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LABORATORY

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Prediction of Acoustics of Transonic Cavities using DES and SAS

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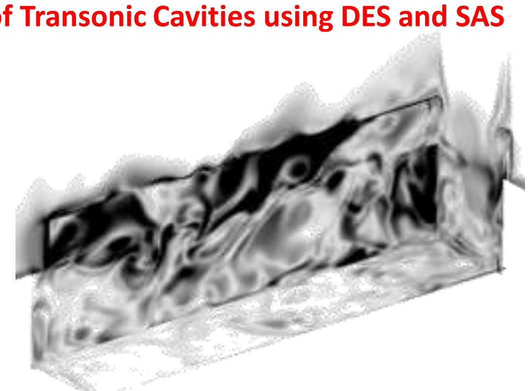
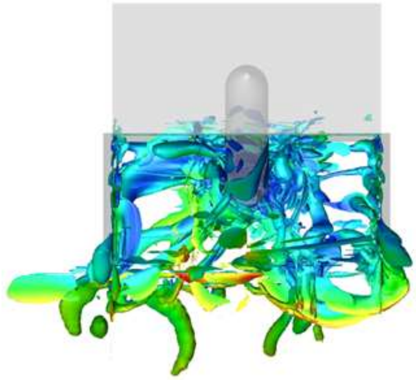


EPSRC MBDA MISSILE SYSTEMS Ministry of DEFENCE

Outline

- Background
- Experimental data
- Simulation approaches
  - CFD method
  - Turbulence modelling
- Results
  - Clean cavities
  - Control attempts
  - More realistic geometries
  - Aeroelasticity
  - Release of stores from cavities
- Summary and future work



Background

Background

- Store separation from weapon bays at transonic speeds may be difficult due to encountered unsteady turbulent flowfield
- Transonic cavity flow can be found in
  - Landing gear bays
  - Large cavities on aircraft (Stratospheric Observatory For Infrared Astronomy)
  - Weapon bays in modern fighter planes and UCAVs
- Cavity flows and their associated acoustics still represent a challenge for predictive methods
- Understanding the fundamental mechanism of this flow may lead to control and alleviation of the acoustic effects

Boeing X-45A

F35

SOFIA

Landing gear bay

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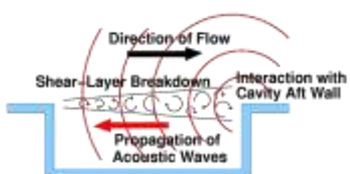
Background - Literature

- **Wind tunnel experiments**
  - Rossiter, Karamcheti, Krishnamurthy (1950s, 1960s)
  - Tam & Block, Rockwell & Naudascher (1970s)
  - Wilcox Jr, Stallings, Tracy (1980, 1990s)
  - Ross (QinetiQ, 2000): PIV (L/D=5 cavity)
  - Knowles (2000): LDA (L/D=10)
- **Computational Fluid Dynamics**
  - Orkwis & Disimile, etc. (1990s): URANS
  - Shieh (2003): DES (L/D=4.4)
  - Rizzetta (2003): LES (L/D=5)
  - Larchevêque (ONERA, 2003,04,07): MILES (L/D=0.42, 5)
  - Nayyar and Barakos (2005) – URANS, LES, DES (L/D=5)
  - Lai and Luo (2007) – LES (L/D=5)
  - Peng and Leicher (2007) – DES (L/D=5)
  - Barakos et al. (2008) – Flow control, URANS, LES, DES (L/D=5)
  - Lawson and Barakos (2009) – Cavity on UCAV

Instantaneous numerical schlieren



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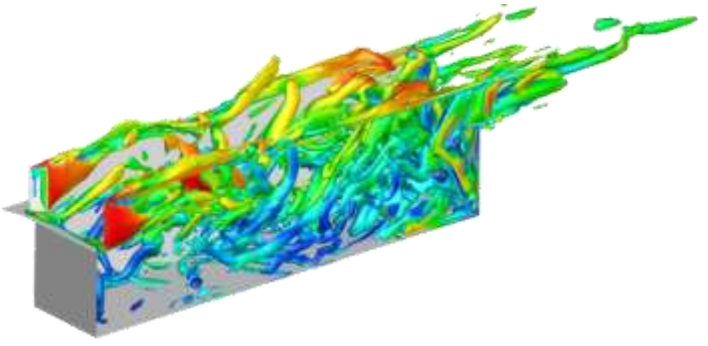
Experimental data



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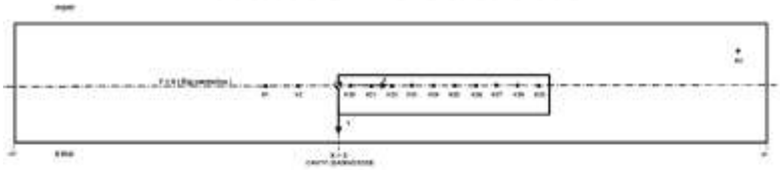
Experimental Data

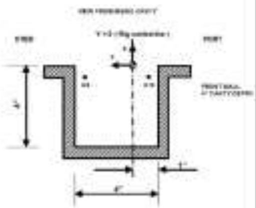
- Data provided by QinetiQ*
  - Wind tunnel at DERA
- M219 cavity with L/D of 5 and W/D of 1
- Cavity with and without bay doors
- Mach number: 0.85
- Reynolds number: 6.78 million (based on cavity length)
- Data also available for cavities with passive flow control
- 10 pressure transducers along cavity floor
- Data sampled at 6kHz for approximately 3.5s

M219 Cavity rig in DERA 8'x8' wind tunnel

***D.A. Nightingale, J.A. Ross, and G.W. Foster, Cavity Unsteady pressure measurements - Examples from Wind-Tunnel Tests, Technical Report Version 3, Aerodynamics & Aeromechanics Systems Group, QinetiQ, November 2005.**

Kulite Locations





Front plate	K1	-7.0		0.0	0.0
	K2	-4.0		0.0	0.0
Rear plate	K4	39.0		-3.0	0.0
4" Front wall	K9	0.0		2.5	-1.0
	K10	0.0		-0.5	-1.0
Ceiling	K20	1.0	0.05	For 4" cavity depth strip is located at Y=0" (ie not on cavity centreline)	
	K21	3.0	0.15		
	K22	5.0	0.25		
	K23	7.0	0.35		
	K24	9.0	0.45		
	K25	11.0	0.55		
	K26	13.0	0.65		
	K27	15.0	0.75		
	K28	17.0	0.85		
	K29	19.0	0.95		
Tunnel wall	K37	-	Port tunnel working section		

[Nightingale *et al*. (2005)]

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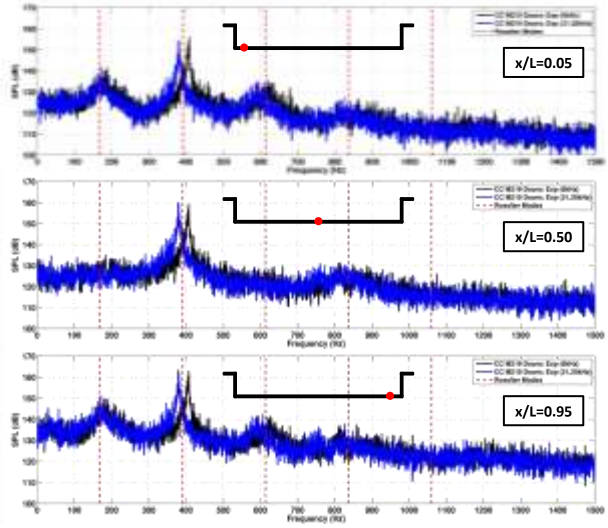
Experimental Data: PIV

- Geometry: Empty cavity, L/D=5, W/D=1, doors-on
- Flow Conditions: M = 0.85, Re_L= 6.783 x 10^6
- Stereoscopic two-camera system with two-head Nd-YaG laser
- 4 data acquisitions taken with each acquisition comprising 2 photographic images taken at 1μs intervals
- Laser width of 5.5'' – cavity length of 20'' covered in 4 sections
- Seeding provided by water droplets sprayed in settling chamber

Effect of Sampling Frequency Using M219 Data



Clean cavity with doors was sampled at **6kHz** and **31.25kHz**. Sampling frequency has an effect on the PSD data.

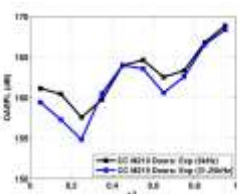
The PSD shows how the strength of a signal is distributed in the frequency domain at a given location and is based on the unsteady pressure. The PSD is calculated using the Burg Estimator (Maximum Entropy Methods) and is presented in terms of decibels (dB). Sound-Pressure Level in dB:

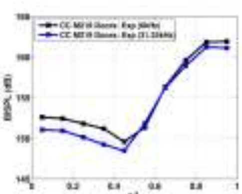
$$SPL(f) = 10\log_{10}\left[\frac{PSD(f)\Delta f_{ref}}{p_{ref}^2}\right]$$

where, Δf_{ref} is a reference frequency usually set to 1 Hz and p_{ref}, is the international standard for the minimum audible sound with a value of $2\text{x}10^{-5}$ Pa.

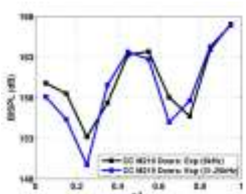
Effect of Sampling Frequency

Locations selected to correspond with wind-tunnel transducers





Mode 1: 50 ≤ f ≤ 250 Hz



Mode 2: 250 ≤ f ≤ 450 Hz

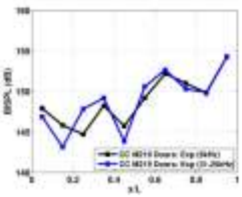
While the unsteady pressure is measured in Pa, OASPLs and BISPLs are presented in decibels. The OASPL is calculated using:

$$OASPL = 20\log_{10}\left[\frac{p'_{rms}}{p_{ref}}\right]$$

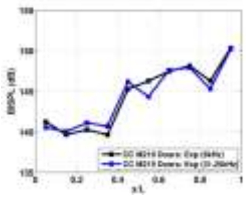
and the BISPL (that shows the energy content for a particular frequency range) is calculated using:

$$BISPL = 20\log_{10}\left[\left(\int_{f1}^{f2} PSD(f)\right)^{1/2} \cdot \frac{1}{p_{ref}}\right]$$

p'_{rms}, is the root-mean-square of the unsteady pressure, p_{ref}, is the international standard for the minimum audible sound with a value of $2\text{x}10^{-5}$ Pa.



Mode 3: 500 ≤ f ≤ 700 Hz



Mode 4: 700 ≤ f ≤ 900 Hz

Differences are seen at x/L between 0.05 and 0.40 and x/L between 0.55 and 0.75.
The higher sampling frequency gives lower SPL at the front (2 to 3dB) and close to the middle (1 to 2dB) of the cavity.
Mode four has a slightly different shape along the middle of the cavity for the two sampling frequencies.

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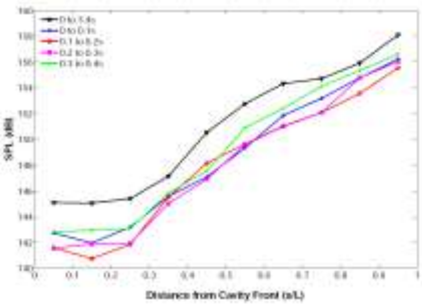
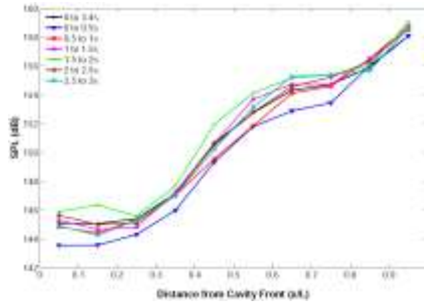
Experimental Data

Signal Length



SPL – Signal split into successive 0.1 second intervals



SPL – Signal split into successive 0.5 second intervals

- All Experimental data signals reduced to same length as numerical signals

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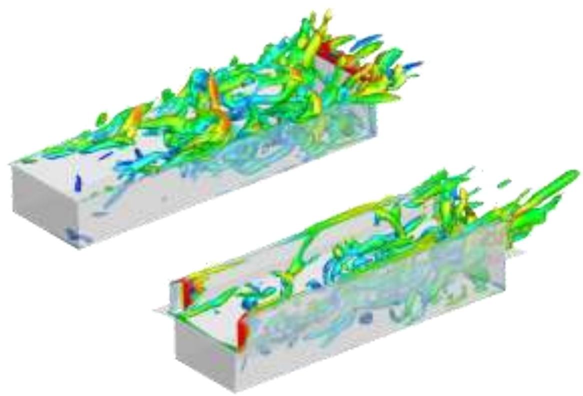
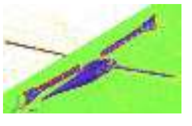
Simulation Approaches



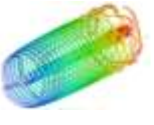
CFD Approaches for Cavity Flows

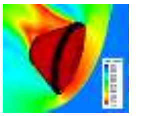
Direct Numerical Simulation (DNS)	Large Eddy Simulation (LES)	Detached Eddy Simulation (DES)	Scale-Adaptive Simulation (SAS)	Unsteady Reynolds-Averaged Navier-Stokes (URANS)
Navier-Stokes equations are numerically solved without a turbulence model	Resolves large scales and models small scales of the flow	URANS near solid walls and LES for separated flow regions	Exhibits steady and scale resolving characteristics depending on the flow solution	Models all turbulent scales and suitable for predicting low frequency large scales
Can resolve full range of turbulent scales	Resolves large energy containing eddies	Resolves some of the turbulent structures	Turbulence-resolving capability validated for several test-cases	Cannot predict full spectrum of turbulent scales
Very fine grid and very small time-step	Fine grid and small time-step	Fine grid and small time-step	Coarse grid with large time steps	Coarse grid with large time steps
Limited application due to computational requirements	Computationally expensive to resolve near-wall turbulent stresses	Computationally expensive compared to URANS and SAS	Least expensive compared to DNS, LES and DES	Least expensive
No available data sets for high Re and Mach number. No application for store release	Limited data sets: Rizzeta, Larchevêque, Nayyar.	Very popular	Less experience with its use	Less popular due to DES

HMB CFD Solver



- Control volume method
- Parallel - Shared and Distributed memory
- Multi-block structured, sliding, overset grids
- LES, DES, URANS and SAS
- DES variations: DDES and IDDES
- Turbulence models: Spalart-Allmaras and k-ω, Transition models
- Implicit and explicit time marching, frequency domain method
- Osher's and Roe's schemes for convective fluxes, AUSM+UP
- All-Mach methods
- MUSCL scheme for formally 3rd order accuracy or flux reconstruction via high-order Taylor expansion
- Stabilised central scheme for LES/DES
- Flight mechanics method- 6DOF and full helicopter model
- Central differences for viscous fluxes
- Krylov subspace linear solver with pre-conditioning
- Aeroelasticity
- Hover formulation, rotor trimming, blade actuation
- Unstructured capability under development
- Documentation
- Validation database
- Range of utilities for processing data, structural models etc.
- Used by academics and engineers





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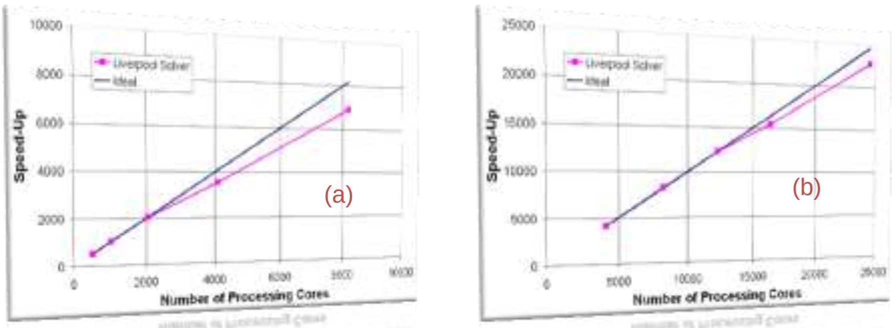
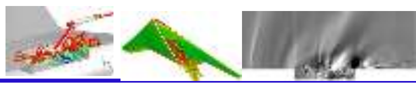
Hector Phase 2B



Helicopter Multi-Block solver using (a) 105 million point mesh with 24576 blocks and (b) 1100 million point mesh with 196608 blocks



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LES Method 1

Compressible Smagorinsky model by Erlebacher et al., JFM, Vol. 238, 1992.

$$\bar{\tau}_{ij} = \mu\left(2\tilde{S}_{ij} - \frac{2}{3}\tilde{S}_{kk}\delta_{ij}\right)$$

Favre-filtered viscous stress tensor

$$\tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

Favre-filtered strain rate tensor

$$\mu_t = C_R \bar{\rho}\Delta^2\sqrt{\tilde{S}_{ij}\tilde{S}_{ij}}$$

$$\bar{\tau}_{ij}^{SGS} = \mu_t\left(2\tilde{S}_{ij} - \frac{2}{3}\tilde{S}_{kk}\delta_{ij}\right) - \frac{2}{3}\bar{\rho}k_{SGS}\delta_{ij}$$

SGS viscous tensor model

$C_R=0.012$

$C_I=0.0066$

$$k_{SGS} = C_I\Delta^2\tilde{S}_{ij}\tilde{S}_{ij}$$

$$q_i^{SGS} = -c_p\frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial \tilde{T}}{\partial x_i}$$

$$\Delta = \sqrt[3]{\Delta x\Delta y\Delta z}$$

WALE Modification by Nicoud & Ducros, FTC, Vol. 62, 1999.
Wollblad et al. AIAAJ, Vol 44, 2006.

$$\mu_t = \bar{\rho}(C_w\Delta)^2\frac{\sqrt{\left(S_{ij}^d S_{ij}^d\right)^3}}{\sqrt{\left(S_{ij}^d S_{ij}^d\right)^5} + \sqrt{\left(S_{ij}^d S_{ij}^d\right)^5}}$$

$$S_{ij}^d = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_k}\frac{\partial \tilde{u}_k}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_k}\frac{\partial \tilde{u}_k}{\partial x_i}\right) - \frac{1}{3}\frac{\partial \tilde{u}_n}{\partial x_k}\frac{\partial \tilde{u}_k}{\partial x_n}\delta_{ij}$$

$$\bar{\tau}_{ij}^{SGS} = \mu_t\left(2\tilde{S}_{ij} - \frac{2}{3}\tilde{S}_{kk}\delta_{ij}\right) - \frac{2}{3}\frac{C_I^n}{\bar{\rho}}\left(\frac{\mu_t}{\Delta}\right)^2\delta_{ij}$$

$C^n_I=45.8$

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LES Method 2

- Zonal approach adopted with coarser grid near the top wall and wall-functions
- Zone boundary placed at mid-height of the test section
- For the conditions of the experiment, current LES grids are 1.5 times coarser than necessary
- Max y^+ of 4 for lower wall
- Max y^+ of 12 for side walls
- Grids of about 7M points
- Attempted to make grid as uniform as possible near the interaction
- Load-balanced on 256 to 512 CPUs

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Scale-Adaptive Simulations

Scale-Adaptive Simulation is an improved URANS formulation allowing for the resolution of the turbulent spectrum in unstable flow conditions. It is based on the introduction of the von Karman length-scale into the turbulence scale equation. The von Karman length-scale allows SAS models to dynamically adjust to resolved structures in a URANS simulation resulting in an LES like behaviour in unsteady regions of the flow.

The governing equations of the SST-SAS model are different to SST-RANS model through the addition of the $\boldsymbol{Q_{SAS}}$ term.

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial \rho u_j k}{\partial x_j}=P_k-\rho c_\mu k\omega+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial \rho u_j \omega}{\partial x_j}=\alpha\frac{\omega}{k}P_k-\rho\beta\omega^2+Q_{SAS}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]+(1-F_1)\frac{2\rho}{\sigma_{\omega 2}}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$$

$\boldsymbol{Q_{SAS}}$ is defined as:

$$Q_{SAS}=\max\left[\rho\zeta_2\kappa S^2\left(\frac{L}{L_{\upsilon K}}\right)^2-C\cdot\frac{2\rho k}{\sigma_\Phi}\max\left(\frac{1}{\omega^2}\frac{\partial \omega}{\partial x_j}\frac{\partial \omega}{\partial x_j},\frac{1}{k^2}\frac{\partial k}{\partial x_j}\frac{\partial k}{\partial x_j}\right),0\right]$$

where $\zeta_2=3.51$, $\sigma_\Phi=2/3$ and C=2. the length scale of the modelled turbulence L and the von Karman length scale $L_{\upsilon\kappa}$ are defined as:

$$L=\frac{\sqrt{k}}{c_\mu^{1/4}\omega},\quad L_{\upsilon K}=\frac{\kappa S}{|U''|}$$

The scalar invariant of the strain rate tensor S_{ij} is given by:

$$S_{ij}=\frac{1}{2}\left[\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right] \quad \text{and} \quad S=\sqrt{2S_{ij}S_{ij}}$$

where $\kappa=0.41$ is the von Karman constant

The second velocity derivative is given by: $|U''|=\sqrt{\sum_i\left(\frac{\partial^2 U_i}{\partial x_j \partial x_j}\right)^2}$

***Y. Egorov, F. R. Menter, R. Lechner and D. Cokliat, The Scale-Adaptive Simulation Method for Unsteady Turbulent Flow Predictions. Part 2: applications to Complex Flows. Flow, Turbulence and Combustion, July 2010, Volume 85, Issue 1, pp 139-165**

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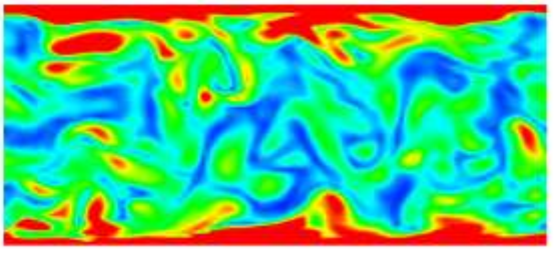
Flow Forcing

- Computations use inflow profiles in order to shorten inflow domain and give realistic inflow conditions.
- Widely used for LES computations to reduce computational cost.
- Various methods exist, including:
  - Random white noise
  - Scaling DNS data
  - Precursor simulation
  - Inverse Fourier methods
  - Synthetic-Eddy methods
- Precursor and Synthetic-Eddy methods tested for cavity flow problem.

Precursor LES Simulation

- High-order LES for flow through a square duct



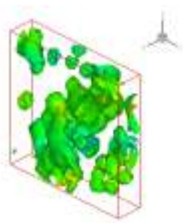
- 6^{th} order central scheme
- Explicit time marching
- 120x80x80 mesh
- Reconstructed using POD and imposed at the inflow of the CFD domain

Synthetic Eddy Method

- Requires 2-dimensional, time-dependent fluctuations for inflow
- Eddies are randomly generated on: $[-\sigma_x, \sigma_x] \times [-\sigma_y, L_y+\sigma_y] \times [-\sigma_z, L_z+\sigma_z]$
- Eddies are convected through inlet plane with reference velocity U_0 using Taylor's frozen turbulence hypothesis: $x_i(t + \mathrm{d}t) = x_i(t) + U_0\,\mathrm{d}t$
- Eddy is regenerated upstream at $x = -\sigma_x$ when $x > \sigma_x$
- The velocity signal at point x now reads:

$$u(x,t) = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} \varepsilon_{ij} f_j\big(x - x_i(t)\big)$$

- Here, $f_j(x) = f(\|x\|)$, where f is a Gaussian function.



Q-Criteria showing structures along a flat plate test grid
- Mach = 0.85, Re = 1 mil.
- DES S–A Model
- 167,400 grid points

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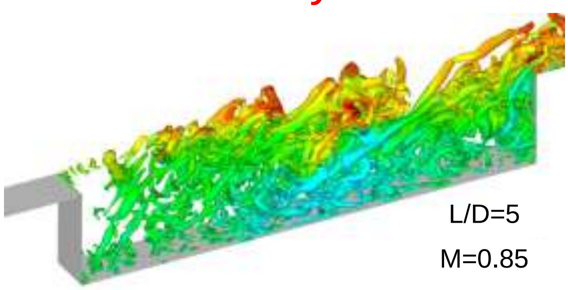
Cavity Flow Simulations

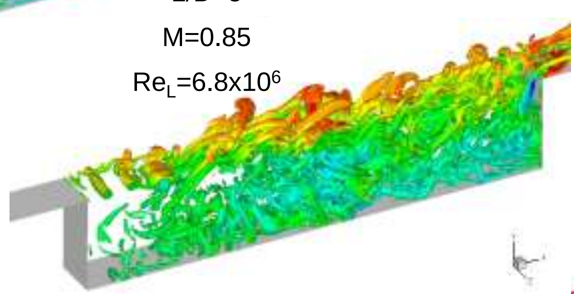


No Inflow Condition

L/D=5

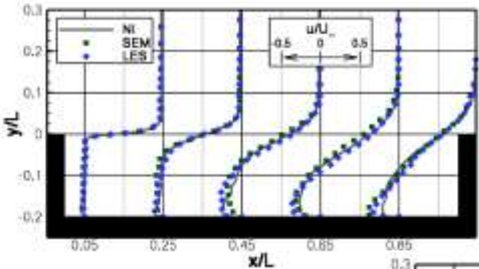
M=0.85

$Re_L=6.8\times10^6$



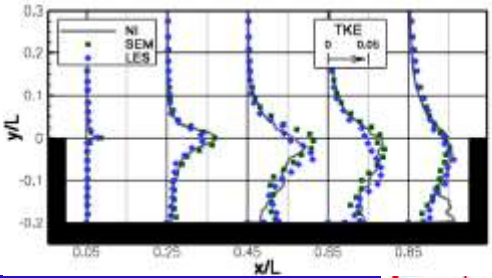
Synthetic Eddy Inflow Boundary Condition

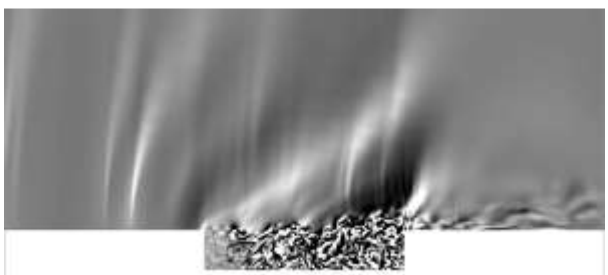
Averaged Profiles

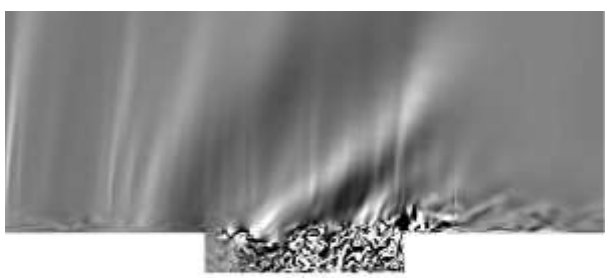


- **Streamwise Velocity Profiles**

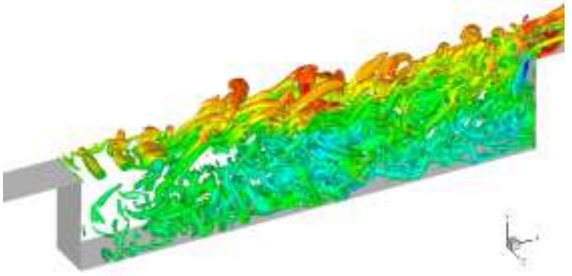
- **Turbulent Kinetic Energy**



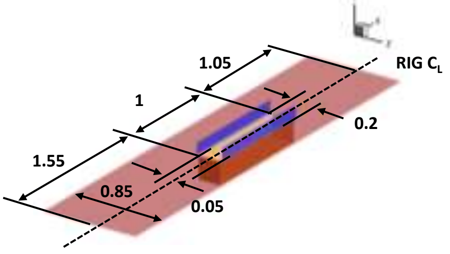




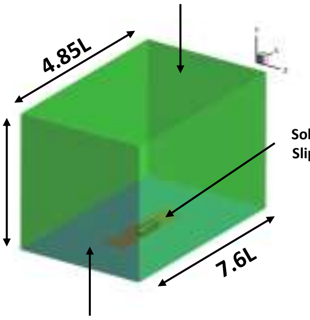
Results – Clean Cavities



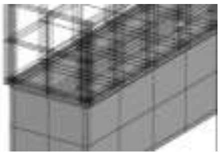
Cavity Geometry and Multiblock Topology



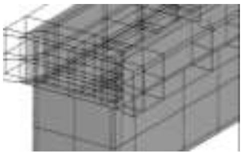
Computational Geometry for Clean Cavity with Doors



Computational Domain with Clean Cavity with Doors



Clean Cavity



Clean Cavity with Doors

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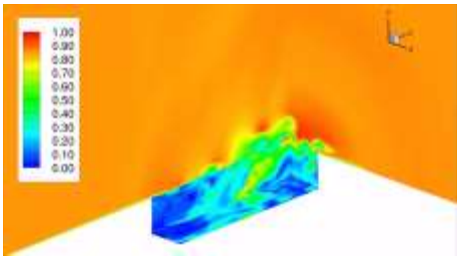
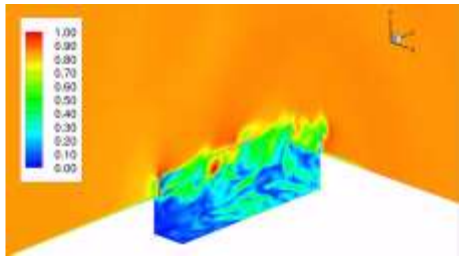
Instantaneous Contours of Mach Number





Clean Cavity with Doors-Off
L/D 5, W/D 1
Grid size: 5.0×10^6
Cells in cavity: 1.0×10^6
Mach number: 0.85
Reynolds number: 6 million (based on cavity length)
Method: SAS SST
CFD time-step: 17.58×10^{-5}s
Travel times: 90
Total signal length: 0.16s

Clean Cavity with Doors-On
L/D 5, W/D 1
Grid size: 5.5×10^6
Cells in cavity: 1.0×10^6
Mach number: 0.85
Reynolds number: 6 million (based on cavity length)
Method: SAS SST
CFD time-step: 17.58×10^{-5}s
Travel Times: 90
Total signal length: 0.16s

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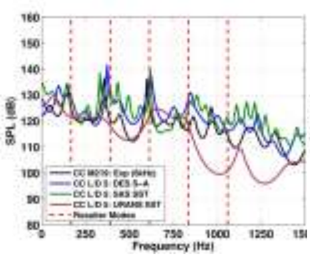
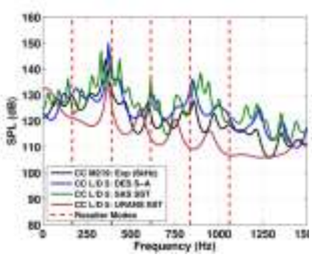
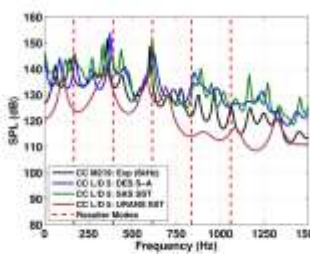
Clean Cavity with Doors-Off



x/L=0.05



x/L=0.50



x/L=0.95

- PSD plots for DES, SAS and URANS are compared
- Mode two and three are dominant at the front and back of the cavity
- Mode two is dominant in the middle of the cavity
- DES and SAS capture these modes accurately
- URANS does not predict the dominant modes correctly

Signal lengths used for comparison: 0.1s (approx 55 travel times)

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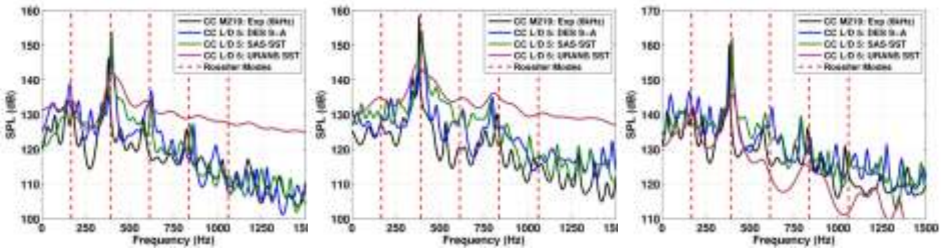
Clean Cavity with Doors-On



x/L=0.05 x/L=0.50 x/L=0.95

Signal lengths used for comparison: 0.1s (approx 55 travel times)

- PSD plots for DES, SAS and URANS are compared
- Mode two is dominant along the length of the cavity
- DES and SAS capture this mode accurately as well as the lower energy modes
- URANS does not compare well at the first two locations but predicts the second mode towards the aft of the cavity

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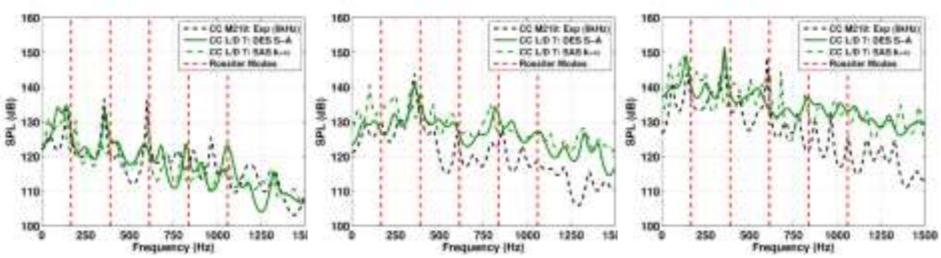
Clean Cavity L/D 7 with Doors-Off



x/L=0.05 x/L=0.50 x/L=0.95

Signal lengths used for comparison: 0.1s (approx 55 travel times)

The PSD shows how the strength of a signal is distributed in the frequency domain at a given location and is based on the unsteady pressure. The PSD is calculated using the Burg Estimator (Maximum Entropy Methods or MEM) and is presented in terms of decibels (dB) through the definition of Sound-Pressure spectrum Level (SPL):

$$SPL(f) = 10\log_{10}\left[\frac{PSD(f)\Delta f_{ref}}{p_{ref}^2}\right]$$

p_{ref}, is the international standard for the minimum audible sound with a value of $2\text{x}10^{-5}$ Pa.

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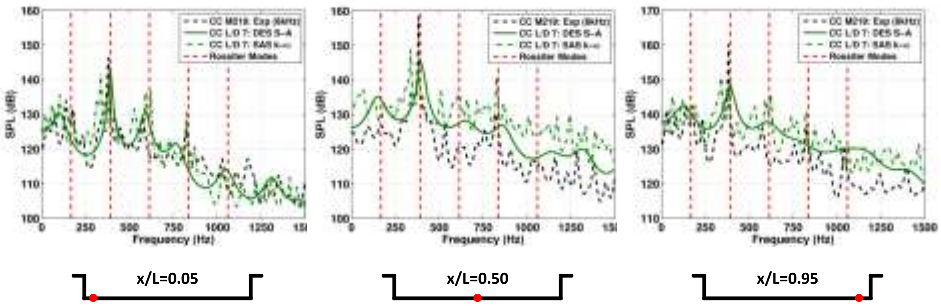
Clean Cavity L/D 7 with Doors-On



The PSD shows how the strength of a signal is distributed in the frequency domain at a given location and is based on the unsteady pressure. The PSD is calculated using the Burg Estimator (Maximum Entropy Methods or MEM) and is presented in terms of decibels (dB) through the definition of Sound-Pressure spectrum Level (SPL):

Signal lengths used for comparison: 0.1s (approx 55 travel times)

$$SPL(f) = 10\log_{10}\left[\frac{PSD(f)\Delta f_{ref}}{p_{ref}^2}\right]$$

p_{ref}, is the international standard for the minimum audible sound with a value of 2x10^{-5} Pa.

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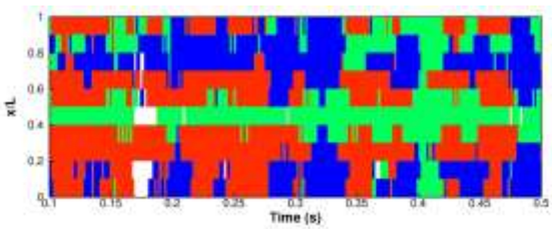
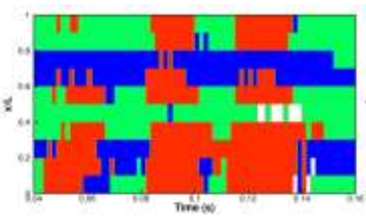
Joint Time-Frequency Analysis for Cavity with Doors-Off

- Time-space maps of dominant Rossiter modes along the length of the cavity.
- The dominant mode in the centre of the cavity (x/L between 0.45 to 0.55) is the second mode but appears to switch occasionally with the **fourth** mode.
- SAS and DES both capture mode one along the rear end (x/L: 0.6 to 0.8) of the cavity
- DES captures more of mode three at the front (x/L: 0.0 to 0.4) of the cavity than SAS

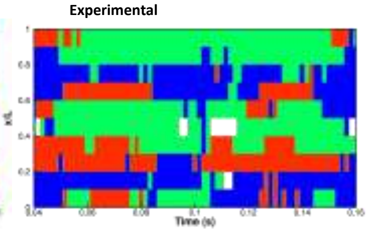


Experimental

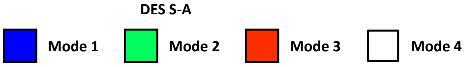
JTFA is used to show the change in the frequency content of a signal over time. JTFA is calculated through Short Time Fourier Transform (STFT).



DES S-A



SAS SST



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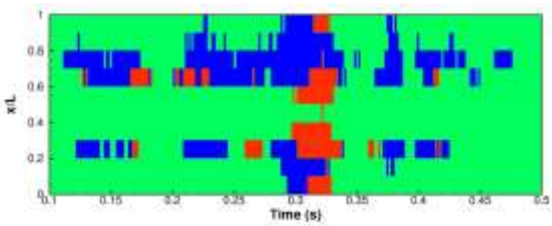
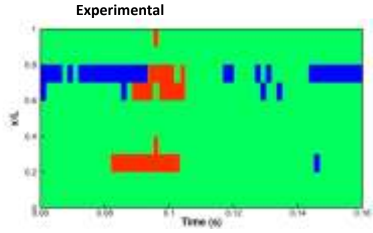
Joint Time-Frequency Analysis for Cavity with Doors-On

- Time-space maps of dominant Rossiter modes along the length of the cavity.
- The dominant mode in the centre of the cavity (x/L between 0.45 to 0.55) is the second mode but appears to switch occasionally with the **third** mode.
- SAS doesn't capture as much of mode one, at the front and rear ends of the cavity, as is seen in the experiment.

JTFA is used to show the change in the frequency content of a signal over time. JTFA is calculated through Short Time Fourier Transform (STFT).



Experimental



SAS SST

Mode 1 Mode 2 Mode 3 Mode 4

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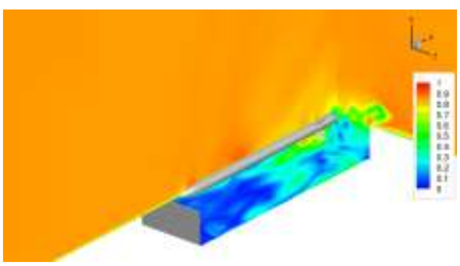
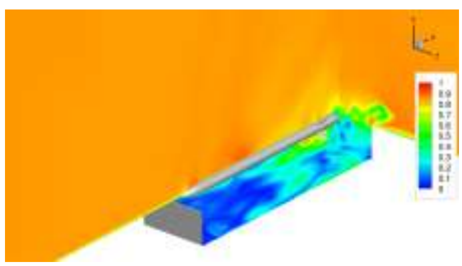
Instantaneous Contours of Mach Number



Store at Cavity Shear Layer
L/D 7, W/D 2
Grid size: 5.0×10^6
Cells in cavity: 1.0×10^6
Mach number: 0.85
Reynolds number: 6 million (based on cavity length)
Method: **DES S-A**
CFD time-step: 1.18×10^{-5}s
Travel times: 55
Total signal length: 0.65s



Store at Cavity Shear Layer
L/D 7, W/D 2
Grid size: 5.5×10^6
Cells in cavity: 1.0×10^6
Mach number: 0.85
Reynolds number: 6 million (based on cavity length)
Method: **SST-SAS k-ω**
CFD time-step: 11.88×10^{-5}s
Travel Times: 30
Total signal length: 0.35s

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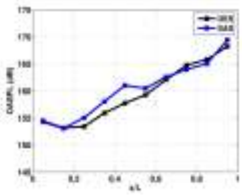
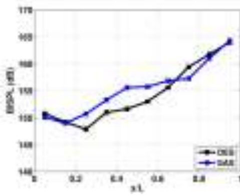
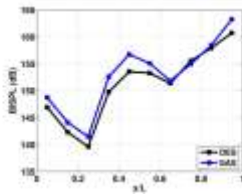
Store at Cavity Shear Layer

Locations selected to correspond with wind-tunnel transducers





Mode 1: 10 ≤ f ≤ 40 Hz



Mode 2: 40 ≤ f ≤ 70 Hz

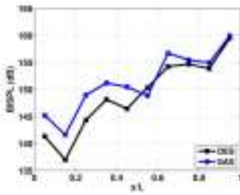
While the unsteady pressure is measured in Pascals, OASPLs and BISPLs are presented in units of decibels. The OASPL is calculated using the following equation:

$$OASPL = 20\log_{10}\left[\frac{p'_{rms}}{p_{ref}}\right]$$

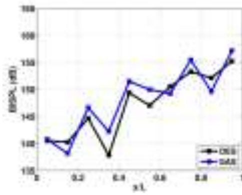
and the BISPL, that shows the energy content for a particular frequency range, is calculated using the following equation:

$$BISPL = 20\log_{10}\left[\left(\int_{f1}^{f2} PSD(f)\right)^{1/2} \cdot \frac{1}{p_{ref}}\right]$$

p'_{rms}, is the root-mean-square of the unsteady pressure, p_{ref}, is the international standard for the minimum audible sound with a value of 2×10^{-5} Pa.



Mode 3: 70 ≤ f ≤ 110 Hz



Mode 3: 110 ≤ f ≤ 140 Hz

Signal lengths used for comparison: 0.3s (approx 25 travel times)

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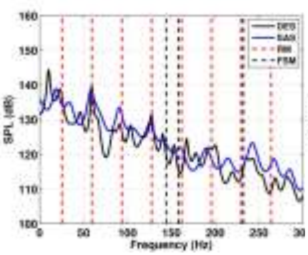
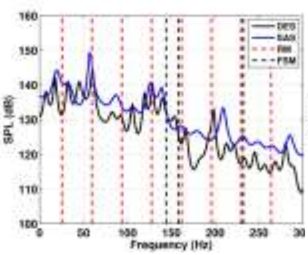
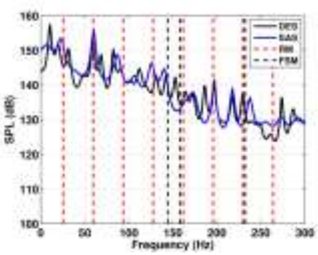
Store at Cavity Shear Layer







x/L=0.05 **x/L=0.50** **x/L=0.95**

The PSD shows how the strength of a signal is distributed in the frequency domain at a given location and is based on the unsteady pressure. The PSD is calculated using the Burg Estimator (Maximum Entropy Methods or MEM) and is presented in terms of decibels (dB) through the definition of Sound-Pressure spectrum Level (SPL):

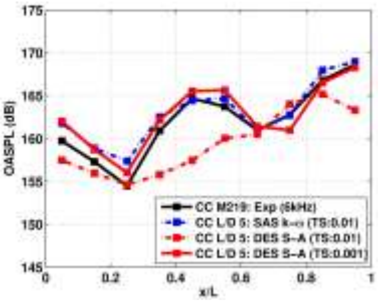
$$SPL(f) = 10\log_{10}\left[\frac{PSD(f)\Delta f_{ref}}{p_{ref}^2}\right]$$

p_{ref}, is the international standard for the minimum audible sound with a value of 2×10^{-5} Pa.

RM – Rossiter Modes
FSM – Fin Structural Modes
Signal lengths used for comparison: 0.3s (approx 25 travel times)

Effect of Time-Step on DES and SAS

- Order of magnitude cost savings for **SAS** comes from using a larger time-step (**0.01**) than DES (**0.001**).
- DES was used in the past with a non-dimensional time-step of 0.001.
- **SAS computations** used a time-step of **0.01** similar to that used by Egorov et al.
- Comparison of DES and SAS at a non-dimensional time-step of 0.01 to study the effect of time-step
  - Clean cavity doors, L/D = 5
  - 5.5m nodes
  - Mach: 0.85, Re: 6×10^6 (based on cavity length)
  - Both computations were run for approximately 7 travel times (first 5 travel times discarded as transient/undeveloped flow)



- **Y. Egorov, F. Menter, R. Lechner and D. Cokljat, The Scale-Adaptive Simulation Method for Unsteady Turbulent Flow Predictions. Part 2: Application to Complex Flows, Flow Turbulence Combustion, Vol. 85, pp. 139-165, 2010.**
- **S.V. Babu, G. Zografakis and G.N. Barakos, Evaluation of Scale-Adaptive Simulations for Transonic Cavity Flows. 5th HRLM Symposium, A&M University, College Station, Texas, USA, 19-21 March 2014.**
- **S.V. Babu and G.N. Barakos, Prediction of Acoustics of Transonic Cavities using DES and SAS. 49th International Symposium of Applied Aerodynamics: Aerodynamics and Environment, Lille, France, 24-26 March 2014.**
- **S.V. Babu, G. Zografakis and G.N. Barakos, Evaluation of Scale-Adaptive Simulations for Transonic Cavity Flows. *International Journal of Engineering Systems Modelling and Simulation. Accepted, 2014.***

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CPU Usage

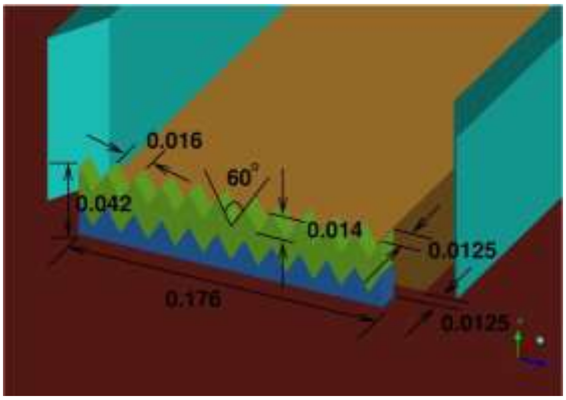
- The SAS model was validated against experimental data for the M219 cavity with and without doors.
- Results were compared against DES and URANS results obtained on the same grid.
- **SAS gives good comparisons using a 10th of the computational time as DES.**

Computation	Method	Grid Size (10^6)	CFD Time-Step (10^{-5} s)	Non-Dimensional CFD Time-Step	Clock Time (hr)
Clean Cavity Doors-off	DES S-A	5.0	2.19	0.001	3909
	SAS SST	5.0	17.58	0.01	312
Clean Cavity Doors-on	DES S-A	5.5	2.19	0.001	4560
	SAS SST	5.5	17.58	0.01	364

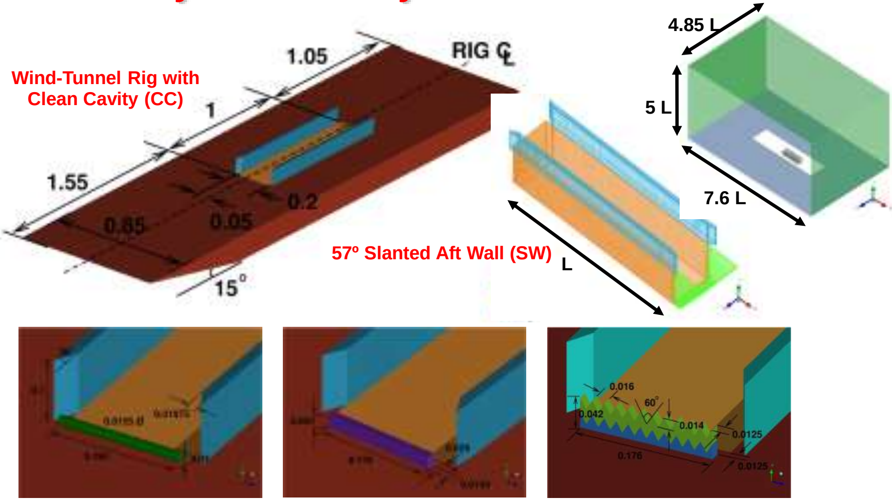
The **Chadwick HPC** cluster of the University of Liverpool was used for the computations.

- 118 nodes, each with 16 cores and 64 GB of memory
- 18 nodes, each with 8 cores and 24 GB of memory
- One 2 TB large memory node with 128 cores
- Two visualisation nodes, each with 12 cores, an Nvidia Quadro 5000 card and 96 GB of memory
- 120 TB (unformatted) storage

Results – Control Attempts



Cavity Geometry and Flow Control

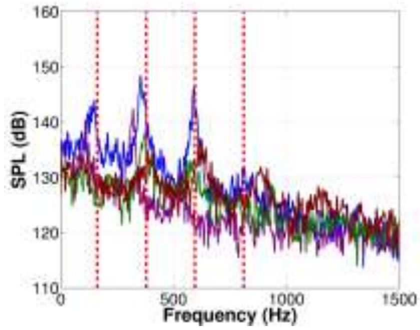


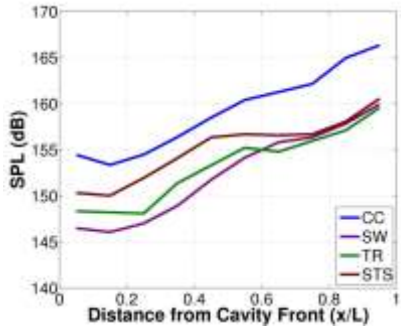
Transverse Rod (TR) of diameter d/L = 0.01

Flat-Top Spoiler (FTS) located at x/L = -0.0125

Saw-Tooth Spoiler (STS) located at x/L = -0.0125

Experimental Data for Control Devices*





$$f_m = \frac{U_\infty}{L}\frac{(m-\alpha)}{\left[\frac{M_\infty}{\sqrt{1+\frac{(\gamma-1)}{2}M_\infty^2}}+\frac{1}{\kappa_V}\right]}$$

where constants $\alpha = 0.25$, $\kappa_v = 0.57$

J.E. Rossiter, 'Wind Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds', Tech Report 64037, RAE, October, 1964

* D.A. Nightingale, J.A. Ross, and G.W. Foster, 'Cavity Unsteady pressure measurements - Examples from Wind-Tunnel Tests, Technical Report Version 3, Aerodynamics& Aeromechanics Systems Group, QinetiQ, November2005.

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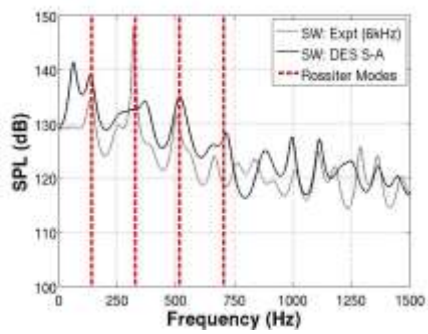
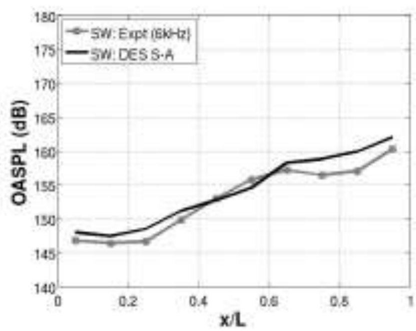
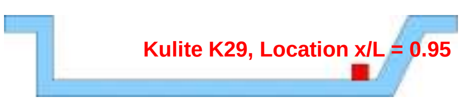
Slanted Aft Wall – Large Grid (12m)







SPL along cavity floor.

0 < *f* < 3000 Hz

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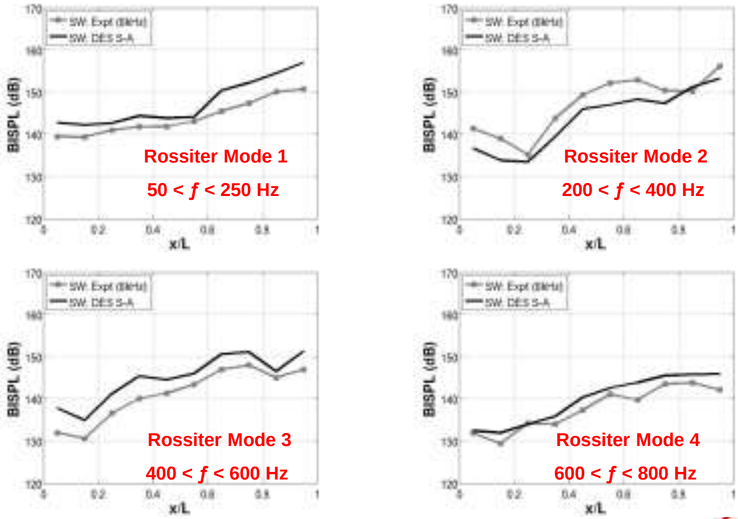
Slanted Aft Wall – Large Grid (12m)



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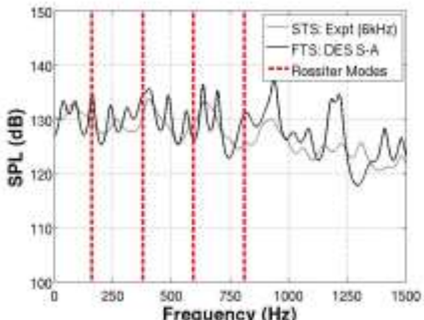
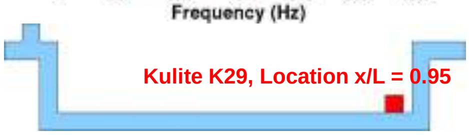
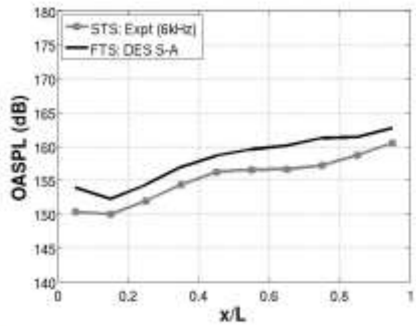
Flat-Top Spoiler



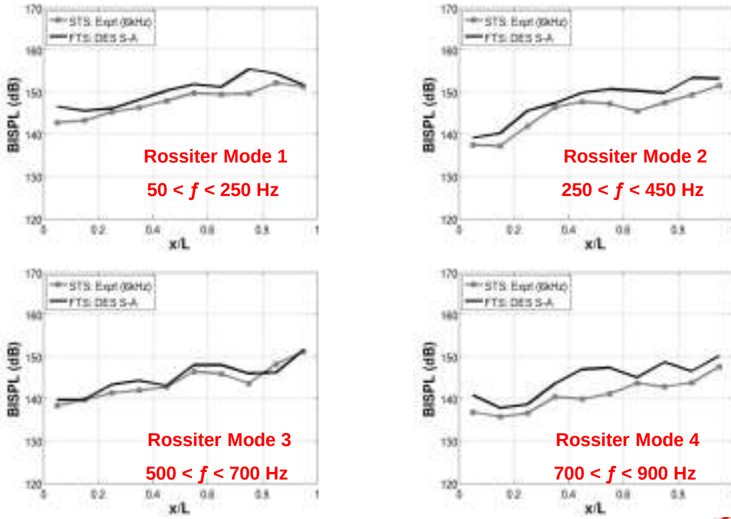




SPL along cavity floor.

0 < f < 3000 Hz

Flat-Top Spoiler



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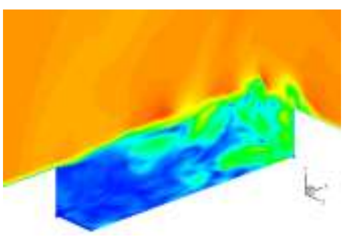
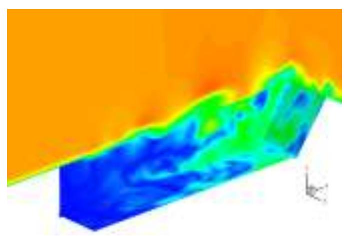
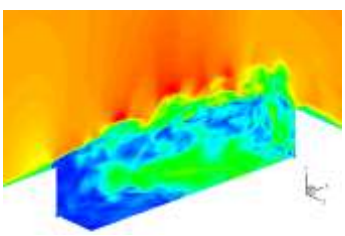
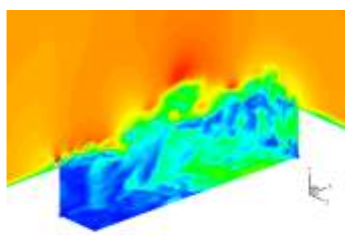
Mach Number Field





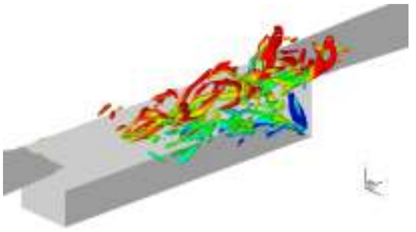
Clean Cavity **Slanted Wall**



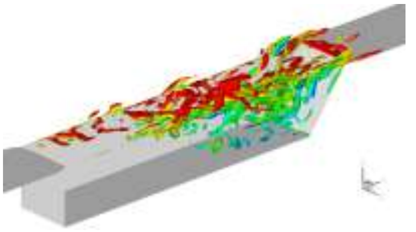


Flat Spoiler **Transverse Rod**

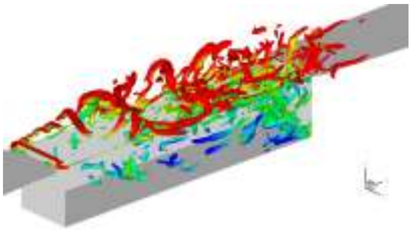
Flow Structures: Q-Criterion



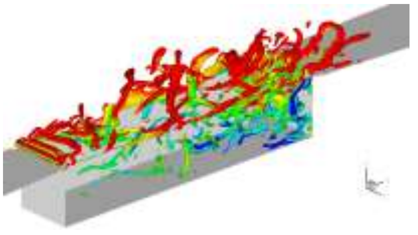
Clean Cavity



Slanted Wall

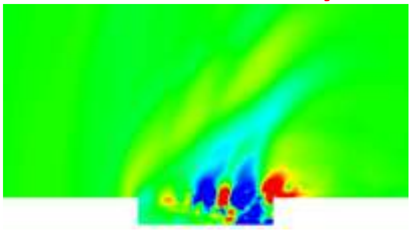


Flat Spoiler

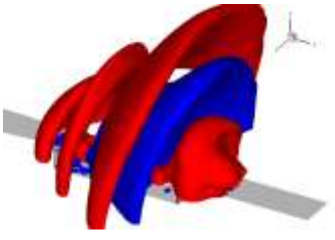


Transverse Rod

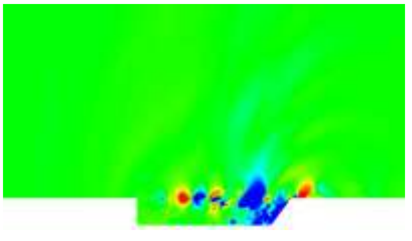
Clean Cavity vs. Slanted Aft Wall

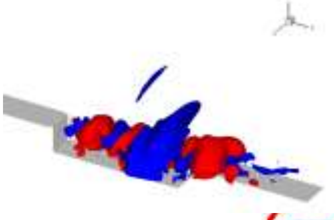


2D Acoustic Pressure

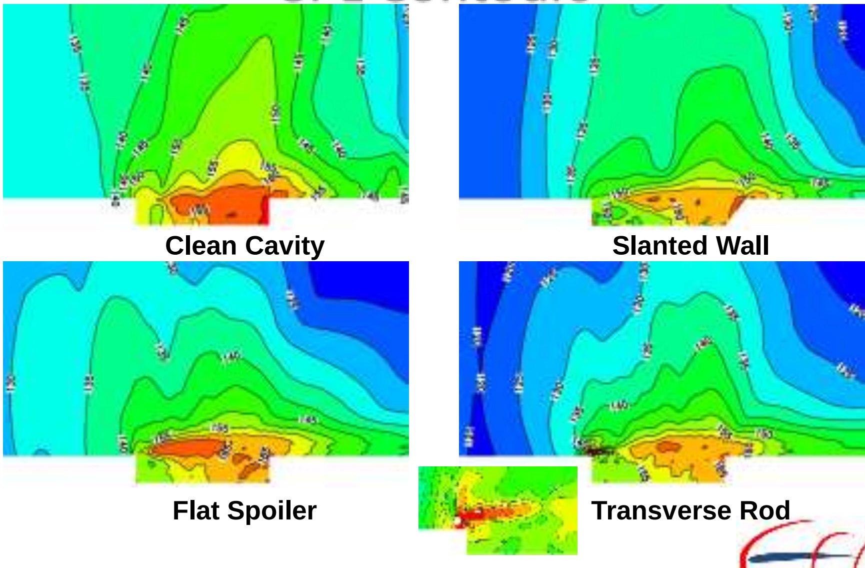


3D Acoustic Pressure





SPL Contours



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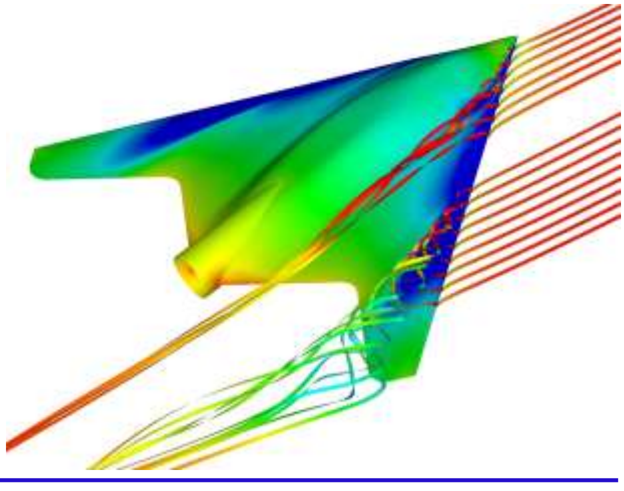
More Realistic Geometries

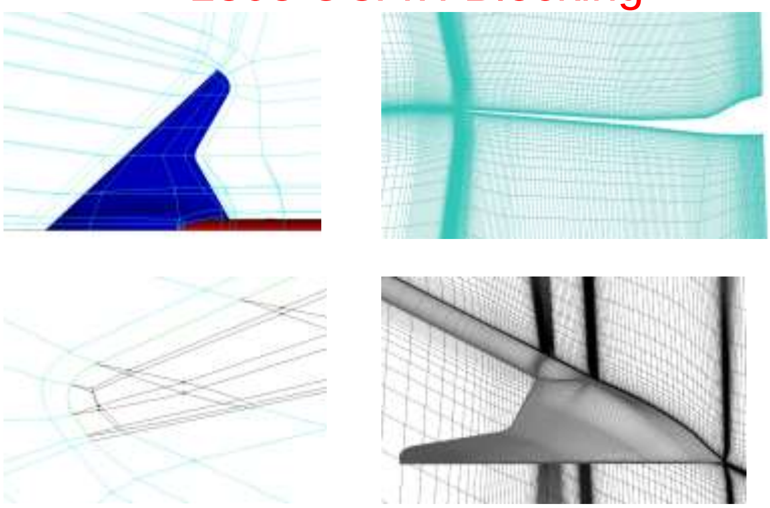


Experimental Data: 1303 UCAV

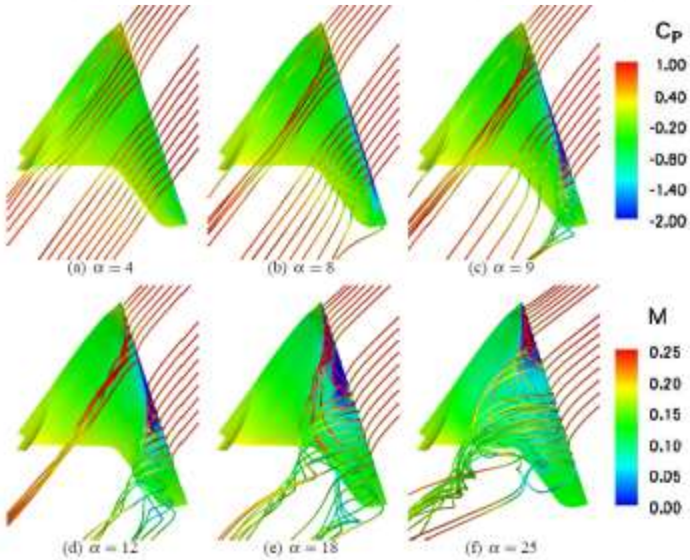
- Data provided by DSTL.
- L/D of 5.45 and W/D of 1.32
- Mach numbers of 0.25, 0.35 and 0.85
- Data also available with passive flow control at Mach number 0.85:
  - Sloping Aft Wall
  - Spoilers
- 10 pressure transducers along cavity floor.
- Store at 4 locations
- Carriage Location (z/L=-0.121)
- Shear Layer (z/L=0)
- Between Doors (z/L=0.079)
- Far-Field (z/L=0.684)

The Technical Cooperation Program (TTCP)
Blind comparisons between the 5 nations participating

1303 UCAV: Blocking



1303 UCAV: Flow Visualisations



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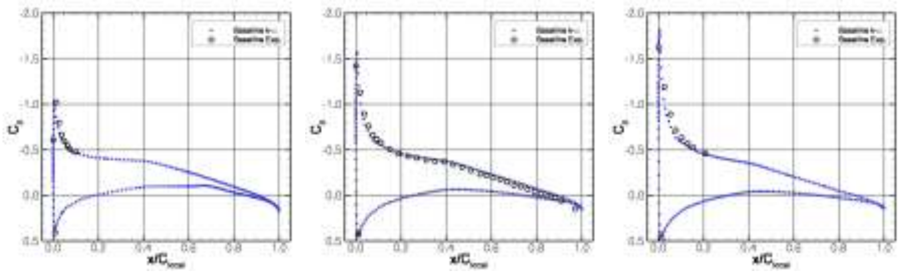
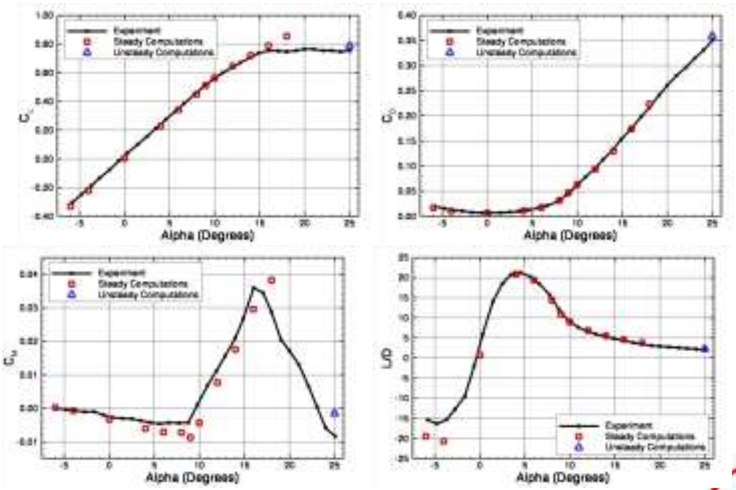
1303 UCAV: Cp Distributions

Wing Section Cp distributions 4.6 Degrees:



η=0.4 η=0.6 η=0.8

1303 UCAV: Integrated Loads



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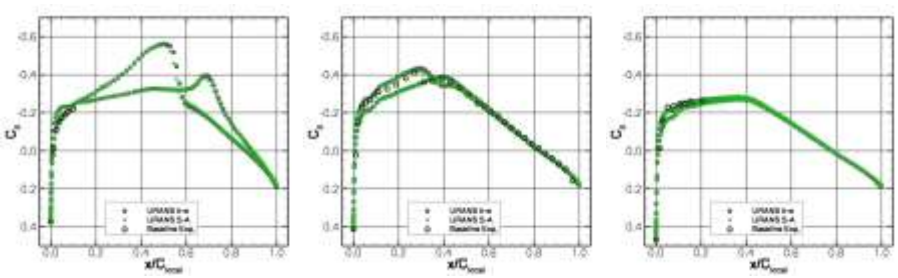
1303 UCAV: Cp Distributions

Wing Section Cp distributions 0 Degrees, Mach 0.85



η=0.4 η=0.6 η=0.8

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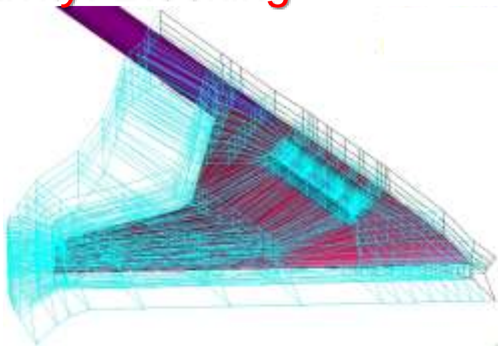
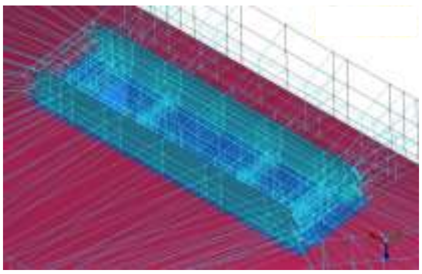
UCAV Cavity: Blocking

- 3027 blocks
- Extension of the h-topology used for clean UCAV
- ~14M cells for cavity region





CFD Group – Department of Engineering – University of Liverpool

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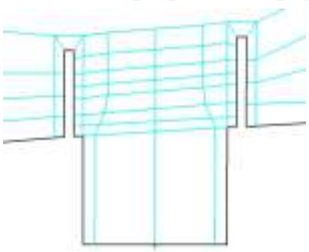
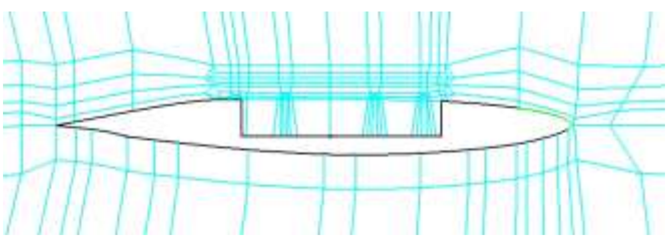
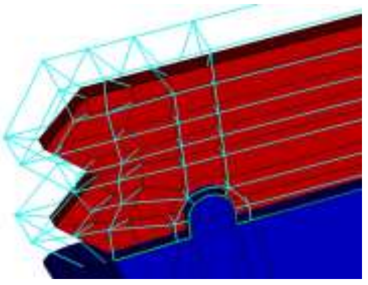
UCAV Cavity: Blocking

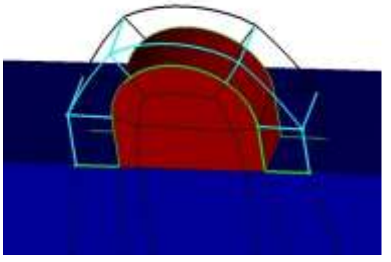




CFD Group – Department of Engineering – University of Liverpool

UCAV Cavity: Blocking





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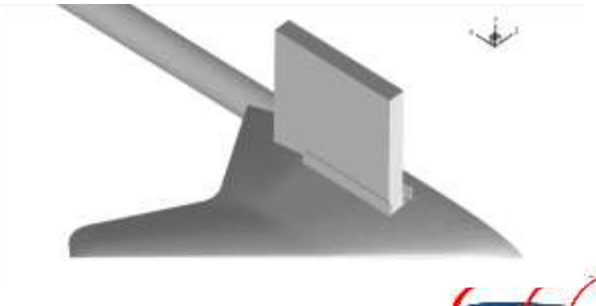
UCAV Cavity + Store



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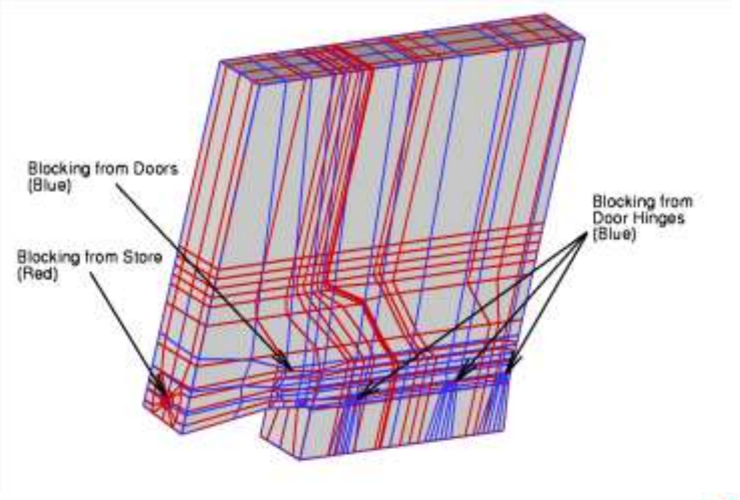
UCAV Cavity + Store



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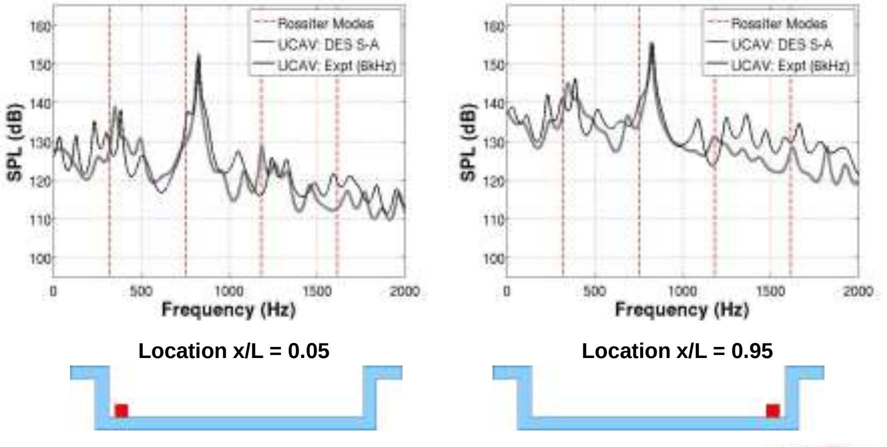
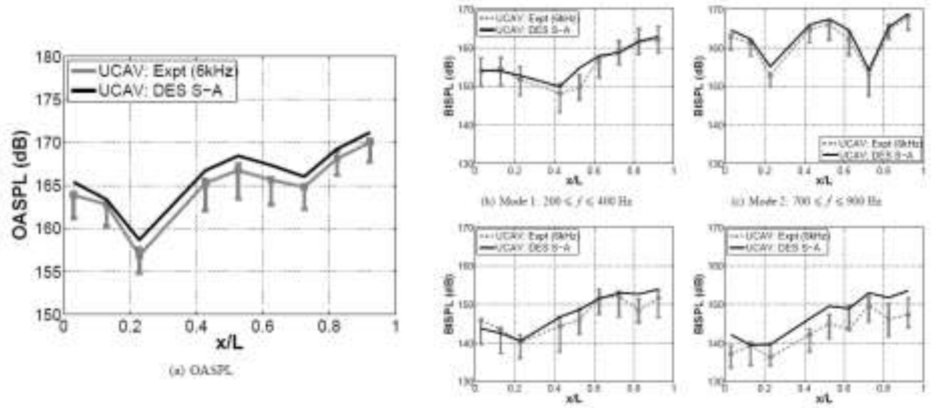
UCAV Cavity: SPL



UCAV Cavity: OASPL and BISPL



(a) OASPL

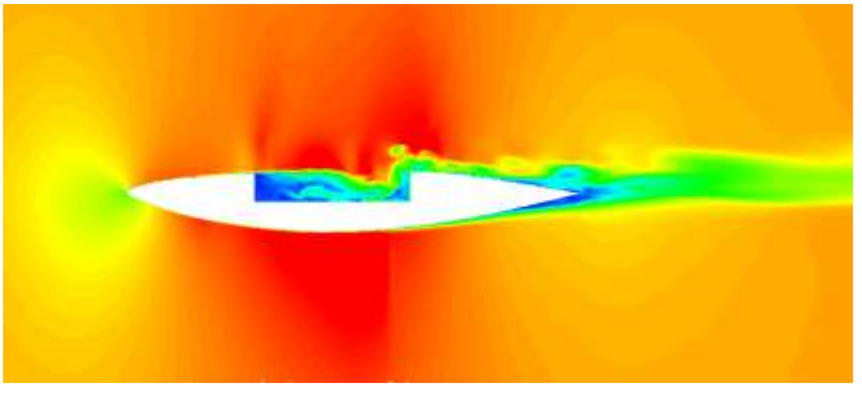
(b) Mode 1: 200 ≤ f ≤ 400 Hz

(c) Mode 2: 700 ≤ f ≤ 900 Hz

(d) Mode 3: 1100 ≤ f ≤ 1300 Hz

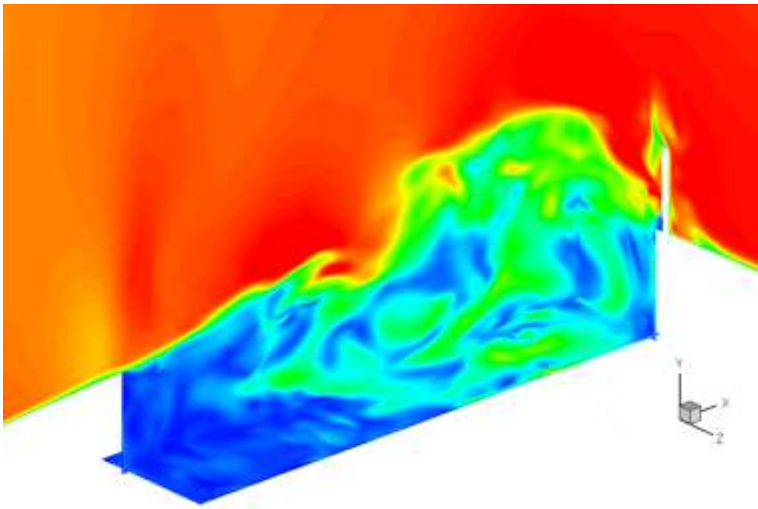
(e) Mode 4: 1500 ≤ f ≤ 1700 Hz

UCAV and Cavity Results



- Instantaneous Mach Contours

UCAV Cavity: Mach Number



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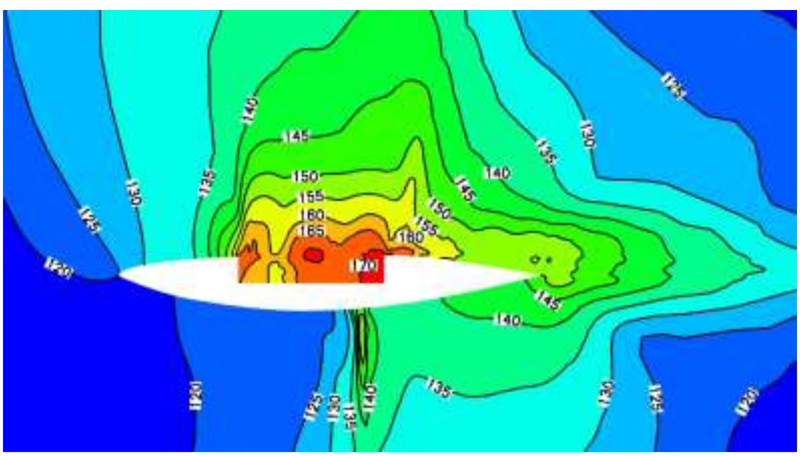
UCAV Cavity: OASPL



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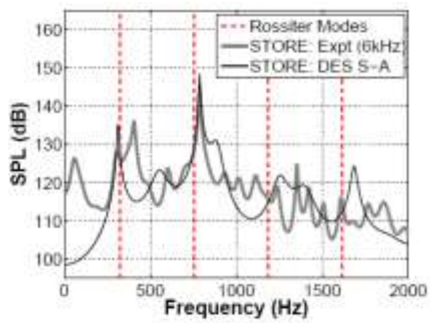
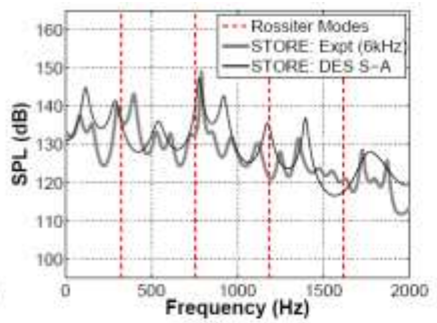
UCAV Store: PSD





Location x/L = 0.05

Location x/L = 0.95

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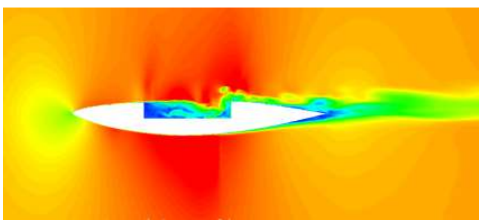
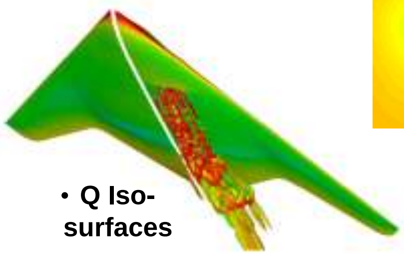
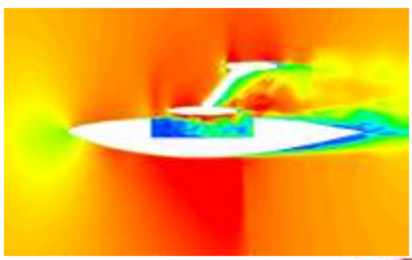
UCAV Cavity: Instantaneous Flow

- Mach Number Contours





- Q Iso-surfaces



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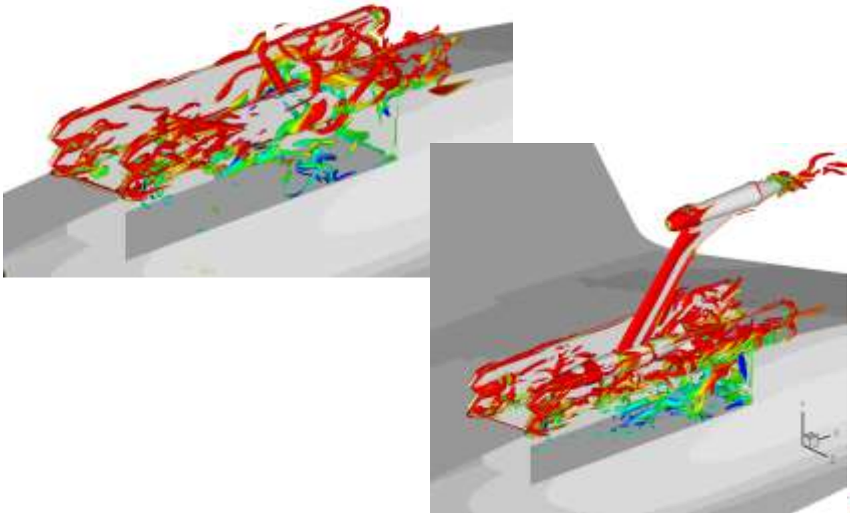
UCAV Cavity: Q-Criteria



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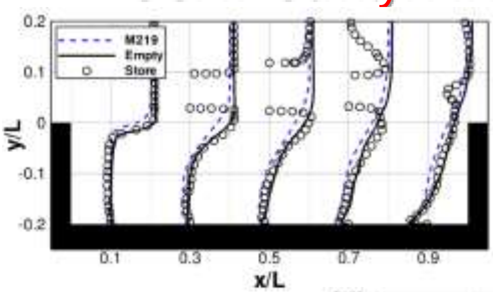
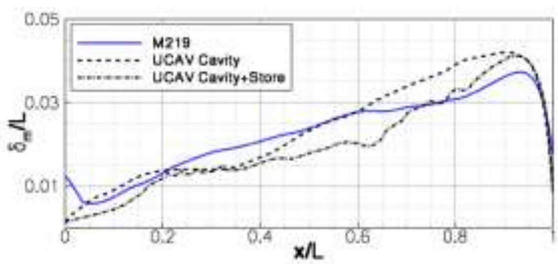
UCAV Cavity: Averaged Profiles

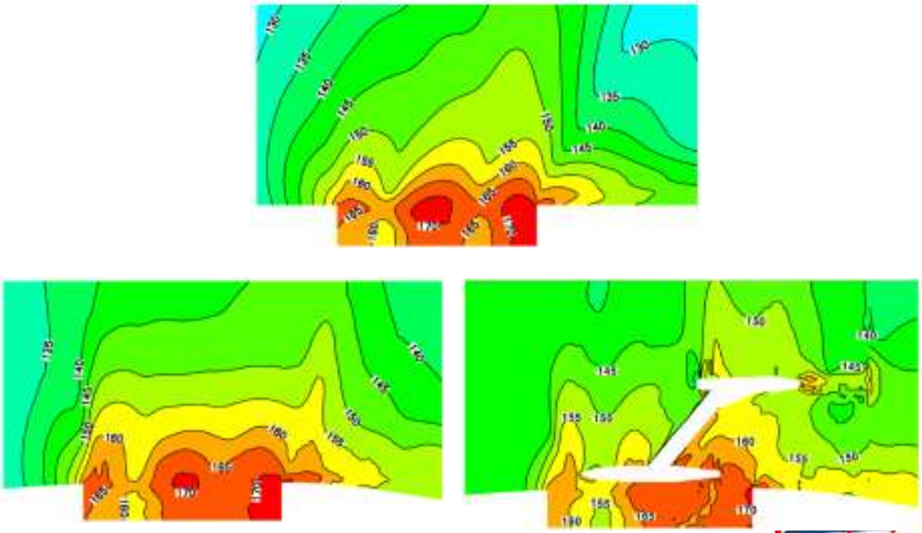


- **Streamwise Velocity Profiles**

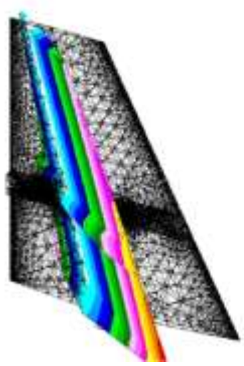
- **Momentum thickness**



UCAV Cavity: OASPL



Stores - Aeroelastics



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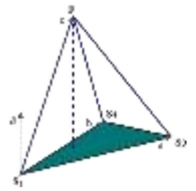
Aeroelastic Coupling Method. Constant Volume Tetrahedron.

Constant Volume Tetrahedron

- Each fluid node is projected to the nearest structural triangular element
- Fluid nodes move linearly with the element
- Find nearest triangular element (S_1,S_2,S_3) to each fluid node (F)
- The location of the fluid node can be expressed as

$$\vec{c} = \alpha\vec{a} + \beta\vec{b} + \gamma\vec{d}$$

- where $\vec{a} = \overrightarrow{S_1S_2},\ \vec{b} = \overrightarrow{S_1S_3},\ \vec{c} = \overrightarrow{S_1F}\ and\ \vec{d} = \vec{a} \wedge \vec{b}$



Fluid node (F), structural triangular element (S_1,S_2,S_3) and the resulting tetrahedron (S_1,S_2,S_3,F)

F. Dehaeze and G. N. Barakos, Mesh Deformation for Rotor Flows. Journal of Aircraft, Vol. 49(1), January 2012, pp. 8292.

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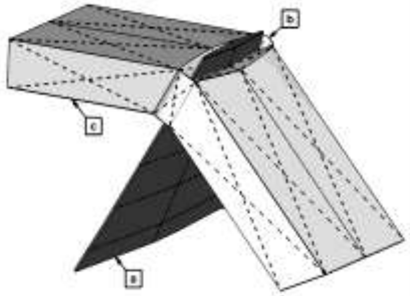
Spring Analogy Method for Deformation of Blocks around Store Fins.

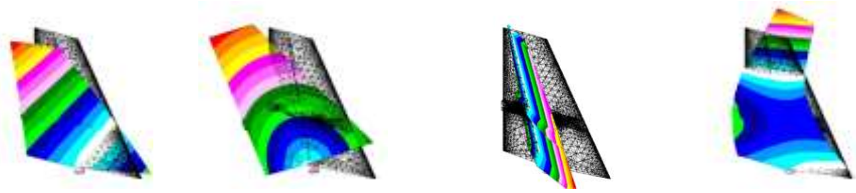
(a) Fin solid surface showing the edges of blocks
(b) First layer of blocks that are kept rigid and move with the fin
(c) Second layer of blocks that are allowed to deform

Solid lines represent the block boundaries that also act as springs.
Dashed lines represent the diagonals of each block face and also act as springs

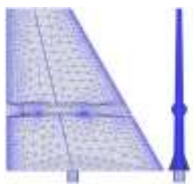


Representation of deforming blocks and spring analogy method for store fins.

Fin FEM Structural and Fin Mode Shapes from NASTRAN™.



Mode 1:144.14 Hz (Bending + Twisting)	Mode 2:158.05 Hz (In-Plane Bending)	Mode 3:232.02 Hz (Twisting)	Mode 4:923.55 Hz (Bending)



Fin Structural Model

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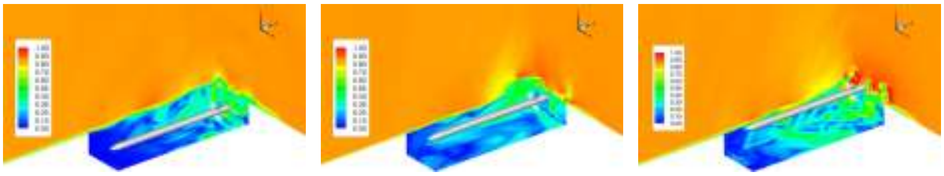
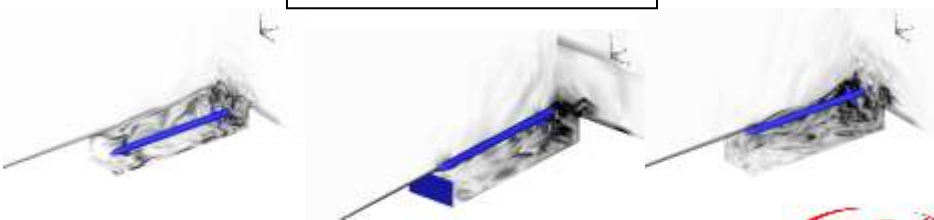
Instantaneous Flow-field. Q-Criterion. Q=2000.

Instantaneous Flow-field.

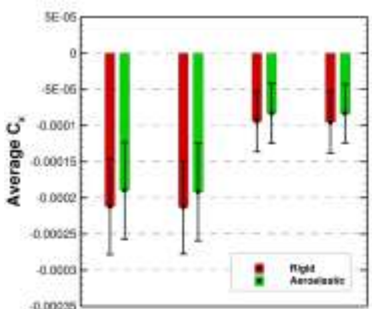
Instantaneous Mach Number Contours



Instantaneous Numerical Schlieren

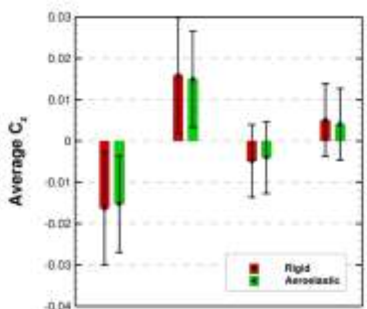


Average Fin Force Coefficients. Store at Carriage Position.



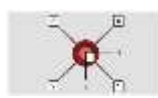
Fin 1 Fin 2 Fin 3 Fin 4

Axial Force Coefficient



Fin 1 Fin 2 Fin 3 Fin 4

Panel Force Coefficient



Error bars show RMS values.

•Axial and normal force coefficients are seen to be lower for the fins close to the cavity floor due to a lower dynamic head by almost 50%.
•Average normal force coefficients imply that the fin pairs (fin 1 and fin 2) and (fin 3 and fin 4) tend to bend away from each other
•Aeroelastic fins are seen to have a 10% reduction in axial force coefficients and about 6% in normal force coefficients.

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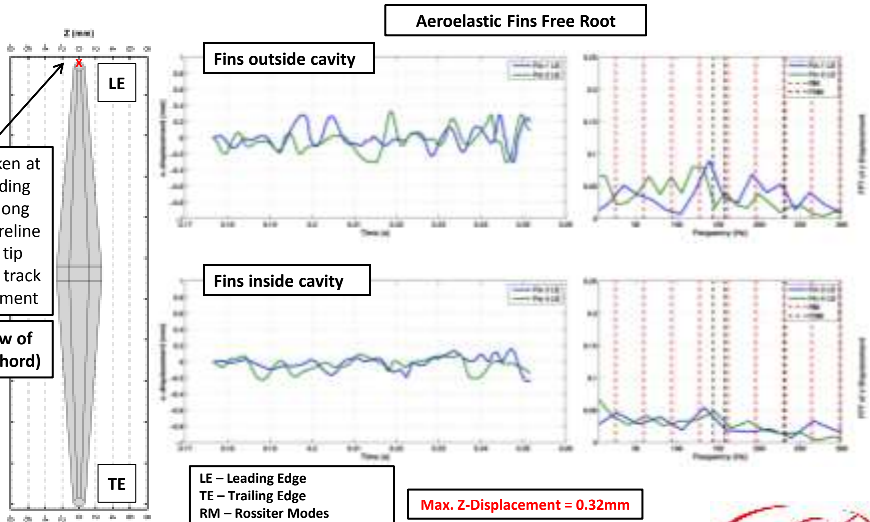
Fin Tip Displacement at Time and Frequency Domains.

Aeroelastic Fins Free Root



Point taken at the leading edge along the centreline of the tip chord to track displacement

Top view of fin (tip chord)

LE – Leading Edge
TE – Trailing Edge
RM – Rossiter Modes
FSM – Fin Structural Modes

Max. Z-Displacement = 0.32mm

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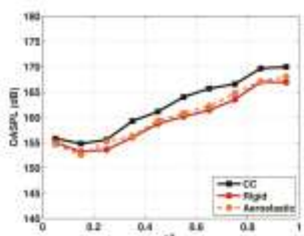
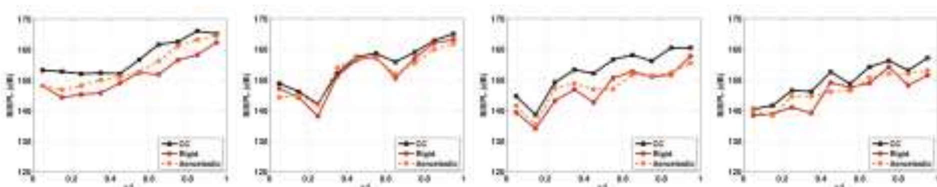
Band Integrated Sound Pressure Level. Store at Shear Layer.



Probes located on cavity floor along cavity centreline



CC – Clean Cavity, Rigid – Rigid Fins, Aeroelastic – Aeroelastic Fins ■ – Probe locations

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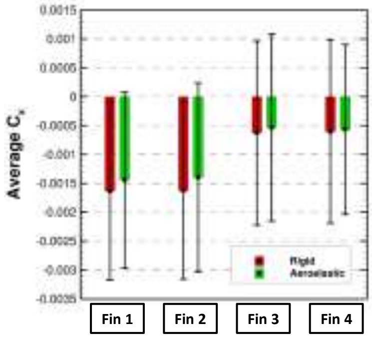
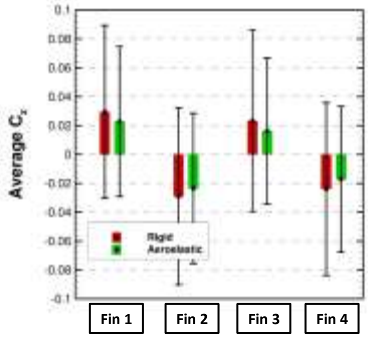
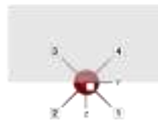
Average Fin Force Coefficients. Store at Shear Layer



Axial Force Coefficient



Panel Force Coefficient



Error bars show RMS values.

- Peak-to-peak values show large fluctuations in the loads and in most cases greater than the average themselves.
- Axial loads on the fins outside the cavity a just over 50% of those inside the cavity.
- The normal loads suggest that the fins pairs (1 and 2) and (3 and 4) want to bend towards each other with about 12% of difference between the fins inside and the fins outside the cavity.

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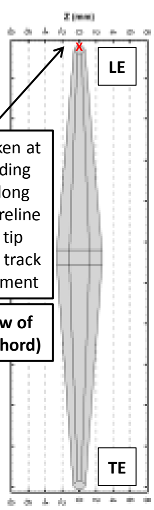
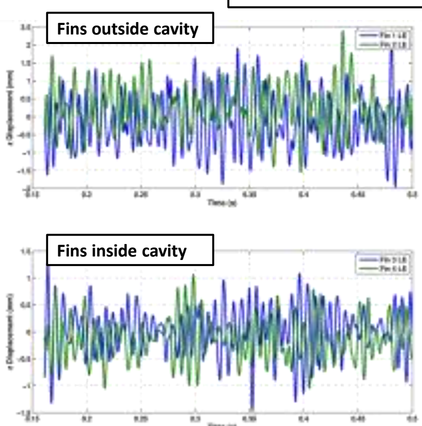
Fin Tip Displacement at Time and Frequency Domains.

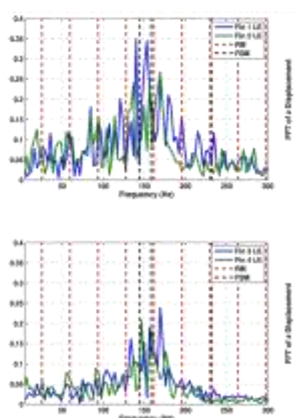


Point taken at the leading edge along the centreline of the tip chord to track displacement

Top view of fin (tip chord)

Aeroelastic Fins Fixed Root





LE – Leading Edge
TE – Trailing Edge
RM – Rossiter Modes
FSM – Fin Structural Modes

Max. Z-Displacement = 2.4mm

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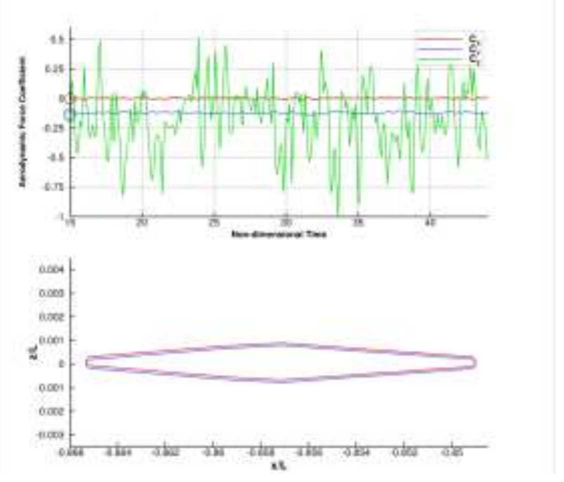
Fin displacement animation



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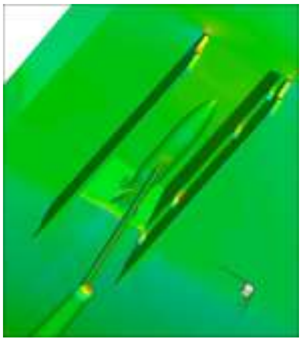
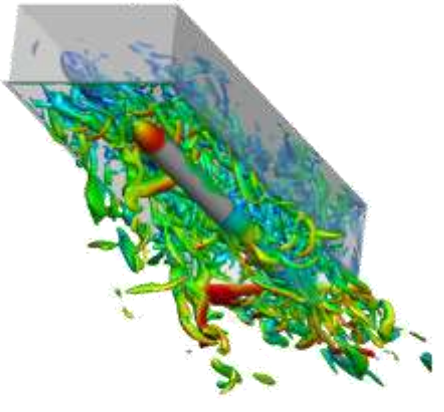
Stores - Release





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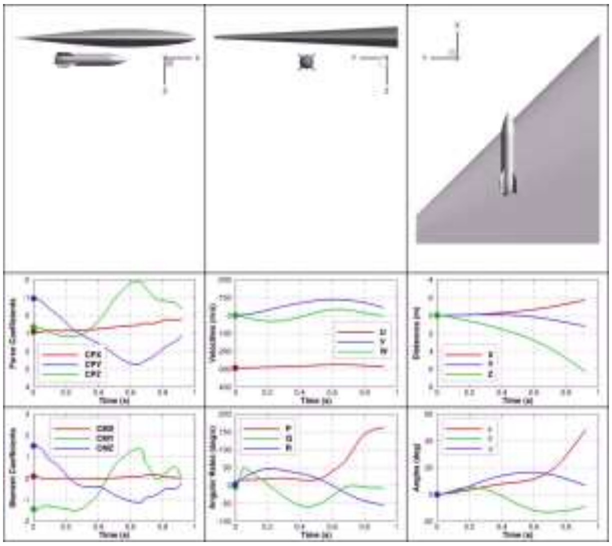
Store Loads and Trajectory



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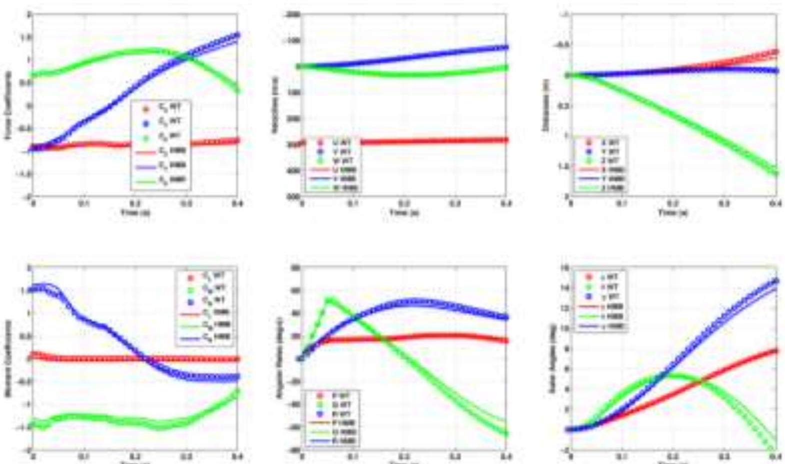
Store Loads and Trajectory

Force and moment coefficients are shown in force model axis system.

X, Y, Z – Distance of store c.g from the pylon axis system that is coincident with the c.g of the store (X is positive in the direction of flight, Y positive to pilot's right, Z is positive downward).

WT – Wind Tunnel
HMB – Computed Results

***Coefficient for base drag correction: 0.09**



Line Integral Convolution – Store at Carriage Position

Line Integral Convolution (LIC)

•LIC is a processing technique for imaging vector fields

•LIC of time-averaged flow-field of the store at carriage position is shown

Computational Details

•Cavity L/D 7

•M=0.85, Re=6.5x10^6 (based on cavity length)

•SAS SST k-ω model

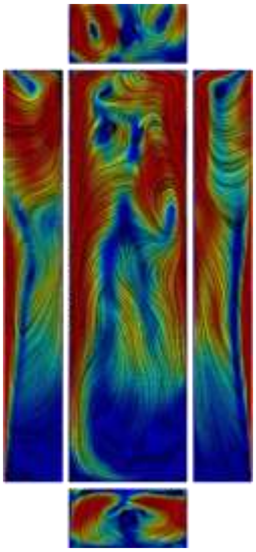
•**21M** nodes, 1104 blocks

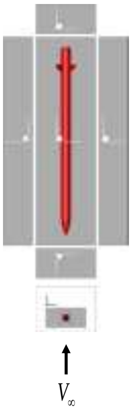
•Two chimera levels:

•Cavity grid (17m nodes, 800 blocks)

•Store grid (4m nodes, 304 blocks)

Flow was developed for **30** travel times





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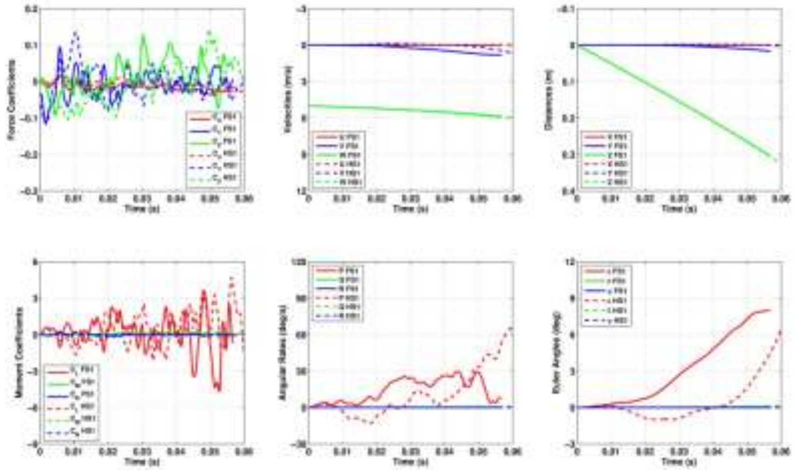
Store Release Simulations using SAS

ID	Unsteady Steps Before Stroke Application	Time Before Stroke Application (s)	Stroke Length
FS1	3000	0.35	Full stroke
FS2	3680	0.42	Full stroke
FS3	3770	0.43	Full stroke
FS4	4200	0.48	Full stroke
FS5	4400	0.51	Full stroke
FS6	3500	0.40	Full stroke
HS1	3000	0.35	Half stroke
HS2	3680	0.42	Half stroke
HS3	3770	0.43	Half stroke
HS4	4200	0.48	Half stroke
HS5	4400	0.51	Half stroke

*** Full stroke: half cavity depth (0.24m) , Half stroke: quarter cavity depth (0.19m)**

Store Loads and Trajectory – FS1 vs HS1



FS1: Steps: 3000, Full Stroke
HS1: Steps: 3000, Half Stroke

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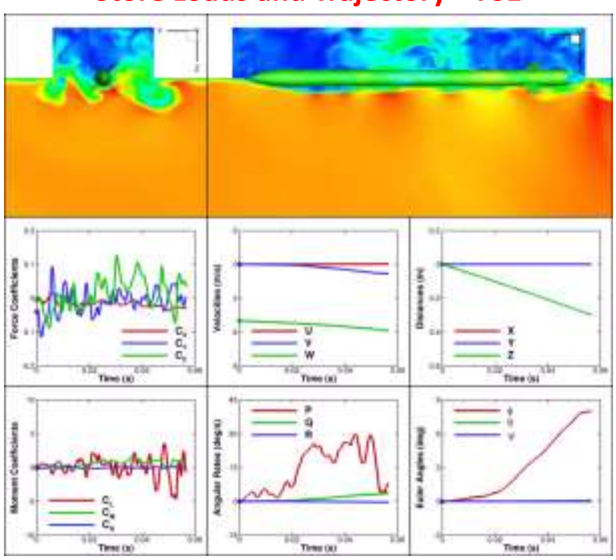
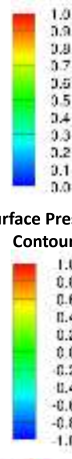
Store Loads and Trajectory – FS1



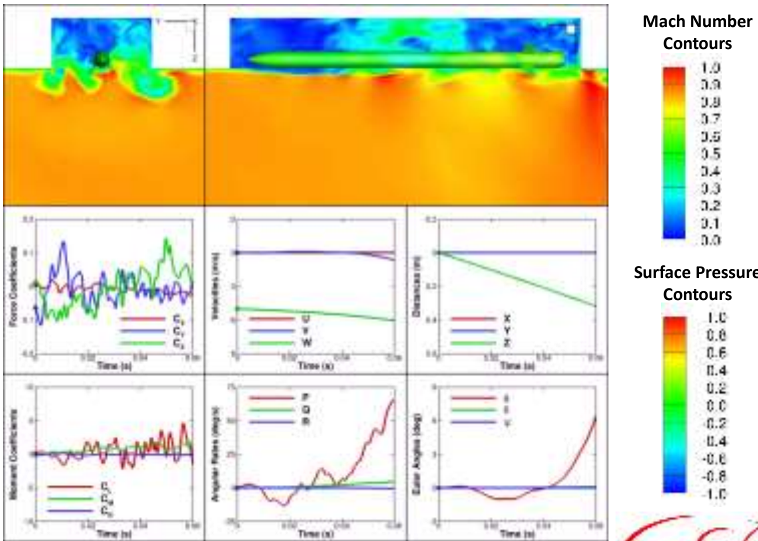
Mach Number Contours

Surface Pressure Contours



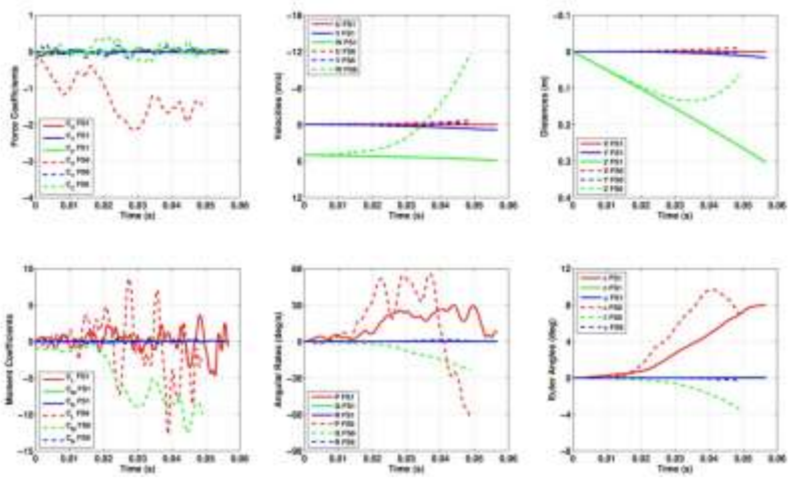
FS1: Steps: 3000, Full Stroke

Store Loads and Trajectory – HS1



HS1: Steps: 3000, Half Stroke

Store Loads and Trajectory – FS1 vs FS6



FS1: Steps: 3000, Full Stroke
FS6: Steps: 3500, Full Stroke

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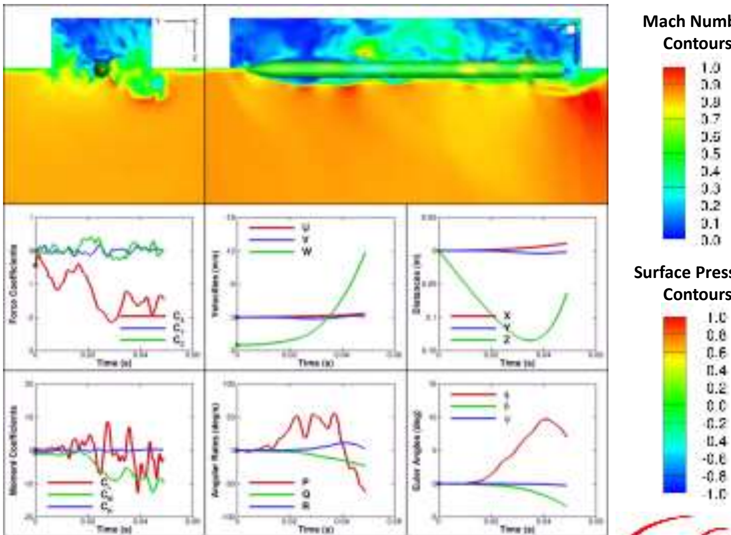
Store Loads and Trajectory – FS6



FS6: Steps: 3500, Full Stroke

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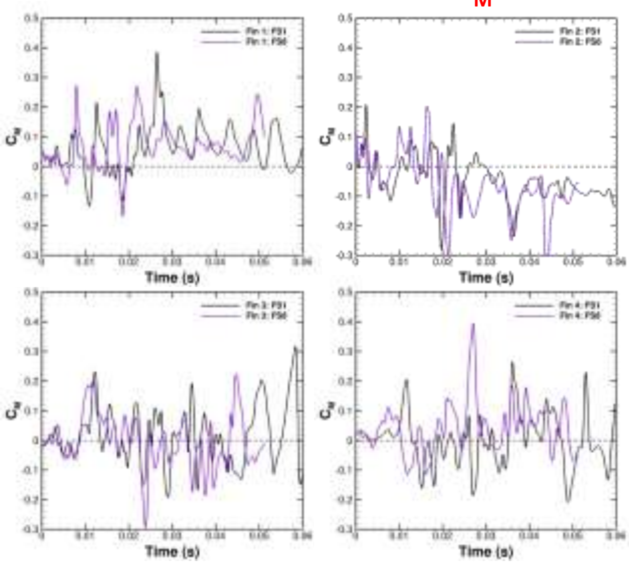
FS1 vs FS6 - Fin Loads - C_M

Fin 1

Fin 2



Fin 3

Fin 4

FS1: Steps: 3000, Full Stroke
FS6: Steps: 3500, Full Stroke

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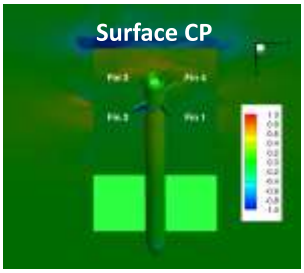
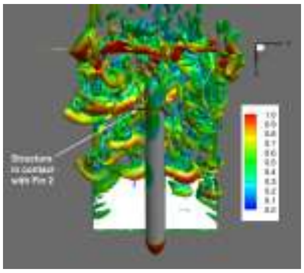
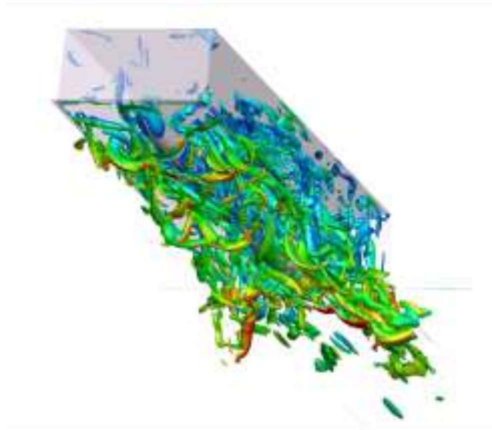
Fin Surface CP and Q-Criteria Structures







Iso-surfaces of Q-Criteria (coloured with Mach number)

Store Release Computation FS1
Steps: 3000, Full Stroke

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Summary and Future Work

Comparison of the effect of time step between DES and SAS

- SAS showed savings in computational time with similar results to DES

The slanted aft wall was found to be the most effective passive method for reducing the cavity acoustics

- Could be combined with other methods like lining of the cavity walls

Aeroelastic effects demonstrated

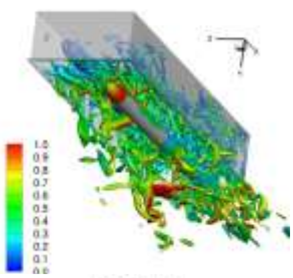
- No data available for comparisons

SAS used for store release simulations from a cavity

- Varying release times and stroke lengths showed very little differences in CG displacement
- Orientation was seen to vary in roll-axis for most cases
- Case FS6 showed different trajectory to other cases

Further computations and investigations underway

- Multi-store configurations
- Attempt release of stores from slated-aft-wall cavities



Cavity Flow Review

- S.Lawson, G. Barakos,
  Review of numerical simulations for high-speed, turbulent cavity flows,
  Progress in Aerospace Sciences, Volume 47, Issue 3, April 2011, Pages 186-216

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