Analysis of the Aerodynamic Coefficients for the Evolvable Demonstrator for Upset Recovery Approaches with Evaluation in the Wind-tunnel

Torbjørn Cunis, Murat Bronz, Jean-Philippe Condomines

Analysis of the Aerodynamic Coefficients for the Evolvable Demonstrator for Upset Recovery Approaches with Evaluation in the Wind-tunnel

Torbjørn Cunis,* Murat Bronz,† and Jean-Philippe Condomines‡

École Nationale de l'Aviation Civile, Toulouse, 31055, France

While in-flight loss of control has remained a severe threat to aviation, few of the upset recovery approaches designed by aeronautical research has been demonstrated in flight tests. Enabled by the on-going success of micro air vehicles, we discuss the concept of an aerial experimental platform for upset recovery, EDURA (Evolvable Demonstrator for Upset Recovery Approaches), allowing cheap and flexible flight demonstrations. The aerodynamic coefficients of the vehicle presented here are numerically computed and extended to a full-envelope aerodynamic model using piece-wise polynomials in pre- and post-stall. Eventually, the aerodynamics are verified with wind-tunnel force measurements for a 3D-printed mock-up.

I. Introduction

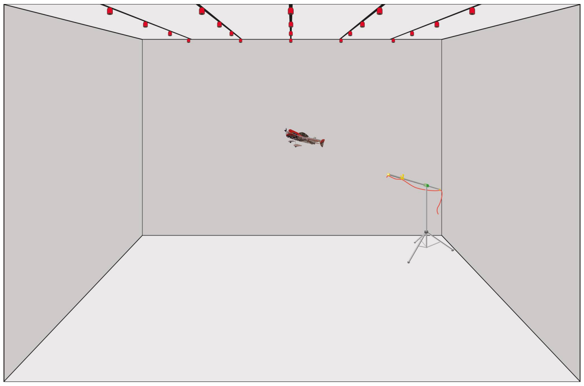
In-flight loss of control (LOC-I) imposes the *highest risk to aviation safety*[1] and has remained the foremost cause of fatal accidents for the last decades. Generally defined as any *deviation from the desired flight-path* by FAA,[2] LOC-I especially includes upset situations such as stall, high and inverted bank angle, as well as post-stall spirals and rotations.[3] Nowadays, current autopilots are not capable to drive the aircraft in such situation. In normal cases, pilots are able to pull back the aircraft by reducing the angle of attack. But if the stall occurs suddenly due to vertical gusts for example, the pilots don't have enough time to react. This can lead to catastrophic consequences. Especially for drone pilots who lack of awareness of the flight situation, it is a harder task to save the drone in case of stall. The case will be worse if the drone has to fly into clouds where vertical gusts often happen and where the visual inspection of the flight condition is not possible. Therefore, an autopilot that can deal with the stall is of high necessity. With their unstable and highly non-linear characterizations, these situations require extensive control effort and adequate approaches to recover the upset aircraft and return into the flight envelope. To handle this problem, non-linear behaviour of aircrafts in the post-stall flight regime has been investigated analytically[4–8] and in wind-tunnel studies.[9,10] As a result, researchers developed control laws for upset recovery.[11–20] For the recovery approaches found in literature as well as proposed by the authors in[21] are model-based, there is a need for reliable flight dynamics data. However, though the NASA *generic transport model* (GTM) offers a scaled unmanned aerial platform, well-investigated in wind-tunnel studies, to test control systems,[22] only Gregory et al.[20] report flight tests of the designed upset recovery approach.

In the past decade, the market for Micro Air Vehicles (MAVs) has grown considerably. Widely available now, MAVs both offer cheap and repeatable experiments while being easy to replace and maintain in case of unsuccessful tests. On the other hand, indoor flight tests provide several benefits such as availability of accurate position tracking systems and reduction of disturbances in the test area, while requiring a small-scale vehicle other than the GTM. Combining the mentioned points—accurate aerodynamic data, indoor tests, and usage of established MAV supply chains—, in this paper we present a first version of a small-scale,

*Associated Doctoral Researcher, URI-Drones, torbjoern.cunis@recherche.enac.fr; Doctoral Researcher at ONERA – The French Aerospace Lab, Department of Flight Dynamics and Control, torbjoern.cunis@onera.fr.

†Assistant Professor, URI-Drones, murat.bronz@enac.fr.

‡Assistant Professor, URI-Drones, jean-philippe.condomines@enac.fr.



(a) Experimental setup. *Commissioned illustration by Sarah Gluschitz, licensed under CC BY-ND.*

(b) ENAC flight hall under construction, to be finished by November 2017.

Figure 1: Setup of the EDURA aircraft and catapult launcher (a) within the ENAC flight hall (b).

fixed-wing experimental platform resembling an easy-to-model flying plate; based on a commercial-off-the-shell aircraft and the open-source autopilot software *Paparazzi UAV*. A catapult launcher allows repeatable and configurable test conditions including upset situtations like insufficient air speed, high angle of attack, or inverted bank angle. Based on a CAD model of the aircraft, we conclude with deriving its aerodynamic coefficients both in the pre- and post-stall part of the flight-envelope. The modelled aerodynamics are to be evaluated in wind-tunnel force measurements with a mock-up which is based on the CAD model.
This paper is organized as follows: in §II, we review upset recovery approaches in recent literature for the context of the paper. The concept of the *Evolvable Demonstrator for Upset Recovery Approaches* (EDURA) and its first prototype with the catapult launcher are presented in §III and §IV. We discuss the aerodynamic coefficients of the aircraft in §V and provide an evaluation by wind-tunnel tests in §VI.

II. Upset Recovery Approaches

Control approaches for upset recovery which have been presented in literature include state-based switching multi-mode control,[8] throttle-only control in case of hydraulic of the control surfaces,[11–13] linear-optimal control,[14] $\mathcal{L}_1$-adaptive control,[15] non-inear dynamic inversion,[16] and Lyapunov-based control.[17] We will review some of those approaches here:

II.A. Multi-mode flight control

As part of his later PhD thesis,[17] Engelbrecht et al. presented a multi-mode flight control system aiming to stabilize the upset aircraft *sequentially*, that is damping angular rates first, afterwards restoring angle of attack and side-slip, air speed (in this order), and finally compensating for height loss.[8]

II.B. LQR feedback control

Based on a linear-quadratic regulator (LQR), an upset recovery system was designed and tested in simulation for a model of an F/A-18 fighter jet.[14]

II.C. $\mathcal{L}_1$-adaptive control

To the authors knowledge, this has been the only approach presented in literature which was tested in a real flight-test.[20]

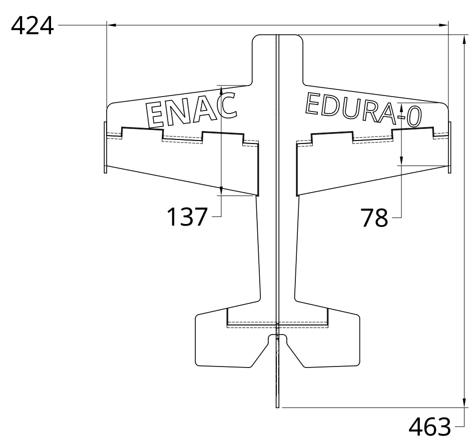
III. EDURA Concept

Indoor flight arenas, as existing at several research sites today, provide an ideal test environment for unmanned air vehicles. Wind and gust disturbances are reduced due to their closed walls and optical tracking systems provide position, attitude, and velocity information at both high accuracy and frequency. However, they are limited in space and hence unsuitable for larger vehicles. While clearly benefiting from indoor flight conditions, a suitable fixed-wing MAV is mainly required to be small.
Depron is a light-weight material which allows effortless processing. Wings cut of a single layer of depron show a rectangular surface and thus can be modelled as flying plate to obtain the aerodynamics coefficients. An aircraft made of depron offers design, making, and aerodynamic modelling of an aerial experimental platform in short iterations, evolving the flight dynamics as suitable. Furthermore, it accounts for the small-scale design necessary for indoor flight tests. Today's miniature microcontrollers, sensors and actuators, and auxiliary boards complete the setup albeit deliver full flight control and navigation on-board.
Eliminating the necessity of propulsion, a catapult launcher initially accelerates the aircraft to the desired air speed. In addition, it provides a configurable initial angle of attack and flight-path angle. The configuration of all three air speed, angle of attack, and flight-path angle after launch is repeatable over multiple executions of a single test case. Fig. 1 shows the general setup of the EDURA aircraft and catapult launcher within the ENAC flight hall. A grid of high accuracy infrared cameras on the ceiling of the flight hall provides tracking of the aircrafts position and attitude during flight test for post-flight evaluation.

IV. EDURA-0 Aircraft

The first aircraft is based on an *E-flite UMX Yak 54 3D* commercial off-the-shelf radio-controlled aircraft,[a] as shown in Fig. 2a. This 35 g vehicle with a wing span of 42.4 cm and length of 46.3 cm is made of 35 mm thick depron and resembles a flying plate with trapeze-shaped wings (Fig. 2b). The control surfaces, elevator, rudder, and left and right ailerons are driven by four linear servos.

(a) Side view.



(b) Top view.

Figure 2: Side view (a) of the EDURA-0 vehicle based on an *E-flite UMX Yak 54 3D* commercial-off-the-shell aircraft; and CAD drawing (b) from the top with measures: wing span, root chord, tip chord, and length (Quantities in millimetres).

The E-flite aircraft has been originally shipped with a *Spectrum* radio receiver, which was replaced by a *Lisa-MXs* autopilot board[b] and an *ESP8266-9* wifi module for UDP-based communication (Fig. 3). The autopilot runs the open-source software *Paparazzi UAV*.[c] For unpropelled flight, the propellor and its motor will be removed and replaced by a respective weight for balance. The catapult launcher (Fig. 4) is designed of three components, the rail, a cart moving lateral along the rail, and a cage to carry the aircraft. The cart is accelerated by an elastic band fixed to the front of the rail, while the same band attached to the end, too,

[a] http://www.e-fliterc.com/Products/?ProdID=EFLU3550
[b] Not publicly available yet.
[c] http://paparazziuav.org

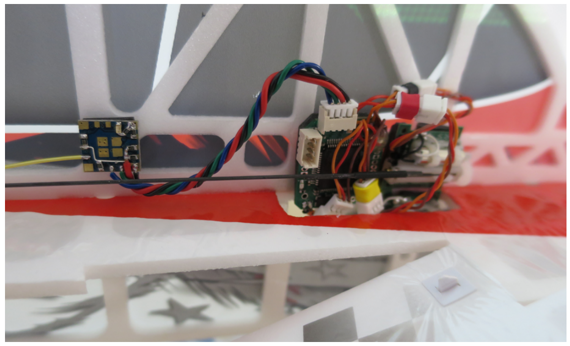
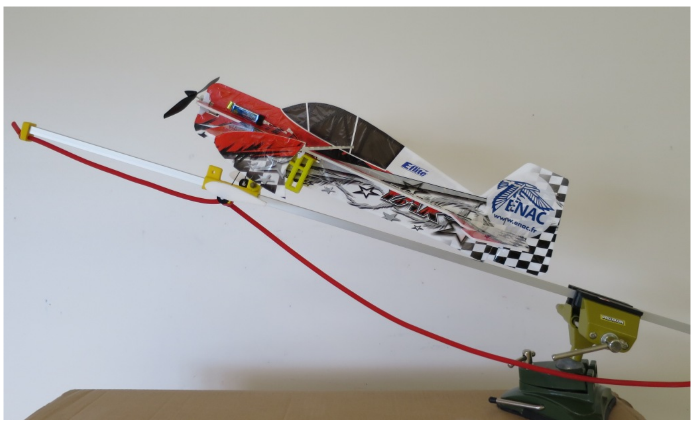
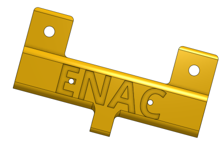


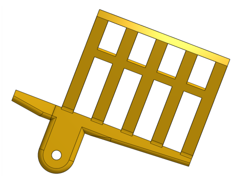
Figure 3: Autopilot configuration (from left to right): ESP8266-9 wifi module, Lisa-MXs board, and the linear servo for the elevator.



(a)



(b) Cart.



(c) Cage.

Figure 4: The EDURA catapult launcher with aircraft (a) and the main components in CAD.

slows down the cart after ejecting the aircraft.
The initial air-speed, *i.e.* the speed of the cart with respect to the rail can be configured by pulling the cart backwards thus stretching the elastic to a certain length with respect to its resting point. The desired angle of attack and flight-path angle at launch is defined by the orientation of the cage and the rail, respectively.

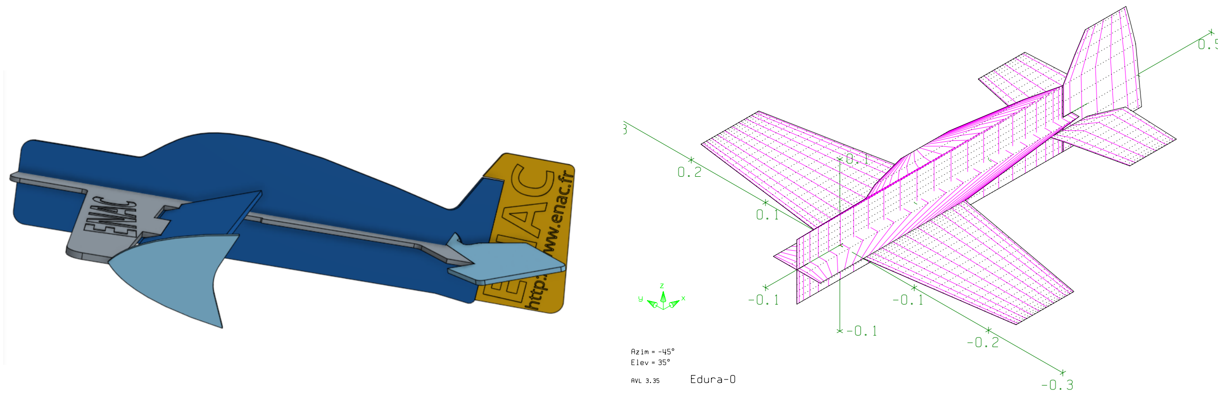
V. Aerodynamic Coefficients

For the design and demonstration of upset recovery approaches, a full-envelope model of the aerodynamic coefficients is crucial. Based on a CAD model of the aircraft, the linear part of the coefficients can be computed and a comparison can be made between the expected and measured flight trajectories. According to the comparison, it will be possible to verify the linear coefficients and identify the non-linear part in order to extend and improve the numerical estimation of the coefficients using the AERODAS polynomial equations[23] for the pre- and post-stall aerodynamic coefficients.

V.A. Linear aerodynamic coefficients

Fuselage, wings, and control surfaces of the UMX Yak 54 3D aircraft were measured and modelled in CAD (Fig. 5). Aerodynamic coefficients are obtained numerically by using a program based on vortex-lattice method, called AVL[d]. As a modification to the existing program, the two-dimensional airfoil characteristics obtained from XFOIL is integrated as a database. This added database supplies the corresponding drag coefficient for each sectional lift coefficients that are calculated at local Reynolds number. Integration of the additional drag over the whole span gives the viscous drag of the wing. As a result, a set of linearized

[d] http://raphael.mit.edu/avl



(a) CAD Model (b) AVL Mesh

Figure 5: CAD model of the EDURA-0 aircraft and its control surfaces(a) and AVL Mesh(b).

stability derivatives around the selected operating point is given in Table 1. (*For the moment the table is representative, and will be corrected for the final paper.*).

	α	β	p	q	r	δ_{elv}	δ_{ail}
C_L	3.9444	0.0	0.0	4.8198	0.0	0.016558	0.0
C_Y	0.0	-0.2708	0.01695	0.0	0.05003	0.0	0.000254
$C_{D_{ff}}$	-	-	-	-	-	0.000409	0.0
e	-	-	-	-	-	0.033728	0.0
C_l	0.0	0.03319	-0.4095	0.0	0.06203	0.0	-0.001956
C_m	-0.3234	0.0	0.0	-1.6834	0.0	-0.0076	0.0
C_n	0.0	0.0228	-0.04139	0.0	-0.01002	0.0	-0.000126

Table 1: (*This table will be updated for the final paper*) Stability derivatives extracted from AVL program for the aircraft at $4\,m/s$ equilibrium cruise speed. All derivatives are in 1/rad or s/rad except the control derivatives δ which are in $1/°$.

Using a linear model, AVL can not determine the stall angle of the examined vehicle. In order to overcome this, the modifications made by Bronz[24] has been used. Basically, the modification adds a subroutine that checks the lift coefficient of each wing strip and compares it with corresponding airfoil's $C_{L_{max}}$ maximum lift coefficient at the defined Reynolds number. If the required strip lift coefficient is higher than the airfoil's $C_{L_{max}}$, then an error message is written into an external log file without disturbing any AVL calculation. With the help of the log file, the user or the external program that calls AVL can see if the aircraft can sustain the equilibrium with the selected airfoil without stall or not.

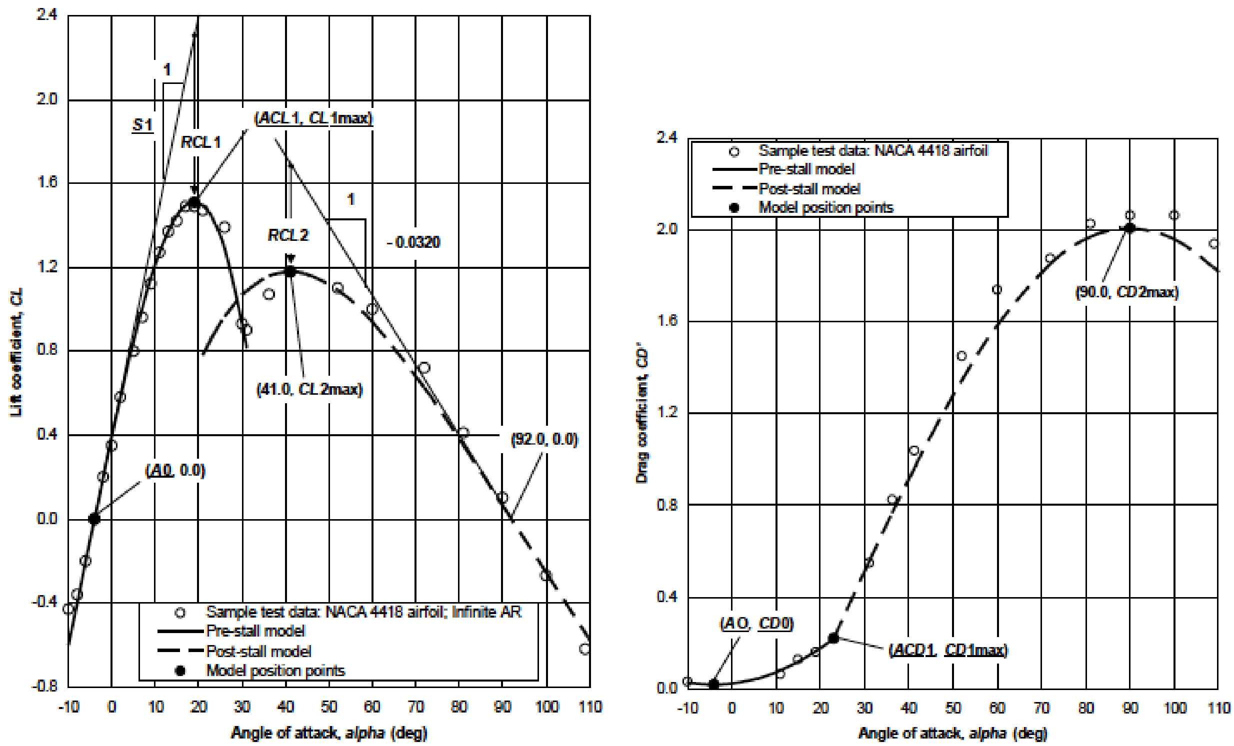
V.B. Pre- and post-stall model

Spera proposed a set of piece-wise defined, polynomial equations for the pre- and post-stall region of the aerodynamic equations,[23] making use of the linear part as well as the stall angle of attack given by AVL. While the AERODAS model is initially designed for infinite-length airfoils, adjustments have been made for finite-aspect wings. The AERODAS model of Spera is displayed in Fig. 6, fitting the lift and drag coefficient piece-wise in the pre- and post-stall regimes. The inputs to AERODAS are the angle of attack A0 at zero lift ($C_L(\mathrm{A0}) = 0$) as well as the corresponding drag $\mathrm{CD0} = C_D(\mathrm{A0})$, the maximal lift CL1max as well as the corresponding angle of attack ACL1 and drag CD1max, and the derivative S1 of the lift coefficient at $A0$; these can be determined using the AVL output of §V.A. The lift and drag coefficients in pre-stall are then given by

$$C_L^{pre}(\alpha) = \mathrm{S1}\,(\alpha - \mathrm{A0}) - \mathrm{RCL1}\left(\frac{\alpha - \mathrm{A0}}{\mathrm{ACL1} - \mathrm{A0}}\right)^{\mathrm{N1}} \tag{1}$$

$$C_D^{pre}(\alpha) = \mathrm{CD0} + (\mathrm{CD1max} - \mathrm{CD0})\left(\frac{\alpha - \mathrm{A0}}{\mathrm{ACD1} - \mathrm{A0}}\right)^{M} \tag{2}$$

with $\mathrm{RCL1} = \mathrm{S1}\,(\mathrm{ACL1} - \mathrm{A0}) - \mathrm{CL1max}$ and $\mathrm{N1} = 1 + \mathrm{CL1max}\,/\,\mathrm{RCL1}$. The post-stall coefficients are now functions of the geometry of the wings and the empirical maxima of C_L and C_D in post-stall.



(a) Lift coefficient

(b) Drag coefficient

Figure 6: Fitting of lift and drag coefficients by the AERODAS model of Spera 2008,[23] Fig. 2.

VI. Wind-tunnel measurements

Static force measurements of lift and drag in the wind-tunnel are state of the art in aeronautical research to determine the aerodynamic coefficients of an aircraft. Rather than initially measuring the aerodynamic coefficients, we are going to verify the data obtained in §V in the wind-tunnel afterwards. However, the Depron material is likely no to withstand the wind forces acting on the structure; we will survey a mock-up model instead. As we have already obtained a full model in CAD of the UMX Yak 54 3D (Fig. 5), we can directly 3D-print a mock-up in any suitable scale. This will lead us to a simplistic as well as, to the authors' knowledge, unprecedented method to investigate the aerodynamics of an aircraft in a wind-tunnel.

VII. Conclusion

In this paper, we have argued the need of an experimental platform for flight tests of upset recovery approaches. We have therefore discussed the benefits of indoor flights of suitable MAVs and proposed the EDURA concept of an evolvable small-scale, fixed-wing MAV as demonstrator. An additional catapult launcher allows repetition of the initial flight conditions. The first prototype based on a commercial-off-the-shelf aircraft has as well been presented as the design of the catapult launcher.

The system illustrated will be evaluated in launch tests with indoor position tracking in order to proof repeatability of the initial conditions. Overall, we have introduced an aerial experimental platform to test and demonstrate upset recovery approaches based on the aerodynamic model of the aircraft, where the *modus operandi* is going to allow the evolution of the vehicle's parameters and test conditions.

We derived the aerodynamic coefficients of the aircraft in the linear part by AVL. Together with the aspect ratio of the wings and the estimated stall angle of attack, we could extend those to a full-envelope aerodynamic model. The results of the modelling will be evaluated with wind-tunnel force measurements using a mock-up of the aircraft.

Acknowledgements

The authors wish to thank the TU Delft Micro Air Vehicle Laboratory for providing the Lisa-MXs hardware and support. CAD models of aircraft and aircraft launcher were created in the free-to-use cloud platform *Onshape*.[e]

References

[1]"Unstable Approaches: Risk Mitigation Policies, Procedures and Best Practices," Tech. rep., International Air Transport Association, Montreal, CA, 2015.

[2]"Airplane Flying Handbook," FAA handbook FAA-H-8083-3B, Flight Standards Service, Washington, US-DC, 2016.

[3]Chambers, J. R. and Grafton, S. B., "Aerodynamic Characteristics of Airplanes at High Angles of Attack," NASA technical memorandum NASA/TM-74097, Langley Research Center, Hampton, US-VA, 1977.

[4]Caroll, J. V. and Mehra, R. K., "Bifurcation Analysis of Nonlinear Aircraft Dynamics," *Journal of Guidance, Control, and Dynamics*, Vol. 5, No. 5, 1982, pp. 529–536.

[5]Jahnke, C. C., *Application of Dynamical Systems Theory to Nonlinear Aircraft Dynamics*, Phd thesis, California Institute of Technology, Pasadena, US-CA, 1990.

[6]Goman, M., Zagainov, G., and Khramtsovsky, A., "Application of bifurcation methods to nonlinear flight dynamics problems," *Progress in Aerospace Sciences*, Vol. 33, No. 9–10, 1997, pp. 539–586.

[7]Kwatny, H. G., Dongmo, J.-E. T., Chang, B.-c., Bajpai, G., Yasar, M., and Belcastro, C., "Nonlinear Analysis of Aircraft Loss of Control," *Journal of Guidance, Control, and Dynamics*, Vol. 36, No. 1, 2013, pp. 149–162.

[8]Engelbrecht, J. A. A., Pauck, S. J., and Peddle, I. K., "A Multi-mode Upset Recovery Flight Control System for Large Transport Aircraft," *AIAA Guidance, Navigation, and Control Conference*, Boston, US-MA, aug 2013.

[9]Foster, J. V., Cunningham, K., Fremaux, C. M., Shah, G. H., and Stewart, E. C., "Dynamics Modeling and Simulation of Large Transport Airplanes in Upset Conditions," *AIAA Guidance, Navigation, and Control Conference and Exhibit*, San Francisco, US-CA, aug 2005.

[10]Frink, N. T., Murphy, P. C., Atkins, H. L., Viken, S. A., Petrilli, J. L., Gopalarathnam, A., and Paul, R. C., "Computational Aerodynamic Modeling Tools for Aircraft Loss of Control," *Journal of Guidance, Control, and Dynamics*, Vol. 0, No. 0, 2016.

[11]Burcham Jr, F. W., Burken, J. J., Maine, T. A., and Fullerton, C. G., "Development and Flight Test of an Emergency Flight Control System Using Only Engine Thrust on an MD-11 Transport Airplane," NASA technical publication NASA/TP-97-206217, Dryden Flight Research Center, Edwards, US-CA, 1997.

[12]Burcham Jr, F. W., Stevens, R., Broderick, R., and Wilson, K., "Manual Throttles-Only Control Effectiveness for Emergency Flight Control of Transport Aircraft," *9th AIAA Aviation Technology, Integration, and Operations Conference*, Hilton Head Island, US-SC, sep 2009.

[13]Urnes Sr, J. M., "Flight Control for Multi-engine UAV Aircraft using Propulsion Control," *AIAA Infotech@Aerospace*, Garden Grove, US-CA, 2012.

[14]Chang, B.-C., Kwatny, H. G., Ballouz, E. R., and Hartmann, D. C., "Aircraft Trim Recovery from Highly Nonlinear Upset Conditions," *AIAA Guidance, Navigation, and Control Conference*, San Diego, US-CA, 2016.

[15]Xargay, E., Hovakimyan, N., and Cao, C., "$\mathcal{L}_1$ adaptive controller for multi-input multi-output systems in the presence of nonlinear unmatched uncertainties," *IEEE American Control Conference*, Baltimore, US-MD, 2010, pp. 874–879.

[16]Stepanyan, V., Krishnakumar, K., Kaneshige, J., and Acosta, D., "Stall Recovery Guidance Algorithms Based on Constrained Control Approaches," *AIAA Guidance, Navigation, and Control Conference*, San Diego, US-CA, 2016.

[17]Engelbrecht, J. A. A., *Automatic Flight Envelope Recovery for Large Transport Aircraft*, Phd thesis, University of Stellenbosch, Matieland, ZA, 2016.

[18]Crespo, L. G., Kenny, S. P., Cox, D. E., and Murri, D. G., "Analysis of Control Strategies for Aircraft Flight Upset Recovery," *AIAA Guidance, Navigation, and Control Conference*, Minneapolis, US-MN, aug 2012.

[19]Richards, N. D., Gandhi, N., Bateman, A. J., Klyde, D. H., and Lampton, A. K., "Vehicle Upset Detection and Recovery for Onboard Guidance and Control," *Journal of Guidance, Control, and Dynamics*, Vol. 0, No. 0, 2016.

[20]Gregory, I., Xargay, E., Cao, C., and Hovakimyan, N., "Flight Test of $\mathcal{L}_1$ Adaptive Control Law: Offset Landings and Large Flight Envelope Modeling Work," *AIAA Guidance, Navigation, and Control Conference*, Portland, US-OR, aug 2011.

[e]http://onshape.com

[21]Cunis, T., Burlion, L., and Condomines, J.-P., "Non-linear Analysis and Control Proposal for In-flight Loss-of-control," *Pre-prints of the 20th IFAC World Congress*, Toulouse, FR, 2017.

[22]Jordan, T. L., Foster, J. V., Bailey, R. M., and Belcastro, C. M., "AirSTAR: A UAV Platform for Flight Dynamics and Control System Testing," *AIAA Aerodynamics Measurement Technology and Ground Testing Conference*, San Francisco, US-CA, 2006.

[23]Spera, D. A., "Models of Lift and Drag Coefficients of Stalled and Unstalled Airfoils in Wind Turbines and Wind Tunnels," NASA Contractor Report NASA/CR-2008-215434, Jacobs Technology, Inc., Cleveland, US-OH, 2008.

[24]Bronz, M., *A Contribution to the Design of Long Endurance Mini Unmanned Aerial Vehicles*, Ph.D. thesis, Institut Supérieur de l'Aéronautique et de l'Espace-ISAE, 2012.