Fondation de Coopération Scientifique Sciences et Technologies pour l'Aéronautique et l'Espace

RTRA-SMARTWING and EMORPH meeting

RTRA – « Réseau Thématique de Recherche Avancée »

The platform ('chantier') SMARTWING

«New concepts for improving the aerodynamic performances of airvehicles»

Introductory presentation by

Marianna BRAZA

IMFT-CNRS

Research Team: "Interaction Fluide –Structure Sous Turbulence" - IFS2T

Research Group "EMT2" Ecoulements Monophasiques, Transitionnels et Turbulents"

PARTNERS SMARTWING

•ISAE

•LAPLACE

•ONERA

•IMT

• IMFT - Coordonnateur

PROJECT : 01/02/2012- 28/02/2015

PARTNERS RTRA – EMMAV – Electroactive Morphing for Micro-Airvehicles : 1/01/2010-1/10/2012

•ISAE

•LAPLACE

•IMFT - Coordonnateur

PROJECT : 01/2010- 30/10/2012

Fondation de Coopération Scientifique Sciences et Technologies pour l'Aéronautique et l'Espace

RTRA – « Réseau Thématique de Recherche Avancée »

1) Research program **EMMAV** – Electroactive Morphing for Micro-Airvehicles

2009-2012 **IMFT, ISAE, LAPLACE**

1) Research PLATFORM **SMARTWING** including :

2012-2015

SMARTWING MORPHING CENTRE

Research program **DYNAMORPH**

4 workshops

1 international conference June 2013

IMFT, IMT, ISAE, LAPLACE, ONERA

« The SMARTWING platform focuses on creation of a **multi-disciplinary structure**, associating the competences of the Toulouse laboratories in the domains of **aerodynamics, aeroelasticity, novel smart materials and of flight control commands**, to improve the aerodynamic efficiency of new generation of air-vehicles, by means of **Electroactive Morphing**"

OBJECTIVES and ORIGINAL ASPECTS IN THE STATE OF THE ART

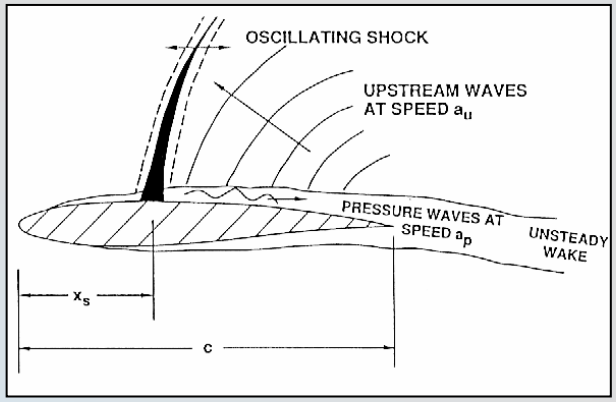
ELECTROACTIVE MORPHING

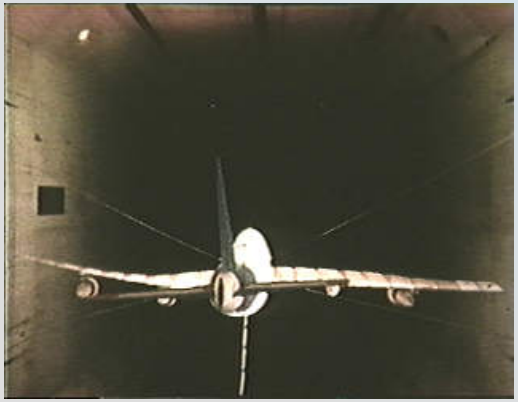
Shape optimisation for increasing performance and controlling instabilities and aerodynamic noise

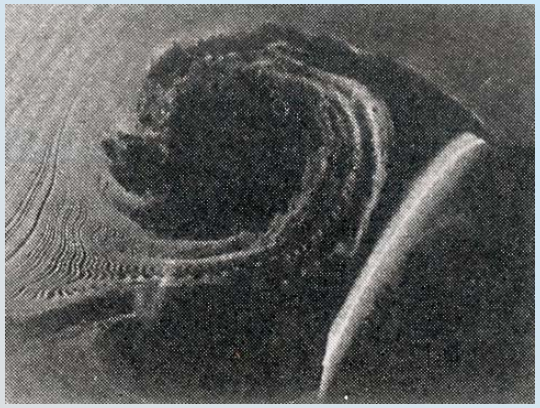
- **Optimisation of aerodynamic efficiency**
- **Real time: <u>Controller Design</u>**
- **<u>Low energetic cost</u> : recuperation and redistribution of environning vibratory energy by smart E-materials**
- **Replacement of hydraulic systems by electrical ones**
- **Loads control – manoeuvrability trailing-edge ailerons**
- **Attenuation of instabilities due to separation and to aeroelastic flutter and of aerodynamic noise due to trailing edge K-H vortices**
- **APPLICATION : drones, ailerons, flexible wings, UAV, rotor blades**

  flying wing, active transonic bumps: laminar wing

Instabilities occurring in aeronautics







Buffeting

- •Drag increase
- •Vibrations

- • materials fatigue
- • Reduction of the range of operation

Flutter phenomenon

Structure destruction

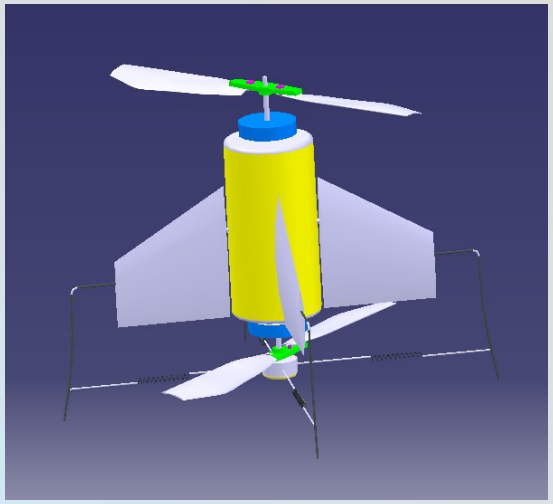
- •Structure enforcement
- •Velocity reduction

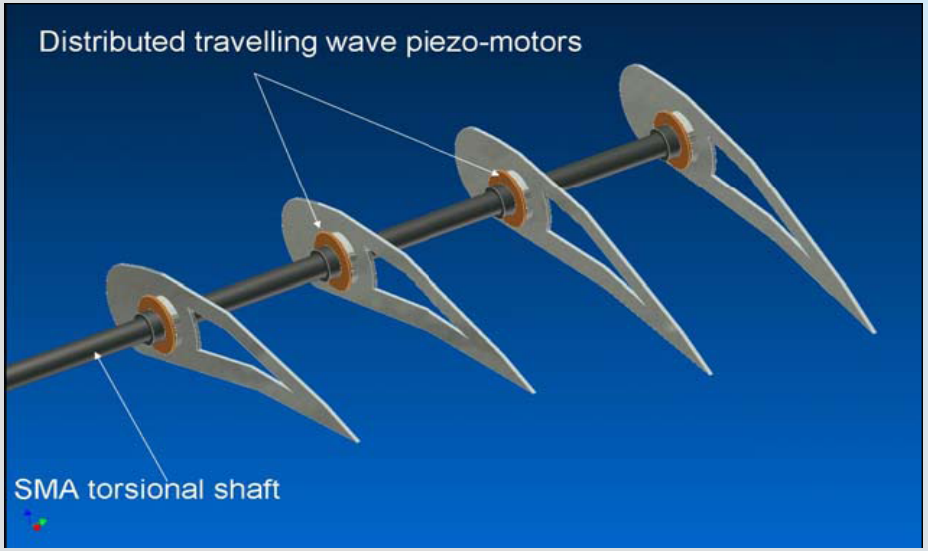
Dynamic stall

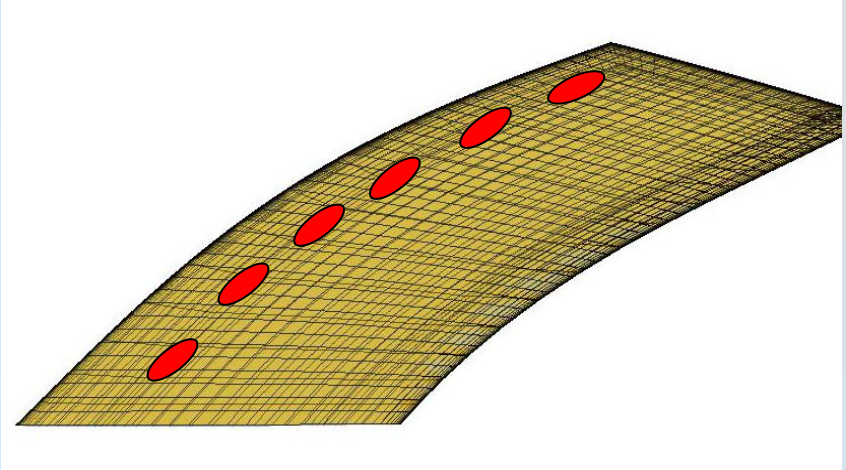
Sudden lift loss

- • Manoeuvrability limitation
- •Velocity reduction (helicopter)

PREMIERE CARACTERISATION DE CONCEPTS D'ACTUATION INNOVANTS – MORPHING ELECTROACTIF





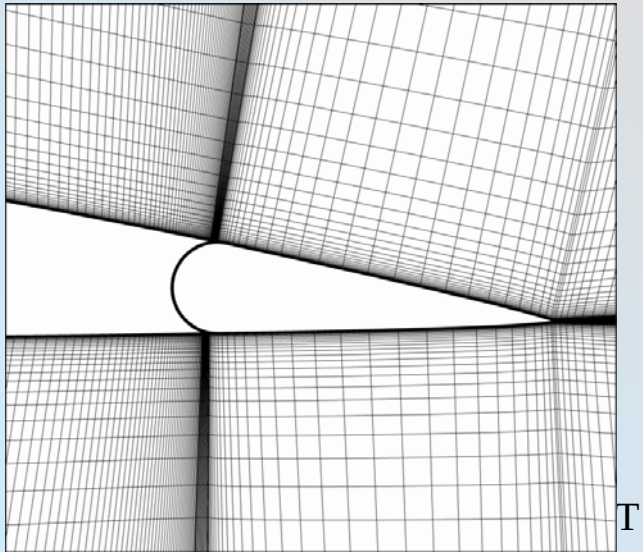


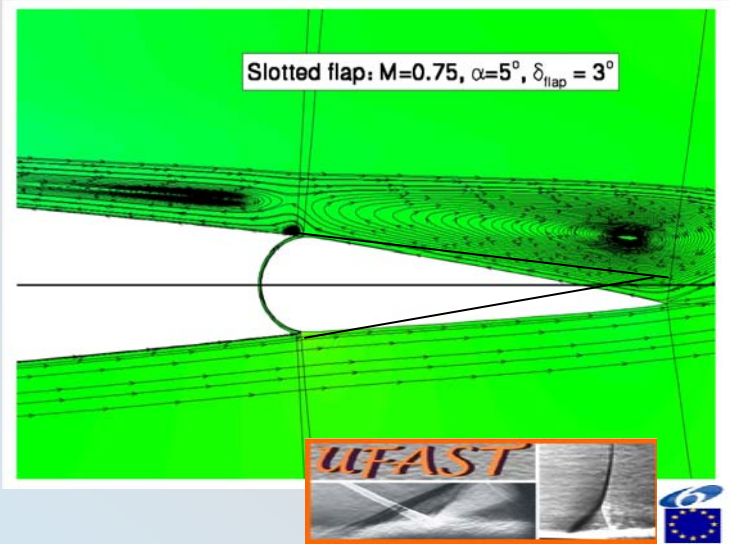
- SMA – Shape Memory Alloys
- Distributed small piezo-actuators, No-MEMS
- Electroactive Polymers
  - **Low actuation cost** thanks to:
    Capacity of vibratory energy recuperation and restitution
  - **Modification of the behavior laws** of the E-material – solid structure

❑ ELECTROACTIVE MORPHING

New aircraft generation with deformable wings and ailerons attending optimal shape in real time

- Ailerons, volets, gouvernes, rotors

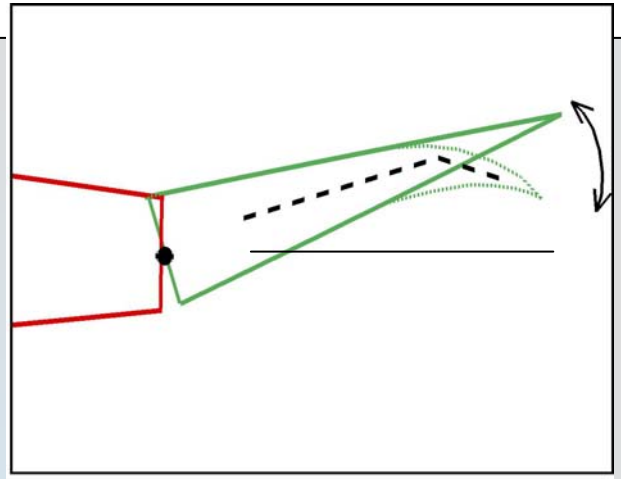




T

Morphing Electroactif

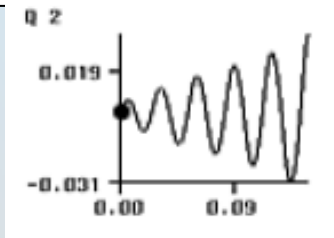
- **SHAPE CONTROLLER DESIGN**
- **FLIGHT CONTROL COMMANDS AND EVALUATION**
- **EXPERIMENTAL DEMONSTRATOR**



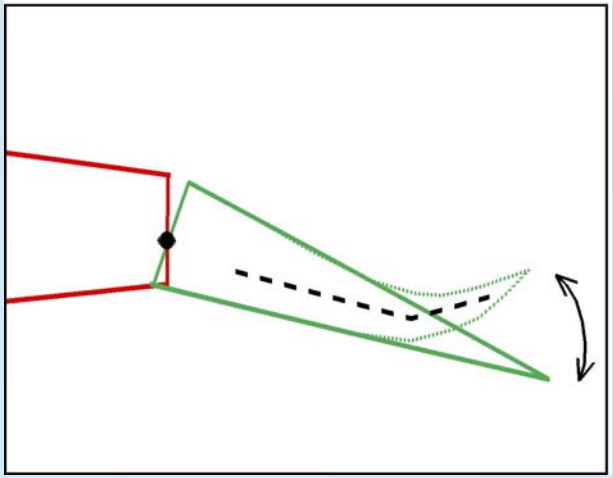
α

a

$\alpha \pm \varepsilon(t)$

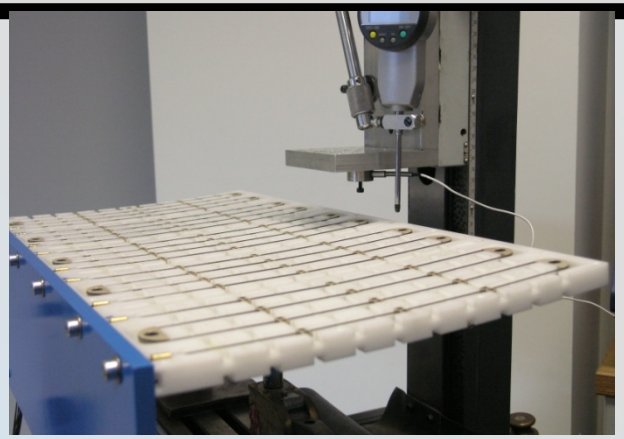


The optimal form is a function of a and depends on M, Re flow regimes



Deformation is reached by continuously distributed E-materials according to optimum design shape

ACTIVATION D'UNE VOILURE DEFORMABLE PAR DES CABLES D'AMF REPARTIS EN SURFACE



Publication Congrès Français de Mécanique, Besançon, sept. 2011

Jean-François ROUCHON[a], Dominique HARRIBEY [a], Enrico DERI [b], Marianna BRAZA [b]

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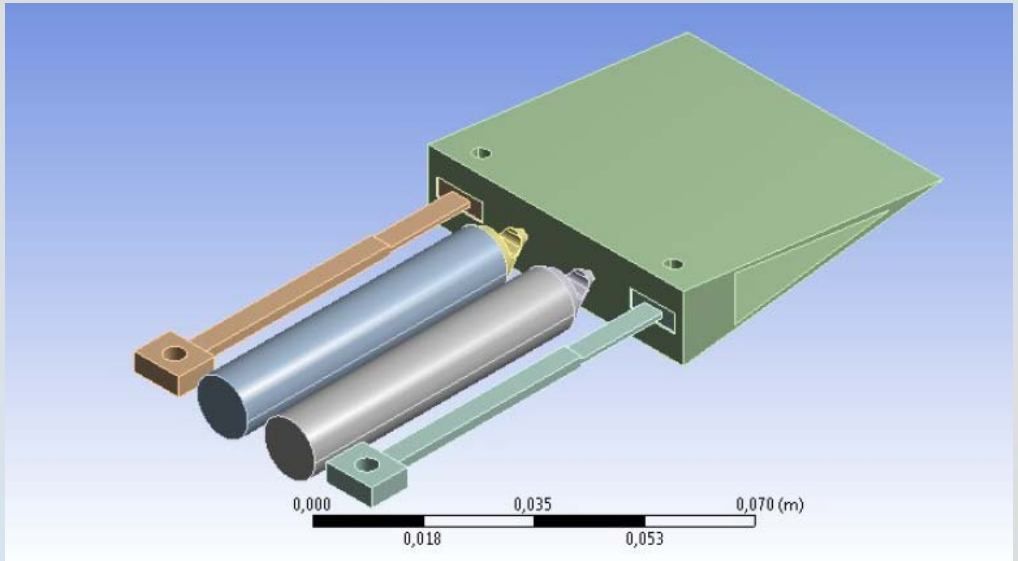
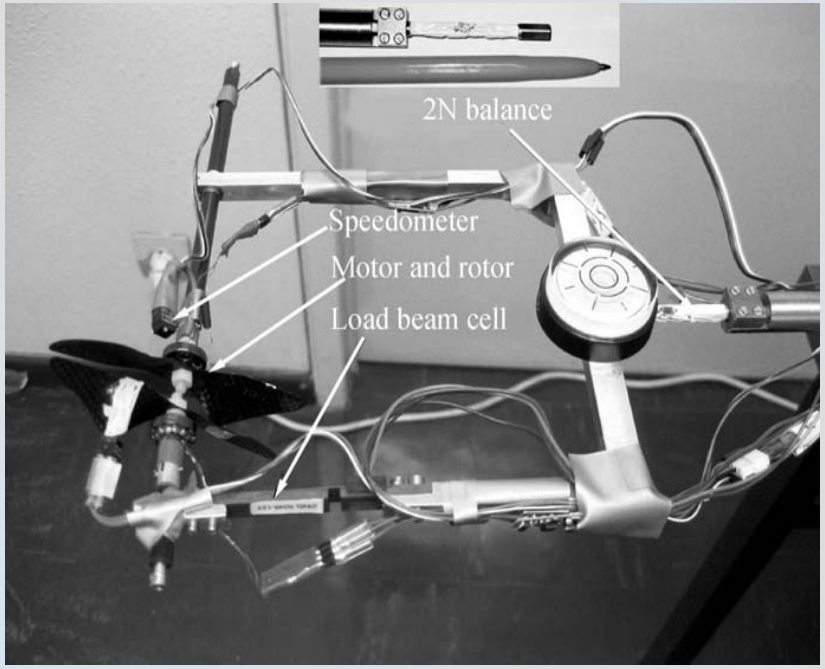
b. Institut de Mécanique des Fluides de TOULOUSE- 1 Allée du Professeur Camille Soula, 31400 TOULOUSE

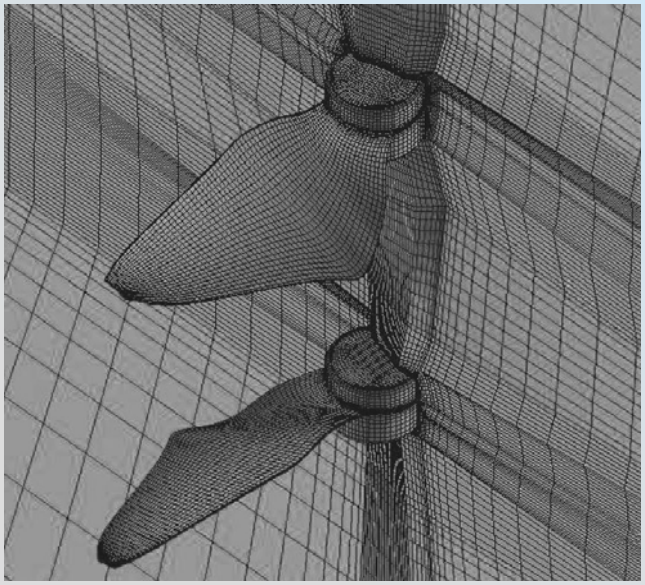
PIEZOACTUATEURS PZT – MORPHING DU BORD DE FUITE DE VOLET/ AILERON

J. Scheller, J.F. Rouchon, M. Chinaud, D. Haribey 2012



Nanorotors coaxiaux: caractérisation et optimisation





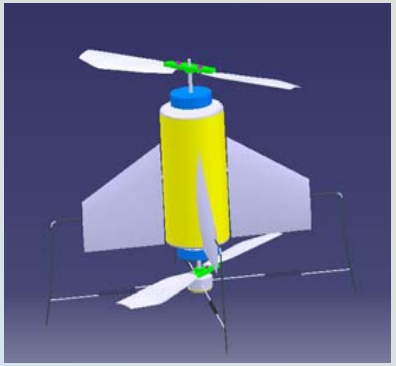
- Montage expérimental sur nano-balance de précision
- Calcul Navier-Stokes par méthode MRF

isae
Institut Supérieur de l'Aéronautique et de l'Espace

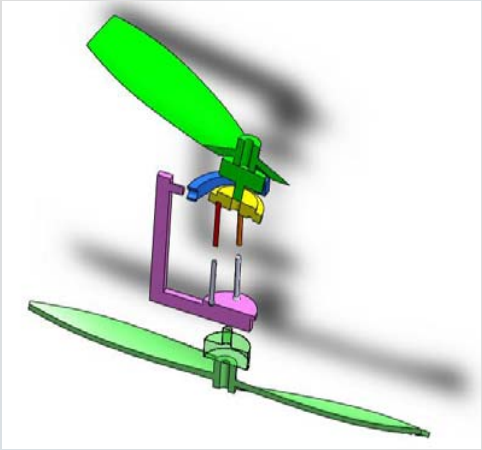
FROM EMMAV TO **SMARTWING/DYNAMORPH**

II.Vers un démonstrateur de drone électroactivé

Concept 1
morphing gouverne **EMMAV**
2009-2012



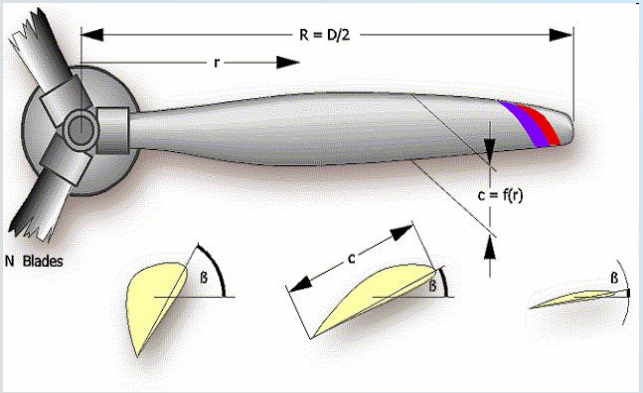
Concept 2 commande
têtes de rotors par
muscles artificiels:
DYNAMORPH 2011-2014

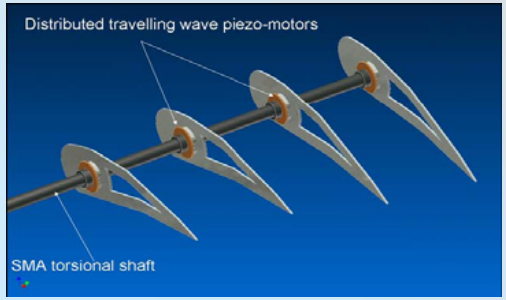


Concept 3

commande par pales électroactives

DYNAMORPH



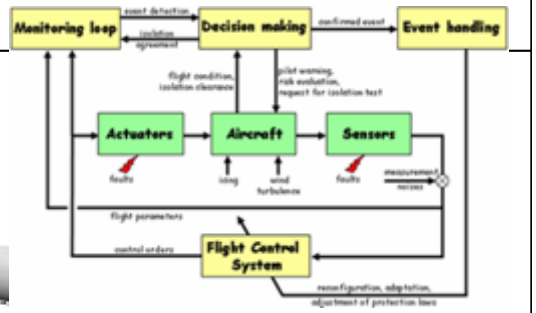


General concept SMARTWING/DYNAMORPH

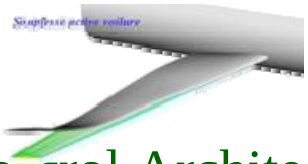
- Hybridation concept : Distributed small piezo-actuators *and* Shape Memory Alloys

- Low actuation cost thanks to:
capacity of vibratory energy recuperation and restitution

Onera / Systems Control & Flight Dynamics Dpt.



- Automatic control
- Controller Design & Flight Control

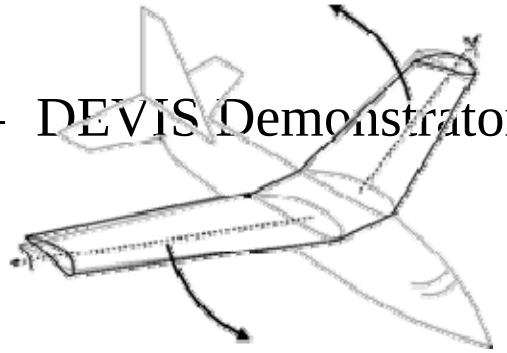


  – Methods & Tools for Control Laws & Control Architecture

  – Morphing aircraft (AVISAC project)

  – IMMUNE Intelligent Monitoring & Autoreconfiguration

  – DEVIS Demonstrator of Innovative Actuators Wing



Onera / Systems Control & Flight Dynamics Dpt.

- Robotics, Artificial Intelligence & Systems
- Controller Design & Flight Control

Embedded Systems Design & Controller Integration

- MAVION Mini Fixed Wing UAV (Cooperation with ISAE)
- Autonomous Systems Robotics Demonstrators

- ‘SATELLITE’ RESEARCH PROGRAMS TO RTRA-EMMAV - DYNAMORPH

AVISAC

IMMUNE

DAVIS

} ONERA, ISAE

DESider

} Coord. EADS

uFAST

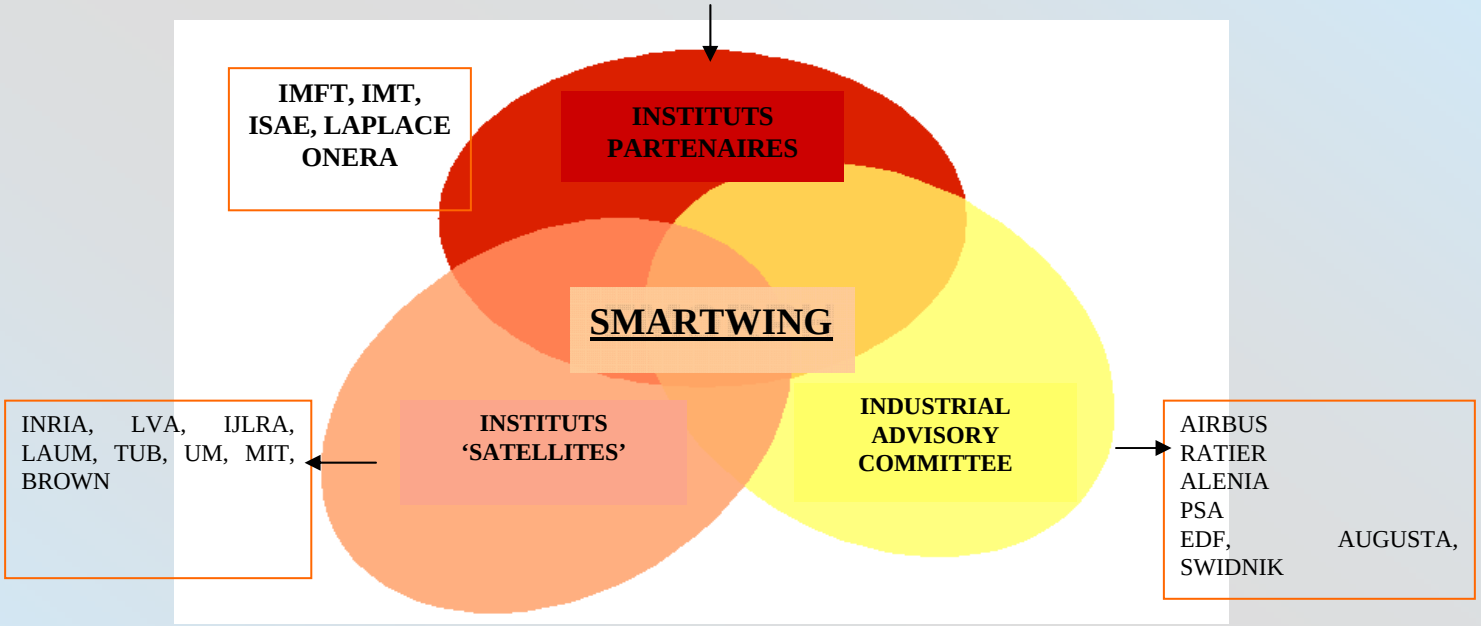
ATAAC

} Coord. DLR

TFAST – FP7

- INTERNATIONAL COLLABORATION:

MIT, BROWN, CORNELL, TEXAS-AUSTIN Universities


IMFT, IMT, ISAE, LAPLACE ONERA
INSTITUTS PARTENAIRES
SMARTWING
INSTITUTS 'SATELLITES'
INDUSTRIAL ADVISORY COMMITTEE
INRIA, LVA, IJLRA, LAUM, TUB, UM, MIT, BROWN
AIRBUS
RATIER
ALENIA
PSA
EDF, AUGUSTA, SWIDNIK

❑ ASPECTS NOVATEURS

S'appuyant sur la compréhension des enjeux acquise au cours du EMMAV:

nécessité de diversifier les types d'actuations:

•mini-piezoactuateurs PZT : haute fréquence de morphing –régime dynamique

•polymères électroactivés IPMC : perspectives technologiques inédites

vers la biomimétique : augmentation des performances

réduction du bruit aérodynamique

•couplage fort fluide - structure :

•actuations rapides de petite amplitude à des actuations lentes de forte amplitude : verrou physique à l'accession à des *gains de performances*

❑ PROJET **DYNAMORPH**

•**OPTIMISATION DE FORME DES AERONEFS (PALES, AILERONS)**

ET DE LA MANOEUVRABILITE DES DRONES

A L'AIDE DE NOUVEAUX CONCEPTS DE MORPHING ET DE

LEUR <u>HYBRIDATION</u>

•*matériaux de type* ***composites ioniques*** :

•**micro-hélicoptères à rotors souples**

❑ ASPECTS NOVATEURS -suite

•**couplage fort fluide - structure :**

•**actuations rapides de petite amplitude à des actuations lentes de forte amplitude : verrou physique à l'accession à des *gains de performances***

•Système d'ailerons de bord de fuite complexes: biomimétique

Augmentation de la portance en régime de faible vitesse

IMFT CONTRIBUTION

MODELING CFDSM : Computational Fluid Dynamics- Structural Mechanics

Unsteady aerodynamics and aeroelasticity: Challengies:

High-Reynolds number flows with thin shear-layer interfaces

Wall flows:Turbulence onset from near-wall

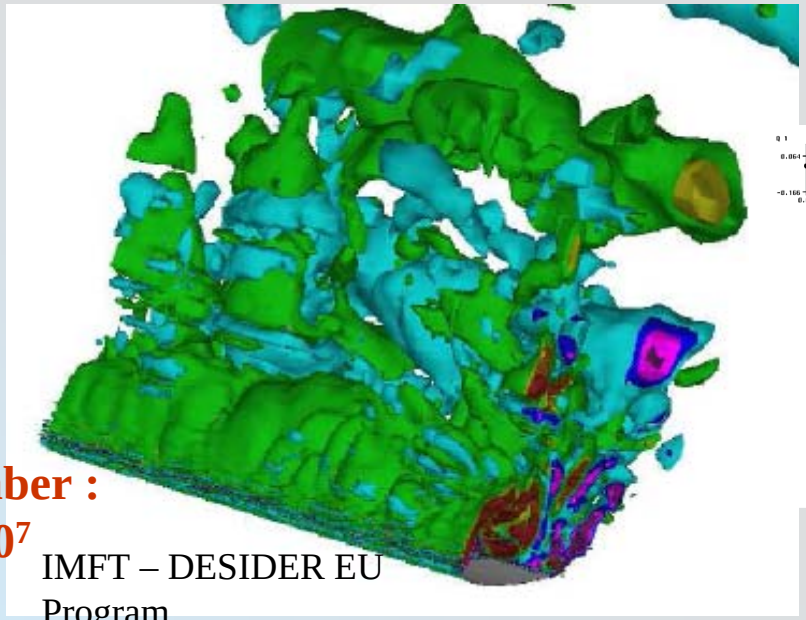
Near-wake modeling : Decisive for prediction ability of aerodynamic forces

•**Nouveaux concepts** de modélisation de la turbulence URANS - LES: cascade énergétique inverse – upscale turbulence modelling

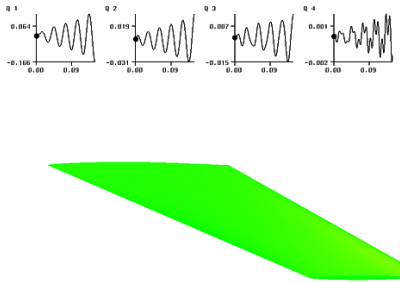
•**Prédiction améliorée d'un ordre de grandeur des coefficients aérodynamiques**

•**Couplage fort** entre la structure et le fluide: résolution simultanée des équations CFD-SM :

•**Modélisation d'ordre réduit** pour des prédictions **réalistes** de modification de forme pour le design



IMFT – DESIDER EU Program



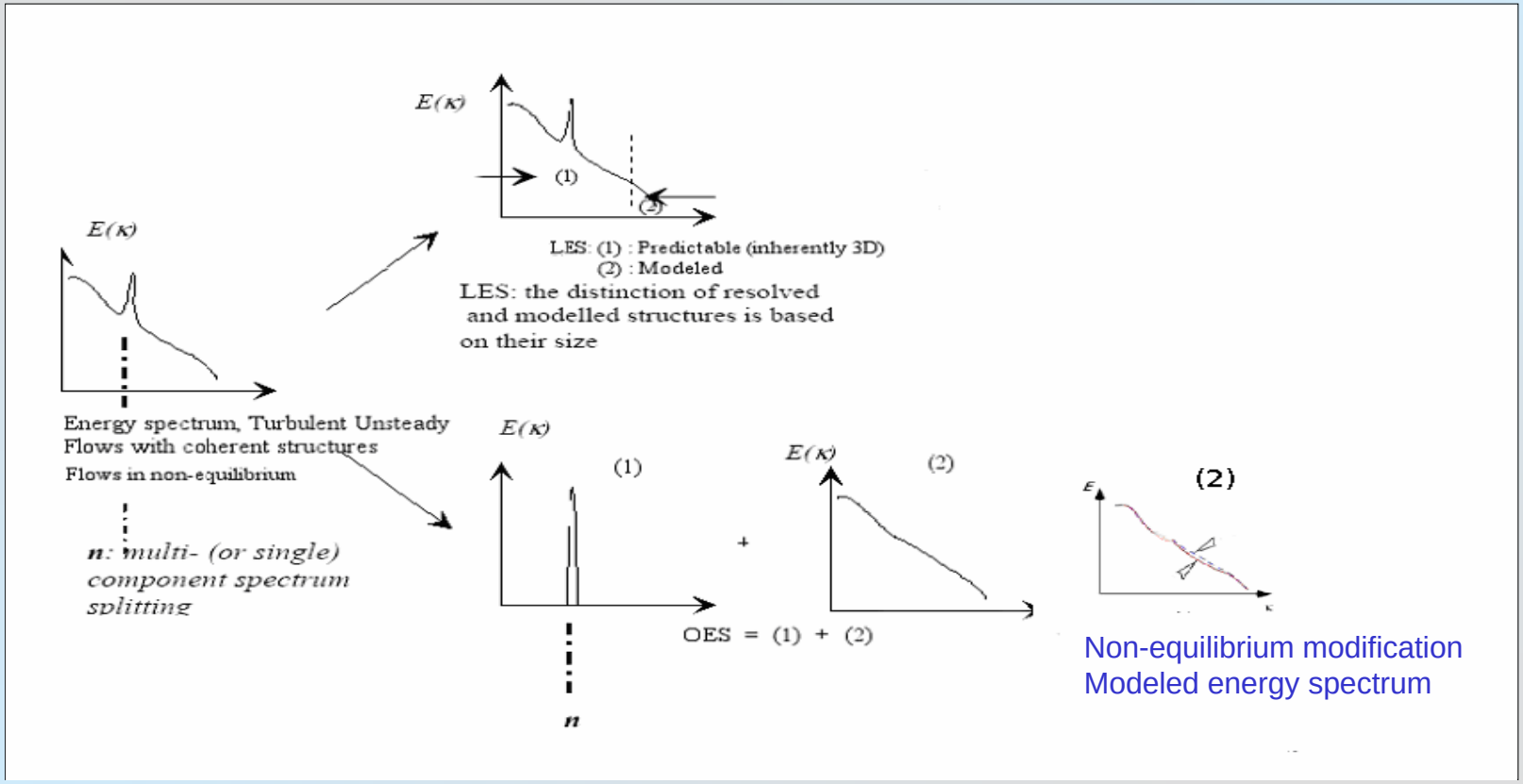
UNSI and DESIDER EU

Reynolds number : order of 10^6-10^7

Turbulence modelling

Organized Eddy Simulation:

Energy spectrum splitting for
Distinction between the structures to be resolved from those to be modeled based on their organised coherent character



Hoarau, Braza, IUTAM Symp. Toulouse 2002
Braza, 2002 , 2006 , Notes on Num. Fluid Mech. vol. 81, vol. 94
Braza, Perrin, Hoarau, J. Fluids Struct. 2006
Bourguet, Braza, J. Fluids & Struct. 2008
Braza, Hunt, European Turb. Conf., 2011

Phase-averaged decomposition – Navier-Stokes equations

$$U_i(x_k,t) = \langle U_i(x_k,t)\rangle + u_i(x_k,t)$$

$$\langle u_i(x_k,t)\rangle = 0 \qquad \langle\langle U_i(x_k,t)\rangle\rangle = \langle U_i(x_k,t)\rangle$$

$$\frac{\partial\langle U_i\rangle}{\partial x_i} = 0$$

$$\frac{\partial\langle U_i\rangle}{\partial t} + \boxed{\langle U_i\rangle\frac{\partial\langle U_i\rangle}{\partial x_j}} = -\frac{1}{\langle\rho\rangle}\frac{\partial\langle P\rangle}{\partial x_i} + \nu\frac{\partial^2\langle U_i\rangle}{\partial x_j\partial x_j}\boxed{-\frac{\partial\langle\tau_{ij}\rangle}{\partial x_j}}$$

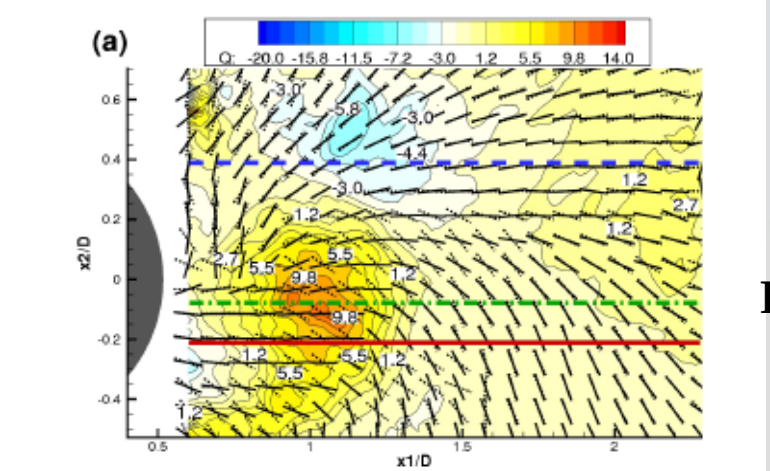
$$\langle\tau_{ij}\rangle = \langle u_i u_j\rangle$$

Navier-Stokes equations in phase-averaged decomposition

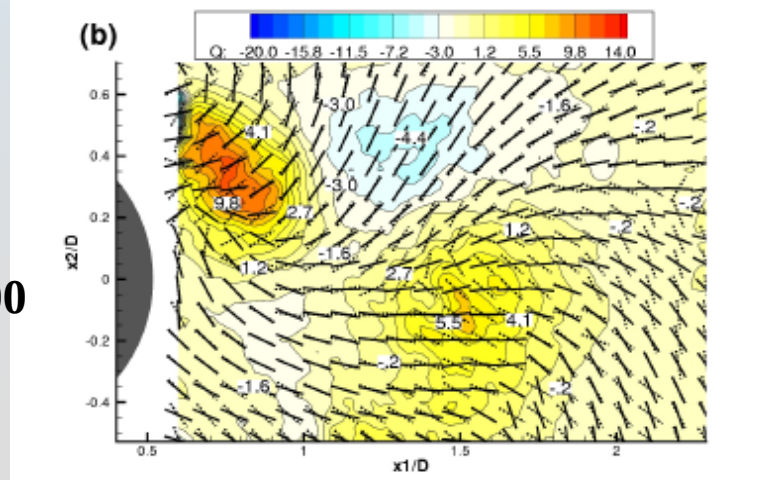
Modification of modelling $\boxed{\langle u_i u_j\rangle}$ to take into account non-equilibrium

Modelling of 3D **stress-strain misalignment**

Exp.Eigenvectors of turbulence stress anisotropy (-a) and of strain rate (S) tensors, 3CTRPIV



Re=140,000



First principal directions of $-a$ and S at phase angle (a) $\varphi = 50^o$ and (b) $\varphi = 140^o$,

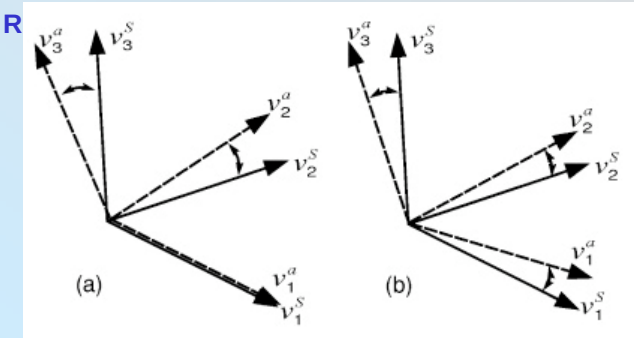
$$-\overline{u_i u_j} + \frac{2}{3} k \delta_{ij} = 2 S_{ik} \left(\nu_{tt}\right)_{kj}$$

Bourguet et al,

AIAA J. , 45, 2007

& J. Fluids and Struct., 2008

Exp. in Fluids, R Perrin 2007



Significant misalignment in coherent structures and in sheared regions

$\longrightarrow$ **anisotropic modulation** of the C_μ eddy-diffusion coefficient in Reynolds stress constitutive law

Anisotropic eddy-viscosity : tensorial definition

$$a \approx -\frac{C_{V\,i}}{\lambda_i^S} S_i = -SV\mathrm{diag}\left(\frac{C_{V1}}{\lambda_1^S}\ \frac{C_{V2}}{\lambda_2^S}\ \frac{C_{V3}}{\lambda_3^S}\right) V^t \quad \text{where} \quad V = \left(v_1^S\ v_2^S\ v_3^S\right)$$

Tensorial eddy-viscosity (Bourguet, Braza et al., AIAA J., 2007,
J. Fluids & Struct. 24 (8), (2008)

$$(\nu_{tt})_{ij} = (\nu_{td})_k \left(v_k^S\right)_i \left(v_k^S\right)_j \quad \text{with} \quad (\nu_{td})_i = \frac{C_{V\,i}}{2\lambda_i^S} k\ , \quad C_{\mu\,i} = \frac{C_{V\,i}}{2} \frac{\varepsilon}{k\lambda_i^S}$$

$\eta_i = \frac{k|\lambda_i^S|}{\varepsilon}$, vectorial version of $\eta = \frac{k\|S\|}{\varepsilon}$ mean flow/turbulent time scale rate

Turbulent stress constitutive law : generalisation of the Linear EVM

$$-\overline{u_i u_j} + \frac{2}{3} k\delta_{ij} = 2S_{ik}\left(\nu_{tt}\right)_{kj}$$

•Generalisation of averaged Navier-Stokes momentum equations

$$\frac{DU_i}{Dt} = \frac{\partial}{\partial x_j}\left(2\nu S_{ij} + 2\left(\nu_{tt}\right)_{kj} S_{ik} - \frac{2}{3} k\delta_{ij}\right) - \frac{1}{\rho}\frac{\partial P}{\partial x_i}$$

Anisotropic closure scheme : directional DRSM

•Transport equations for Cvi projection coefficients, for q = 1,2,3

$$\frac{DC_{Vq}}{Dt} = -(V_q)_{ij}\frac{Da_{ij}}{Dt} - a_{ij}\frac{D(V_q)_{ij}}{Dt}\ ,\ (V_q)_{ij} = \left(v_q^S\right)_i\left(v_q^S\right)_j$$

•Projection of Speziale, Sarkar and Gatski second order closure scheme

J. Fluid Mech., 227, 1991

$$\begin{aligned}\frac{DC_{Vq}}{Dt} &= \left(\frac{4}{3} + c_3^* II_a^{\frac{1}{2}} - c_3\right)(V_q)_{ij}S_{ij} + (2-2c_4)(V_q)_{ij}\,a_{ik}S_{jk} - \frac{c_2\varepsilon}{k}(V_q)_{ij}a_{ik}a_{kj}\\ &+ (2-2c_5)(V_q)_{ij}a_{ik}\Omega_{jk} + (1-c_1)\frac{\varepsilon}{k}C_{Vq} + (1+c_1^*)\,C_{Vq}a_{ij}S_{ij} + \frac{c_2 II_a\varepsilon}{3k}\\ &+ \frac{2(c_4-1)}{3}a_{ij}S_{ij} - a_{ij}\frac{D(V_q)_{ij}}{Dt} + D^{C_{Vq}}\end{aligned}$$

where c_i and c_i^* are SSG model constants

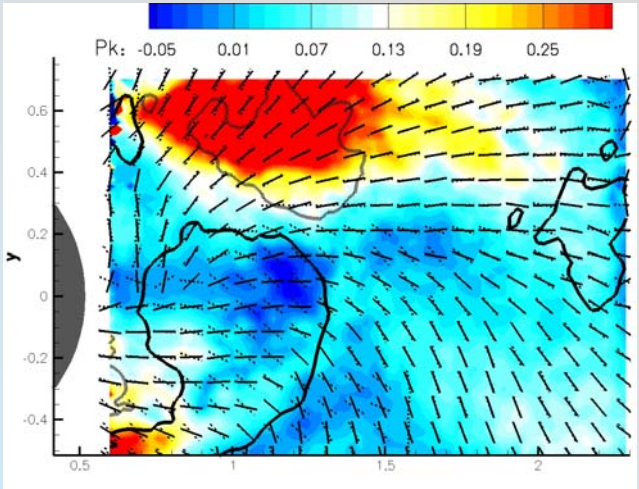
$$\hat{a}_{ij}\frac{D(V_q)_{ij}}{Dt} = -C_{Vr}V_r\frac{D(V_q)_{ij}}{Dt} = 0 \text{ and } D^{C_{Vq}} = \frac{\partial}{\partial x_i}\left(\left(\nu + \frac{(\nu_{tt})_{ij}}{\sigma_{C_{Vq}}}\right)\frac{\partial C_{Vq}}{\partial x_j}\right)$$

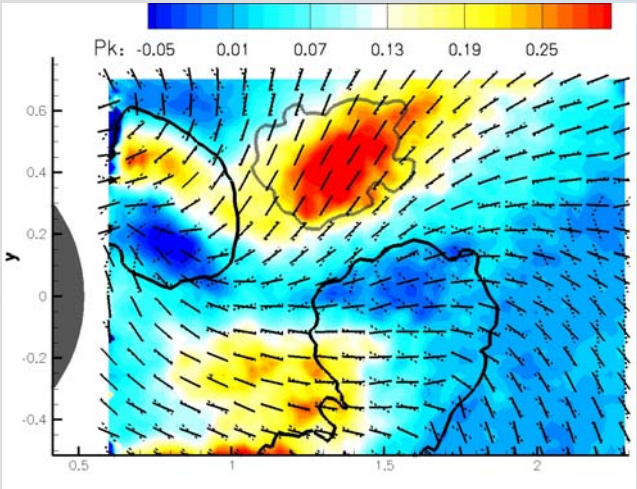
A tensorial eddy-diffusion coefficient $C_{\mu,i}$ can be derived. For faster computations, can be assumed scalar with equivalent optimum values of order 0.02

Tensorial eddy-viscosity modeling:

Ability of capturing negative production

of turbulence kinetic energy regions - relaminarisation





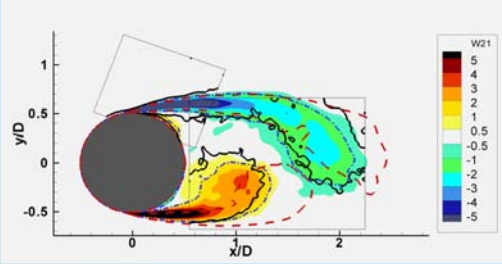
$$\mathcal{P}_{ij}=\langle u_i u_j\rangle\, \partial\langle U_i\rangle / \partial x_j$$

Exp

Modeled

Detached Eddy Simulation

Turbulent length scale: $$l_{DES} = \min\left(l_{RANS}, C_{DES} \times \Delta\right)$$
$$\Delta = \max\left(\Delta x, \Delta y, \Delta z\right)$$



- For *Spalart-Allmaras* model*: $l_{DES} = \min\left(d_w, C_{DES} \times \Delta\right)$

➔Augmentation of the dissipation term in the eddy-viscosity transport equation:

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\left(1 - f_{t2}\right)\tilde{S}\,\tilde{\nu} + \frac{1}{\sigma}\left[\nabla.\left(\left(\nu + \tilde{\nu}\right)\nabla\tilde{\nu}\right) + c_{b2}\left(\nabla\tilde{\nu}\right)^2\right] - \boxed{\left(C_{w1} f_w - \frac{C_{b1}}{\kappa^2} f_{t2}\right)\left(\frac{\tilde{\nu}}{l_{DES}}\right)^2}$$

- For *k- ω** model*: $l_{DES} = \min\left(k^{1/2} / \beta\omega, C_{DES} \times \Delta\right)$

➔Augmentation of the dissipation term in the *k* transport equation:

$$\frac{D\overline{\rho}k}{Dt} = \tau_{ij}\frac{\partial U_j}{\partial x_i} - \boxed{\frac{\rho k^{3/2}}{l_{DES}}} + \frac{\partial}{\partial x_j}\left[\left(\mu + \sigma^* \mu_t\right)\frac{\partial k}{\partial x_j}\right]$$

- Improvement of l_{RANS} adopted from equilibrium turbulence within DES using l_{OES} in inertial regions

$$\boxed{l_{OES} = \frac{k^{1/2}}{C_\mu \omega}}$$

➔➔**DES/OES** approach

DDES – avoid Modeled Stress Depletion

- **Hybrid Turbulence Modelling**

$$l_{DDES} = l_{RANS} - f_d \max(0, l_{RANS} - C_{DES} \times \Delta)$$

$$\Delta = \max(\Delta x, \Delta y, \Delta z)$$

$$f_d = \begin{cases} 0, & \text{close to wall} \\ 1, & \text{far from wall} \end{cases}$$

Delayed **D**etached **E**ddy **S**imulation:

- URANS (near body surface)
- LES (shear layer, detached flow…)

$$r_d = \frac{\nu + \nu_t}{S_{ij}\kappa^2 d^2} \qquad f_d = 1 - tanh[(8r_d^3)]$$

DDES-k-ω-SST

DDES-k-ω-OES

$$\frac{Dk}{Dt} = P_k - C_\mu k\omega + \text{div}\left[(\nu + \sigma_k \nu_t)\,\underline{\text{grad}}\,k\right]$$

$$\frac{D\omega}{Dt} = \gamma\frac{P_k\omega}{k} - \beta\omega^2 + \text{div}\left[(\nu + \sigma_\omega \nu_t)\,\underline{\text{grad}}\,\omega\right] + 2\,(1 - F_1)\,\sigma_{\omega 2}\frac{1}{\omega}\underline{\text{grad}}\,k \cdot \underline{\text{grad}}\,\omega$$

$$\omega = \frac{\varepsilon}{\beta^* k} \qquad \nu_t = \frac{k}{\omega}$$

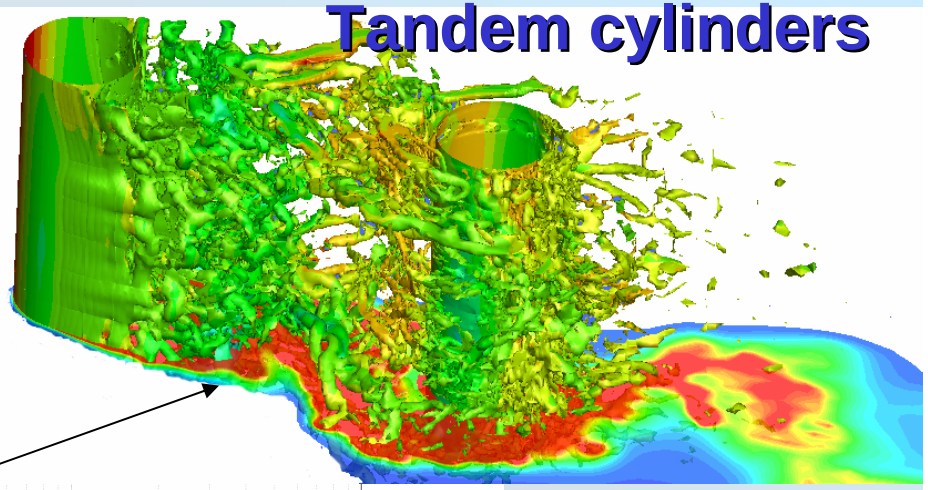
URANS model:
k: turbulent kinetic energy
*1/*ω**:** turbulence time scale
•*SST*: Shear-Stress-Transport limiter of eddy viscosity
•OES: Organised Eddy Simulation

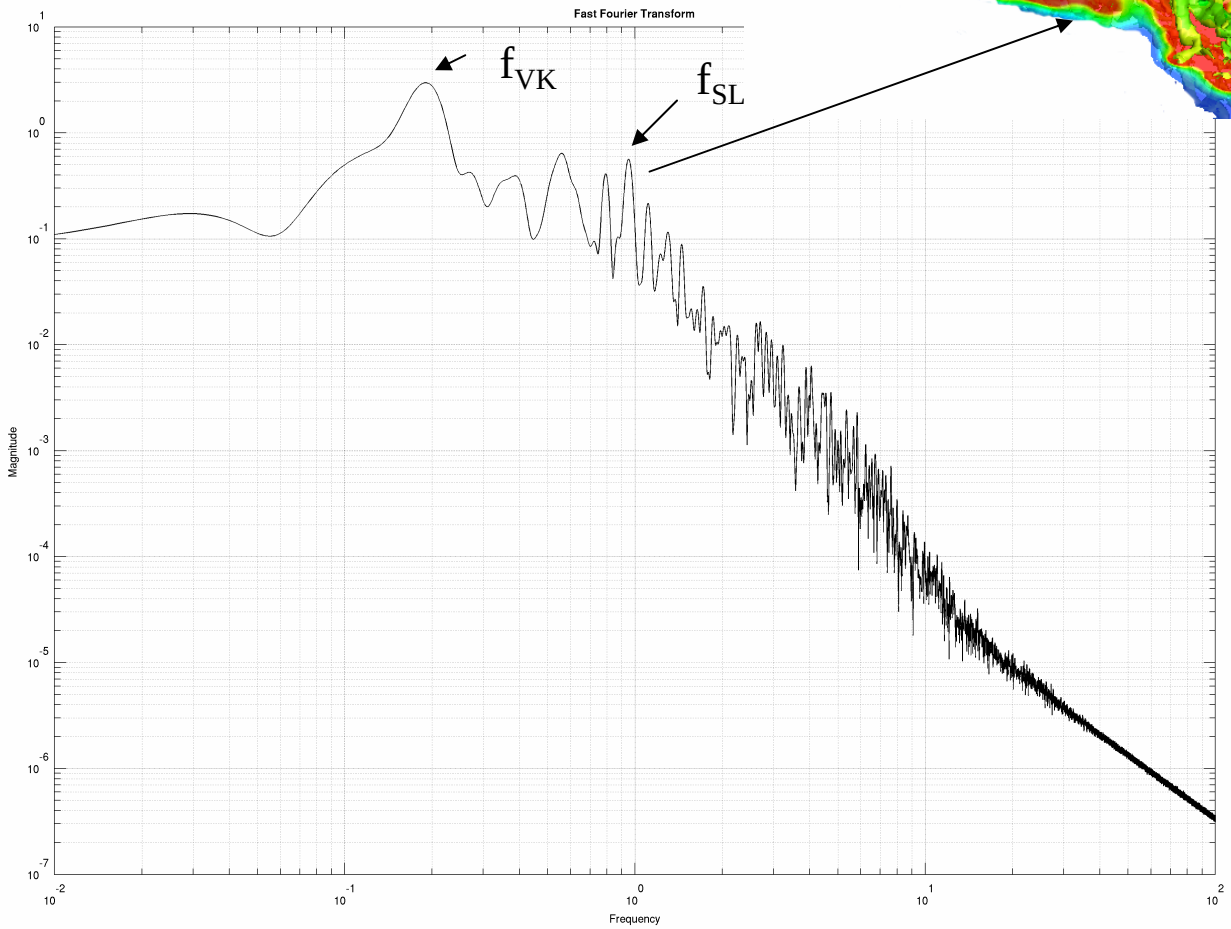
References:
Wilcox: AIAA-Journal, 31(8), 1414-1421, 1993

Menter: AIAA-Journal, 32(8), 1598-1605, 1994

Braza, Hoarau, JFS, 2006, Bourguet, Braza, 2008

Tandem cylinders

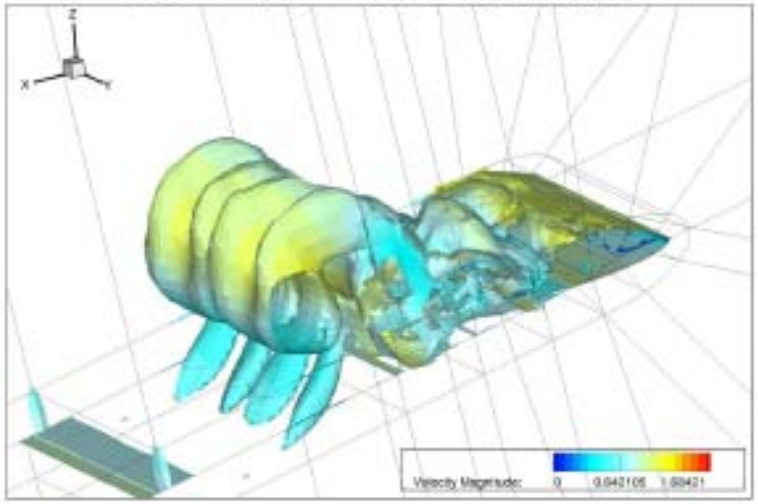




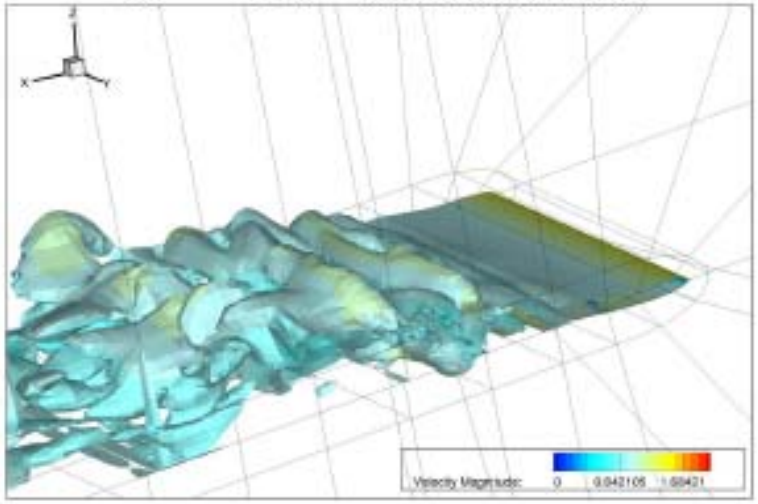
Re=165 000

DDES ***k-ω***-OES

3D pitching wing flow a wing – Re=10^6



$\alpha = 14^o$ descendant

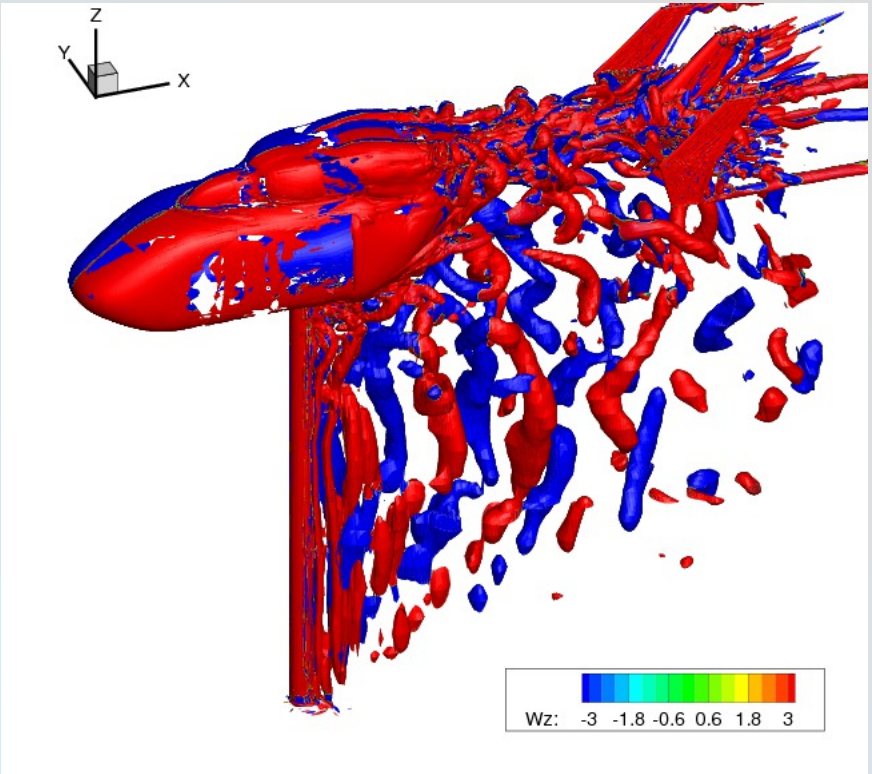


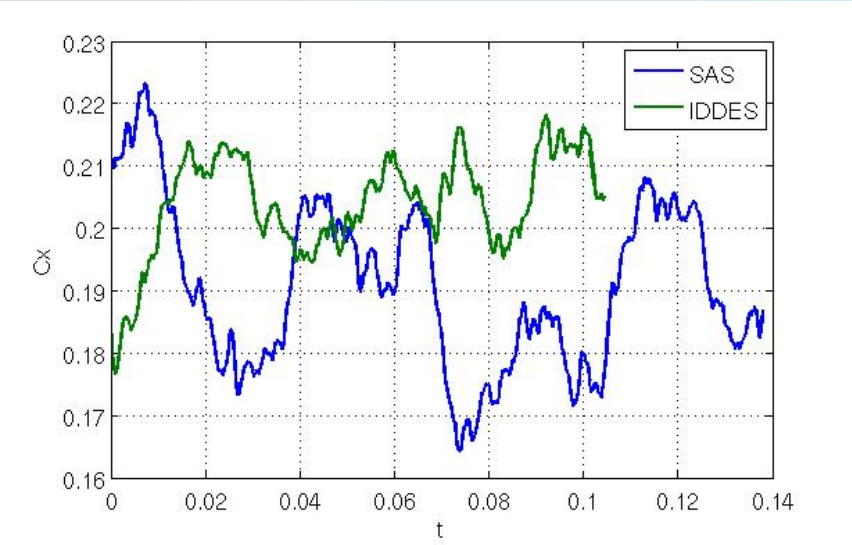
$\alpha = 8^o$ descendant

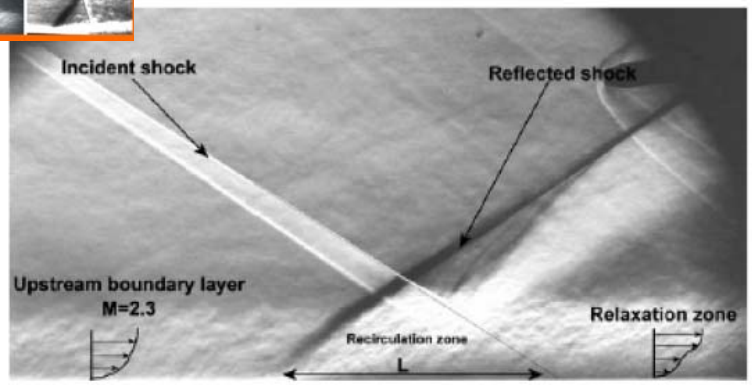
PhD G. Martinat – IMFT-équipe IFS

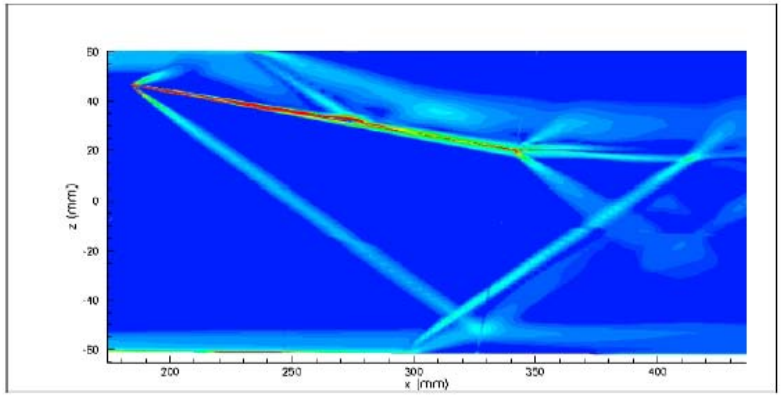
Helicopter EC145

Iso-λ_2 surfaces coloured
by ω_z vorticity



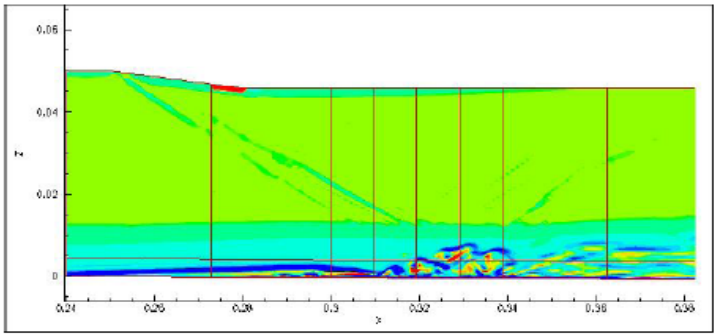




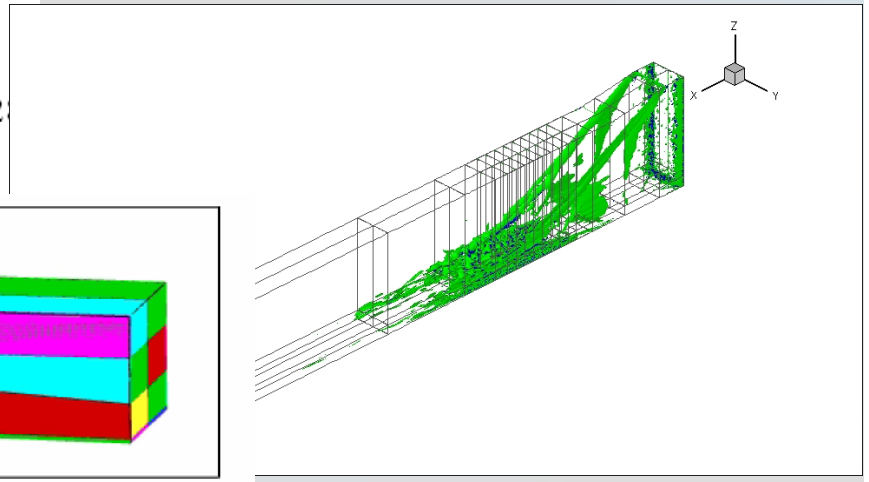


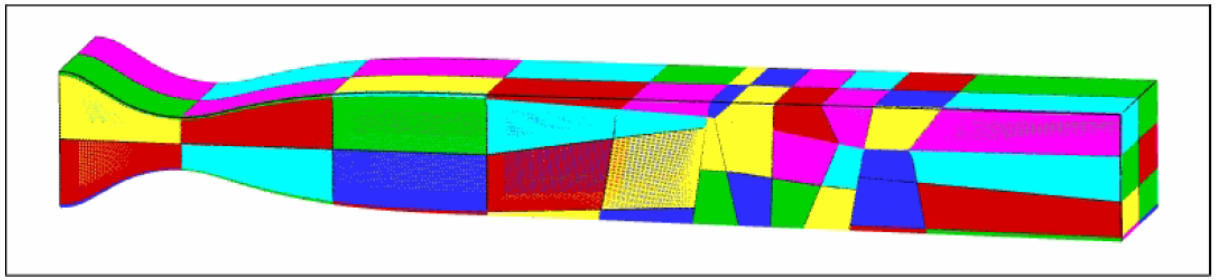
DES-OES

Figure: magnitude of $\frac{grad\,\rho}{\rho}$

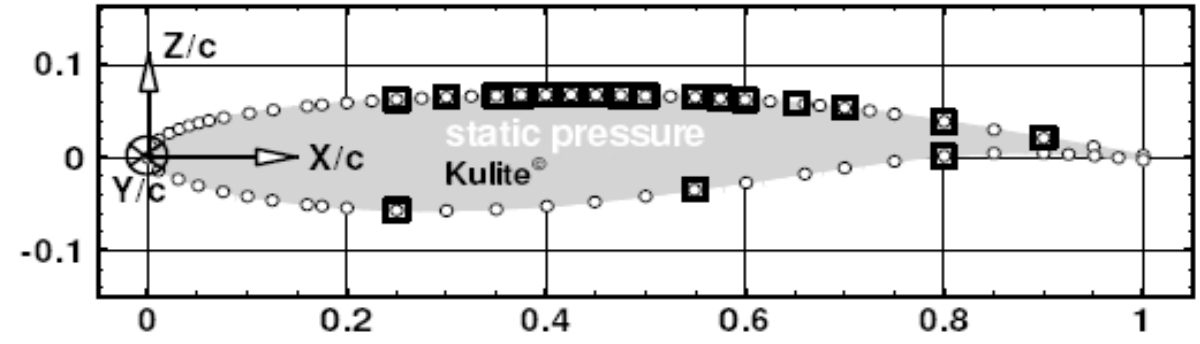


z=0.2

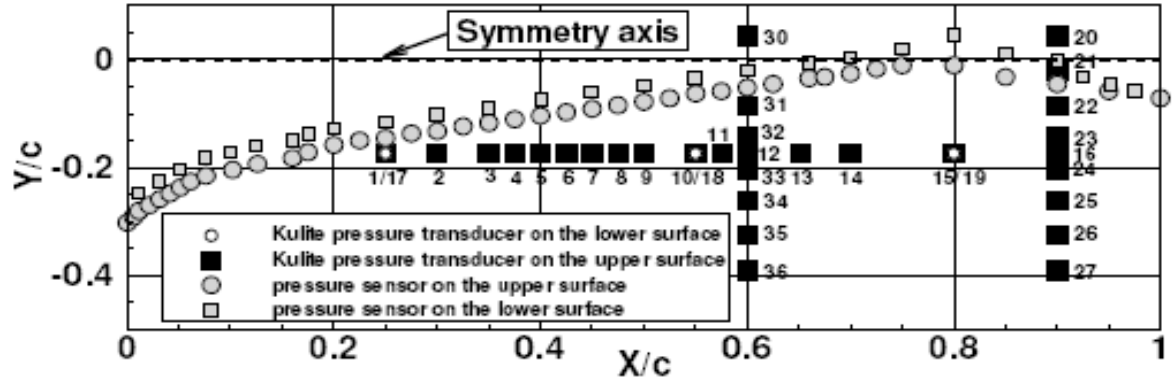




II. ST06 – OAT15A
Experimental set-up and flow parameters

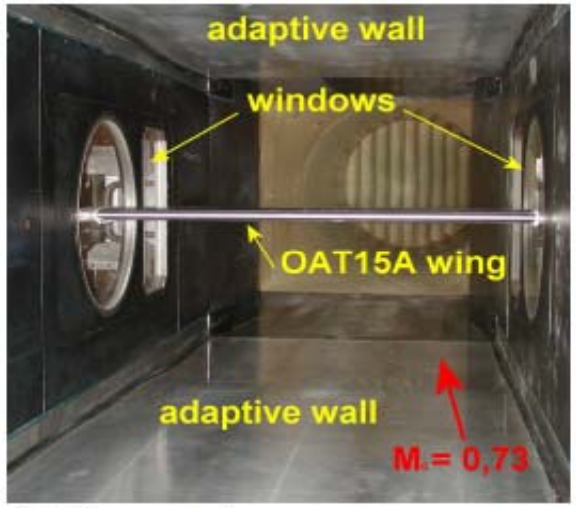


(a) Lateral view



(b) Upper view

Figure 2. Locations of the pressure orifices and Kulite transducers



OAT15A in S3Ch wind tunnel

ONERA-Meudon

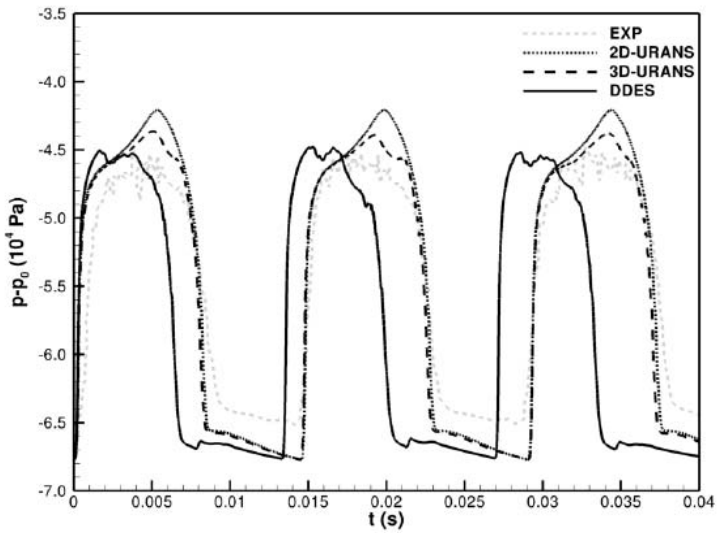
Jacquin et al, (2005), (2009)

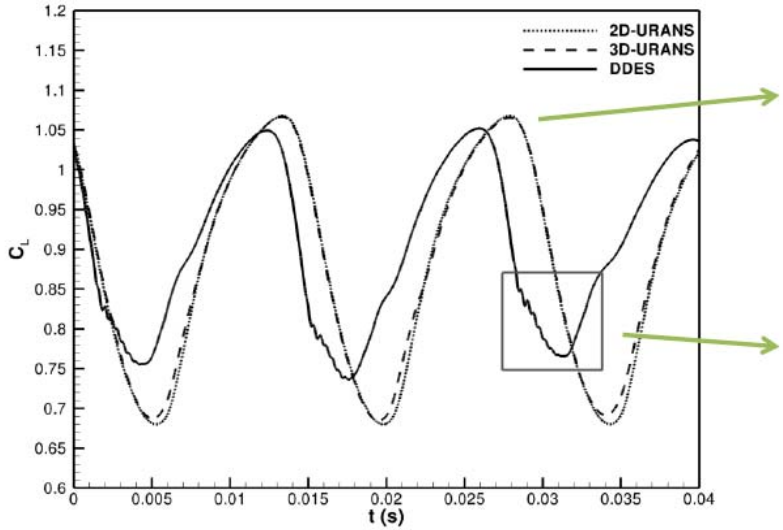
Flow conditions: - Mach: 0.73 - Re: 3×10^6 - $\alpha = 3.5°$

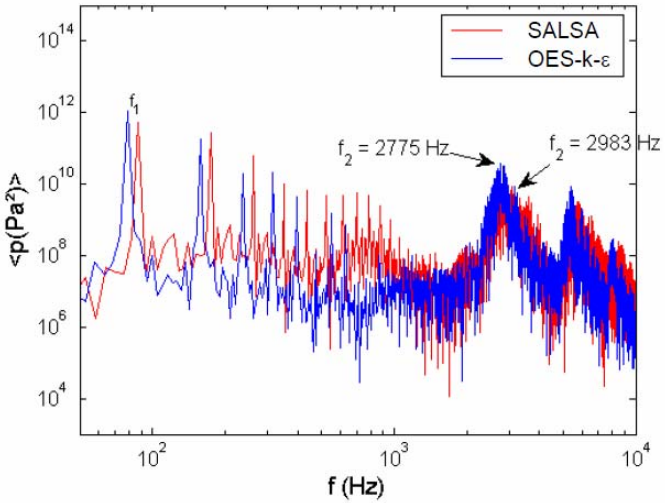
Transition fixed by carborundum strips at x/c = 0.07

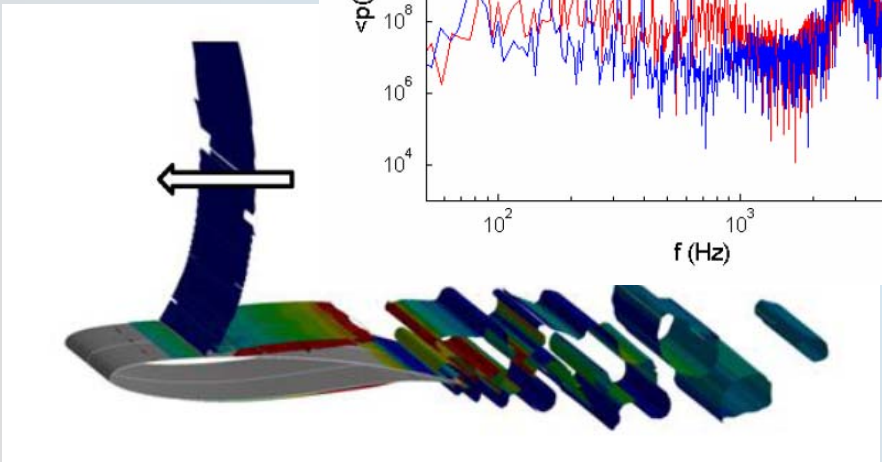
Buffet frequency

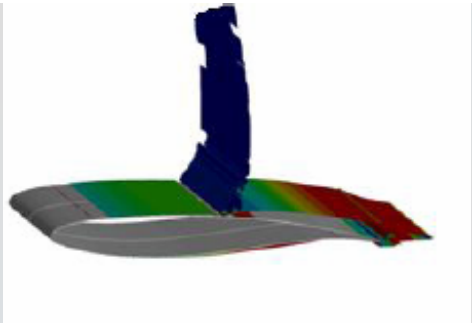
2D-URANS: 69 Hz DDES: 72-74 Hz
3D-URANS: 68 Hz (Exp. ≈ 69 Hz)











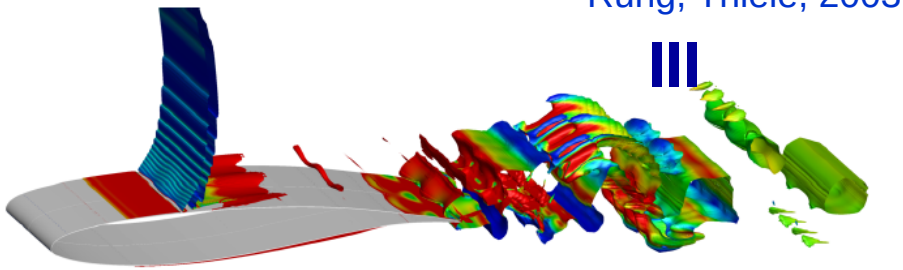
I

DDES-SALSA

Spalart-Allmaras

Anisotropy Sensitized,
Rung, Thiele, 2003

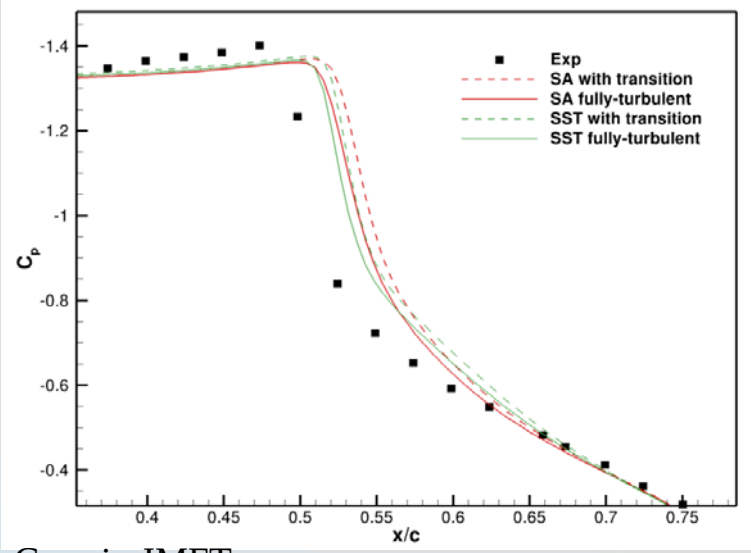
III



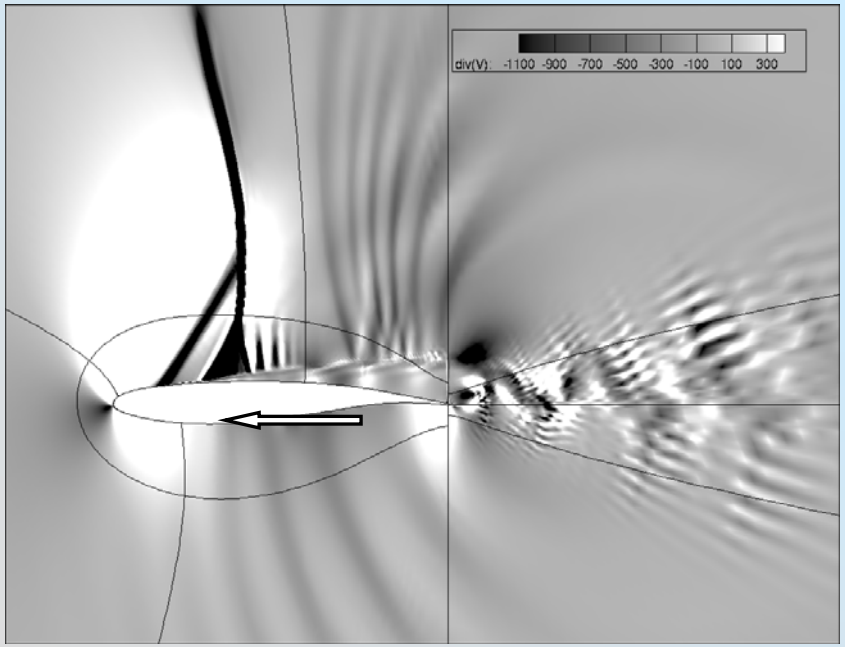
* 4th symposium on Hybrid RANS-LES methods, Beijing, 2011

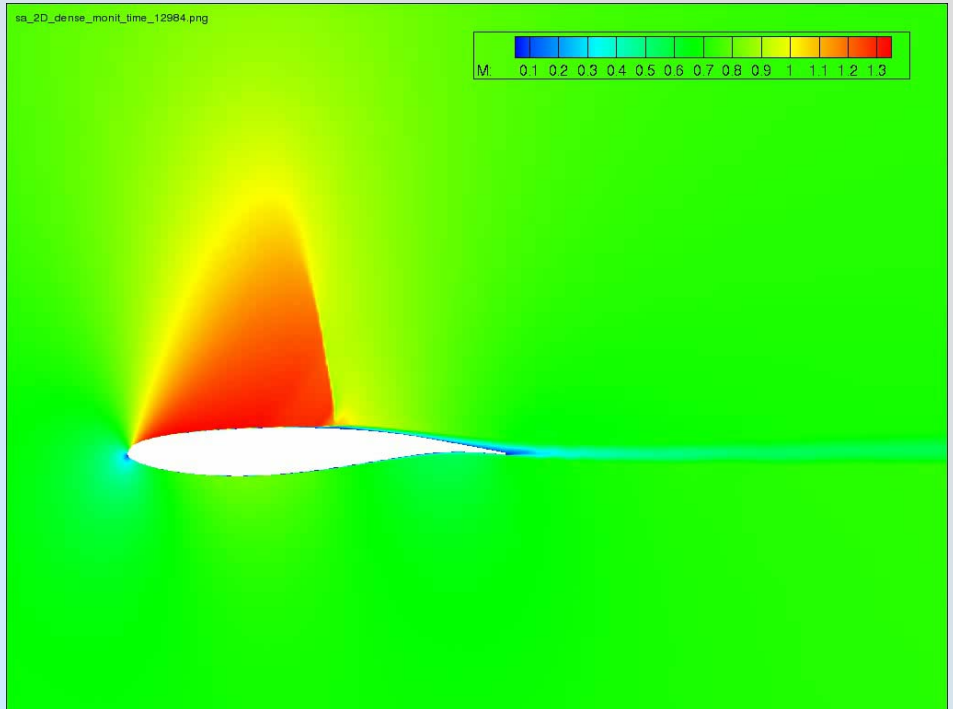
F. Grossi, M. Braza, 4th HRLM*

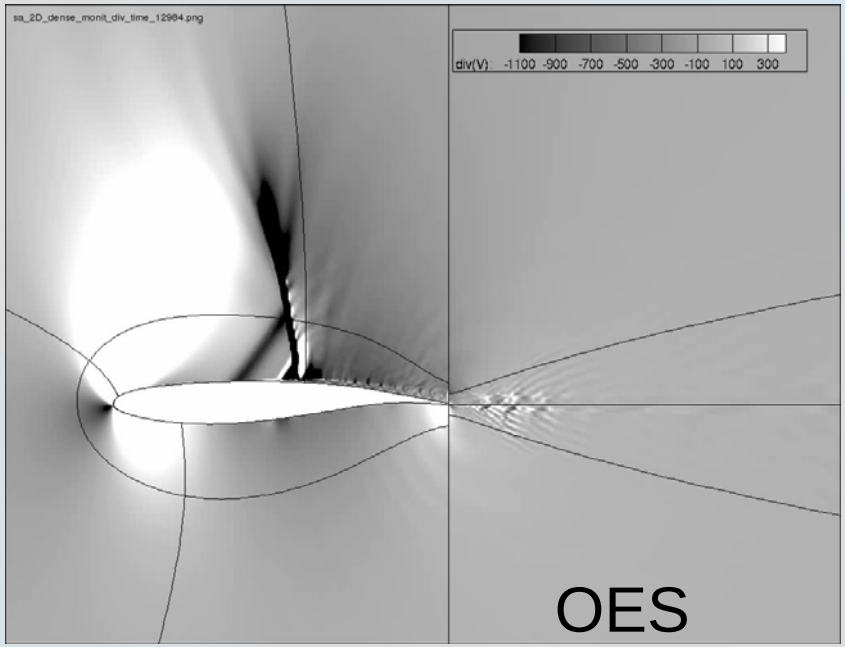
- Flow Physics



F. Grossi - IMFT







D. Szubert - IMFT

Reduced Order Modelling

- Galerkin Projection of the Hi-Fidelity system
- Use of Hadamard's formulation for surface deformation

  on a basis of most energetic modes
- Example: The Proper Orthogonal Decomposition POD modes
- Achievements:

  Description of the most important complex transfers irregular – and of aperiodic effects

  by a reduced number of degrees of freedom
- Possible use of ROM for shape modification in optimum design

Proper Orthogonal Decomposition:

the Karhunen-Loève (KL) expansion. Given a random vector process $\vec{u} = u_i$, KL provides the best approximation based on an energetic criterion. More precisely, considering all possible processes $\vec{\psi} = \psi_i$, the KL solution maximizes the following quantity:

$$\max_{\psi} \frac{\overline{|(u,\psi)|^2}}{(\psi,\psi)} = \frac{\overline{|(u,\phi)|^2}}{(\phi,\phi)} \qquad (f,g) = \int_{\Omega} f(x)\, g^*(x)\, dx$$

where $\langle .,. \rangle$ represents a stochastic dot product. According to the KL theory, the solution is provided by the eigenmodes $\vec{\phi}^{(n)} = \phi_i^{(n)}$ of the second-order space-time correlations tensor and the random process can be expanded as a linear combination of these deterministic eigenvectors:

$$\int_{\Omega} \overline{u_i(x) u_j^*(x')} \phi_j(x') dx' = \lambda \phi_i(x)$$

$$u_i(\vec{x},t) = \sum_{n=1}^{\infty} a^{(n)} \phi_i^{(n)}(\vec{x},t)$$

-Reconstruction

$$u_i(x,t) = \sum_k a_k \phi_i^{(k)}(x,t) \qquad a_k = \int \int_{\Omega} u_i(x,t) \phi_i^*(x,t) dx dt \qquad \overline{a_k a_{k'}} = \delta_{kk'} \lambda_k$$

-correlations tensor

Berkooz, Holmes & Lumley, Ann. Review Fluid Mech., 1993

$$R(x,x') = \overline{u_i(x) u_j(x')} = \sum_k \lambda^{(k)} \phi_i^{(k)}(x) \phi_j^{(k)}(x')$$

Low Order Modelling

Galerkin projection – Navier-Stokes eqns

Incompressible flow

$$\int_\Omega \boldsymbol{\phi}_m(\boldsymbol{x}) \cdot \left(\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V} \cdot \nabla)\boldsymbol{V} + \nabla p - \frac{1}{Re}\nabla^2 \boldsymbol{V} \right) \mathrm{d}\boldsymbol{x} = 0,$$

$$\int_\Omega \boldsymbol{\phi}_m(\boldsymbol{x}) \cdot (\nabla \cdot \boldsymbol{V})\, \mathrm{d}\boldsymbol{x} = 0.$$

Résultat : Système ODE

$$\frac{da_i(t)}{dt} = \mathcal{A}_i + \sum_{j=1}^{N_{\mathrm{gal}}} \mathcal{B}_{ij} a_j(t) + \sum_{j=1}^{N_{\mathrm{gal}}} \sum_{k=1}^{N_{\mathrm{gal}}} \mathcal{C}_{ijk} a_j(t) a_k(t) + \mathcal{D}_i \frac{d\gamma}{dt}$$

$$+ \left(\mathcal{E}_i + \sum_{j=1}^{N_{\mathrm{gal}}} \mathcal{F}_{ij} a_j(t) \right) \gamma + \mathcal{G}_i \gamma^2, \quad i = 1, \ldots, N_{\mathrm{gal}}.$$

Ma & Karniadakis, *JFM* ***458***, *2002*

Bergmann *et al*, *Phys. Fluids*, **17**, 2005,

Noack & Monkewich, *JFM* **523**, 2005

COMPRESSIBLE FLOWS ROM: USE OF THE TRANSFORMATION ($1/\rho$) to ensure quadratic form of the projected eqns:

Vigo, Dervieux, (2007), Bourget, Braza (Phys Fluids *Physics of Fluids*, **19**, 111701, 2007, Phys. Fluids *Phys. Fluids* ***21(9)***, pp. 111701-111701, 2009)

2. POD-Galerkin model

The compressible Navier–Stokes equations are expressed as quadratic fluxes by means of the previously defined state formulation (2), as reported in Ref. 13 for $i=1,2,3$,

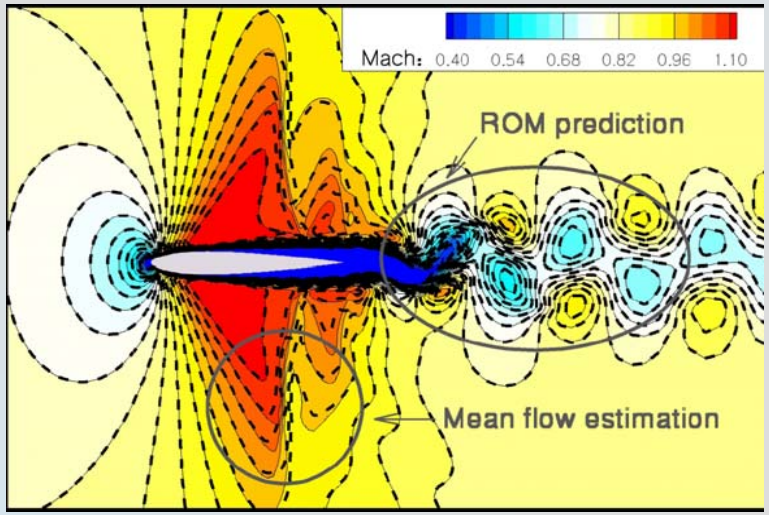
$$\frac{\partial(1/\rho)}{\partial t}+u_\alpha\frac{\partial(1/\rho)}{\partial x_\alpha}-\frac{\partial u_\alpha}{\partial x_\alpha}(1/\rho)=0,$$

$$\frac{\partial u_i}{\partial t}+u_\alpha\frac{\partial u_i}{\partial x_\alpha}+(1/\rho)\frac{\partial p}{\partial x_i}=(1/\rho)\frac{\partial \tau_{i\alpha}}{\partial x_\alpha}, \qquad (6)$$

$$\frac{\partial p}{\partial t}+\gamma p\frac{\partial u_\alpha}{\partial x_\alpha}+u_\alpha\frac{\partial p}{\partial x_\alpha}=\frac{\gamma\mu}{\mathrm{Pr}}\frac{\partial^2(p/\rho)}{\partial x_\alpha^2}+(\gamma-1)\frac{\partial u_\alpha}{\partial x_\beta}\tau_{\alpha\beta},$$

where $\tau_{ij}=\mu(\partial u_i/\partial x_j+\partial u_j/\partial x_i-2/3\,\partial u_\alpha/\partial x_\alpha\delta_{ij})$. Greek sub- and superscripts are used to specify implicit summations in previous expressions and in the following. μ is the fluid dynamic viscosity, Pr=0.72 is the Prandtl number, and δ_{ij} is the Kronecker symbol.

- Interaction Fluide-Structure parois déformables
- Reduced Order Modelling ROM



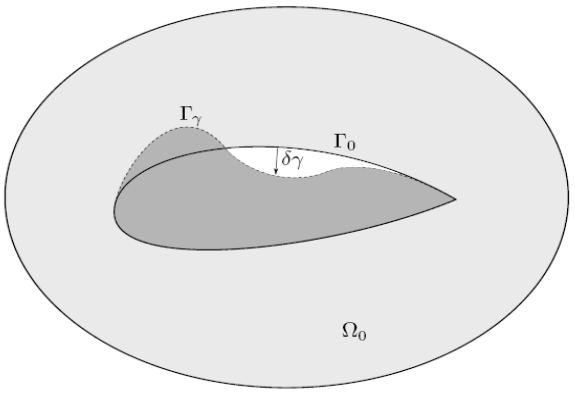
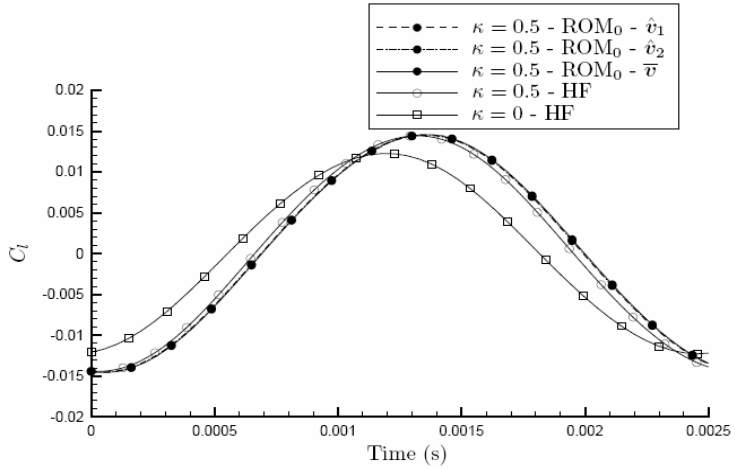


FIG. 7: Reference domain and modified boundary.



Galerkin projection of the transport eqns

on a basis of orthogonal most energetic modes via “Proper Orthogonal Decomposition”

Efficient formulation for Compressible

Ficticious Domain conditions approach

Bourguet et al, Phys. Fluids, 2009

A. Hadamard formulation for domain deformation

In his pioneering work [57], Hadamard studied the variation of the solution of a partial differential equation with respect to its domain Ω_γ in the neighborhood of a reference domain Ω_0. He demonstrated that this variation can be well defined on the reference domain. This Hadamard derivative is the solution of a differentiated partial differential equation with a boundary source term distributed on $\Gamma_0 = \partial\Omega_0$ which is linear with respect to the boundary variation. Following Hadamard, the boundary variation is parameterized by a normal displacement $\gamma \boldsymbol{n}$ (figure 7):

$$\Gamma_\gamma = \{\boldsymbol{x} = \boldsymbol{x}_0 + \gamma(\boldsymbol{x}_0)\boldsymbol{n}(\boldsymbol{x}_0), \forall \boldsymbol{x}_0 \in \Gamma_0\}. \tag{26}$$

In the following, $\boldsymbol{R}$ denotes the differential volumic residual:

$$\boldsymbol{R}(\boldsymbol{v}) = \boldsymbol{v}_{,t} + \boldsymbol{F}_{\alpha,\alpha} - \boldsymbol{F}^{\text{vis}}_{\alpha,\alpha}, \tag{27}$$

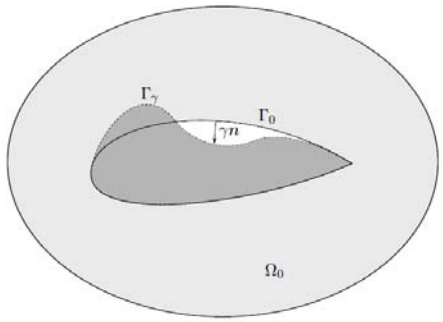


FIG. 7: Reference domain and modified boundary.

For a given geometry Ω_γ defined by γ, $\boldsymbol{v}^{\text{NS}}(\gamma)$ is the set of flow variables solving the HF Navier-Stokes equations as introduced in (2). In an integral formulation where $\boldsymbol{\Psi}_1$, $\boldsymbol{\Psi}_2$ and $*$ correspond respectively to two test functions and to a dimensionally consistent scalar product in $\mathbb{R}^4$, this can be written as follows:

$$\boldsymbol{v}^{\text{NS}} = \begin{bmatrix} \rho^{\text{NS}} \\ \rho^{\text{NS}} u_1^{\text{NS}} \\ \rho^{\text{NS}} u_2^{\text{NS}} \\ \rho^{\text{NS}} e_{\text{NS}} \end{bmatrix}, \tag{29}$$

$$\boldsymbol{v} = \boldsymbol{v}^{\text{NS}}(\gamma) \;\Leftrightarrow\; \int_{\Omega_\gamma} \boldsymbol{\Psi}_1 * \boldsymbol{R}(\boldsymbol{v})\, d\boldsymbol{x} + \int_{\Gamma_\gamma} \boldsymbol{\Psi}_2 * \boldsymbol{C}(\boldsymbol{v})\, d\sigma = 0, \;\forall \boldsymbol{\Psi}_1, \boldsymbol{\Psi}_2. \tag{30}$$

The Hadamard's formulation

For a variation $\delta\gamma$ of the shape, the variation $\delta\boldsymbol{v}^{\mathrm{NS}}$ of the flow unknown $\boldsymbol{v}^{\mathrm{NS}}$ is approximated by the following truncated Taylor formula that is second-order accurate with respect to an adhoc norm of $\delta\gamma$:

$$\delta\boldsymbol{v}^{\mathrm{NS}}(\gamma,\delta\gamma)=\boldsymbol{v}^{\mathrm{NS}}(\gamma+\delta\gamma)-\boldsymbol{v}^{\mathrm{NS}}(\gamma)\approx\frac{\partial\boldsymbol{v}^{\mathrm{NS}}}{\partial\gamma}(\gamma)\,\delta\gamma. \tag{31}$$

RHS in (31) is obtained from the total derivative of the flow equation (30):

$$\begin{aligned}&\int_{\Omega_\gamma}\boldsymbol{\Psi}_1*\frac{\partial\boldsymbol{R}}{\partial\boldsymbol{v}}\frac{\partial\boldsymbol{v}}{\partial\gamma}\delta\gamma d\boldsymbol{x}+\int_{\Gamma_\gamma}\boldsymbol{\Psi}_2*\frac{\partial\boldsymbol{C}}{\partial\boldsymbol{v}}\frac{\partial\boldsymbol{v}}{\partial\gamma}\delta\gamma d\sigma+\int_{\Gamma_\gamma}\boldsymbol{\Psi}_1*\boldsymbol{R}(\boldsymbol{v})\,\delta\gamma d\sigma\\&+\int_{\Gamma_\gamma}\boldsymbol{\Psi}_2*\nabla_n\boldsymbol{C}(\boldsymbol{v})\,\delta\gamma d\sigma+\int_{\Gamma_\gamma}\boldsymbol{\Psi}_2*\mathcal{H}\boldsymbol{C}(\boldsymbol{v})\,\delta\gamma d\sigma=0,\ \forall\boldsymbol{\Psi}_1,\boldsymbol{\Psi}_2,\end{aligned} \tag{32}$$

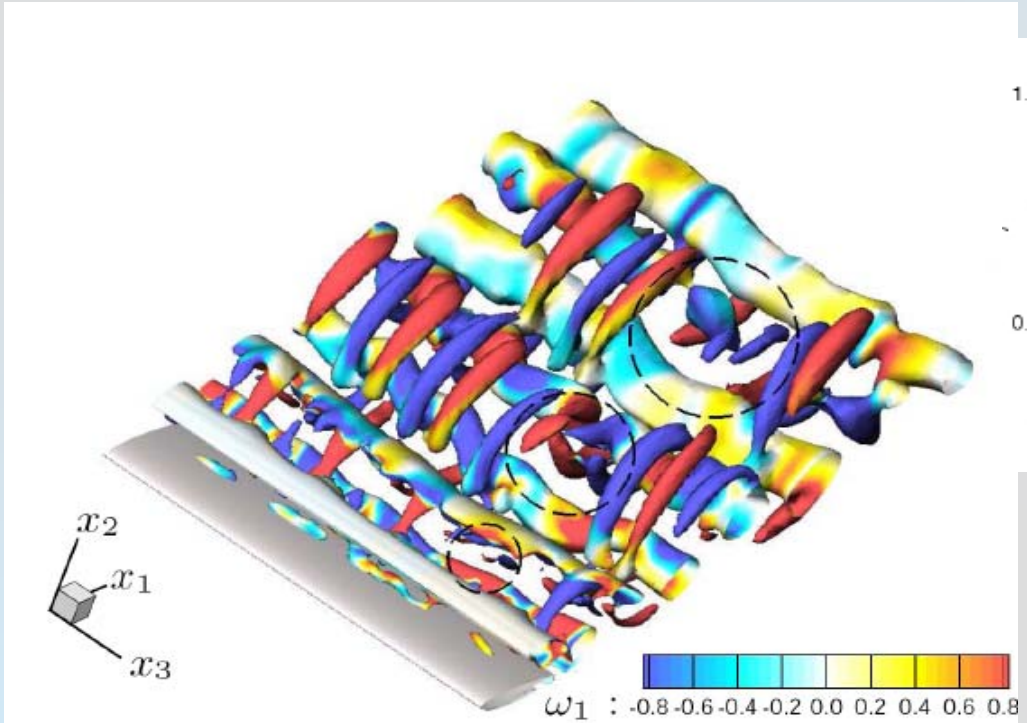
where $\mathcal{H}$ is Γ_γ curvature. Since $\boldsymbol{v}^{\mathrm{NS}}(\gamma)$ is solution of the flow system for γ, then the third and fifth integrals in (32) vanish.

In the following, a small perturbation $\delta\gamma$ is considered about $\gamma=0$:

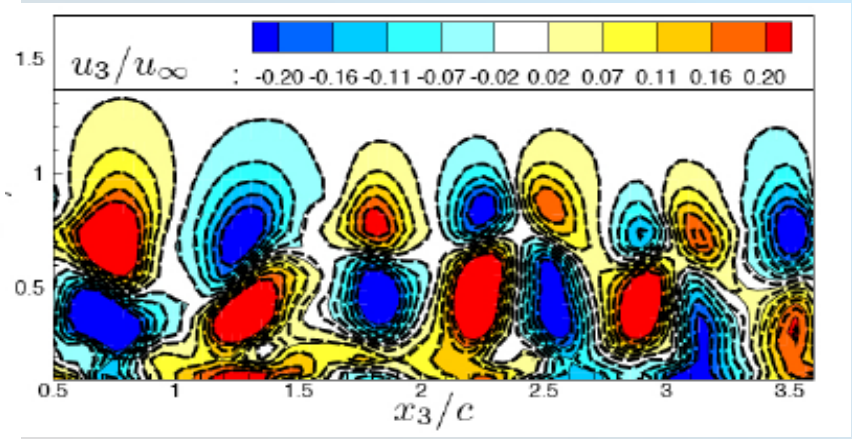
$$\boldsymbol{v}^{\mathrm{NS}}(\delta\gamma)=\boldsymbol{v}^{\mathrm{NS}}(0)+\delta\boldsymbol{v}^{\mathrm{NS}}(0,\delta\gamma) \tag{33}$$

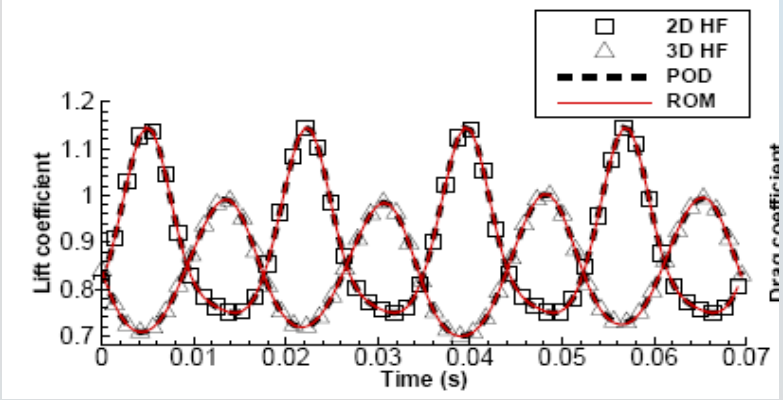
$$\text{and}\quad \delta\boldsymbol{v}^{\mathrm{NS}}(0,\delta\gamma)\approx\frac{\partial\boldsymbol{v}^{\mathrm{NS}}}{\partial\gamma}(0)\,\delta\gamma. \tag{34}$$

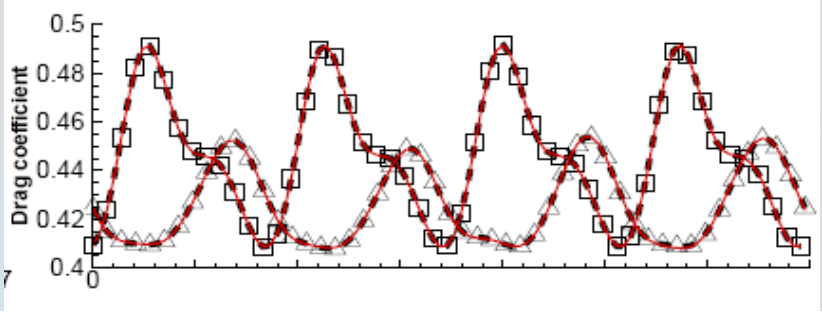
- Capturing of **irregular effects** in the near-wall vorticity patterns by Reduced Order Modelling



Iso-surface of Q criterion ($= 0.3$) coloured by x_1 vorticity component







DNS – High fidelity basis for POD snapshots

Phys. Fluids, (2009)

POD analysis of the near-wake structure
Re=140,000
From OES – IMFT's Circular Cylinder
DESIDER EU program

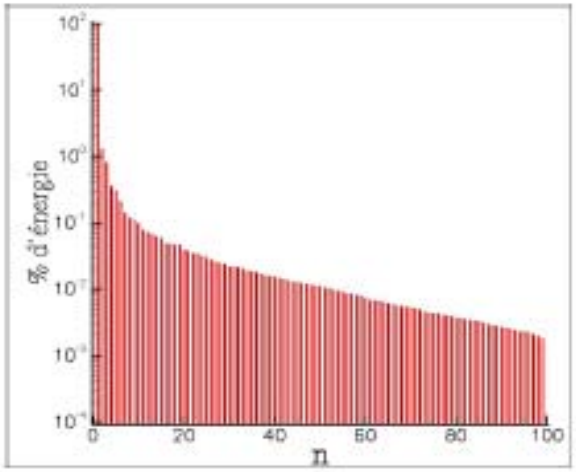


FIG. 6.21 – Pourcentage d'énergie des 100 premiers modes

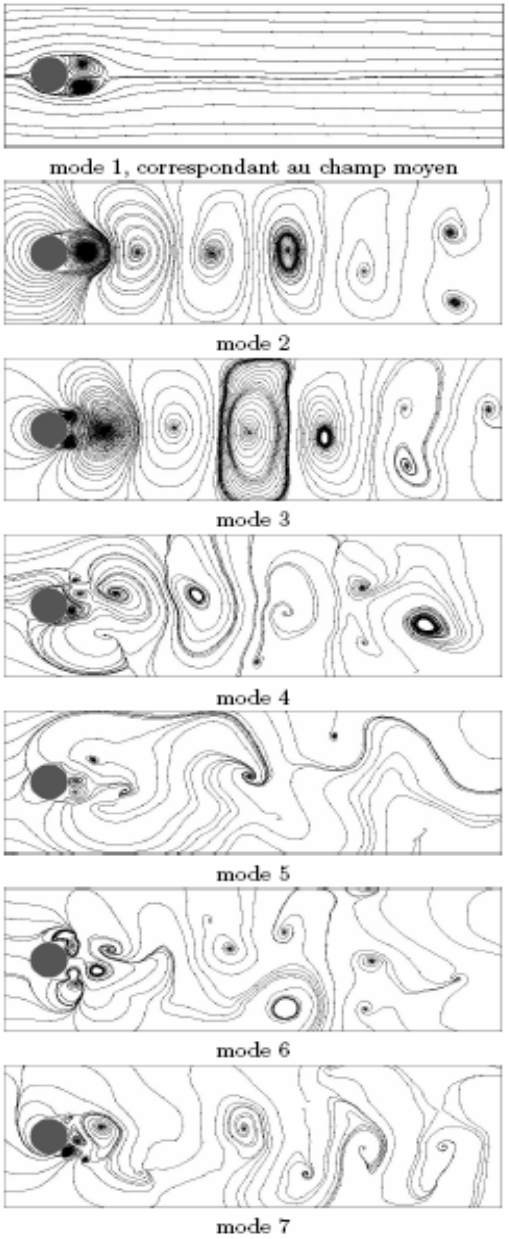


FIG. 6.22 – Topos des modes P.O.D. les plus énergétiques

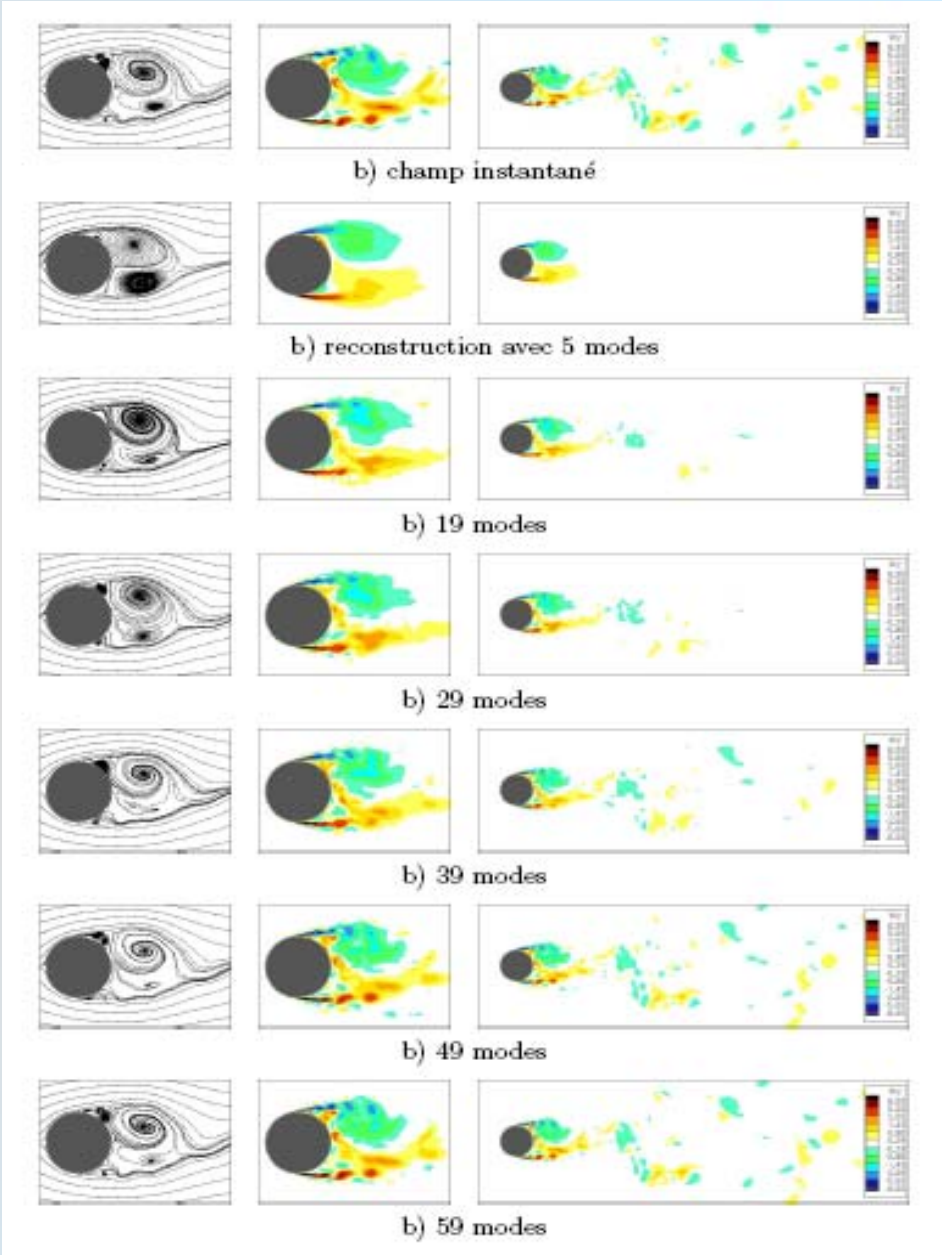
El Akoury, Braza et al, 2009,

in Notes on Num. Fluid Mech. and multidiscipl. design, eds, Haase et al, Springer

First application: DES/OES

IMFT's Circular cylinder

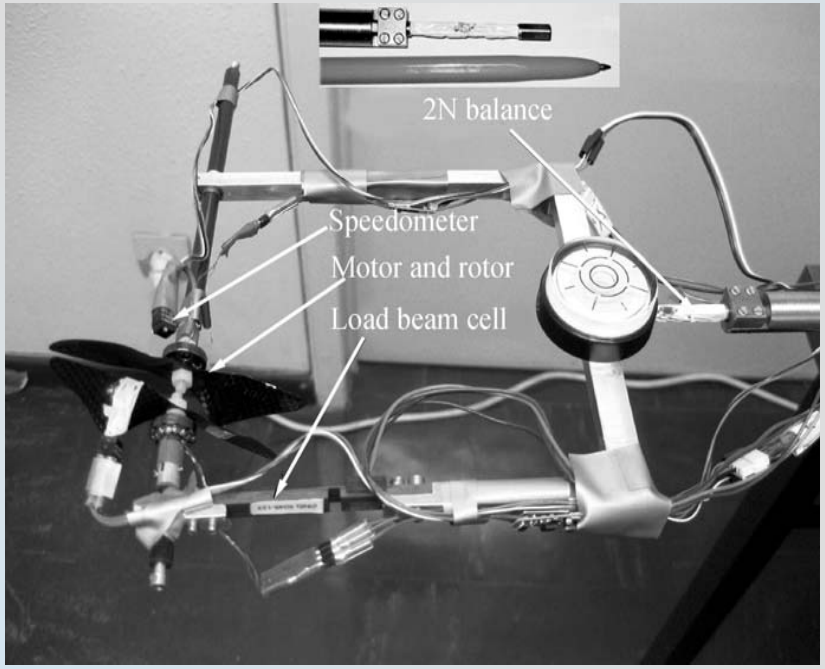
Capturing not only the von Karman Vortices but also the shear-layer Instability:
Kelvin-Helmholtz vortices
Past the separation point
By POD reconstruction

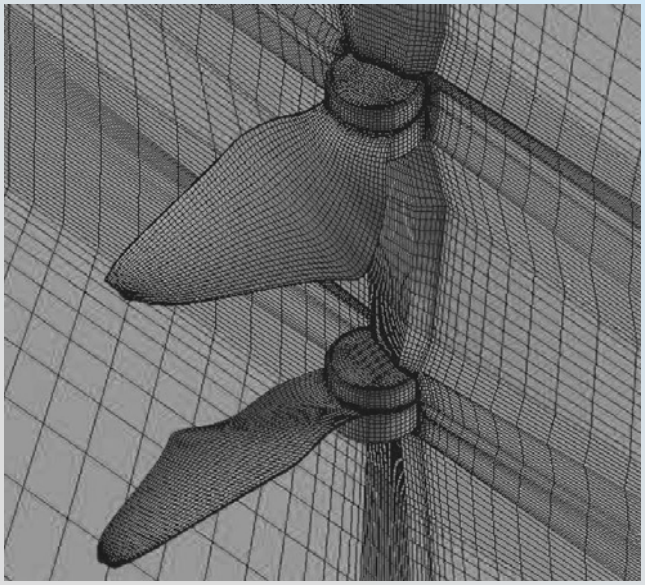


El Akoury et al, *Notes on Num. Fluid Mech. And Multidisciplinary Design Vol.* ***103***

POD reconstruction of the Kelvin-Helmholtz vortices

Nanorotors coaxiaux: caractérisation et optimisation





- Montage expérimental sur nano-balance de précision
- Calcul Navier-Stokes par méthode MRF

isae
Institut Supérieur de l'Aéronautique et de l'Espace

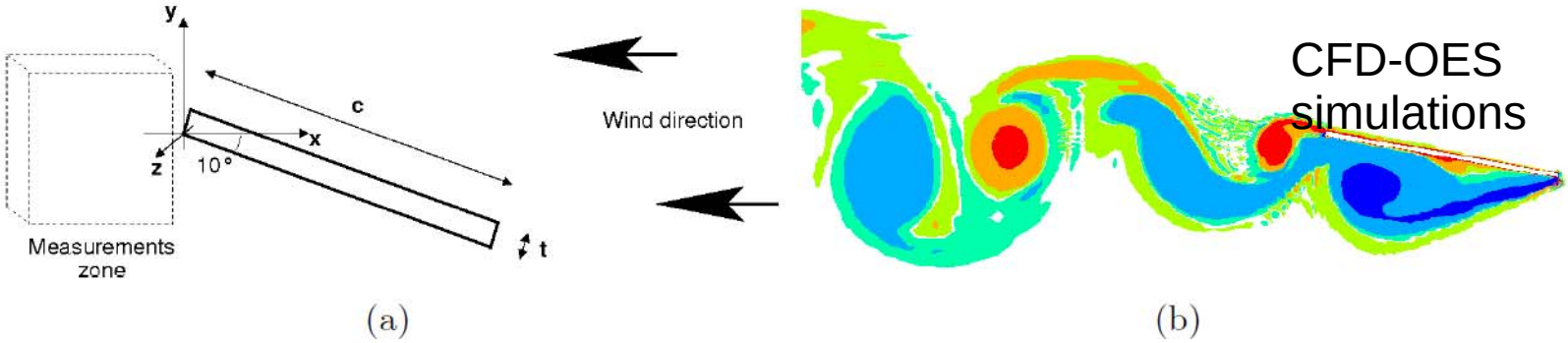


Figure 1: Schematic representation of the flow configuration (a). The frame origin is on the trailing edge at the half of the plate's span. View of phase-averaged iso-vorticity field, CFD simulations by Ouvrard et al (2010), (b).

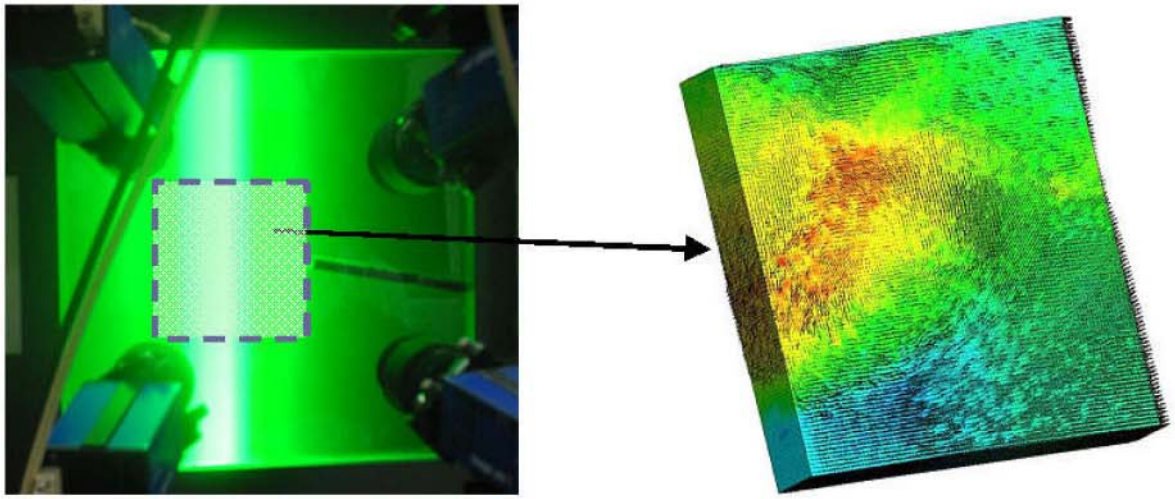
CONFIGURATION GENERIQUE DE VOLET DEFORMABLE

Tomo-PIV

IMFT S4 wind tunnel

Contribution:

La Vision Co



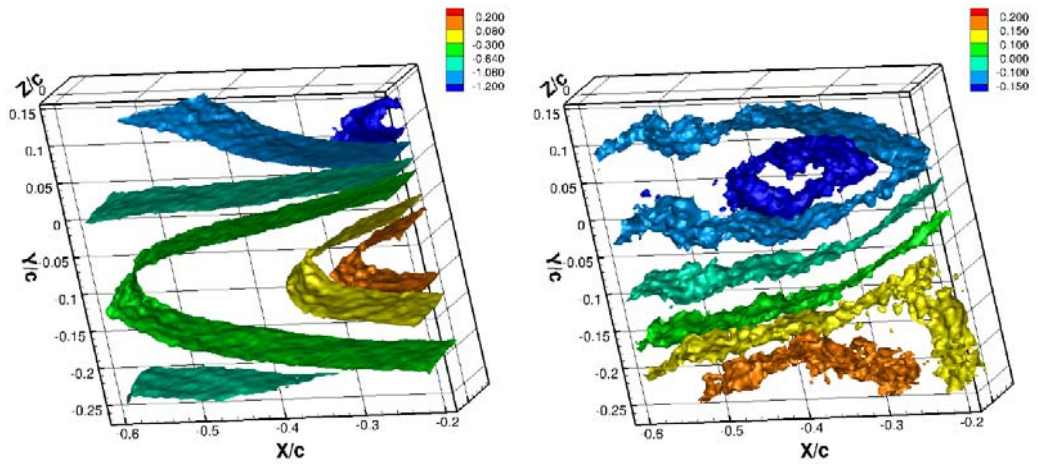
(a)

Re=200 000

Figure 2: View of the experimental set-up and of an instantaneous 3D velocity field

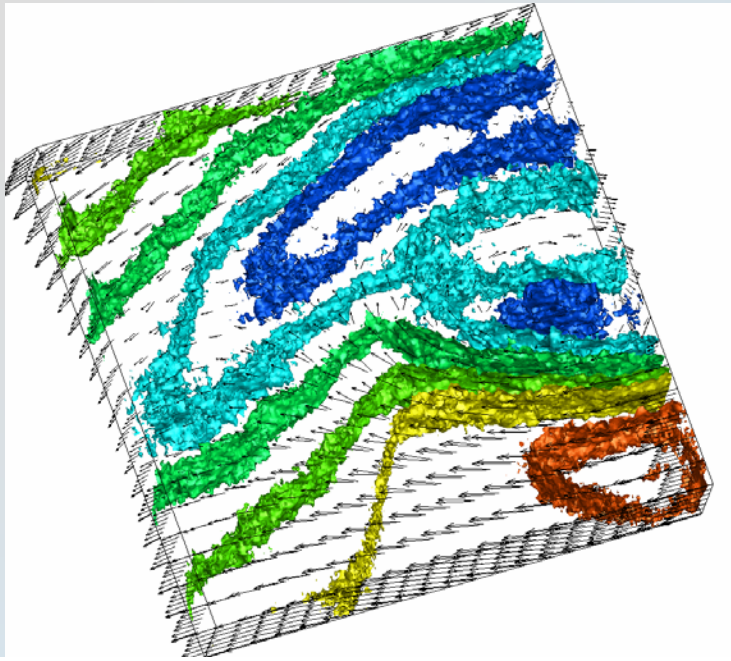
Tomo-PIV

3.1 Reynolds averaged quantities



(a) U (b) V

Figure 3: Reynolds averaged quantities measured by Tomo-PIV: streamwise U velocity and vertical V velocity.



S4 wind tunnel IMFT

Post-doc EMMAV E. Deri

Tomo-PIV

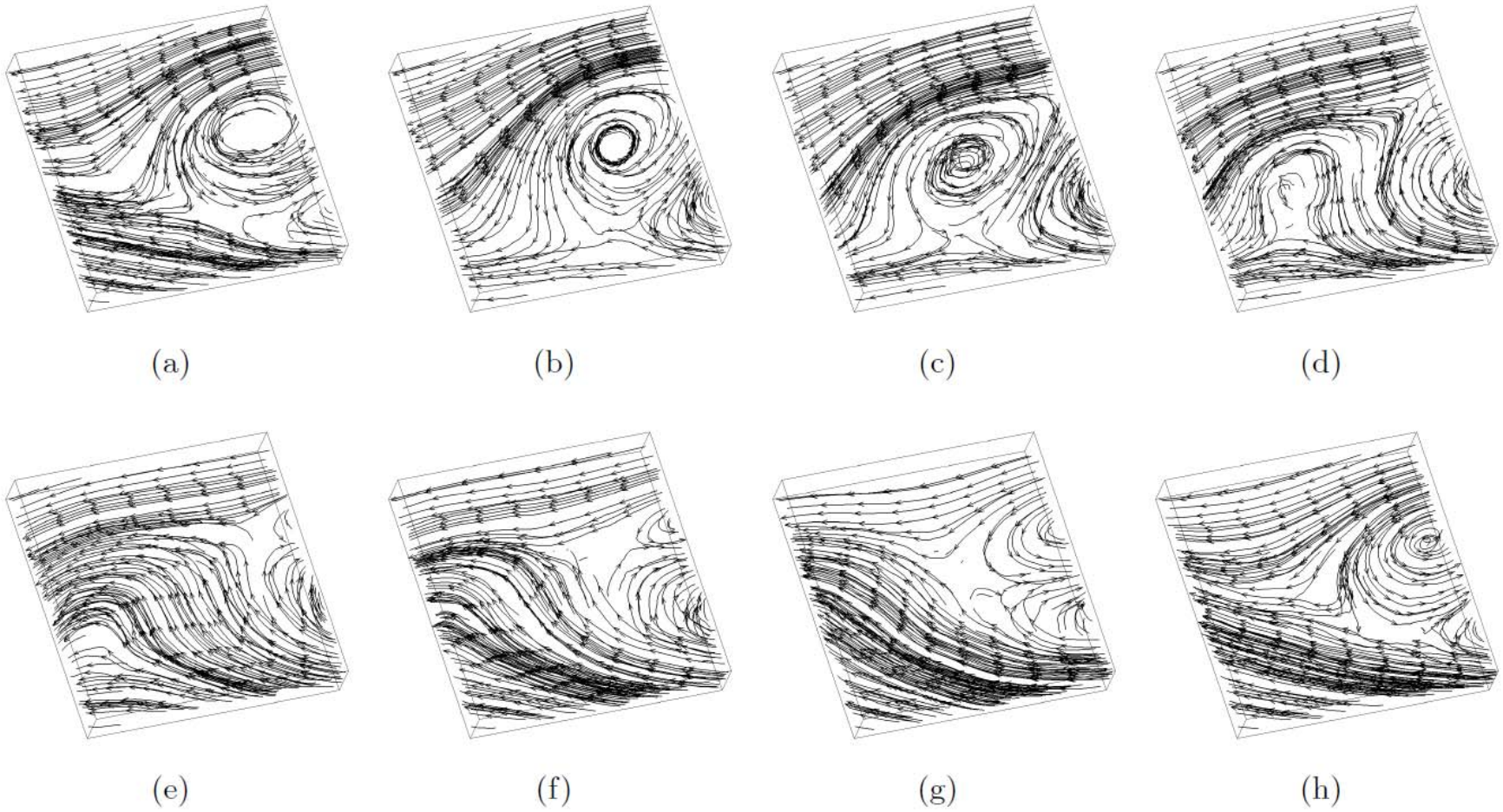


Figure 12: Phase averaged streamlines.

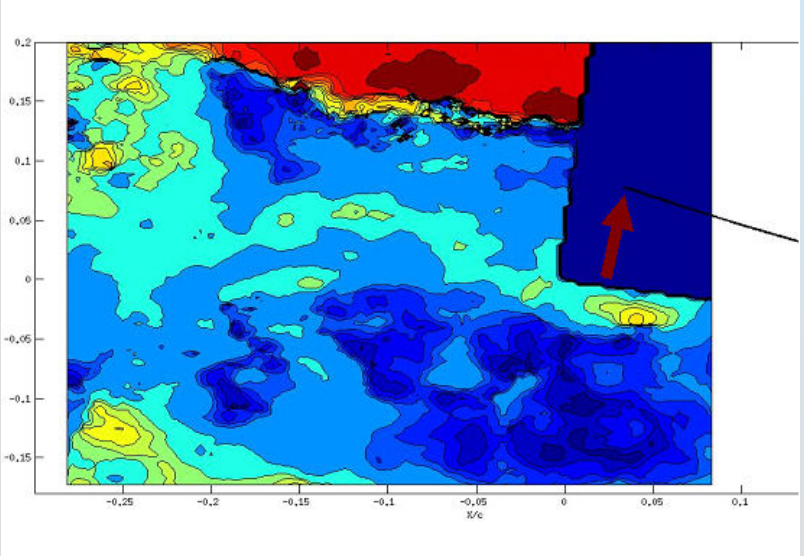
MORPHING DE VOLET DEFORMABLE PAR ALLIAGES A MEMOIRE DE FORME – « SHAPE MEMORY ALLOYS » – INSTRUMENTE AU LAPLACE

AMELIORATION DE LA VITESSE DE REFROIDISSEMENT –

ACTIONNEMENT PLUS RAPIDE

MESURE DU CHAMPS DE VITESSE INSTATIONNAIRE DANS LA REGION PROCHE EN SOUFFLERIE S4 - IMFT

2 Films



MERCI DE VOTRE ATTENTION