CFD Analysis of Transonic Cavity Flow Using DES and LES

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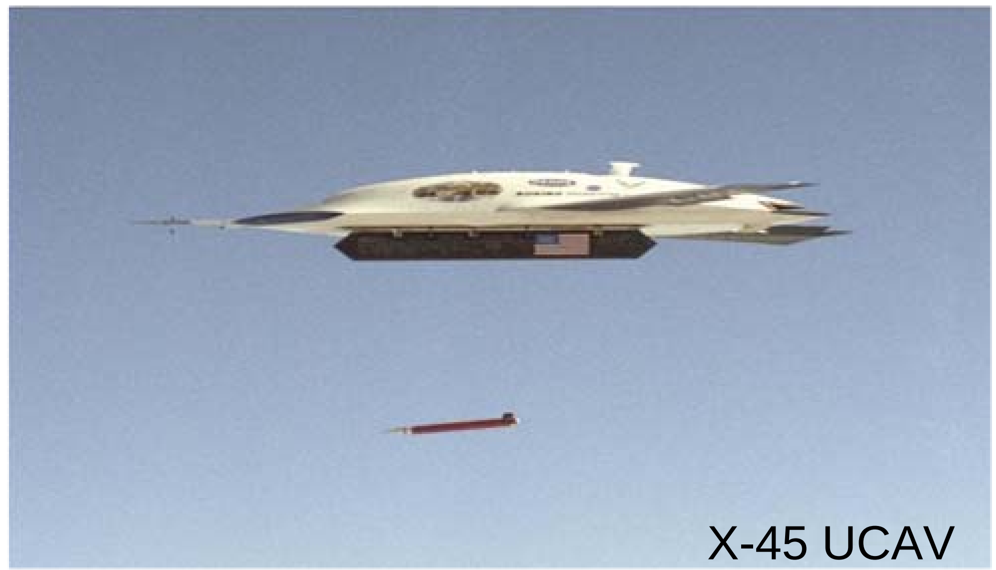
Background

F-102 Delta Dagger

- Reduced aircraft drag
- Enhanced manoeuvrability
- Reduced aerodynamic heating of stores
- Reduced radar cross-section

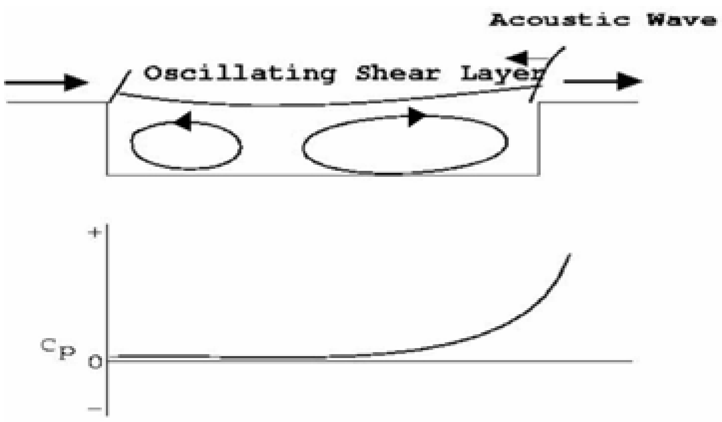
- Problems occur when weapon bay doors are opened to release store
- Exposure to free-stream produces undesirable effects
  - Depends on weapon bay geometry (modelled using a cavity)

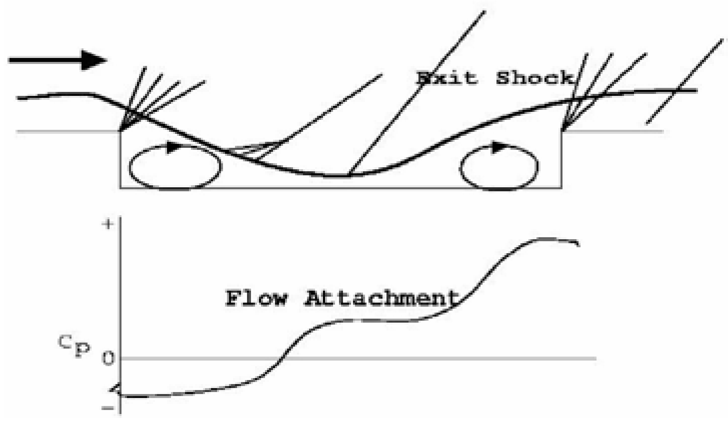


X-45 UCAV

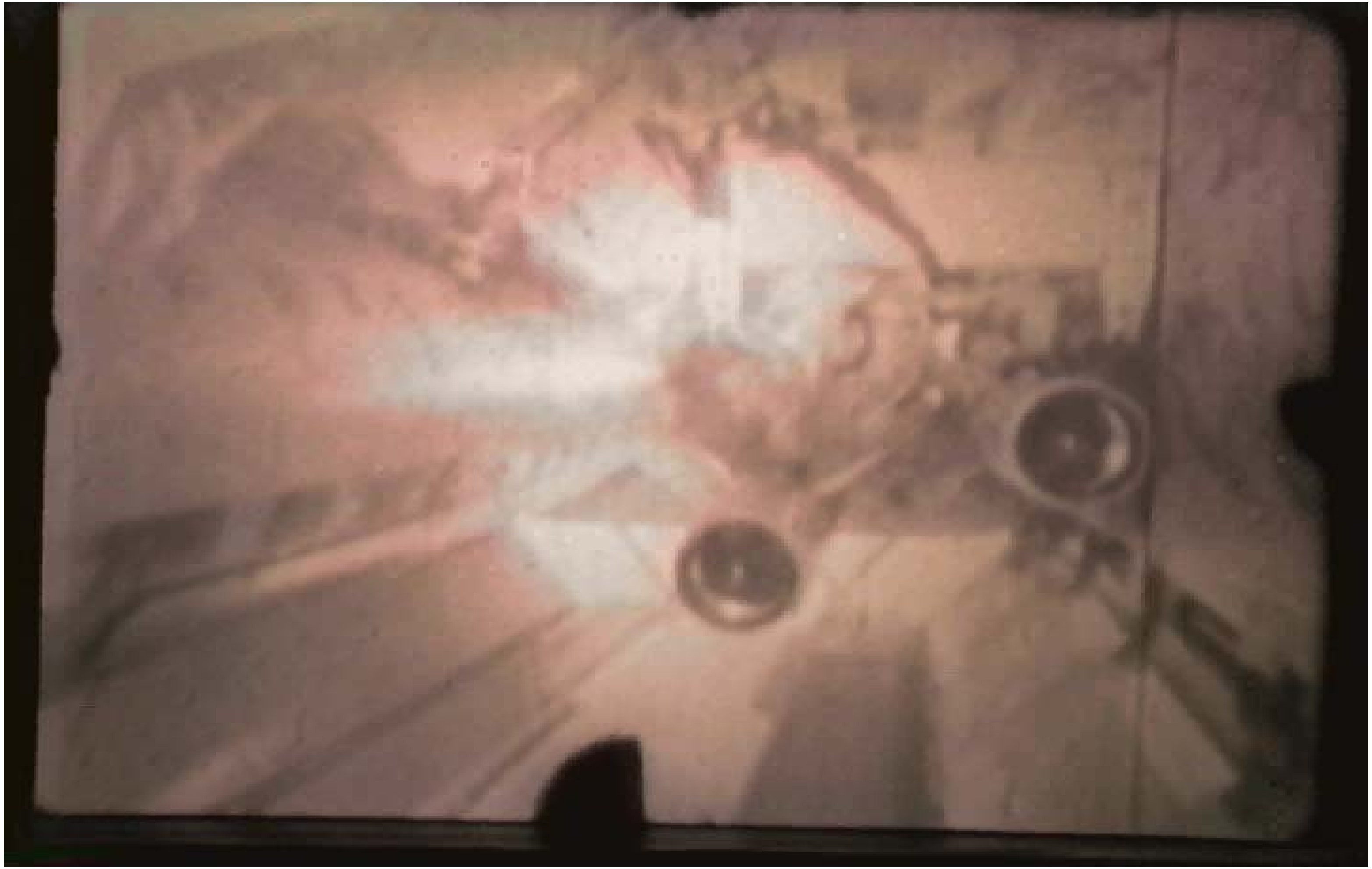
Background

- Open cavities:
  - Shear layer spans cavity
  - Acoustic pressure waves propagate externally and internally
  - Mass ejection/injection
  - High noise levels & frequencies
- Closed cavities:
  - Separation, re-attachment, separation
  - Large pitching moments
  - Store separation & release problems
- 3D, L/D = 5, W/D = 1, M=0.85
  - open cavity





F-111 Flight Test

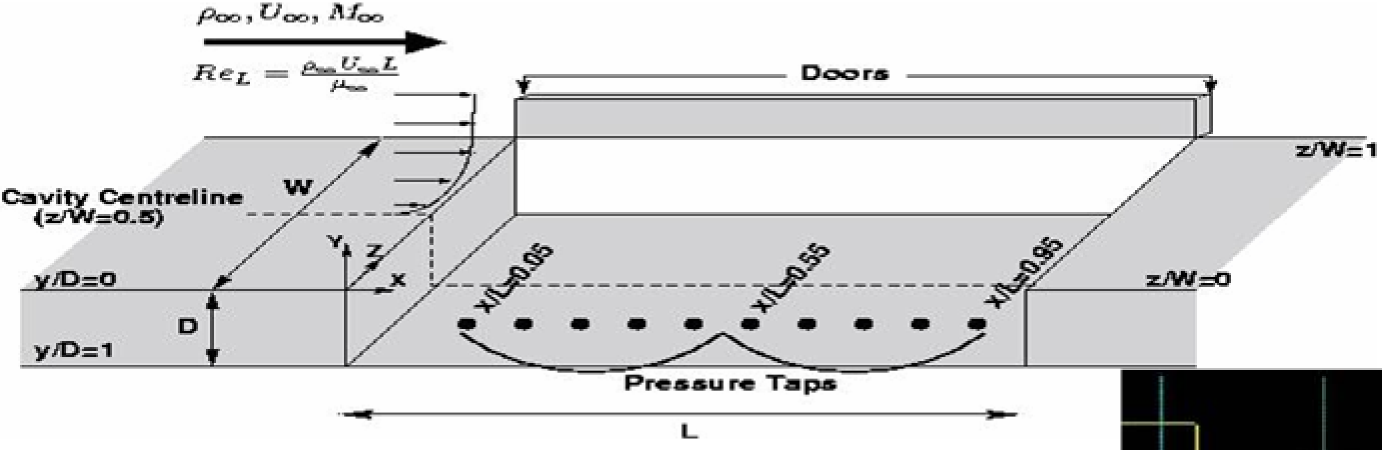


Previous Cavity Flow Research

- Researched since 1950s
- Wind tunnel experiments
  - Rossiter, Karamcheti, Krishnamurthy – acoustics, buffet
  - Tam & Block, Rockwell & Naudascher (1970s) – acoustics & flow physics
  - Stallings, Wilcox Jr. (1980s) – store separation and release
  - Ross (QinetiQ, 2000) - PIV (L/D=5 cavity)
  - Knowles (Cranfield, 2000) – LDA (L/D=10 cavity)
- Computational Fluid Dynamics
  - Orkwis & Disimile, etc. (1990s) – URANS
  - Shieh (2003) – DES (L/D=4.4 cavity)
  - Rizzetta (2003) – LES (L/D=5 cavity)
  - Larchevêque (ONERA, 2003) – LES (L/D=2 cavity)

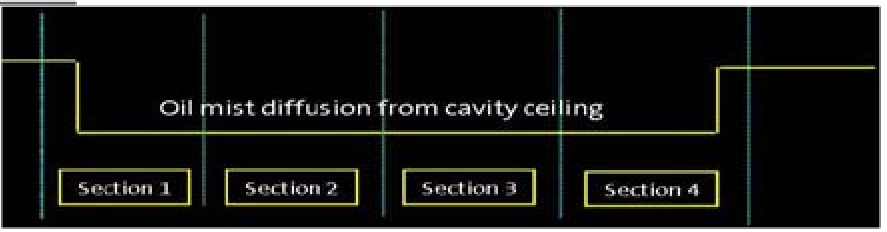
Experimental Data: Pressure

- Source: DERA (Bedford, UK) – Ross, Wrisdale, Peto (2000)
- Geometry: Empty cavity, L/D = 5, W/D = 1, doors-off & doors-on
- Pressure transducers (doors-off & doors-on), PIV (doors-on)
- Flow Conditions: M = 0.85, $Re_L = 6.783 \times 10^6$



Pressure Transducers Set-Up

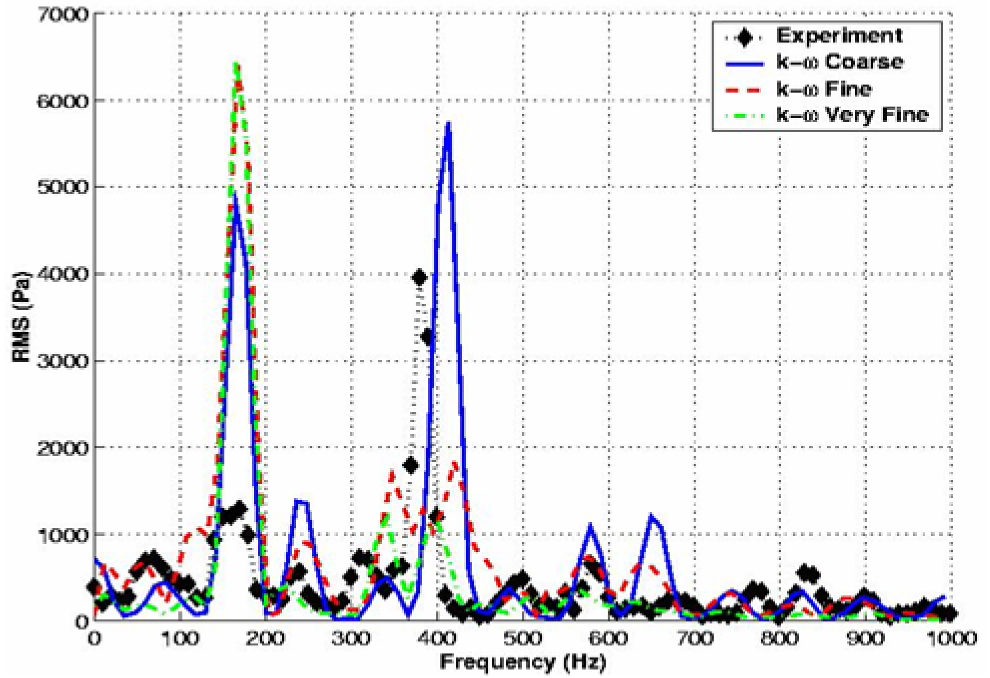
PIV Set-Up



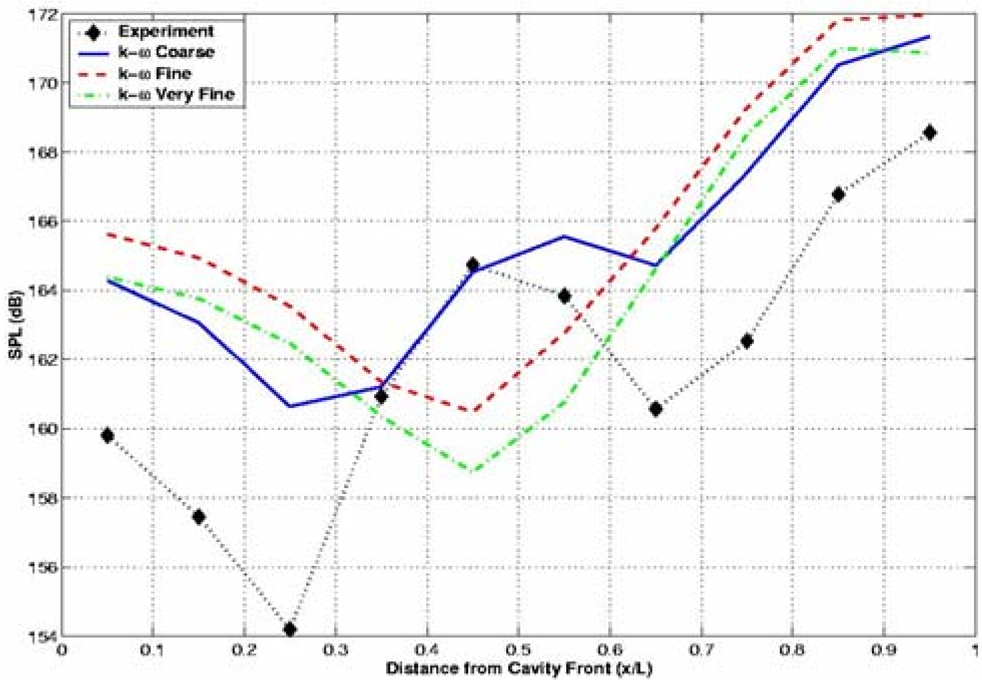
Flow Solver: Parallel-Multi Block (PMB)

- Control Volume method
- Parallel (distributed memory)
- Multi-Block structured grids, moving grids
- Implicit time marching
- Osher's and Roe's schemes for convective fluxes
- MUSCL scheme, formally 3rd order accurate
- Central differences for viscous fluxes
- Krylov sub-space linear solver with pre-conditioning
- Variety of turbulence models as well as turbulent simulation methods

2D Results: Cavity Floor

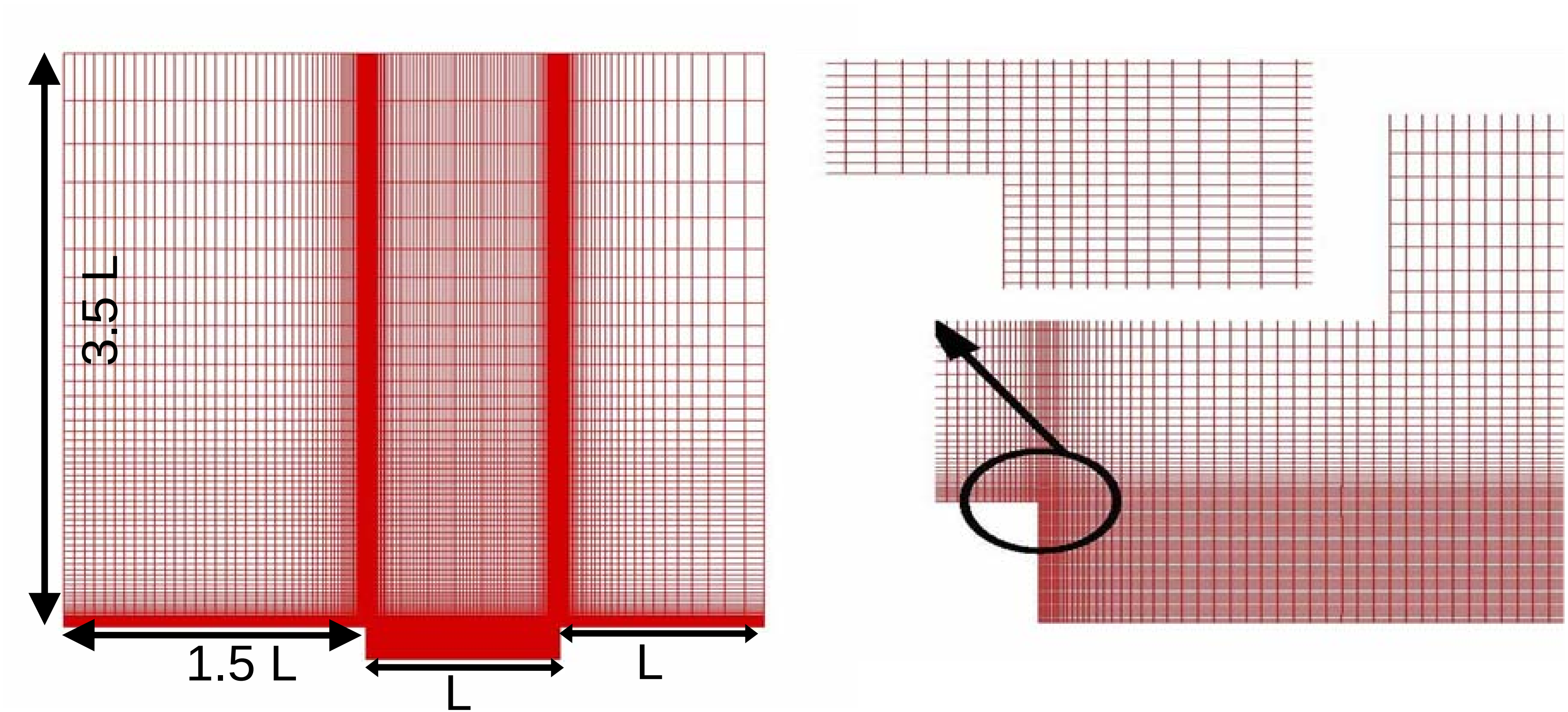


SPLs



PSD (x/L = 0.95)

3D Computational Domain



L/D = 5 , W/D = 1

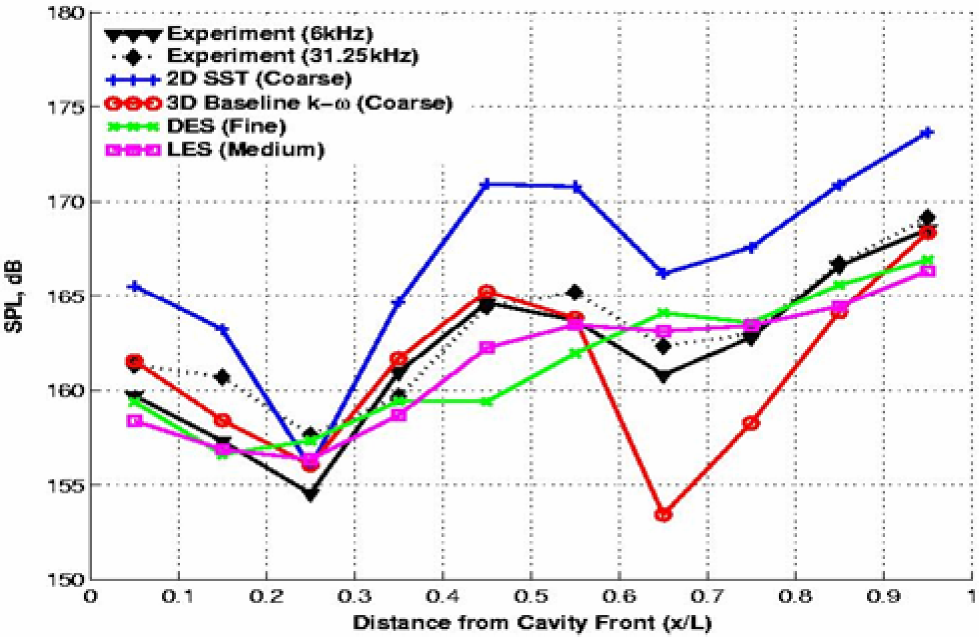
CPU Time on Beowulf and HPCX

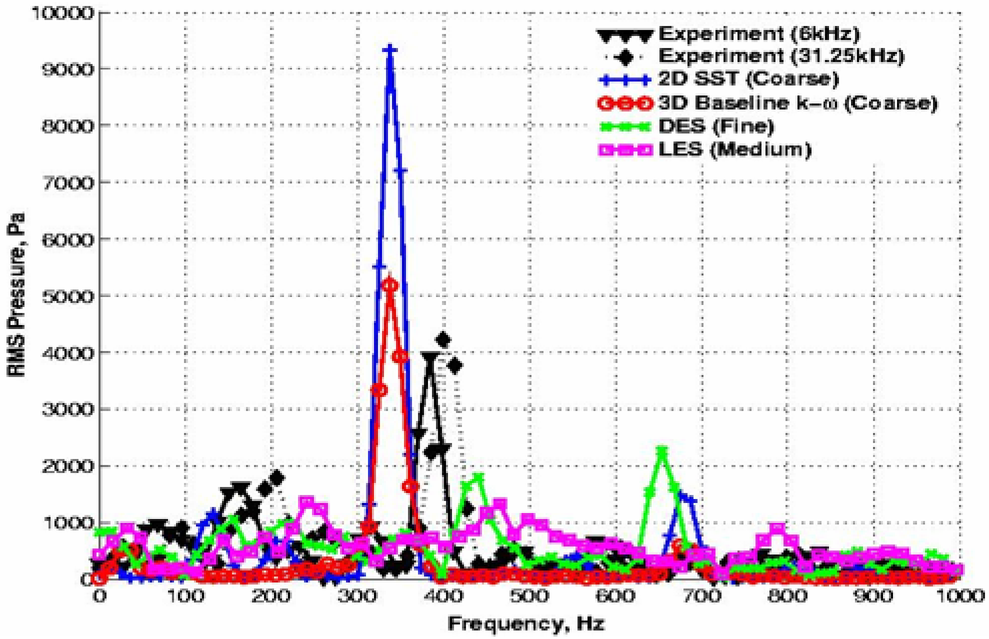
DES, LES and URANS calculation details on HPCx and Beowulf cluster

Calculation Details	DES	LES	URANS
Platform	HPCx	Beowulf cluster	Beowulf cluster
Cavity Configuration	Doors-On	Doors-Off	Doors-On
Grid Size	4.5×10^6	4.5×10^6	1.5×10^6
Processors	320	24	19
Time-Step (s)	1.81×10^{-6}	1.81×10^{-6}	1.81×10^{-5}
Pseudo-Steps/Time-step	6	4	39
Time-Steps/min.	9.72	0.723	0.425
Total Time-Steps	50,200	50,000	5,506
Total CPU Hours	28,100	**27648**	**4104**
Signal Duration	0.1 s	0.1 s	0.1 s
Total Run-time	3.46 days	48 days	9 days

Doors-On Results: Cavity Floor

SPLs



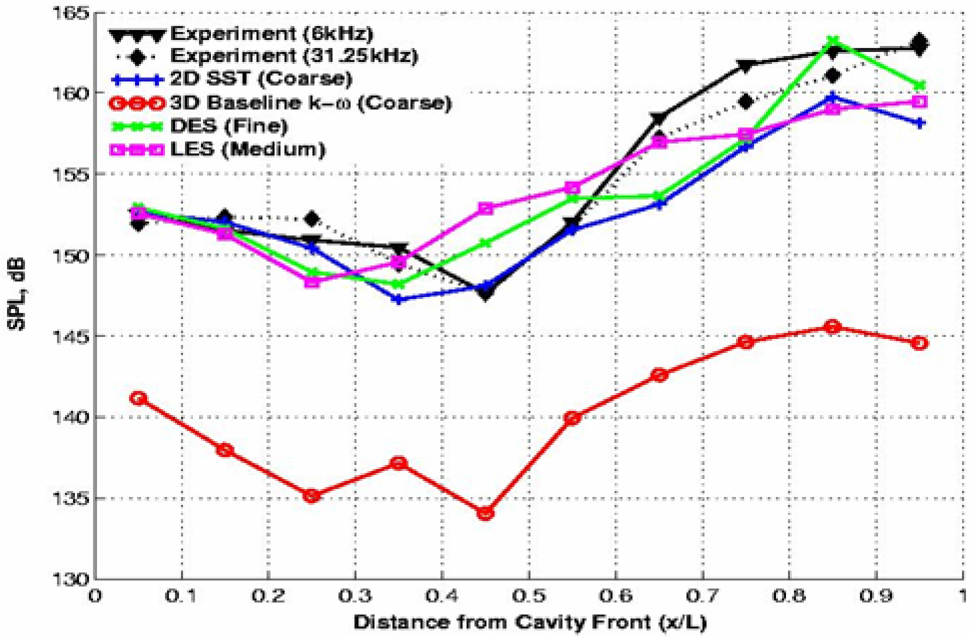


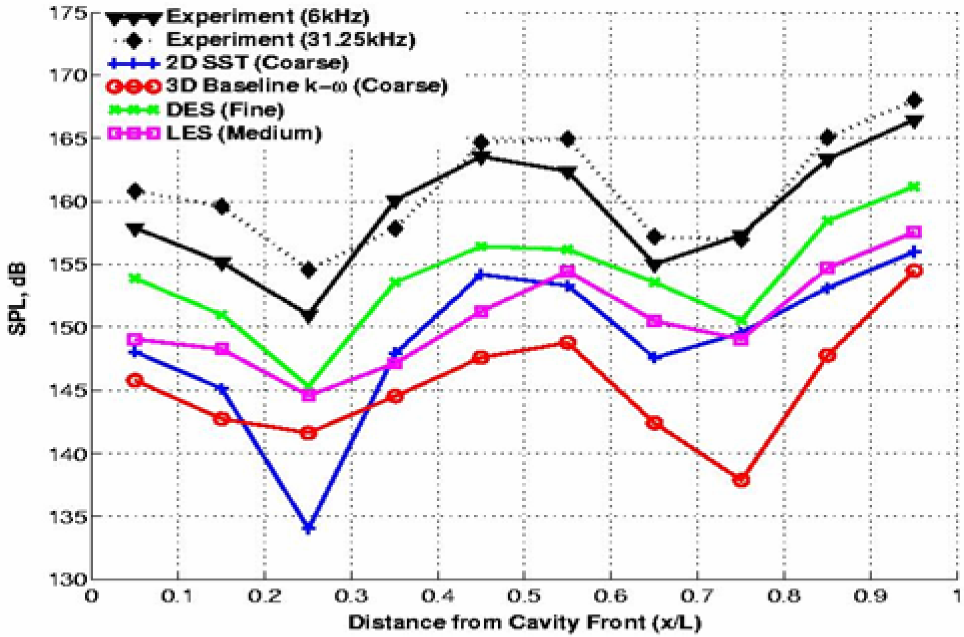
PSD (x/L = 0.95)

Doors-On Results: Cavity Floor

Band-Limited SPLs

50 Hz ≤ f ≤ 250 Hz



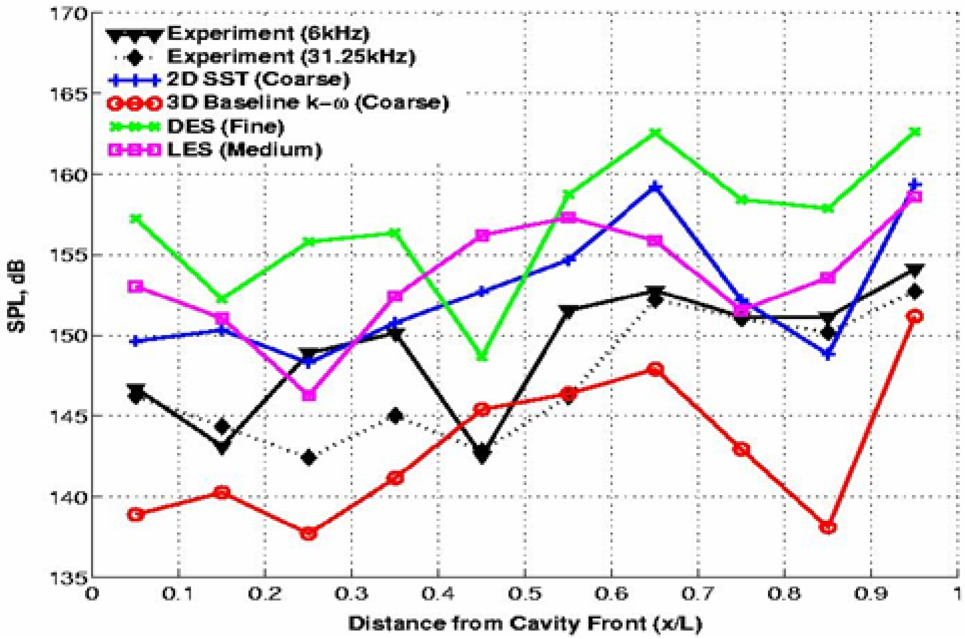


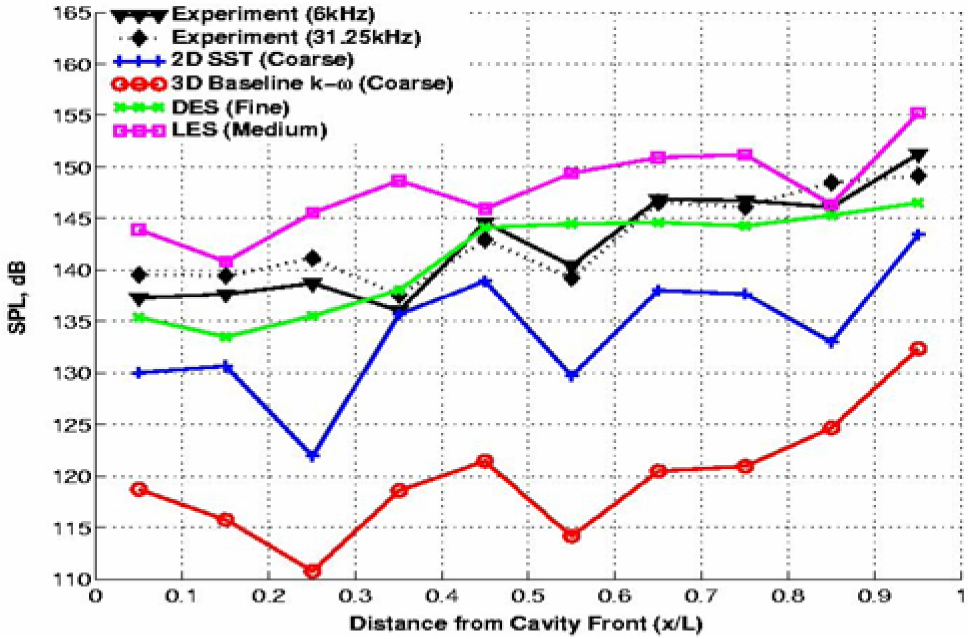
350 Hz ≤ f ≤ 450 Hz

Doors-On Results: Cavity Floor

Band-Limited SPLs

500 Hz ≤ f ≤ 700 Hz

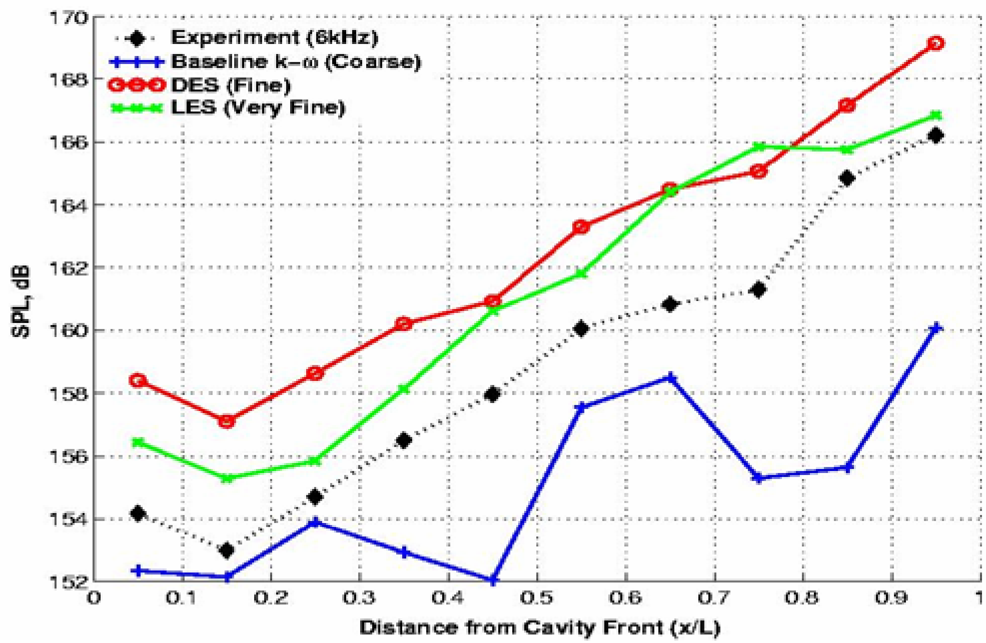


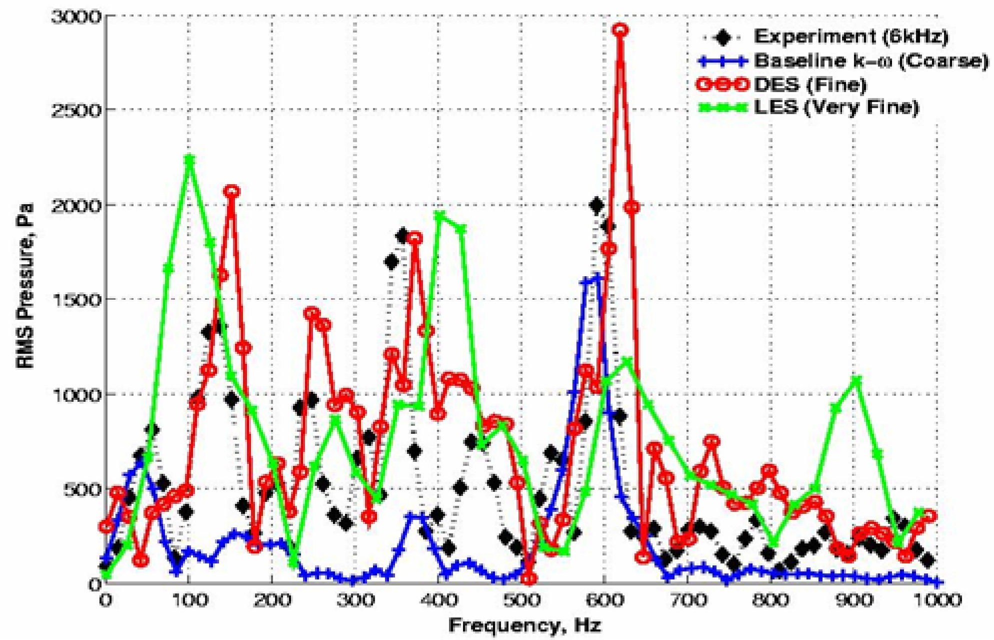


750 Hz ≤ f ≤ 850 Hz

Doors-Off Results: Cavity Floor

SPLs



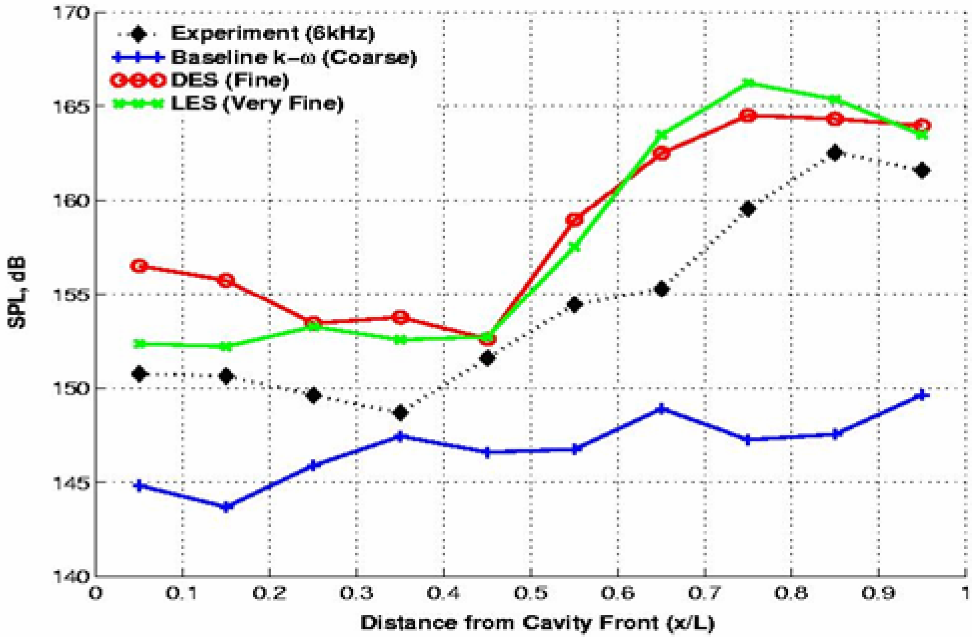


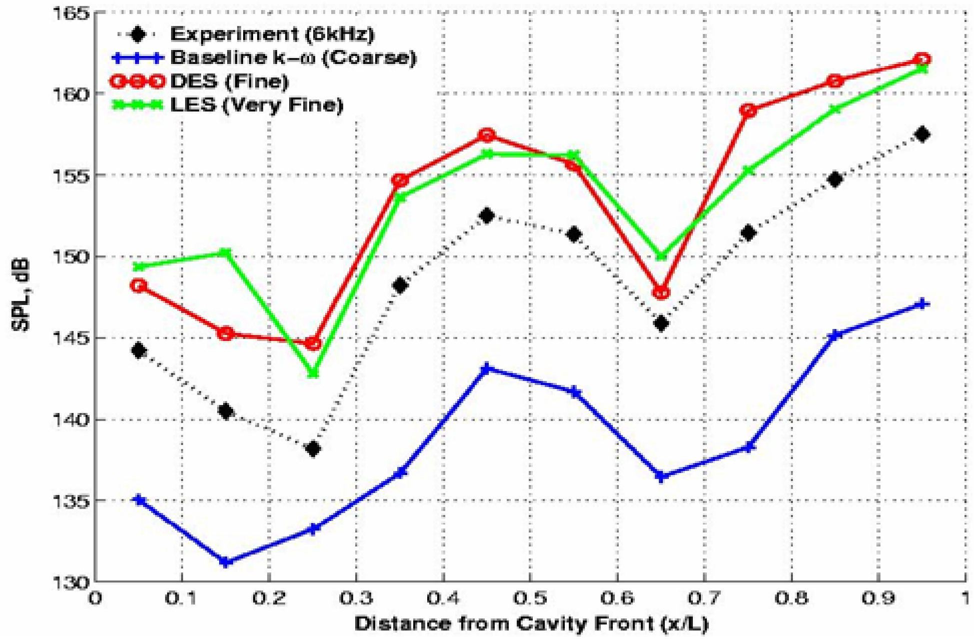
PSD (x/L=0.95)

Doors-Off Results: Cavity Floor

Band-Limited SPLs

50 Hz ≤ f ≤ 250 Hz





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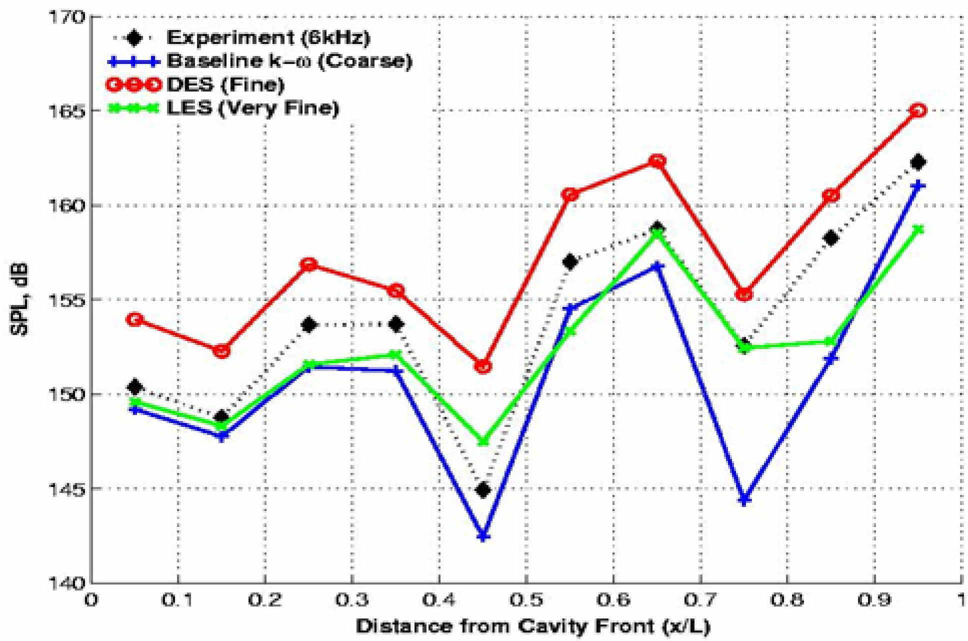
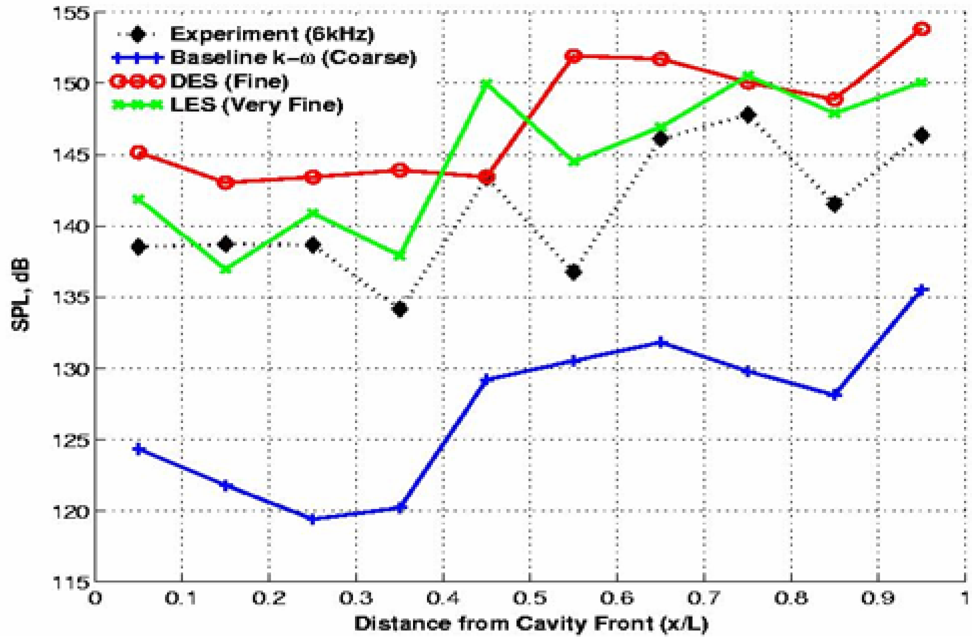
Doors-Off Results: Cavity Floor

Band-Limited SPLs

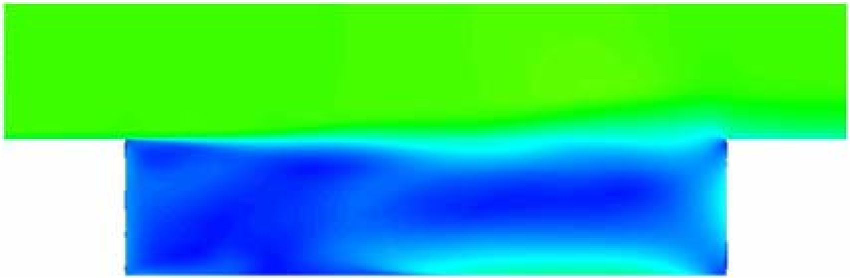
500 Hz ≤ f ≤ 700 Hz



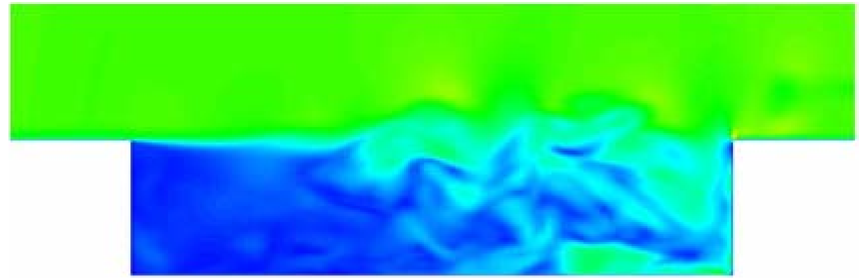


750 Hz ≤ f ≤ 850 Hz

Doors-Off Results: Flow-Field

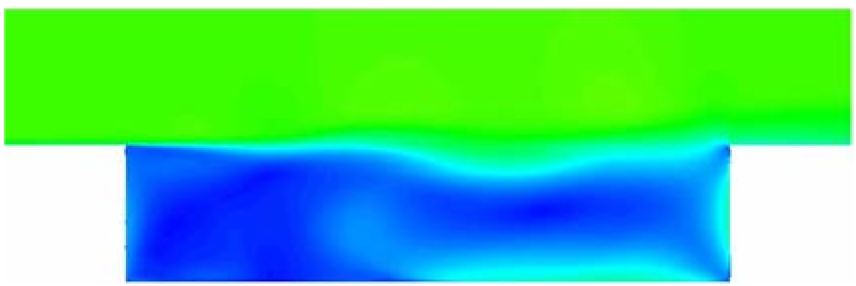


t = 0.0816 s (Baseline k-ω)

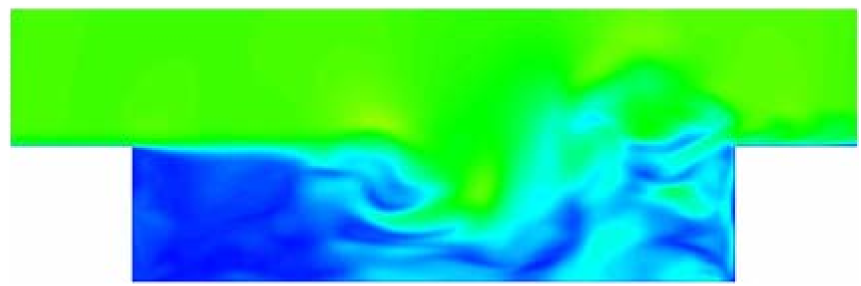


t = 0.0816 s (DES-SA)

Instantaneous Mach Contours

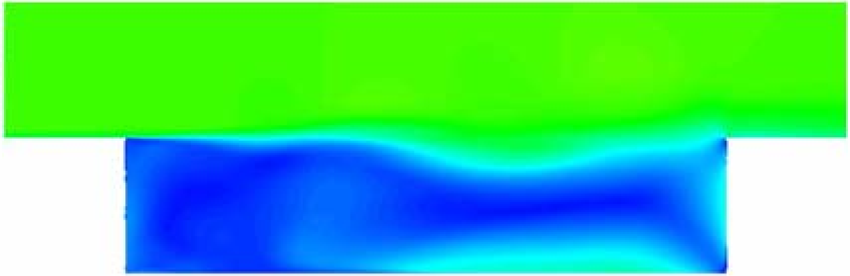


t = 0.0834 s (Baseline k-ω)

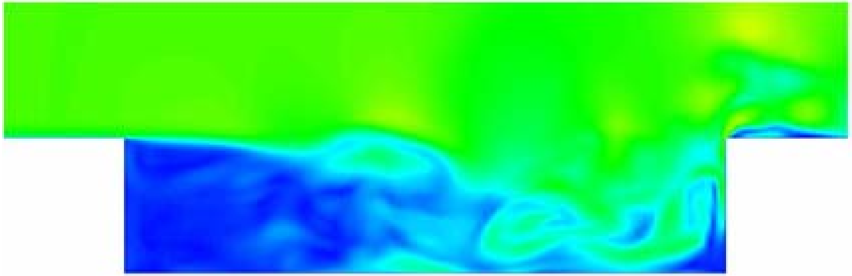


t = 0.0834 s (DES-SA)

Doors-Off Results: Flow-Field

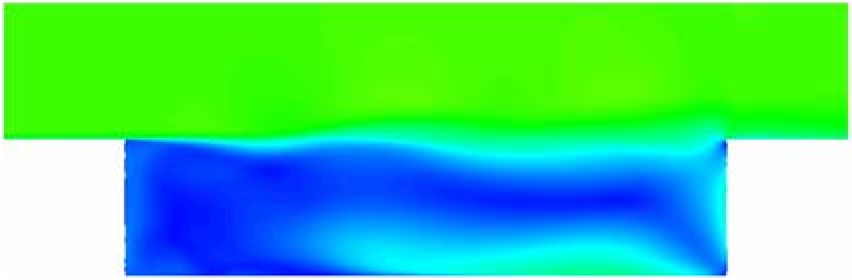


t = 0.0852 s (Baseline k-ω)

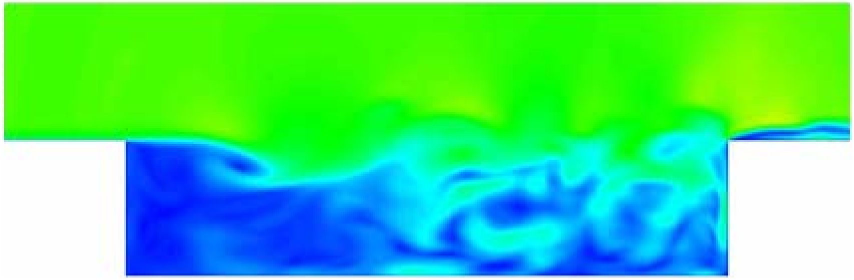


t = 0.0852 s (DES-SA)

Instantaneous Mach Contours



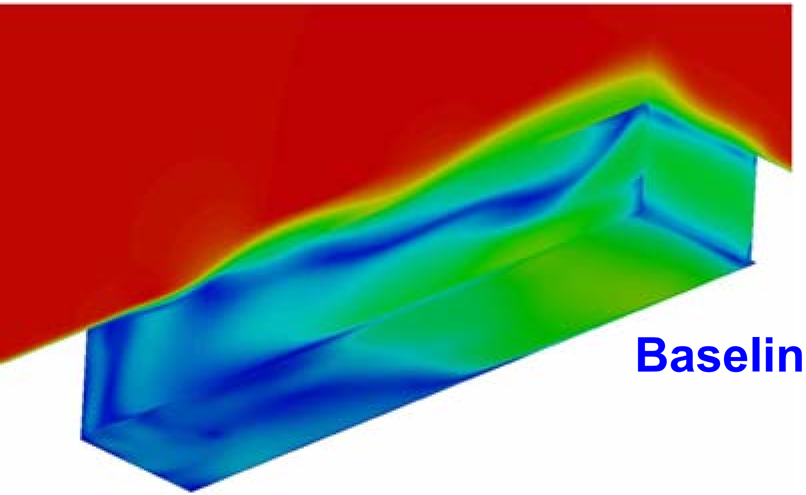
t = 0.0870 s (Baseline k-ω)



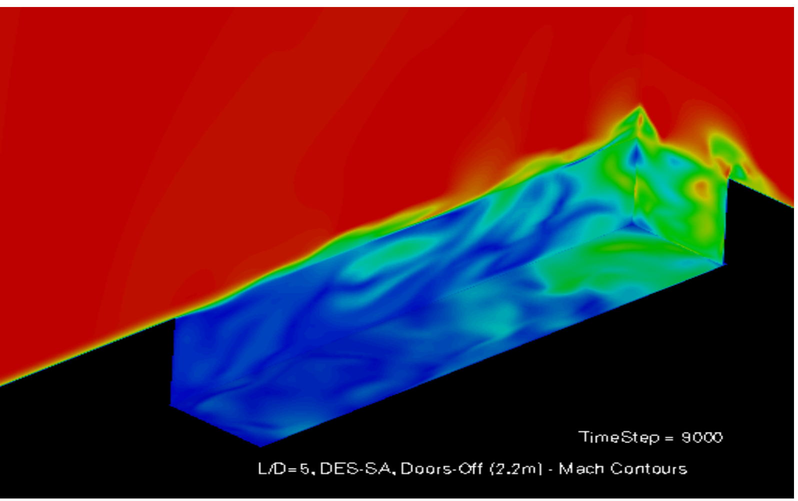
t = 0.0870 s (DES-SA)

Doors-Off Results: Flow-Field

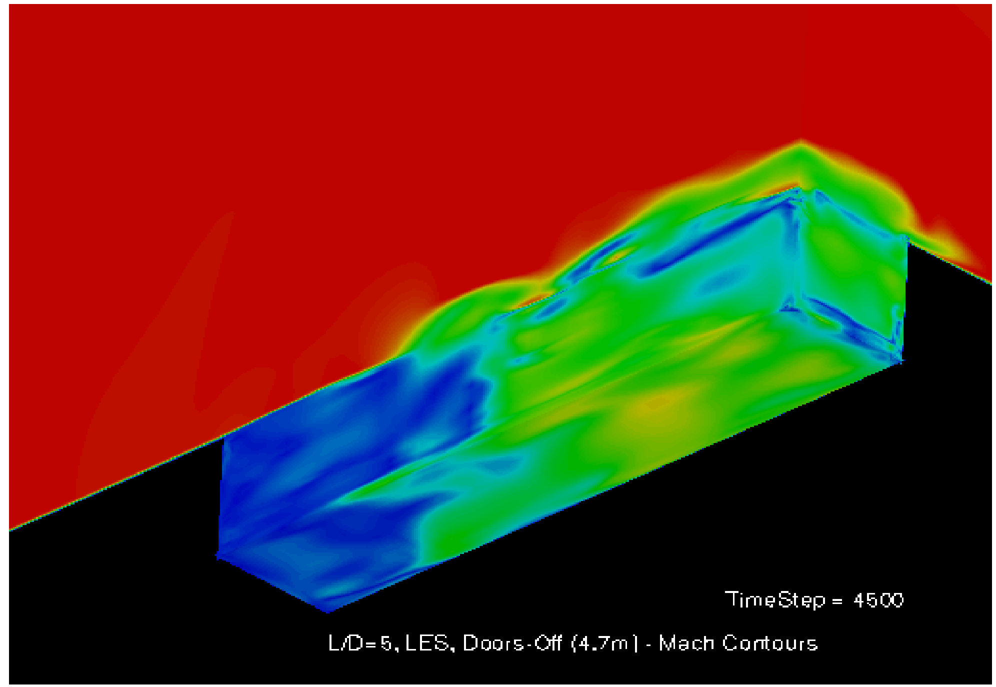
Instantaneous Mach Contours



Baseline k-ω

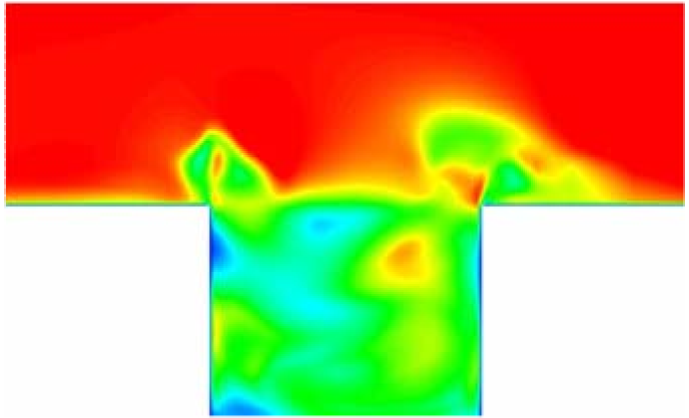


DES-SA

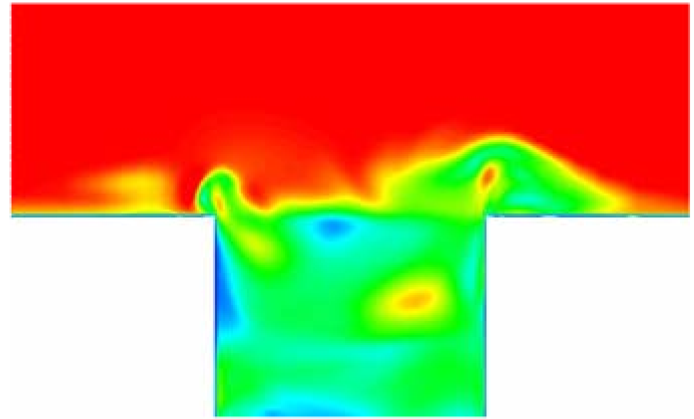


LES

Doors-Off Results: Downstream Wall

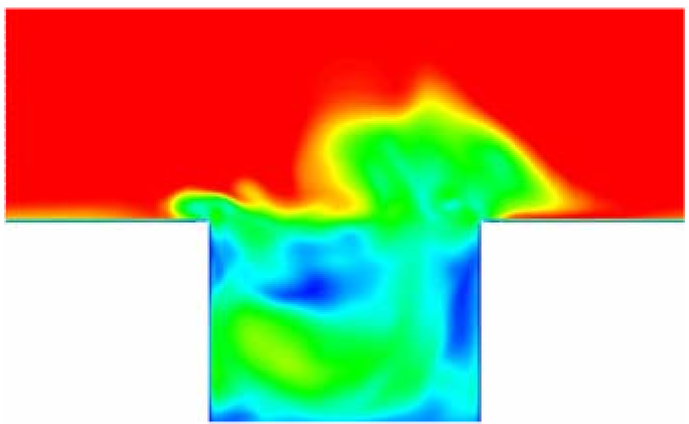


t = 9000 s (DES-SA)

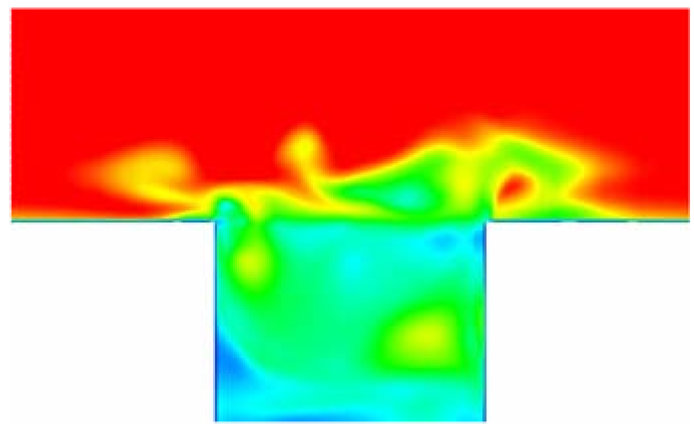


t = 9020 s (DES-SA)

Instantaneous Mach Contours: Vortical ‘Spillages’

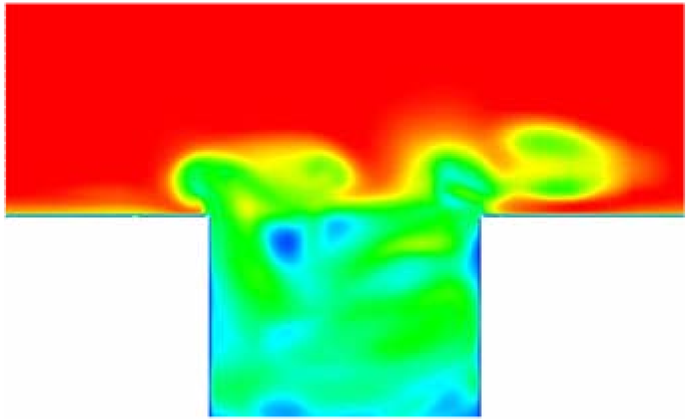


t = 9100 s (DES-SA)

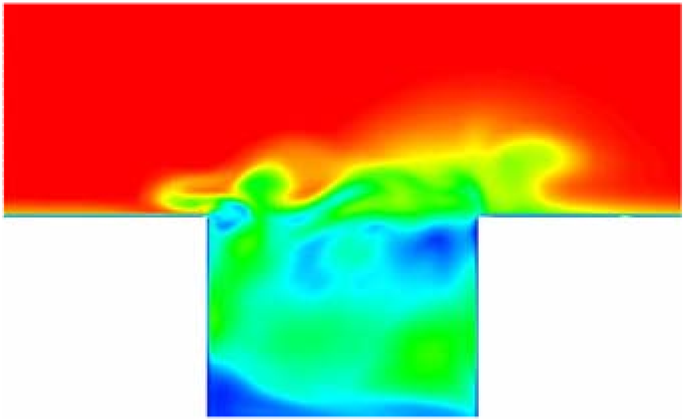


t = 9040 s (DES-SA)

Doors-Off Results: Downstream Wall

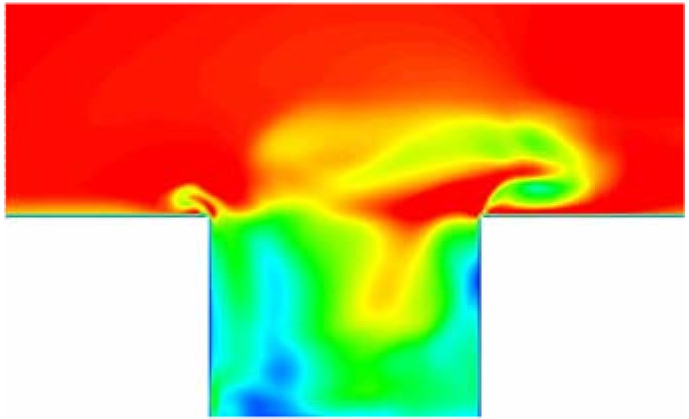


t = 9200 s (DES-SA)

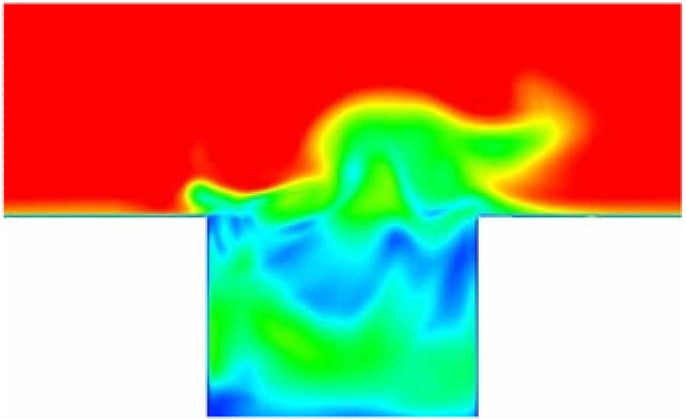


t = 9060 s (DES-SA)

Instantaneous Mach Contours: Vortical 'Spillages'



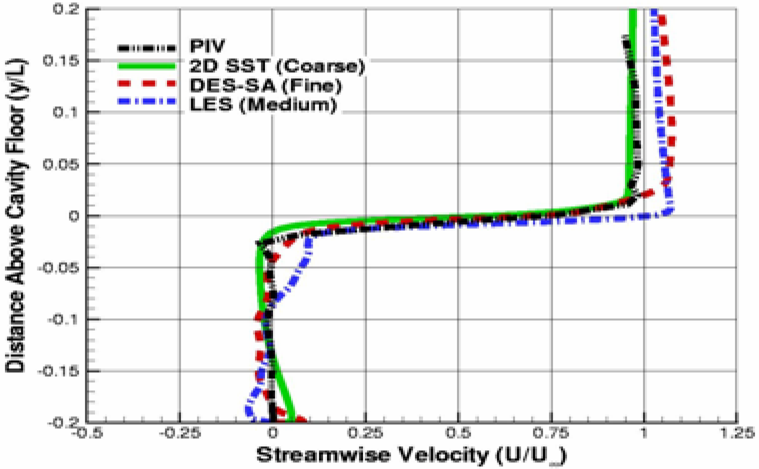
t = 9300 s (DES-SA)



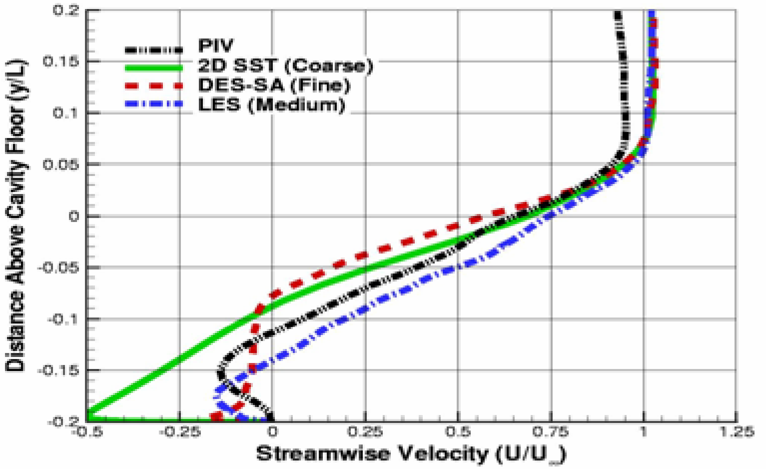
t = 9080 s (DES-SA)

PIV Comparisons: Doors-On

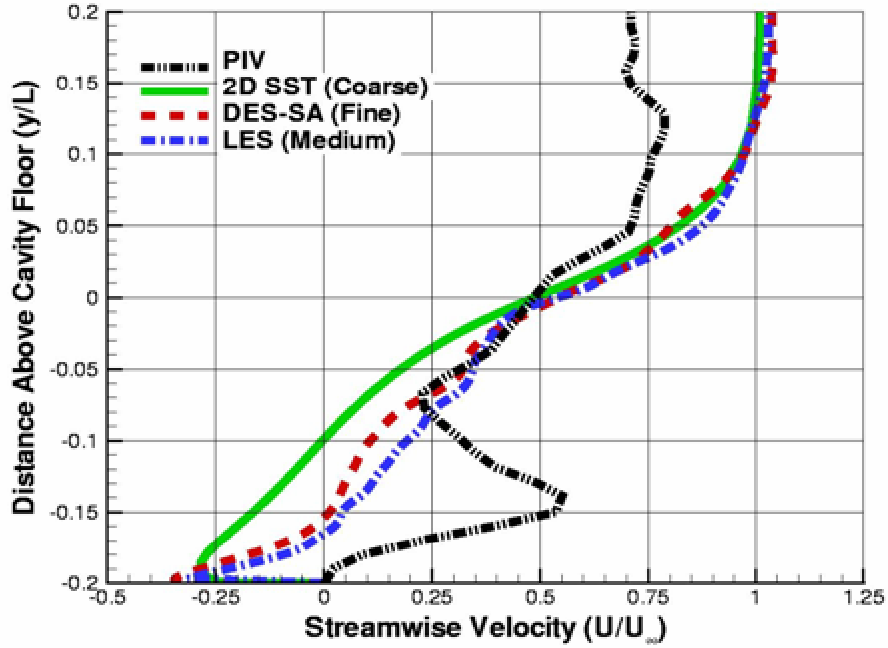
Streamwise (U) Velocity Profiles



x/L = 0.05



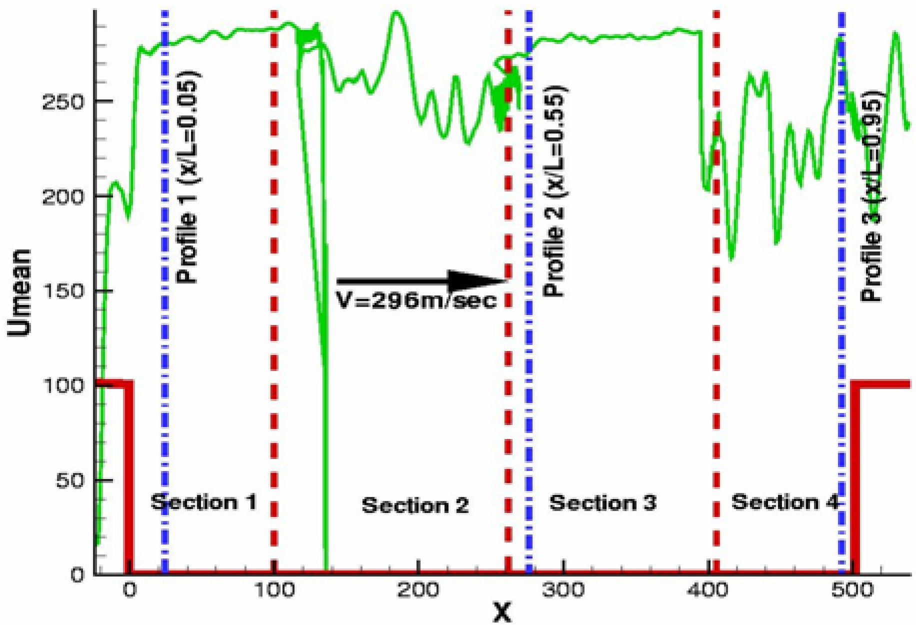
x/L = 0.55

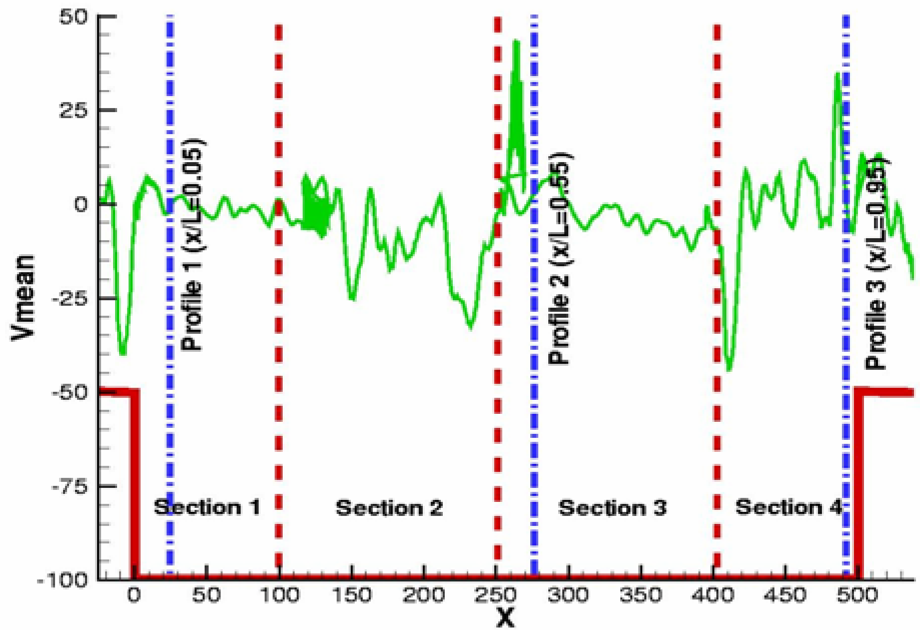


x/L = 0.95

PIV Comparisons: PIV Resolution

Streamwise (U) Velocity





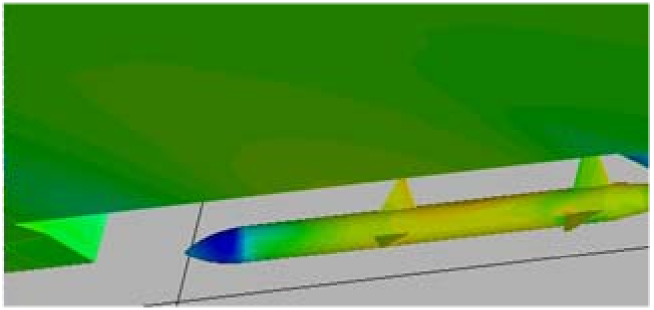
Transverse (V) Velocity

Conclusions

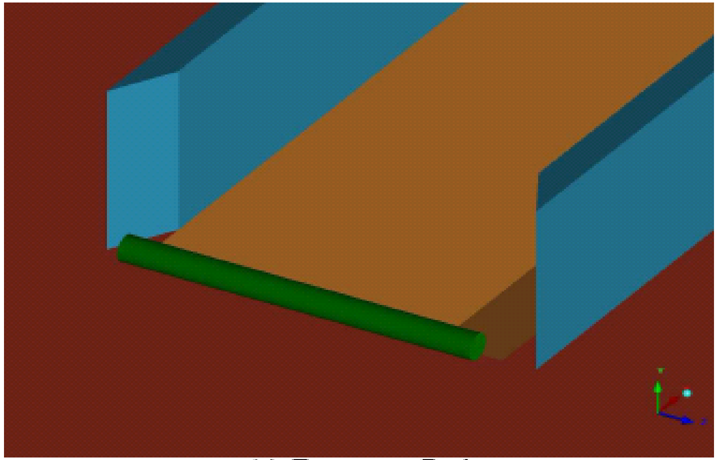
- Doors-On:
  - 2nd Rossiter mode (380 Hz) dominant
  - URANS compares well with experiment SPLs but closer inspection reveals poor comparison at high frequencies
  - LES fares much better: captures higher frequencies & amplitudes
- Doors-Off:
  - 3rd Rossiter Mode (600Hz) dominant
  - URANS still predicts characteristics of 'doors-on' results
  - LES/DES consistently predict correct SPLs & flow features
  - URANS results poor due to failure in predicting shear layer break down
- Good comparison between LES/DES and PIV

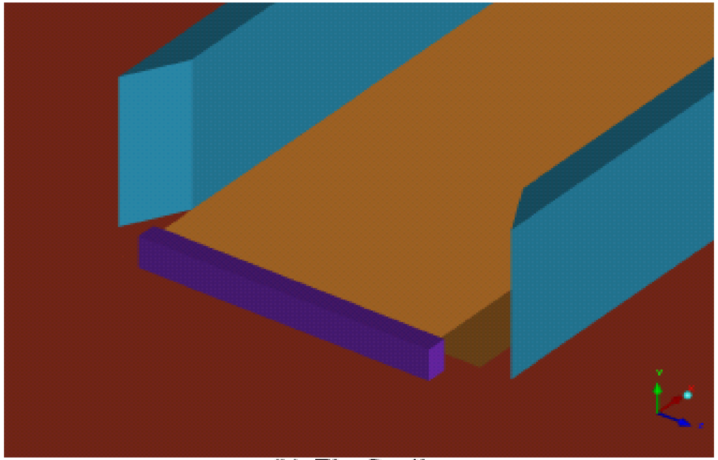
Follow-on Project

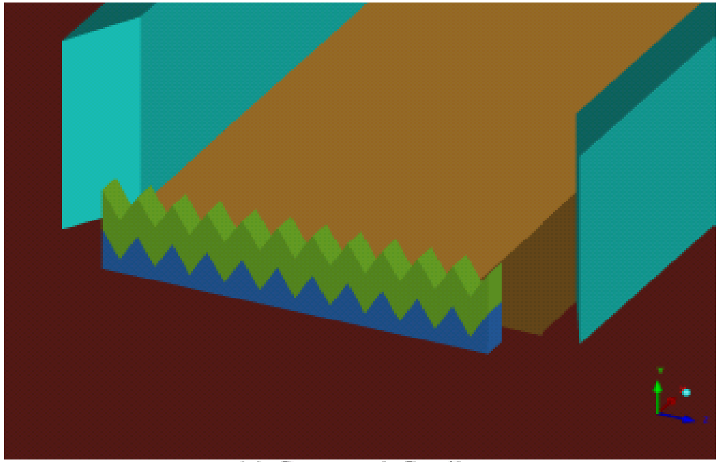
- High Performance Computing for High Fidelity, Multi-disciplinary Analysis of Flow in Weapon Bays including Flow Control
- Funded by EPSRC - call for High End Computing Studentships
- 4-years of effort
- Student to register for PhD in Engineering and MSc in HPC



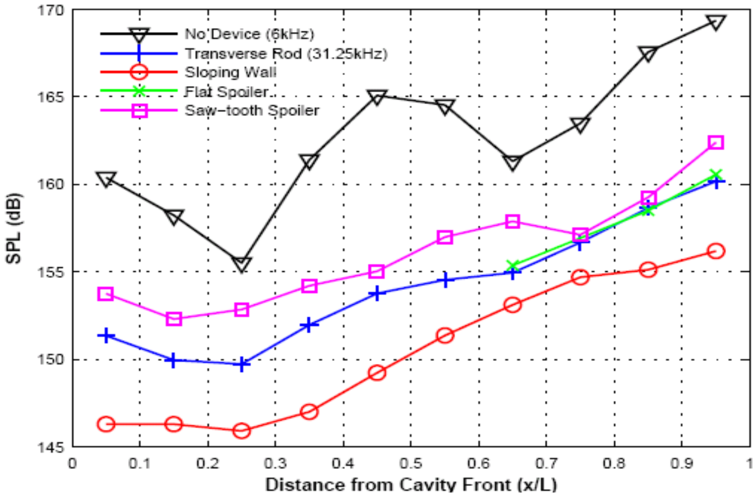
Future Work: Flow Control Devices


(a) Transverse Rod

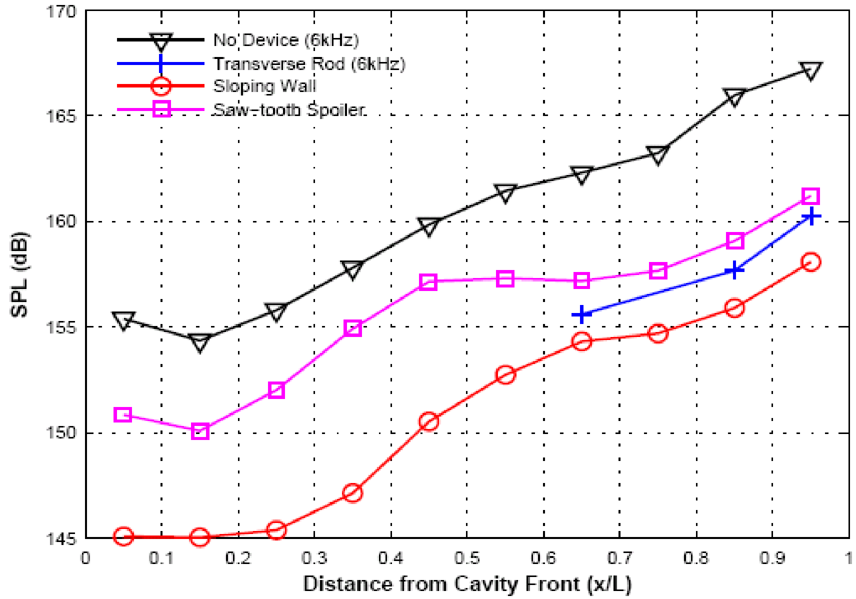

(b) Flat Spoiler


(c) Saw-tooth Spoiler

Flow Control Effectiveness – Experiments by QinetiQ



Doors On

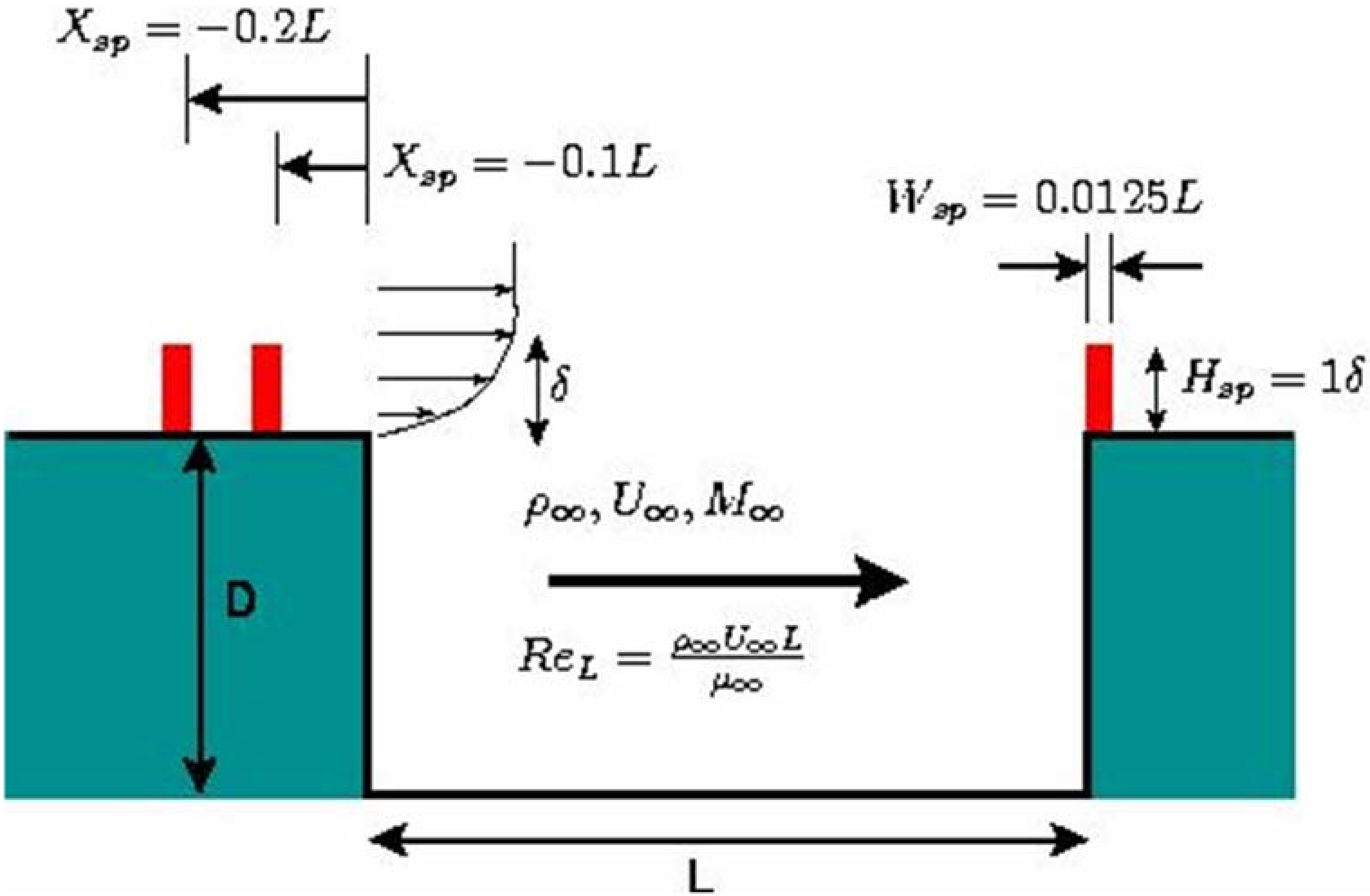


Doors Off

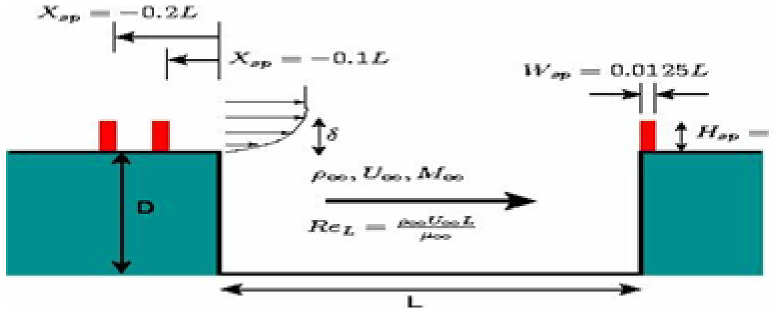
Flow Control

- 2D, L/D=5 cavity with SST turbulence model
  - Flow less unsteady and turbulent better dealt by turbulence models
  - LES/DES not used to reduce calculation run-times
- **Passive Control**: involves manipulating existing cavity geometry by adding external device or changing shape of cavity geometry
- Investigated effects of following devices at different positions:
  - Spoiler
  - Slanted Cavity Walls
  - Steady Jet Blowing
- No experimental data available
  - Comparisons made with experiment (without any control device)

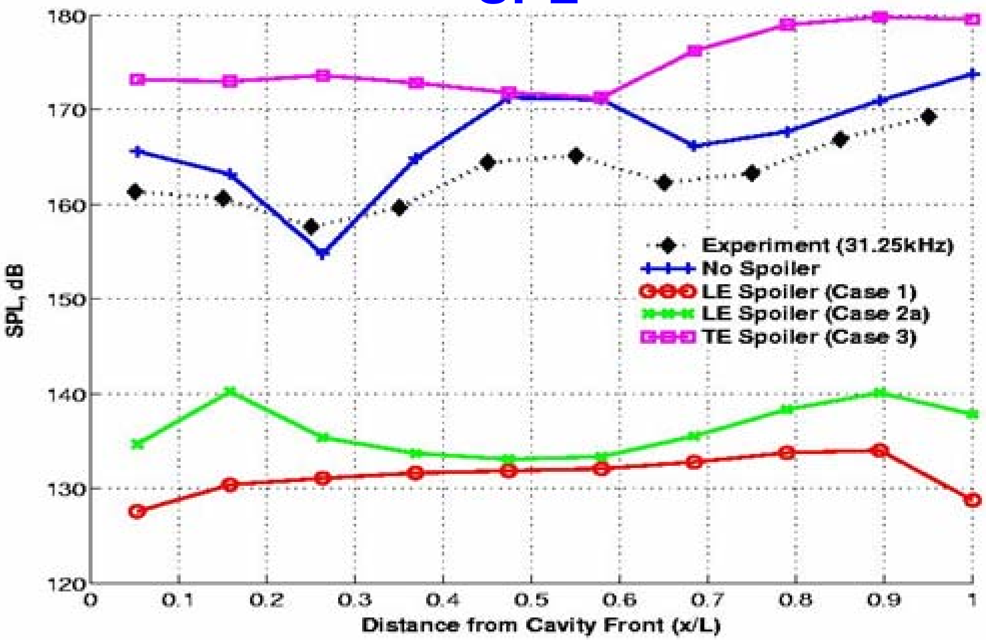
Flow Control - Spoiler

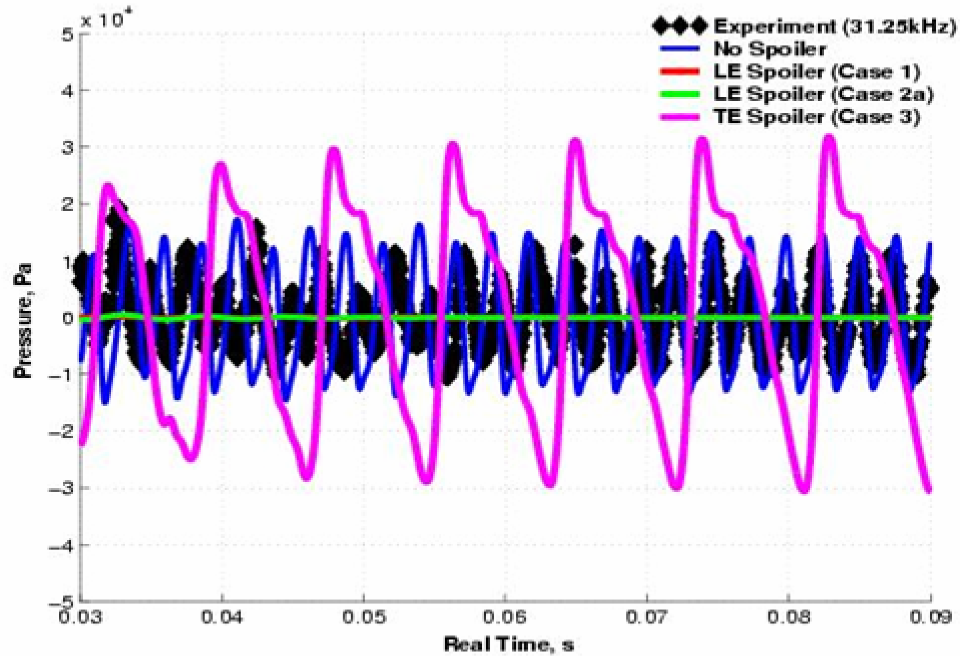


Flow Control – Spoiler (Pressure)



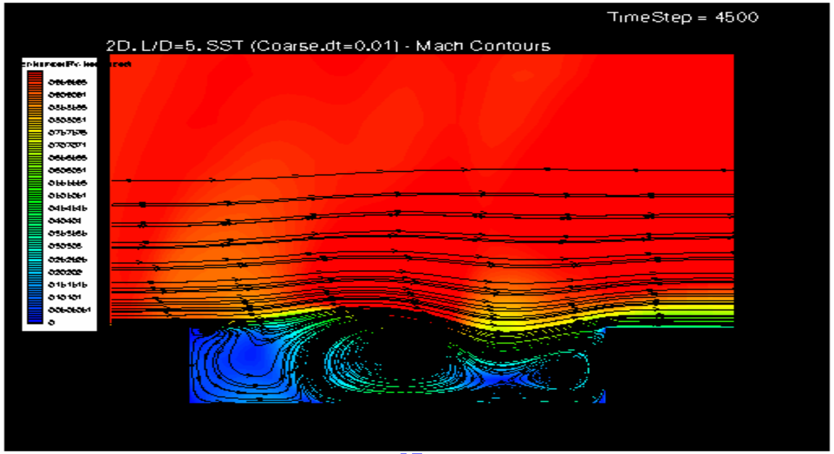
SPL



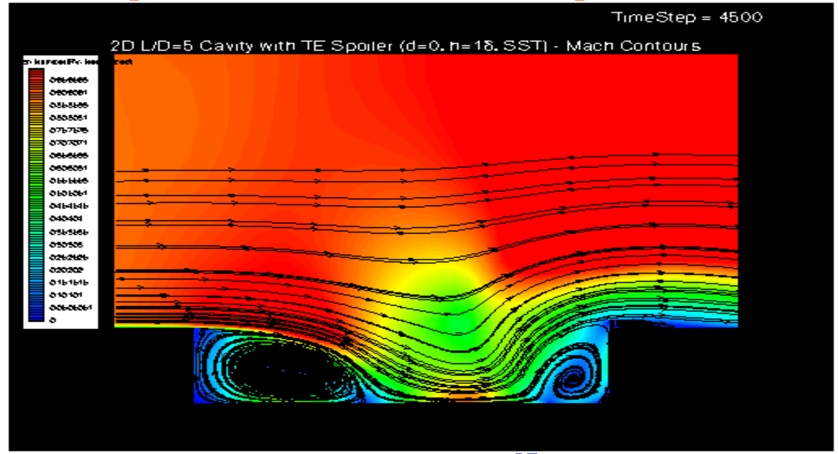


Pressure (x/L = 0.95)

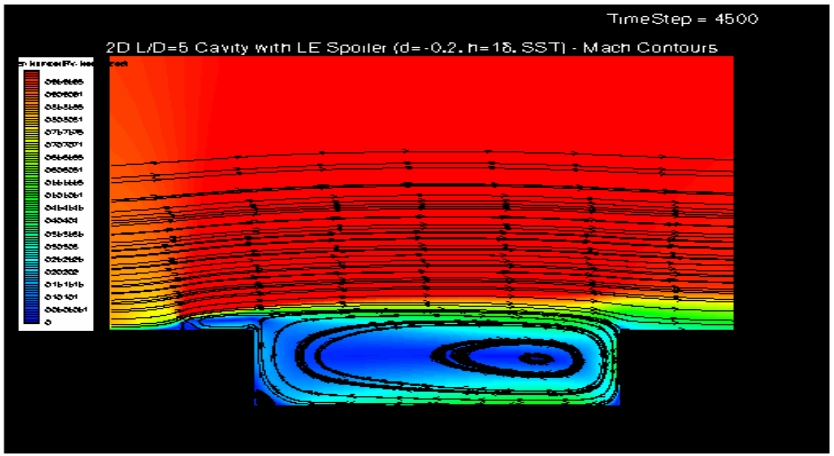
Flow Control – Spoiler (Flow-Field)



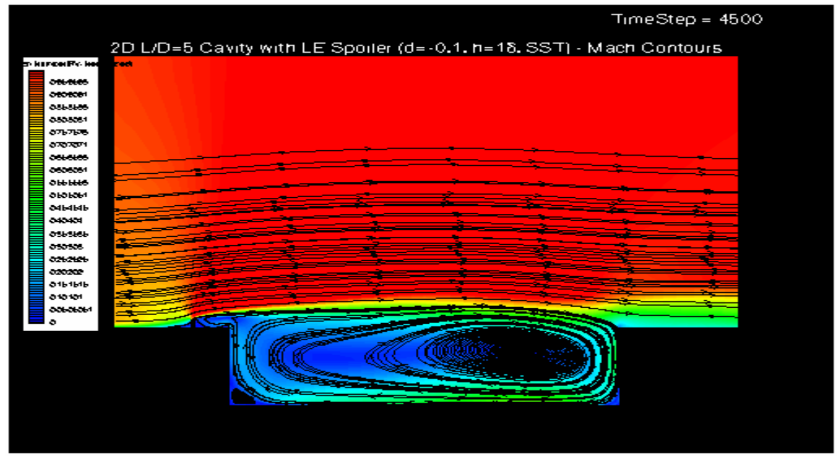
No Spoiler



TE Spoiler

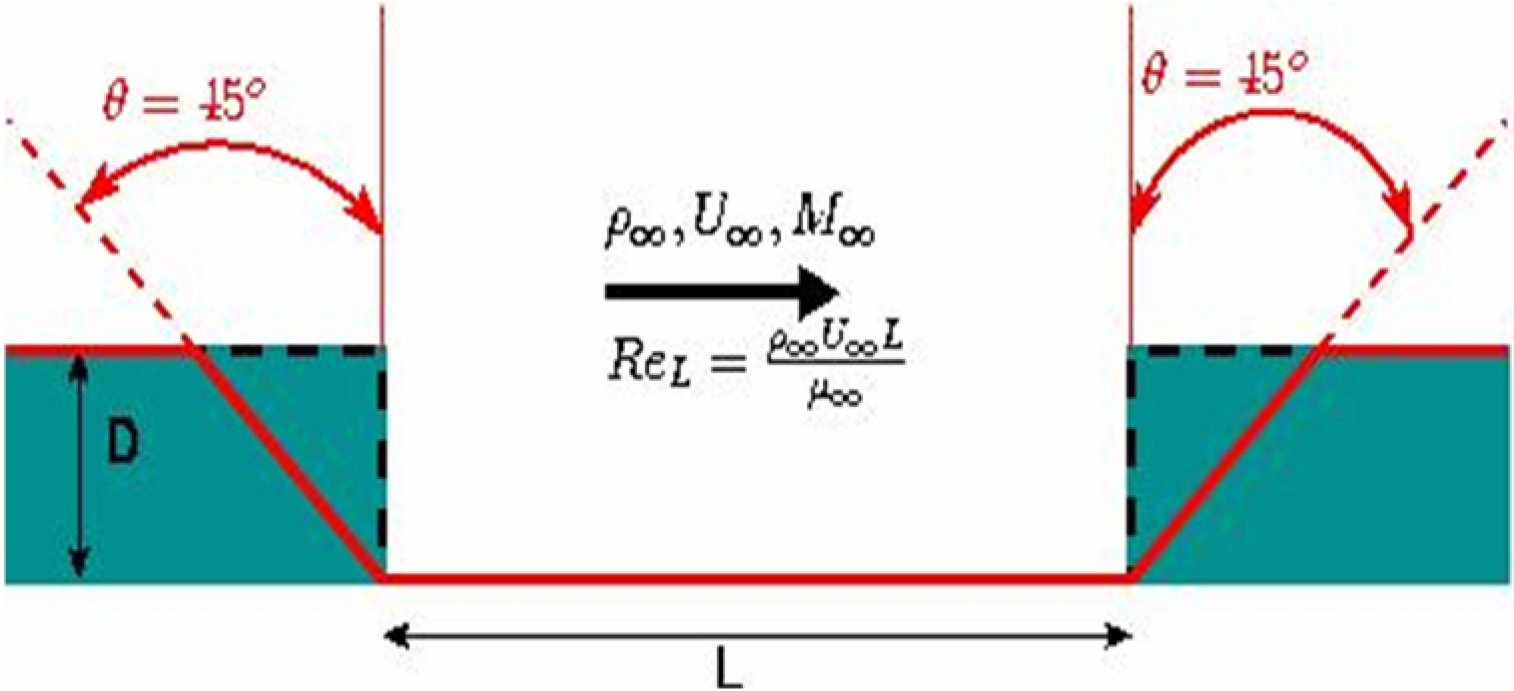


LE Spoiler (x_{sp} = -0.2L)

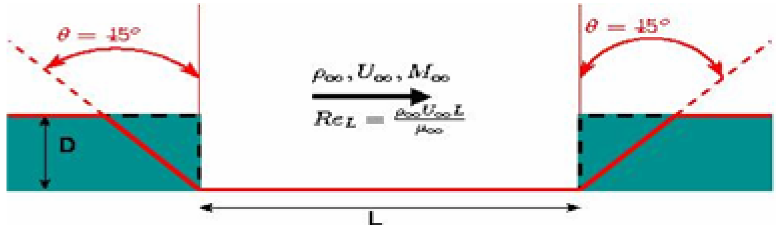


LE Spoiler (x_{sp} = -0.1L)

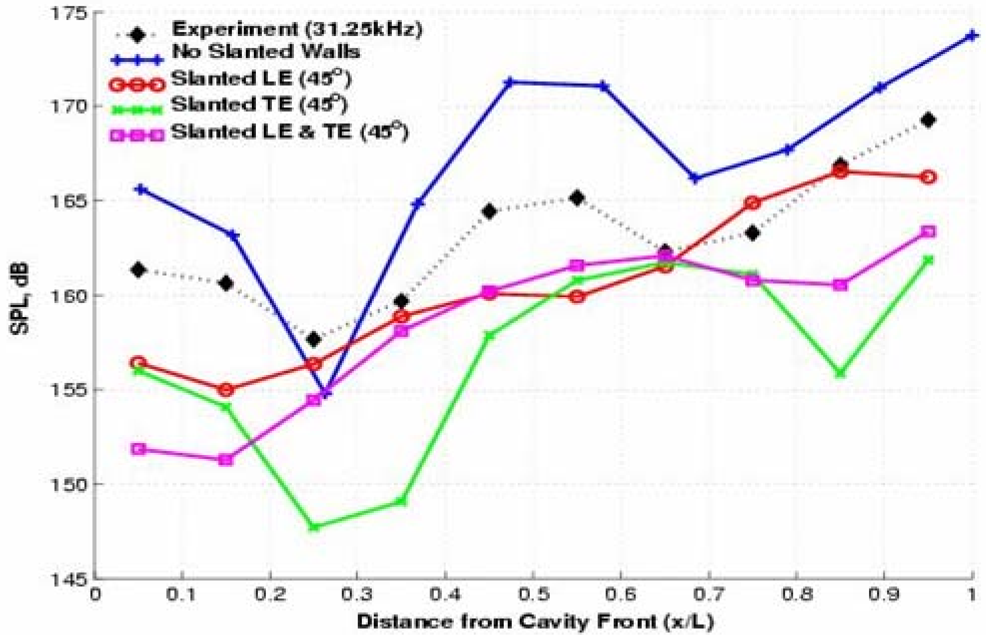
Flow Control – Slanted Walls

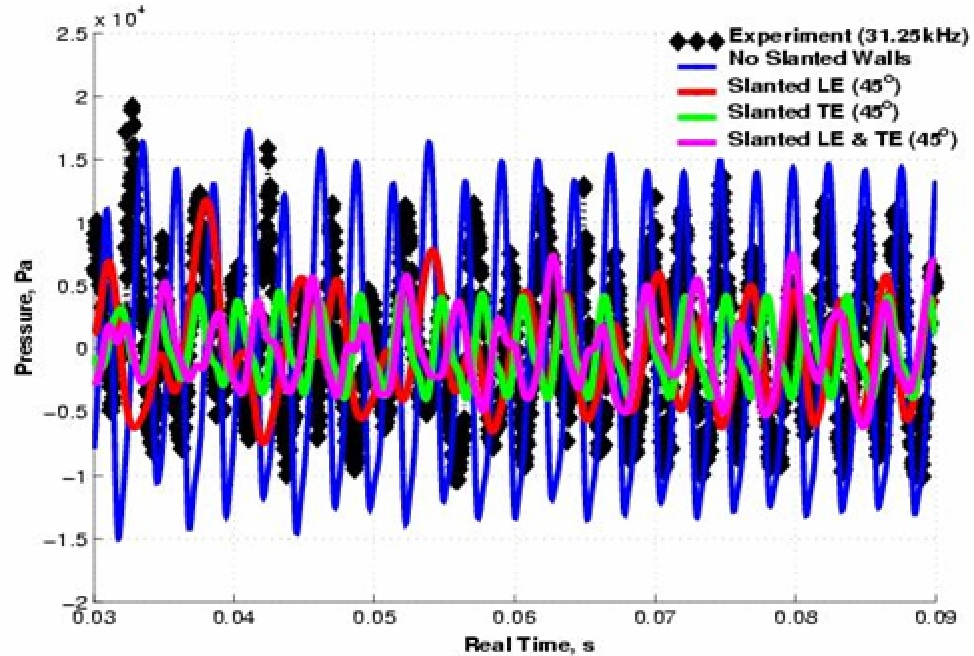


Flow Control – Slanted Walls (Pressure)



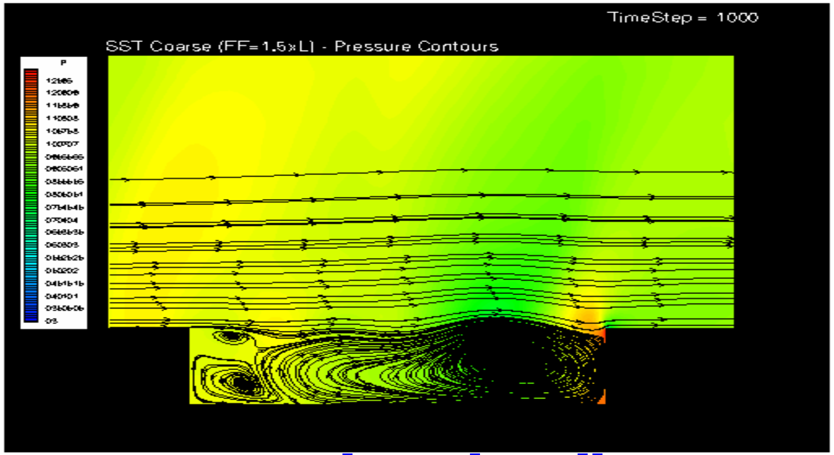
SPL



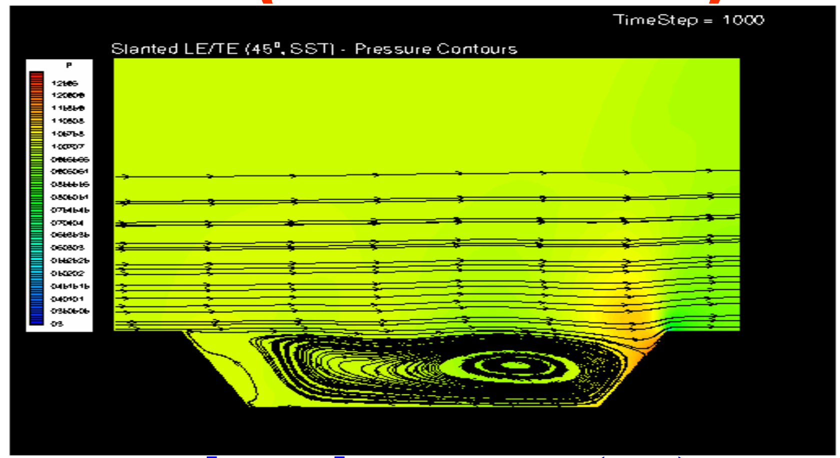


Pressure (x/L = 0.95)

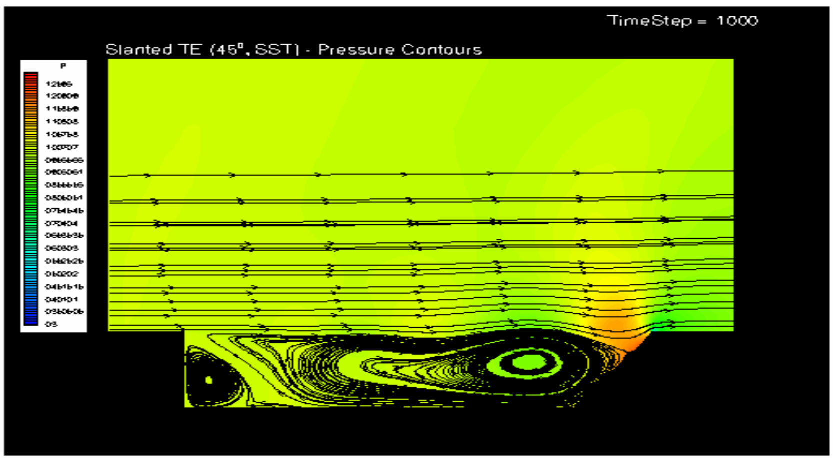
Flow Control – Slanted Walls (Flow-Field)



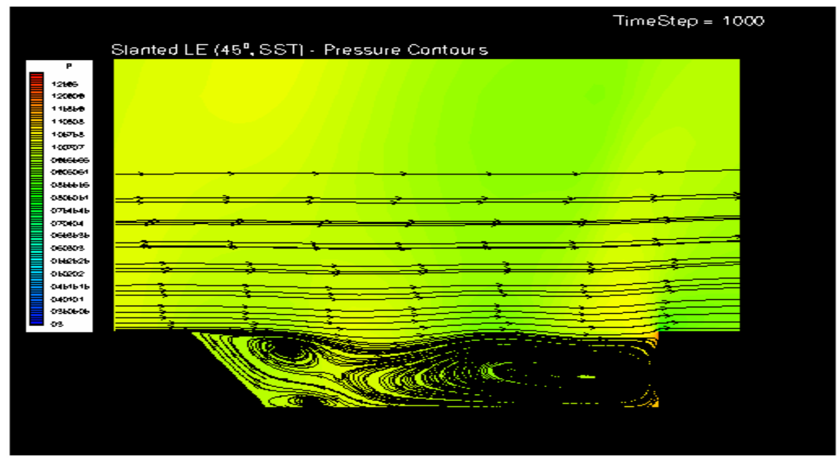
No Slanted Walls



Slanted LE & TE (45°)

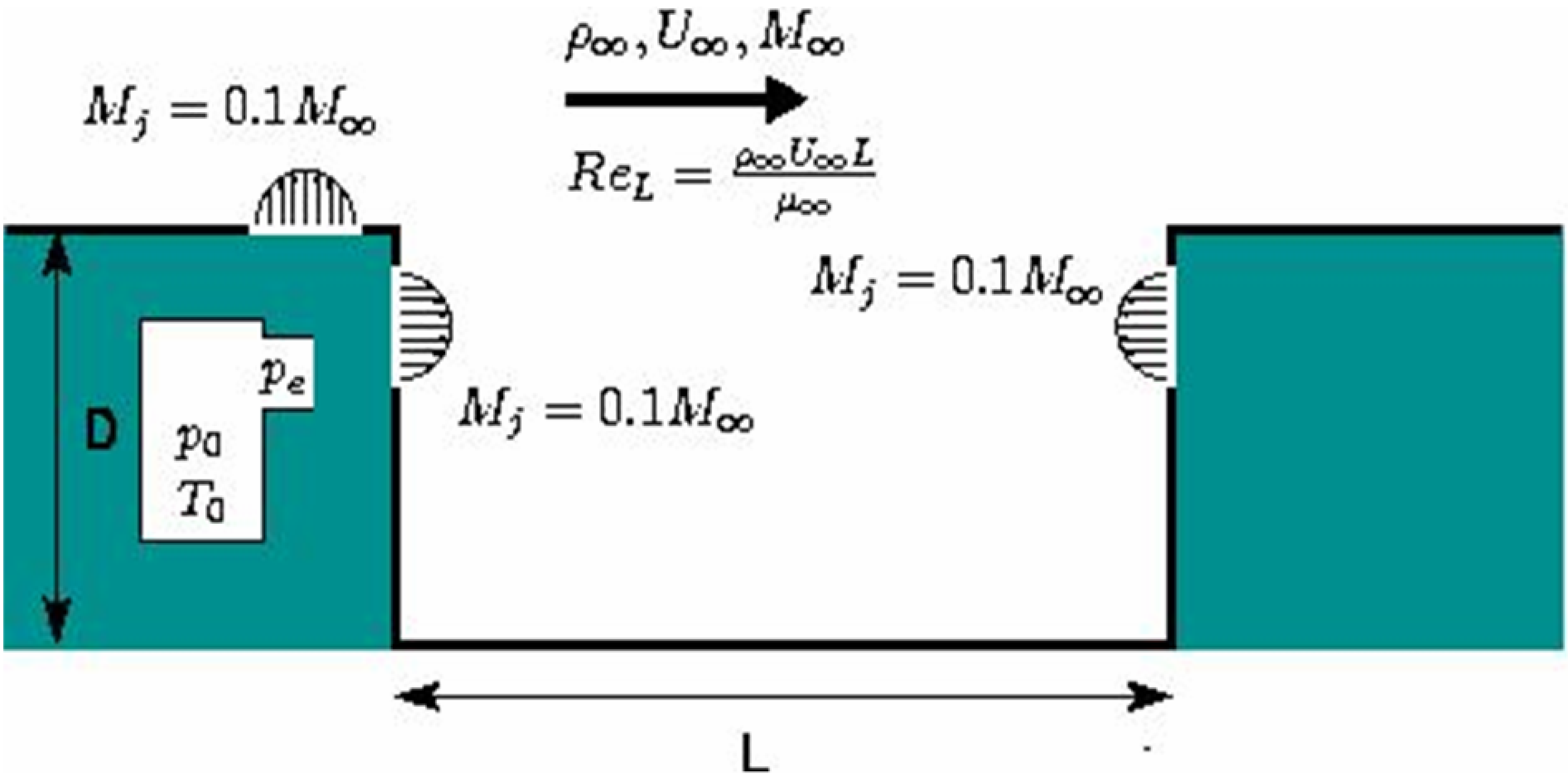


Slanted TE (45°)

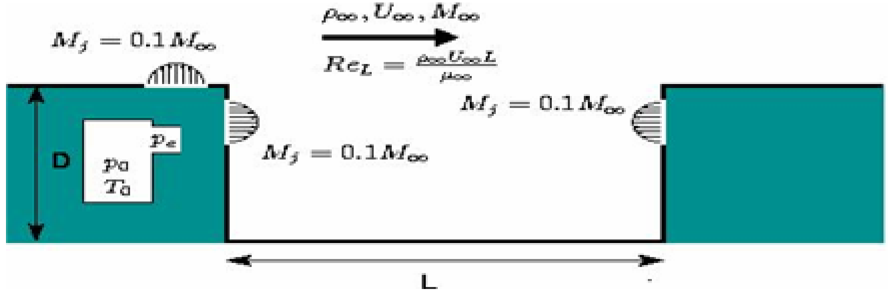


Slanted LE (45°)

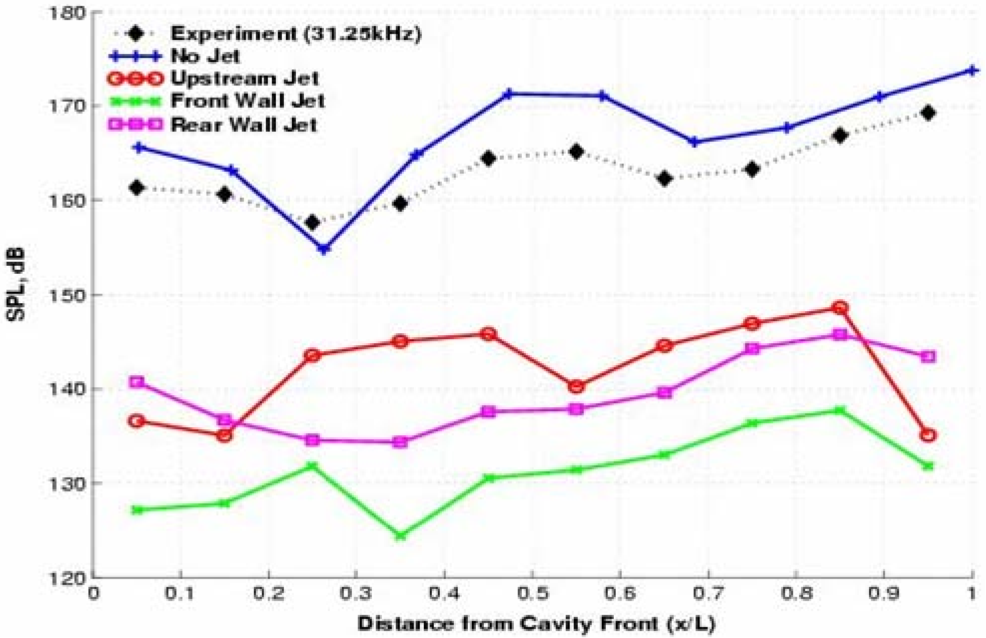
Flow Control – Steady Jet

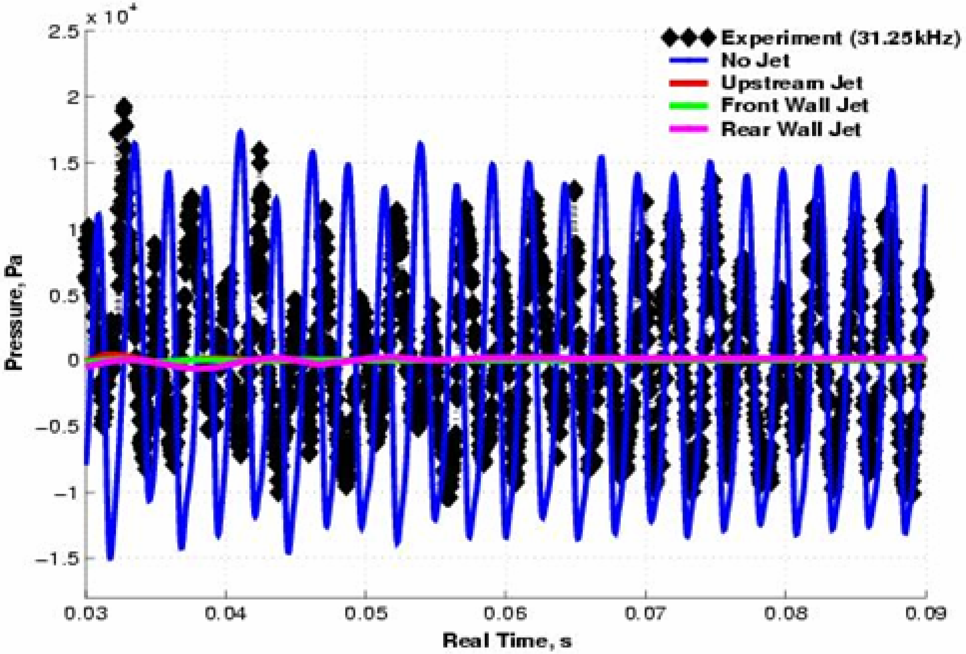


Flow Control – Steady Jet (Pressure)



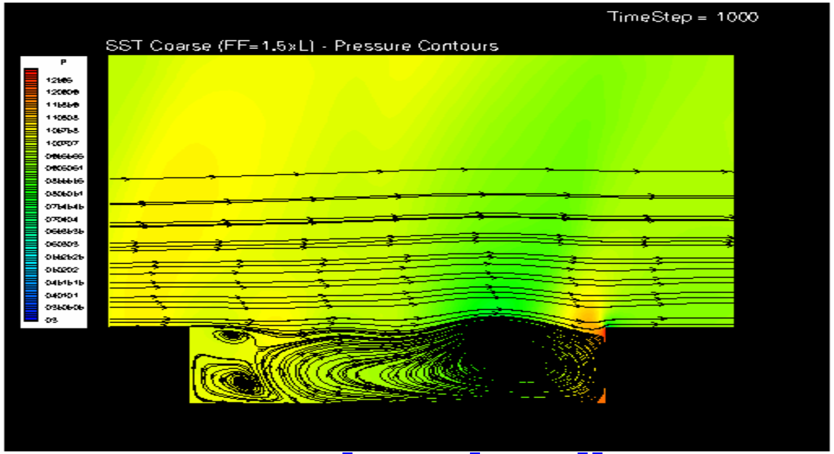
SPL



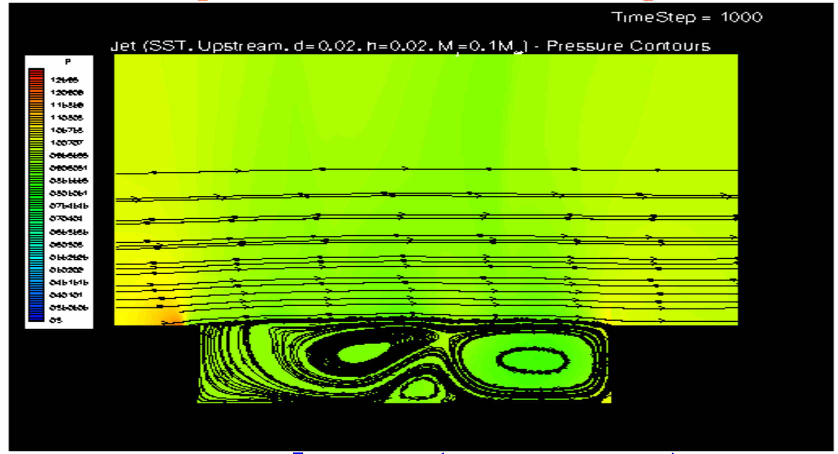


Pressure (x/L = 0.95)

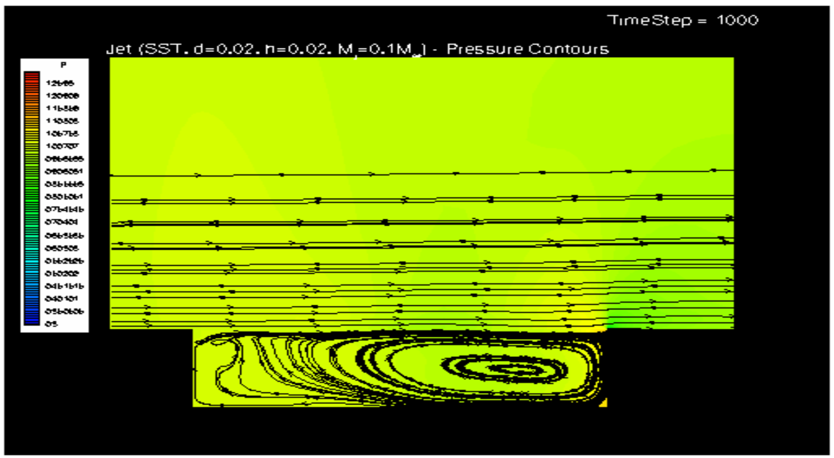
Flow Control – Steady Jet (Flow-Field)



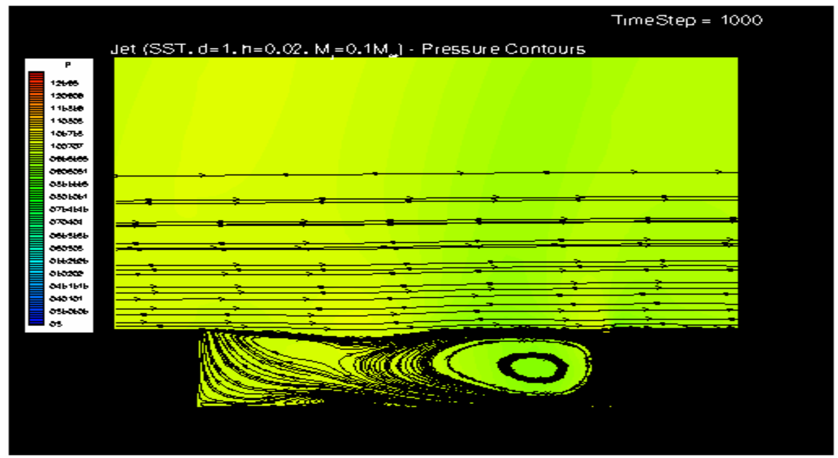
No Slanted Walls



Steady Jet (Upstream)



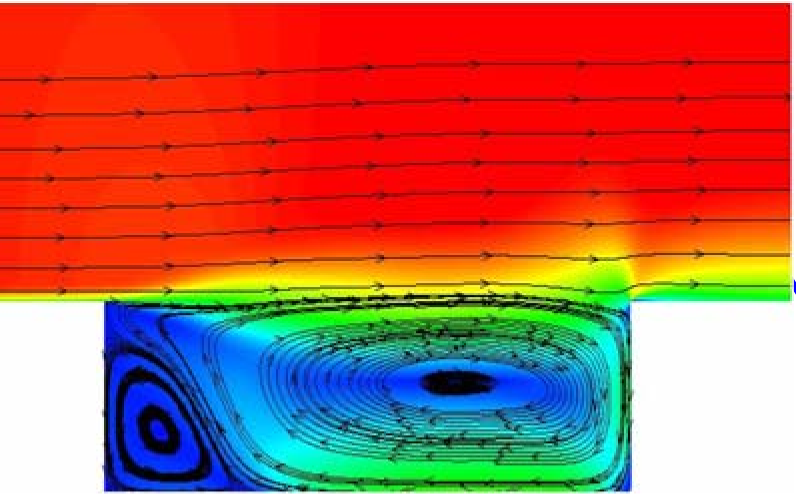
Steady Jet (Front Wall)



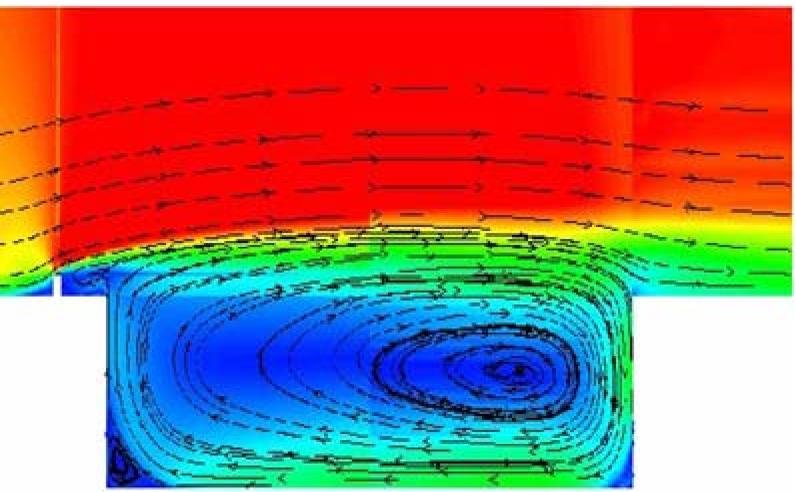
Steady Jet (Rear Wall)

Flow Control: Spoiler (Flow-Field)

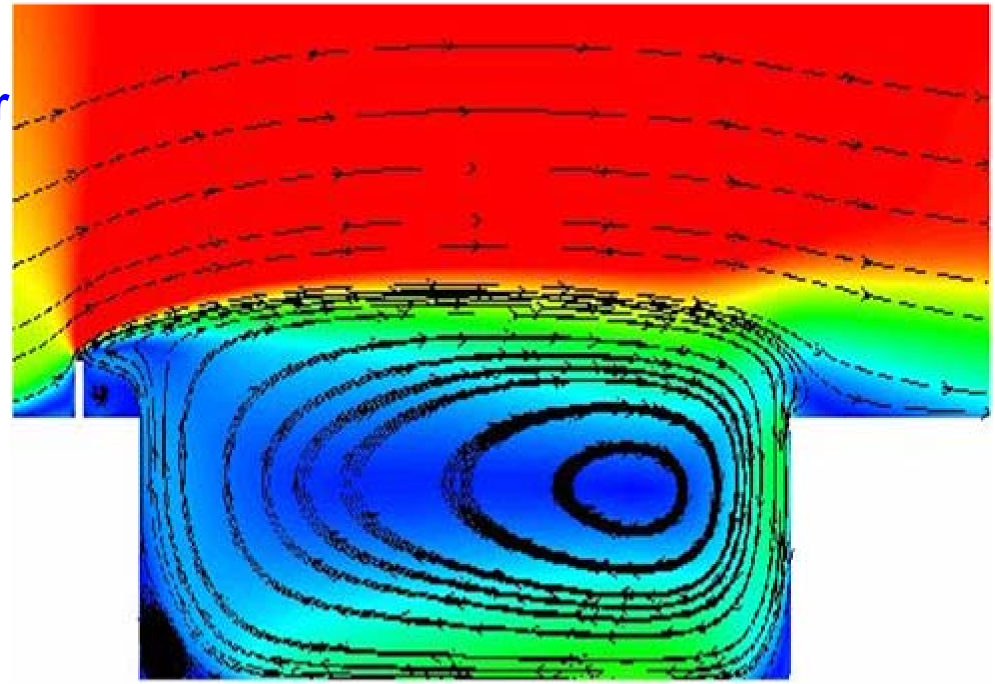
Height Effects: LE Spoiler (x/L = -0.1)



No Spoiler



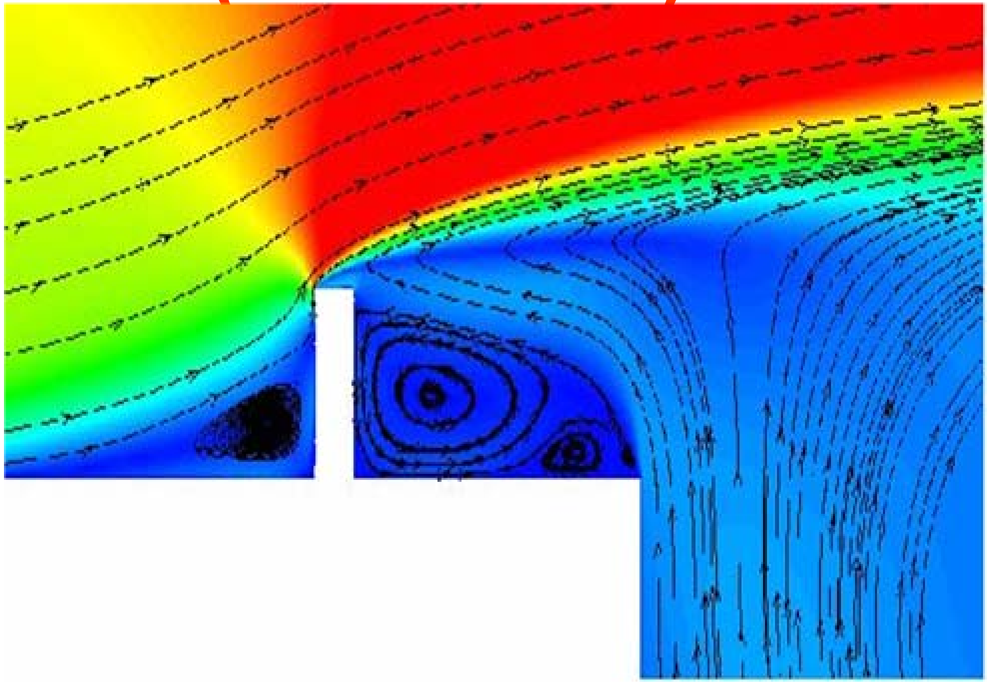
$h_{sp} = 1\ \delta$



$h_{sp} = 2\ \delta$

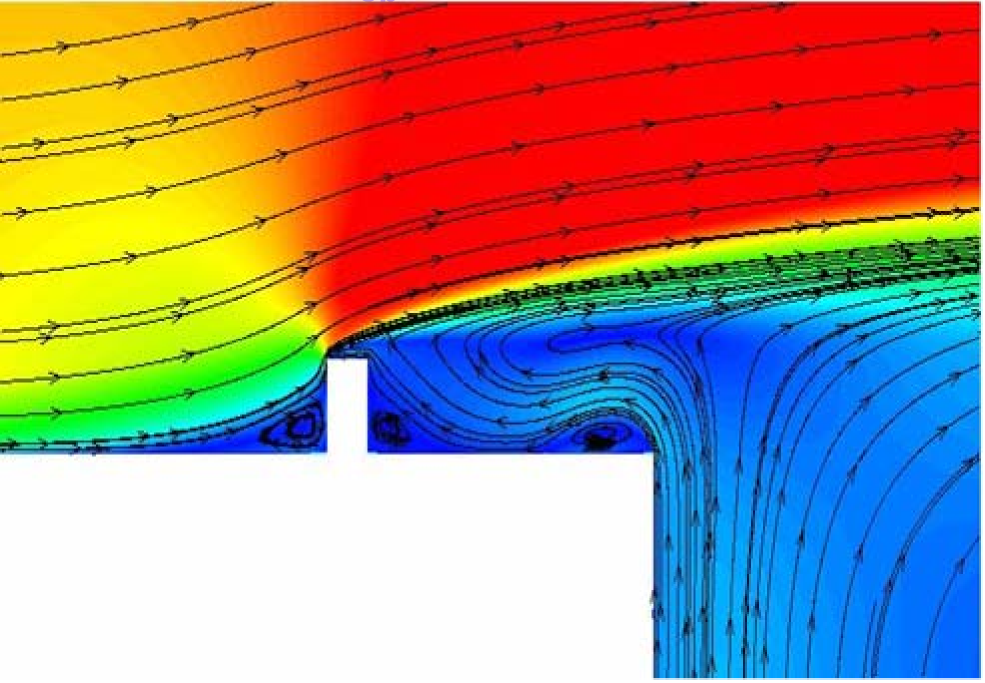
Flow Control: Spoiler (Flow-Field)

Height Effects: LE Spoiler (x/L = -0.1)



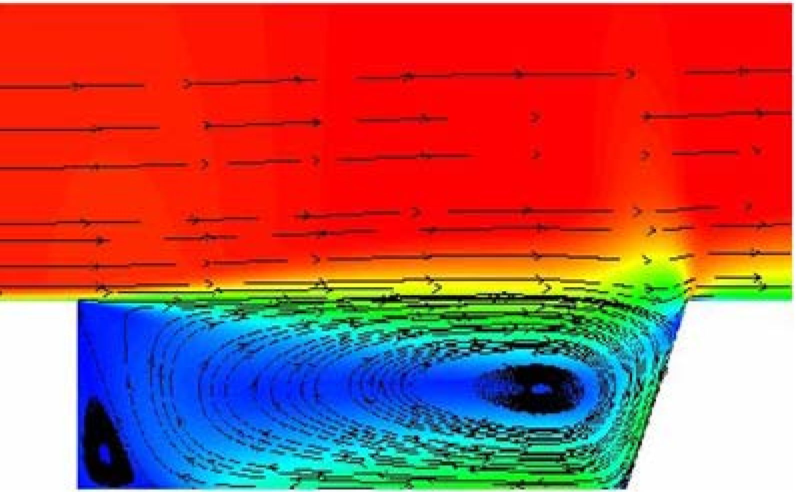
$h_{sp} = 2\delta$: Close-Up

$h_{sp} = 1\delta$: Close-Up

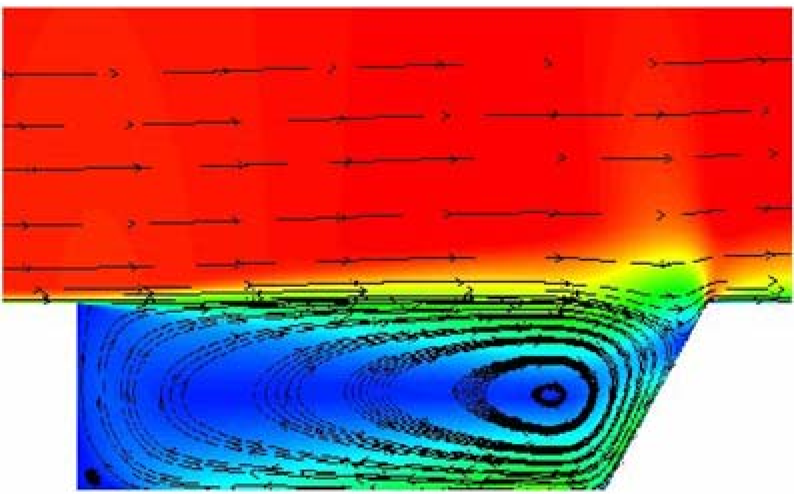


Flow Control: Slanted Walls (Flow-Field)

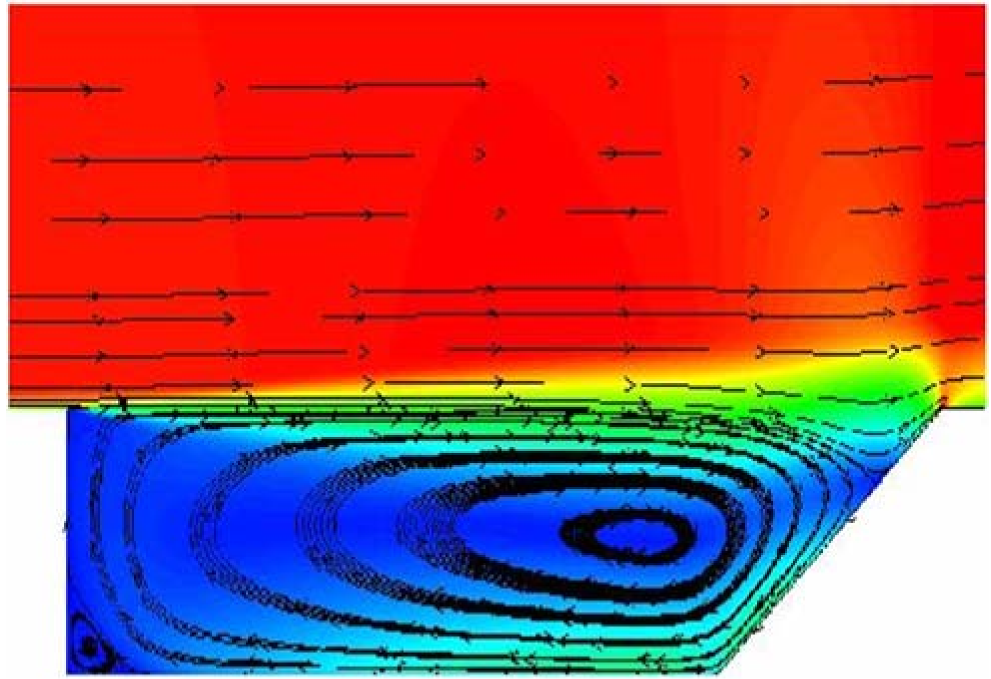
Angle Effects: Slanted TE Wall



30°



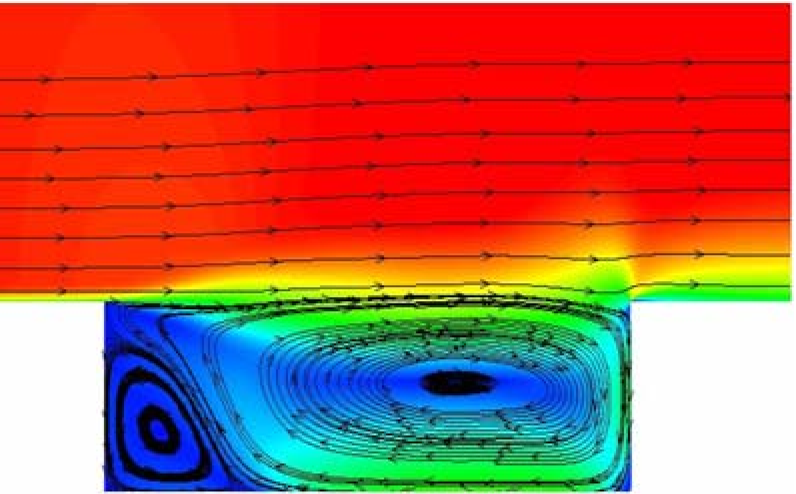
45°



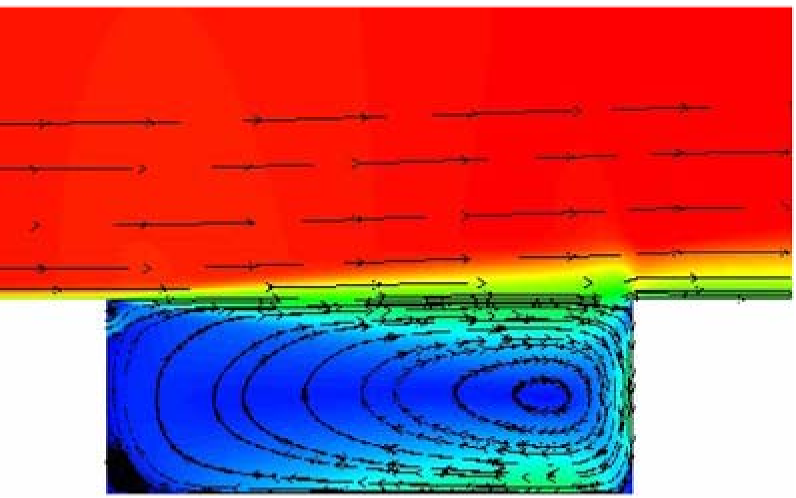
60°

Flow Control: Steady Jet (Flow-Field)

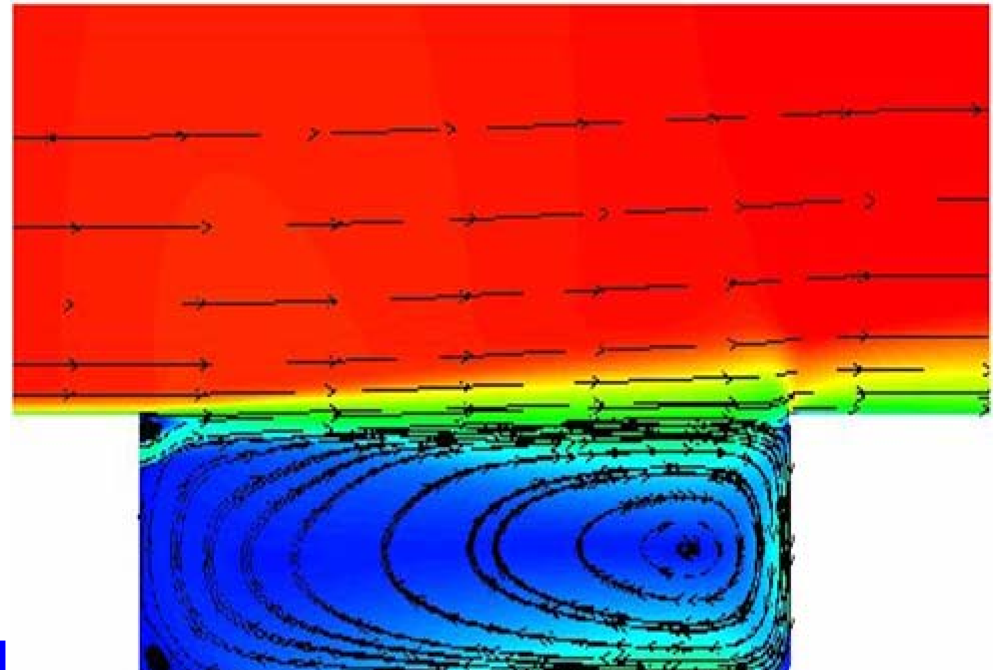
Exit Jet Velocity Effects: Front Wall Jet



No Jet



$M_j = 0.1\ M_\infty$

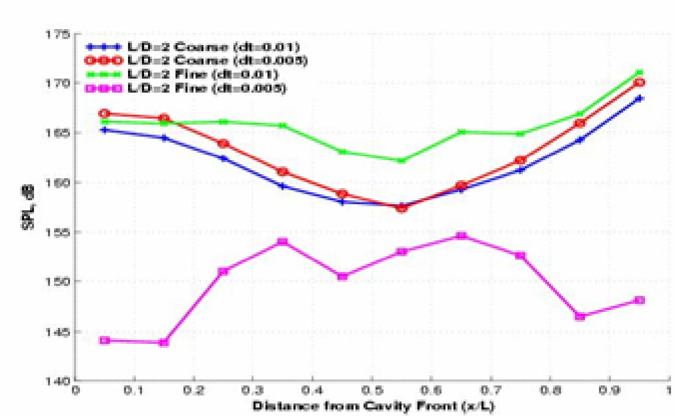


$M_j = 0.2\ M_\infty$

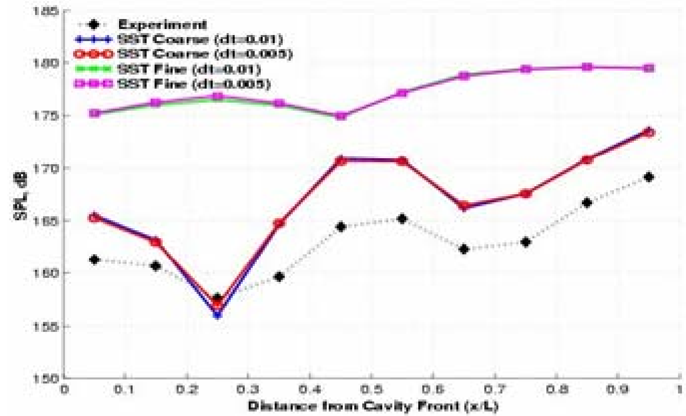
Conclusions – Flow Control

- Passive control effective for reducing cavity SPLs & frequencies
- Spoiler:
  - overall SPL reduced by about 20 dB and all frequencies eliminated
  - location important: trailing-edge spoiler noisier
- Slanted cavity walls:
  - not as good as spoiler: overall SPL reduced by 1-10 dB but lower frequencies still present
  - location important: slanted front noisier; slanted rear more effective
- Steady jet blowing:
  - overall SPL reduced by as much as 30-35 dB and all frequencies completely eliminated
  - location imporant: upstream jet noisier; front wall jet most effective

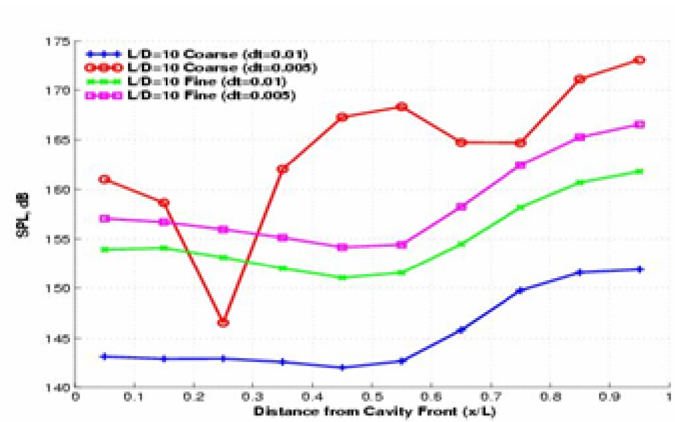
Different Cavity Aspect Ratios: SPL



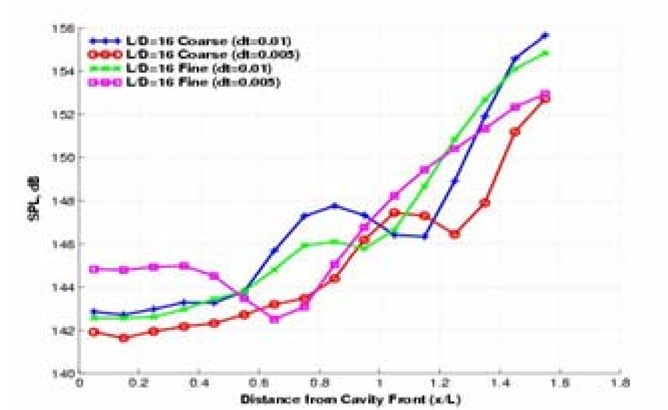
L/D = 2



L/D = 5

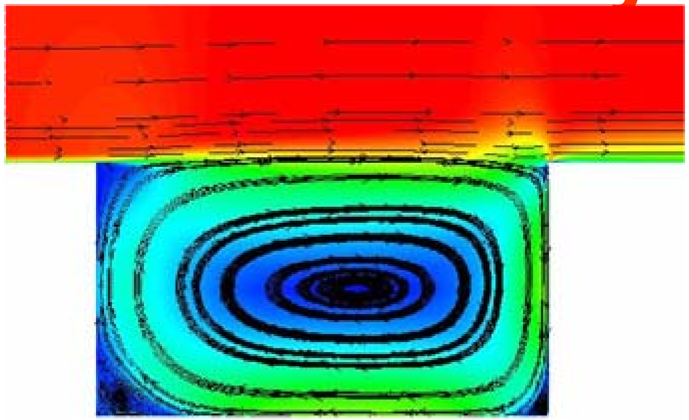


L/D = 10

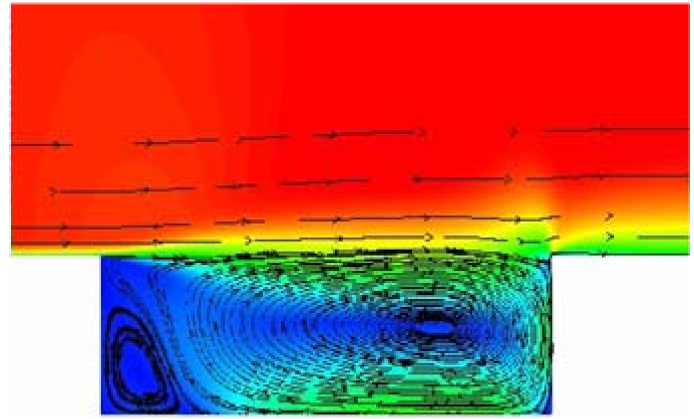


L/D = 16

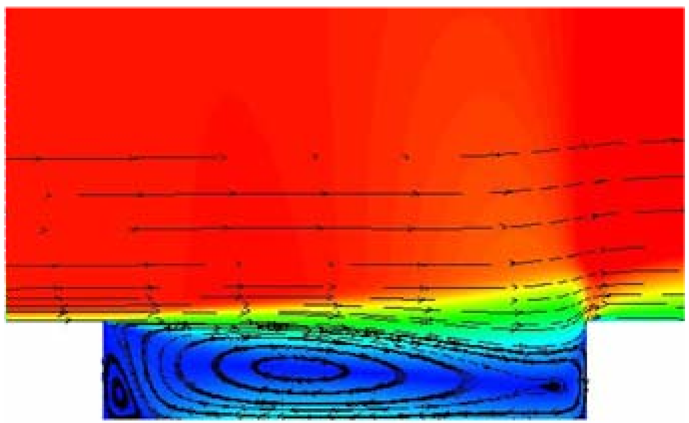
Different Cavity Aspect Ratios: Flow-Field



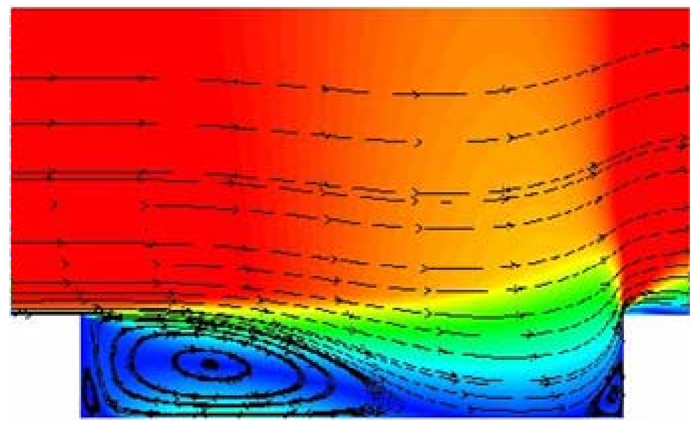
L/D = 2



L/D = 5



L/D = 10



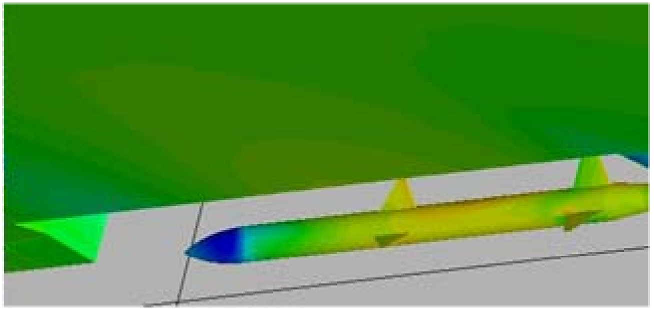
L/D = 16

Further Work

- Parametric studies:
  - L/W, Re, M effects
- Cavity with stores:
  - Missile with(out) fins
  - Missile in different cavity locations
  - Missile inside different cavity geometries/configurations
- Flow Control:
  - Pulsating jet
  - Closed loop control strategies
  - Flow control strategies with missile in cavity
- Acoustics

Follow-on Project

- High Performance Computing for High Fidelity, Multi-disciplinary Analysis of Flow in Weapon Bays including Flow Control
- Funded by EPSRC - call for High End Computing Studentships
- 4-years of effort
- Student to register for PhD in Engineering and MSc in HPC
- £99,999.99 of value



Objectives

- To simulate the flow in a weapons bay using DES/LES, including effects of store carriage and active flow control.
- Exploit HPC to visualise, analyse, archive and reduce the obtained data.
- To identify the forces on the stores inside the cavity and the effect of these during the release phase of the weapons.
- To combine CFD with Computational Structural Dynamics (CSD) and Computational Aeroacoustics (CAA) in order to predict all aspects of cavity flow and their effect on the loads of stores inside the cavity
- To examine active and passive flow control strategies for cavity-flow aerodynamics and demonstrate their benefit. Open and closed-loop control will be used.

Questions?