Design of silent flow duct systems for aircraft applications

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Motivation: flow duct systems in aircraft
Outline

• Motivation: flow duct systems in aircraft
• Acoustic network models and multi-port characterization
• Aeroacoustic characterization of ECS components: trim air valve
• Liner impedance eduaction using multi-port models
• Conclusion
Acoustic network models and multi-port characterization
Acoustic network models
Acoustic propagation through flow ducts

Acoustic pressure field in a straight duct with rigid walls and uniform flow

- sum of duct modes:

\[ p'(\omega, x, y, z) = \sum_{m,n} \Psi_{mn}(x, y) (p^+_{mn}(\omega) e^{-j k^+_mn z} + p^-_{mn}(\omega) e^{j k^-_mn z}) \]
Acoustic propagation through flow ducts

Acoustic pressure field in a straight duct with rigid walls and uniform flow

- sum of duct modes:

\[ p'(\omega, x, y, z) = \sum_{m,n}^{\Psi_{mn}(x,y)} (p_{mn}^+(\omega) e^{-jk_{mn}^+z} + p_{mn}^-(\omega) e^{jk_{mn}^-z}) \]

Axial wavenumbers

Modal amplitudes

Cut-off frequency

- \( f < f_c \): evanescent (cut-off) mode
- \( f > f_c \): propagating (cut-on) mode
- the plane mode is always cut-on

\( f = 0.36 f_c \) \hspace{1cm} \( f = 0.22 f_c \)
Acoustic network models
Acoustic multi-port models

Consider a duct component mounted between ducts with rigid walls, sufficiently far from other duct components, sources, ...

- the acoustic field in the duct is dominated by cut-on modes
- all cut-off modes can be neglected at the inlet/outlet of the component

inlet duct: acoustic field described by the modal amplitude vectors $p_i^+$ and $p_i^-$

outlet duct: acoustic field described by the modal amplitude vectors $p_o^+$ and $p_o^-$
Acoustic multi-port models

Multi-port model

\[
\begin{bmatrix}
    p^+_o(\omega) \\
    p^-_i(\omega)
\end{bmatrix} =
\begin{bmatrix}
    T^+(\omega) & R^-(\omega) \\
    R^+(\omega) & T^-(\omega)
\end{bmatrix}
\begin{bmatrix}
    p^+_i(\omega) \\
    p^-_o(\omega)
\end{bmatrix}
+ \begin{bmatrix}
    p^+_o(\omega) \\
    p^-_o(\omega)
\end{bmatrix}
\]

**Inlet duct:** acoustic field described by the modal amplitude vectors $p^+_i$ and $p^-_i$.

**Outlet duct:** acoustic field described by the modal amplitude vectors $p^+_o$ and $p^-_o$.

Complete description of the aeroacoustic behavior, independent of upstream and downstream components.
Acoustic multi-port characterization

Multi-port characterization

\[
\begin{bmatrix}
  p^+_o(\omega) \\
  p^-_i(\omega)
\end{bmatrix} =
\begin{bmatrix}
  T^+(\omega) & R^-(\omega) \\
  R^+(\omega) & T^-(\omega)
\end{bmatrix}
\begin{bmatrix}
  p^+_i(\omega) \\
  p^-_o(\omega)
\end{bmatrix} +
\begin{bmatrix}
  p^+_s(\omega) \\
  p^-_s(\omega)
\end{bmatrix}
\]

1. passive characterization: scattering matrix [2N x 2N]
   • 2N (or more) measurements with external excitation

2. active characterization: source vector [2N x 1]
   • 1 additional measurement without external excitation
Acoustic multi-port characterization

Modal decomposition: 2N (or more) microphones

\[ \min \left( \sum \Psi_m(x_s, y_s) \left[ p_m^+(\omega) \exp(-j k_m^+(\omega) z_s) + p_m^-(\omega) \exp(j k_m^-(\omega) z_s) \right] \right) \]

- Multiple microphone method:
  - known wavenumbers: \( k_m^\pm(\omega) = f(\omega, c_0, M_0) \)
  - linear system of equations

- Iterative modal decomposition method
  - multiple microphone method
  - correction of model parameters \((c_0, M_0)\)

Characterization of an ECS valve

Engine liner impedance eduction
Aeroacoustic characterization of ECS components: trim air valve
Environmental Control System (ECS) noise

Aeroacoustic characterization of a butterfly valve

- **Butterfly valve**: obstacle in the duct
  - partial transmission and reflection of incident acoustic waves
  - aerodynamic sound generation

- Active multi-port model

\[
\begin{pmatrix}
    p^+_o \\
    p^-_i
\end{pmatrix} = \begin{pmatrix}
    T^+ & R^- \\
    R^+ & T^-
\end{pmatrix} \begin{pmatrix}
    p^+_i \\
    p^-_o
\end{pmatrix} + \begin{pmatrix}
    p^+_s \\
    p^-_s
\end{pmatrix}
\]

Active multi-port characterization of a trim air valve

Trim air valve from an ECS
- butterfly valve
- diameter 84.9 mm
- opening angle between 0° (closed) and 90° (open)

Active multi-port characterization of a trim air valve

Microphone arrays
- 12 flush-mounted microphones
- modal decomposition up to 3900 Hz
- (0,0), (1,0) and (-1,0) modes cut-on

Active multi-port characterization of a trim air valve

Loudspeaker arrays
• 6 loudspeakers
• designed for frequencies up to 3900 Hz
• only for passive characterization

Passive multi-port model

Transmission coefficients in a quiescent medium (M = 0)

Passive multi-port model

Transmission coefficients in a moving medium \((M \approx 0,1)\)

Active multi-port model

Normalized source spectra for an opening angle of $60^\circ$ ($M \approx 0.1$)
Active multi-port model

Normalized source spectra for an opening angle of 30° (M ≈ 0,1)

Active multi-port model

Normalized source spectra for the plane mode ($M \approx 0,1$)

Advanced noise control strategies: modal filters

Advanced noise control strategies: modal filters

Liner impedance eduction
Noise control along the transmission path

- **Turbofan engine = duct system**
  - efficient transmission path for turbomachinery and combustion noise
  - noise control: acoustic wall treatments

- **honeycomb liners**
  - perforated facing sheet
  - honeycomb backing
  - characterized by their acoustic surface impedance
Liner impedance measurement

Standardized method (ISO 10534-2)  In-situ method (Dean 1974)

→ Impedance eduction methods

Two-port impedance eduction method

Acoustic pressure measurements

- iterative modal decomposition with parameter optimization
- passive two-port model: acoustic transfer matrix $[T_{\text{exp}}]$

Semi-analytical multi-port model

- least attenuated mode
  
  $[T_L] = f(k^+_z, k^-_z)$ and $k^+_z = f(Z_{\text{liner}})$

- hard wall – soft wall transitions
  
  $[T] = [T_{\text{tr}}]^{-1} \ [T_L] \ [T_{\text{tr}}]$

\[ T_L = f(k^+_z, k^-_z) \text{ and } k^+_z = f(Z_{\text{liner}}) \]
Impedance eduction of a SDOF honeycomb liner

honeycomb liner samples

• staggered perforation pattern

• 2 samples with identical specifications

Impedance eduction of a SDOF honeycomb liner

- Effect of grazing flow on the liner impedance

Impedance eduction of a SDOF honeycomb liner

- Repeatability of the results

Conclusion
Conclusion

• Flow duct systems play an important role in aircraft interior and exterior noise emissions.

• Active multi-port models can be used to characterize the acoustic behavior of duct components, to predict their influence on the system level using network modelling tools and to design performant noise mitigation strategies.

• Multi-port models can be used to characterize acoustic wall treatments, such as honeycomb liners for aircraft engines, under grazing acoustic incidence and grazing flow.