Acoustic Field Around a Transonic Cavity Flow

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Cavity Flow

- Weapon bay are used in modern aircraft:
  - UCAV.
  - F-35.

- Complex cavity flow physics:
  - Feedback loop.
  - Rossiter modes.
  - CFD needs LES, DES, SAS for this flow.

- Cavity flows are characterized by:
  - Large unsteadiness.
  - High levels of noise.
  - Complex waves/shear layer interactions.

- Leading to:
  - Structure fatigue.
  - Stealth reduction.
  - Store release variability.

Boeing X-45 Weapon Bay.

Schlieren image of a cavity flow at M=0.85. DES simulation.
Noise Analysis

- Tools commonly used for cavity flows:
  - Sound Pressure Levels (SPL)
  - Overall Sound Pressure Levels (OASPL)

- Drawbacks:
  - Applicable in wind tunnel test to a limited number of probe points.
  - The temporal fluctuations are not known.

- Application of two more advanced noise field analysis:

  - The beamforming: analysis of the entire noise field with a microphone array.
  - The wavelet transform: spatio-temporal analysis of the noise.
**CFD Solver – Core HMB3 Features**

- Control volume method
- **Parallel** - Shared and Distributed memory
- **Multi-block structured grids** - Complex geometries
- **Fully-Implicit** time marching / **Frequency** domain
- Osher, Roe, AUSM+/UP schemes for all Mach numbers
- MUSCL scheme for formally 3<sup>rd</sup> order accuracy
- Central differences for viscous fluxes
- Krylov subspace linear solver with pre-conditioning
- RANS, URANS, LES, DES, SAS, turbulence and transition models
- Actuator Disk method
- Blade Actuation, Aeroelasticity, Rotor Trimming
- Moving/Deforming grids, Sliding Planes, Overset
- Steady Hover formulation, Unsteady Wind-tunnel and Vehicle formulations
- **Adjoint Method** for computing aerodynamic derivatives
- Validation Database
- Utilities for processing data, structural models etc.
- Used by Academics and Engineers
Cavity Computations with HMB

- Key journal papers:
  - HMB is validated for cavity flows.
**Geometry & Conditions**

- **Idealised clean cavity:**
  - \( L = 3.59 \text{m} \)
  - \( L/D = 7 \)
  - \( W/D = 2 \)

- **Main parameters:**
  - \( M = 0.85 \)
  - \( \text{Re}_L = 6.5 \text{million} \)
  - SAS \( k-\omega \)
  - \( dt = 1\% \) of bay crossing time
  - 34 millions cells
Beamforming Analysis

- Use of a **microphone (sensor) array** for noise analysis:
  - Multi-spiral distribution.
  - 101 sensors.
  - 2 and 4 cavity depth from shear layer

- A grid of discrete points in space is scanned.
Beamforming Analysis

- Delay and Sum Beamforming:
  - For each of the $m$ sensors a time delay $\Delta_m$ from the source and a reference sensor (0) is calculated:

$$\Delta_m = \frac{r_m - r_0}{c}$$

- The beamformer output is given by $Z(\omega)$:

$$Z(\omega) = \mathcal{F} \left\{ \sum_{m=0}^{M-1} y_m(t - \Delta_m) \right\} = \sum_{m=0}^{M-1} Y_\omega e^{-j\Delta_m \omega}.$$  
  
  $y_m(t)$ is the signal from each sensor.

- The accuracy of the result depends on the distances computation:
  - Hypothesis on wave propagation.
Computation of Distances

Planar wave propagation:
- No matching with the BISPL.
- This hypothesis is not valid.

The velocity flowfield has to be taken into account:
- Freestream at M0.85
- The waves are transported.
Computation of Distances

1. The path from a scan point to a microphone is computed taking into account the flowfield.
2. The wave travel on a distance $d_{\text{travel}}$ at a mean velocity $c_{\text{travel}}$.
3. The equivalent distance at a speed $c$ is:

$$r_m = d_{\text{travel}} \frac{c}{c_{\text{travel}}}$$

Ideal propagation model (Arrays 2 and 4).

Full propagation model (Arrays 2 and 4).
Array Position

- Array 2 is **too close** to the cavity:
  - The shear layer is not captured.

- Array 4 has better result:
  - The shear layer is captured.
  - The middle source is not correctly localised.

- Arrays 2 and 4:
  - The two shear layer sources agree with the BISPL.
  - The **combination** give a **better vertical accuracy**.

Beamforming for different array position with full propagation model. (Doors 110 degrees)
Mode shapes

BISPL for modes 1 to 3 (Doors 110 degrees).

Beamforming for modes 1 to 3 (Doors 110 degrees).
Wavelet Transform

- A spectral decomposition of a signal shows what are the **main frequencies** but does not show **when they appear**.
- The Wavelet Transform shows the **distribution of the energy** in the **frequencies** at every instance in time.
- Give the **spatio-temporal fluctuations** of the pressure field.

Scalogram for doors at 110 degrees at aft wall lip centre.

BIW at the cavity centreplan for mode 1 at an instance in time.
Cavity Flow Pressure Fluctuations

- Nodes and antinodes.
- Phase opposition between two antinodes.
- Cavity flow tones are produced by standing waves.

BIW at the cavity centreplan.

BIW at the cavity ceiling for the store at carriage.
Cavity Flow Pressure Modulations

- BIW envelop show the peaks amplitude.
- The nodes and antinodes are more visible.
- The standing waves are modulated in time.

BIW envelop at the cavity ceiling for the doors at 110 degree.

BIW envelop at the cavity centreline
M219 Pressure Fluctuations

- M219 Cavity experiments by Nightingale et al.

- Ideal cavity.
- $M=0.85$
- $L/D=5$
- $Re_L: 6.5$ million
- 10 kulites along the ceiling
- 3 sec signal.

Standing waves.

Standing wave modulation.

Mode switching.
1. Initialisation:
   - Closed cavity flow.
   - The flow impinges the cavity ceiling.
   - A vortex forms at the cavity front.

2. Transition:
   - The front vortex grows.
   - The attachment point reaches the aft wall.

3. Shear layer development:
   - Open cavity flow.

Cavity Flow Door Opening

- The wavelet is able to **track transitory state** of the opening:
  - The **travel of the jet** is visible during transition.
  - The different door velocities show different transition strength.

Spatio-temporal fluctuations along the cavity ceiling of the cavity opening.

**Jet path**

- **Slow** - 110 deg/s
- **Medium** - 220 deg/s
- **Fast** - 440 deg/s
The mode 1 is **trigged by the transition**.

- The modes 2 and 3 noticeably increase from 70 degrees.
  - **Pacifying effect** of the doors for small angle.

Spatio-temporal fluctuations along the cavity ceiling of the cavity opening (220 deg/s) for modes 1 to 3.
Noise directivity at 2 cavity depths from the shear layer.

Sound waves are transported downstream by the flowfield.

- More noise is generated at the aft wall.
- The directivity is larger over the second half of the cavity.
- The flowfield transports the sound waves downstream.
- More noise is generated at the aft wall.

Simulation of the noise propagation with the full wave propagation model.
Summary and Conclusion

- Beamforming:
  - The mean flowfield has to be taken into account to be accurate.
  - Able to localise the main sources of noise at the shear layer.
  - Captures the mode shapes.
  - Applicable to wind tunnel with PIV measurements.

- Wavelet transform:
  - Extracts the spatio-temporal fluctuations of the noise.
  - Exhibits a standing wave like behaviour for shallow cavity flow.
  - Tracks the noise fluctuations of unsteady phases of cavity flow.

- Noise propagation:
  - The flowfield has large influence on the noise propagation.
  - A large part of the noise radiate over the second half of the cavity.