



The FutureWings Project - G.A. 335042

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UNIVERSITÀ DI PISA



A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections

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A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Summary

□ Introduction

- *About the FutureWings project and its objectives (3)*
- *Some notes on the hybrid structures concept (4 – 10)*
- *Preliminary Analyses of morphing wing sections (11 – 20)*

□ The piezo-controlled wing and the traditional wing

- *Model and FSI analyses of the Reference Wing (the aileron-wing) (21 – 32)*
- *Model and FSI analyses of the Morphing Wing (the piezo-wing) (33 – 46)*
- *Comparison of the aerodynamic performances of the wings (47 – 48)*

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- *Results of the FSI analyses of the two wings (rolling moment contributions) (49 – 52)*

□ Conclusions and future research activities



A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Main objectives of the FutureWings project

The FutureWings project focused on the study of a futuristic wing having the capability of changing its aerodynamic shape (“self-shaping wing”) through the use of hybrid materials, made up of piezoelectric patches co-cured with a composite substrate.

For a morphing wing, traditional control surfaces (such as ailerons, flaps, slats and so on) are no longer required; that allows us to save weight in wing structures and reduce the sources of vibrations.

The deformed shape of a wing required by a given flight maneuver will be obtained as a result of medium/high voltages applied to the active piezo-electric patches.

The final goal of the FutureWings project was to manufacture a small scale model of a Future Wing section.

This required a proper design of the hybrid active composite laminate (composite layup, ply stacking sequence, piezo electric fibers orientation and so on), supported by testing activities and finite element non-linear analyses.

Deformation tests on the Future Wing model have been carried out to verify the technical feasibility of the FutureWings concept.



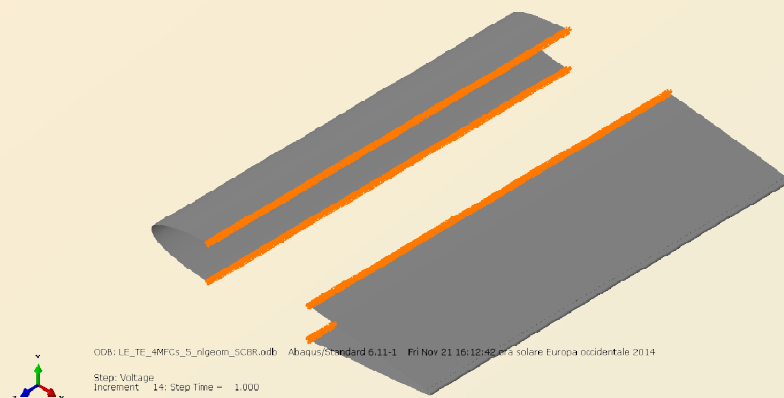
A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



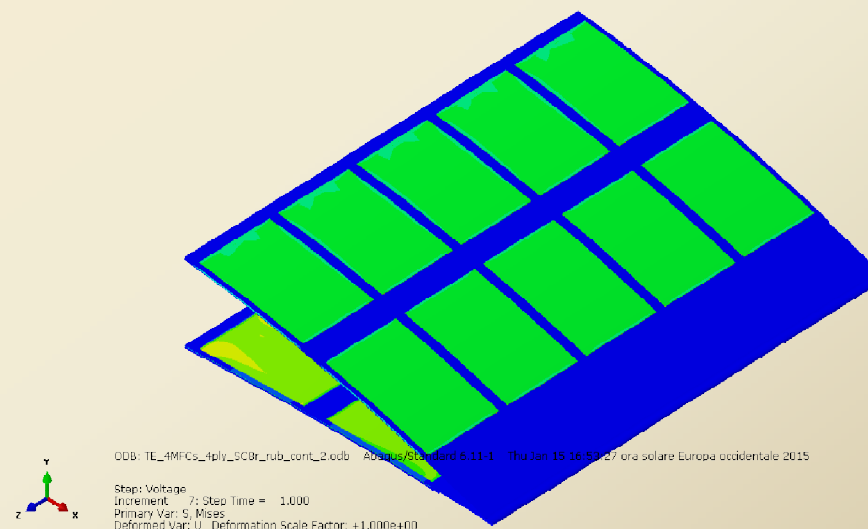
Some notes on the hybrid structures concept

FE analyses of the FutureWing UNIT

Boundary Conditions



Trailing Edge: MFC Patches model



<http://www.smart-material.com/MFC-product-main.html>
(MFC = Macro Fiber Composite)

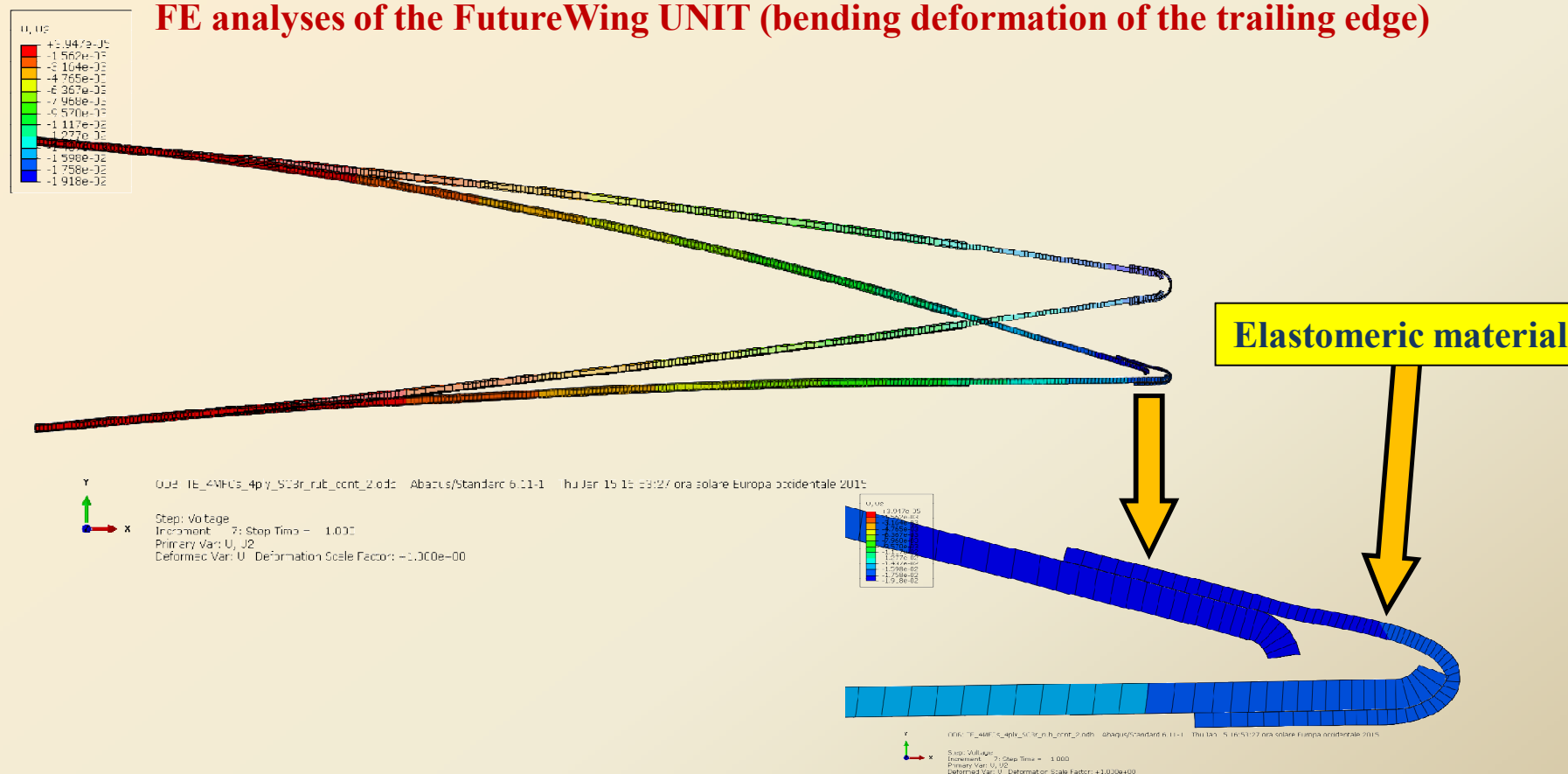


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Some notes on the hybrid structures concept

FE analyses of the FutureWing UNIT (bending deformation of the trailing edge)



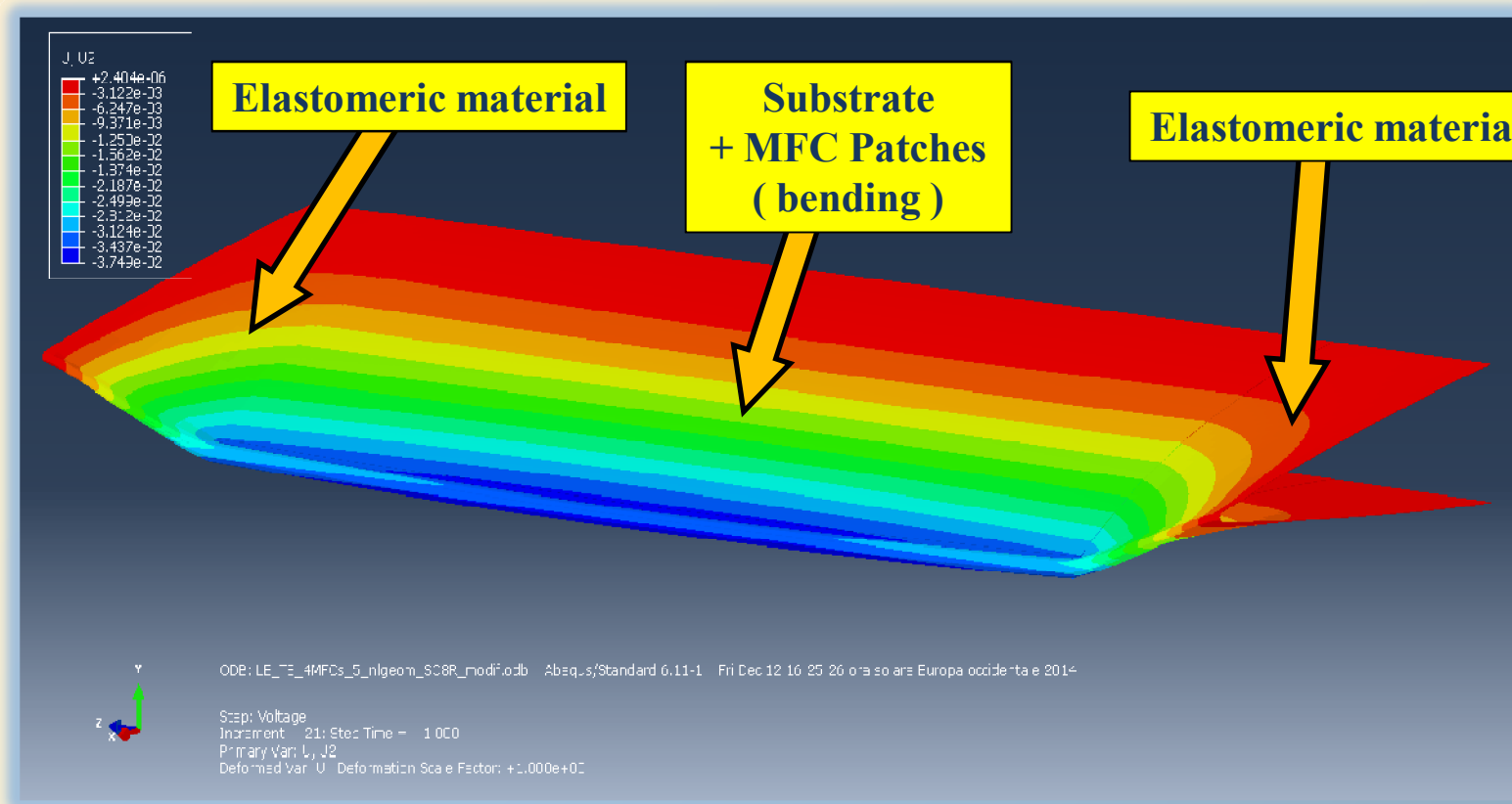


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Some notes on the hybrid structures concept

FE analyses of the FutureWing UNIT (bending deformation of the trailing edge)



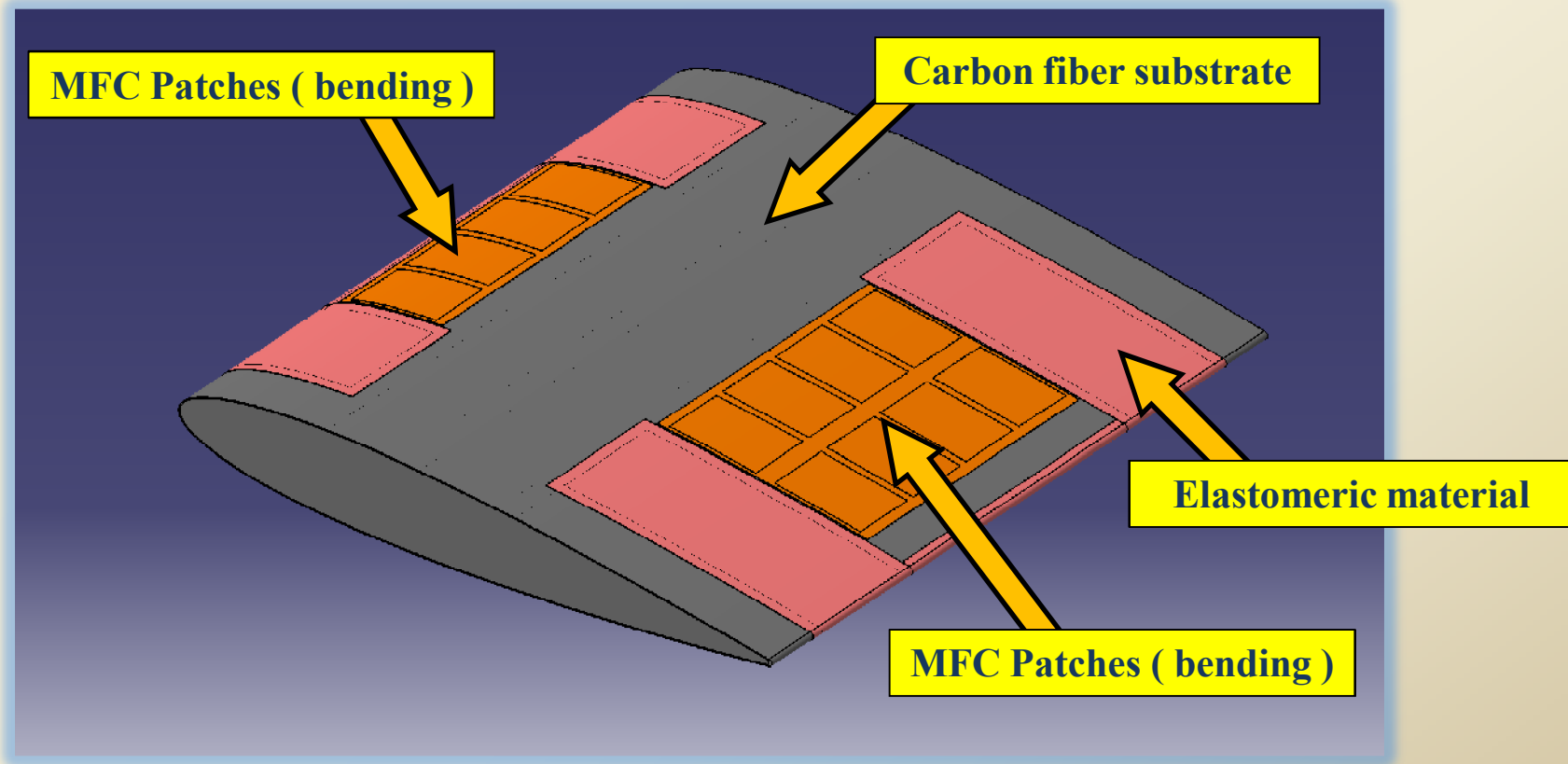


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Some notes on the hybrid structures concept

Conceptual Design of the Future Wing Unit 1 (skeleton curvature's change)





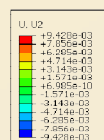
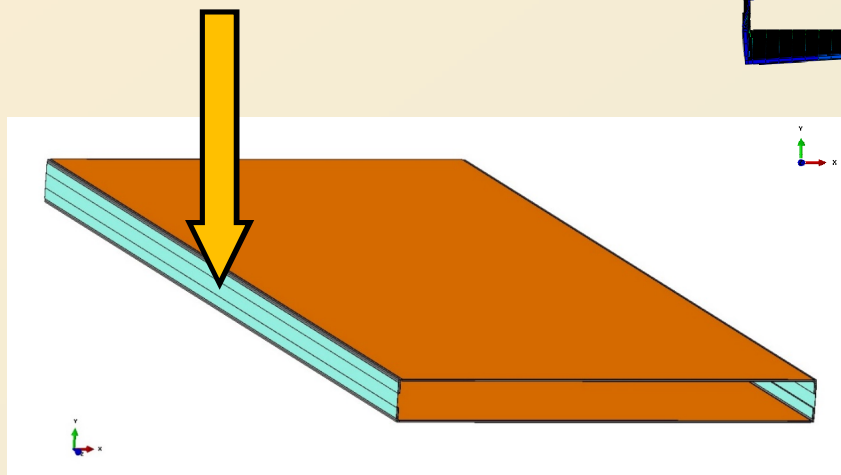
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Some notes on the hybrid structures concept

Conceptual Design of the Future Wing Unit 2 (torsion control)

Elastomeric material



ODB: RW-rubber-hinge.odb Abaqus/Standard 6.11-1 Thu Jan 15 19:10:10 ora 1000 opa occidentale 2015
 Step: Voltage
 Increment: 48/ Stop Time = 0.6536
 Primary Var: U, U2
 Deformed Var: U, U2 Deformation Scale Factor: +1.000e+00

The Centre of Rotation remains
very close to the skins

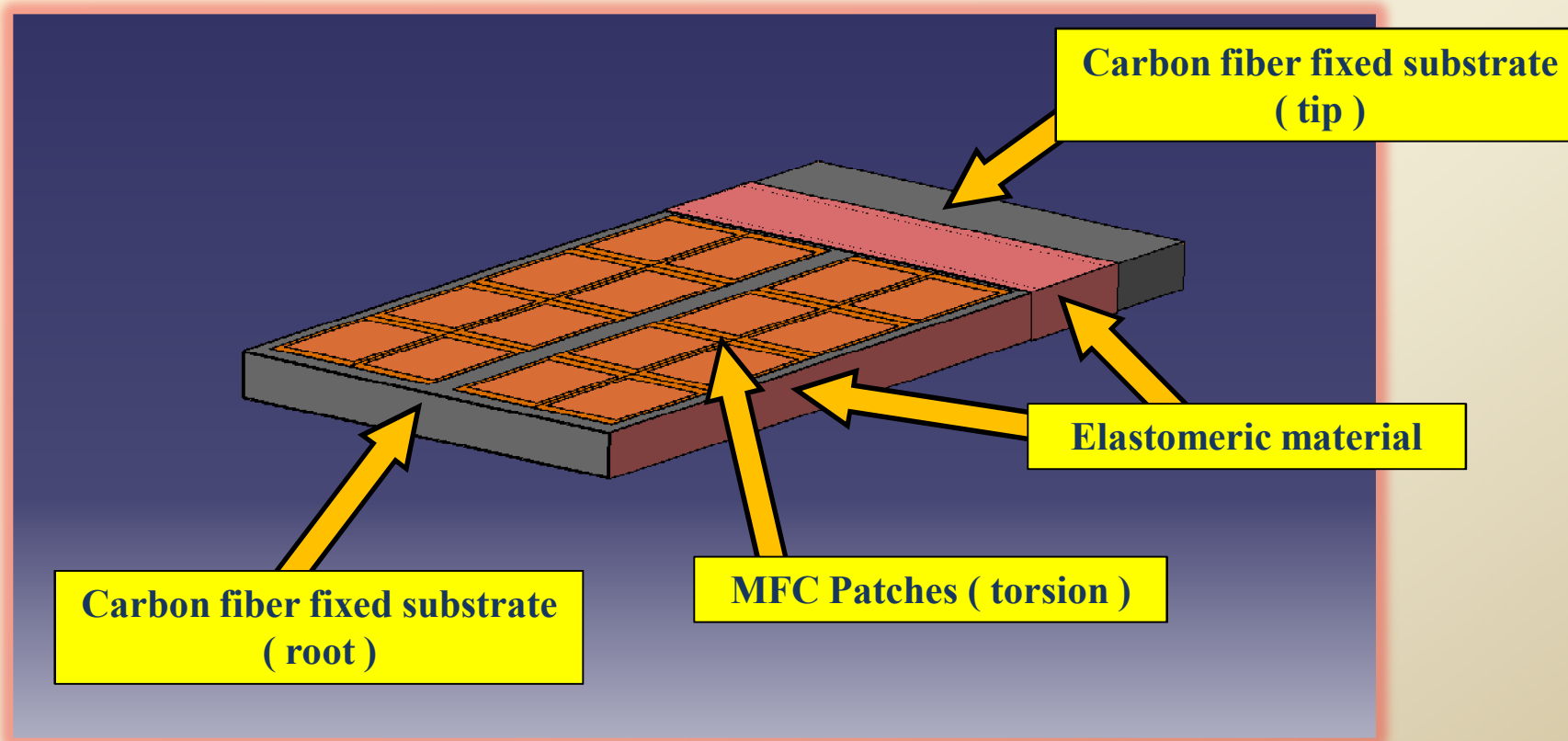


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Some notes on the hybrid structures concept

Conceptual Design of the Future Wing Unit 2 (torsion control)



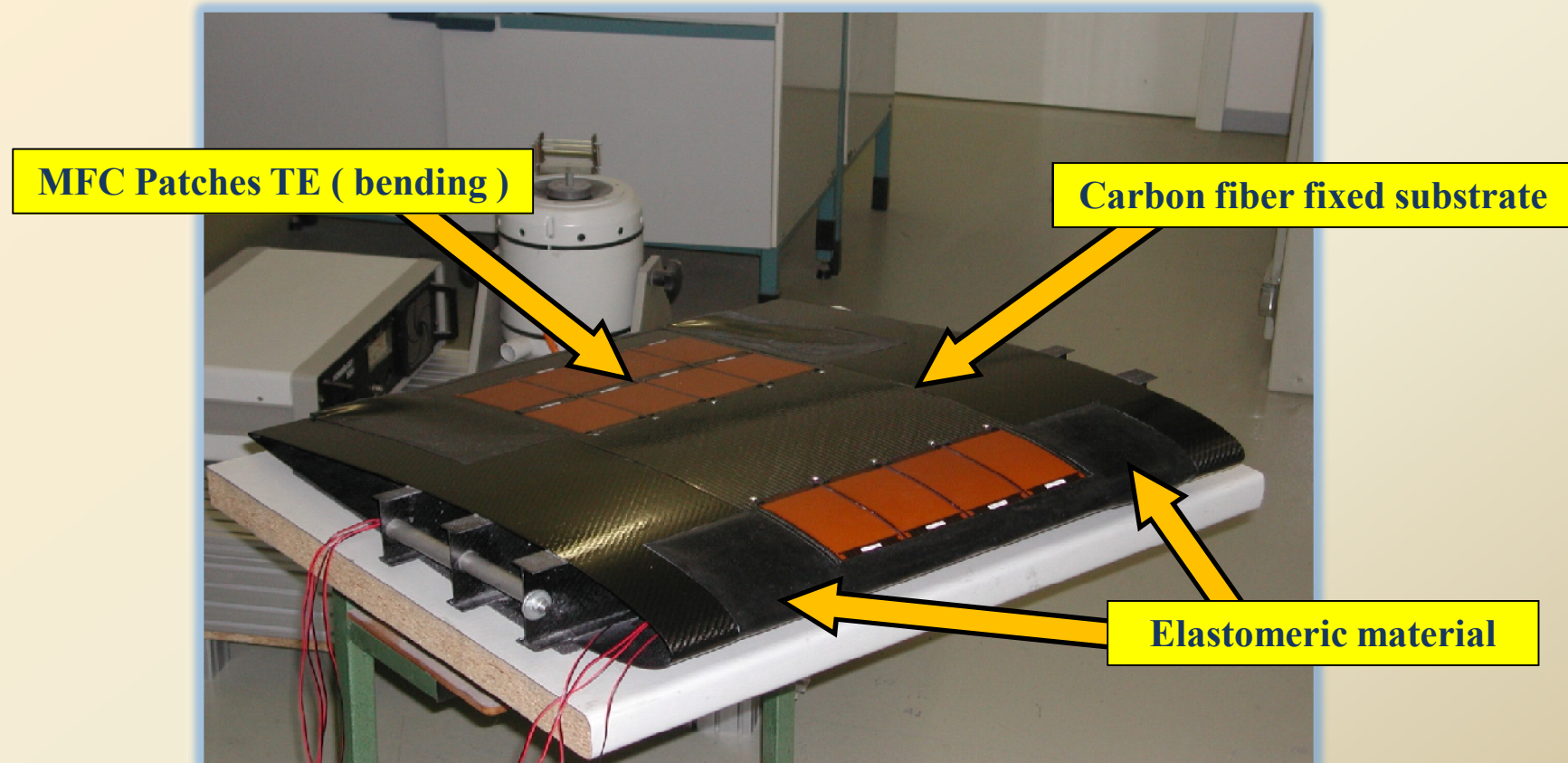


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Some notes on the hybrid structures concept

The Future Wing Unit 1 (skeleton curvature's change)



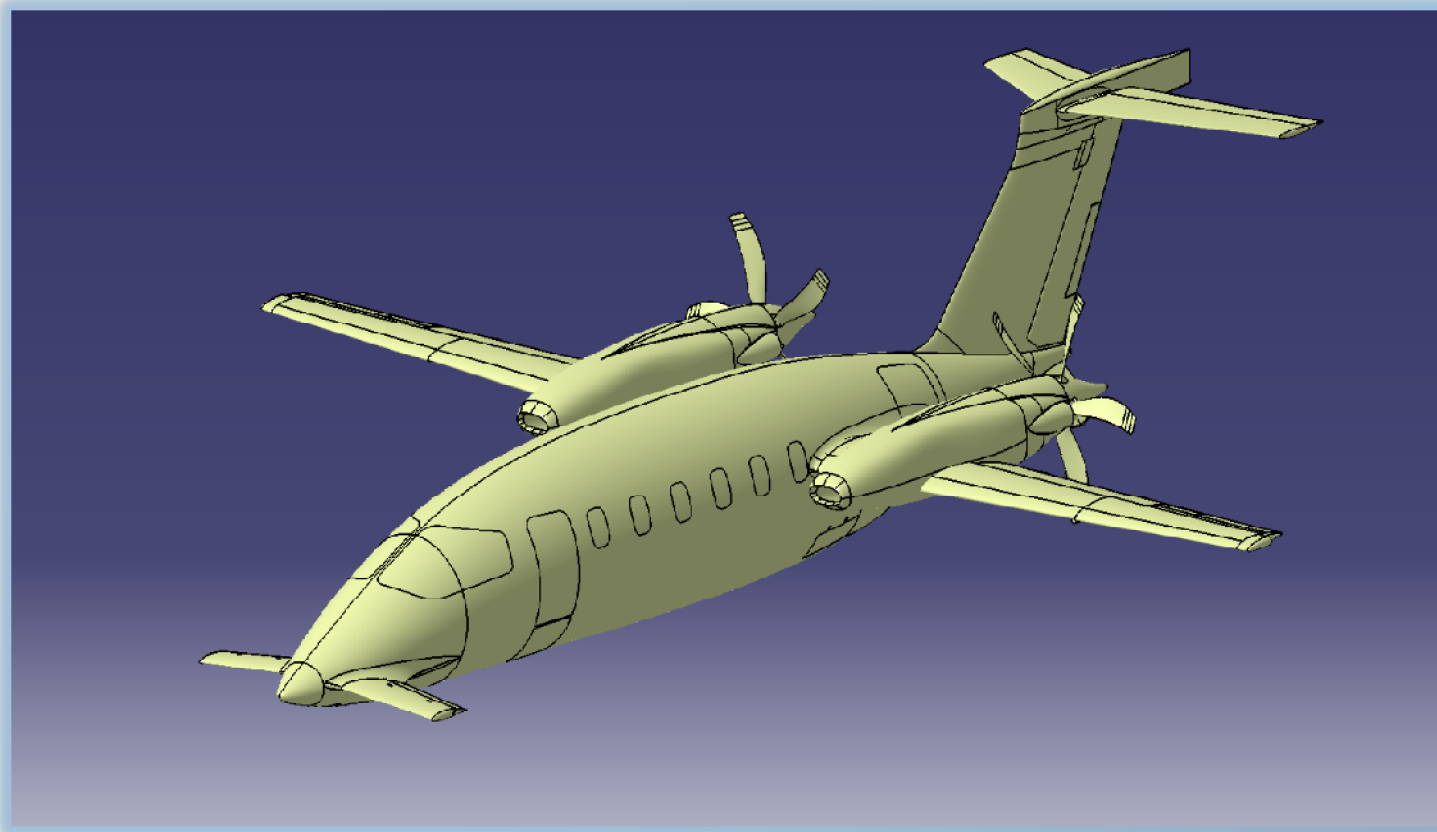


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Preliminary Analyses of morphing wing sections

The reference aircraft (the P180 geometry source file)



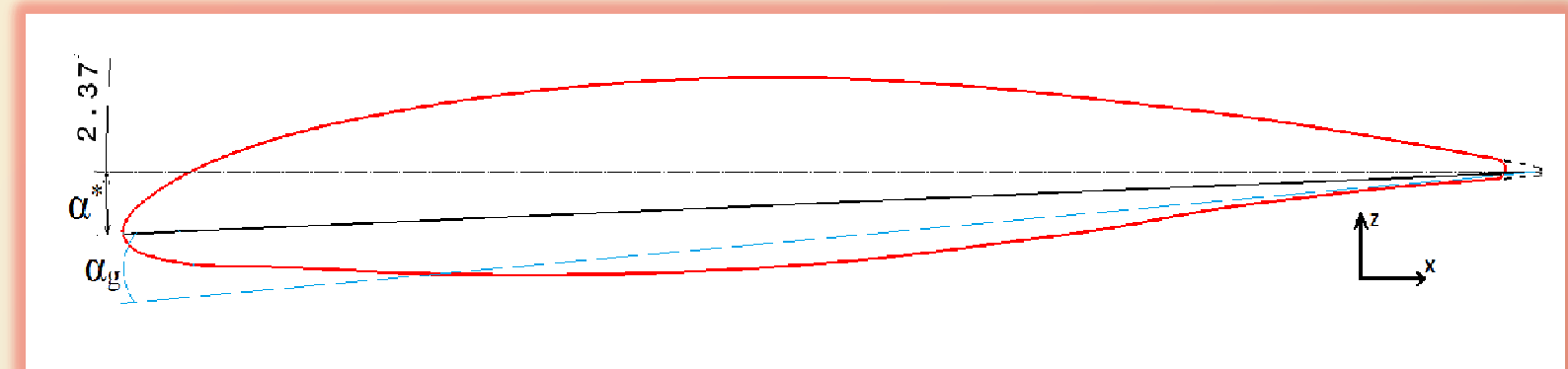
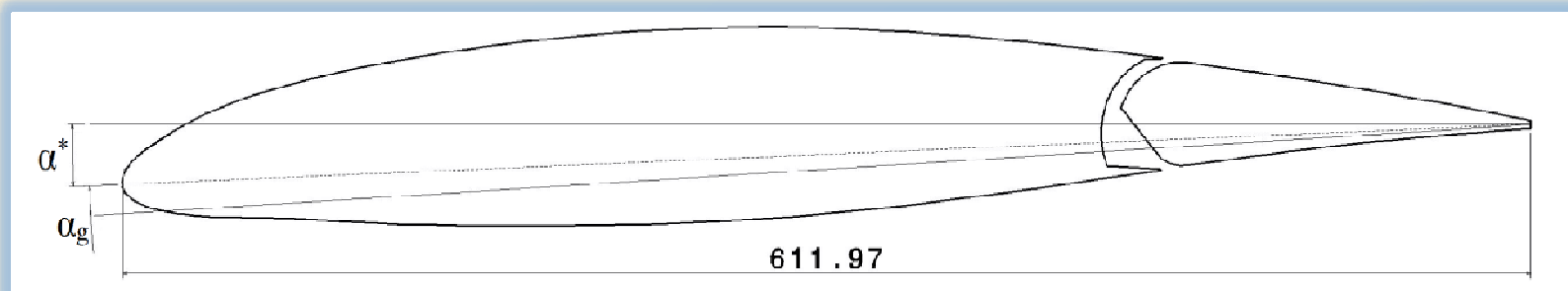


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Preliminary Analyses of morphing wing sections

The reference aileron-section (from the P180 geometry source file) and the piezo-section



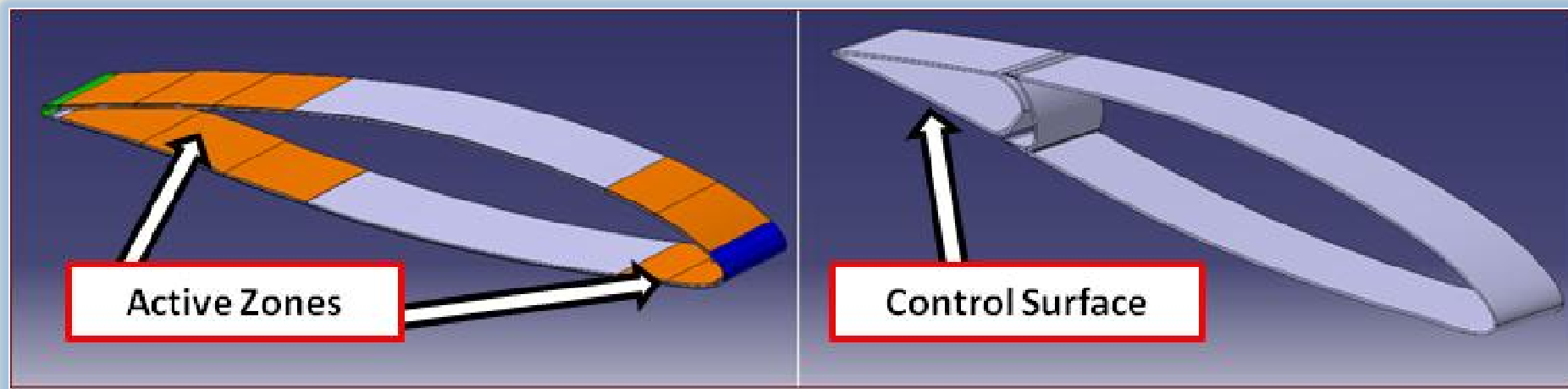


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Preliminary Analyses of morphing wing sections

The reference aileron-section and the piezo-section (the basic models)



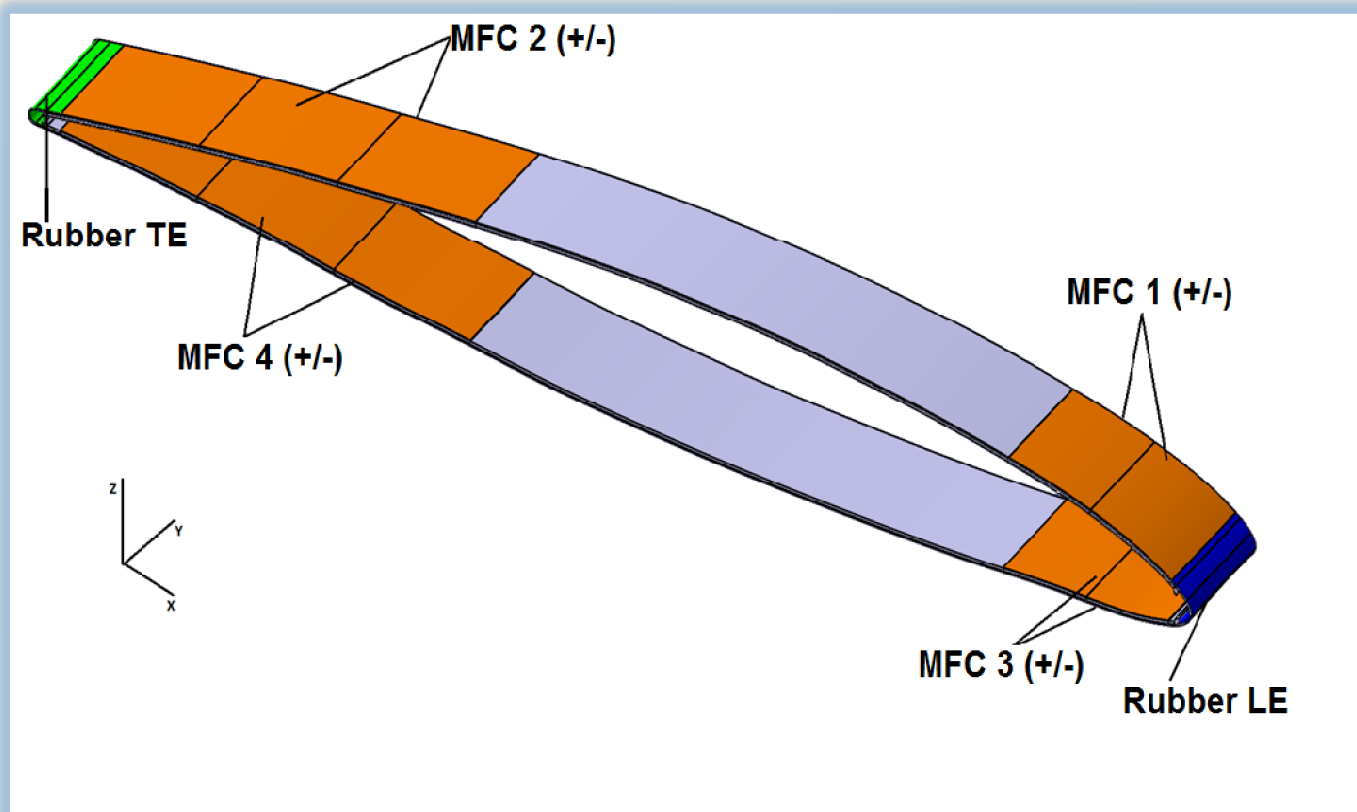


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Preliminary Analyses of morphing wing sections

The MFC nomenclature





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Preliminary Analyses of morphing wing sections

The voltage loading cases

Realistic Case



V/V*	Case	Patches	Voltage [V]
-5	-5	MFC 1/2	-7500/15000
		MFC 3/4	-3750/7500
-2	-3	MFC 1/2	-3000/6000
		MFC 3/4	-1500/3000
0	0	MFC 1/2	0/0
		MFC 3/4	0/0
0.5	1	MFC 1/2	750/-375
		MFC 3/4	1500/-750
1	2	MFC 1/2	1500/-750
		MFC 3/4	3000/-1500
2	3	MFC 1/2	3000/-1500
		MFC 3/4	6000/-3000
4	4	MFC 1/2	6000/-3000
		MFC 3/4	12000/-6000
5	5	MFC 1/2	7500/-3750
		MFC 3/4	15000/-7500



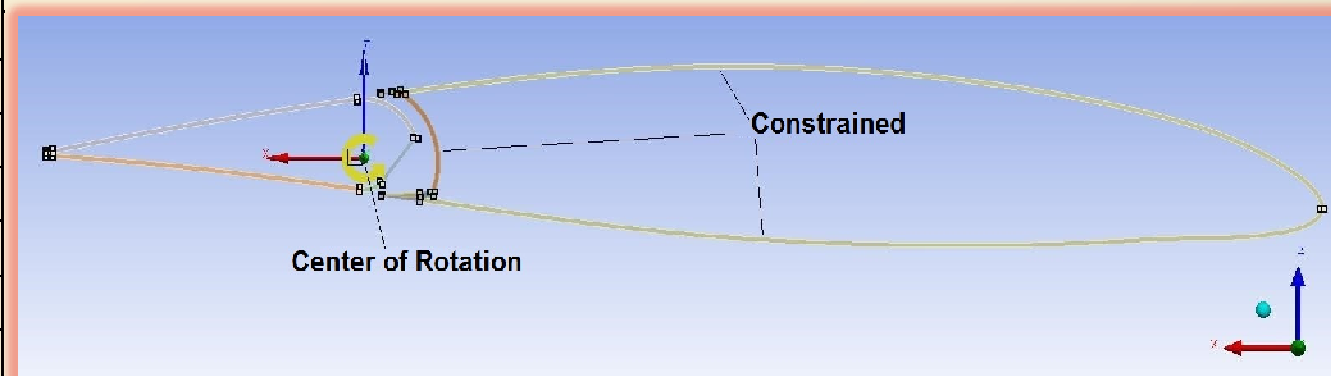
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Preliminary Analyses of morphing wing sections

The aileron positions analyzed

Case Number	Aileron Deflection [deg]
0	-15°
1	-10°
2	-5°
3	0°
4	5°
5	10°
6	15°
7	18°



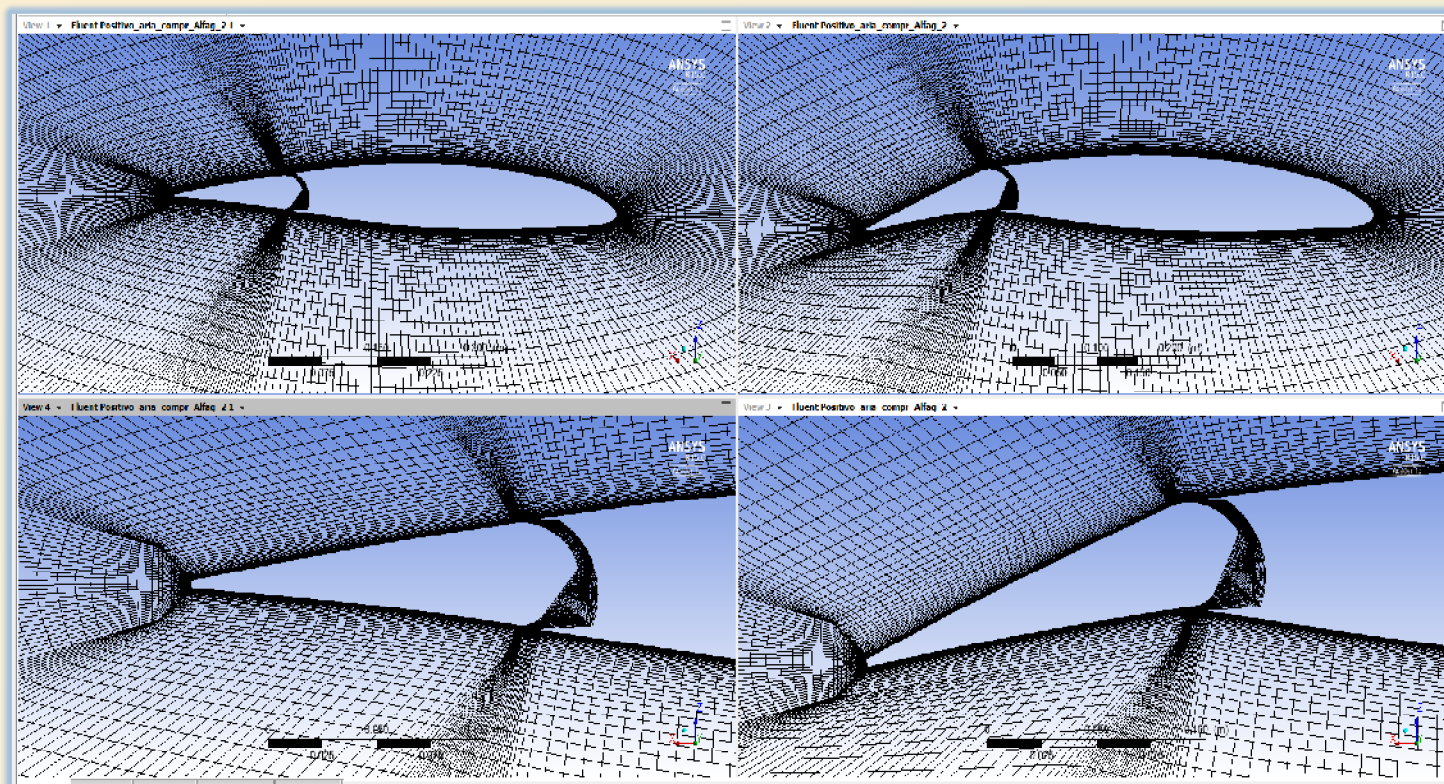


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Preliminary Analyses of morphing wing sections

The aileron-wing section: sketch of deformed aero-grid



($\delta a = 15 \text{ deg}$, $h = 0 \text{ m}$, $\alpha_g = 2 \text{ deg}$, $M = 0.17$)

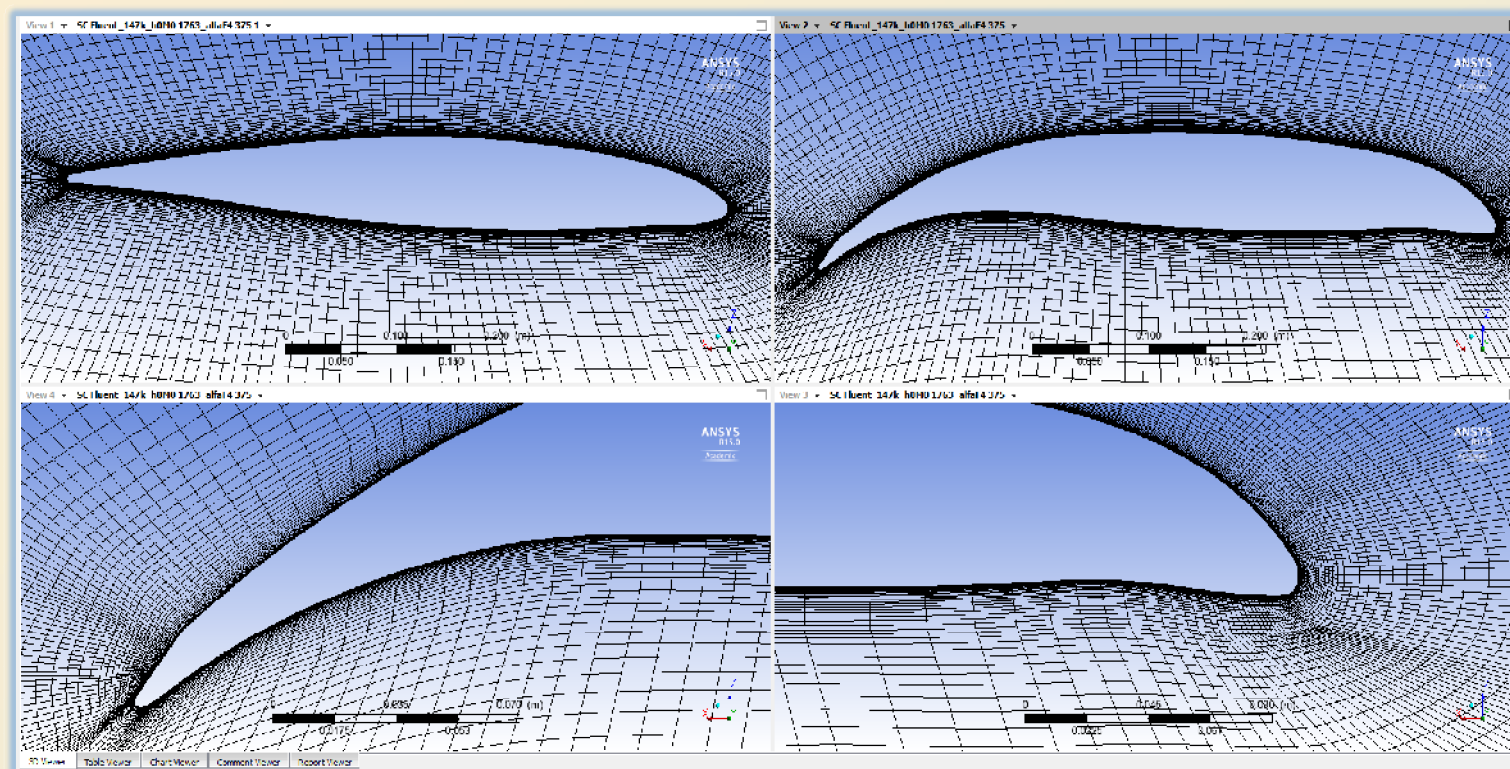


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Preliminary Analyses of morphing wing sections

The piezo-wing section: sketch of deformed aero-grid ($V^* = 1500$ V)



($V/V^* = 5$ - hypothetical case , $h = 0$ m , $\alpha_g = 2$ deg , $M = 0.17$)

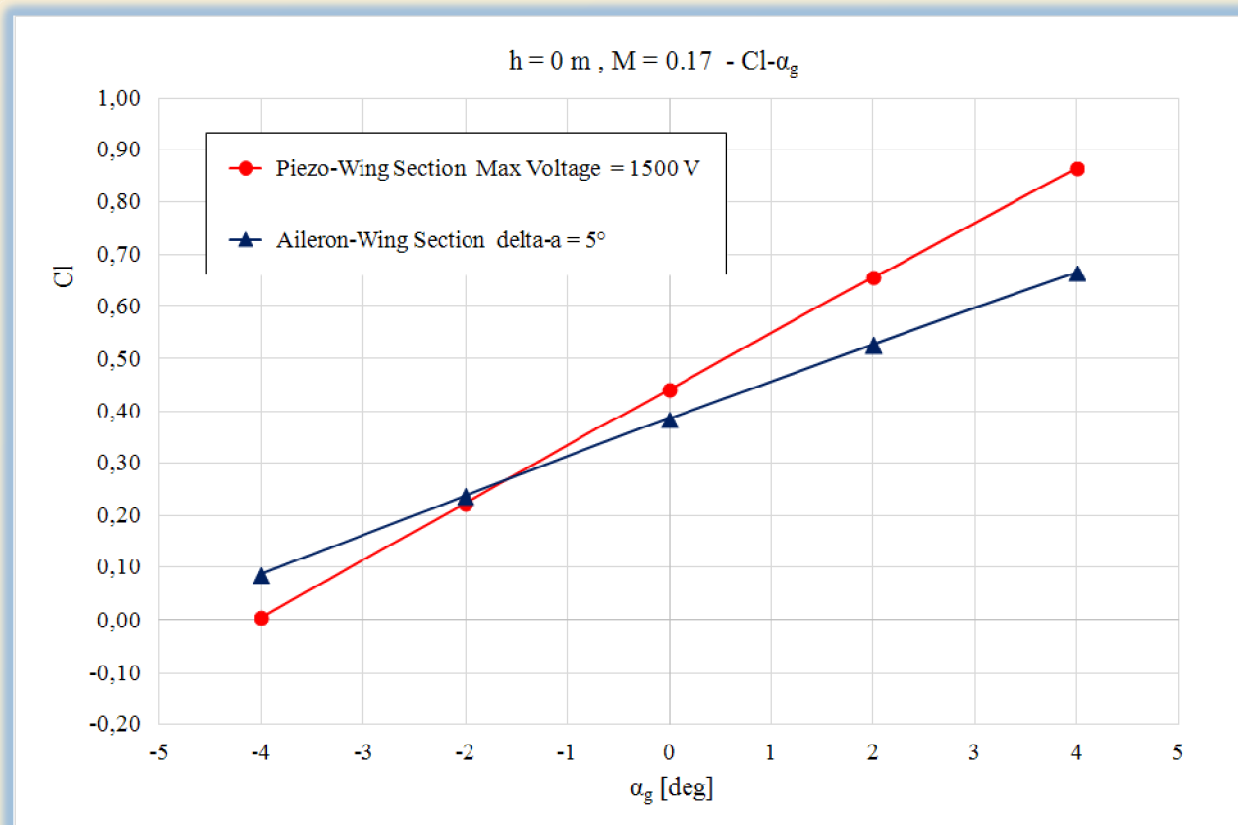


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Preliminary Analyses of morphing wing sections

Comparison of the aerodynamic performances of the wing sections ($V/V^* = 0.5$)



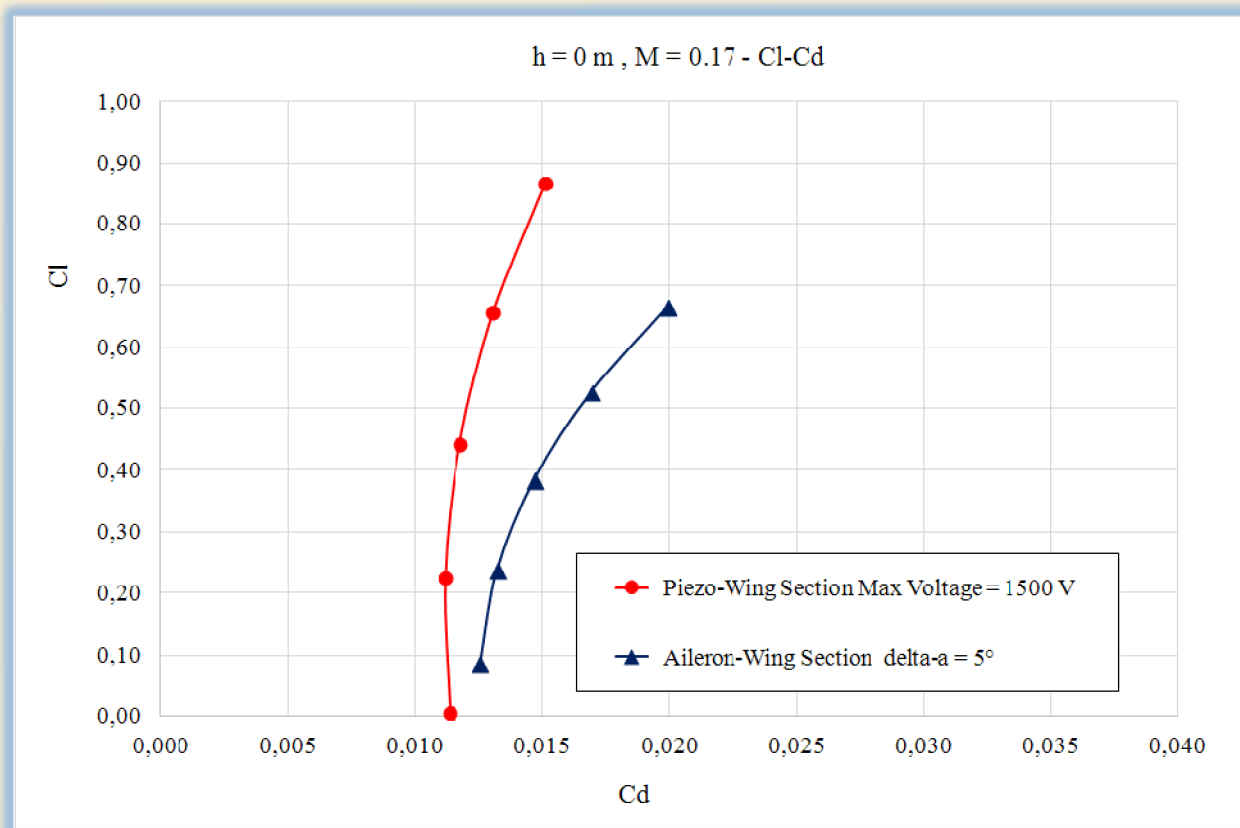


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Preliminary Analyses of morphing wing sections

Comparison of the aerodynamic performances of the wing sections (polar drag curves - $V/V^* = 0.5$)



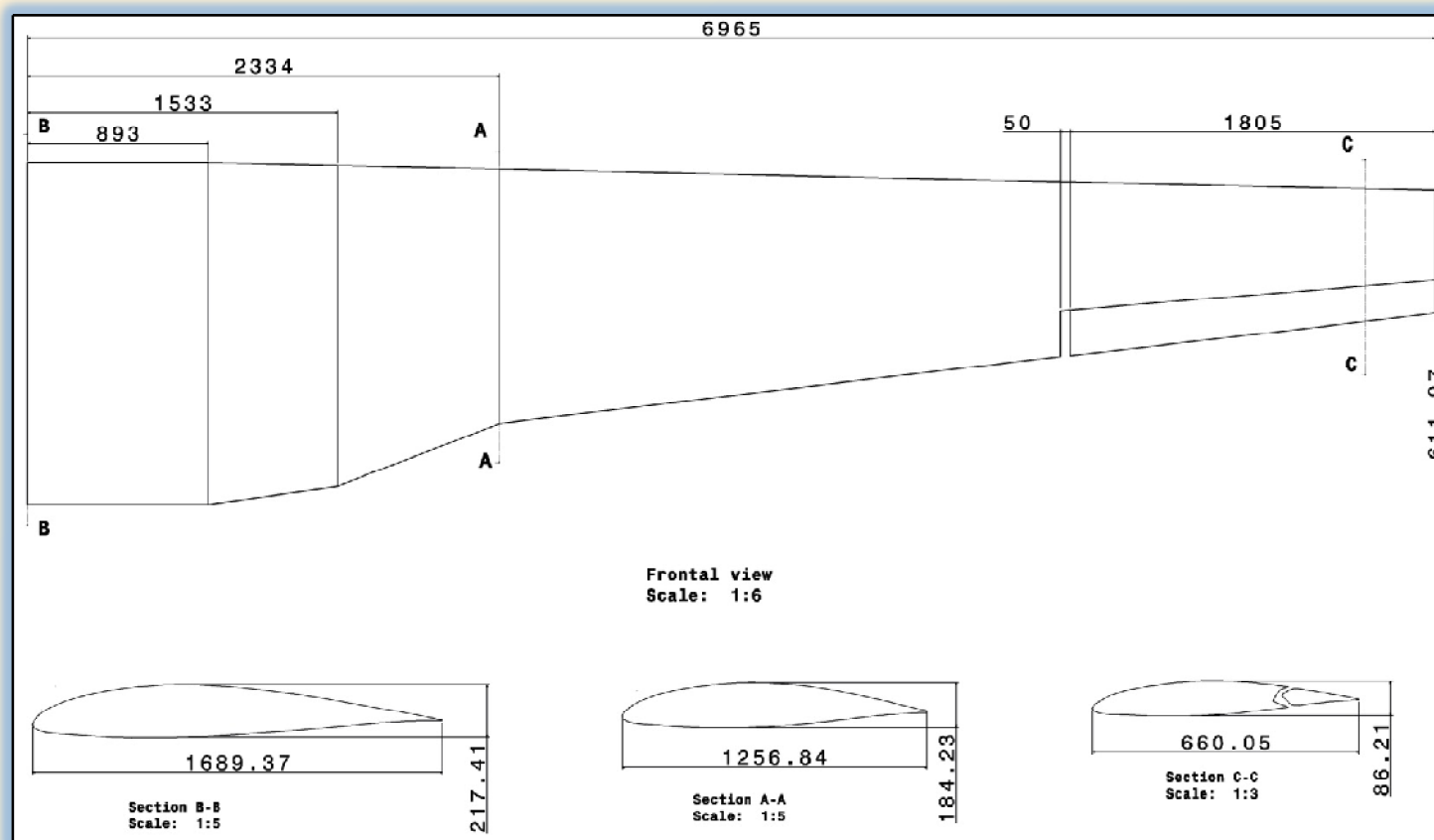


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Model and FSI analyses of the Reference Wing (the aileron-wing)

Geometry of the aileron-wing



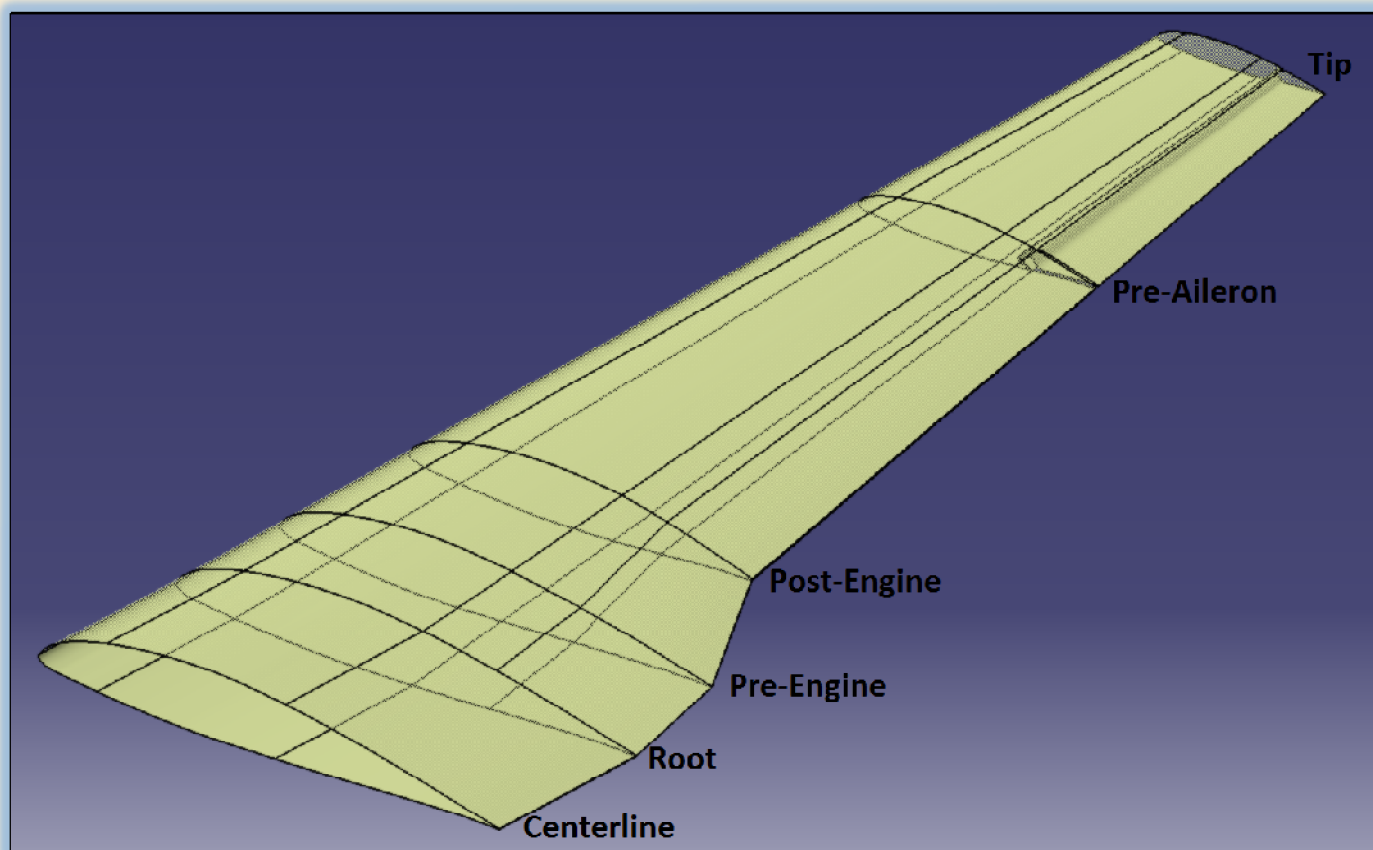


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Model and FSI analyses of the Reference Wing (the aileron-wing)

Geometry of the aileron-wing



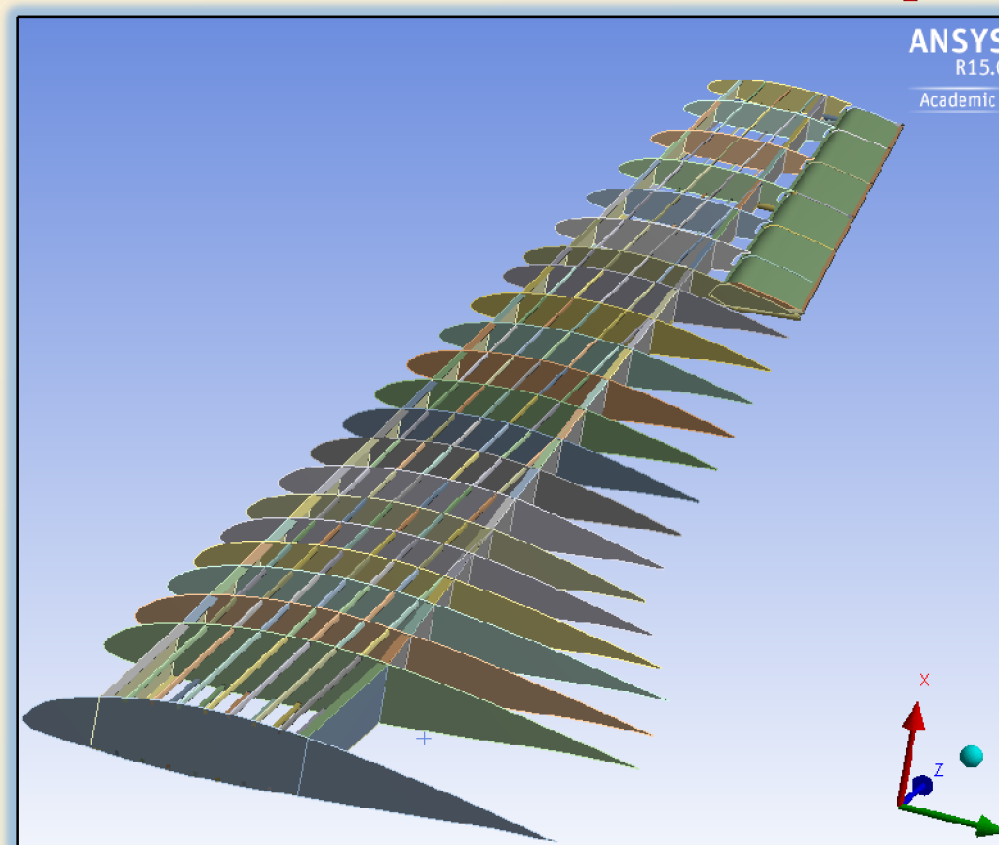


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Model and FSI analyses of the Reference Wing (the aileron-wing)

The finite element model of the aileron-wing



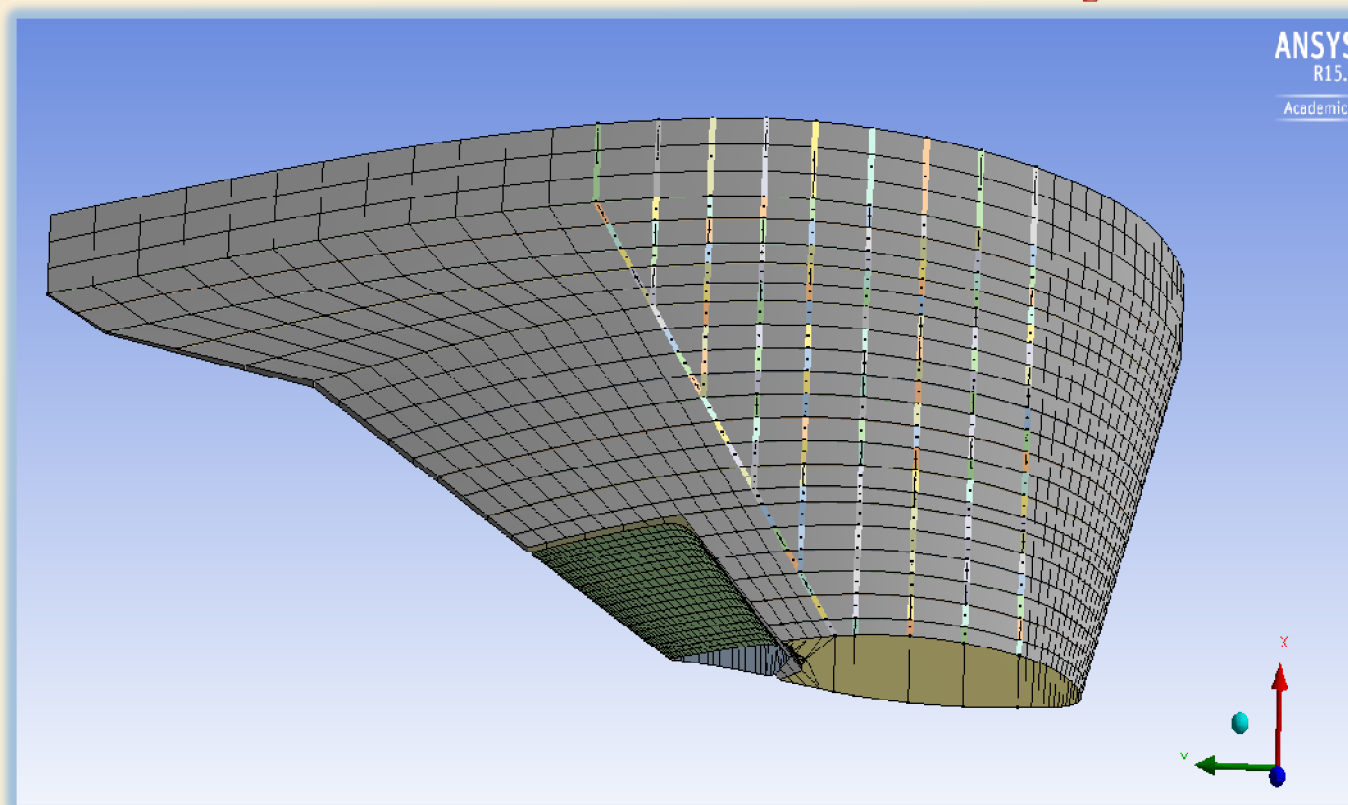


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Model and FSI analyses of the Reference Wing (the aileron-wing)

The finite element model of the aileron-wing



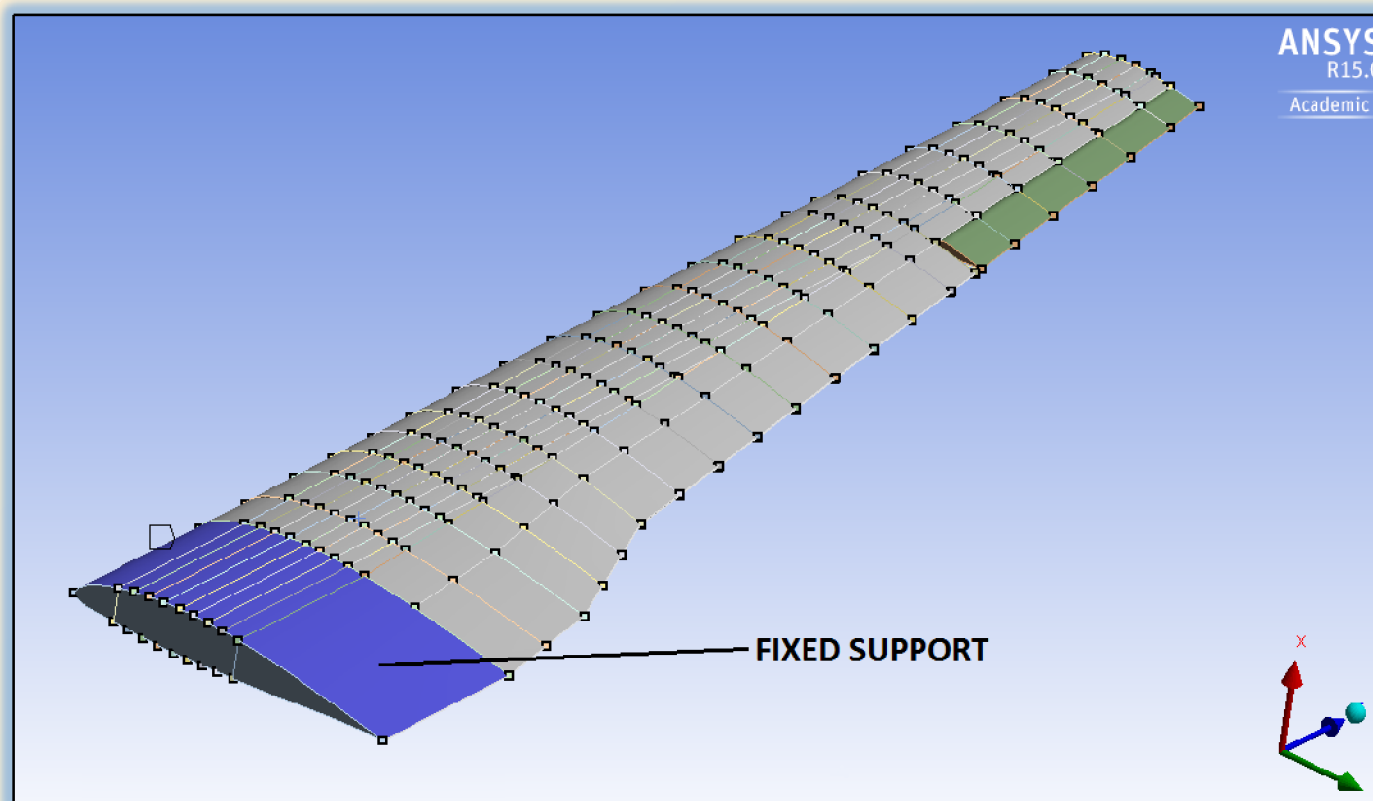


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Model and FSI analyses of the Reference Wing (the aileron-wing)

The finite element model of the aileron-wing



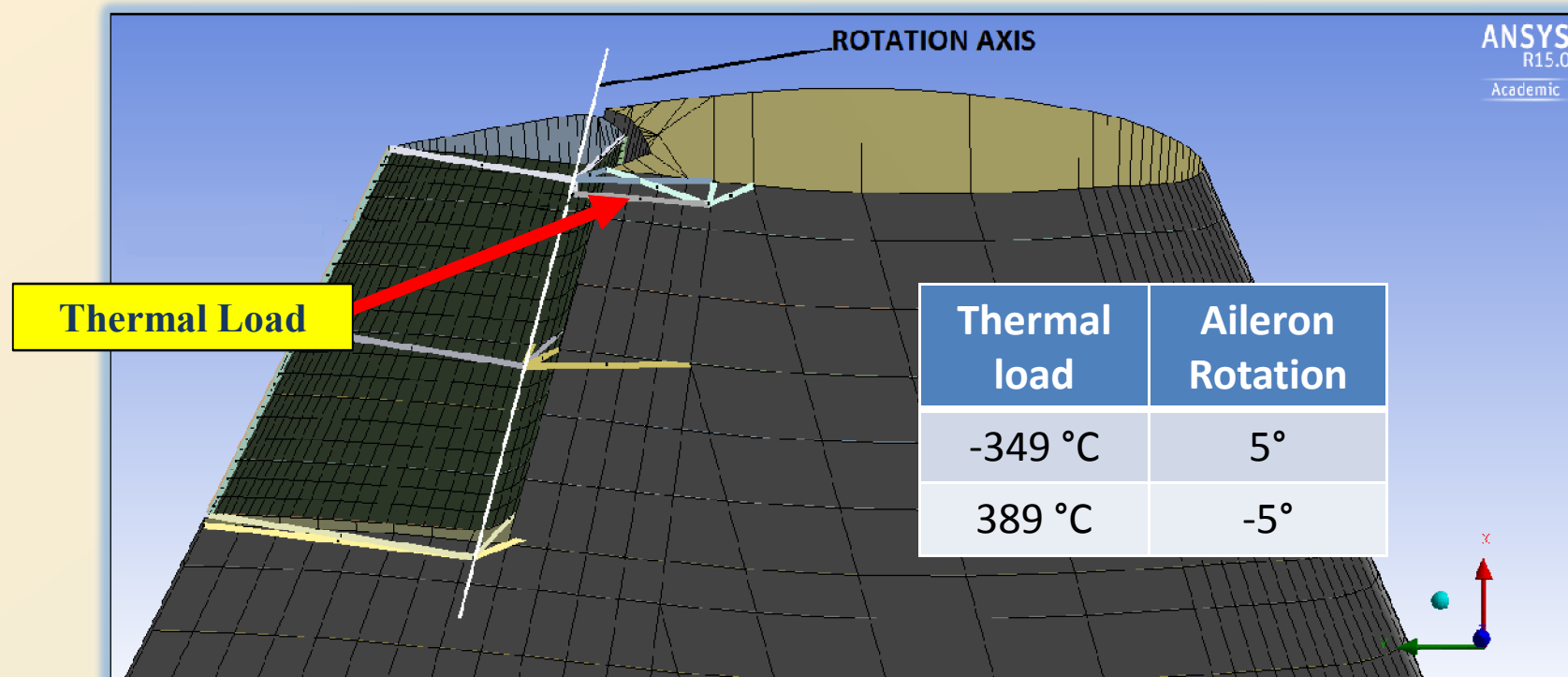


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Model and FSI analyses of the Reference Wing (the aileron-wing)

Fictitious actuation system to simulate the aileron movement





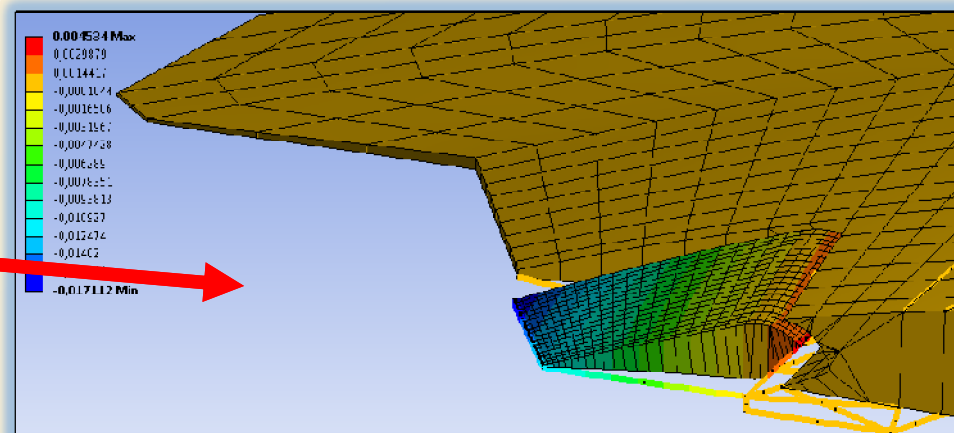
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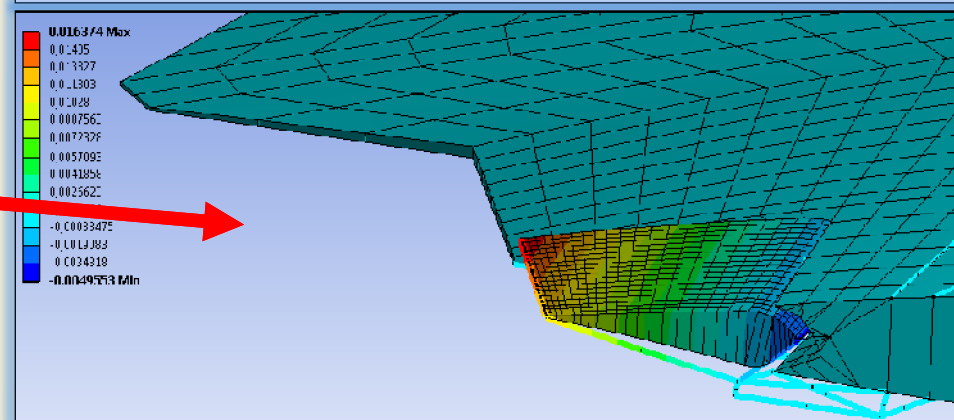
Model and FSI analyses of the Reference Wing (the aileron-wing)

Fictitious actuation system to simulate the aileron movement

Aileron rot. + 5 deg



Aileron rot. - 5 deg



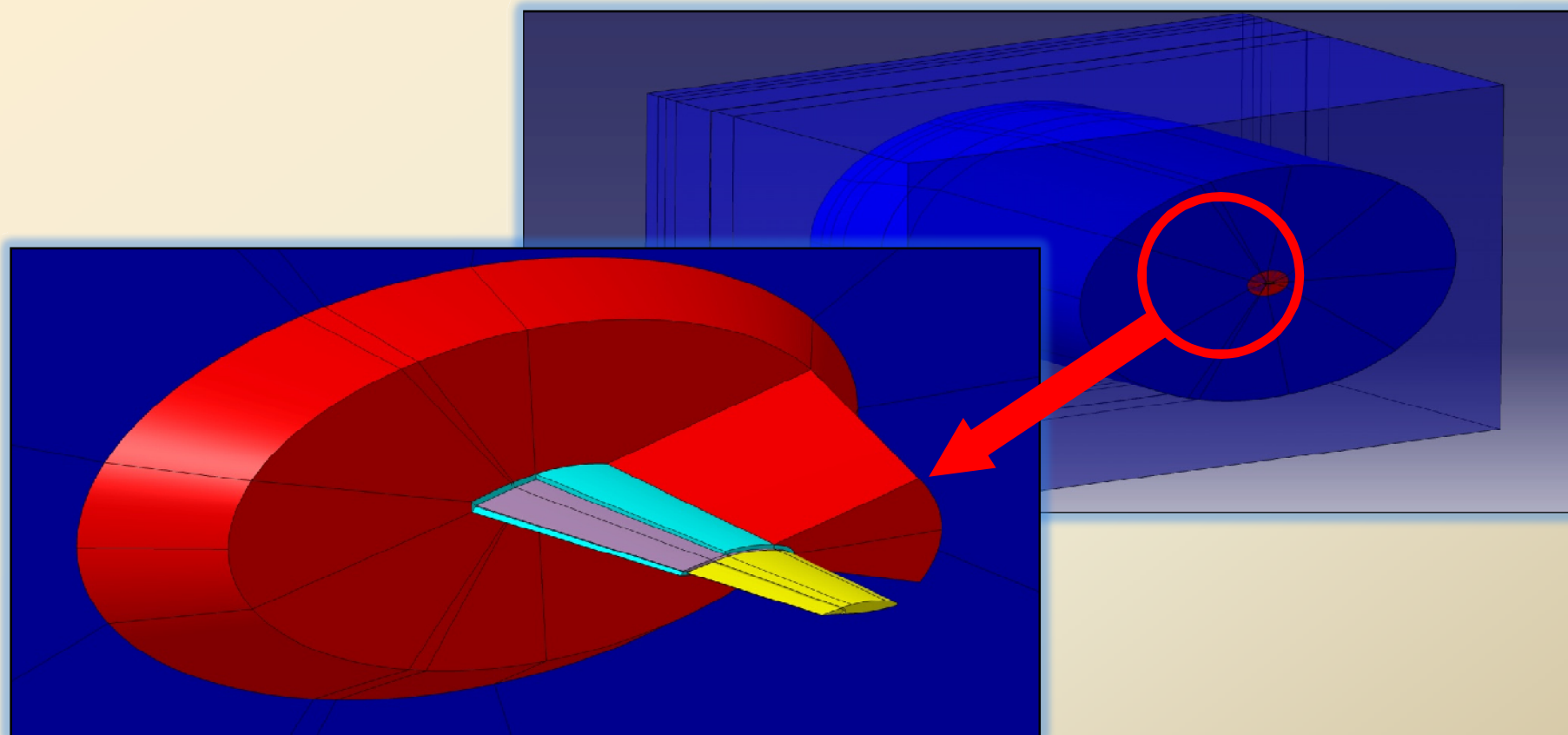


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Model and FSI analyses of the Reference Wing (the aileron-wing)

CFD model: fluid domain geometry





A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections

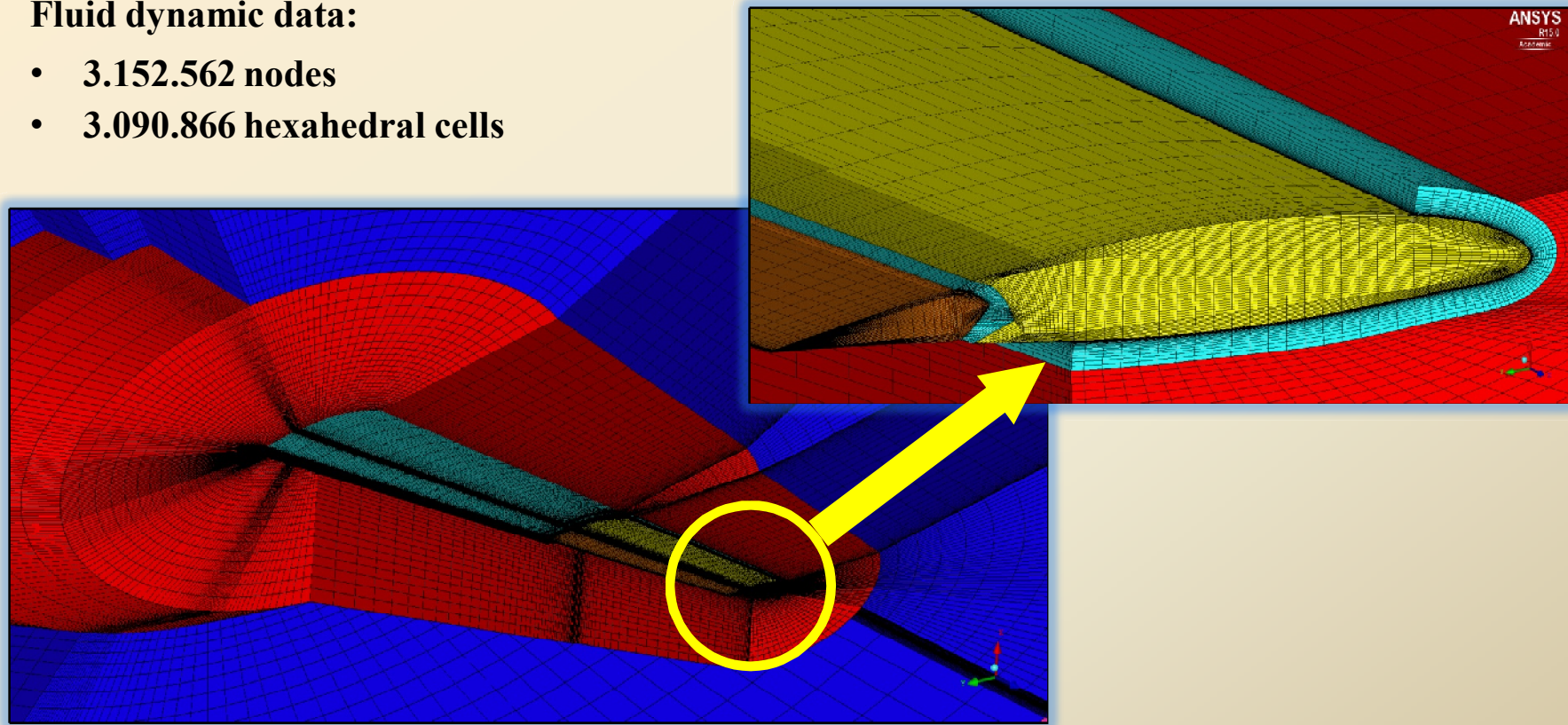


Model and FSI analyses of the Reference Wing (the aileron-wing)

CFD model: fluid domain grid (structured)

Fluid dynamic data:

- 3.152.562 nodes
- 3.090.866 hexahedral cells



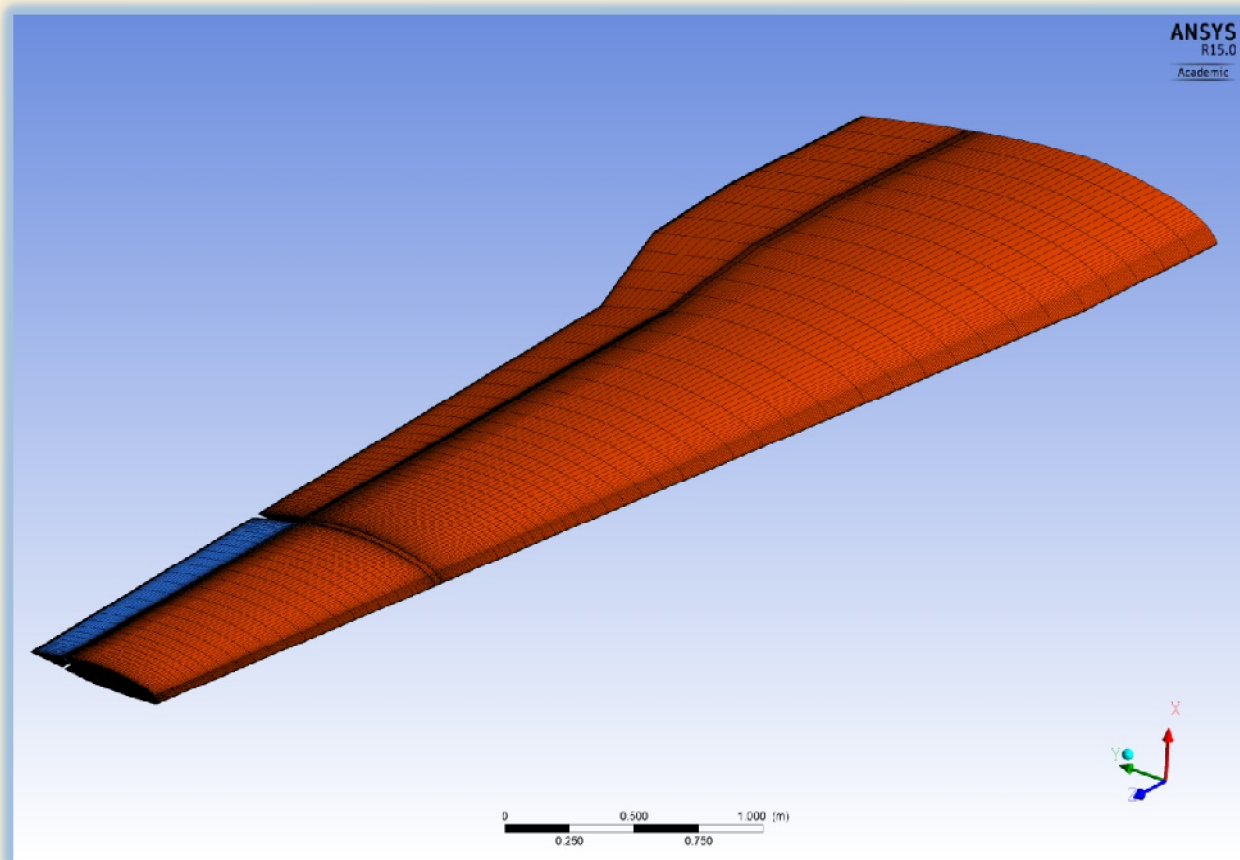


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Model and FSI analyses of the Reference Wing (the aileron-wing)

The aerodynamic model of the aileron-wing (the surface grid)





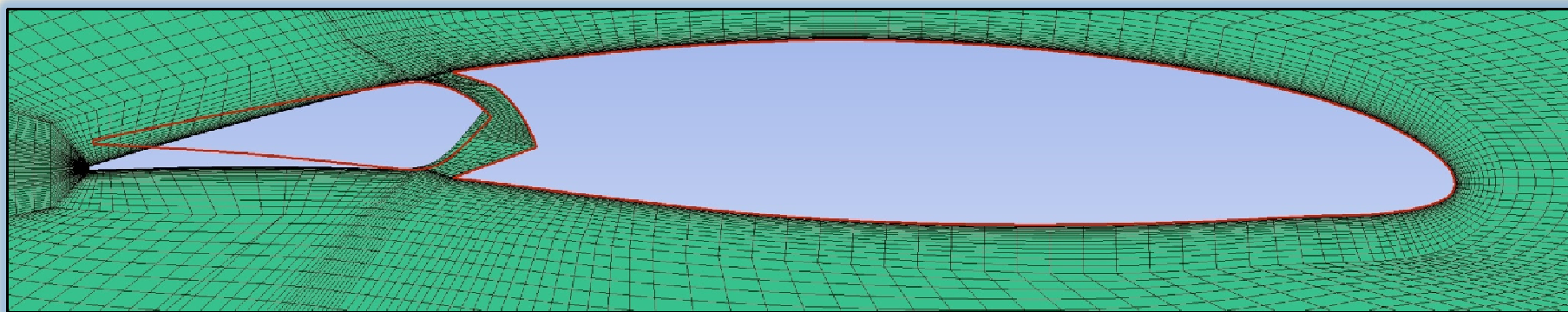
A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Model and FSI analyses of the Reference Wing (the aileron-wing)

FSI 2-ways results

- Cross section plane @ 6 m
- $\delta a = 5$
- $h = 0$ m
- $M = 0.17$
- $\alpha_g = 0$



Deformed fluid dynamic mesh in true scale.
The red line represents the undeformed profile.

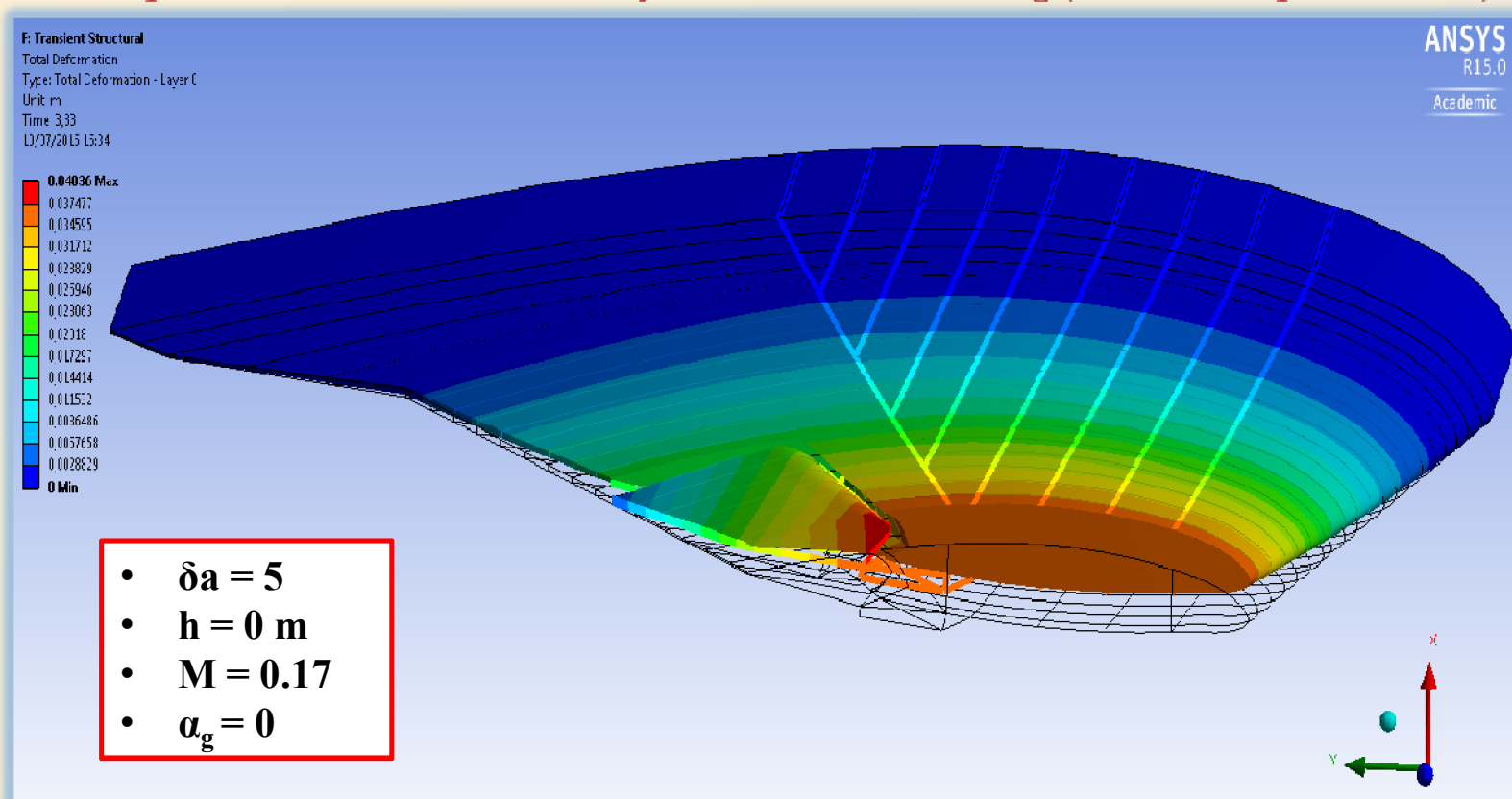


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Model and FSI analyses of the Reference Wing (the aileron-wing)

Example of results of the FSI analyses of the aileron-wing (vertical displacements)



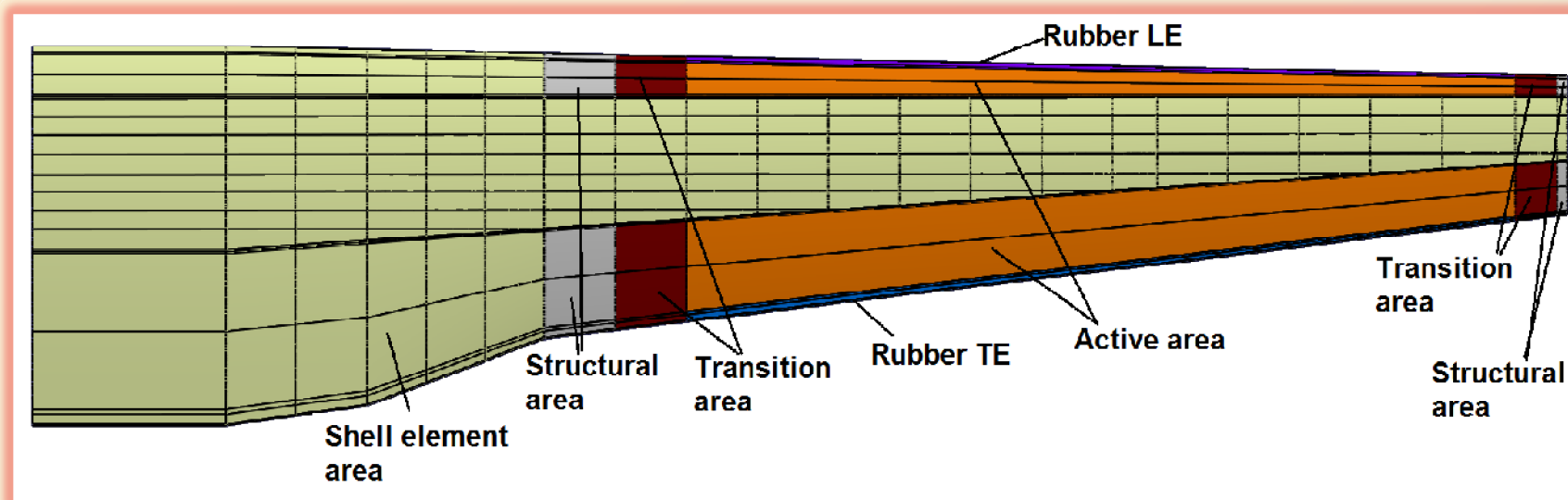


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing



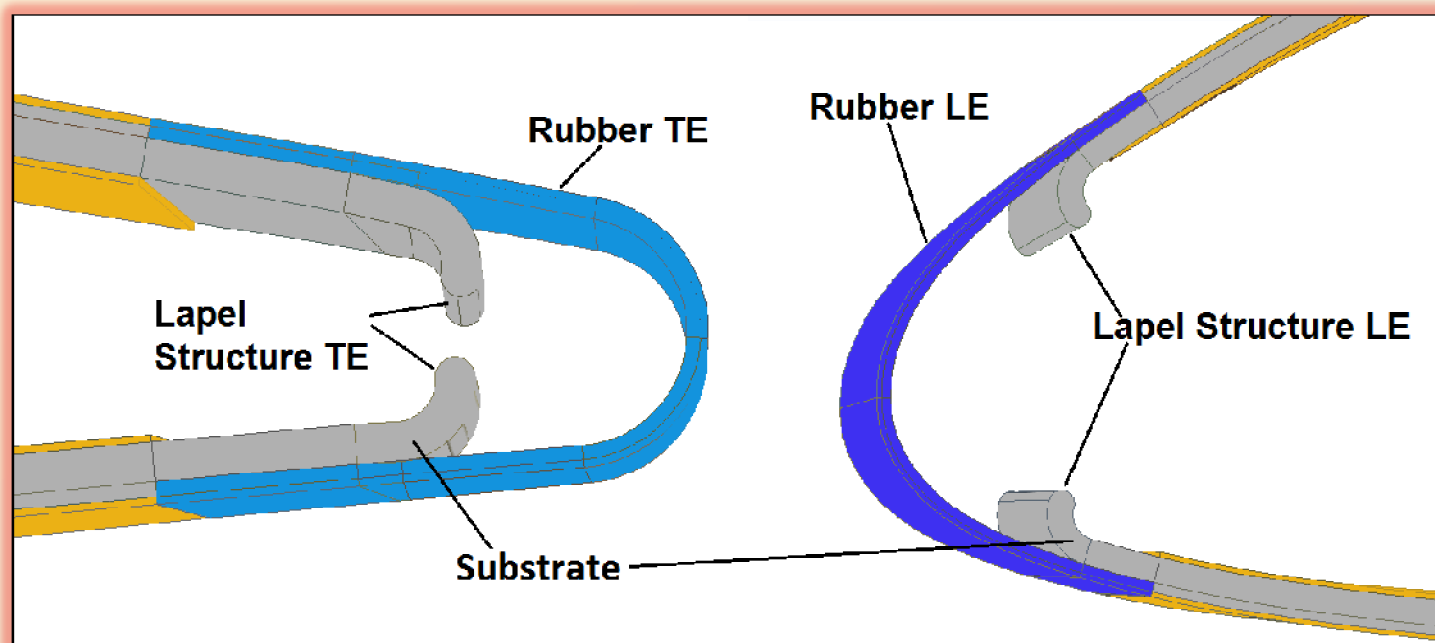


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing (details of LE and TE)





A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections

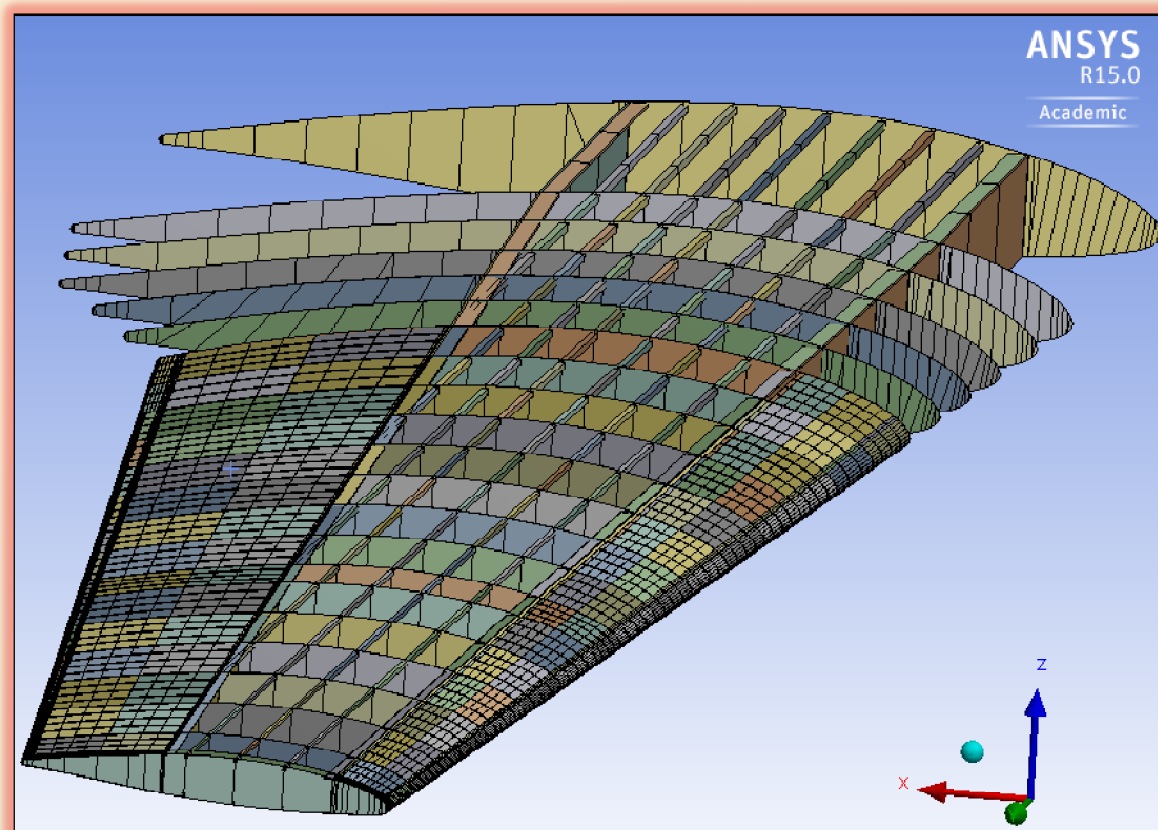


Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing

Mesh characteristics:

- 103160 nodes
- 19459 elements



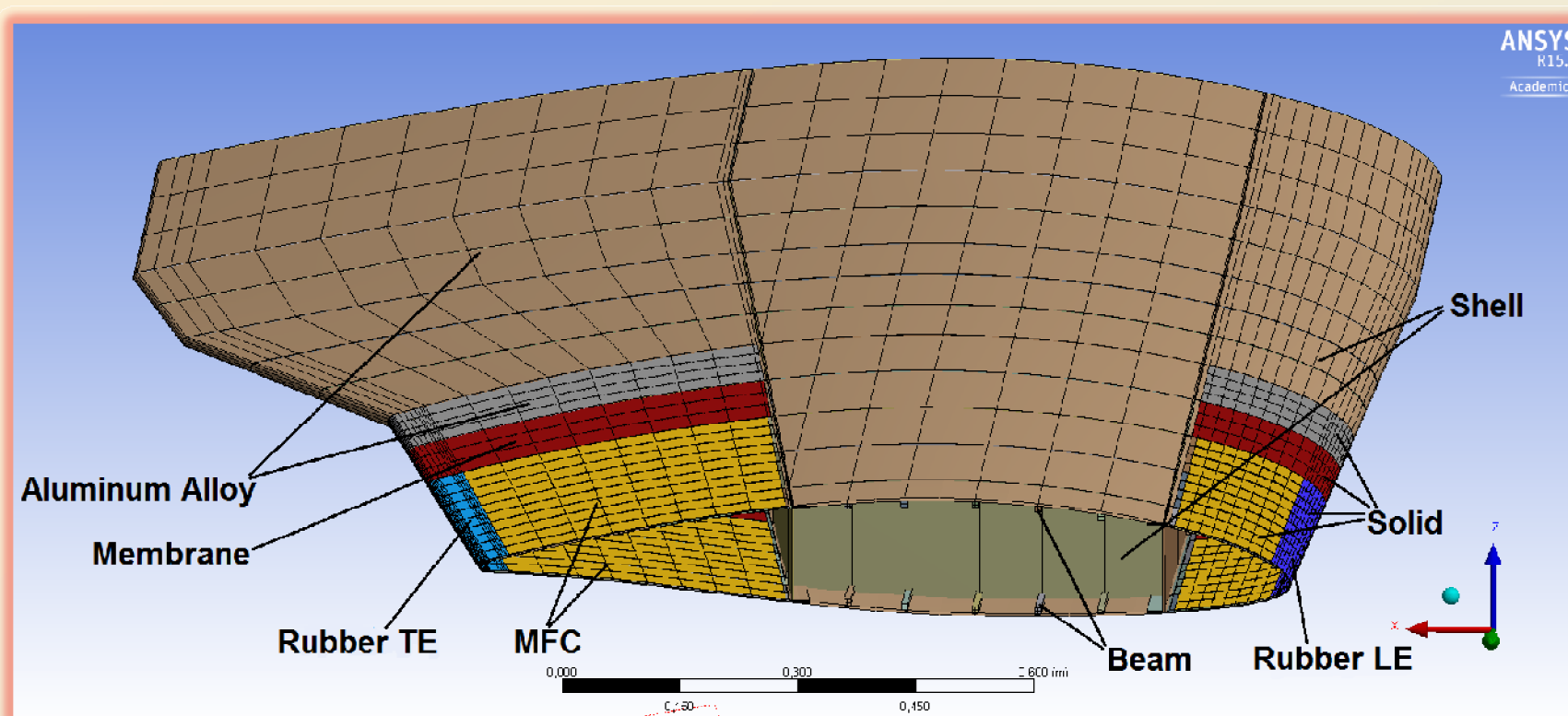


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

Partial sketch of the mechanical model of the piezo-wing



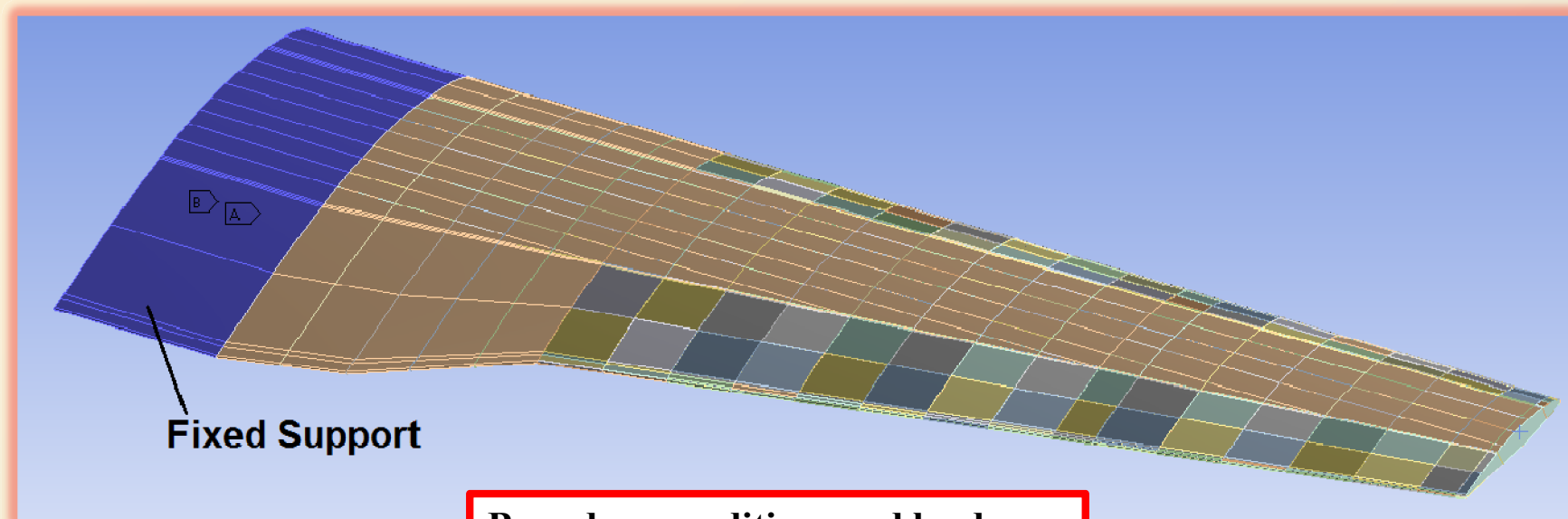


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing



Boundary conditions and loads:

- **Fixed Support**
- Thermal Pre-Strain areas
- Voltage load cases ($V^*=1500V$)

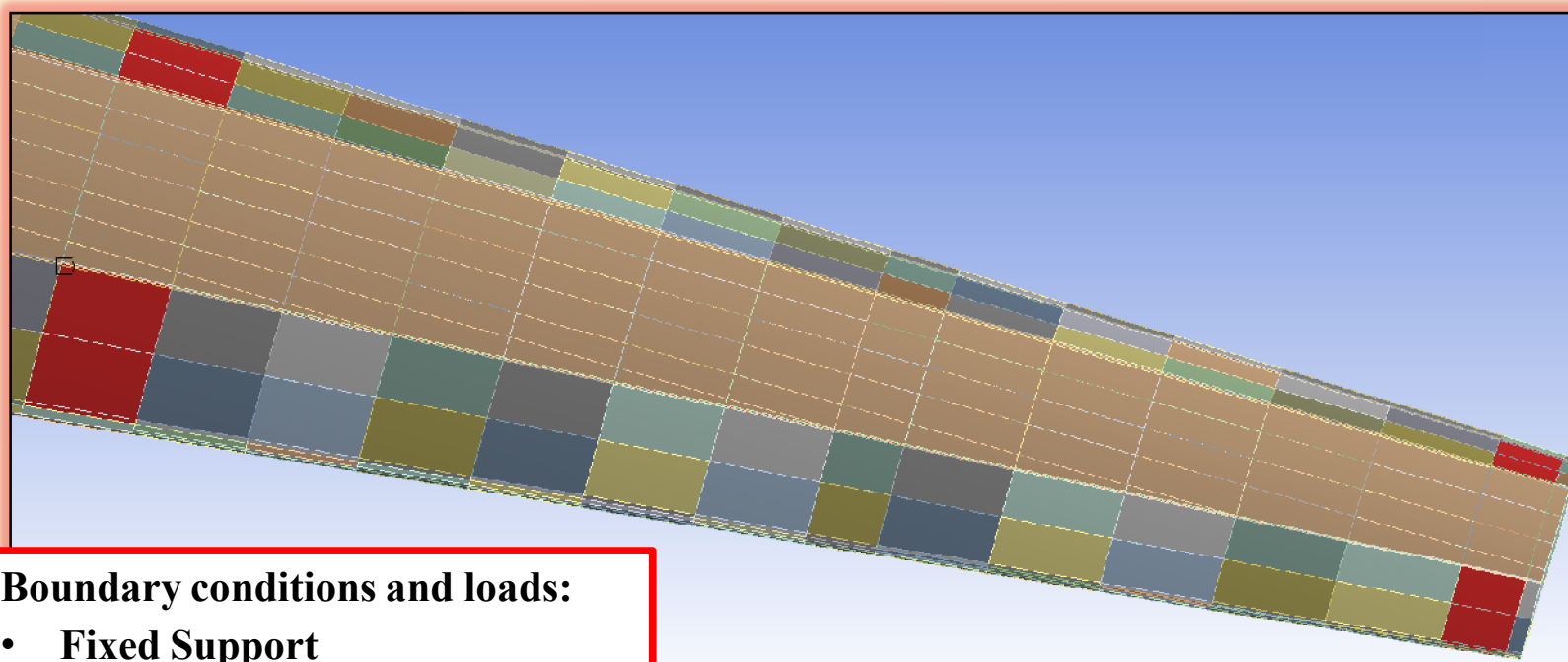


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing



Boundary conditions and loads:

- Fixed Support
- Thermal Pre-Strain areas
- Voltage load cases ($V^*=1500V$)

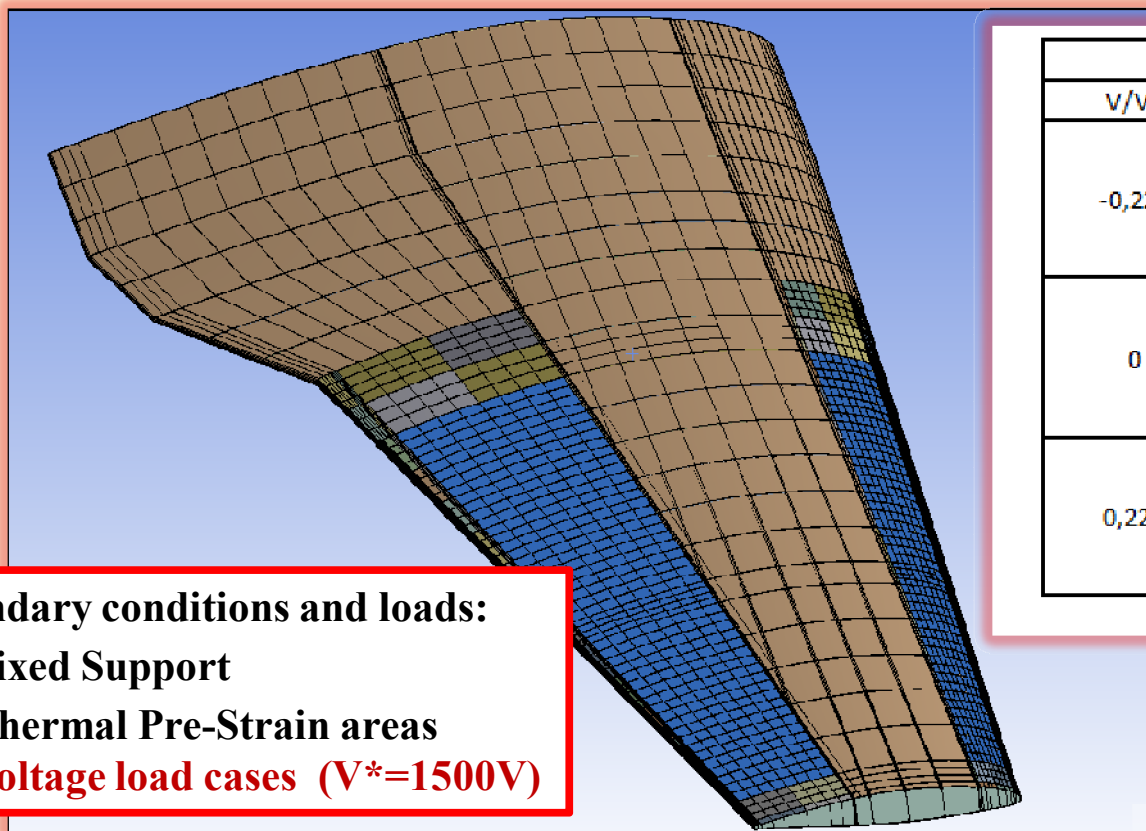


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing



Boundary conditions and loads:

- Fixed Support
- Thermal Pre-Strain areas
- Voltage load cases ($V^*=1500V$)

v/v*	TE - LE		Voltage [V]
-0,225	Upper Skin	Up	-337,5
		Down	675
	Bottom Skin	Up	-168,75
		Down	337,5
0	Upper Skin	Up	0
		Down	0
	Bottom Skin	Up	0
		Down	0
0,225	Upper Skin	Up	337,5
		Down	-168,75
	Bottom Skin	Up	675
		Down	-337,5

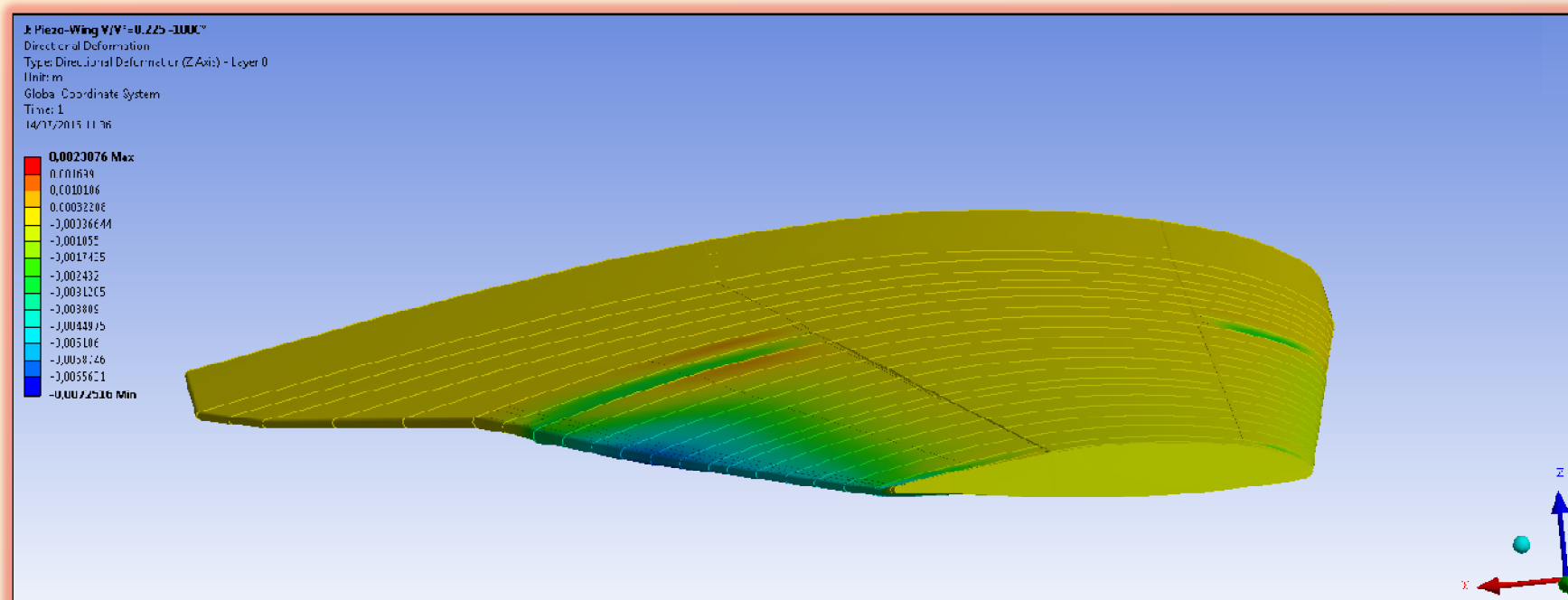


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing



Results due to voltage effects: $V/V^* = 0.225$

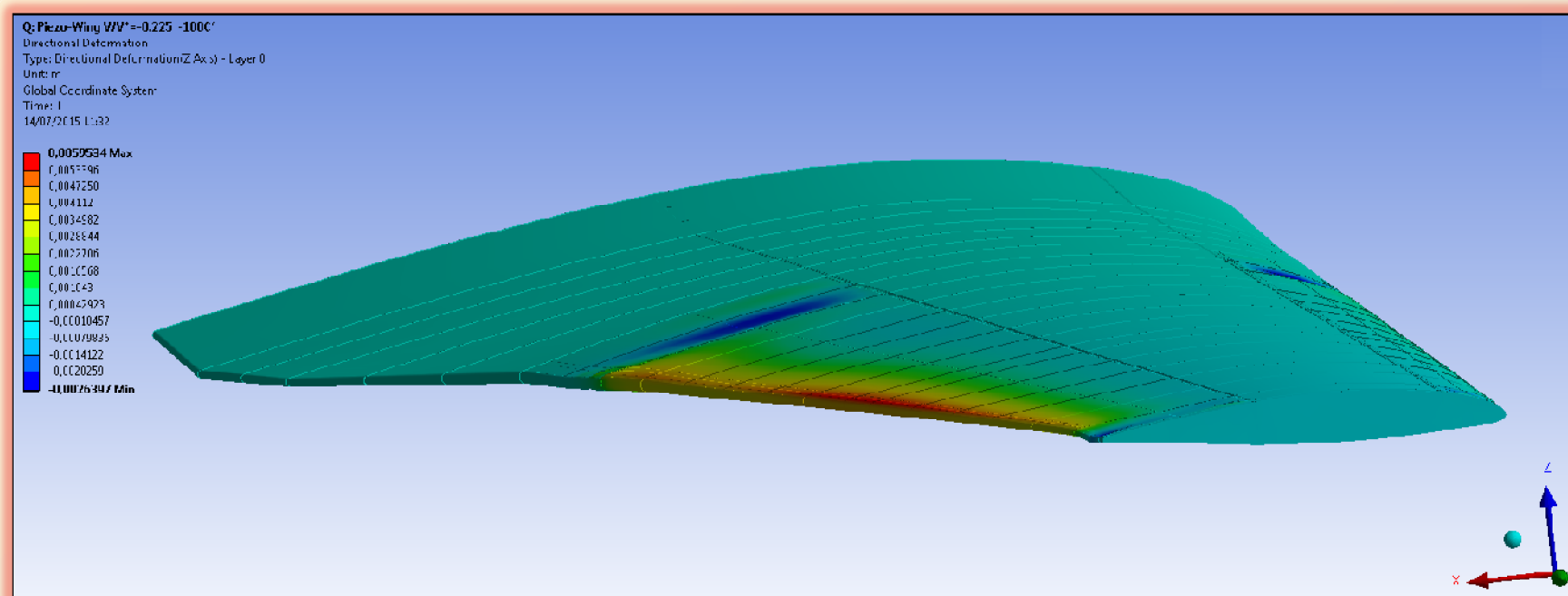


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Model and FSI analyses of the Morphing Wing (the piezo-wing)

The finite element model of the piezo-wing



Results due to voltage effects: $V/V^* = -0.225$

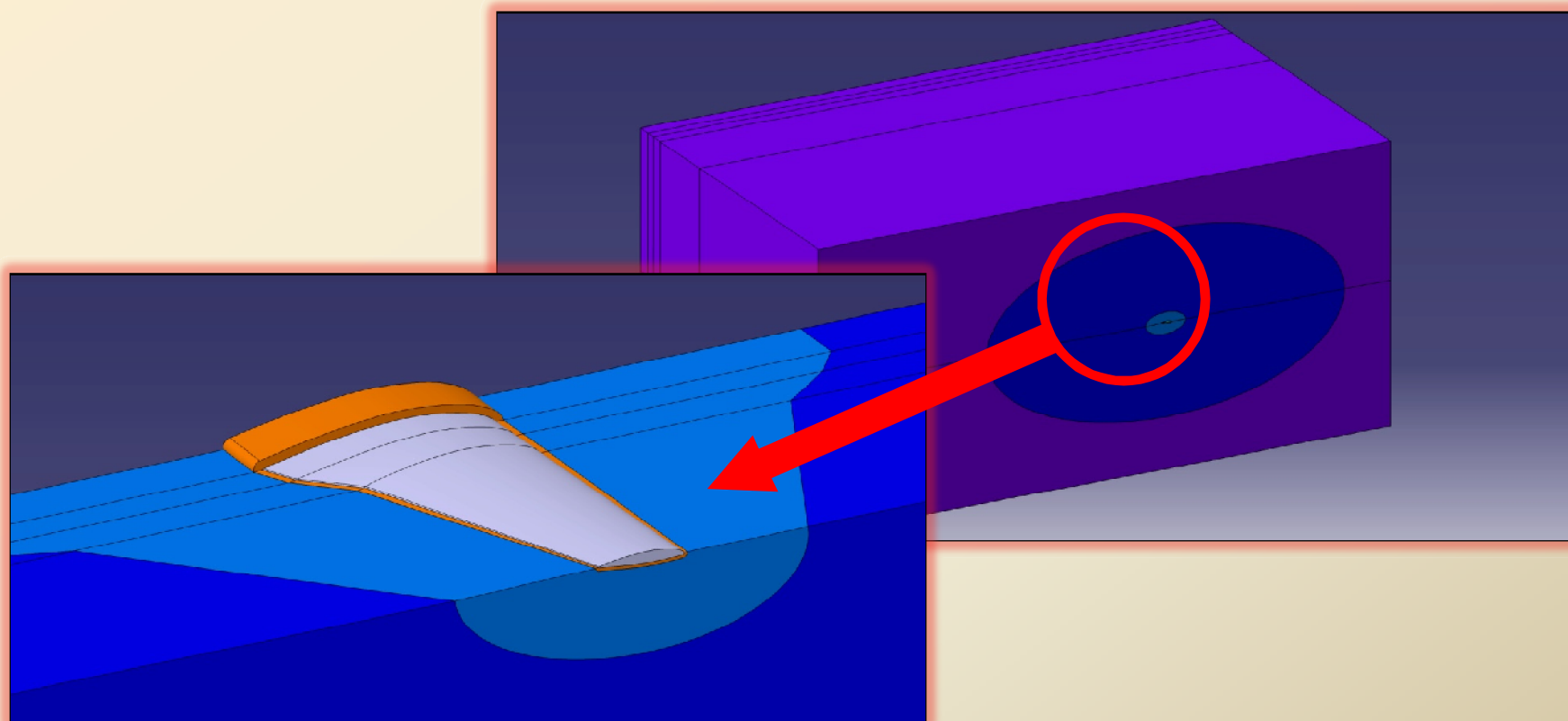


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

CFD model: fluid domain geometry



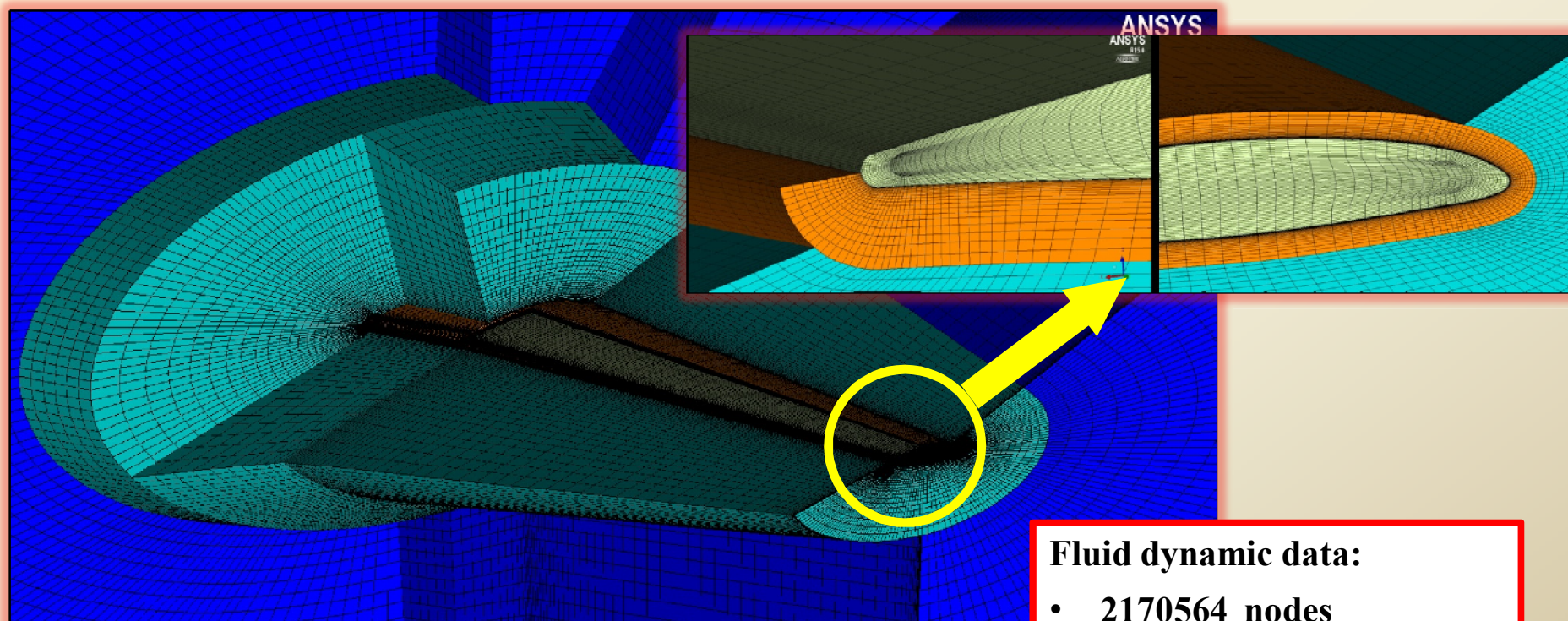


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Model and FSI analyses of the Morphing Wing (the piezo-wing)

CFD model: fluid domain grid (structured)



Fluid dynamic data:

- 2170564 nodes
- 2130258 hexahedral cells

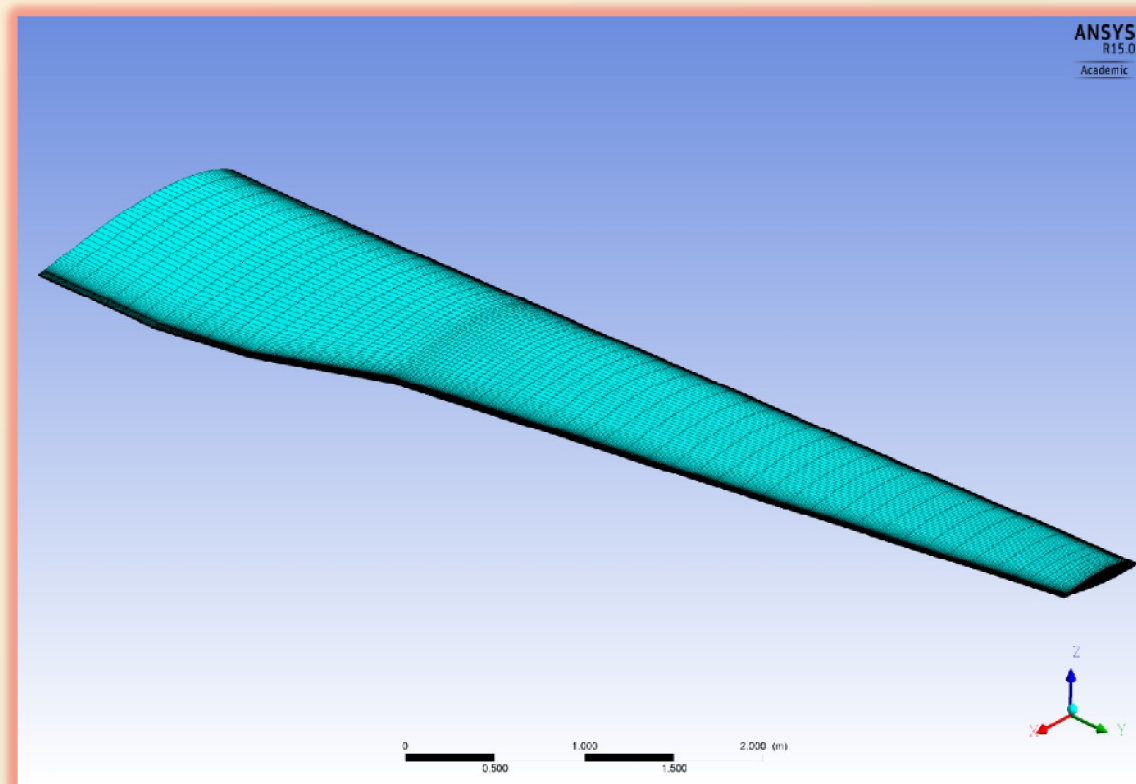


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

The aerodynamic model of the piezo-wing (the surface grid)



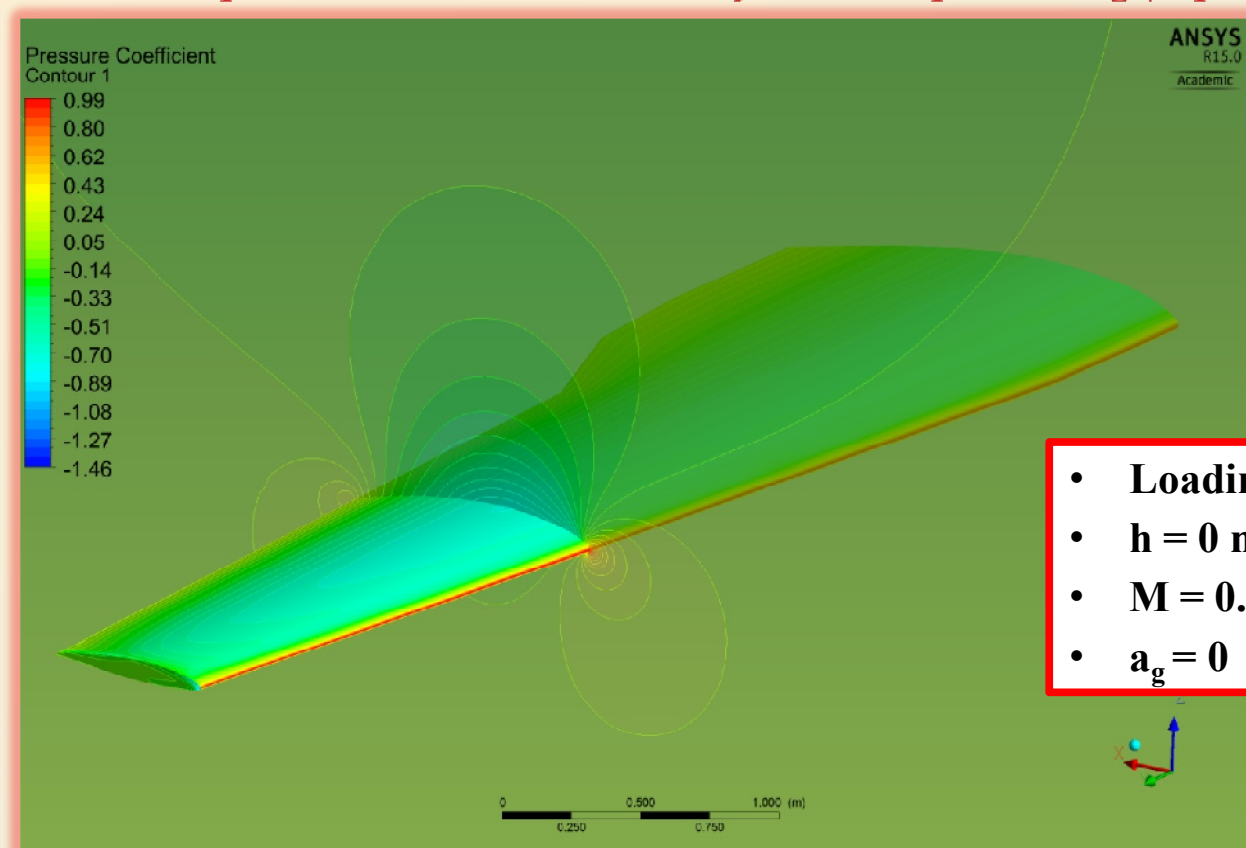


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Model and FSI analyses of the Morphing Wing (the piezo-wing)

Example of results of the FSI analyses of the piezo-wing (C_p distribution)



- Loading case $V/V^* = 0.225$
- $h = 0$ m
- $M = 0.17$
- $a_g = 0$



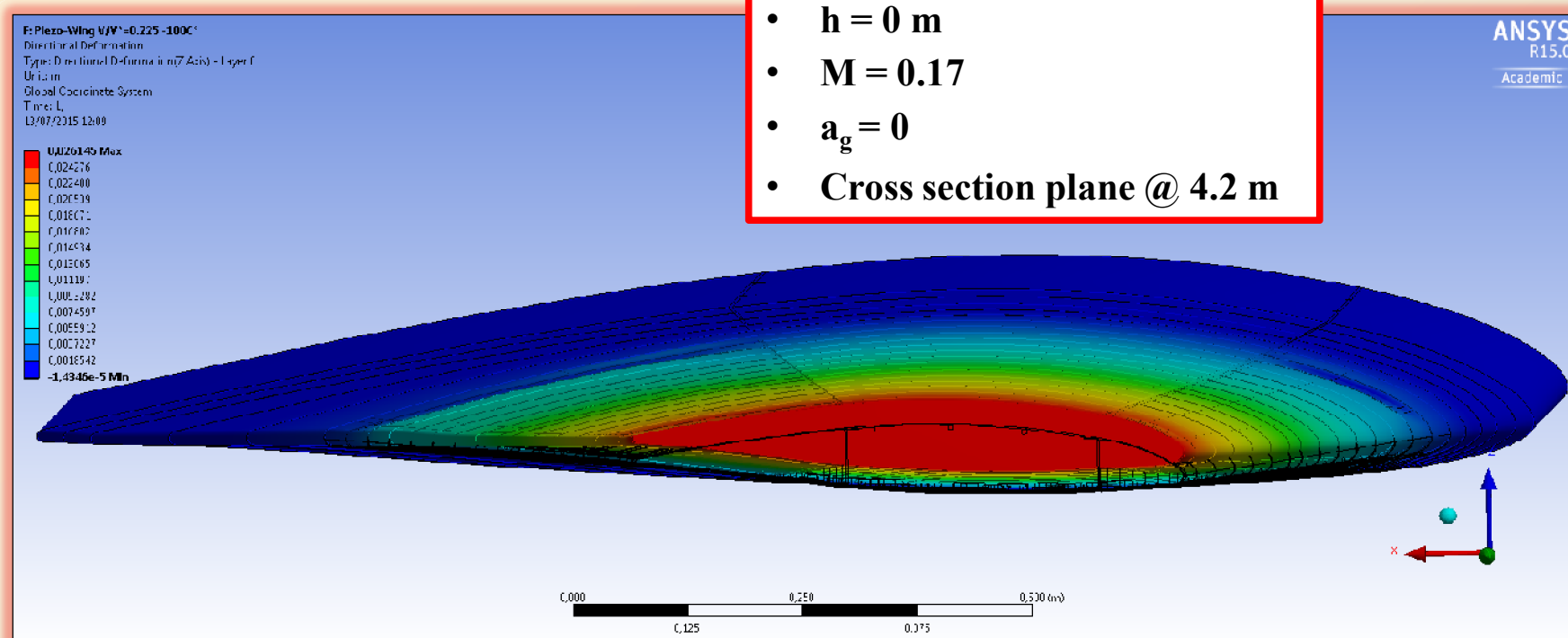
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Model and FSI analyses of the Morphing Wing (the piezo-wing)

Example of results of the FSI analyses of the piezo-wing (vertical displacements)

- Loading case $V/V^* = 0.225$
- $h = 0$ m
- $M = 0.17$
- $a_g = 0$
- Cross section plane @ 4.2 m



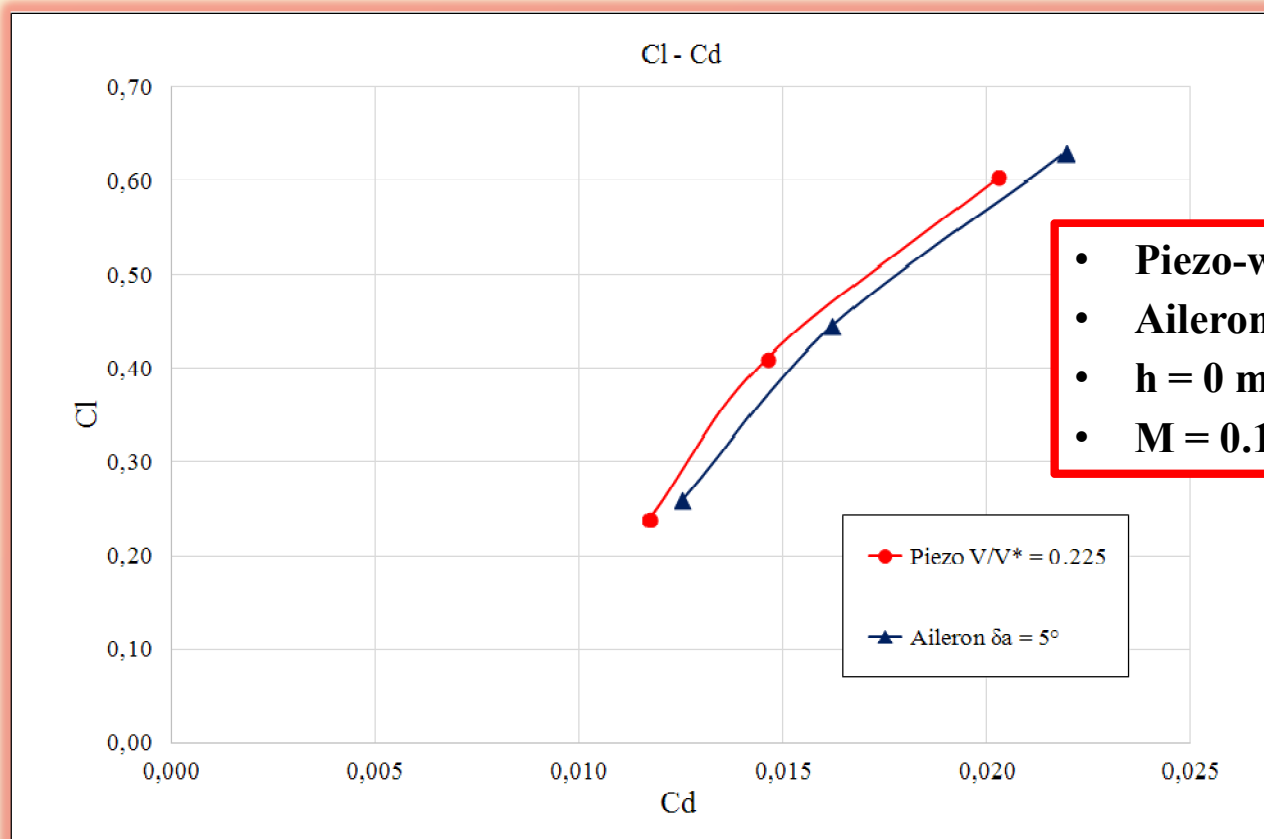


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Comparison of the aerodynamic performances of the wings

Comparison of results of the FSI analyses of the two wings (drag polar curves)



- Piezo-wing: $V/V^* = 0.225$
- Aileron-wing: $\delta a = 5$
- $h = 0$ m
- $M = 0.17$

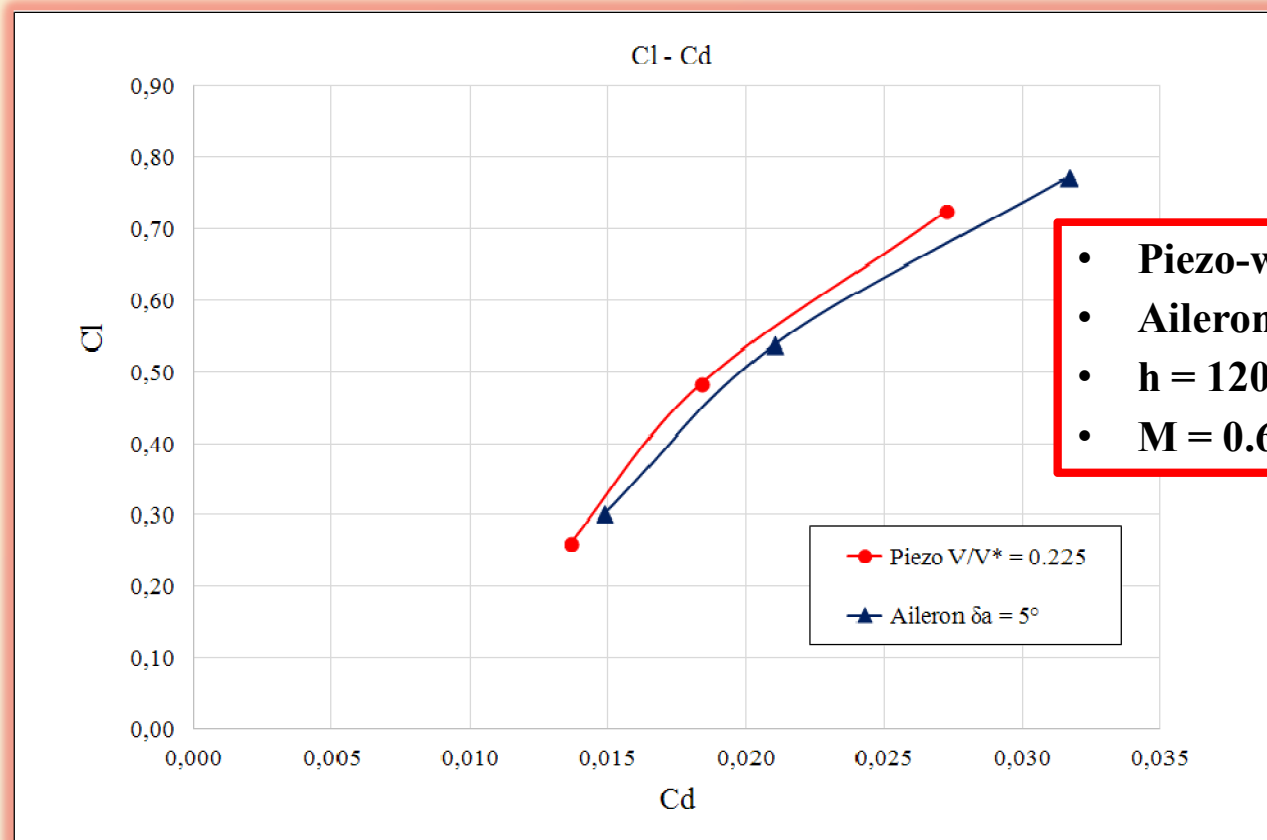


A Numerical Comparison between a Morphing Wing and a Traditional Wing: Aerodynamic Effects of Controlled Piezoelectric Deflections



Comparison of the aerodynamic performances of the wings

Comparison of results of the FSI analyses of the two wings (drag polar curves)



- Piezo-wing: $V/V^* = 0.225$
- Aileron-wing: $\delta a = 5$
- $h = 12000$ m
- $M = 0.65$

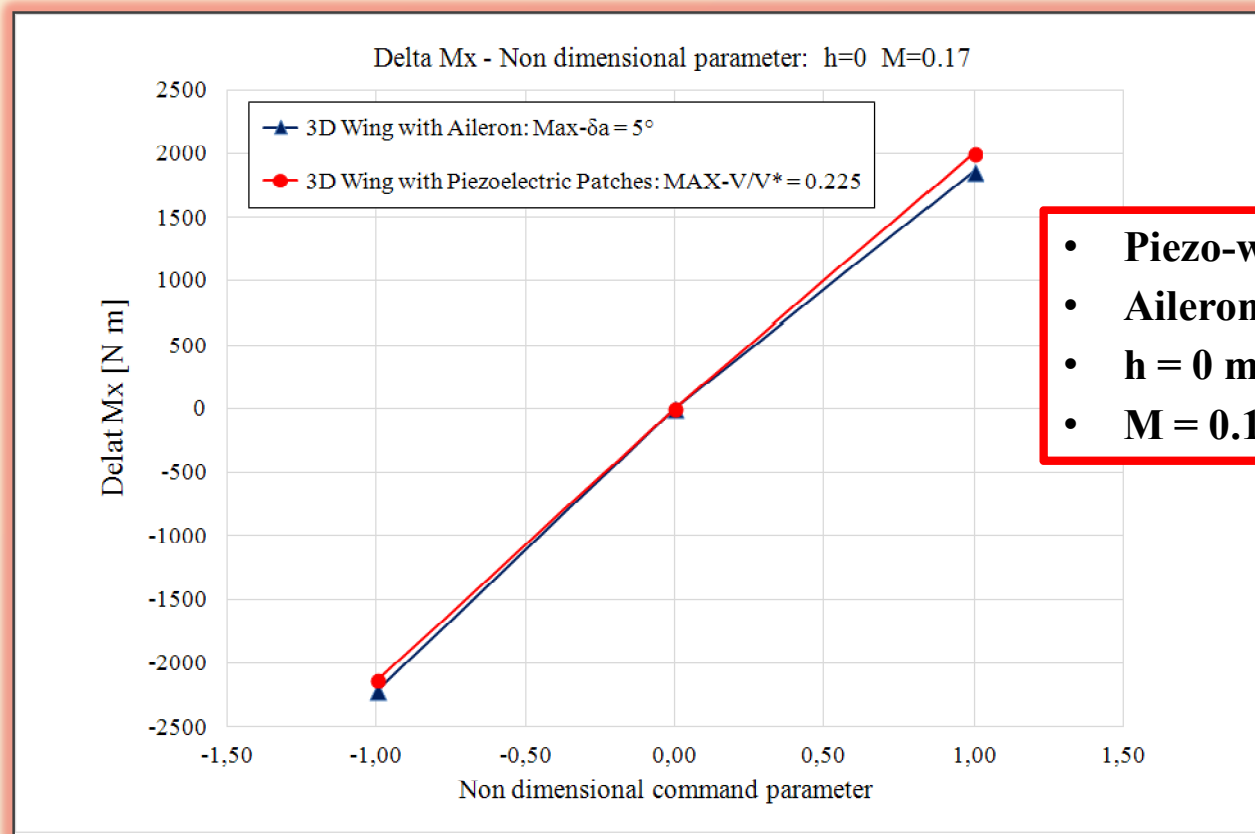


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Comparison and discussion of the static aeroelastic results

Results of the FSI analyses of the two wings (rolling moment contributions)



- **Piezo-wing: $V/V^* = 0.225$**
- **Aileron-wing: $\delta a = 5$**
- **$h = 0$ m**
- **$M = 0.17$**

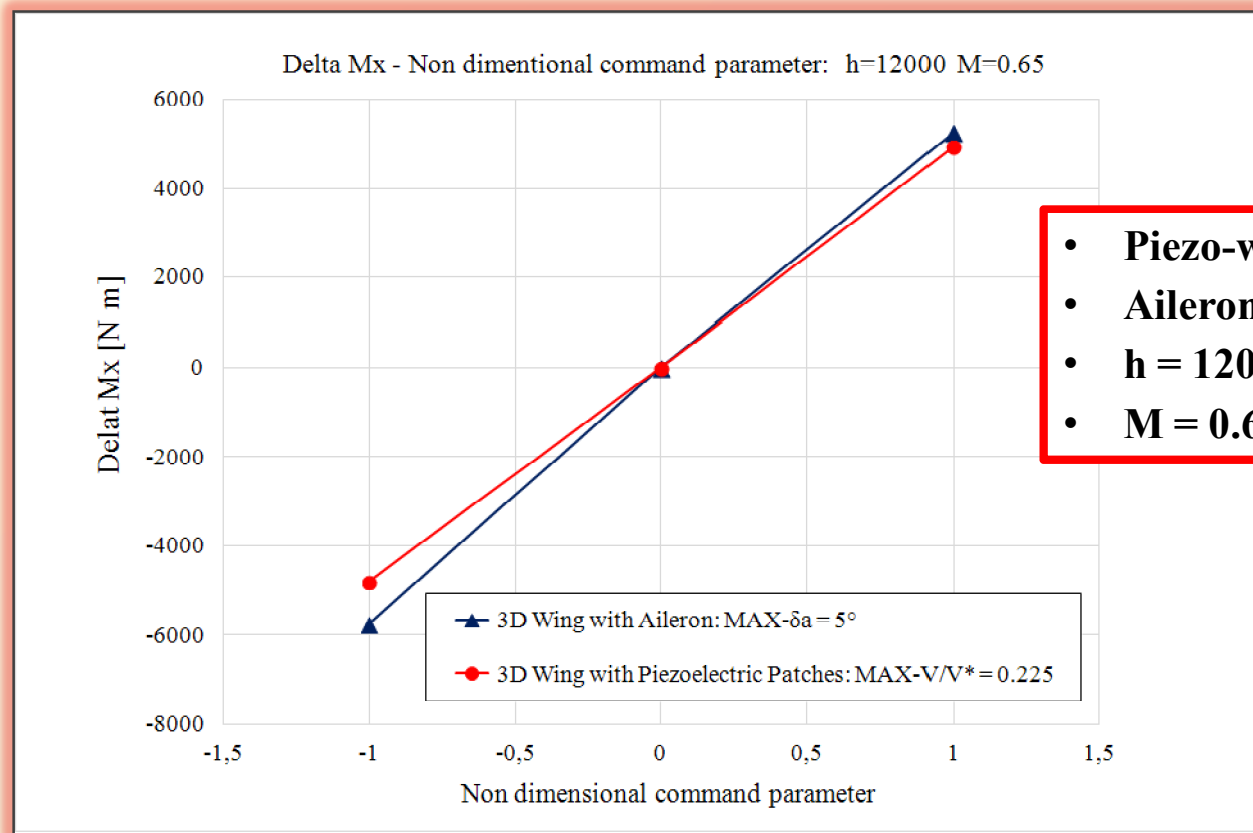


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Comparison and discussion of the static aeroelastic results

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Comparison and discussion of the static aeroelastic results

Results of the FSI analyses of the two wings (rolling moment contributions)

Piezo-Wing $h = 0$ $M = 0.17$ $\alpha_g = 0^\circ$				
V/V* (slide 39)	Non dimensional parameter	Mx [Nm]	Delta-Mx [Nm]	Delta-Mx Tot [Nm]
-0.225	-1	16,077	-2,138	4,135
0	0	18,214	0	
0.225	1	20,212	1,998	

Aileron-Wing $h = 0$ $M = 0.17$ $\alpha_g = 0^\circ$				
δa (aileron angle)	Non dimensional parameter	Mx [Nm]	Delta-Mx [Nm]	Delta-Mx Tot [Nm]
-4°	-1	17,690	-2,218	4,078
0°	0	19,908	0	
5°	1	21,768	1,860	



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Comparison and discussion of the static aeroelastic results

Results of the FSI analyses of the two wings (rolling moment contributions)

Piezo-Wing $h = 12000$ $M = 0.65$ $\alpha_g = 0^\circ$				
V/V* (slide 39)	Non dimensional parameter	Mx [Nm]	Delta-Mx [Nm]	Delta-Mx Tot [Nm]
-0.225	-1	47,826	-4,801	9,728
0	0	52,627	0	
0.225	1	57,554	4,927	

Aileron-Wing $h = 12000$ $M = 0.65$ $\alpha_g = 0^\circ$				
δa (aileron angle)	Non dimensional parameter	Mx [Nm]	Delta-Mx [Nm]	Delta-Mx Tot [Nm]
-4°	-1	56,628	-5,748	10,998
0°	0	62,376	0	
5°	1	67,627	5,250	



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Conclusions and future research activities (1 of 3)

- The 3D piezo-wing model under the effect of the control parameter $V/V^* = 0.225$, that is, under the application of voltage loads that are fully compatible with the MFC patches available at present, provides an aerodynamic behavior similar to an aileron-wing. In fact the drag polar curves of the two wings are very similar (for $h=0$ m and $M=0.17$ and for $h=12000$ m and $M=0.65$).
- **Under the conditions examined the piezo-wing seems to be slightly more efficient with respect to the traditional aileron wing.**
- **At low speed and at low altitude flight condition** ($h=0$ and $M=0.17$ with $\alpha_g = 0^\circ$) the total roll moment of the piezo-wing is equal to 4,135 Nm , while the total roll moment of the aileron-wing corresponding to a deflection of $\delta a = -4^\circ$ and $\delta a = +5^\circ$ of the right and left aileron surfaces respectively is equal to 4,078 Nm. **The piezo-wing provide an aeromechanical performance similar to the traditional aileron-wing (for a little deflection of the aileron surface).**
- **At a cruise flight condition** (that is $h=12000$ and $M=0.65$ with $\alpha_g = 0^\circ$) the total roll moment of the piezo-wing is equal to 9,728 Nm while the total roll moment of the aileron-wing corresponding to a deflection of $\delta a = -4^\circ$ and $\delta a = +5^\circ$ of the right and left aileron surfaces respectively is equal to 10,998 Nm. **In this case the piezo-wing, for the control voltages applied, provides a lower value of the roll moment but very close to the traditional aileron-wing data.**



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Conclusions and future research activities (2 of 3)

- The result obtained, on the basis of fluid structure interaction analyses under static loading conditions, show that at present the use of piezoelectric patches as actuators to control the shape of a realistic wing gives aeromechanical effects similar to the aileron control surfaces for low values of angle of deflection (a roll manoeuvre with ailerons deflection of 5° – 8° can be performed).
- **From a mechanical point of view the structure of the piezo-wing provides a very good behaviour, in fact the deformation levels are similar to the reference wing also for high Mach numbers.** Moreover the thicknesses of the morphing substrate can be reduced allowing a higher deformation of the cross section and then a higher increase of the airfoils' curvature that may provide better aerodynamic performances of the morphing wing.



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Conclusions and future research activities (3 of 3)

- From a practical point of view further analyses carried out within the FutureWings project, that can't be presented in the present work for the sake of simplicity, have shown that **with an hypothetical increase of the MFC performances of about 4 times, a Future-Wing Aircraft (that is an aircraft with morphing piezoelectric wings) could be able to execute the take off manoeuvre of the reference aircraft. In this sense further research on the development of high performances piezoelectric materials are strongly desirable.**
- Another result regards the **behaviour of a morphing wing at high angles of attack**: preliminary analyses show that the stall of a clean piezo-wing happens in a smoother manner and for higher values of the angle of attack with respect to a wing equipped with high lift systems; anyway, detailed and more complex analyses need to be executed on this topic.



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Thank You Very Much for Your Attention