Fundamental Study of Aero Acoustic Emission of Single and Tandem Cylinder

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Brief Review of Flow Over Cylinder
Rationale

• Landing gear system – major contributor to airframe noise during approach
• Cylinder–like structure includes: Gear main strut, hydraulic lines, brake pistons, wheels and axles
• Unsteady wake interacts with downstream components to create dominant noise sources
• Tandem cylinder – simplified prototype
• Models component level interactions
• To understand noise generation mechanism and achieve reduction of airframe noise
Wake Characteristics of a Wake Behind a Cylinder

- At very low Re number < 49, the wake is steady and the wake comprises of two symmetrically placed vortices on each side of the wake.
- At higher Re number, the wake becomes unsteady forming a vortex street as seen in (b).
Wake Shedding Frequency vs Re from Single Cylinder

Figure 2.23. Strouhal number, $St_D$ (frequency non-dimensionalized by the free stream velocity and the cylinder diameter) as a function of Reynolds number (adapted from Tropea (2007) : Handbook of Experimental Fluid Mechanics).
Flow Interference Flow Characteristics (Cylinders in Tandem)

- Flow interference imposes continuous and discontinuous changes in vortex shedding
- Cylinder oscillations modified by and strongly dependent on cylinder arrangement
Wake Shedding States (Cylinders in Tandem)

- Critical tandem cylinder spacing configuration of L/D = 3.7 chosen
- Bistable flow state exists between cylinders

Figure 2. Classification of flow regimes in side-by-side and tandem arrangements for stationary cylinders.
CFD Simulations of Cylinder Flow at Re = 3900 (URANS, LES & DES)
Meshing and Testing Conditions

- Trimmer mesh of 3 million cells
- URANS, LES, DES
- Diameter of 20mm and span of 80mm (4D)
- Periodic boundary conditions at cylinder ends
- Time –Step: $1.0 \times 10^{-5}$ sec
- Reynolds Number studied: 3900
- Aeroacoustics module:
  - Ffowcs Williams – Hawkings
Comparison of Time Averaged Results (Re=3900)

<table>
<thead>
<tr>
<th>Cases</th>
<th>Span</th>
<th>Cd</th>
<th>Strouhal no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>4D</td>
<td>1.01</td>
<td>0.205</td>
</tr>
<tr>
<td>URANS</td>
<td>4D</td>
<td>1.078</td>
<td>0.214</td>
</tr>
<tr>
<td>LES</td>
<td>4D</td>
<td>0.998</td>
<td>0.213</td>
</tr>
<tr>
<td>DES</td>
<td>4D</td>
<td>1.088</td>
<td>0.196</td>
</tr>
</tbody>
</table>

Far Field Frequency of 333 Hz -> Strouhal no. ~0.196
Streamwise Reynolds Stresses

Streamwise Reynolds Stress

$\langle u'u' \rangle$ vs $z/d$ at $x/d=1.54$ plane

- DES predicts comparable peak values as compared to exp results
- Higher level of mixing predicted at the wake centre
- LES under predicts peak values as compared to exp results
- URANS under predicts $\langle u'u' \rangle$ in the wake
Shear & Spanwise Reynolds Stress

\( \langle u'v' \rangle \) vs \( z/d \) at \( x/d=1.54 \) plane

\( \langle w'w' \rangle \) vs \( z/d \) at \( x/d=1.54 \) plane

- Experiment
- URANS
- LES
- DES
Flow Structures Visualized by the Q Criteria
(DES simulation, Re=3900)

• Pairs of counter-rotating streamwise vortices -> Karman vortex shedding characteristics

• Longitudinal vortices interlaced between counter-rotating vortices
## OSPL Comparison at 70 Diameter

<table>
<thead>
<tr>
<th>Cases</th>
<th>Overall Sound Pressure Level (OSPL)</th>
<th>Peak Frequency</th>
<th>Peak Strouhal no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT data (Journal of Sound and Vibration)</td>
<td>83.8</td>
<td>308</td>
<td>0.193</td>
</tr>
<tr>
<td>DES</td>
<td>83.6</td>
<td>313</td>
<td>0.196</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Receiver position**
- **70D**
- **D**
Far-Field Sound Directivity Pattern

- Microphones are placed at 70D around the cylinder monitoring total pressure.
- Compute the $\Delta P'_{rms}$ (pressure fluctuation component) at $r=70D$, non-dimensionalised by free stream velocity and density.

Far field directivity pattern exemplify the characteristics of dipole sound propagation.

- Microphones are placed at 70D around the cylinder monitoring total pressure.
- Compute the $\Delta P'_{rms}$ (pressure fluctuation component) at $r=70D$, non-dimensionalised by free stream velocity and density.
CFD Simulations of Cylinder Flow at Re = 46,000 (DES)
Meshing and Testing Conditions

- Trimmer mesh of 3.6 million cells
- DES
- Diameter of 9.8mm and span of 29.4mm (3D)
- Periodic boundary conditions at cylinder ends
- Time –Step: 1.0e-5 sec
- Reynolds Number studied: 46000
- Aeroacoustics module: Ffowcs Williams – Hawkings
Time Averaged Results for Re = 46000

<table>
<thead>
<tr>
<th>Cases</th>
<th>$C_D$,average</th>
<th>$C_D$,rms</th>
<th>Strouhal no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>1.35</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>LES_OpenLit</td>
<td>1.24</td>
<td>0.10</td>
<td>0.19</td>
</tr>
<tr>
<td>DES_current</td>
<td>1.235</td>
<td>0.141</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Far Field Frequency of 1455.8 Hz -> Strouhal no. ~0.20
Reynolds Stresses Characteristics at $x/d=1.54$ (Re=46,000)

- Trends of the Reynolds stresses are typical to that of a turbulent wake
Flow Structures Visualized by the Q Criteria (DES simulation, Re=46,000)
Sound Directivity Pattern in terms of $P_{\text{rms}}$ & OSPL

- SPL of Experiment: 91dB
- SPL of DES: 92dB
  Occurring at 1455.8Hz which corresponds to St number of 0.20
- SPL at other positions match quite closely between experimental and CFD results.
CFD Simulations of Tandem Cylinder Flow at Re = 1.66E5 (DES)
Meshing and Testing Conditions

- Trimmer mesh of 6.2 million cells
- DES (K-w sst)
- Diameter of 57.15mm and span of 171.45mm (3D)
- Periodic boundary conditions at cylinder ends
- Time Step: 2.0e-5 sec
- Physical Time Simulated: 0.216 sec
- Reynolds Number studied: 1.66E5
- Aeroacoustics module:
  - Ffowcs Williams – Hawkings
Comparison of Time Averaged Results

<table>
<thead>
<tr>
<th>Upstream 90 Deg</th>
<th>Experiment</th>
<th>CFD(Literature)</th>
<th>DES_Near field</th>
<th>DES_Far field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span</td>
<td>18D</td>
<td>18D</td>
<td>3D</td>
<td>3D</td>
</tr>
<tr>
<td>Frequency</td>
<td>178Hz</td>
<td>166Hz</td>
<td>158Hz</td>
<td>166Hz</td>
</tr>
<tr>
<td>Strouhal no.</td>
<td>0.232</td>
<td>0.219</td>
<td>0.203</td>
<td>0.213</td>
</tr>
</tbody>
</table>

Near field Frequency of 158 Hz -> Strouhal no. ~0.203

Far field Frequency of 166 Hz -> Strouhal no. ~0.213
Flow Structures Visualized by the Q Criteria (DES simulation, Re=1.66E5)

- Counter-rotating streamwise vortices observed in inter-cylinder flow region
- Constant shedding flow state upstream
- Wake interference amplifies downstream shedding and oscillation
- Only shear layer roll up is observed in inter-cylinder flow region
- Intermittent shedding state upstream
• Shedding frequency of near field spectra in good agreement with literature CFD results.

• Deviation in peak values could be attributed to insufficient simulation time, where the bi-stable flow behaviour have yet to be statistically converged.
Microphone Spectra at 30D

- Receiver / Microphone position
- Microphone A
- Microphone B
- Microphone C

- Peak SPL (dB) = 92.5 (exp 93.7)
- Peak SPL (dB) = 91.6 (exp 95.6)
- Peak SPL (dB) = 88.5 (exp 92.7)
Summary

- Flow over cylinder at Re 3900 using URANS, DES and LES
  - Strouhal number at vertical height of 70D away from the cylinder = 0.196 (exp 0.193); OSPL = 83.6 dB (exp 83.8 dB)
  - Directivity pattern of Δp’rms of receivers around the cylinder exemplify dipole sound propagation characteristics
  - Trends of DES predicted Reynolds stresses were in relative good agreement with experimental results
  - URANS & LES had tendency to under predict the magnitude of the principal components of the Reynolds stresses
- Flow over cylinder at Re 46,000 using DES
  - Fundamental Strouhal number = 0.2 (exp 0.19) at frequency of 1455.8 Hz
  - SPL at vertical height of 70D away from = 92 dB (exp 91dB)
  - Directivity pattern of Δp’rms of receivers around the cylinder exemplify dipole sound propagation characteristics
  - Trends of the Reynolds stresses are typical to that of a turbulent wake
Summary

- **Flow over tandem cylinder at Re 1.66E5 DES**
  - Bi-stable flow states at critical cylinder spacing captured
  - Flow between cylinder switches between constant shedding and intermittent shedding modes
  - Near field strouhal number at cylinder surface = 0.203 and far field = 0.213\(\exp 0.232\)
  - Trends of DES predicted surface pressure distribution were in relative good agreement with experimental results
  - Good farfield OASPL agreement with experiment at respective microphone locations. **Microphone A = 92.5 (exp 93.7) Microphone B = 91.6 (exp 95.6) Microphone C = 88.5 (exp 92.7)**
  - Directivity pattern of \(\Delta p'\)rms of receivers around the cylinder exemplify dipole sound propagation characteristics