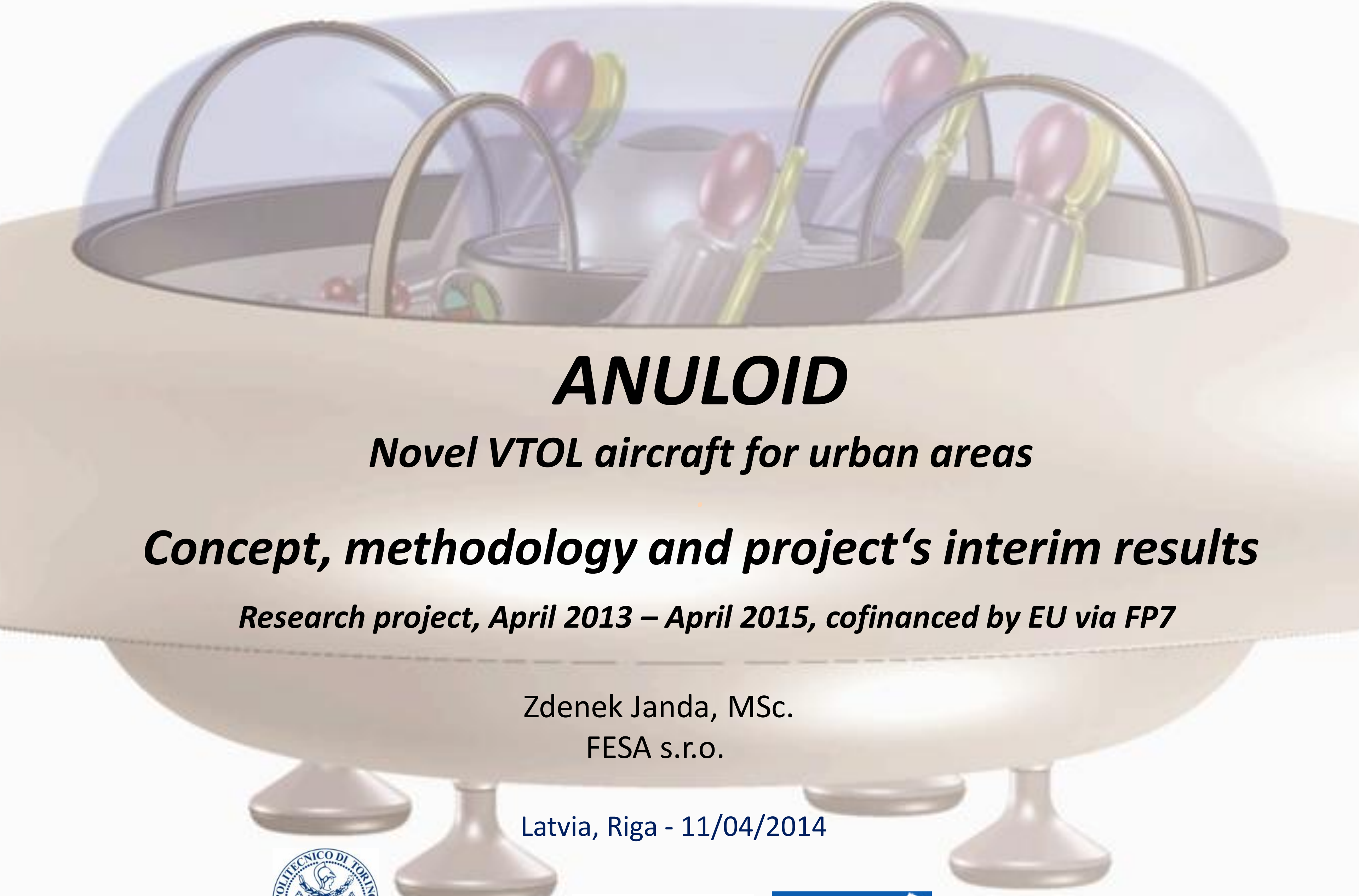

ANULOID

Novel VTOL aircraft for urban areas

Concept, methodology and project‘s interim results

Research project, April 2013 – April 2015, cofinanced by EU via FP7

Zdenek Janda, MSc.
FESA s.r.o.

Latvia, Riga - 11/04/2014

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Project consortium

- **Politecnico di Torino** **(Italy)** **-** Coodinator of project

  Contact person: Prof. Erasmo Carrera – Project leader (erasmo.carrera@polito.it)

- **Universite Paris Ouest Nanterre – La Defense, Institute of Engineering Sciences** **(France)**

  Contact person: Prof. Olivier Polit (Olivier.Polit@u-paris10.fr)

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- **Vyzkumny a zkusebni letecky ustav, a.s.** **(Czech Republic)** (Aerospace Research and Test Establishment)

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- **FESA s.r.o.** **(Czech Republic)**

  Contact person: Zdenek Janda, MSc. (zdenek.janda@centrum.cz)

Project objectives

- Design and computationally investigate novel concept of VTOL aircraft Anuloid, compare it with known VTOL aircraft concepts, in relation to transport missions in urban areas
- Design and manufacture scale model(s) of Anuloid
- Experimentally investigate scale model(s) of Anuloid

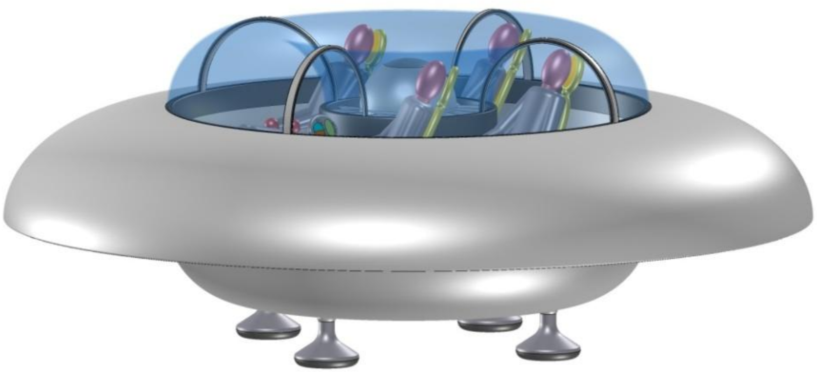
Computational investigation is based on multidisciplinary approach, including computational fluid dynamics, flight mechanics, structural analysis and aeroelastic analysis.

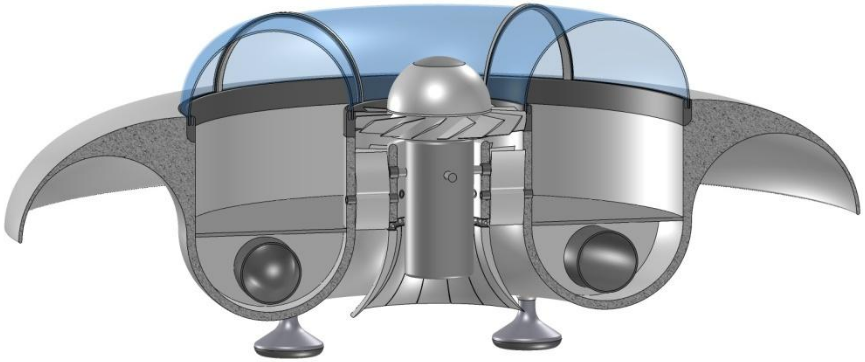
Experimental investigation consists of static and dynamic tests performed on earth and in aerodynamic tunnel.

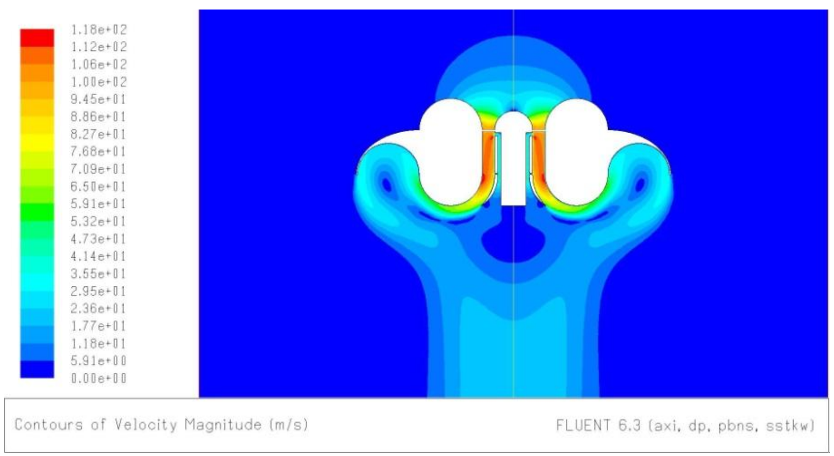
More details about project: http://www.mul2.polito.it/anuloid/

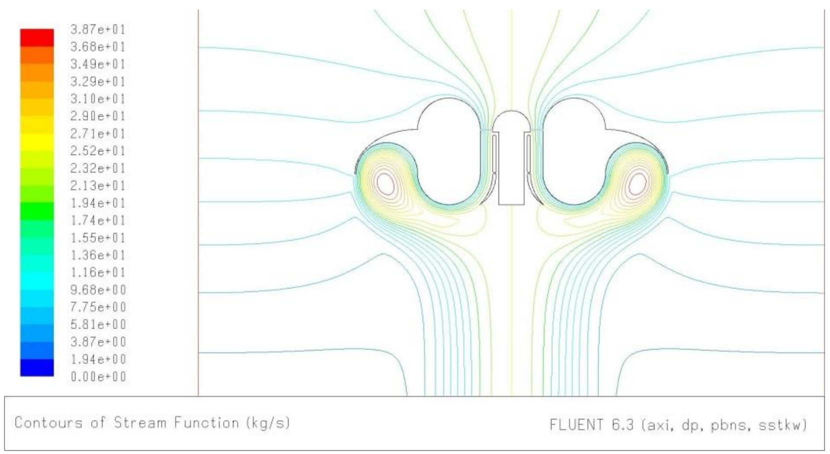
Anuloid concept

Created by Zdenek Janda, MSc. (FESA s.r.o.), Czech patent CZ 303326 (2009, "Aircraft propeled by ducted fan„)









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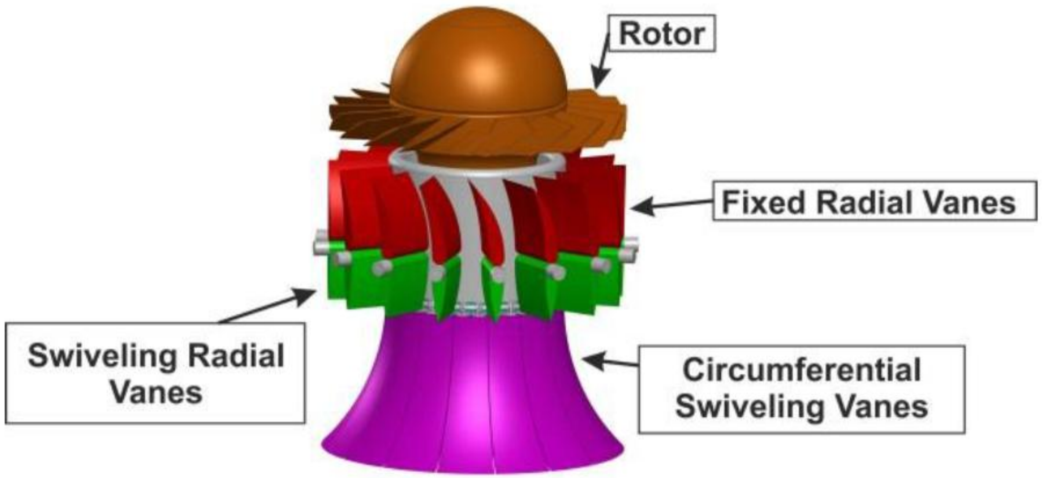
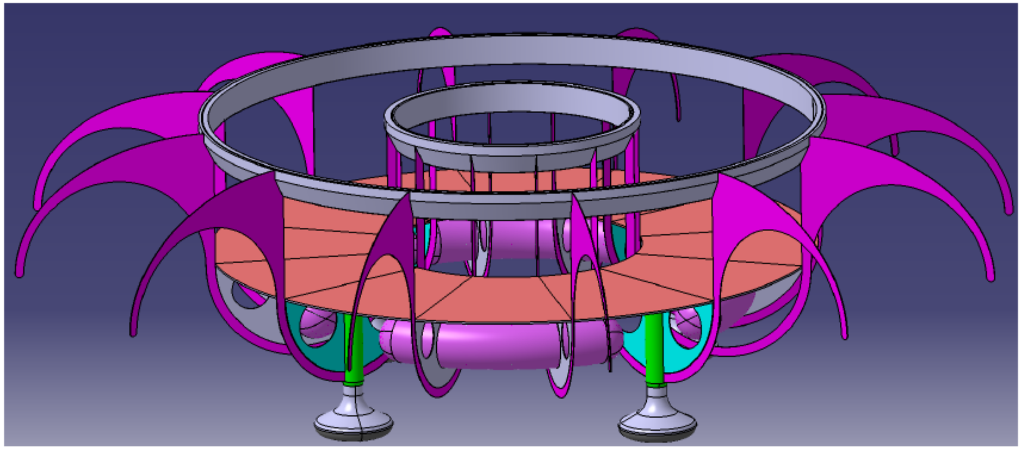
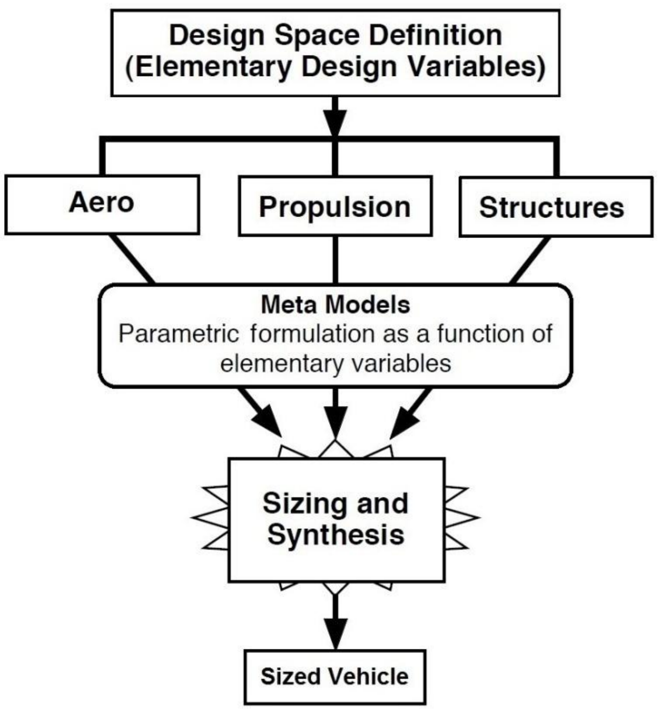
System of control vanes and ribs



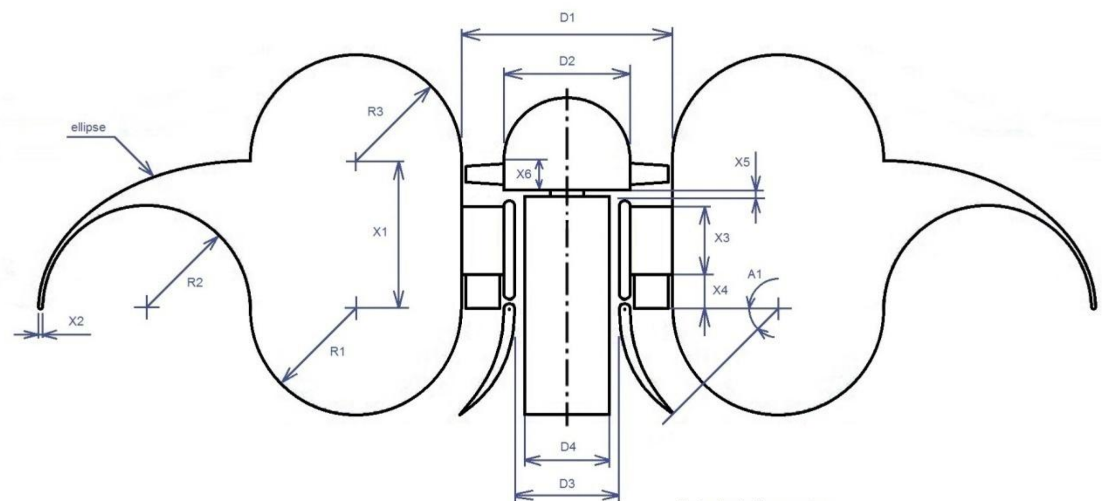


Design and analysis methodology

Generic methodology



Parametrization of Anuloid



Initial values of main parameters for full scale Anuloid aircraft:

Overall diameter = 5 m
Rotor diameter = 1 m
Wall jet thickness = 0,2 m

Initial values of main parameters for 1:4 scale model of Anuloid:

Overall diameter = 1,25 m
Rotor diameter = 0,25 m
Wall jet thickness = 0,05 m

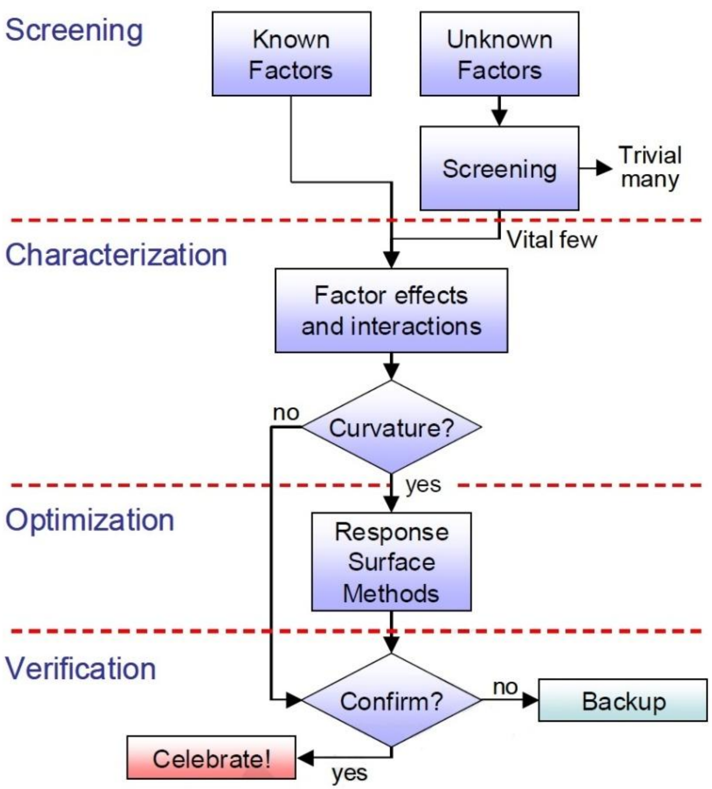
Main physical parameters:

Weights (empty, with people, with fuel)
Center of gravity
Inertia moments
Engine characteristics
Rotor characteristics
Angle of attack
Angle of attack rate
Rolling rate
Yaw rate
Height over ground (during VTOL)
Horizontal velocity
Vertical velocity
Air flow rate through rotor
Angles of control vanes
Air standard properties

Design and analysis methodology

Design Of (computer) Experiments + Response Surface Methods

Developed during 50's and be in common usage worldwide.
Into aerospace introduced in 90's by NASA, Boeing, Lockheed-Martin, etc.



Example of Design Of (computer) Experiment (DOE) table

	Factor levels coded			Responses	
Id	A	B	C	Y1	Y2
1	-1	-1	-1	263.99	107.42
2	1	-1	-1	389.94	96.12
3	-1	1	-1	205.84	66.92
4	1	1	-1	292.53	110.06
5	-1	-1	1	290.10	141.33
6	1	-1	1	302.32	147.24
7	-1	1	1	164.29	79.95
8	1	1	1	160.37	82.63
9	-1.68	0	0	211.04	57.15
10	1.68	0	0	272.08	53.42
11	0	-1.68	0	293.78	68.93
12	0	1.68	0	147.13	39.40
13	0	0	-1.68	418.55	221.96
14	0	0	1.68	273.06	193.89
15	0	0	0	268.38	64.29

Responce surface function Y (e.g. polynom of second order) is created for each response column, through least squares fitting, and approximates relevant response in all design space.

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j$$

k = number of factors (parameters)

One or more responce surface function can be optimized in relation to factors (parameters) and in relation to relevant constraints. For simultaneous optimization of several responce surface functions it is used some composed objective function, e.g. "desirability function".

CFD analysis of vertical flight

- **56 analysis cases**

  (= Double of definition coefficients for response surface function of 2nd order)

- **6 input parameters (a.k.a. factors)**

  (Rotor diameter, Lenght of radial control vanes, Angle of radial control vanes, Number of radial control vanes, Volume flow through rotor, Aircraft vertical velocity)

- **5 outputs**

  (Axial moment, Pressure (body) lift, Rotor lift, Total lift, Required power)

- **Rotor was substituted by annular surface with prescribed volume flow**

- **CFD software: Fluent 14.5 with Reynold stress turbulence model (RSM)**

CFD analysis of vertical flight

Inputs for the CFD analysis of the vertical flight

Parameter	Range	Unit
Rotor diameter	1.0 - 1.2	m
Number of the radial control vanes	8 - 16	-
Length of the radial control vanes	0.2 - 0.3	m
Angle of the radial control vanes	0 - 10	deg
Volume flow through the rotor	80 - 100	m^3/s
Vertical velocity	-5 - 5	m/s

Example of output response surface function: Total lift (N)

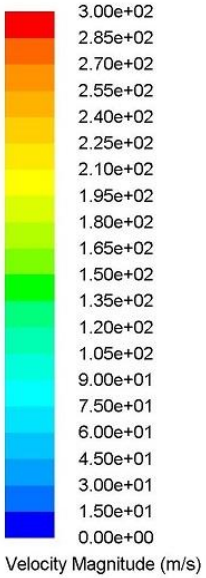
Final Equation in Terms of Coded Factors:

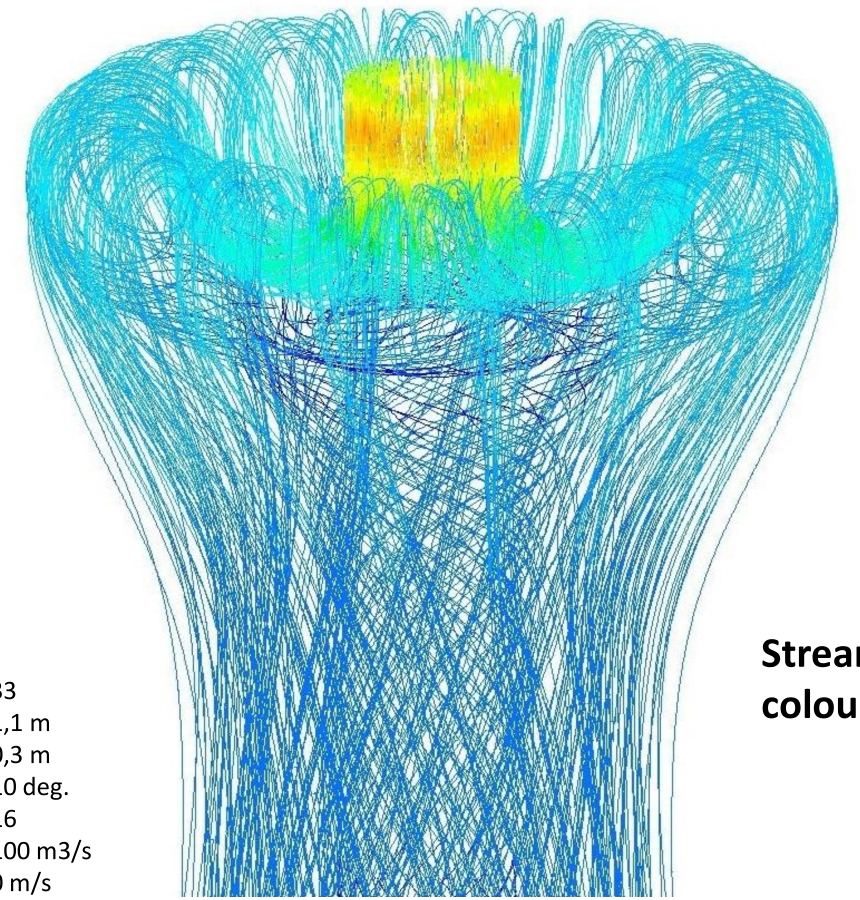
Total lift	=
+4964.59	
-501.93	* A
-87.65	* B
-122.92	* C
+299.04	* D
+1611.75	* E
-3231.44	* F
-4.51	* A * B
+20.84	* A * C
+91.89	* A * D
-133.94	* A * E
+122.56	* A * F
+20.13	* B * C
+49.80	* B * D
-99.56	* B * E
+73.27	* B * F
-164.62	* C * D
-39.13	* C * E
-122.90	* C * F
+90.05	* D * E
-167.50	* D * F
-487.68	* E * F
+160.40	* A^2
+52.52	* B^2
-113.67	* C^2
-80.51	* D^2
+326.51	* E^2
+2868.43	* F^2

Final Equation in Terms of Actual Factors:

Total lift	=
+29681.33674	
-30992.10492	* Diameter of rotor
+3264.68696	* Lenght of radial control vane
+124.10808	* Angle of swivel of radial control vane
-280.89136	* Number of control vanes
-252.54136	* Volume flow through rotor
+13.71492	* Vertical velocity
-901.96670	* Diameter of rotor * Lenght of radial control vane
+41.67364	* Diameter of rotor * Angle of swivel of radial control vane
+229.72701	* Diameter of rotor * Number of control vanes
-133.94038	* Diameter of rotor * Volume flow through rotor
+245.12228	* Diameter of rotor * Vertical velocity
+80.53435	* Lenght of radial control vane * Angle of swivel of radial control vane
+249.01599	* Lenght of radial control vane * Number of control vanes
-199.11229	* Lenght of radial control vane * Volume flow through rotor
+293.07579	* Lenght of radial control vane * Vertical velocity
-8.23116	* Angle of swivel of radial control vane * Number of control vanes
-0.78252	* Angle of swivel of radial control vane * Volume flow through rotor
-4.91595	* Angle of swivel of radial control vane * Vertical velocity
+2.25127	* Number of control vanes * Volume flow through rotor
-8.37482	* Number of control vanes * Vertical velocity
-9.75365	* Volume flow through rotor * Vertical velocity
+16039.93799	* Diameter of $rotor^2$
+21007.56452	* Lenght of radial control $vane^2$
-4.54661	* Angle of swivel of radial control $vane^2$
-5.03167	* Number of control $vanes^2$
+3.26515	* Volume flow through $rotor^2$
+114.73726	* Vertical $velocity^2$

CFD analysis of vertical flight





Example of analysis results:

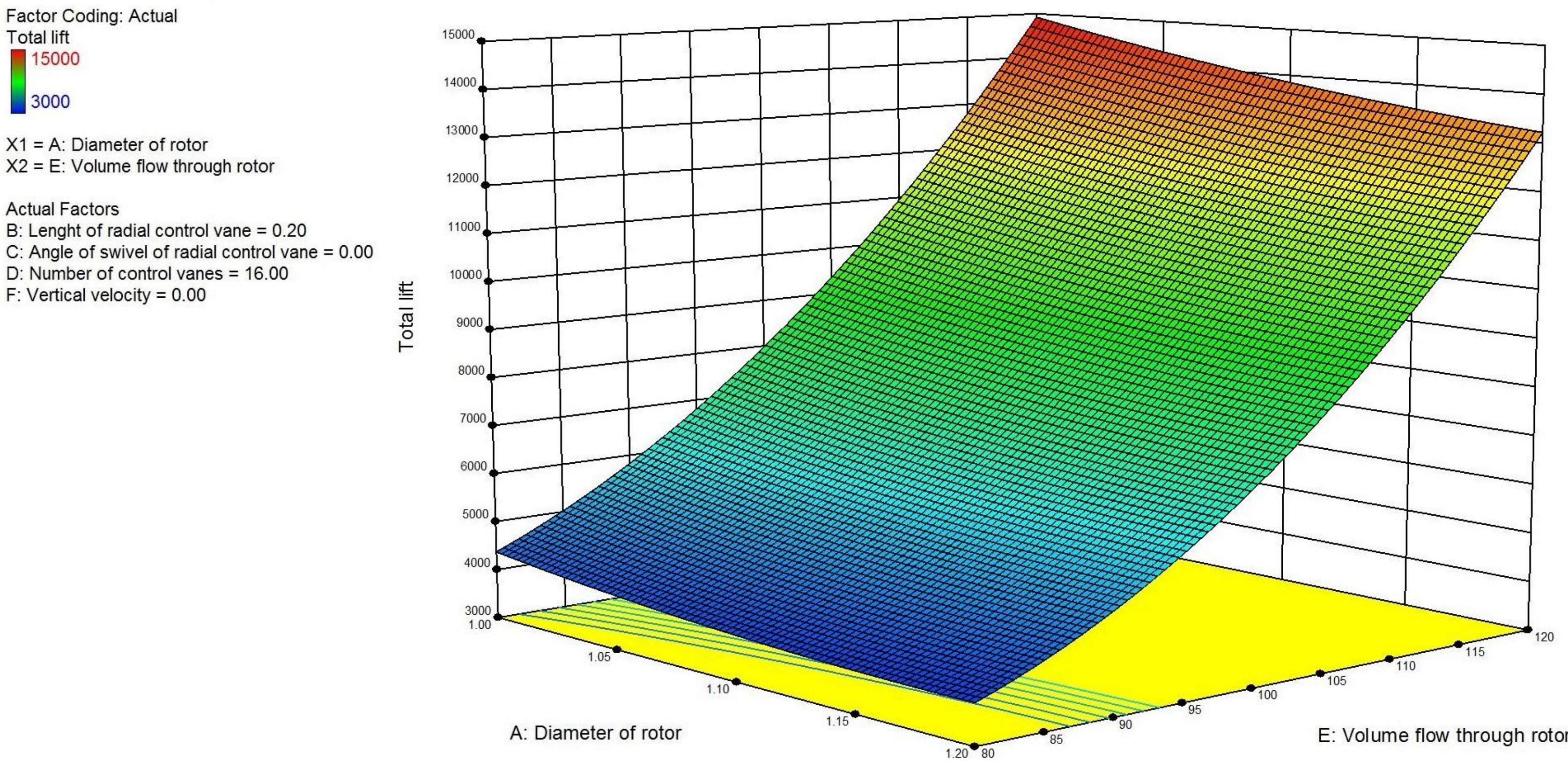
Analysis case:	33
Rotor diameter:	1,1 m
Lenght of radial control vane:	0,3 m
Angle of radial control vanes:	10 deg.
Number of radial control vanes:	16
Volume flow through rotor:	100 m3/s
Aircraft vertical velocity:	0 m/s

Streamlines outgoing from rotor coloured by velocity magnitude

CFD analysis of vertical flight

Example of output response surface function:

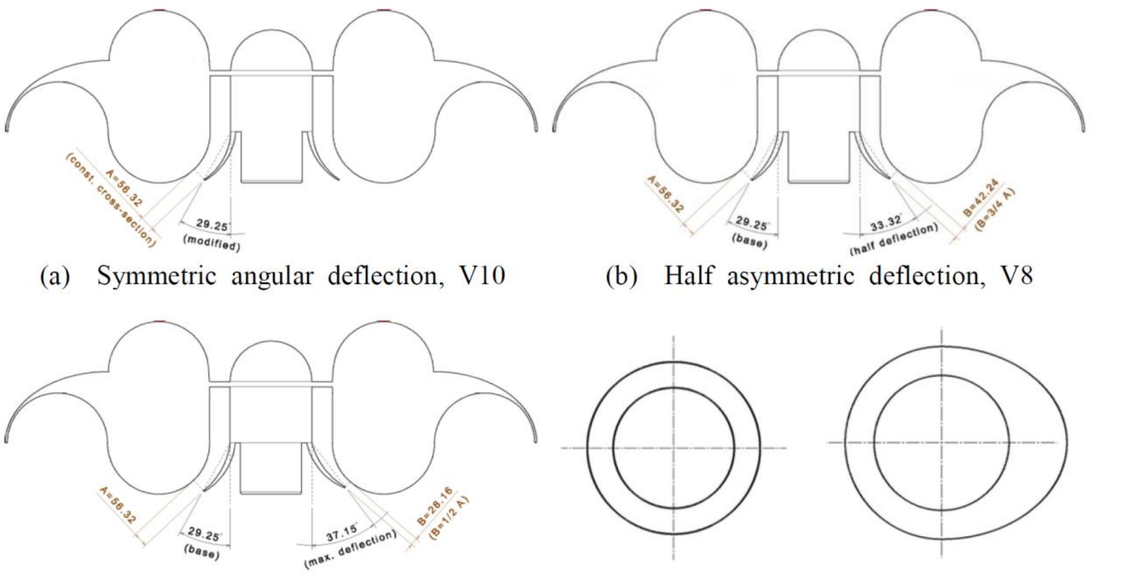
Dependency of Total lift on Diameter of rotor and Volume flow through rotor



CFD analysis of horizontal flight

- **30 analysis cases**
  (= Double of definition coefficients for response surface function of 2nd order)
- **4 input parameters (a.k.a. factors)**
  (Position of circumferential control vanes, Horizontal velocity, Volume flow through rotor, Angle of attack)
- **5 outputs**
  (Tilting moment, Pressure (body) lift, Rotor lift, Total lift, Required power)
- **Rotor‘s diameter was fixed on 1,2 m, based on results of vertical flight analysis**
- **Rotor was substituted by annular surface with prescribed volume flow**
- **CFD software: EDGE (FOI‘s in-house) with Reynold stress turbulence model (RSM)**

CFD analysis of horizontal flight



(a) Symmetric angular deflection, V10

(b) Half asymmetric deflection, V8

(c) Fully asymmetric deflection

(d) Horizontal plan of symmetric and asymmetric deflection of the "collar" of the circumferential control vanes

Final baseline deflection of the circumferential control vanes

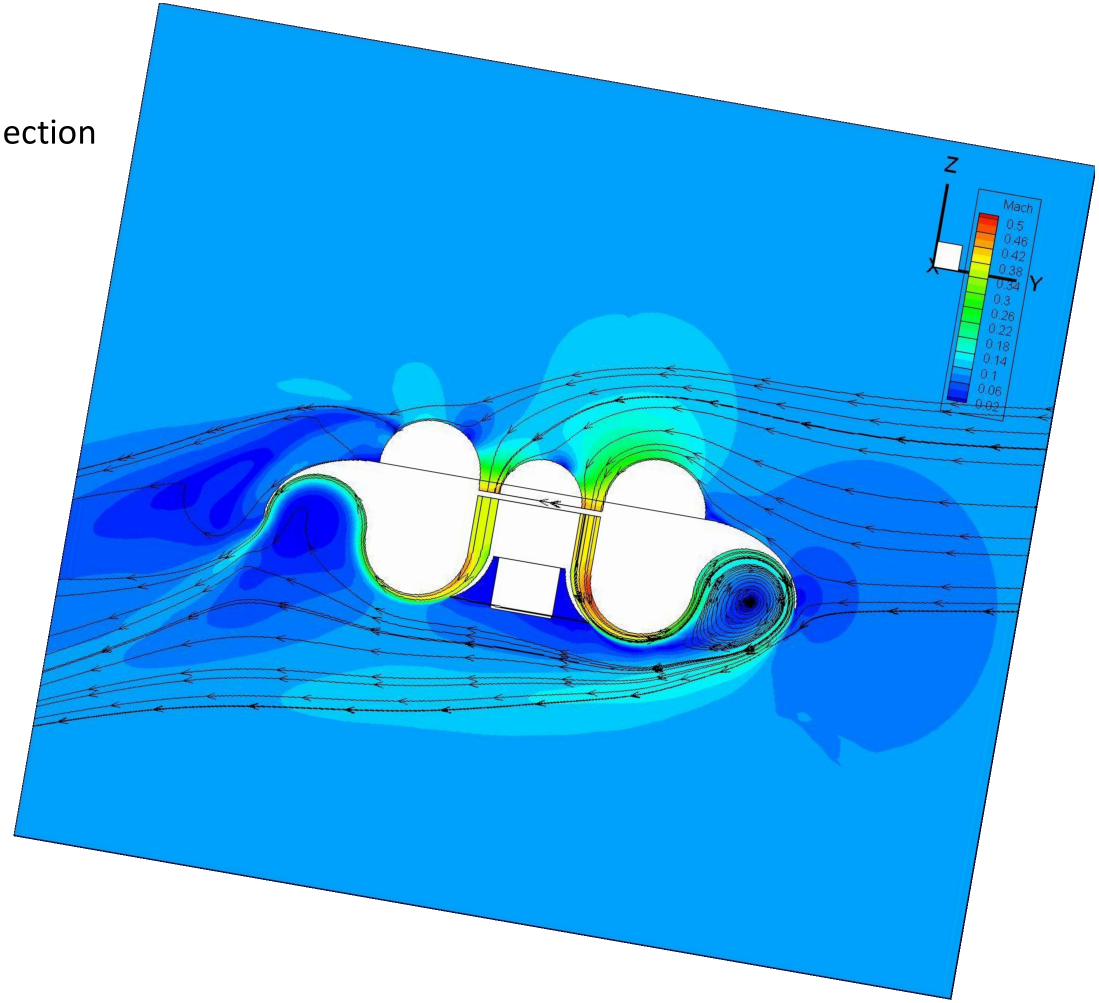
Computed combinations of input parameters (factors)

combination	control vanes	velocity	mass flow	AoA
1	asymm	-30	100	-10
2	symm	30	100	10
3	symm	30	100	-10
4	asymm	-30	80	-10
5	symm	-30	80	0
6	symm	-30	80	10
7	asymm	30	100	-10
8	asymm	1	90	-10
9	symm	-30	100	-10
10	symm	-30	100	10
11	asymm	30	80	-10
12	1/2 asymm	-30	80	-10
13	asymm	30	80	0
14	asymm	30	100	10
15	symm	30	80	10
16	asymm	-30	80	10
17	symm	1	80	-10
18	symm	1	100	0
19	asymm	-30	90	10
20	asymm	-30	100	0
21	symm	30	90	10
22	symm	30	80	-10
23	1/2 asymm	1	90	0
24	1/2 asymm	30	100	-10
25	asymm	1	100	10
26	1/2 asymm	1	80	10
27	asymm	30	80	10
28	symm	-30	90	-10
29	1/2 asymm	-30	100	10
30	1/2 asymm	30	90	0

CFD analysis of horizontal flight

Example of analysis results:
Combination: 12
Control vanes: 1/2 symmetric deflection
Freestream velocity: -30 m/s
Mass flow: 80 m^3/s
Angle of attack: -10 deg

Mach contours and streamlines



Conclusions of CFD analysis

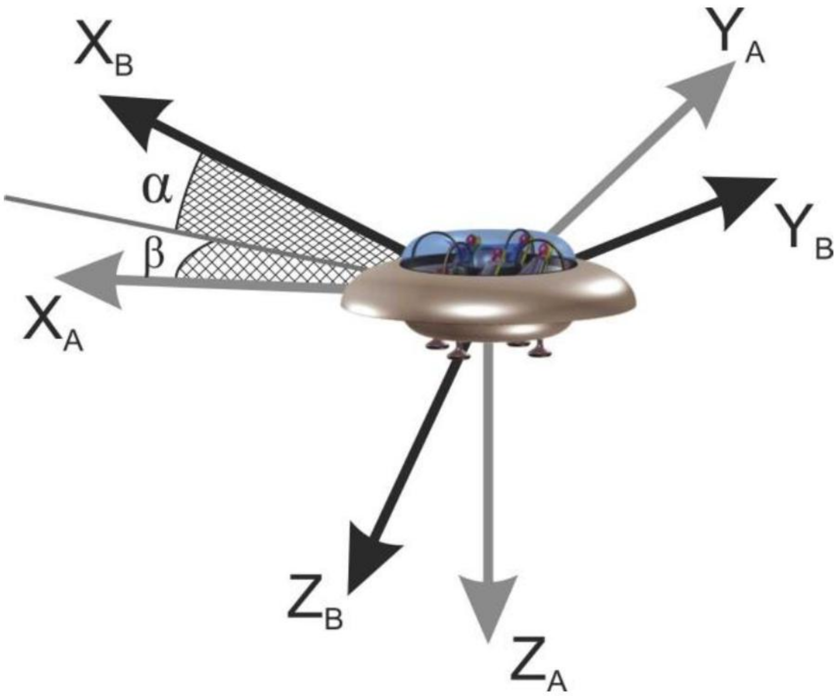
- CFD computations provided response surface functions (i.e. value functions) of aerodynamic forces, moments and of required power with respect to relevant input parameters

- Coanda effect is stable at all studied combinations of input parameters

- Control vanes are able to create axial and tilting control moments

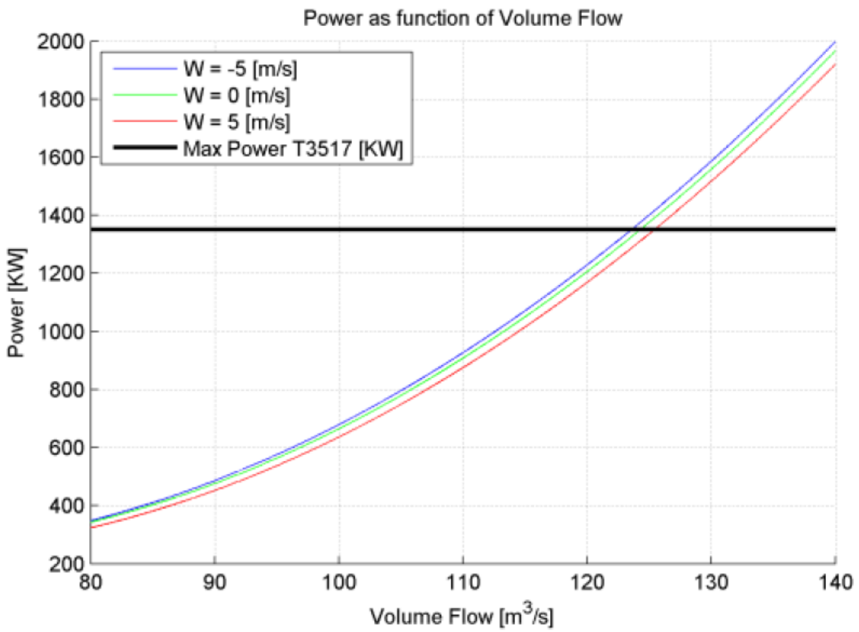
Flyability analysis

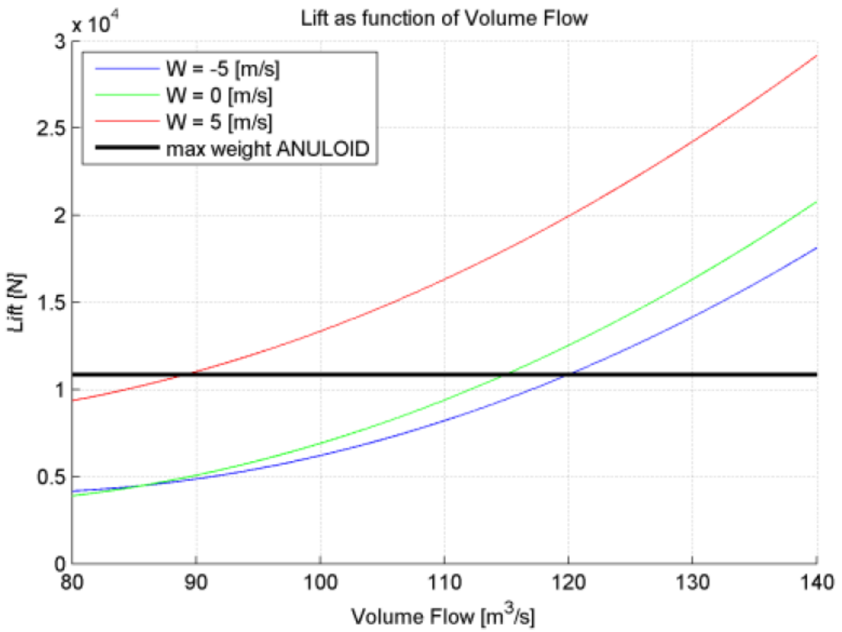
Combination of static performance together with a static and dynamic stability analysis



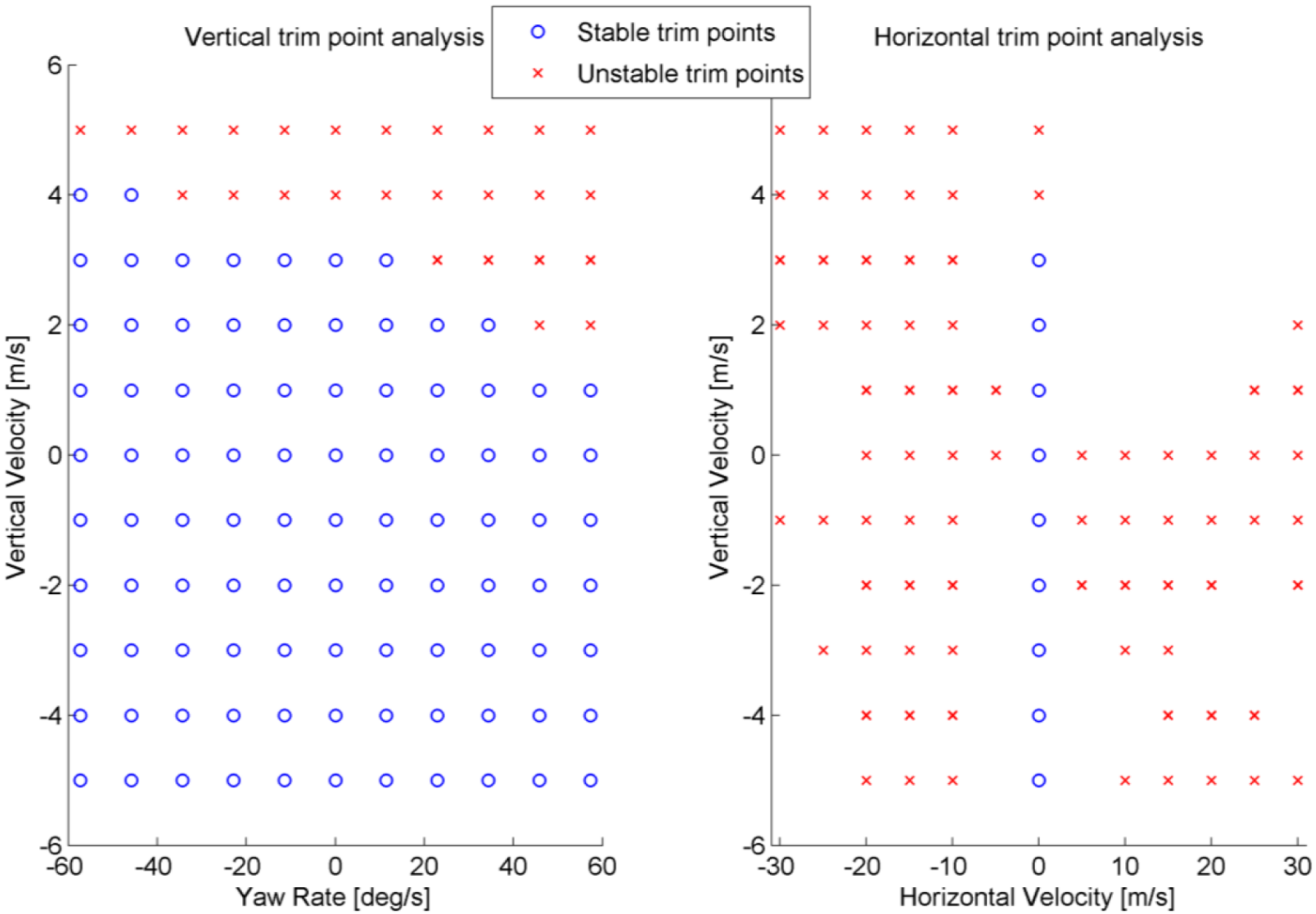
Reference frame for the flyability analysis

Flyability analysis





Flyability analysis



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Conclusions of flyability analysis

- The Anuloid can provide sufficient lift and thrust to take off, fly horizontally, and land using the considered Honeywell T3517 engine.

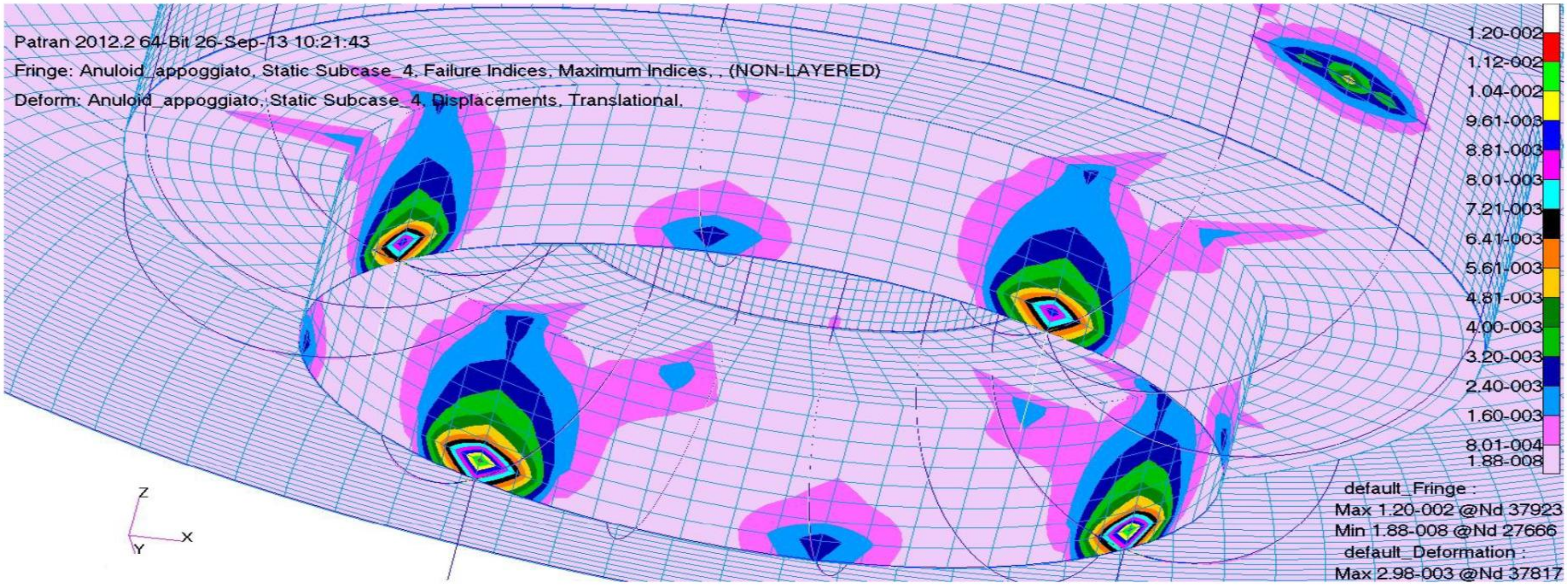
- The Anuloid is statically unstable during the horizontal flight and the effect of the pitch control vanes on the pitching moment reverses at an angle of attack of 10 degrees.

- The Anuloid has desirable (linear) dynamic responses during vertical flight. Many stable trim points can be found in this flight region, with the only instabilities occurring during the fast ascending flight.

- The Anuloid is dynamically unstable during the horizontal flight, with a time to double the amplitude of 2 seconds. While not dramatically unstable, the Anuloid is projected to have inadequate handling qualities during forward flight, so the system for control augmentation or autopilot is recommended.

Structural static analysis

Failure index (FI) distribution around landing legs



MAX FI = 0.01 (Well below 1)

Structural modal analysis

No RIBS

Modo di vibrare N°	Frequenza di vibrazione [Hz]
1	15.203
2	15.342
3	17.536
4	17.537
5	21.125
6	21.125
7	29.781
8	29.804
9	29.877
10	29.878
11	39.886
12	39.886
13	43.125
14	43.242

RIBS

Modo di vibrare N°	Frequenza di vibrazione [Hz]
1	39,154
2	39,235
3	39,292
4	39,292
5	46,730
6	47,127
7	48,453
8	48,454
9	49,871
10	49,944
11	50,024
12	50,026
13	74,686
14	77,013

GLOBAL MODES – LOCAL MODES

Conclusion of structural analysis

- The structural analysis has shown that no particular issues should arise from the design

- The suitable incorporation of radial ribs into Anuloid suppress global modal modes

Conclusions from first year of the project

- The CFD analyses have highlighted the efficiency of the control vanes and the stability of the Coanda effect
- The flyability analysis has shown that the vertical flight of the Anuloid has satisfactory flying qualities and that there is a sufficient lift production with considered engine.
- The dynamic stability analysis has shown that the Anuloid is dynamically unstable during horizontal flight. While not dramatically unstable, the Anuloid can have inadequate handling qualities during the 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 structural analysis has shown that no particular structural issues should arise from the structural design.

Ongoing project work deals with the experimental analysis of the Coanda effect and of the anti-torque mechanism, with the development of an automatic flight control system and a with detailed CFD analysis of the internal and external flows and of the transition phases (between vertical flight and horizontal flight).

Acknowledgment: The research (project Anuloid) described in this presentation is financially supported by the European FP7 grant system (ACP2-GA-2013-334861-ANULOID).