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PRELIMINARY DESIGN OF A DEVICE TO PERFORM ROLL CYCLE LIMIT OSCILLATIONS AND WING ROCK PHENOMENON IN LOW-SUBSONIC WIND TUNNEL

Hermann Luís Lebkuchen
Roberto Gil Annes da Silva
Technological Institute of Aeronautics - ITA. Praça Marechal Eduardo Gomes, 50 - Vila das Acacias, São José dos Campos - SP, Brazil
lebkuchen@ita.br, gil@ita.br

Abstract. *The self induced roll oscillations are encountered when slender delta wings flight at high angles of attack. These oscillations are investigated as limit cycle oscillations in numerical analysis of dynamic problems. One particular flight mechanics phenomenon in slender delta wings with high sweep angle is the wing rock. This paper presents the preliminary design of an apparatus to experimentally investigate the induced roll oscillations produced by the wing rock. The apparatus requirements as well as the wind tunnel test section and its neighborhood limitations are considered on the search of the most feasible solution. In order to accomplish that, a morphologic matrix of possible solutions is developed considering forced and free experiment cases. The roll mechanism, as well as the data acquisition systems are proposed for both free and forced experiments. As a result, the best alternatives are chosen and justified, and a final preliminary model is proposed to be manufactured and tested in the low speed subsonic wind tunnel at the Brazilian Institute of Aeronautics and Space.*

Keywords: *wing rock, experimental aerodynamics, low-subsonic wind tunnel, cycle limit oscillation, flight mechanics.*

1. INTRODUCTION

The wing geometry of aircrafts may have several different configurations depending on the desired mission and flight envelope (Raymer, 1992). Supersonic modern aircraft generally needs to be highly maneuverable and able to operate at high angle of attack (AoA) either for civil or military applications (Heibst and Krogull, 1973). As depitcted in Fig. 1, military and commercial aircrafts have been designed with delta wings, like the *Mirage IV* and *2000*, *Dassault Rafale*, *Eurofighter Typhoon*, *Aéropostiale/BAC Concorde*, among many others. These combination of high AoA with delta wing geometry and high length to thickness ratio, known as slender delta wings, leads to the wing rock phenomena, as suggest Hsu and Lan (1985). Anderson (2010) states that when the air flows on slender delta wings at high AoA, two main vortex are created at each side of wing in relation to longitudinal plane. Thus, the interaction between each vortex develops an undesired oscillatory roll movement. Bakaul *et al.* (2014) published that many reasons were proposed in order to explain wing rock phenomenon, such as asymmetric vortex liftoff, vortex breakdown, and hysteresis. Nevertheless, the wing rock is even pronounced in the absence of all of them, which confirms the complexity of the phenomenon.

Figure 1: Aircrafts with slender delta wings, from left to right, *Mirage 2000*, *Eurofighter Typhoon* and *Aéropostiale/BAC Concorde* (Airplane-Pictures, 2017).

The research available in the literature explore analytical, numerical as well as experimental approaches. The analytical approaches applied either complex or simplified formulations, as given in Hsu and Lan (1985); Ericsson (1987, 1990); Ramnath (2010) and Liebst and Nolan (1993). The work developed by de Oliveira Neto (2007), proposed an investigation of unsteady aerodynamic formulation to represent the wink rock phenomenon. Pietrucha *et al.* (2009) presented a comparative analysis applying control theory to augment the nonlinear system behavior. Badcock *et al.* (2008)

and Ericsson (2000) stated that due the complexity of the flow in this phenomenon, numerical investigations demand high computational efforts and time consuming techniques, what most of times is unfeasible.

As presented above, the wing rock phenomenon has high interesting to be further investigated not only because fighters and supersonic civilian aircrafts have slender delta wings, but also due the complexity of air flow on numerical simulations. The work de Oliveira Neto (2007) stated that contemporaneous aircrafts still in service such as A-4 Skyhawk, F-4 Phanton, F-5 Tiger, F-16 Fighting, F-18 Hornet, X-31, Tornado, Harrier are some aircrafts that experienced wing rock phenomenon during development phase. Thus, experimental analysis represent an interesting alternative to better understand the vortexes created on each side of delta wing. In an effort to perform experimental investigation about wing rock phenomenon, Arena and Nelson (1994) has published an extensive work proposing a set up to investigate limit cycle oscillations and wing rock phenomenon in low subsonic wind tunnel at NASA Ames Research Center. Because the device proposed in that work was published in a time ago, a different device with most actualized acquisition systems is proposed in this work.

Thus, this paper presents the preliminary design of an apparatus capable of represent limit cycle oscillations and the wing rock phenomenon on low speed wind tunnel available in the aerodynamics department at the Brazilian Institute of Aeronautics and Space.

2. METHODOLOGY

Firstly the wing rock phenomenon is briefly discussed. Following that, the design requirements of the apparatus are identified and listed. Parallel to that, the wind tunnel properties as well as delta wing models are defined. Based on collected requirements, a general block diagram is proposed to represent the experiment strategy and apparatus architecture. Next, the integrated product design methodology available in Back *et al.* (2008) is employed to create the morphologic matrix of possible solutions. Finally, the most appropriate technology for each demand is chosen and justified.

2.1 Wing Rock Phenomenon

The wing rock came up in aeronautics as a source of problem. When engineers started to design supersonic and transonic military aircrafts with slender delta wings, the flow on fuselage was divided on the longitudinal symmetric plane of aircraft, as depicted in Fig 2. Because of this behavior, when the aircraft is submitted to high angles of attack α, the flow triggers one vortex in each side of delta wing. This vortex induces a roll angle $\varphi(t)$, which starts to change in magnitude according to the value of attack angle. Small values of attack angle, ie. up to $20°$, trigger modest roll oscillations. When $20° < \alpha < 50°$ the roll angle starts to oscillate in a limit cycle (LCO). If $\alpha > 50°$ the roll oscillations vanish.

(a) Zero roll angle: $\varphi = 0°$. (b) Positive roll angle: $+\varphi$. (c) Negative roll angle: $-\varphi$.

Figure 2: Representation of vortex generation and roll angle right hand sign convention at each side of a delta wing in high attack angle.

The normative MIL-S-83691A (USAF, 1972) defines wing rock as an *"uncommanded lateral-directional motion, viewed by the pilot primarily as a roll oscillation"*. According to literature, the wing rock phenomenon has three main classifications: slender-wing rock, conventional-wing rock, and forebody-induced wing rock. Slender-wing rock occurs on highly swept back, sharp leading edge delta wings, alone or with blended bodies, at sufficiently high AoA. Models of flat plates or slender delta wings, as depicted in Fig. 2, belong to this class. Next, the conventional wing rock is pronounced on airplanes with straight or moderate-swept wings and moderate aspect ratio. Last, the forebody-induced wing rock happens because of vortices generated by the fuselage forebody.

Since this investigation has as objective to decrease the number of variables that may unleash wing rock and design an apparatus to investigate the phenomenon in wind tunnel tests, the slender wing rock type is chosen. In this way, once the phenomenon is described, the wind tunnel properties are presented followed by the device requirements.

2.2 Wind Tunnel Properties

The wind tunnel TA-02 is a closed loop wind tunnel located in the Department of Aerodynamics of the Brazilian Institute of Aeronautics and Space in São José dos Campos - SP. The test section is rectangular and has the dimensions $(t \times h \times l) = (3 \times 2.1 \times 3)m$. The flow speed varies from $5m/s \leq V_{\infty} \leq 127m/s$ with 0.2% of uncertainty. The turbulence intensity is around 0.7%. The wind tunnel has an aerodynamic balance installed under test section. This balance may be able to size forces from $8kN$ to $16kN$ and moments of $\pm 1.65kNm$ with 0.3% of uncertainty. The test section is depicted in Fig. 3. No space is available under or upper the test section to attach devices to complement an experiment, like the one proposed in this work. Besides that, the option of attachments on section on left or right wall sides is not appropriate since they are made of glass and are used to visualize the flow either in naked eye or by using flow visualization techniques, such as smoke or Particle Image Velocimetry (P.I.V.).

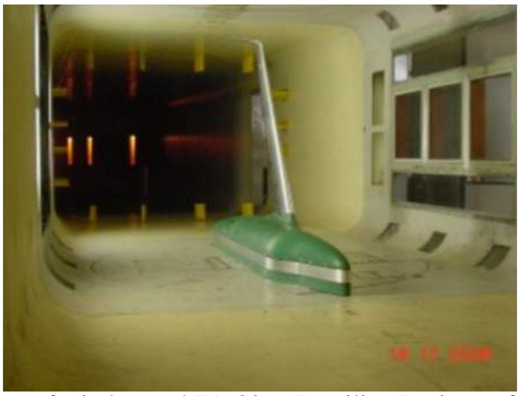


Figure 3: Test section of wind tunnel TA-02 at Brazilian Institute of Aeronautics (IAE).

2.3 Device Requirements

The device must have the following design requirements to perform roll cycle oscillations as well as to lead wing rock:

1. reproduce limit cycle oscillations and wing rock phenomenon;
2. reproduce free roll oscillations;
3. reproduce forced roll oscillations;
4. vary the attack angle from $\alpha = 0°$ to $\alpha = 60°$ respecting the test section wall effects;
5. record the roll angle as a function of time: roll angle time history, $\varphi = f(t)$;
6. monitoring of flowfield vortex;
7. acquire the pressure distribution on the slender delta wing model;
8. monitoring the aerodynamic forces and moments.

2.4 Systematic Method to Preliminary Design Concepts

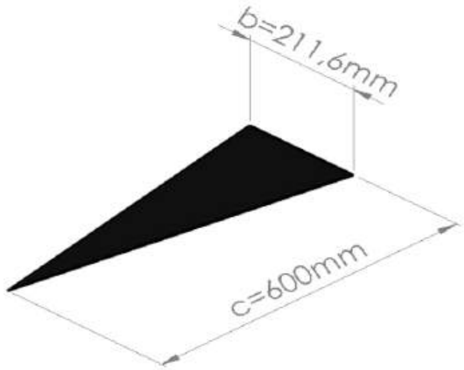
The systematic method to define the preliminary design concepts based on Back *et al.* (2008) is briefly described below. The method states that the following steps need to be performed to create the morphologic matrix of design concepts: (I) to identify the device processes or functions and system parameters. Thus, (II) the first column of morphologic matrix is filled with the device processes and parameters listed before. The general functions may be adjusted to the specific parameters that the device may be sought. Next, (III) an alternative solution principle is pursued for each process found in (II). The description of each solution may be literal or graphical based on the literature, benchmarking, brainstorming, among others. With the application case, function, parameters and particular solutions already defined, (IV) it is possible to search candidate concepts based on the combination of alternatives stated in (III). (V) The evaluation of each global solution is now performed and most of times several combinations are deleted because they did not behave well together. Finally, (VI) the best combination of alternatives is chosen as final preliminary design concept. The six steps briefly described above are represented in a generic morphologic matrix form in Tab. 1.

Table 1: Representation of the systematic method to preliminary design concepts.

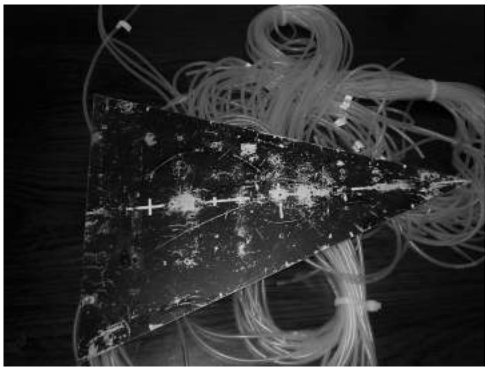
Generic Morphologic Matrix			Particular Alternatives				Concept
Case	1. Function (a)	Parameter (a1)	a1.1.1	a1.1.2	...	a1.1.n	Viable Alternative
			a1.2.1	a1.2.2	...	a1.2.n	Viable Alternative
		Parameter (a2)	a2.1.1	a2.1.2	...	a2.1.n	Viable Alternative
			a2.2.1	a2.2.2	...	a2.2.n	Viable Alternative
	.... Function (...)	Parameter (...)	....1.1	....1.2	...	....1.n	Viable Alternative
			....2.1	....2.2	...	....2.n	Viable Alternative
		Parameter (...)	....1.1	....1.2	...	....1.n	Viable Alternative
			....2.1	....2.2	...	....2.n	Viable Alternative
	$n.th$. Function ($n.th$)	Parameter ($n1$)	n1.1.1	n1.1.2	...	n1.1.n	Viable Alternative
			n1.2.1	n1.2.2	...	n1.2.n	Viable Alternative
		Parameter ($n2$)	n2.1.1	n2.1.2	...	n2.1.n	Viable Alternative
			n2.2.1	n2.2.2	...	n2.2.n	Viable Alternative

2.5 Delta Wing Models

Two models are proposed to be attached to the device, as depicted in Fig. 4. Both comprehend into a slender delta wing. The first one has a sweep angle of $\Lambda = 70°$, while the second one has $\Lambda = 80°$. The span/thickness ratio is equal $b/t = 36$ for both, characterizing a slender wing.



(a) Representation of delta wing model with $\Lambda = 80°$ and its main dimensions.



(b) Slender delta wing model with $\Lambda = 70°$.

Figure 4: Slender delta wing models which may be attached to the apparatus.

3. RESULTS

Based on the phenomenon description and the apparatus requirements, a block diagram, depicted in Fig 5, is developed to give an overview of the apparatus functions and parameters as well as to guide the development of possible alternatives of morphologic matrix of solutions, as listed in Tab. 1.

The experiment is divided in two main parts. Firstly, the apparatus is left to free roll with the roll angle time history data acquisition system turned on. The roll angle time history is recorded with some rotary encoder type sensor. The lift coefficient C_L is determined and a flow visualization technique is employed to monitor the vortex generation and intensity. Following that, the free oscillation motion, recorded in the first experiment, is replied in the wind tunnel with a forced oscillation experiment. The free and forced experiments are justified because of the influence of instrumentation in the free oscillations case. Thus, in forced oscillations the roll data is replayed by a motor while the aerodynamic loads and moments, as well as the steady and unsteady pressure distribution are measured. This strategy seek to record the free roll oscillations with lowest influence of mechanical and instrumentation system as possible.

In this way, the case comprehends in a device with two main functions: the capability to perform free and forced roll oscillation experiments under $0° \leq \alpha \leq 60°$. Each experiment case has its particular parameters, divided in device and data acquisition system. These general parameters are break down in specific parameters. The device for free oscillation experiment is subdivided in 1.1.1. Structure; 1.1.2. mechanism to vary attack angle ($\Delta\alpha$); 1.1.3. mechanism to perform free roll movement with lower influence of mechanical system, as friction; and 1.1.4. sting material, which holds the delta wing models depicted in Fig. 4. For each one of these specific parameters, diverse particular alternatives are

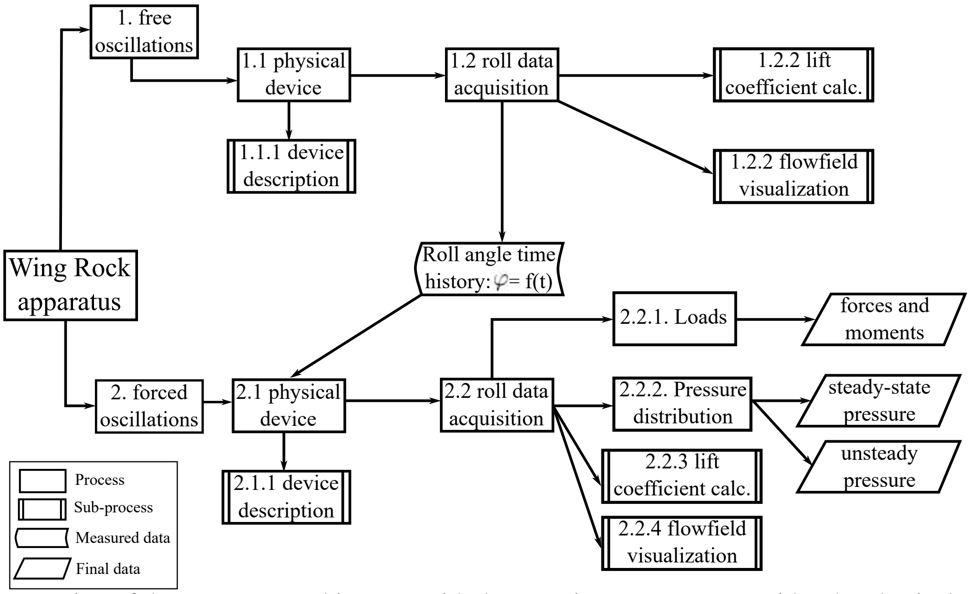


Figure 5: Representation of the apparatus architecture with the experiment strategy. Besides the physical device, the flow visualization techniques and instrumentation hardware are necessary.

Table 2: Wing Rock/Roll device morphologic matrix with respective functions, parameters, particular and viable alternatives and final concept.

Morphologic Matrix				Particular Alternatives			Concept
Wing Rock / Roll Device	Free Oscil. Exp.	Device	1.1.1. Structure	2 Mast	Circ. Sector	Half Circ.	Half Circumference
				Robotic Arm	Mast with Arm	Under floor	
			1.1.2. $\Delta\alpha$	Power Screw	Pinion-Rack	Magnetic	Pinion-Rack
				Crank Arm	Pulley		
			1.1.3. Free Roll	Air Bearing	Standard bearing	magnetic	Air Bearing
				Surf. with Graphite	Surf. with Teflon	Surf. with Ceramic	
			1.1.4. Sting	Steel	Composite	Plastic	Aluminum
				Wood	Aluminum		
		Data Acq.	1.2.1. Roll Angle	Potentiometer	R.I.O.E.	R.A.O.E	R.I.O.E.
				Accelerometer	Laser		
			1.2.2. Flow Visualization	Surf. Oil	P.I.V.	Smoke	P.I.V; Smoke; Video; Strob.
				Video	Stroboscope		
	Forced Oscil. Exp.	Device	2.1.1 Structure	Same as presented in 1.1.1.			Half Circ.
			2.1.2 $\Delta\alpha$	Same as Presented in 1.1.2.			Pinion-rack
			2.1.3 Power Transmission	Step Motor	Servo Motor	CC Motor	Servo motor
				Motor CA			
			2.1.4 Fix Roll Angle	Motor Breaks	Pneumatic Breaks	Magnetic Breaks	Motor breaks
				Mechanic Breaks			
		Data Acq.	2.2.1. Loads and Moments	External Balance	Internal Balance		External Balance
			2.2.2. Steady Pressure	Piezo Gauge	Differential	Absolute	Piezo Gauge; Absolute
				Video			
			2.2.3. Unsteady Pressure	Gauge	Differential	P.I.V	PSP; Piezo Gauge
				Video	PSP		

proposed based on literature, benchmarking and brainstorming performed with experienced engineers in the department of aerodynamics at Brazilian Institute of Aeronautics and Space. In 1.1.1. the viable structure is the half circumference since the wind tunnel does not have enough space out of test section and a robotic arm is not viable economically. Besides that, this chosen concept keeps the delta wing center of mass coincident with the circumference center as the attack angle varies, decreasing the wind tunnel wall effects. The 1.1.2 attack angle mechanism consists in a pinion-crack system attached in the internal radius of half circumference structure. The sting in 1.1.4. is defined as made of aluminum 7075 because its high specific strength and low cost. Still in the free roll oscillation experiment, the data acquisition system is subdivided in 1.2.1 measurement of roll angle time history and 1.2.2. flow visualization technique. The instrumentation to acquire the roll angle variation in function of time has different options, the terms R.I.O.E and R.A.O.E listed in Tab. 2, mean, respectively, Rotational Incremental Optical Encoder and Rotational Absolute Optical Encoder. The R.I.O.E is adopted as the viable option since it has no contact with sting vanishing the influence of instrumentation on roll angle time history. Commercial available R.I.O.E with serial connection 485 is compatible with TA-02 wind tunnel acquisition system and has resolution up to $0.00549°$ with 16 bits. The flow visualization technique may have more than one final viable alternative, thus Particle Image Velocimetry (P.I.V.), smoke, video and stroboscope are addressed in the final concept.

Next, the forced oscillation experiment alternatives are described. The forced experiment also is divided in device and data acquisition system. The first two particular parameters are the same as presented for free roll oscillations. The parameter 2.1.3 applies the power necessary to perform the recorder roll time history in free experiment case. The $\varphi(t)$ may be played with step, servo, CC or CA motors. Based on the requirement to perform limit cycle with positive and negative roll angles in moderate frequency values, the servo motor is considered the most appropriate device to transmit the power necessary to perform measured roll angle. The parameter 2.1.4. considers the case where a desired fixed roll angle wants to be measured. Thus, the servo motor breaks may be able to hold the desired φ. The instrumentation in forced experiment aims to acquire aerodynamic loads and moments as well as steady and unsteady pressure fields. In 2.2.1. the aerodynamic loads and moments are measured with external aerodynamic balance device since the slender delta wings have high span-thickness ratio. The adoption of an internal balance will make necessary to add a hump in the delta wing, changing the vortex dynamics on the wing surface. Finally, the parameters 2.2.2. and 2.2.3. account for pressure field measurement. In the steady case piezoresistive and absolute sensors are adopted. Commercial piezoresistive may measure pressures from 0.01 to more than $600bar$ with accuracy of $\pm 0.25\%$ in full scale. The unsteady pressure also adopts piezoresistive sensor together with pressure sensitive painting (PSP), which has great accuracy of $\leq 0.05\%$ in full scale.

The final concept with half circumference, attack angle variation mechanism, sting, slender delta wing, servo motor and instrumentation has been drawn with computer aided design (CAD) and is depicted in Fig. 6.

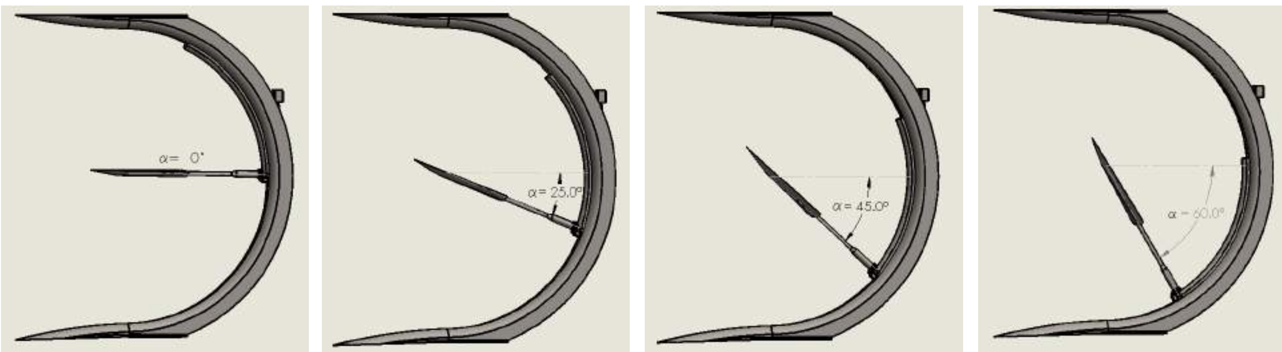


Figure 6: Proposed design of the device to perform roll cycle limit oscillations.

4. CONCLUSIONS

These paper proposed the preliminary design of an apparatus to study roll cycle limit oscillations and wing rock phenomenon on the low-subsonic wind tunnel TA-02 in the department of aerodynamics at Brazilian Institute of Aeronautics and Space. The methodology followed the product design strategy proposed by Back et. al using the morphologic matrix of viable concepts. Based on the understanding of the physic of the wing rock phenomenon, the apparatus requirements could be stated as well as the most appropriate wing models and limitations of wind tunnel facilities. With regard on the requirements, the system block diagram have been developed in order to depict a tool to resume the apparatus case, functions, parameters and particular alternatives, which guided the development of the morphologic matrix of solutions. So, the morphologic matrix of solutions has been developed and all particular alternatives combined in order to find the best group to attend the device requirement. The most appropriate solution based on technical requirements, costs and commercial availability of technologies have been grouped to generate the preliminary design of proposed device to perform limit cycle oscillations and represent the wing rock phenomenon. A CAD model has also been presented for attack angle varying from 0° to 60°. The next steps comprehend to perform the device detailed design and manufacture as well.

5. ACKNOWLEDGEMENTS

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