Transonic Buffet Control on 3D Turbulent Wings using Fluidic Devices. Part 2: an experimental investigation of a closed loop methodology

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The BUFFET phenomenon

- **Buffeting**: structural response to unsteady aerodynamic loads
  - can appear in different A/C locations and depending on flight conditions

- **Studied case**: upper wing surface for transonic flow
  - Phenomena: flow separations, shock wave / B.L. interaction
  - Conditions: high mach, high lift coeff. Value
  - Risks:
    - Generation of structural fatigue (strong design constraints)
    - Limitation of flight envelope (certification issue)
    - Decrease passengers comfort and A/C manoeuvrability

⇒ Specific needs for a deep understanding, accurate predictions and efficient means for buffet alleviation
The “BUFET’N Co” project

- An ONERA internal research project
  (structured multi-disciplinary project / 5 years / leader: E. Coustols)
- In parallel with the EU-funded projects (AVERT and Clean Sky SFWA)
- Main objectives: characterisation and control of the buffet phenomenon
  - Buffet: the aerodynamic instabilities on 3D turbulent wing in transonic flow conditions
  - Buffet vs Buffeting: choice of an aerodynamic approach
  - Control using closed loop approach (CL elements: sensor, actuator and controller)
  - Demonstration in an “industrial-type” Wind Tunnel Environment

⇒ Overview of the whole steps led to the definition, the implementation and the demonstration of the defined control strategy
4 Wind Tunnel Campaigns (2 half models)

S3Ch - 2009  S2Ma - 2010  S3Ch - 2011  S2Ma - 2012

Acquisition and analysis of steady and steady database (wall pressures and accelerations)

- Improvement of the buffet characterisation and the comprehension of physical phenomena (for different aerodynamic conditions $M, Pi, \alpha$)
  
  ⇔ *A reference experimental database*

- Tests of different actuators (*Fluidic Vortex Generators*, *Fluidic Trailing Edge*) and comparison with baseline configuration and classical actuators (Mechanical VG)
  
  ⇔ *Previous presentation of J. Dandois*

- Continuous improvement of the actuator functioning (performed in collaboration with the Model Design and Manufacture Department)
  
  ⇔ *No detailed description of the actuator internal functioning (ONERA Patent)*
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Part 2: an experimental investigation of a closed loop methodology

4 Wind Tunnel Campaigns (2 half models)

S3Ch - 2009  S2Ma - 2010  S3Ch - 2011  S2Ma - 2012

Acquisition and analysis of steady and steady database (wall pressures and accelerations)

Open loop data acquisition
Aerodynamic and structural behaviours recorded for different driving signals

Closed loop demonstration
Basic then improved tests of closed loop approaches
Characterisation of the actuator behaviour and its effects on buffet

Reminder: “VG Fluidic actuator” add momentum and kinetic energy to the turbulent boundary layer which develops upstream of the shock ⇒ decrease/suppress the appearance of separated unsteady flows

Fluidic VG principle: functioning between blowing or unblowing states
⇒ average level not equal to zero
⇒ definition of 2 ways of functioning
  • a quasi static functioning: slow adjustment of the mean level
  • a dynamic functioning (inducing necessarily static component)

⇒ In the next slides, examples of dynamic or quasi static open loop data
  • Actuator driven by a defined (and measured) electric signal
    (type of signal, averaged level, frequency and amplitude, external parameters …)
  • Unsteady pressures (and accelerometers) recorded synchronously
**Quasi static behaviour for M=0.82, AoA = 3.5°**

Ramp driving command

- **Flow rate VS command**
  - "linear part" with hysteretic
  - Residual leaks

- **RMS pressure fluctuations (near T.E.) VS command**
  - Sufficient flow rate

- **Strong efficiency on the RMS level reduction with a saturation effect** ⇒ **Strong reduction of the flow separation**

- **Improvements and definition of a “linear part” of functioning**

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Fluidic Vortex Generators

Upper side @ x/c = 15%
Dynamic behaviour for $M=0.82$, $AoA = 3^\circ$
Harmonic sinusoidal command
so that $Q = 4 \text{ g/s } +/- 4 \text{ g/s}$ pulsed @ 10Hz
**Dynamic behavior for** $M=0.82$, $\text{AoA} = 3^\circ$

Harmonic sinusoidal command so that $Q = 4 \text{ g/s} \pm 4 \text{ g/s} \text{ pulsed @ 10Hz}$

The shock location oscillates:
- At the driven frequency (with non-linearities)
- Between 2 positions (the controlled and uncontrolled for continuous fluidic action) without any control
**Dynamic** behaviour for $M=0.82$, $\text{AoA} = 3^\circ$

Sweep sine command $[0 ; 700]$ Hz

so that $Q = 4 \text{ g/s} +/- 4 \text{ g/s}$ pulsed

Determination of the transfer function **Shock location/Command**

Ability of the actuator to move dynamically the shock location over a wide frequency bandwidth with significant amplitude:
- attenuation of the amplitude shock displacement with an increase of frequency (actuator bandwidth, buffet physical phenomena …)
- estimation of time delays of the system
Classical feedback control theory
- to control the behaviour of the system
- by finding the appropriate controller (stability and performances)

According to the Fluidic VG functioning: 2 possible strategies
- a quasi static OR a dynamic approach (inducing static component)

Studied application limited to a **Quasi static approach**
- No reference & Basic approach (no model)
- Output is filtered into an integrator block to estimate a criterion over a long time
- Actuator command is proportionally defined through the feedback gain
- An efficient Buffet CL control consist in modifying “slowly” the flow characteristics such that it reaches an “optimal state”
Open loop databases ⇒ various possibilities in terms of control architecture based on:

- **Sensor data**
  - Unsteady pressure sensor at TE ⇒ qualification of flow separation
  - Synthesised signal of shock location
    Chord of sensors simultaneously analysed ⇒ qualification of the shock wave instability

- **Criterion associated to an objective function**

<table>
<thead>
<tr>
<th>Criterion Sensor</th>
<th>RMS value</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure @ Trailing edge</td>
<td>Minimisation</td>
<td>Maximisation</td>
</tr>
<tr>
<td>Shock location signal</td>
<td>Minimisation</td>
<td>Maximisation</td>
</tr>
</tbody>
</table>
Main Characteristics

- Hardware setup based on a real time system (dSpace)
- Decoupling with the data acquisition setup
- Development of specific interfaces for real time visualisation and parameterisation (sensor, criterion …)
- Implementation of control laws using Matlab / simulink
Validation of CL Control in a research WT (S3Ch)

- Demonstration of feasibility in WT environment
- Validation of the test setup (hard and software)
- Validation of the methodologies based the shock location or pressure level at trailing edge

Example:
- Studied case: M=0.82, \( \alpha = 3^\circ \) (buffet onset)
- 1 driving signal for the synchronous command of Fluidic VGs
- Actuator command estimated in real time from the analysis of the unsteady pressure sensors data
Validation of CL Control in a research WT (S3Ch) $M=0.82 \ \alpha=3^\circ$

Strategy based on the RMS fluctuation pressure @ TE

- Starting from an uncontrolled configuration
- Manual tuning of feedback gain

Snapshots of pressure distributions on the upper side of the wing

- Uncontrolled configuration
- Maximal control efficiency
- Final control

Corde @ $y/b = 60\%$

RMS sur $[T-0.25s ; T+0.25s]$

Control ON

Control OFF
Validation of CL Control in a research WT (S3Ch) $M=0.82 \; \alpha=3^\circ$

Strategy based on the Mean value of the shock location
- “Shock Estimator“ based on 10 Kulite (in real time - 2kHz sampling)
- Starting from an uncontrolled configuration
- Manual tuning of feedback gain

Snapshots of pressure distributions on the upper side of the wing
- Uncontrolled configuration
- Maximal control efficiency
- Final control
Demonstration of CL Control in an “industrial type” WT (S2Ma)

- Reproduction of the good results obtained at S3Ch
- Improvements of the control strategy (“method” for adaptive control gain)
- Qualification of the “robustness” of the CL control strategy

Examples:

- Studied cases: M=0.82 \( \alpha = 3.5^\circ \) (buffet) or polar with continuous variation of \( \alpha \)
- 1 driving signal for the synchronous command of Fluidic VGs
- Actuator command estimated in real time from the analysis of the unsteady pressure sensors data
Demonstration of CL Control in an “industrial type” WT (S2Ma)

- M=0.82 and $\alpha=3.5^\circ$ (buffet)
- Strategy based on the RMS fluctuation pressure @ TE
  - **Fixed** feedback gain (manually)

After a transient time, the control command converged to a fixed value.

Unsteady pressure fluctuations considerably decreased
- Mean pressure value increased
  $\Rightarrow$ Strong effect on the flow separation in this area
Demonstration of CL Control in an “industrial type” WT (S2Ma)

• $M=0.82$ and $\alpha=3.5^\circ$ (buffet)
• Strategy based on the RMS fluctuation pressure @ TE
  • Adaptive feedback gain (using a gradient method)

![Command VS Time](image1)

- Period required to adapt the feedback gain

![Unsteady Pressure VS Time](image2)

- Adaptation of the gain
  $\Rightarrow$ Command modification
  $\Rightarrow$ Sequence of transient states on the pressure distribution (RMS and Mean)
Demonstration of CL Control in an “industrial type” WT (S2Ma)

- $M=0.82$ and $\alpha=3.5^\circ$ (buffet)
- Strategy based on the RMS fluctuation pressure @ TE
  - Adaptive feedback gain (using a gradient method)

$\Rightarrow$ Demonstration of feasibility but very difficult practice implementation
  - Example of “Oscillating” Fluidic VG command

$\Rightarrow$ Periodic oscillation of the command between 2 states (with and without any blowing)
Demonstration of CL Control in an “industrial type” WT (S2Ma)

- $M=0.82$ and continuous variation of $\alpha$ [0° $\Rightarrow$ 6° $\Rightarrow$ 0°]
- Strategy based on the RMS fluctuation pressure @ TE
  - Fixed feedback gain and starting from activated CL control

$\Rightarrow$ Qualification of the robustness of the CL control strategy

In such way, the command adapts to the Buffet states

No Buffet $\Rightarrow$ Strong Buffet
Demonstration of CL Control in an “industrial type” WT (S2Ma)
- $M=0.82$ and continuous variation of $\alpha : [0^\circ \rightarrow 6^\circ \rightarrow 0^\circ]$

$\Rightarrow$ Comparison with Baseline and continuous blowing configurations

- Similar efficiency and robustness on global and local parameters over the wide AoA range

- But in the CL case, the flow rate is “adapted” to the buffet configuration
• The ONERA BUFET’N Co project has generated a wide and relevant experimental database
  ⇒ Analysis of experimental database still on going

• Using the results of the different WTT, a closed-loop methodology for buffet control was defined using Fluidic Vortex Generator
  • Based on a quasi static approach
  • Different control architecture implemented (sensors, control laws …)
  • Demonstration of efficiency and robustness with hard point (parameters tuning)

• Perspectives in term of closed loops control :
  • Spatial approach of the control to adapt to the topology of flow separated areas
  • Integration of a energetic cost criterion (important point in the view of a potential application on a real A/C )
  • (New) investigation of dynamic closed loop control
  • Approaches based on structural data