Identification and robust load control in response to gust

. . . from subsonic to transonic, a wind tunnel application

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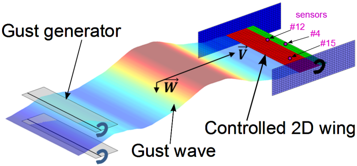
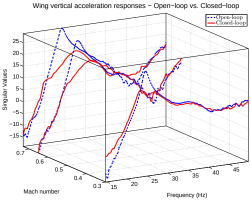




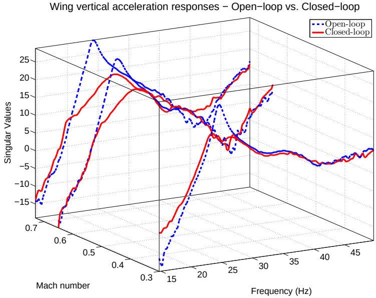
Objectives

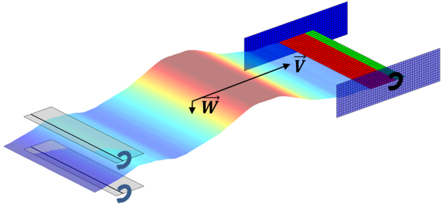
Load and vibration control...

Loads alleviation and vibration reduction is crucial in aeronautics for structure stress and fatigue reduction, potential wing weight reduction, consumption reduction, lifetime enhancement. . . .

Amount the potential lever:

- Passive solution (earoelasticity, material, shape, . . .)
- **Active solutions** (control law, actuators, . . .)





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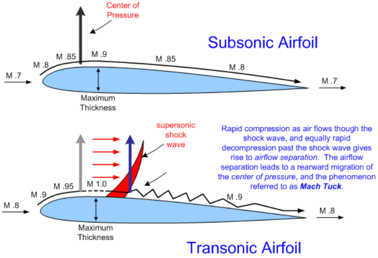
Objectives

… and associated challenges

Many challenges are presents:

- Complex disturbance (discrete, large spectrum …)
- Limited actuator and computer burden
- **System flexibility and aeroelasticity**
- **Operate over a wide range of flight conditions** (subsonic, transonic)

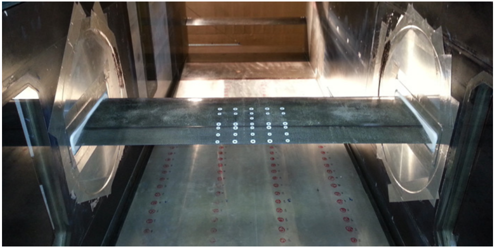


Objectives

Outline

A control approach...

- Experimental set-up
- Dynamical modelling & control design
- Implementation & results



(video)

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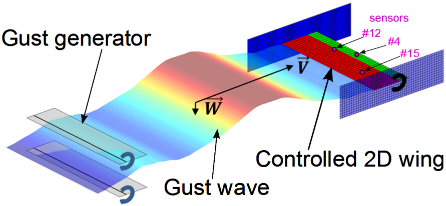
Outlines

Experimental set-up

Wind tunnel set-up (DAFE & DADS, Meudon, France)

- Wind Tunnel at Onera S3Ch
- Gust generator
- 2D wing profile, many accelerometers and one single control surface
- **Interest in working in a "controlled" area to master the disturbances**



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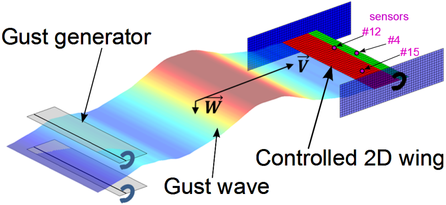
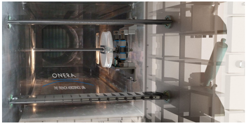
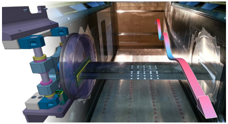




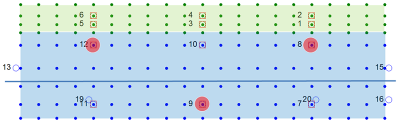


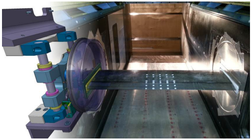
(i) wind tunnel (ii) gust generator (iii) flow stream trajectory and controlled wing

Experimental set-up

Controlled aeroelastic wing (DADS)

- Dynamics along vertical and rotational axis
- Additional structure models (torsion, bending, ...)
- Controlled surface along the wingspan (angle) & angle of attack





(i) schematic view of the wing (ii) controlled system facing the wind

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Experimental set-up

Controlled aeroelastic wing (DADS)

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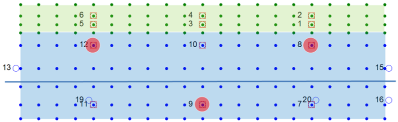
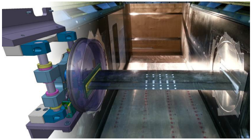
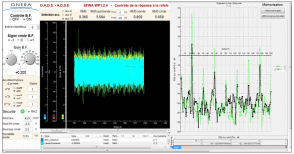




(i) schematic view of the wing (ii) controlled system facing the wind

- About 20 accelerometers
- Controlled wind and disturbances
- Acquisition system



(iii) DADS interface

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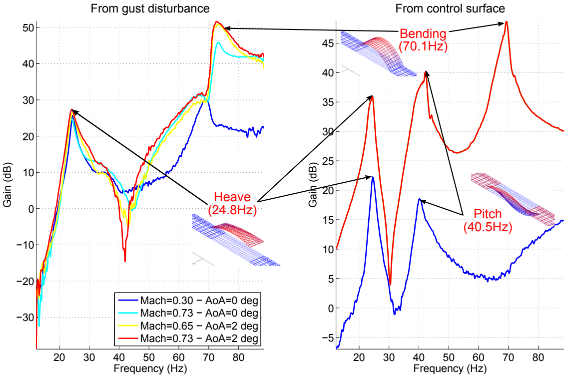
Experimental set-up

Open-loop experiments (DADS & DAFE)

- Many weeks of work for calibrating the gust generator
- Many iterations for obtaining open-loop controlled wing surface transfer
- Set-up of an acquisition system



(i) some open-loop results...

Outlines

Experimental set-up

Modelling and identification
- Problem formulation
- First approach: Loewner framework
- Second approach: subspace with LMI constraint
- Some conclusions

Control design

Epilogue

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Modelling and identification

Problem formulation

Problem

Given frequency samples ω_i and responses $\mathbf{\Phi_i} \in \mathbb{C}^{n_y \times n_u}$

$$H(\imath\omega_i) = \mathbf{\Phi_i} \quad , i = 1, \ldots, N. \tag{1}$$

where H is the **exact** transfer function of the system, the objective is to obtain a rth-order rational LTI model of the form, $\hat{H}(s) = \hat{C}(s\hat{E} - \hat{A})^{-1}\hat{B} + \hat{D} \in \mathcal{H}_\infty^{n_y \times n_u}$, with realization defined as:

$$\hat{\mathbf{H}} : \hat{E}\dot{\hat{\mathbf{x}}}(t) = \hat{A}\hat{\mathbf{x}}(t) + \hat{B}\mathbf{u}(t) \, , \, \mathbf{y}(t) = \hat{C}\hat{\mathbf{x}}(t) + \hat{D}\mathbf{u}(t), \tag{2}$$

that **well matches the obtained frequency sample** $\{\omega_i, \mathbf{\Phi_i}\}$ **and hopefully reproduces the actual transfer** H. Let $\hat{\mathbf{x}}(t) \in \mathbb{R}^r$, $\mathbf{u}(t) \in \mathbb{R}^{n_u}$ and $\mathbf{y}(t) \in \mathbb{R}^{n_y}$ be the states, inputs and outputs vectors, respectively.

1 based on the **Loewner framework**,

2 based on the **subspace one with LMI constraints**.

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Modelling and identification

First approach: Loewner framework[1]

Set

$$\begin{array}{rcl} [\omega_1, \omega_2, \ldots, \omega_N] & = & [\mu_1, \mu_2, \ldots, \mu_{\underline{n}}] \cup [\lambda_1, \lambda_2, \ldots, \lambda_{\overline{n}}] \\ [\mathbf{\Phi_1}, \mathbf{\Phi_2}, \ldots, \mathbf{\Phi_N}] & = & [\tilde{v}_1, \tilde{v}_2, \ldots, \tilde{v}_{\underline{n}}] \cup [\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_{\overline{n}}] \end{array} \quad (3)$$

and define

- $\mathbf{l}_i \in \mathbb{C}^{1 \times n_y}$ $(i = 1, \ldots, \underline{n})$ and
- $\mathbf{r}_j \in \mathbb{C}^{n_u \times 1}$ $(j = 1, \ldots, \overline{n})$

the $\underline{n}$ left and $\overline{n}$ right tangential directions ($\underline{n} + \overline{n} = N$). Using these tangential directions, one can then compute

- $\mathbf{v}_i = \mathbf{l}_i \tilde{v}_i \in \mathbb{C}^{1 \times n_u}$ and
- $\mathbf{w}_j = \tilde{w}_j \mathbf{r}_j \in \mathbb{C}^{n_y \times 1}$

the left and right tangential values, respectively.

[1] L. Meier III and D. G. Luenberger, *"Approximation of linear constant systems"*, IEEE Transactions on Automatic Control, vol. 12, no. 5, pp. 585-588, 1967.

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Modelling and identification

First approach: Loewner framework - Exact interpolation [2]

General interpolation problem

Given *left* and *right interpolation data*:

$$\{(\mu_i, \mathbf{l}_i, \mathbf{v}_i) | \mu_i \in \mathbb{C}, \mathbf{l}_i \in \mathbb{C}^{1\times n_y}, \mathbf{v}_i \in \mathbb{C}^{1\times n_u}, i = 1, \dots, \underline{n}\} \tag{4}$$

$$\{(\lambda_j, \mathbf{r}_j, \mathbf{w}_j) | \lambda_j \in \mathbb{C}, \mathbf{r}_j \in \mathbb{C}^{n_u\times 1}, \mathbf{w}_j \in \mathbb{C}^{n_y\times 1}, j = 1, \dots, \overline{n}\} \tag{5}$$

construct a realization $\mathbf{H} = (E, A, B, C, 0)$ of appropriate dimensions whose transfer function $H(s) = C(sE - A)^{-1}B$ both satisfies the *left* and *right constraints*:

$$\mathbf{l}_i H(\mu_i) = \mathbf{v}_i,\ \ i = 1, \dots \underline{n} \tag{6}$$

$$H(\lambda_j)\mathbf{r}_j = \mathbf{w}_j,\ \ j = 1, \dots \overline{n}. \tag{7}$$

[2] L. Meier III and D. G. Luenberger, *"Approximation of linear constant systems"*, IEEE Transactions on Automatic Control, vol. 12, no. 5, pp. 585-588, 1967.

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Modelling and identification

First approach: Loewner framework - Exact interpolation [3]

Theorem: Loewner interpolation

Given *left* and *right interpolation data* as in (4)-(5), and assuming that $\underline{n} = \overline{n} = \breve{n}$, the $\breve{n}$-th order rational transfer function $H(s) = C(sE - A)^{-1}B$, with realization $\mathbf{H} = (E, A, B, C, 0)$ constructed as

$$E = -\mathbb{L},\ A = -\mathbb{L}_\sigma,\ B = V \text{ and } C = W, \tag{8}$$

interpolates the left and right constraints (6)-(7), if

$$\begin{aligned} [\mathbb{L}]_{ij} &= \frac{\mathbf{v}_i \mathbf{r}_j - \mathbf{l}_i \mathbf{w}_j}{\mu_i - \lambda_j} = \frac{\mathbf{l}_i \Big(H(\lambda_i) - H(\mu_j)\Big)\mathbf{r}_j}{\mu_i - \lambda_j} \\ [\mathbb{L}_\sigma]_{ij} &= \frac{\mu_i \mathbf{v}_i \mathbf{r}_j - \mathbf{l}_i \mathbf{w}_j \lambda_j}{\mu_i - \lambda_j} = \frac{\mu_i \mathbf{l}_i \Big(H(\lambda_i) - H(\mu_j)\Big)\mathbf{r}_j \lambda_j}{\mu_i - \lambda_j} \end{aligned} \tag{9}$$

known as the Loewner and the shifted Loewner matrices, respectively, and $W = [\mathbf{w}_1, \dots, \mathbf{w}_{\breve{n}}]$, $V^T = [\mathbf{v}_1^T, \dots, \mathbf{v}_{\breve{n}}^T]$.

[3] A. Ionita and A. Antoulas, *"Data-driven parametrized model reduction in the Loewner framework"*, SIAM Journal on Scientific Computing, vol. 36, no. 3, pp. 984-1007, 2014.

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Modelling and identification

First approach: Loewner framework - Approximation [4]

Theorem: Loewner approximation

To obtain a reduced order model $\hat{\mathbf{H}}$ of order $r \leq n$ that well approximates $\mathbf{H}$ one should simply apply a **SVD** as follows:

$$\mathbb{L} = \begin{bmatrix} Y_1 & Y_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & \\ & \Sigma_2 \end{bmatrix} \begin{bmatrix} X_1^* \\ X_2^* \end{bmatrix} \tag{10}$$

where $\Sigma_1 \in \mathbb{R}^{r \times r}$, $\Sigma_2 \in \mathbb{R}^{(n-r)\times(n-r)}$ and Y_1, Y_2, X_1, X_2 of appropriate dimensions. Then the reduced order model is simply obtained by the Petrov-Galerkin projection:

$$\begin{aligned} \hat{\mathbf{H}} &= (\hat{E}, \hat{A}, \hat{B}, \hat{C}, 0) \\ &= (-Y_1^* \mathbb{L} X_1, -Y_1^* \mathbb{L}_\sigma X_1, Y_1^* V, C X_1, 0). \end{aligned} \tag{11}$$

[4] A. Ionita and A. Antoulas, *"Data-driven parametrized model reduction in the Loewner framework"*, SIAM Journal on Scientific Computing, vol. 36, no. 3, pp. 984-1007, 2014.

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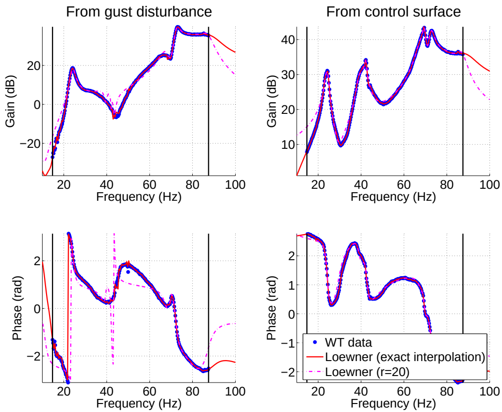
Modelling and identification

First approach: Loewner framework - MORE toolbox (Mach 0.70, AoA 0deg)

- $N = 584$ sampled data points, $n_y = 3$ outputs and $n_u = 2$ inputs,
- $\underline{n} = \overline{n} = \breve{n} = 292$, and $r = 20$.



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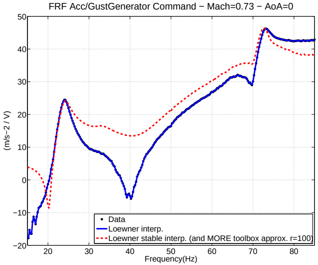
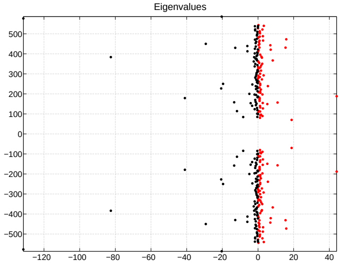
Modelling and identification

First approach: Loewner framework - Some issues





(i) illustration of a problem (ii) Eigenvalues of the Loewner approximation

→ **However, some issues have to be handled:**

- interpolant of high dimension,
- and unstable,
- selection of tangential directions.

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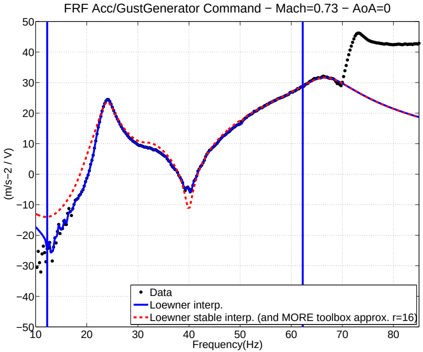
Modelling and identification

First approach: Loewner framework - Some issues



(i) a clue to handle $\mathcal{H}_2$ optimality objective and the l_2 one

- discrete filtering
- sampling
- ...?

Modelling and identification

Second approach: subspace with LMI constraint

Define a framework in the discrete-domain:

- Let us first consider the frequency domain discrete state-space representation:

$$\begin{array}{rcl} e^{\imath\omega}X(\omega) & = & AX(\omega)+BU(\omega) \\ Y(\omega) & = & CX(\omega)+DU(\omega) \end{array} \tag{12}$$

- Moreover, if a discrete frequency domain data set $\{\omega_i, \mathbf{\Phi_i}\}$ $(i=1,\ldots,N)$ is considered then, one has $G(\omega_i)=\mathbf{\Phi_i}$ and the following relation holds:

$$\mathbf{G} = O\mathbf{X}^c + \Gamma\mathbf{W} \tag{13}$$

$$\mathbf{G} = \left[\begin{array}{ccc} \mathbf{\Phi_1} & \ldots & \mathbf{\Phi_N} \\ e^{\imath\omega_1}\mathbf{\Phi_1} & \ldots & e^{\imath\omega_N}\mathbf{\Phi_N} \\ \vdots & \ddots & \vdots \\ e^{\imath(q-1)\omega_1}\mathbf{\Phi_1} & \ldots & e^{\imath(q-1)\omega_N}\mathbf{\Phi_N} \end{array}\right] \in \mathbb{C}^{n_y q\times n_u N}$$

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Modelling and identification

Second approach: subspace with LMI constraint

$$\mathbf{G} = O\mathbf{X}^c + \Gamma \mathbf{W} \tag{14}$$

$$\mathbf{X}^c = [X^c(\imath\omega_1), \dots, X^c(\imath\omega_N)] \in \mathbb{C}^{n \times n_u N} \quad , \quad O = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{q-1} \end{bmatrix} \in \mathbb{R}^{n_y q \times n}$$

and

$$\mathbf{W} = \begin{bmatrix} I_{n_u} & \dots & I_{n_u} \\ e^{\imath\omega_1} I_{n_u} & \dots & e^{\imath\omega_N} I_{n_u} \\ \vdots & \ddots & \vdots \\ e^{\imath(q-1)\omega_1} I_{n_u} & \dots & e^{\imath(q-1)\omega_N} I_{n_u} \end{bmatrix} \in \mathbb{C}^{n_u q \times n_u N}$$

$$\Gamma = \begin{bmatrix} D & 0 & \dots & 0 \\ CB & D & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{q-2}B & CA^{q-3}B & \dots & D \end{bmatrix} \in \mathbb{R}^{n_y q \times n_u q}.$$

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Modelling and identification

Second approach: subspace with LMI constraint

- The extended observability matrix O, which depends on A and C, can be written as a combination of inputs/outputs data $\mathbf{G}$, $\mathbf{X}^c$, and $\mathbf{W}$, only. Then, an elegant way to extract A and C matrices from O, is to first apply an orthogonal projection $\mathbf{W}^\perp$ defined as

$$\mathbf{W}^\perp = I - \mathbf{W}^T(\mathbf{W}\mathbf{W}^T)^{-1}\mathbf{W}, \tag{15}$$

- Indeed, by right multiplying with $\mathbf{W}^\perp$, the following is obtained:

$$\mathbf{G}\mathbf{W}^\perp = OX^c\mathbf{W}^\perp.$$

- Then, an effective way to extract A and C is to use a **QR** and a **SVD** of $\mathbf{G}\mathbf{W}^\perp$, and by noticing that

$$\begin{aligned} \mathbf{G}\mathbf{W}^\perp = R_{22}Q_2^T \quad &= \quad \hat{U}\hat{\Sigma}\hat{V}^TQ_2^T \\ &= \quad [\hat{U}_s \quad \hat{U}_0] \begin{bmatrix} \hat{\Sigma}_s & 0 \\ 0 & \hat{\Sigma}_o \end{bmatrix} \begin{bmatrix} \hat{V}_s^T \\ \hat{V}_o^T \end{bmatrix} Q_2^T. \end{aligned}$$

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Modelling and identification

Second approach: subspace with LMI constraint

- $\hat{A}$ and $\hat{C}$ are obtained as

$$\hat{A} = (J_1 \hat{U}_s)^\dagger J_2 \hat{U}_s$$

$$\hat{C} = J_3 \hat{U}_s$$

where

$$\begin{array}{ccl} J_1 & = & [I_{(q-1)n_y} \quad 0_{(q-1)n_y \times n_y}] \\ J_2 & = & [0_{(q-1)n_y \times n_y} \quad I_{(q-1)n_y}] \\ J_3 & = & [I_{n_y} \quad 0_{n_y \times (q-1)n_y}] \end{array}$$

- $\hat{B}$ and $\hat{D}$ are obtained as

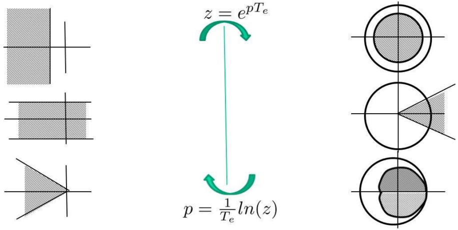
$$\{\hat{B}, \hat{D}\} = \arg \min_{\substack{\hat{B} \in \mathbb{R}^{n \times n_u} \\ \hat{D} \in \mathbb{R}^{n_y \times n_u}}} \sum_{k=1}^{N} \| \mathbf{\Phi_k} - \hat{H}(\omega_k, \hat{B}, \hat{D}) \|_F^2.$$

Modelling and identification

Second approach: subspace with LMI constraint - LMI regions

$\mathbf{Re}(z) < 0$	$\Leftrightarrow$	$z + \overline{z} < 0$	$\Leftrightarrow$	left side
$\mathbf{Re}(z) < -\alpha$	$\Leftrightarrow$	$z + \overline{z} + 2\alpha < 0$	$\Leftrightarrow$	shifted left side
$\lvert z \rvert < r$	$\Leftrightarrow$	$\begin{pmatrix} -r & z \\ \overline{z} & -r \end{pmatrix} < 0$	$\Leftrightarrow$	disc with radius lower than r
$\alpha_1 < \mathbf{Re}(z) < \alpha_2$	$\Leftrightarrow$	$\begin{pmatrix} (z + \overline{z} - 2\alpha_2 & 0 \\ 0 & (z + \overline{z} + 2\alpha_1 \end{pmatrix} < 0$	$\Leftrightarrow$	vertical strips
$\mathbf{Re}(z) tan(\theta) < -\lvert \mathbf{Im}(z) \rvert$	$\Leftrightarrow$	$\begin{pmatrix} (z + \overline{z}) sin\theta & (z - \overline{z}) cos\theta \\ (z - \overline{z}) cos\theta & (z + \overline{z}) sin\theta \end{pmatrix} < 0$	$\Leftrightarrow$	conic region

Equivalence s to z



Modelling and identification

Second approach: subspace with LMI constraint

Proposition

Given $P = P^T$,Q real matrices, then $\hat{A} = \varphi^\dagger b$ has its eigenvalues in the stability domain:

$$\mathbf{C}_{stab} = \{z \in \mathbf{C} | P + Qz + Q^T \overline{z} < 0\} \tag{16}$$

if one can sole the minimization problem under LMI constraints:

$$\min_{\tilde{A},\Psi,\beta \in \mathbf{R}} \beta$$

$$\begin{array}{rcl} P \otimes \Psi + Q \otimes \tilde{A} + Q^T \otimes \tilde{A}^T & < & 0 \\ \begin{pmatrix} I & (\varphi \tilde{A} - b\Psi) \\ (\varphi \tilde{A} - b\Psi)^T & \beta \end{pmatrix} & > & 0 \\ \Psi & > & 0 \\ \beta & > & 0 \end{array}$$

where $\tilde{A} = \hat{A}\Psi$ et $\Psi = \Psi^T$.

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Modelling and identification

Second approach: subspace with LMI constraint - Algorithm

1. Compute $\tilde{A} = \hat{A}\Psi$ by solving the following constrained optimization problem:

$$\min_{\tilde{A},\Psi,\beta\in\mathbb{R}} \beta$$

$$\begin{array}{rcl} P\otimes\Psi + Q\otimes\tilde{A} + Q^T\otimes\tilde{A}^T & < & 0 \\ \left(\begin{array}{cc} I & (\varphi\tilde{A} - b\Psi) \\ (\varphi\tilde{A} - b\Psi)^T & \beta \end{array}\right) & > & 0 \\ \Psi & > & 0 \\ \beta & > & 0 \end{array}$$

2. Compute $\hat{A} = \tilde{A}\Psi^{-1}$ and $\hat{C} = J_3\hat{U}_s$
3. Determine $\hat{B}$ and $\hat{D}$ (where $\hat{H}(\omega, \hat{B}, \hat{D}) = \hat{C}(e^{\imath\omega}I - \hat{A})^{-1}\hat{B} + \hat{D}$)

$$\{\hat{B}, \hat{D}\} = \arg \min_{\substack{\hat{B}\in\mathbb{R}^{n\times n_u} \\ \hat{D}\in\mathbb{R}^{n_y\times n_u}}} \sum_{k=1}^{N} \|\mathbf{\Phi_k} - \hat{H}(\omega_k, \hat{B}, \hat{D})\|_F^2.$$

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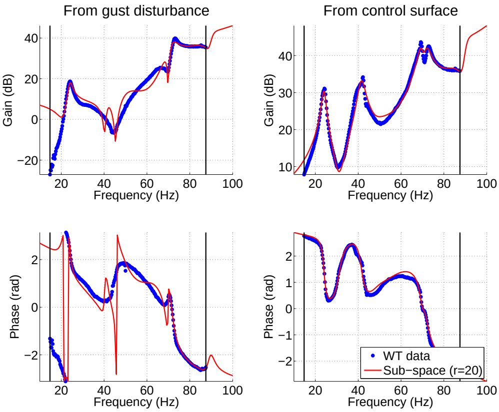
Modelling and identification

Second approach: subspace with LMI constraint - MORE toolbox (Mach 0.70, AoA 0deg)

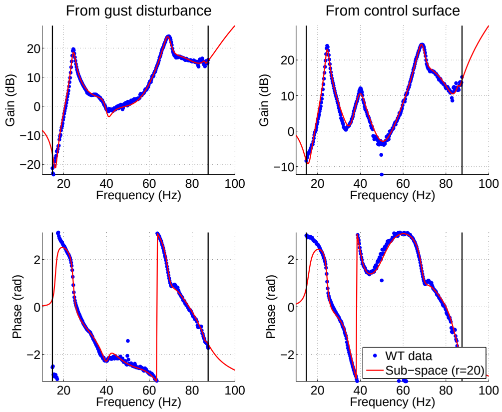
- $N = 584$ sampled data points, $n_y = 3$ outputs and $n_u = 2$ inputs,
- LMI region and $r = 20$.



Modelling and identification

Second approach: subspace with LMI constraint - MORE toolbox (Mach 0.70, AoA 0deg)

- $N = 292$ sampled data points, $n_y = 3$ outputs and $n_u = 2$ inputs,
- LMI region and $r = 20$.



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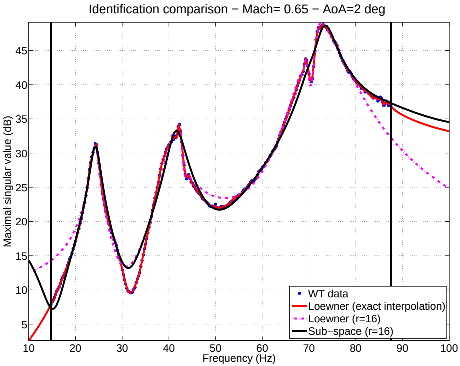
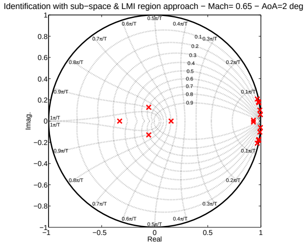
Modelling and identification

Some conclusions

- Two nice approaches
- However, the Loewner approach cannot guarantee pole location



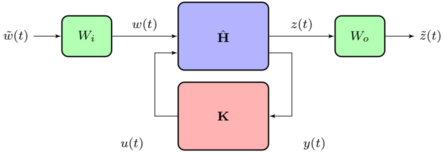


Outlines

Control design

Structured LTI robust controller[5]

$$K^\star := \underset{\substack{\textbf{rank}({\color{red}K}) = n_c \\ {\color{red}K} \in {\color{red}\mathcal{K}} \subseteq \mathcal{H}_2^{1\times 2}}}{\textbf{argmin}} \left\| \begin{bmatrix} T^{(1)}_{\tilde{w}\to\tilde{z}}({\color{red}K}) & & \\ & \ddots & \\ & & T^{(n_s)}_{\tilde{w}\to\tilde{z}}({\color{red}K}) \end{bmatrix} \right\|_{\mathcal{H}_\infty} \quad (17)$$

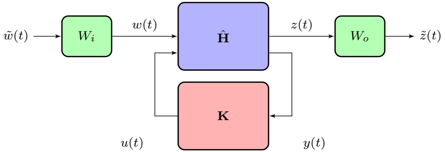


- ${\color{red}\mathcal{K}}$ is the set of all stable rational functions with derivative action and roll-off of second order
- ${\color{red}T^{(i)}_{\tilde{w}\to\tilde{z}}(G)} = W_i \mathcal{F}_l(\hat{H}^(i), G) W_o$, as described on the above figure ($i = 1, \dots, n_s$)

5 P. Apkarian and D. Noll, *"Nonsmooth $\mathcal{H}_\infty$ Synthesis"*, in IEEE Transaction in Automatic Control, Vol. 51(1), January, 2006, pp. 71-86.

Control design

Structured LTI robust controller[6]



$$W_o(s) = \begin{bmatrix} W_p(s) & 0 \\ 0 & W_u(s) \end{bmatrix} \text{ and } W_i(s) = 1 \quad (18)$$

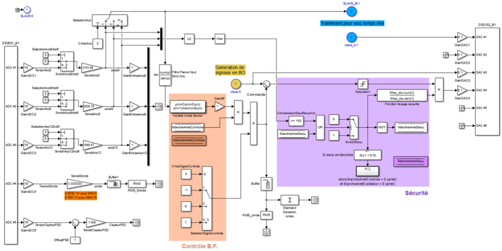
$$\begin{aligned} W_p(s) &= \frac{G(s/10w_p+1)}{s/w_p+1} I_2 \\ W_u(s) &= \frac{s/w_{act}+1}{s/10w_{act}+1} \end{aligned} \quad (19)$$

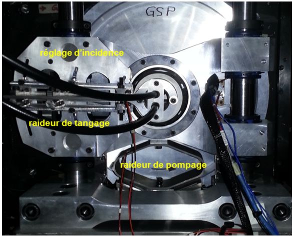
where G is the $\mathcal{H}_\infty$-norm of the performance transfer, $w_p = w_{act} = 30 \times 2\pi$rad/s.

6 P. Apkarian and D. Noll, *"Nonsmooth $\mathcal{H}_\infty$ Synthesis"*, in IEEE Transaction in Automatic Control, Vol. 51(1), January, 2006, pp. 71-86.

Control design

Real-time implementation (user-friendly interface)

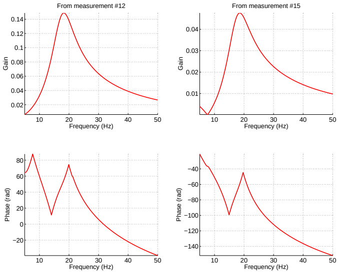


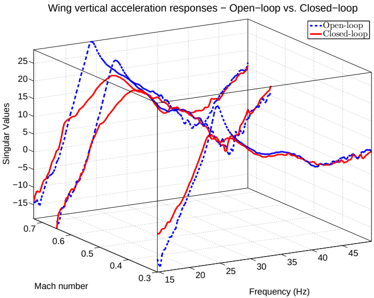


- Easy to adjust the control law,
- and after some iterations...

Control design

Results - Angle of Attack 0 deg / Mach 0.30 and 0.73





- Controller structure high pass and roll-off
- Gain around 10dB at the peak value
- Robust to Mach variations

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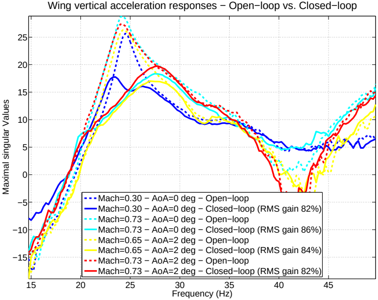
Control design

Results - Angle of attack 2 deg / Mach 0.65 and 0.73



- Gain around 10dB at the peak value
- Robust to Mach variations & AoA

Outlines

Epilogue

What to keep in mind?

- WTT performed at Onera S3Ch
- **2 frequency-domain identification procedures** (numerically robust)
- **Robust active control solution** implemented on a real-time computer
- Attenuation at **sub and transonic conditions**: **first time in Europe**

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Envol

LE FIL L'INVITÉ ANALYSE FOCUS ENSEMBLE UNE JOURNÉE AVEC CHRONIQUES

Des rafales et des ailes

5 novembre 2014 : dernière journée d'essai à la soufflerie S3 de Meudon. Dans quelques heures, le bruit impressionnant de la soufflerie laissera la place au silence. Après des millions de cycles de fonctionnement, le générateur de rafale sera arrêté et le dispositif d'essai démonté. La maquette sollicitée à de forts niveaux vibratoires pourra enfin sortir de « cette zone de turbulence » pour un repos bien mérité. La campagne expérimentale pour le contrôle actif de charge à la rafale[1] se termine sur une première européenne : l'ONERA vient de démontrer que l'on peut réduire fortement les effets induits par une rafale sur une structure d'aile d'avion en condition transsonique. Retour sur cette campagne, l'aboutissement d'un projet qui a mobilisé dans l'ONERA DADS, DAFE et DCSD.

Autres articles Une journée avec

LE CONTEXTE

Les programmes de recherche actuels tels que Cleansky, visent au développement de nouvelles configurations « vertes » d'aéronefs, qui répondent aux objectifs de l'ACARE[2] à l'horizon 2050 (réduction des émissions de CO2 de 75% de l'émission de suies à 90% et du bruit perçu de 65%). Les principaux axes investigués comme l'allégement des structures ou la laminarité[3] imposent d'étudier leurs impacts sur la sécurité et le confort des passagers. Le contrôle des charges est l'un de ces points clés.

LES ENJEUX

Dans le cadre de Cleansky SFWA ITD[4], l'ONERA a piloté un projet sur la thématique du « contrôle de charge à la rafale ». Objectif : réduire fortement l'effet induit par une rafale sur une structure d'aile d'avion, par une approche expérimentale en soufflerie.

IMAGES D'ESSAI

Clean Sky Innovation takes off

Horizon 2020 European Union Funding for Research & Innovation

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Active gust load alleviation on an Aeroelastic model

Share Print

26/05/2015

Wind Tunnel (WT) tests in the transonic range at the ONERA S3Ch facility at the Meudon Centre were completed at the end of 2014 in the framework of SFWA-ITD.. These experimental investigations had been part of the Technology Stream "Load Control Functions and Architectures". They aimed to first study the effects of impacting gusts on an aeroelastic model and then assessing the efficiency of the active control methodologies. In line with the global objective of the Clean Sky program of pollutant emissions reduction, these research activities will contribute to a potential reduction of the aircraft weight (and fuel consumption levels) through innovative load control concepts.

The experimental set-up was designed and manufactured through an ONERA and Aviation Design collaboration-Aviation Design being a French S.M.E. winner of one particular Call for Proposal (Batch#7 – Project: Wind tunnel). The set-up is composed of a cylindrical gust generator and a 2D aeroelastic aerofoil, equipped with a trailing edge flap. After some laboratory qualification and calibration, ONERA conducted several test campaigns aiming to characterise the gust generation capabilities and then, analyse the gust impact on aerodynamic and aeroelastic behaviours of the model. The relevant database is currently used in a benchmark exercise by Dassault-Aviation, Airbus Operations S.A.S and ONERA for the validation of high fidelity numerical codes as well as their capabilities to compute the gust responses. Furthermore, gust load control based upon closed loop approaches was investigated; for the first time in transonic flow conditions, active gust load alleviation was successfully completed. The measured structural acceleration fields for both gust perturbations and control surface commands were analysed in order to perform at first the identification of a system model and then a synthesis of control laws. Real time feedback controls demonstrated significant reductions of the model structural responses to gust.

Epilogue

... and next steps

Forthcoming challenges

Bench Move toward 3D wing profile & more flexible wings [Clean Sky 2]

Publi Publish results [IEEE trans. CST]

Methods Enhanced modelling procedures [Data-based $\mathcal{H}_2$ model approximation][a] [b] [c]

Methods Parametric / adaptive control

Mixed Use additional and/or different actuators (*e.g.* pulsed fluid)

[a] Z. Drmac, S. Gugercin and C.A. Beattie, *"Vector Fitting for Matrix-valued Rational Approximation"*, Submitted. Available as arXiv:1503.00411.

[b] I. Pontes Duff Pereira, C. Poussot-Vassal and C. Seren, *"Realization independent single time-delay dynamical model interpolation and H2-optimal approximation"*, submitted.

[c] C. Poussot-Vassal and P. Vuillemin, *"Introduction to MORE: a MOdel REduction Toolbox"*, In Proceedings of the IEEE Multi-conference on Systems and Control (MSC CCA'12), Dubrovnik, Croatia, October, 2012, pp. 776-781.

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Epilogue

… and next steps

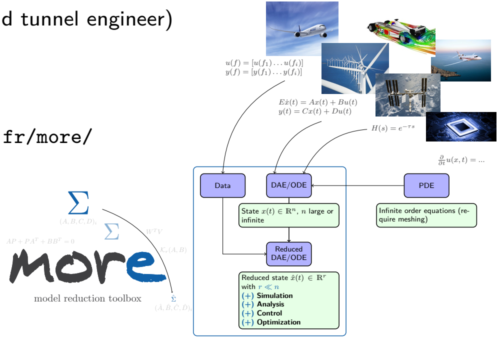
(Some) Acknowledgements

DADS Arnaud Lepage (project leader),
DADS Dominique Le Bihan (modelling and control),
DADS Yannick Amosse (mechanical integration),
DAFE Jean-Charles Abart (S3Ch Meudon wind tunnel responsible),
DAFE Vincent Brion (wind tunnel engineer)

Clean Sky 2

MORE toolbox

- `http://w3.onera.fr/more/`



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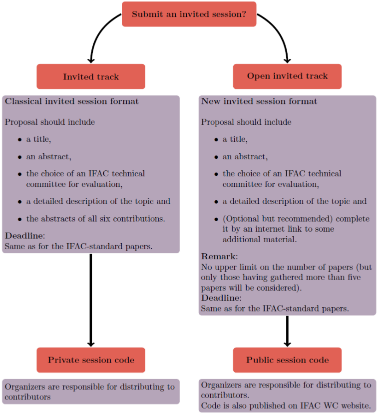
Announcement

Forthcomming 20th IFAC WC, Toulouse, France (2017)

New invited session format

- classical invited sessions or
- new open invited tracks

More on `https://www.ifac2017.org/invited`



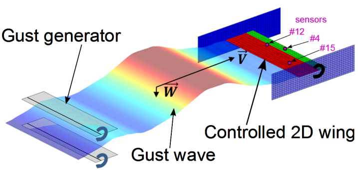
Identification and robust load control in response to gust

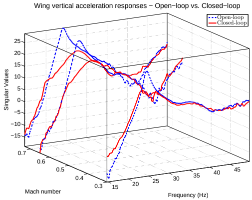
. . . from subsonic to transonic, a wind tunnel application

C. Poussot-Vassal, F. Demourant &
A. Lepage, D. Le Bihan

THE FRENCH AEROSPACE LAB

April 2015, Onera





Proof of the subspace approach with LMI constraints

... and next steps

$J_1\hat{U}_s\hat{A} = J_2\hat{U}_s \Leftrightarrow \hat{A} = (J_1\hat{U}_s)^\dagger J_2\hat{U}_s \Leftrightarrow \hat{A} = \varphi^\dagger b$ avec $\varphi = J_1\hat{U}_s$ et $b = J_2\hat{U}_s$. Or
$\hat{A} = \varphi^\dagger b \Leftrightarrow \hat{A}\Psi = \varphi^\dagger b\Psi \Leftrightarrow \tilde{A} = \varphi^\dagger b\Psi \Leftrightarrow \min \|\varphi\tilde{A} - b\Psi\|_2^2$
Moreover

$$\min \|\varphi\tilde{A} - b\Psi\|_2^2 \Leftrightarrow \begin{array}{c} \min_{\beta\in\mathbf{R}} \beta > 0 \\ (\varphi\tilde{A} - b\Psi)^T(\varphi\tilde{A} - b\Psi) < \beta \end{array}$$

From Schur lemma:

$$\begin{array}{cccc} & (\varphi\tilde{A} - b\Psi)^T(\varphi\tilde{A} - b\Psi) & < & \beta \\ \Leftrightarrow & (\varphi\tilde{A} - b\Psi)^T(\varphi\tilde{A} - b\Psi) - \beta & < & 0 \\ \Leftrightarrow & \begin{pmatrix} I & (\varphi\tilde{A} - b\Psi) \\ (\varphi\tilde{A} - b\Psi)^T & \beta \end{pmatrix} & > & 0 \end{array}$$

From Chilali and Gahinet proposition:
$P \otimes \Psi + Q \otimes \hat{A}\Psi + Q^T \otimes (\hat{A}\Psi)^T < 0 \Leftrightarrow P \otimes \Psi + Q \otimes \tilde{A} + Q^T \otimes \tilde{A}^T < 0$
where $\tilde{A} = \hat{A}\Psi$ et $\Psi = \Psi^T > 0$