Liner cooling system's impact on combustor acoustics

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All data and results reported in this presentation have been already published in journal paper or presented at international conferences and therefore their dissemination has been authorized by the consortium of the relevant projects.
Introduction

- Stricter and stricter NOx emissions standards for civil aero-engines
  - Implementation of lean-burning combustion systems
    - Sooner or later adopted by all manufacturers
  - Need to address thermo-acoustics issues to keep engine operation stable and safe
  - Passive damping systems are preferred with respect to active control criteria

- Multi-perforated liners
  - Reduction of air available for wall cooling
  - Advanced cooling systems such as effusion cooling
    - Angled effusion cooling
    - Double skin configuration
  - Acoustic dampers

courtesy of AvioAero – NEWAC Lean Burn combustor
Outline

1. Integration of thermal and acoustic characterization of perforated liners by means of dedicated experimental tests
   – Overall scope is to draw out a dual database describing the effects of drilling geometry and flow conditions on cooling efficiency and acoustic absorption capabilities
   – The key objective of the research is to explore possible twofold design guidelines for efficient effusion cooled liners with acoustic damping capabilities

2. Assessment of the role and impact of multi-perforated liner in the prediction of stability of thermoacoustics modes
   – Definition of a numerical model to accurately represent liner wall impedance

3. Aeroacoustics LES investigation to go beyond linear regime of acoustic forcing
Part I

Investigation on acoustics/thermal behaviour of effusion liners
Definition of test matrix

- Reference geometry is a typical angled effusion cooling perforation
  - 7 geometries considered
  - Guidelines for test matrix definition

### Geometric parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holes diameter</td>
<td>D</td>
<td>[mm]</td>
</tr>
<tr>
<td>Perforation Porosity</td>
<td>( \sigma )</td>
<td>[%]</td>
</tr>
<tr>
<td>Perforation pattern - Sx/Sy</td>
<td>( \Sigma )</td>
<td>[-]</td>
</tr>
<tr>
<td>Holes tilting</td>
<td>( \alpha )</td>
<td>[°]</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>t</td>
<td>[mm]</td>
</tr>
<tr>
<td>Hole length</td>
<td>L</td>
<td>[mm]</td>
</tr>
</tbody>
</table>
Final test matrix

- **Fluidodynamics conditions**
  - Ambient conditions
  - Acoustic test
    - $M_{\text{grazing}}$ up to 0.10
    - $M_{\text{bias}}$ up to 0.13
  - Thermal tests
    - Velocity Ratio (VR) up to 5

<table>
<thead>
<tr>
<th></th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
<th>G6</th>
<th>G7</th>
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<tr>
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<td>[-]</td>
<td>1</td>
<td>0.8</td>
<td>1.25</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>$\alpha$</td>
<td>[°]</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\sigma$</td>
<td>[%]</td>
<td>1.82</td>
<td>1.17</td>
<td>2.84</td>
<td>2.84</td>
<td>1.16</td>
<td>1.82</td>
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<td>14</td>
<td>14</td>
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<tr>
<td>$L/D$</td>
<td>[-]</td>
<td>5</td>
<td>6.25</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>[-]</td>
<td>1.24</td>
<td>1.24</td>
<td>1.24</td>
<td>1.24</td>
<td>1.35</td>
<td>1.93</td>
</tr>
</tbody>
</table>
Acoustic test rig

- Tubular acoustic test rig based on two-source multi-microphone technique
  - Measurement of acoustic damping in the linear regime and in the planar wave frequency range
    - 200 Hz – 1500 Hz
  - Data presented in terms of Helmholtz number
    » Constant perforation length $L_p$ for all geometries

![Geometrical features table]

<table>
<thead>
<tr>
<th>Geometrical features</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{\text{main duct}}$</td>
<td>130 [mm]</td>
</tr>
<tr>
<td>$t$</td>
<td>5 [mm]</td>
</tr>
<tr>
<td>$L_{\text{total}}$</td>
<td>5.5 [m]</td>
</tr>
<tr>
<td>$\Phi_{\text{speaker ducts}}$</td>
<td>35 [mm]</td>
</tr>
<tr>
<td>$f_{\text{cuton}}$</td>
<td>1500 [Hz]</td>
</tr>
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</table>

![Fluidynamics conditions table]

<table>
<thead>
<tr>
<th>Fluidodynamics conditions</th>
<th>$M_{\text{grazing}}$</th>
<th>$M_{\text{bias}}$</th>
</tr>
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<tbody>
<tr>
<td>0.02</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

$$He = \frac{2\pi f L_p}{c}$$
Acoustic test rig
Measured acoustic parameters

- Experimental results are mainly reported in terms of EDC
  - Energy Dissipation Coefficient
    - According to Heuwinkel et al. (2010) definition
- Two source technique
  - Cannot neglect the transmitted acoustic waves $t^+$ and $t^-$
  - Two-side acoustic forcing with respect to grazing flow direction
    a. concordant
    b. discordant

Reflection
$$R^+ = \frac{P_{1a}P_{2b} - P_{1b}P_{2a}}{P_{1a}P_{2b} - P_{1b}P_{2a}}$$
$$R^- = \frac{P_{2b}P_{1a} - P_{2a}P_{1b}}{P_{1a}P_{2b} - P_{1b}P_{2a}}$$

Transmission
$$t^+ = \frac{P_{2a}P_{2b} - P_{2b}P_{2a}}{P_{1a}P_{2b} - P_{1b}P_{2a}}$$
$$t^- = \frac{P_{1a}P_{1b} - P_{1b}P_{1a}}{P_{1a}P_{2b} - P_{1b}P_{2a}}$$

Absorption
$$EDC^\pm = 1 - \left( \frac{(1 \mp M)^2}{(1 \pm M)^2} \right) \left| R^\pm \right|^2 \left| t^\pm \right|^2$$
Dependence on Strouhal number

\[ St = \frac{f D_J}{V_J} \]
Acoustic results

- Reference geometry G1
  - Dependence on frequency

- Analysis of results by looking at normalized averaged EDC+
  - \( \text{EDC}^+_{\text{REF}} \) is the acoustic damping of smooth channel
  - Frequency range 360Hz - 560Hz
Effect of flow conditions - Grazing

- Influence of Grazing flow Mach number
  - As confirmed in other studies, $M_{\text{grazing}}$ has a reduced effect on EDC
  - No appreciable impact of geometry on such dependence
Effect of flow conditions - Bias

- Influence of Bias flow Mach number
  - A reduction of acoustic damping properties is confirmed when bias flow increases
  - At higher bias flow the plate behaves like a rigid wall
Effect of inclination angle

- Normal holes plate shows a slight greater absorption
  - Effect is more pronounced at lower bias flow
  - A positive inclination angle modifies the relation between EDC+ and EDC-
    - High grazing flow
      - Inclined holes report a non symmetric behavior when increasing Bias flow
      - EDC- always greater than EDC+ for normal holes
Effect of geometric features

- Angled geometries are considered separately
  - Comparison of geometries with different features but same porosity

\[ \sigma = 1.82\% \]

- No appreciable effect can be ascribed to perforation pattern

\[ \sigma = 2.86\% \]

- No significant effect can be ascribed to hole diameter

- Same porosity
- Same diameter
- Different pattern

- Same porosity
- Same pattern
- Different diameter
Data reduction

- Porosity is the only relevant geometric parameter affecting acoustic absorption

- For each Grazing flow level, a clear trend with respect to porosity is observed through a relation with Bias flow Mach number.
Data reduction

- A polynomial law correlates EDC with porosity for each bias Mach number

\[
\frac{\sigma^\theta}{M_{bias}}
\]

- The proposed parameter correlates with acceptable accuracy at each grazing flow level
  - \(\theta > 1\)
Measurements of thermal efficiency

- **Objectives of experimental tests**
  - Adiabatic effectiveness measurements using Pressure Sensitive Paints technique
  - Overall effectiveness using thermocouples inside thermal test sample
  - Same geometry test matrix of acoustics tests (planar plates)
  - 6 Velocity Ratio values for each test sample (VR range 0.5-5)
  - Effect of free-stream turbulence investigated

- **Open loop, blowing type test rig**
  - Square main duct (100x100mm²) with constant section
  - Interchangeable passive turbulence manipulator
  - Effusion array fed by a plenum chamber with air or nitrogen (pressure tank)
Thermal test rig

**Front view of test rig**
- Geometry G1 coated with PSP
- Passive turbulence manipulator

**Rear view of test rig without plenum chamber**
- 8 thermocouples inside test plate to evaluate overall effectiveness
Experimental technique

- Adiabatic effectiveness (2D distributions)
  - Pressure Sensitive Paint (PSP) technique based on heat and mass transfer analogy (Hp: Le_t ≈ 1)
  - Mainstream and coolant at ambient temperature

\[ \eta_{aw} = \frac{T_{main} - T_{aw}}{T_{main} - T_{cool}} \equiv \frac{C_{main} - C_w}{C_{main}} = 1 - \frac{P_{O_2;fg}/P_{O_2;r}}{P_{O_2;air}/P_{O_2;r}} \]

- 1st test: Air for main and N_2 for cooling line
- 2nd test: Air for main and cooling lines

**Raw intensity images**

- Tracer N_2 image (1st test)
- Ref image (no flow)
- Air image (2nd test)

**Partial pressure of oxygen**

- 1st test
  \[ P_{O_2;fg} / P_{O_2;ref} \]

- 2nd test
  \[ P_{O_2;air} / P_{O_2;ref} \]

**Calibration curve**

\[ \frac{P}{P_r} = f \left( \frac{I_f}{I} \right) \]
Experimental technique

- Overall effectiveness (local values)
  - Evaluated using up to 8 thermocouples inside thermal test sample
  - Mainstream was heated up by means of an electric heater (24kW) up to approximately 60°C
  - Coolant temperature approximately at 18°C

\[ \eta_{ov} = \frac{T_{\text{main}} - T_{\text{wall}}}{T_{\text{main}} - T_{\text{cool}}} \]

- Evaluated using TC in the main flow before the test plate
- TCs inside thermal test sample
- Evaluated using TC in the plenum chamber

G5: TCs location (T_{wall})
Results: effect of free stream turbulence

$Tu = 17\%$ (first row of holes)
decay to 5% (last row of holes without coolant injection)

$Tu = 1.5\%$ (first row of holes)
- Laterally average adiabatic effectiveness distributions
  - VR 0.5 and VR1 have similar adiabatic effectiveness values
  - Similar behaviour for all geometries
- Overall effectiveness distributions along centerline
  - $\eta_{ov}$ increases as the velocity ratio is increased (common to all geometries)
Overall test matrix results: averaged data

- In order to perform general comparisons among different geometries results are recast in terms of spatially averaged adiabatic and overall effectiveness for all geometries varying velocity ratio
  - Porosity ($\sigma$) is a direct measure of coolant consumption at each VR level

<table>
<thead>
<tr>
<th>$\sigma$=1.16%</th>
<th>$\sigma$=1.82%</th>
<th>$\sigma$=2.84%</th>
</tr>
</thead>
<tbody>
<tr>
<td>G2-G5-G7</td>
<td>G1-G6</td>
<td>G3-G4</td>
</tr>
</tbody>
</table>

![Graph showing effectiveness vs. VR for different geometries](image)
Averaged results: effect of hole pattern

- Comparison between G1 and G6
- Adiabatic and overall effectiveness average values
  - The influence of pattern aspect ratio is not appreciable in all range of investigated velocity ratio number

Spatially averaged adiabatic and overall effectiveness

![Graph showing adiabatic and overall effectiveness comparison between G1 and G6](image)
Averaged results: effect of hole inclination

- Comparison between G2 and G7

- Spatially averaged adiabatic effectiveness
  - For lower VR, G2 (α=30°) shows better wall protection (coolant jets remain attached to the wall)
  - For high velocity ratio number the effect of hole inclination angle seems to disappear

- Overall effectiveness
  - For low velocity ratio G2 and G7 have same thermal efficiency
  - For VR=3 and VR=5 normal angle shows a slightly greater efficiency

![Spatially averaged adiabatic and overall effectiveness](image)
Averaged results: effect of hole inclination

- Thermal efficiency is strongly dependent on engine operating conditions: values are then strictly valid for tested conditions only
  - Mainstream flow does not have a 3D flow field
    - High jet penetration, typical of 90° hole angle, could interact with the tridimensional flow field of combustor reducing coolant wall protection
    - Jet-Mainstream mixing is recorded as near wall coolant in the simple configuration of the test rig

- No heat transfer by thermal radiation is considered
  - 30° holes induce a greater heat transfer augmentation on gas side than 90° holes
    - Data computed by a correlative post-processing of measured data
    - If $T_{wall} > T_{aw}$ an higher HTC on the gas side may have a beneficial effect on liner temperature
Data reduction

- In order to point out the actual thermal performances normalizing the weight of coolant consumption, a data reduction strategy was carried out.
  - Due to the necessity to include gas side effects to perform a proper comparison with normal hole geometry (G7), only angled perforations were considered.
- The required correlation parameter should include:
  - Effect of porosity
    - Direct impact on film effectiveness and heat transfer
      - $\sigma$
  - Effect of coolant consumption
    - Coolant to mainstream Blowing Ratio x Perforation Porosity
      - $BR \cdot \sigma$
  - Contribution of convective heat transfer inside holes (heat sink effect)
    - Length-to-diameter ratio of the hole
      - $L/D$

$$(BR \cdot \sigma)^a \cdot \sigma^b \cdot (L/D)^c$$
Data reduction

- A good data reduction is obtained with positive values for the three parameters
  - $a > 0$ – $b > 1$ – $c > 1$
  - $b = c$, $b > a$

![Graph showing data reduction effectiveness]
Impact on combustor design

- Looking at the two reduced sets of experimental data it’s possible to point out some general design guidelines
  - Angled geometries
- Acoustic damping
  - For each grazing flow Mach number, it can be obtained an increase in EDC through a reduction of Bias Mach flow and an increase in perforation porosity
    - A lower limit on Bias Mach number exists after which EDC starts to decrease
Impact on combustor design

- Thermal effectiveness
  - An improvement of cooling effectiveness can be obtained by increasing plate porosity, Blowing Ratio or hole aspect ratio
    - In order to have an improvement in overall effectiveness with same coolant consumption, an increase in porosity should be carried out by reducing coolant exit Mach number (Bias)
      - Reduction of ΔP/P across the plate
Geometry G1 represents a typical effusion cooling design with angled holes

- $\sigma = 1.8\%$
- Reference operating conditions
  - $BR = 3$
  - $M_{bias} = 0.15$
Impact on combustor design - Example

- A possible twofold improvement can be obtained with an increase of perforation porosity
  - To maintain a fixed coolant mass flow a correspondent reduction of $\Delta P/P$ is required

- Geometry G4
  - $\sigma = 2.6\%$
  - Same hole diameter and length
  - Increase of total hole number

Operating conditions
- $BR \cdot \sigma \approx \text{constant}$
- Reduction of BR ($M_{bias}$)
  - $BR \approx 2.1$
  - $M_{bias} \approx 0.1$
Multiperofrated liner design

- From a design viewpoint, a modification of drilling geometry such as that from G1 to G4 with a fixed coolant mass flow, can be obtained by reducing $\Delta P/P$ across the damping/cooling plate.

- To respect overall combustor pressure drop, possible practical design solutions are:
  - Double skin configurations
  - Turbulators on the cold side

- Similar conclusions and configurations have been already discussed in some recent published studies:
  - Behrendt and Gerendas, 2012
  - Jayatunga et al., 2012
  - Rupp et al., 2011
  - Heuwinkel et al., 2010
  - Bahayaraju et al., 2010
Concluding remarks

- It’s important to stress on the assumptions and hypothesis behind the two experimental surveys
  - Acoustics damping
    - Ambient temperature and pressure conditions
    - Linear planar wave regime
  - Overall thermal effectiveness
    - No radiative heat transfer is considered
      - May have a significant impact on relative weight between heat sink effect and adiabatic film effectiveness
    - Simplified flow-field on the gas side

- Geometry G7 with 90° holes
  - Additional investigation are required on the thermal side
    - Effect of actual combustor flow-field
Part II

Impact of effusion liners on thermoacoustic behavior – linear stability
Impact on thermoacoustic behavior – linear stability

○ Numerical analysis of the effect of multi-perforated liners on the thermoacoustic behavior of a full annular aero-engine lean combustor

  – Assessment of different numerical models for multi-perforated liner adsorption
    • Validation with measured data
      – Typical geometrical configurations of aero-engine combustors
    • Comparisons in terms of Energy Dissipations Coefficient

  – Evaluation of the effect of multi-perforated liners on the stability properties of the system
    • Passive simulation (without flame)
    • Active simulation
    • Comparison with experimental data

  – Numerical tool:
    • 3D FEM simulation with COMSOL Multiphysics (acoustic module)
Mathematical model

- The following inhomogenous Helmholtz equation is solved:

\[ \frac{\lambda^2}{c^2} \hat{p} - \rho \nabla \cdot \left( \frac{1}{\rho} \nabla \hat{p} \right) = -\frac{\gamma - 1}{c^2} \lambda \hat{q} \]

  - Generic quantity: \( \phi'(t) = Re[\phi \exp(i\omega t)] \)
  - \( \lambda = -i\omega \rightarrow \) eigenvalue

- Frequency domain analysis
  - Response to an external forcing

- Eigenfrequency analysis
  - Thermoacoustic instability analysis
  - Complex eigenvalues: \( \omega = \omega_R + i\omega_I \)
    - Real part: resonant frequency
    - Imaginary part: growth rate \( g = -\omega_I \)

NOTE: the presence of mean flow is not accounted for in this formulation.

The following phenomena are not considered:
- Dissipation
- Effect on acoustic propagation
Assessment of multi-perforated liner modeling

• Numerical model
  – COMSOL Multiphysics
    • Solution of the Helmholtz equation with an acoustic forcing
      – Frequency domain
    • Presence of mean flow not considered
    • Liner modeled as an internal impedance
      – Interface between two different domains
  – Boundary conditions
    • Acoustic impedance
      – Liner
      – Plenum foam (exp measured)
      – Right and left ends (exp measured)
    • Acoustic pressure source
      – 4 speakers

Objective:
• Comparison between numerical results and experimental measurements in terms of acoustic adsorption.
• Evaluation of the capabilities of the different models.
Assessment of multi-perforated liner modeling

• Liner geometries

  – Three different geometries have been considered

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Porosity</th>
<th>Tilting angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>G2</td>
<td>0.0116</td>
<td>30 deg</td>
</tr>
<tr>
<td>G3</td>
<td>0.0284</td>
<td>30 deg</td>
</tr>
<tr>
<td>G7</td>
<td>0.0116</td>
<td>90 deg</td>
</tr>
</tbody>
</table>

  – Simulations were performed varying:
    • Frequency of the acoustic source
    • Bias flow Mach number
      – Influences the value of liner impedance
Numerical models

• Liners are modeled by the means of internal impedance
• Liner impedance modeling:
  – Howe model (HM) [1]
    • The bias flow velocity is taken into account by means of the Strouhal number.
    • The computation of wall impedance is based on the Rayleigh conductivity.
      \[ K_R = 2a(\Gamma + i\Delta) \quad \text{and} \quad Z_W = \frac{i\omega \rho d^2}{K_R} \]
  – Modified Howe Model (MHM) [2]
    • Also accounts for plate thickness
      \[ K_R = 2a \left( \frac{1}{\Gamma + i\Delta} + \frac{2h}{\pi a} \right)^{-1} \]

References:
Numerical model

- Liner impedance modeling:
  - Bauer model (BM)
  - Considers the presence of both bias and grazing flow.
  - Gives directly the value of the wall impedance.

\[
Z_w = \rho c \left[ \frac{1}{C_D} \sqrt{\frac{8\mu k}{\rho c}} \left(1 + \frac{h}{2a}\right) + \frac{\beta M_g}{\sigma} + \frac{\alpha M_b}{\sigma C_D} + \frac{ik}{\sigma C_D} (h + \delta F_{int}F_d) \right]
\]

- \( K_R \) = Rayleigh conductivity
- \( Z_w \) = wall impedance
- \( a \) = hole radius
- \( k \) = wave number
- \( h \) = plate thickness
- \( C_D \) = discharge coefficient
- \( M_g \) = Mach number of grazing flow
- \( M_b \) = Mach number of bias flow
- \( F_{int}, F_d \) = flow effect in acoustic reactance and interaction between holes

References:
Assessment of multi-perforated liner modeling

• Results: G7
  – The geometry is symmetric

• MHM and BM (Cd=0.7) are in good agreement with experimental data.
  – The discharge coefficient in the BM greatly influences the adsorption properties
  – A suitable value of $C_D$ has to be used

• At low Bias flow Mach number the HM is not able to follow the trend of experimental data
  – The plate thickness influences the adsorption properties at low bias flow Mach numbers and high frequencies
Assessment of multi-perforated liner modeling

• Results: G2
  – The geometry has tilted holes

• MHM and BM are in good agreement with experiments.

• The value of $C_D$ greatly influences the acoustic absorption:
  – In this case $C_D = 0.7$ could not be the best choice.
  – The different behavior of Bauer’s model with respect to G7 is probably due to the non-symmetric characteristics of this geometry which are not accounted for in the impedance expressions.

• HM and MHM gives very different results at low Bias flow Mach numbers and high frequencies.
  – The term representing plate thickness has a great influence.
Assessment of multi-perforated liner modeling

○ Results: G3
  - The geometry with tilted holes and the highest porosity
    • The same conclusions of G2 can be drawn
    • The models are able to follow the adsorption enhancement due the increase of porosity
  - **MHM** appears the best model in reproducing the acoustic absorption of multi-perforated liners
Simulation of a full annular Lean Burn combustor (AvioAero)

- **Geometry**
  - Annular combustor composed by 18 elementary burners
  - Advanced lean-burn injection system
    - **PERM** (Partially Evaporating and Rapid Mixing)
    - Partially premixed flame

- The presence of liquid fuel makes the description of the coupling between heat release rate and acoustic field very complex
  - What are the most important driving mechanisms?
  - A proper FTF has to be developed
Simulation of a full annular Lean Burn combustor (AvioAero)

• Numerical model
  – Main geometry simplifications
    • Double swirler airblast
    • Bleeding ports
    • Fuel line removed
  – Flame region with conical shape
    – Obtained from a the RANS simulation of the single sector using a CO mass fraction iso-contour

– Acoustic boundary conditions:
  • Inlet and outlet: plenum (p’=0)
  • Internal and bounding walls: hard wall (u’=0)
  • Multi-perforated liners: MHM internal impedance
    – In the previous analysis the MHM has been proved the most reliable model in all operating conditions
Simulation of a full annular Lean Burn combustor (AvioAero)

• Numerical model
  – The single sector geometry has been replicated obtaining the full annular configuration
  – Two different cases analyzed
    • Passive simulation
      – Without flame
      – Evaluation of the effect of multi-perforated liners on the acoustic properties of the combustor.
    • Active simulation
      – A Flame Transfer Function has to be activated in the flame region
      – Evaluation of the effect of multi-perforated liners on the thermoacoustic stability properties of the modes
  • Experimental measurements of resonant frequencies in the flame tube are available for both cases

<table>
<thead>
<tr>
<th></th>
<th>Passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{in}$ [K]</td>
<td>420</td>
<td>550</td>
</tr>
<tr>
<td>$T_{ft}$ [K]</td>
<td>420</td>
<td>from CFD</td>
</tr>
<tr>
<td>$p$ [bar]</td>
<td>4.8</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Simulation of a full annular Lean Burn combustor (AvioAero)

- Passive simulation
  - Each mode mainly affects a particular region of the combustor
  - Comparison with experiments
    - Resonant frequencies measured in the flame tube are well predicted by the FEM solver
    - The numerical simulation predicts a great number of resonant frequencies
  - Effect of multi-perforated liner
    - The multi-perforated liner makes the system more stable
    - The effect depends on the acoustic mode considered

NOTE: Values of frequency and growth rate normalized using the first resonant frequency.
Simulation of a full annular Lean Burn combustor (AvioAero)

- Passive simulation

- The dissipation effect is negligible for modes mainly affecting the diffuser zone
Simulation of a full annular Lean Burn combustor (AvioAero)

• Passive simulation

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The effect of the adsorption properties of the multi-perforated liner is evident for modes acting in the flame tube zone or annulus region.
Numerical model

○ Flame Transfer Function
  - Typical formulation of premixed gaseous flames
    \[
    \frac{\dot{q}}{q} = -K \frac{\bar{u}_i}{\bar{u}_i} \exp(-i\omega \tau_{conv}) \quad (1)
    \]
    - Driving mechanism: equivalence ratio oscillations
    - Liquid fueled combustors
      - Delay time due to evaporation and mixing

  - Airblast diffusion flame (Eckstein [6])
    - Quasi-steadiness assumption
    - Low Frequency analysis
      \[
      \frac{\dot{q}}{q} = \psi \frac{\bar{u}_i}{\bar{u}_i} \exp(-i\omega \tau_{conv}) \quad (2)
      \]
    \[\tau_{conv} = \frac{\xi}{U_{mean}}\]

Simulation of the full annular combustor (AVIO)

- **Active simulation**
  - FTF 1 - calibration of $K$ to match the first experimental resonant frequency
    - Typical FTF for premixed flames:
      $$\hat{q} \overline{q} = -K \hat{u}_i \overline{u}_i \exp(-i\omega \tau_{conv})$$
    - Not able to completely describe the complex behavior of liquid fueled combustors

NOTE: The multi-perforated liners makes the system more stable
Simulation of a full annular Lean Burn combustor (AvioAero)

• Active simulation

– The modes that appear unstable are the ones related to the flametube
Conclusions

• Main achievements
  – In this work a thermoacoustic analysis of an aero-engine combustor equipped with an advanced lean burn injector has been performed with the main aim of determining the effects of multi-perforated liner modelling on the numerical analysis of the stability properties of the combustor.

• Assessment of numerical models for multi-perforated liner impedance:
  – The Modified Howe Model (MHM) appears to be the most promising model
  – The Howe’s model is not able to follow the trend of experimental results especially at low bias flow Mach numbers and high frequencies
    • The plate thickness has a the great influence in these conditions.
  – The Bauer’s model could give good results but a proper calibration of the hole discharge coefficient appearing in the formulation is needed, especially when asymmetric geometries are considered where the fluid dynamic discharge coefficient could not be the best choice.

• Application to aeroengine full annular combustor
  – Both passive and active cases showed the stability effect exerted by the perforated liners which contribute to acoustic energy dissipation preventing the evolution of unstable modes.
Part III

Aeroacoustics LES investigations
Aeroacoustics LES investigations

- To investigate the impact of an increasing forcing amplitude, up to non linear regime, a LES CFD study was carried out

- Objectives
  - Estimate the acoustic damping permitted by the perforated plate with bias flow under realistic conditions
  - Verify acoustic-aerodynamic mutual coupling
  - Investigate linear regime limits
Code and Methodology

- Open source finite volume toolbox Open-FOAM®
  - Weakly compressible segregated pressure based solver (PISO loop)
    - Backward Euler scheme for time integration
    - Time steps selected to limit Courant number below 0.5
      - Improve solver stability
      - Second order centered discretization scheme
  - SGS modelling
    - Smagorinsky and WALE tested
      - No sensible differences observed
    - Sub-grid viscosity corrected near walls with Van Driest damping
  - Acoustics on domain boundaries
    - Navier-Stokes Characteristic Boundary Conditions (NSCBC) for partially/fully reflecting boundaries
    - Linear Relaxation Method (LRM) for incoming waves
      - Acoustic forcing
Code and Methodology

- Non and partially reflective boundary conditions (Bianchini, 2011)
  - Navier Stokes Characteristic Boundary Conditions NSCBC
  - Analysis of characteristic waves moving across the boundary
    - Incoming waves: fixed using Linear Relaxation Method (LRM)
    - Outgoing waves: extrapolation of solution from the internal domain exploiting Local One Dimensional Inviscid (LODI) hypothesis
  - Integration of Navier Stokes Equations in Characteristic form to estimate primitive variables
    - Introduction of transverse and viscous terms

\[
L_{\phi} = \sigma_{\phi}(\Phi - \Phi^T)
\]

\[
L_{\phi} = f\left( \frac{\partial u}{\partial n}, \frac{\partial p}{\partial n}, \lambda, \rho, c \right)
\]
Numerical acoustic forcing waves

- Sinusoidal far-field pressure wave was applied in the LRM to generate the desired acoustic forcing.
- Multi-harmonic pressure wave employed to impose the forcing in the entire frequency range in a single computation.

\[ p^\infty = p_{\text{REF}} + \sum_{i=1}^{N} p_{0,i}\cos(2\pi f_i t + \phi_i) \]

- Verification of multi-harmonic strategy
  - 90° case
    - Three single frequencies computations
      - 700, 1000, 1300 Hz
    - Double frequencies
      - 1000 and 1300 Hz
    - Narrow banded 4 frequencies
      - 550, 700, 850, 1150 Hz
Code and Methodology

- Numerical set-up
  - Acoustic and aerodynamic analysis
  - Bi-periodic domain (in-line arrangement)
    - Aerodynamic and acoustic within each hole is the same
  - Acoustic BC
    - Fully-reflecting inflow velocity conditions
    - Non-reflecting fluctuating pressure outflow
  - Post-processing
    - Multi-microphone technique (4 virtual microphones)
  - Mean crossflow in streamwise periodic configuration
    - Additional source term in momentum equation
      - Feedback with mean velocity to maintain desired level of crossflow
      - Uniform source in JCF domain
      - Under-relaxation factor to stabilize transient ramps
Assessment of methodology accuracy

- Numerical simulation of the Bellucci et al. [5] test case

Back plate

P-

P+

Acoustic source

Flow conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$U_b$</td>
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<tr>
<td>$T_\infty$</td>
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<tr>
<td>$p_\infty$</td>
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<td>$\Delta p$</td>
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Analysis of acoustic forcing magnitude

- Considered geometries
  - Geometry | Porosity | Inclination angle
  - G2       | 0.0116   | 30 deg
  - G7       | 0.0116   | 90 deg

- Flow conditions
  - Mach bias = 0.05 and 0.1
  - Mach grazing = 0 for G7 and 0.08 for G2

- Acoustic forcing
  - Pure tone 1000 Hz
Free jets aerodynamics

- A-posteriori validation of LES filter width
  - Modeled kinetic energy / Resolved kinetic energy < 0.25
Free jet aerodynamics

- Proper Orthogonal Decomposition of near hole pressure field showed:
  - Jet shear layer is composed of aligned and misaligned vortex rings
    - Unsteady flow structures responsible for acoustic damping
  - Chosen frequency forcing does not interact with principal free jet modes
Acoustic forcing levels

4 levels of increasing acoustic forcing SPL are considered
When dP/ΔP is below 10% linear regime is expected

<table>
<thead>
<tr>
<th>α (°)</th>
<th>Ma&lt;sub&gt;b&lt;/sub&gt;</th>
<th>ΔP (Pa)</th>
<th>SPL (dB)</th>
<th>dp/Δp (%)</th>
<th>dP/ΔP (%)</th>
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<tr>
<td>90</td>
<td>0.1</td>
<td>1426</td>
<td>134</td>
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<td>2.5</td>
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<tr>
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<td>0.05</td>
<td>382</td>
<td>119</td>
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<td>0.1</td>
<td>1961</td>
<td>129</td>
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<tr>
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</table>

Acoustic forcing amplitude

Mean pressure drop across the hole

ΔP

TANGO WORKSHOP – ANSALDO ENERGIA

September 18th 2015

Antonio Andreini
Impact of acoustics on aerodynamic (G7-Maₜ=0.1)

- Aerodynamic is strongly influenced by acoustic forcing also at high Maₜ
- No flow inversion appears even at 160 dB (dp/Δp>100%)
Impact of acoustics on aerodynamic (G2-Ma_b=0.05)

- Far-field aerodynamic is not influenced by forcing phase
- No inversion at max stable forcing 150 dB (dp/Δp≈100%)
Aerodynamic effects on acoustics (G7-Ma_b=0.05)

- Aerodynamic is strongly influenced by acoustic forcing
- Only at 160 dB (dp/Δp>300%) flow inversion appears
Forcing amplitude effects on acoustics

- Forcing amplitude shows not relevant effects on acoustic absorption
  - Low forcing level
    - Effect of turbulent noise and numerical dissipation become higher
  - Flow inversion reduces absorption
Summary and conclusions

- LES is exploited to compute acoustic absorption of perforated plates with bias flow

- High computational cost is rewarded by deep insight on fundamental phenomena characterizing acoustic damping

- Variable acoustic forcing showed:
  - Large effects on jet aerodynamics already for $dp/\Delta p<10\%$
  - Small effects on jet acoustics even at $dp/\Delta p>100\%$

- Absorption is affected only in case of flow reversal through the hole
  - Linear regime is guaranteed at least up to $dp/\Delta p=300\%$
References


7. A. Andreini, B. Facchini, A. Giusti, F. Turrini, (2014), Assessment of Flame Transfer Function Formulations for the Thermoacoustic Analysis of Lean Burn Aero-engine Combustors, ENERGY PROCEDIA (ISSN:1876-6102), 1422 - 1431, 45
