ANULOID

Investigation of novel vertical take-off and landing (VTOL) aircraft concept, designed for operations in urban areas

Funding: European (7th RTD Framework Programme)
Duration: Apr 2013 - Mar 2015
Status: Complete with results
Total project cost: €763,653
EU contribution: €577,924

Call for proposal: FP7-AAT-2012-RTD-L0
CORDIS RCN: 108882

Objectives:
Principal objective of the proposed project is a computational and experimental investigation of the novel concept of the VTOL (Vertical Take-Off) aircraft with the nickname Anuloid regarding its flight properties and flying qualities, and to then compare Anuloid with helicopters, tilt rotor aircraft, or other VTOL aircraft concepts, in relation to the potential utilization for transport missions in urban areas.

Parent Programmes:
FP7-TRANSPORT - Transport (Including Aeronautics) - Horizontal activities for implementation of the transport programme (TPT)

Institute type: Public institution
Institute name: The European Commission
Funding type: Public (EU)

Lead Organisation:

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<tr>
<th>Politecnico Di Torino</th>
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</thead>
<tbody>
<tr>
<td>Address: Corso Duca Degli Abruzzi 10129 Torino Italy</td>
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<tr>
<td>Organisation Website: <a href="http://www.polito.it">http://www.polito.it</a></td>
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<td>EU Contribution: €193,361</td>
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Partner Organisations:

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<th>Fesa Sro</th>
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<tr>
<td>Address: Belohorska 260 39 169 00 Praha Czech Republic</td>
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<td>EU Contribution: €61,060</td>
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Universite Paris Nanterre
Technische Universiteit Delft

Address:
STEVINWEG 1
2628 CN DELFT
Netherlands

Organisation Website:
http://www.tudelft.nl

EU Contribution: €79,278

Technologies:
Aircraft design and manufacturing
Vertical take-off and landing

Development phase: Research/Invention

Key Results:

Final Report Summary - ANULOID (Investigation of novel vertical take-off and landing (VTOL) aircraft concept, designed for operations in urban areas)

Executive Summary: The principal objective of this project is the computational and experimental investigation of a novel concept of VTOL (Vertical Take-Off and Landing) aircraft - the Anuloid – with respect to its flying qualities, structural feasibility, and aerodynamic...

Executive Summary:

The principal objective of this project is the computational and experimental investigation of a novel concept of VTOL (Vertical Take-Off and Landing) aircraft - the Anuloid – with respect to its flying qualities, structural feasibility, and aerodynamic characteristics. The Anuloid is conceived for transport missions in urban areas.

The Anuloid is a VTOL aircraft with a toroidal shape and a turboshaft engine in its centre that drives a ducted rotor. The outer diameter is equal to 5 m; the maximum take-off weight should not exceed 1200 kg. Only one propulsion system is implemented for both lift and cruise; this should lead to a more favourable payload-to-empty weight ratio. The forward flight speed of the Anuloid is expected to be in the 100-200 km/h range. The typical operating scenarios are the emergency missions and civil transportation in urban areas.

The Anuloid concept is based on the following three main features:

• The use of a ducted fan powered by a turboshaft for the lift production to take-off and fly.

• The Coanda effect that is developed through the circular internal duct and the bottom portion of the aircraft to provide further lift and control capabilities.
• The adoption of a system of ducted fixed and swivelling radial and circumferential vanes for the anti-
torque mechanism and the flight control.

This aircraft can be considered as an enhanced VTOL with respect to helicopters in terms of lowered
noise pollution (due to the ducted engine) and wider operational scenarios.

The research activity had dealt with the structural design, the aerodynamic analysis - CFD and wind
tunnel -, flight mechanics, and manufacturing.

The main outcomes of the project are the following:

• The structural and aeroelastic design of the ANULOID is not critical. The combined adoption of
stiffened thin-walled structures and composite materials makes the ANULOID structure light and robust.

• The Coanda effect is in place during vertical and horizontal flight. Such an effect can be considered as
one of the lift and control sources.

• The ANULOID surrounding flow can be 3D with flow separation regions.

• The anti-torque mechanism is qualitatively valid.

• The pitching moment is always negative for all the range of the incidences tested. In particular
increasing the incidence the pitching also increases.

• The vertical flight characteristics of the ANULOID are desirable. On the other hand, the horizontal flight
characteristics of the ANULOID in its current form render the aircraft flyable, but not controllable.

A few main recommendations can be drawn for future developments,

• The performance of the ANULOID, in particular, the CL/CD ratio for horizontal flight, should be
improved.

• A nonlinear multi-channel and multi-loop controller should be developed for ANULOID that will allow
piloted control of the aircraft.

• To support efficiently the Coanda effect on the lower annular cavity some active flow control
techniques can be also taken into consideration. For example, the suction or the presence of synthetic
jets appropriately positioned and oriented can maintain the flow attached to all the curved surface.

Project Context and Objectives:

The principal objective of this project is the computational and experimental investigation of a novel
concept of VTOL (Vertical Take-Off and Landing) aircraft - the Anuloid – with respect to its flying
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The ANULOID has 5 participants; Politecnico di Torino (Polito), Universite Paris Ouest Nanterre (UPO), TU
Delft (TUD), Vyzkumny a zkusebni letecky ustav, a.s. (VZLU), and FESA. Polito is the coordinator.
Furthermore, Polito is in charge for the structural and aeroelastic analyses of the aircraft, and the wind
tunnel activities. UPO is in charge for the design of digital mock-ups, and for the anti-torque mechanism
experimental activities. TUD deals with the flight dynamics and control design and the flying qualities of
the aircraft. VZLU deals with CFD analyses and the manufacturing of the fuselage of the scaled aircraft
model. FESA’s contributions are CFD analyses, optimization, design and CAD modelling.

The project has five work packages: Project Coordination; Design and Analysis of Anuloid Aircraft;
Design and Manufacturing of Scaled Model; Measurements and Wind Tunnel Tests; Dissemination.
The main objectives of the project are the following:

- Setup of the initial configuration, and preliminary flyability studies.
- Creation of a full-scale digital mock-up of the aircraft.
- Analysis of the external and internal aerodynamics of the full-scale aircraft through CFD analysis tools.
- Creation of the flight dynamics model of the full-scale aircraft to analyse its flying qualities, performance parameters and flight envelope.
- Analysis of the structural and aeroelastic behaviour of the full-scale aircraft.
- The design of the reduced scale mock-up of the aircraft for the manufacturing and the following measurements and wind tunnel tests.
- Manufacturing of the fuselage of the reduced scale mock-up
- Measurements and Wind Tunnel Tests.

A brief description of the main activities that were carried out is given hereafter. The initial configuration structural configuration was improved by the design of a structural frame that is composed of radial and circumferential stiffeners and ribs.

A preliminary flyability analysis was conducted from M0 to M6. The flyability analysis consisted of a static flight performance analysis, a static stability analysis and a dynamic stability analysis. These analyses exploited the results from the initial configuration setup (mass properties) and the results from the computational fluid dynamics (CFD) for the horizontal and vertical flight. The CFD analyses highlighted the efficiency of the control vanes and the stability of the Coanda effect given a minor modification of the internal duct geometry. The flyability analysis showed that the vertical flight of the Anuloid has satisfactory flying qualities. The dynamic stability analysis showed that the Anuloid is dynamically unstable during horizontal flight. While not dramatically unstable, the Anuloid can have inadequate handling qualities during forward flight. Due to the observed instability, the Anuloid can require an automatic flight control system that is capable of stabilizing the aircraft, in particular during horizontal flight. The most critical issues were detected, and they are related to the stability of the Coanda effect, the effectiveness of the anti-torque mechanism and the dynamic instability of the aircraft. On the basis of these outcomes, from M6 to M12, priority was given to the experimental and CFD analyses of the Coanda and anti-torque mechanism and to further flight mechanics developments.

The main workplan variations at the end of the first year were the following:

- The aerodynamic experimental activity was extended to a small scale 3D printed model of the aircraft to investigate the Coanda effect.
- A small-scale simplified model of the rotor-vane mechanism is being built to investigate the anti-torque mechanism.
- Other activities - Power means, flight control means and remote (or tethered) control system; Fuselage with integrated power means, flight control means and other devices – were suspended.

The final months of the project aimed at the definition of configuration modifications for future developments of the aircraft with higher TRL.

Project Results:

WP-1, Project Coordination

The main management tasks and achievements are the following:

- The risk mitigation plan. The main outcomes of this task were the suspension of two tasks and the definition of two new experimental activities on the Coanda effect and the anti-torque mechanism.
- Management of the deliverable writing and uploading.
- Management of the website and the intranet.
- Management of the coordination activities during the period in question and organization of the meetings.
- Management of the development of configuration modifications for future developments of the ANULOID with higher TRL.
WP-2, Design and Analysis of Anuloid Aircraft

Significant results:

• The structural design of the aircraft is not a critical task since potential detrimental structural behaviours can be easily dealt with. In particular, no aeroelastic phenomena were observed.

• Although the CFD analyses confirmed the stability of the Coanda effect, experimental activities showed that the Coanda effect can be weak. Geometrical modifications proved to be effective in strengthening the Coanda effect. Further experimental and CFD analyses have to be carried out.

• There are some doubts about whether the current control effectors provide sufficient control authority to stabilize ANULOID during forward flight. Some configuration changes could be needed. Moreover, more detailed CFD analyses of the transition phases are needed. The design of an automatic control flight system is mandatory.

• The Coanda effect is continuously present at the lower surface of the ANULOID during the steady vertical and horizontal flight and the horizontal acceleration for both examined angles of attack as well. During the horizontal acceleration, the aerodynamic forces and moments remain constant or continually increased (according to their physical character) with the time and thus with the flight speed. The preliminary conclusion can be deduced that moderate acceleration does not adversely influence the ANULOID aerodynamic characteristics.

• The results show that Coanda effect with the improved geometry of the circumferential control vanes is very strong during takeoff/landing flight. Furthermore, there exist ground effect from base takeoff/landing position up to height range ca 2.5 - 3.75 m above ground, where the transition to free flight occurs. In the interval 3.75 to 5 m. The properties of flow change only a few percent and from 5 m upward they can be then considered as properties in free air flight.

• The vertical flight characteristics of ANULOID are desirable.

• The horizontal flight characteristics of ANULOID in its current form render the aircraft flyable, but not controllable.

• An in-depth analysis of the pitch and roll authority shows that the control moment components of the total pitch and roll must be amplified by a factor of 4 to for adequate control of ANULOID. Adequacy is defined as the ability to track a 5 deg/s pitch rate and roll rate reference signal.

• The engine angular momentum has a significant effect on the flight dynamics of the ANULOID, coupling all pitch and roll motions.

• The inclusion of dynamic damping terms significantly increases the stability of ANULOID during high amplitude manoeuvres. The magnitude of the damping is relatively small compared to the controlled and uncontrolled (aerodynamic) forces and moments.

• The effectiveness of the pitch and roll control vanes should be increased by a factor of at least 4.0 in order to allow tracking of roll and pitch rate references of 5 deg/s without saturating the control vanes, which can be seen as a minimum performance requirement.

• The effectiveness of the rotor volume flow as a control effector must be increased by a factor of at least 10.0 in order to be able to maintain a 1 m/s ascending flight.

WP-3 Design and Manufacturing of Scaled Model

Significant result:

• The manufacturing of the reduced scale model for the wind tunnel testing was completed.

WP-4 Measurements and Wind Tunnel Tests

This WP was carried out, and these activities were conducted,

• Wind tunnel tests on the 1:5 scale model.

• Coanda effect tests on the printed 3D model.

• Anti-torque mechanism test on a simplified test rig.

Significant result:

• The Reynolds effect is evident for the range of positive incidences for the lift force and the pitching moment while it is nearly absent for negative incidences. Particularly evident is instead the Reynolds
effect for the drag. In particular at higher Reynolds number the drag curve is always lowered respect to the case of low Reynolds number.

- The behaviour of some aerodynamic coefficients, namely the lift, drag and rolling moment, change drastically their trend around $\pm 0^\circ$. This suggests that a significant variation of the flow topology around the body and especially on the lower side can take place.

- The pressure maps highlight very complex 3D flow developing the model. At negative incidences, a vortical structure can be present in the circumferential curved lower cavity wall in the fore-body part of the model creating the Coanda effect. This effect as the incidence increase negatively tend to disappear. The upper side of the model presents attached flow in the anterior part of the model at all the incidences. Whereas the flow is separated and also unsteady in its rear part in an angular sector $\pm 45^\circ$ respect to the symmetry plane.

- The comparison between the experimental results obtained by POLITO and the CFD results obtained by the VZLU, evidence a good agreement for the incidences analysed.

- Flow visualizations confirm the results obtained by the force and moment measurements and especially also by the pressure data. The videos show 3D separated flow regions on both sides of the model and moreover flow unsteadiness are evidenced according to the incidence. It has to be remark that the present results are related to a configuration of the model without the fan effect for the reasons reported in the present work.

- The proposed test rig permitted to answer the question whether the swivelling vanes system can control the yaw motion by means of more refined and instrumented measurements of the yaw moment: all results confirmed that by swivelling the vanes the system could be rotated about the yaw axis.

WP-5, Dissemination

This WP was regularly carried out.

Significant result:

- The results that were obtained in M0-M6 were published in a paper:


- The following paper conference was presented by Dr. Janda (FESA):

  ANULOID Novel VTOL aircraft for urban areas. Concept, methodology and project' interim results, at AVIA-INVEST international conference, Riga 10 -11 April, 2014

- An oral presentation to a wider public: was carried out by UPO:

  ANULOID Overview at the 50th anniversary of the Université Paris Ouest Nanterre La Défense.

- Another journal paper will be submitted in the next weeks in which the final results of the project will be described.

- The ANULOID project will be presented at the next AERODAYS meeting in London.

Potential Impact:

The Anuloid could represent an effective mean to alleviate the increasing problems with emergency and urgent transport in urban areas. Traffic congestion and disrupting ground transport will occur during next decades more frequently and more extensively, due to an increasing urban population and traffic, as the Focus group of European Commission for future transport has recently alerted. Today, helicopters are the standard solution for emergency and urgent transport in the open environment, but their operations are severely limited by weather and they cannot take-off and land near buildings. It should be especially noted that 20% - 30% of helicopter missions are lost annually in Europe due to weather conditions, and more than half of those are directly associated with icing.

The Anuloid is a ducted fan VTOL vehicle. It has the capability of performing rescue missions in areas that are totally inaccessible to helicopters. It can work in very gusty winds (relying on fly-by-wire control system), and is capable of operating in icing conditions. In addition, the Anuloid will have a much lower noise level than helicopters, achieved

By using new low noise blades and by having rotor contained inside double-walled ducts, with optional
additional passive or active acoustic treatment placed on the duct walls.

The ANULOID project outlined a number of main technical issues to be deal with in the case of future developments. The primary Anuloid issues are the forward flight instability and insufficient control authority. The secondary Anuloid potential issue, indicated by the CFD analysis, seems to be very high drag, but the magnitude of this drag must validated in future in wind tunnel with model with fully functioning rotor and with functioning wall jet (Coanda effect), because drag calculation by CFD are very often for complex geometries (such as Anuloid) not precise due very high sensitivity of drag on computational grid resolution, type and parameters of turbulence model and on near-wall treatment of flow. Moreover, as far as the anti-torque system is concerned, it can be stated that the proposed configuration is qualitatively able to produce anti-torque. Further, quantitative analyses are required to enhance the reliability of the anti-torques system.

As a general guideline, the reconfiguration of the ANULOID should move from a “flying-disk-shaped” to an “aircraft-shaped” ANULOID. This means that, for instance, a number of primary components should be added, such as

- Lateral wing-like surfaces with movable surfaces.
- Small rotors (both for control and anti-torque capabilities).

In the event of an ANULOID follow-up, the following high-priority activities should be carried out:

1. Additional wind tunnel experiments in which rotor thrust is present must be conducted to validate the CFD dataset, in particular during forward flight. The cause of the very strong nose-down moment predicted by the horizontal CFD response surfaces should be investigated.

2. Flight testing must be performed with a scale model to further validate the accuracy of the current aerodynamic dataset. In particular, dynamic effects (gyroscopic coupling, dynamic damping, Coriolis forces), which cannot be obtained in a wind tunnel, must be evaluated. The true dynamic damping coefficients can be estimated via flight testing.

3. The performance of ANULOID, in particular, the CL/CD ratio for horizontal flight, should be improved; the current model cannot sustain altitude and forward velocity for flight speeds above 15 m/s. This problem is alleviated by increasing the effectiveness of the rotor volume flow as a control effector by a factor of at least 10.0.

4. ANULOID is statically and dynamically unstable, meaning that un-augmented control is infeasible. Therefore, a nonlinear multi-channel and multi-loop controller should be developed for ANULOID that will allow piloted control of the aircraft.

5. To support efficiently the Coanda effect on the lower annular cavity some active flow control techniques can be also taken into consideration. For example, the suction or the presence of synthetic jets appropriately positioned and oriented can maintain the flow attached to all the curved surface.

The results that were obtained in M0-M6 were published in a paper:


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The ANULOID project will be shown at the AERODAYS 2015, London, UK 20-23 October 2015.

List of Websites:

http://www.mul2.polito.it/anuloid/

Documents:
Final Report Summary - ANULOID (Investigation of novel vertical take-off and landing (VTOL) aircraft concept, designed for operations in urban areas)

STRIA Roadmaps: Other specified
Transport mode: Air transport
Transport sectors: Passenger transport
Transport policies: Digitalisation
Geo-spatial type: Urban