasing AR. This may have occurred because the wingspan is larger and increases the momentum relative to the roll angle.

5. ACKNOWLEDGEMENTS

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