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DIRECTIONAL STABILITY ISSUES OF A THREE LIFTING SURFACE AIRCRAFT

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ABSTRACT

This paper deals with the evaluation of the interference effects among aircraft components in a three lifting surface configuration, an innovative layout for a high-capacity turboprop (130pax), which is supposed to be competitive with respect to short/medium haul regional jets. The feasibility study of such a configuration is framed within the Innovative turbopROp configuratioN (IRON) project.

An experimental wind tunnel test campaign has been performed on a 1:25 scaled model at the main subsonic wind tunnel facility of the Industrial Engineering Department of the University of Naples Federico II. Beside the well-known detrimental effects of the angle of attack on the sidewash, the experimental tests have highlighted a strong directional stability reduction due to the canard interference with both the fuselage and the vertical tail. Results have shown that the canard increases the fuselage instability of about 14%. The canard wake displacement also affects the aircraft directional stability. Results collected in this work have been useful to perform a redesign of the aircraft empennage and to schedule numerical high-fidelity analyses as well as a second wind tunnel test campaign on the updated aircraft model to get further insights on the aerodynamic interference, including propulsive effects.

1 INTRODUCTION

The present research work is framed in the Innovative turbopROp configuratioN (IRON) project complying with the European Union topic JTI-CS2-2015-CPW02-REG-01-03 (Green and cost-efficient Conceptual Aircraft Design including Innovative Turbo-Propeller Power-plant) as part of the Clean Sky 2 program for Horizon 2020. The topic leader is Leonardo S.p.a. and several core-partners are involved into the project, with CIRA[1] (Italian Aerospace Research Centre) as coordinator.

The project focuses on the feasibility study of an innovative turboprop regional configuration, which is supposed to be competitive with respect to short/medium haul regional jets.

Design of Aircraft and Flight technologies (DAF[2]) research group of the University of Naples Federico II is involved in the preliminary design, aerodynamic analysis, performance evaluation and Direct Operating Costs (DOC) estimation of this innovative regional aircraft.

Within the IRON project, different design loops with increasing level of complexity and fidelity, are expected, aiming to complete the design through numerical simulations, and experimental validations.

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[1] www.cira.it

[2] www.daf.unina.it

The first loop of design started in July 2016 from a baseline configuration provided by Leonardo and ended in January 2017. The aircraft configuration is an innovative layout with low wing and rear-mounted engines installed at the horizontal tail-plane tip. Aerodynamics target provided by Leonardo are very challenging, aiming for a cruise efficiency of about 18 at Mach number equal to 0.64, at a cruise altitude of 30 kft, and relatively high maximum lift coefficients: 2.4 and 3.0 for take-off and landing respectively. Top level aircraft requirements (TLAR) are presented in [1],[2]. The baseline rear propeller configuration has been deeply investigated during the first design loop, as shown in [1]. Aerodynamic design and analysis provided a laminar wing with improved high-lift capabilities and an increased aerodynamic efficiency with winglets. Stability and control were checked in the whole flight envelope, according to preliminary centre of gravity shift provided by Leonardo.

At the beginning of second loop, a careful weight and balance breakdown revealed a very large centre of gravity excursion, compelling to review the aircraft configuration, as summarized in [2]. A Multidisciplinary Design Analysis and Optimization (MDAO) has been performed using in-house software named “JPAD” [3][4], selecting a three lifting surface layout as the best solution. This configuration is the result of a multidisciplinary analyses and optimization process involving the following disciplines: weight and balance, aerodynamics, stability and control, performance, and DOC. Approaches used for the MDAO process have also included several methodologies developed by DAF research group dealing with both vertical tail design and sizing [5],[6] and fuselage aerodynamics prediction method [7].

According to the chosen number of design parameters, more than 7000 different aircraft configurations have been generated and analysed to define a response surface with which to perform the optimization process. Targets of the optimization process have been the cruise parameter W/E (representing the cruise drag) and take-off and landing factors $W/(S_w C_{L\max})$, which affect the ground performance. Several optimization algorithms have been exploited, including the approach of game theory applied to aircraft design [8]. Some of the major geometrical characteristics of the chosen three lifting surface aircraft are illustrated in Table 1. The three views of the aircraft layout are shown in Figure 1, details of the nacelle geometry have been intentionally blurred for confidential duties.

Fuselage	Height/width	3.535 m
	Length	38.04 m
Wing	Planform area	98.6 m^2
	Aspect ratio	12
	Leading edge sweep angle	10°
Canard	Planform area	11.49 m^2
	Aspect ratio	5.57
	Leading edge sweep angle	10°
Horizontal tail	Planform area	38.43 m^2
	Aspect ratio	4.4
	Leading edge sweep angle	10°
Vertical tail	Planform area	24.45 m^2
	Aspect Ratio	1.36
	Leading edge sweep angle	45°

Table 1: IRON three-surface aircraft major geometric characteristics.

An extended wind tunnel test campaign has been accomplished on a 1:25 scaled model of the aircraft under investigation at the main subsonic wind tunnel facility of the Industrial Engineering Department of the University of Naples Federico II. Experimental tests have been addressed to the estimation of the both longitudinal and directional characteristics. This paper is focused on the evaluation of the aerodynamic interference effects on the directional stability of the three-lifting surface aircraft configuration.

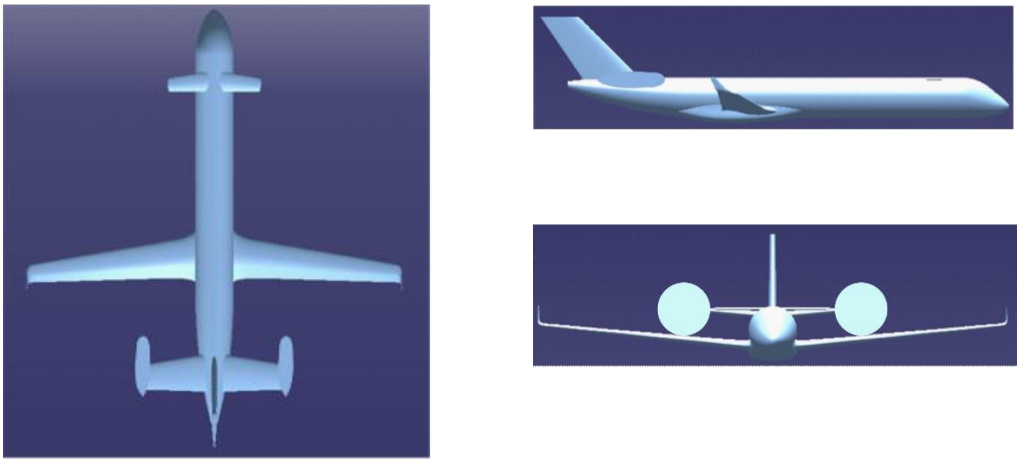

Figure 1: IRON loop 2 three lifting surface aircraft, three-views.

As concern a possible three-lifting surface transport aircraft, several works can be found in the open literature. Rokhsaz and Selberg in [9]-[11] have investigated analytically and by applying a vortex lattice method a conventional, a pure canard, and a three surfaces configuration. The aim of their works was to determine each configuration's induced drag as well as the pressure and viscous drag for a six-seats business aircraft. Kendall [12] applied the classical Prandtl-Munk theory to a modern three-surface airplane, showing that the induced drag due to the trim can be zero at any longitudinal position of the centre of gravity, leading to a potential saving of the induced drag about 7% relative to the conventional tail-aft design. Strohmeyer et al. in [13] have designed and optimized a three lifting surface transport aircraft highlighting the effects of canard design parameters (span, aspect ratio, thickness, sweep, longitudinal and vertical positioning) on the overall aircraft longitudinal aerodynamic characteristics. Ostowari and Naik [14],[15] made a series of wind tunnel experiments to investigate the lift, drag, and longitudinal stability of a three-lifting surface configuration for an un-yawed typical business jet.

All these research works dealt with design and optimisation for minimum drag, only focusing on the evaluation of longitudinal aerodynamic characteristics. As concern the evaluation of lateral-directional characteristics of a three-lifting surface configuration, some experimental data are available on a fighter aircraft. Grafton and Croom in [16] have studied the low-speed, high-angle-of-attack stability characteristics of a three-surface fighter concept based on the F-15 configuration. They have experimentally measured in a wind tunnel static-force data over an angle-of-attack from 0° to 85° and a sideslip angle from $-10°$ to 10°. Their results have highlighted that the canard adversely affects both static directional and lateral stability at high-angle-of-attack. According to authors, this loss is due to the canard causing a large flow separation on the windward fuselage part.

Similar results have been also highlighted by Agnew, Lyerla and Grafton in [17]. In this work authors have provided a study to a detailed understanding of the aerodynamics of a close-coupled horizontal canard in a three-lifting (canard-win-tail) configuration for a fighter aircraft. This study has highlighted that the vortex interaction phenomenon is responsible of beneficial effect in terms of extending the angle of attack range for the aerodynamic linearity, since the vortex interaction maintains attached the flow over large area that would be normally separated. The abrupt nature of this vortex system's breakdown causes an adverse effect in terms of lateral-directional characteristics.

Section 2 of this work provides the description of the experimental apparatus, some details about the accuracy of the measurements systems, and shows the scaled model under investigation. In section 3 a summary of the main experimental results is shown, highlighting the interference effects introduced by the canard in terms of directional stability. Finally, in section 0 some concluding remarks are drawn.

2 EXPERIMENTAL APPARATUS

The wind tunnel facility is a closed-return, low-speed wind tunnel, shown in Figure 2. Its main characteristics are reported in Table 2. For the measurement of the lateral-directional aerodynamic characteristics a tri-axial internal balance has been used, also supporting the model in the test section. The measurement instrumentation consists of an internal strain gage balance for the measurement of aerodynamic forces and moments, a Venturi system to measure the dynamic pressure, a tilt sensor CrossBow CXLA01 to measure the angle of attack, a potentiometer to measure the sideslip angle (0.1° accuracy, −15° to 25° range), and a temperature probe to measure the static temperature in the test section.

The internal strain gauge balance, used for the directional tests, has three channels and it is used to measure the sideforce, yawing moment, and rolling moment. It is made from an Al-2024-T3 block and it has an estimated accuracy of 0.1% full scale, calibrated suggested in Ref. [8]. The angle of attack is changed with a stepper motor driving the balance sting on a steel circular arc, such that the assembly balance-model rotates about the balance centre in the longitudinal plane. The assembly motor-balance-model rotates about the vertical axis through a mechanism located below the test section floor, allowing to change the sideslip angle.

The required wind tunnel corrections have been applied by following the criteria proposed by Barlow, Rae, and Pope [8]. All the aerodynamic forces have been reduced to the usual aerodynamic coefficients, assuming as reference parameters the test section dynamic pressure, the wing mean aerodynamic chord (mac), wing span, and wing area.

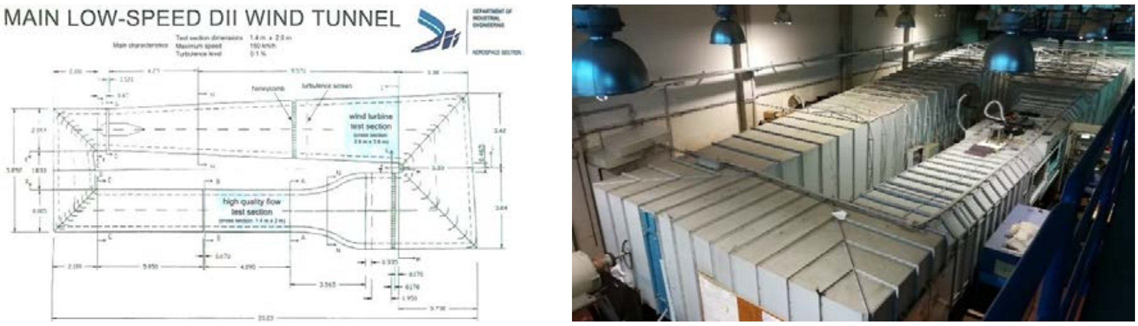

Figure 2: Main subsonic wind tunnel of the Dept. of Industrial Engineering.

Test cross-section dimensions	2.0 m x 1.4 m
Turbulence level	0.10%
Max shaft power	150 KW
Max wind speed	50 m/s
Test wind speed	38 m/s

Table 2: Wind tunnel of the DII, main characteristics.

The wind tunnel model of the airplane has been manufactured in aluminium alloy, through CNC machining. It has a scale ratio of 1:25 with a wing span of 1.50 m, a mac of about 0.13 m, and a fuselage length about 1.52 m. Wind tunnel test have been performed at an average wind tunnel speed of about 38-40 m/s, thus the Reynolds number, evaluated with mac, is about 315000. To replicate the boundary layer of the full-scale aircraft, trip strips were installed to add artificial roughness to the model, forcing the flow transition at the desired stations [8]. The thickness and the right position of the trip strips has been estimated with flow visualization technique using fluorescent oil, as shown in Figure 3. Results led to the conclusion that two layers of tape are enough to get the boundary layer transition at the desired place. The location of the trip strips is at about 5% local chord for wing and horizontal tail, even closer to the leading edge for the vertical tail.

3 DIRECTIONAL STABILITY EXPERIENTAL RESULTS

An extended experimental test campaign has been conducted investigating both the longitudinal and the lateral-directional stability characteristics. However, this work is focused only on the results dealing with the directional stability characterization including the aerodynamics issues of a such unconventional configuration. The objective of this investigation is the evaluation of the interference effects of a small forward wing (the canard) with the fuselage and the vertical stabilizer components.

To address this objective, the experimental tests have been carried out on several configurations, as reported in Table 3, with the aerodynamic derivative of interest, i.e. the yawing moment coefficient curve slope. The reference point for the calculation of the moment is the leading edge of the mean aerodynamic chord, which has been estimated to be a plausible location of the centre of gravity for this rear-engine aircraft configuration.

In Figure 5 the yawing moment coefficient of the isolated body and the body plus the canard are compared. As highlighted by the directional stability derivatives ($C_{N\beta}$) in Table 3, the canard presence increases the fuselage instability of about 14%. This effect is typical of high wing configurations, in which the wing surface creates a high-pressure region on the windward fuselage side. In this case it is magnified because of the longitudinal positions of the canard which is placed quite forward the fuselage centre of gravity.

The horizontal tail leads to an increment of about 5% of the overall aircraft $C_{N\beta}$. This contribution can be appreciated by comparing the $C_{N\beta}$ of the canard-off configuration with and without the horizontal summarized in Table 3, while the yawing moment coefficient curves of these configurations are illustrated in Figure 6. Tests with and without nacelles have highlighted that nacelles do not affect the directional capabilities of the aircraft as shown in Table 3. Same results have been achieved with winglets, which affect in a sensible way the lateral stability, but this latter is not the objective of this paper.

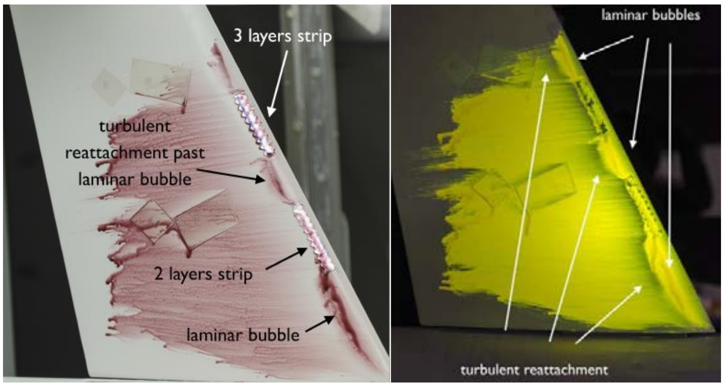

Figure 3: Fluorescent oil visualization on vertical tail.

Configuration	Symbol	Der.	Value (deg^{-1}) @ AoA = 0°	Value (deg^{-1}) @ AoA = 5°
Body	B	$C_{N\beta}$	–0.0022	n.a.
Body-Canard	BC	$C_{N\beta}$	–0.0026	n.a.
Wing-Winglet-Body-Vtail	WWBV	$C_{N\beta}$	0.0020	0.0011
Wing-Winglet-Body-Htail-Vtail	WWBHV	$C_{N\beta}$	0.0021	0.0011
Wing-Winglet-Body-Htail-Vtail-Nacelle	WWBHVN	$C_{N\beta}$	0.0021	n.a.
Wing-Winglet-Body-Htail-Vtail-Canard	WWBHVNC	$C_{N\beta}$	0.0013	0.0000

Table 3: Aircraft configurations and directional stability derivatives at Re = 315000.

(a) B (b) BC

(c) WWBHVN (d) WWBHVNC

Figure 4: Some of the investigated configurations in the test section.

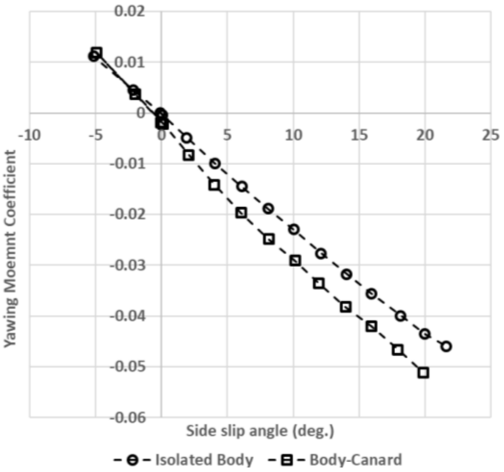

Figure 5: Yawing moment coefficient, canard effect on the fuselage.

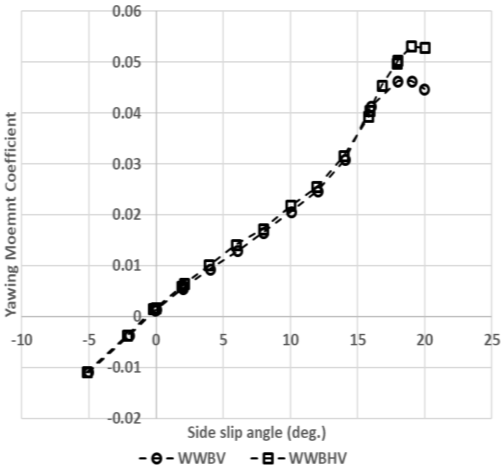

Figure 6: Yawing moment coefficient, horizontal tail effects.

The complete aircraft $C_{N\beta}$ derivative of is about 0.0021 deg^{-1} in the canard-off configuration (see Table 3). The full-scale vertical tail has 25 m^2 planform area, but the directional stability that it is providing is almost the half of the contribution that it should bring accordingly with its size. This latter is due to a wrong taper ratio, which provides for a constant sweep angle along the chord direction, i.e. the sweep angle at the half of the mean chord is 45° as well as at the leading edge, this latter significantly lowers the empennage lift capabilities.

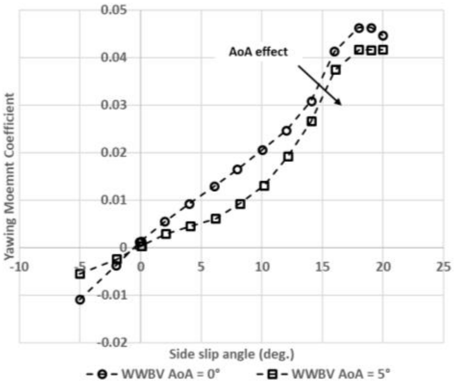

Figure 7: Yawing moment coefficient, effects of the angle of attack.

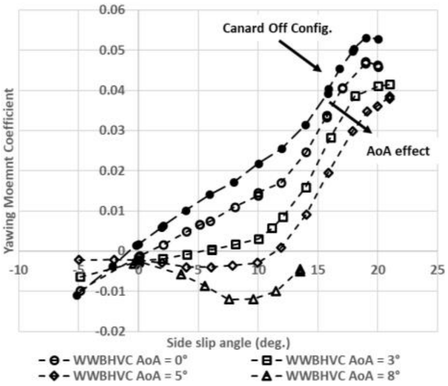

Figure 8: Yawing moment coefficient, canard and angle of attack effects.

The effects of the angle of attack are illustrated in Figure 7, where the yawing moment coefficient of the WWBV configuration at 0° and +5° angle of attack are compared. It is well known [18] that when the angle of attack increases the vertical tail effectiveness is lowered because of the fuselage wake impinging on the empennage. By looking at Table 3 $C_{N\beta}$ is almost halved. It must be remarked that the experimental data are related to a low Reynolds number, this means that the effects of the angle of attack dealing with the fuselage boundary layer thickness could be overestimated.

The most detrimental effect on the directional stability is introduced by the canard surface. As it is shown in Figure 8 and reported in Table 3, the canard reduces the directional stability derivatives by 38% at zero angle of attack. The combined effects of incidence angle and canard leads to a dramatic reduction of the directional stability, till the aircraft become even unstable when the angle of attack become higher than 5°. This strong effect is introduced by the vortex system which is impinging on the vertical empennage. In Figure 9 and Figure 10 flow visualization by means of tufts rake placed on the trailing edge of the canard is shown at two sideslip angle. From flow visualization it can be appreciated that at low sideslip angles the canard tip vortex is impinging the windward side of the vertical tail reducing its capability to produce sideforce. As the sideslip angle increases the tip vortex moves across the vertical tail, when it reach the leeward side of the empennage the lifting capabilities of the tail is suddenly recovered. This latter occurs at sideslip angle higher than 10°, as it can be appreciated in the charts of Figure 8. A similar phenomenon has been also observed by Agnew, Lyerla and Grafton in [17] for a three-surface fighter aircraft, the physical behaviour is similar standing the clear differences in the aircraft configurations.

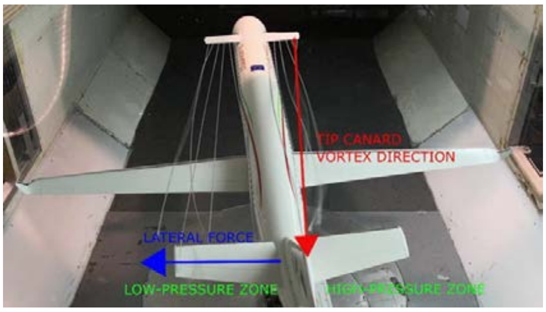

Figure 9: Flow visualization with tufts rake, β = 8°

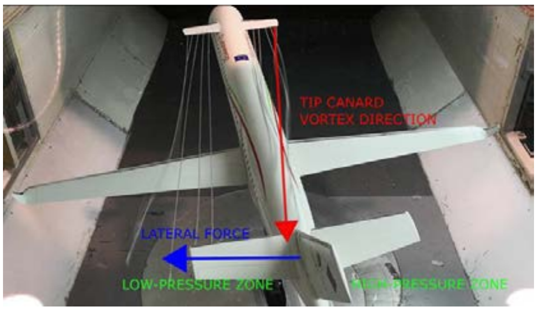

Figure 10: Flow visualization with tufts rake, β = 10°

Canard vertical position has been fixed accordingly the architectural constraints coming from Leonardo company's experts. A lower position has been discarded because of the presence of the avionics system structural bay. Moreover, a lower position of the canard would introduce strong detrimental effects on the wing maximum lift capabilities required to comply with the ground performance prescribed by the Top-Level Aircraft Requirements (TLARs). A redesign of the vertical tail has been already performed and numerical analyses are still in progress at the time of writing. If the new vertical empennage will not solve stability issues and if the magnitude of the canard tip vortex effect will be confirmed, authors will investigate possible systems to improve directional stability like aft body strakes.

4 CONCLUDING REMARKS

This paper has provided experimental results on the directional stability characteristics of a three-surface transport aircraft. Experimental tests have highlighted the detrimental effects of the canard on the vertical empennage capability in producing sideforce. Canard tip vortex moves across the windward and the leeward side of the empennage introducing non-linear effects on the directional stability. Moreover, experimental tests have highlighted that the vertical tail planform must be revised to increase the directional stability of the aircraft. A redesign of the vertical tailplane has been already performed and numerical high-fidelity analyses are still in progress at both wind tunnel and full-scale Reynolds number to have a better comprehension of the aerodynamic behaviour of such a configuration. A new wind tunnel test campaign on the updated aircraft configuration, also including propulsive effects, has been scheduled by the end of year 2019.

5 ACKNOWLEDGEMENTS AND REFERENCES

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REFERENCES

[1] F. Nicolosi, S. Corcione, P. Della Vecchia, V. Trifari, M. Ruocco, A. De Marco, "Design and aerodynamic analysis of a regional turboprop innovative configuration", 6th CEAS Air & Space Conference Aerospace Europe, Bucharest, Romania, 2017.

[2] F. Nicolosi, S. Corcione, P. Della Vecchia, V. Trifari, M. Ruocco, "Aerodynamic design and analysis of an innovative regional turboprop configuration", 31th Congress of the International Council of the Aeronautical Sciences, Belo Horizonte, Brazil, September 09-14, 2018.

[3] F. Nicolosi, A. De Marco, L. Attanasio, P. Della Vecchia, "Development of a Java-Based Framework for Aircraft Preliminary Design and Optimization" Journal of Aerospace Information System, Vol 13, pp. 234-242, 2016.

[4] V. Trifari, M. Ruocco, V. Cusati, F. Nicolosi, A. De Marco, "Java framework for parametric aircraft design–ground performance", Aircraft Engineering and Aerospace Technology (EMERALD); Volume 89, Issue 4, 2017. DOI: 10.1108/AEAT-11-2016-0209.

[5] F. Nicolosi, D. Ciliberti, P. Della Vecchia, S. Corcione, V. Cusati, "A comprehensive review of vertical tail design", Aircraft Engineering and Aerospace Technology, Vol. 89, Issue: 4, pp. 547-557, 2016. DOI: 10.1108/AEAT-11-2016-0213

[6] D. Ciliberti, P. Della Vecchia, F. Nicolosi and A. De Marco, "Aircraft directional stability and vertical tail design: A review of semi-empirical methods", Progress in Aerospace Sciences, Vol 95, pp. 140-172, 2017. DOI: 10.1016/j.paerosci.2017.11.001

[7] F. Nicolosi, P. Della Vecchia, D. Ciliberti and V. Cusati, "Fuselage aerodynamics prediction methods", Aerospace Science and Technology, Vol 55, pp. 332-343, 2016. DOI: 10.1016/j.ast.2016.06.012

[8] J. B. Barlow, W. H. Rae, A. Pope, "Low-speed wind tunnel testing", 3rd ed., Wiley, New York, 1999. ISBN: 0471557749

[9] K. Rokhsaz, B. P. Selberg, "Analytical Study of Three-Surface Lifting Systems", SAE Technical Paper Series 850866, General Aviation Aircraft Meeting and Exposition, Wichita, Kansa, April 16-19, 1985.

[10] K. Rokhsaz, B. P. Selberg, "Three-Surface Aircraft-Optimum vs Typical", Journal of Aircraft, Vol. 26, No. 8, August 1989. DOI: 10.2514/3.45827

[11] K. Rokhsaz, B. P. Selberg, "Aerodynamic Tradeoff Study of Conventional, Canard, and Trisurface Aircraft Systems", Journal of Aircraft, Vol. 23, No. 10, October 1986. DOI: 10.2514/3.45379

[12] E. R. Kendall, "The Aerodynamics of Three-Surface Airplanes", AIAA/AHS/ASEE Aircraft Design Systems and Operations Meeting, San Diego, California, October 31-Novemebr 2, 1984. DOI: 10.2514/6.1984-2508

[13] D. Strohmeyer, R. Seubert, W. Heinze, C. Österheld, L. Fornasier, "Three Surface Aircraft – A Concept for Future Transport Aircraft", 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 2000. DOI: 10.2514/6.2000-566

[14] C. Ostowari, D. Naik, "An Experimental Study of a Three Lifting Surface Configuration", 15th Congress of the International Council of the Aeronautical Sciences, London, England, September 7-12, 1986.

[15] C. Ostowari, D. Naik, "Experimental Study of a Three-Lifting Surface Configuration", Journal of Aircraft, Vol. 25, No. 2, DOI: 10.2514/3.45549

[16] S. B. Grafton, A. Croom, "High-Angle-of-Attack Stability Characteristics of a Three-Surface Fighter Configuration", NASA Technical Memorandum 84584, NASA-TM-84584 19830011486, Langley Research Center Library NASA, Hampton, Virginia, March 1983.

[17] J. W. Agnew, G. W., S. B. Grafton, "Linear and Nonlinear Aerodynamics of Three-Surface Aircraft Concepts", Journal of Aircraft, Vol. 18, No. 11, May 2012. DOI: 10.2514/3.57586

[18] J. Roskam, "Airplane design part VI: preliminary calculation of aerodynamic, thrust and power characteristics", DAR Corporation, Lawrence (Kansas), 2000. ISBN: 1-884885-52-7.