Analysis and Control of Coherent Structures in Jet Noise and Shock/Boundary Layer Interactions
EXPERIMENTS

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Objectives

- Large-scale coherent structures play significant, and often dominating role, in many high-speed and high Reynolds number flows of interest to the Air Force – the two selected problems for study for this project are jet noise and shock/boundary layer interactions

- The main objectives of the work are to use a tightly integrated experimental and computational work:
  - To develop an in-depth understanding of the nature and role of these structures, and
  - To effectively and efficiently control the structures & the flow

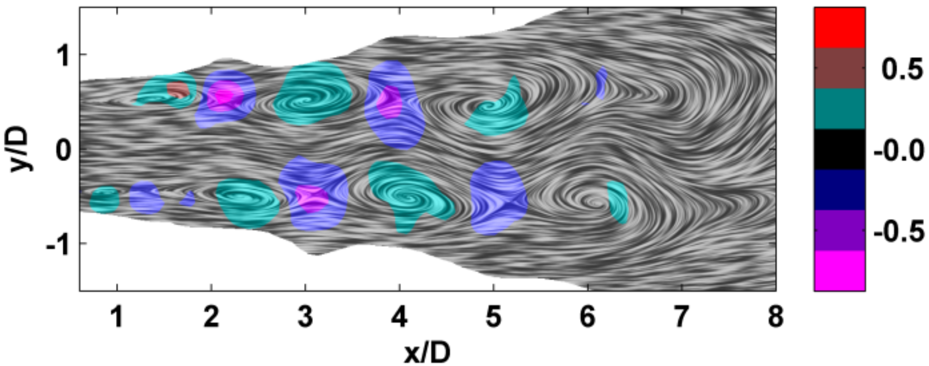
Outline of Presentation

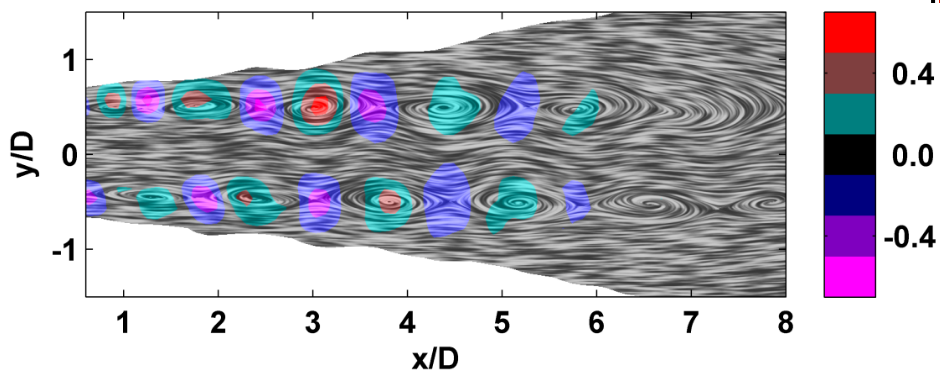
- We have made significant progress in both areas, but today's presentation will focus on jet noise
- For Shock/Boundary Layer Interaction work see:
  - Webb et al. AIAA 2012-2810 & Mullenix and Gaitonde AIAA 2012-2702 presented in New Orleans
- Jet noise experiments
  - A brief introduction to jet noise control
  - High speed jets and the role of large-scale structures
    - Peak far-field noise in baseline (uncontrolled) jet
    - Impulse and harmonic response of jet
- Jet simulations and comparison with experiments
  - Coherent structures
  - Near field
- Outstanding scientific/research issues

Control Effects on Flow Structures

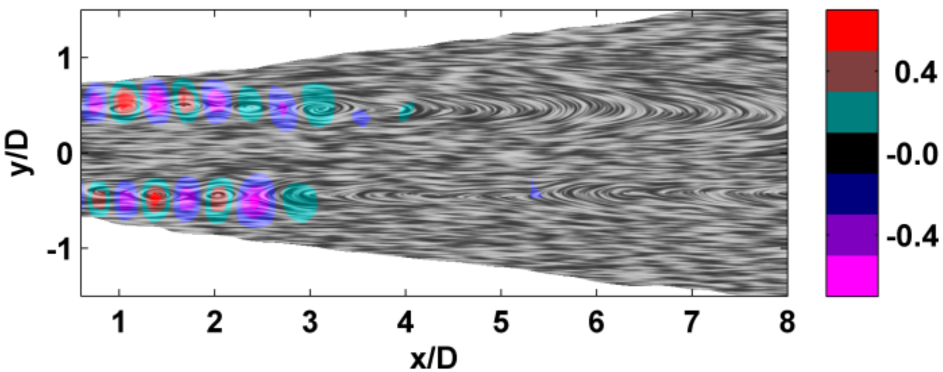
(M=1.3; Re_D=1.07x10^6; m=±1)

St_{DF}=0.33





St_{DF}=0.52



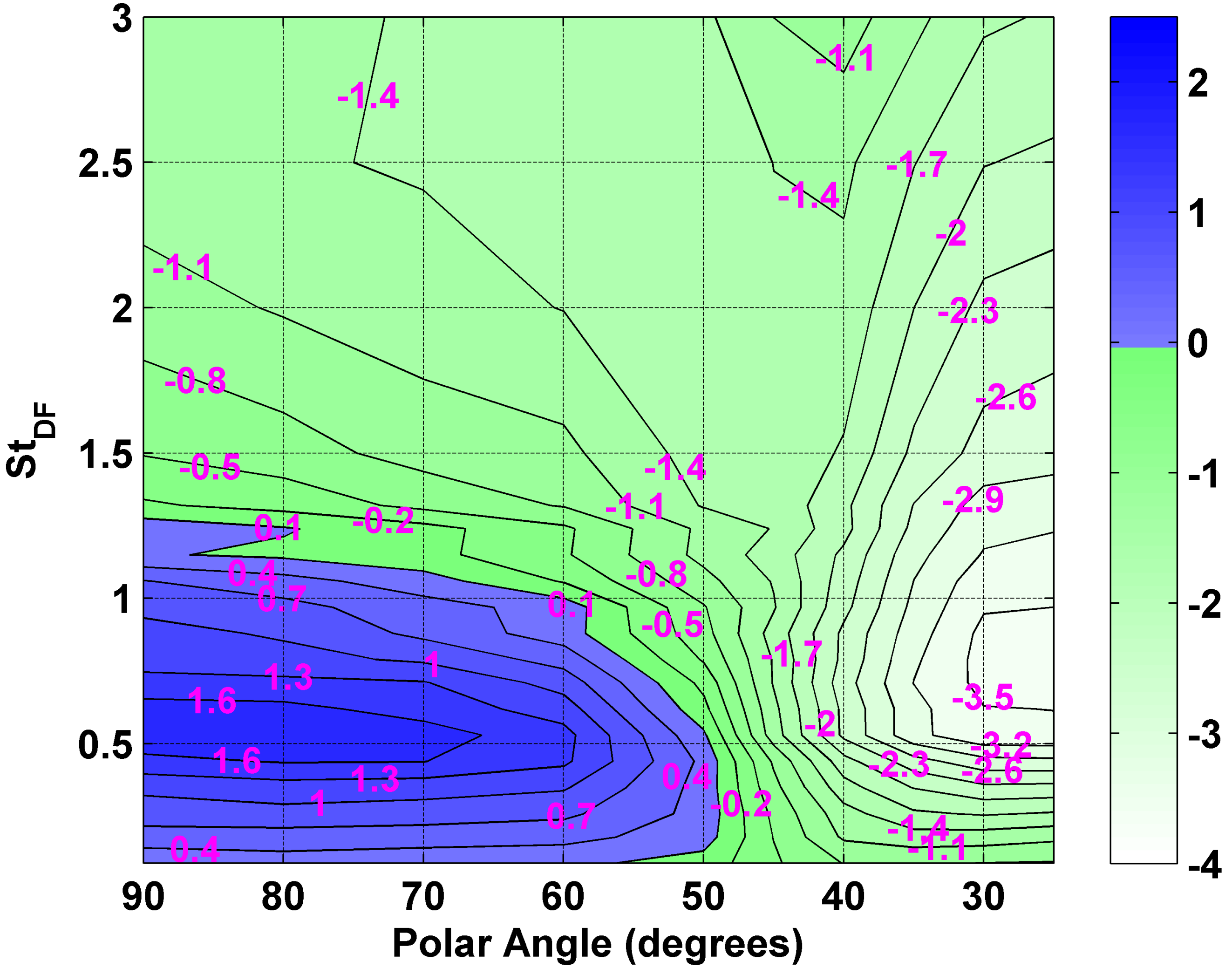
St_{DF}=1.05

Have shown robust control authority over a wide range of Mach number, temperature, and Reynolds number

Galilean streamlines superimposed on Q-criterion contours using PIV measurements

$$Q = \frac{1}{2}\left(\|\boldsymbol{\Omega}\|^2 - \|\boldsymbol{S}\|^2\right)$$

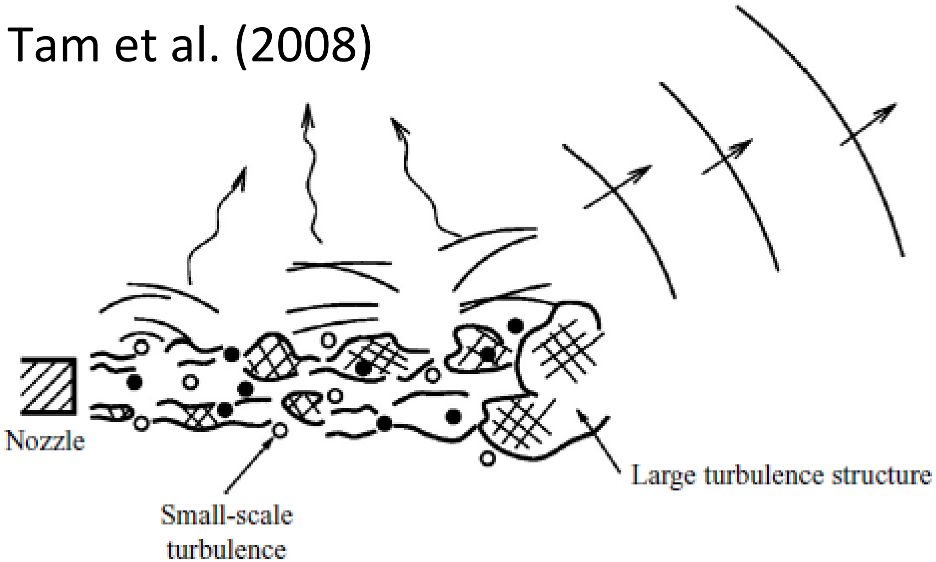
Control Effects on Far-Field Noise (ΔOASPL) – (M=1.3; m=3 & TTR = 2)

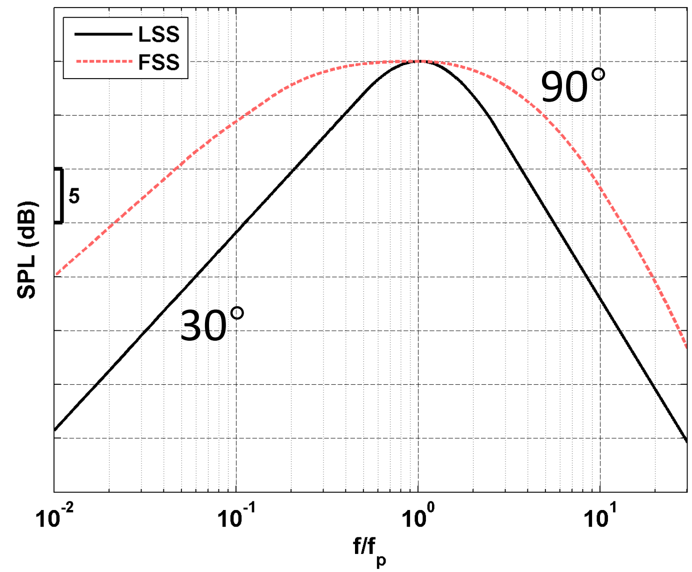


Jet Noise Sources

- Several sources
  - Mixing noise in both subsonic and supersonic jets
  - In addition, could have shock noise & Mach waves in supersonic jets

Tam et al. (2008)

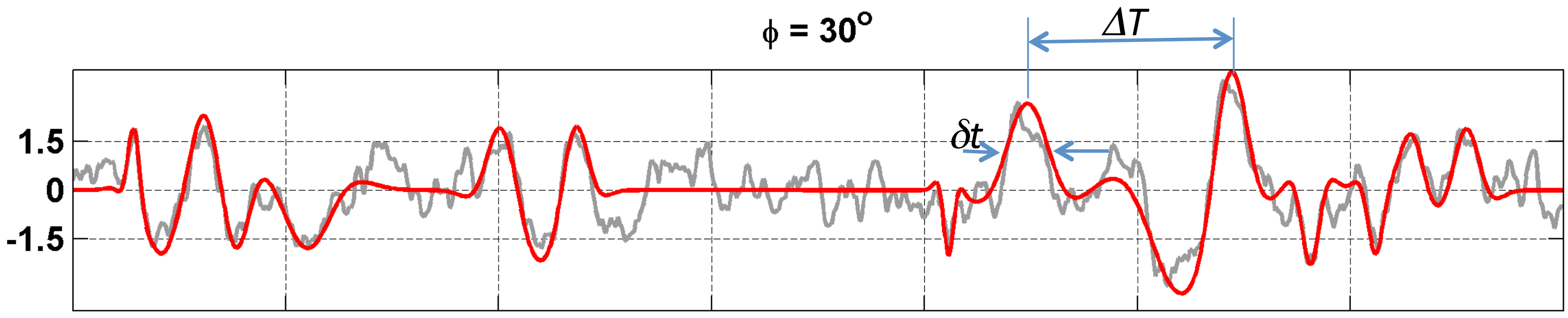




10 to 20 dB higher peak noise in shallow angles attributed to large scale structures

Far-Field Noise Events

- Shallow-angle noise consists of long-lived, intermittent swings that are well captured by a Mexican Hat Function
- Defined by: events width, δt_i (with mean of $\overline{\delta t}$), time between two events, T_i (with mean of $\overline{\Delta T}$), and event amplitude, A_i (with mean of)



$$\psi_i(t) = A_i\left(1 - \frac{(t-T_i)^2}{\delta t_i^{\,2}\epsilon}\right)\exp\left[\frac{-(t-T_i)^2}{\delta t_i^{\,2}\epsilon}\right]$$

Experimental Database

AAPL at NASA GRC & GDTL at OSU

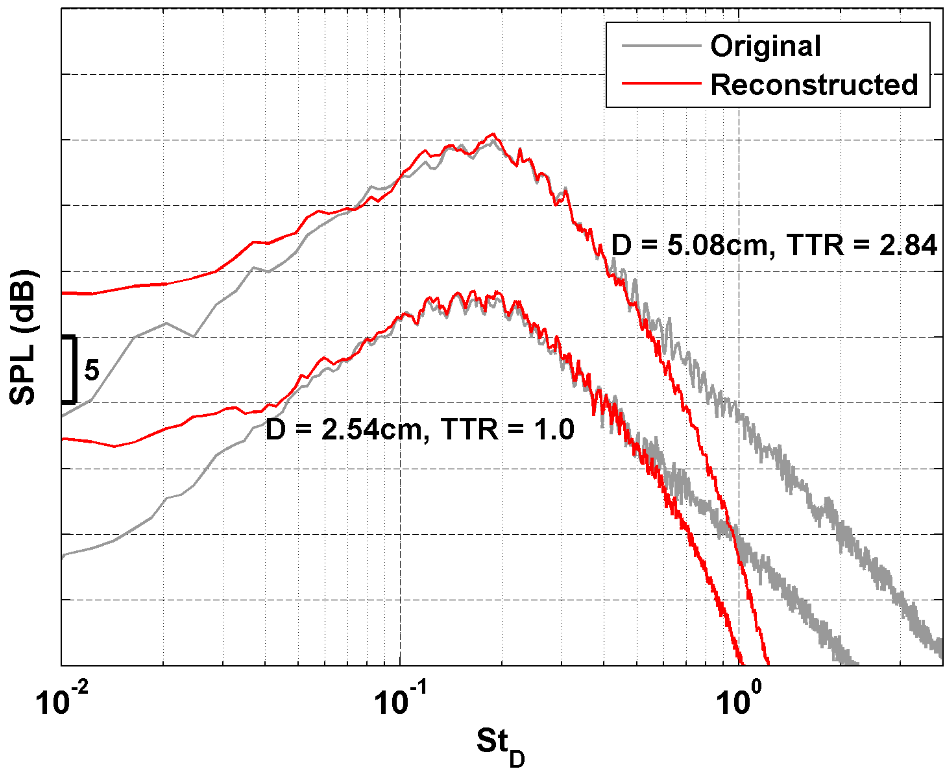
- 24 microphones arranged from 15 to 130 degrees in 5 degree intervals

D (cm)	TTR	M_a	ETR	Case Number
2.54	1.0	0.5, 0.6, 0.7, 0.8, 0.9	0.95, 0.93, 0.90, 0.87, 0.84	1-5
	1.0, 1.5, 2.0, 2.5	0.8, 1.0, 1.2, 1.3	0.86, 1.29, 1.72, 2.15	22-25
5.08	1.00	0.5, 0.6, 0.7, 0.8, 0.9	0.95, 0.93, 0.90, 0.87, 0.84	6-10
	1.81, 1.92	0.5, 0.9	1.76	16-17
	2.31, 2.43	0.5, 0.9	2.27	18-19
	2.75, 2.84	0.5, 0.9	2.70	20-21
7.62	1.00	0.5, 0.6, 0.7, 0.8, 0.9	0.95, 0.93, 0.90, 0.87, 0.84	11-15

Kearney-Fischer et al. AIAA-2012-1167 & AIAA-2012-2209

Experimental Results – First Important Observation

- Time-domain reconstruction using only peak noise events is used to determine the spectrum
- **Spectra are well reconstructed for the peak noise portions of the low angles across a wide range of diameters, acoustic Mach numbers, and temperatures**

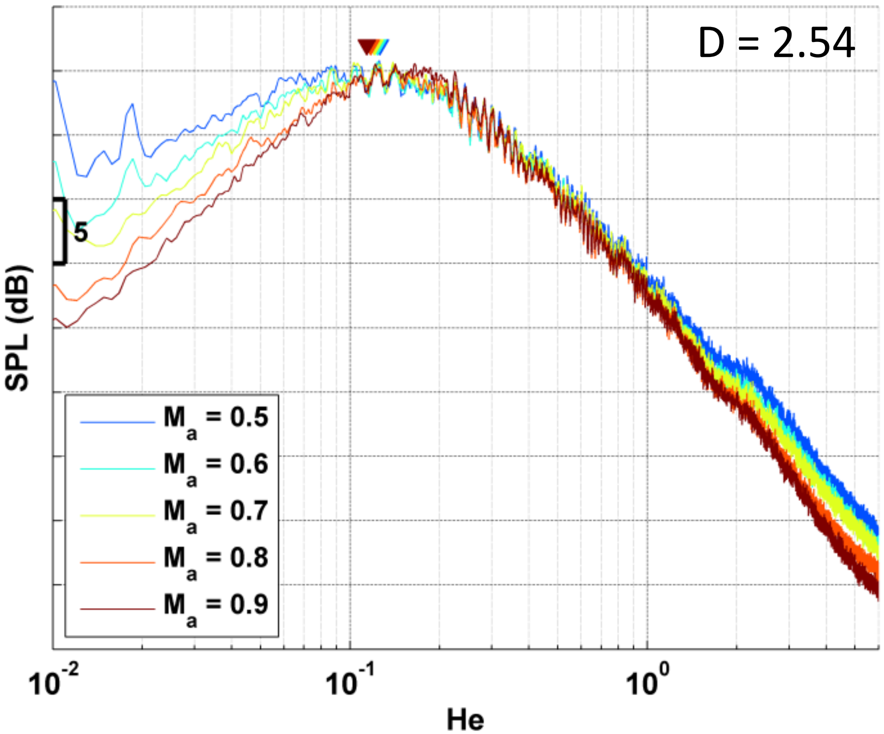


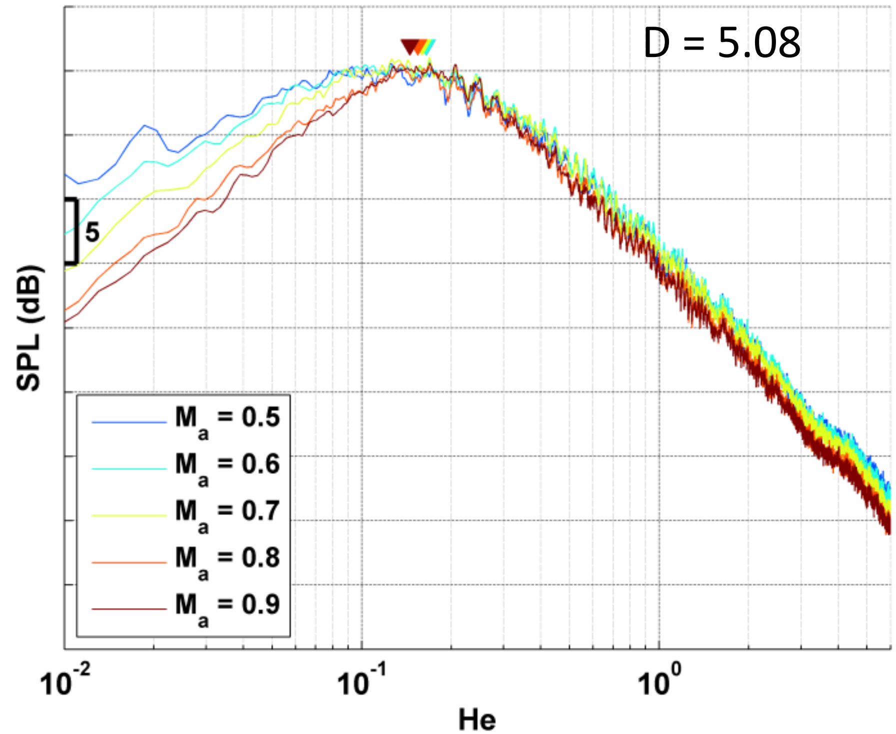
Reconstruction uses 13% of time signal (ignoring 87% of it).

Ma = 0.9, ϕ = 30°
Case # 5 & 21

Experimental Results – Second Important Observation

- The mean time between two noise events ($\overline{\Delta T}$) at 30° is a good predictor of the peak spectral frequency in cold jets of any Mach number or nozzle diameter

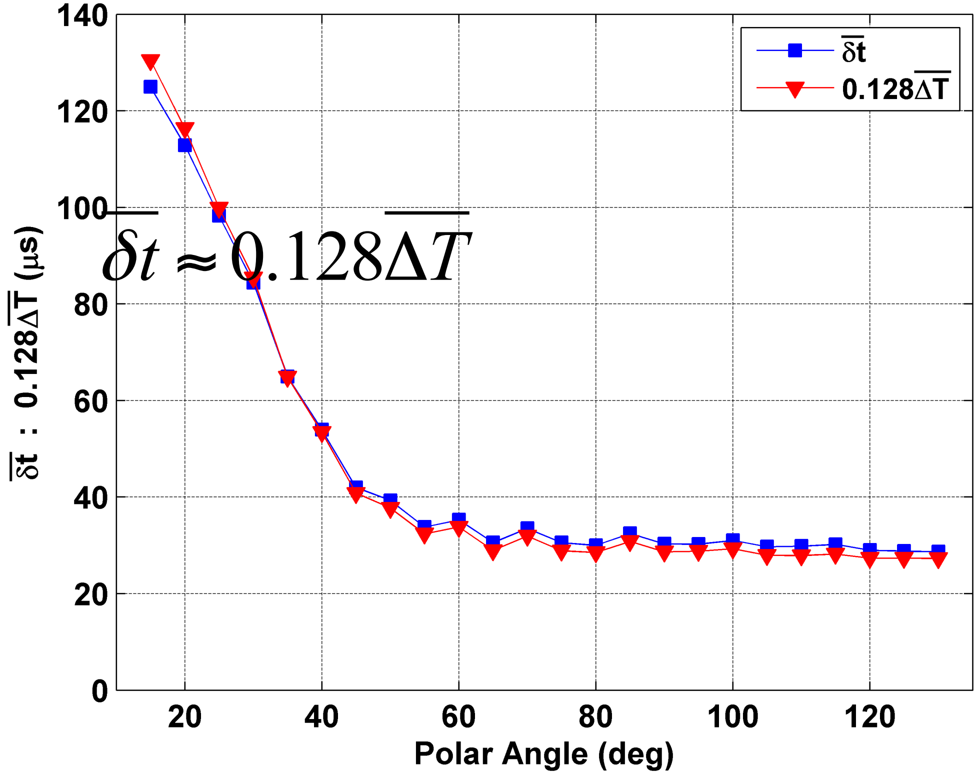




He (Helmholtz number) = fD/a_∞

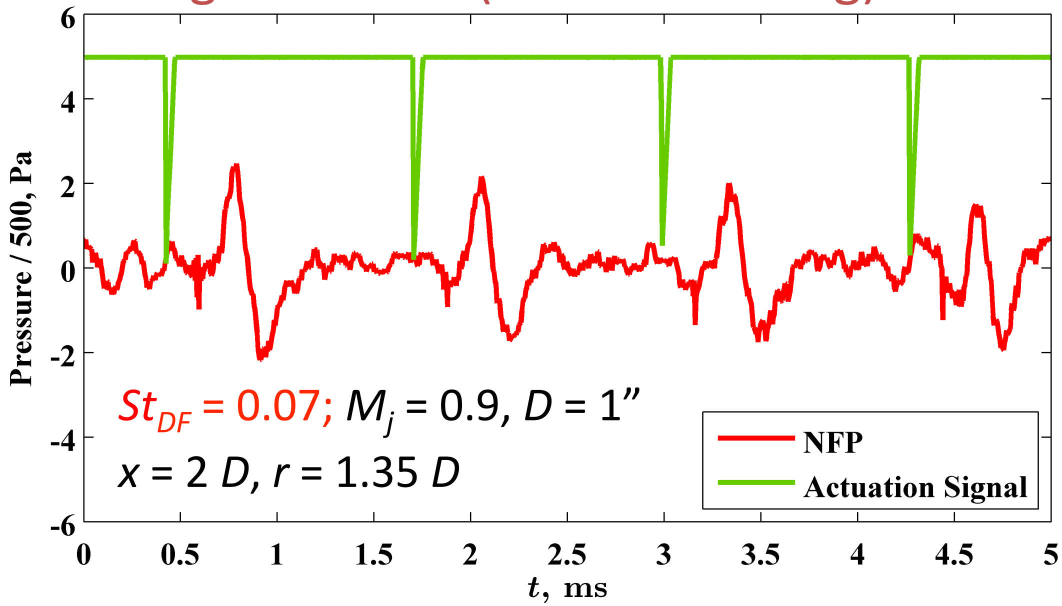
Experimental Results – Third Important Observation

- **The mean width ($\overline{\delta t}$) and mean time between events ($\overline{\Delta T}$) are strongly correlated - relationship is consistent regardless of jet diameter, velocity, or temperature.**
- **Frequency of occurrence of noise sources/events and their duration are much more organized than flow structures**



Impulse Response of Jet - Phase Averaging Process

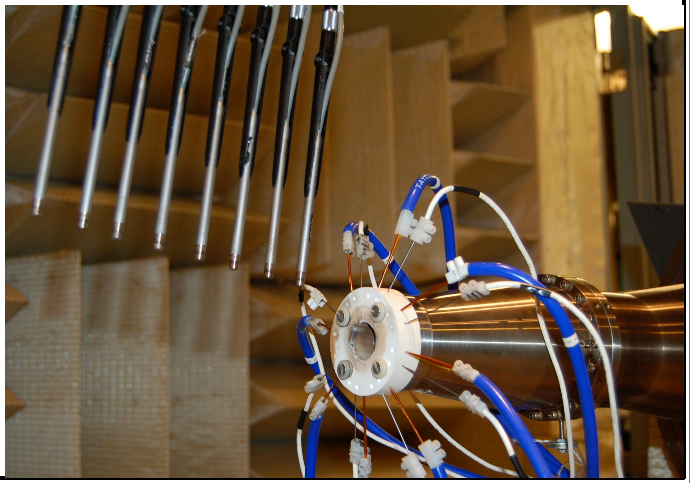
Generating individual (non-interacting) vortex rings



Triple Decomposition: $\underbrace{P}_{\text{Total}} = \underbrace{\overline{P}}_{\substack{\text{Mean}\\ \text{(Ambient)}}} + \underbrace{p}_{\text{Fluctuation}} = \overline{P} + \underbrace{\tilde{p}}_{\text{Wave}} + \underbrace{p'}_{\text{Turbular}}$

Microphones located at irrotational near-field

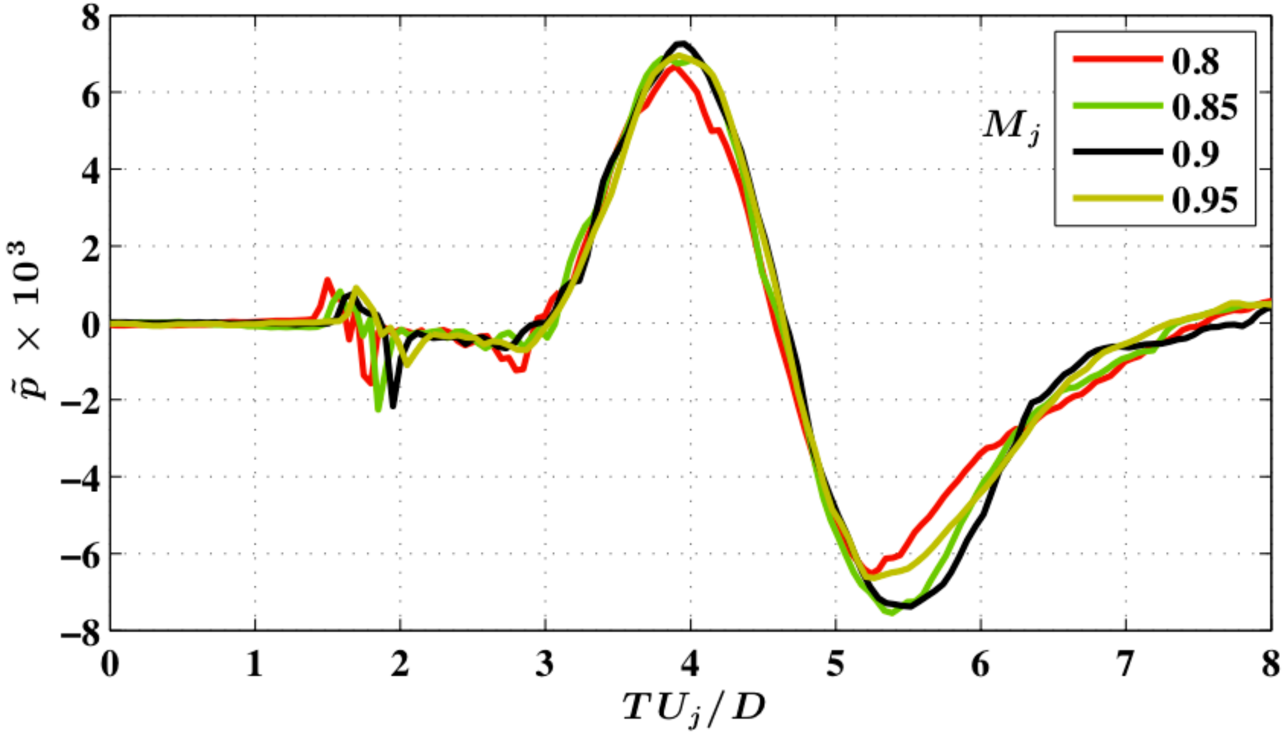
Wave component: $\tilde{p}\left(T; f_F\right) = \lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N-1} p\left(T + n / f_F\right)$



Sinha et al. AIAA-2012-2142

Wave Pressure (Vortex Ring Signature): Impulse Response

Inverse Strouhal number scaling of vortex ring



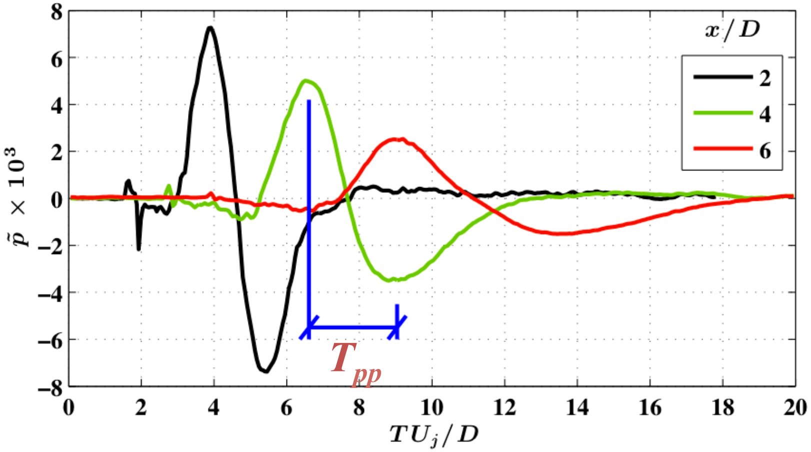
Forcing frequency:
$f_F \approx 250$ Hz
($St_{DF} \approx 0.02 – 0.04$)

Probe location:
$x = 2\ D$, $r = 1.35\ D$

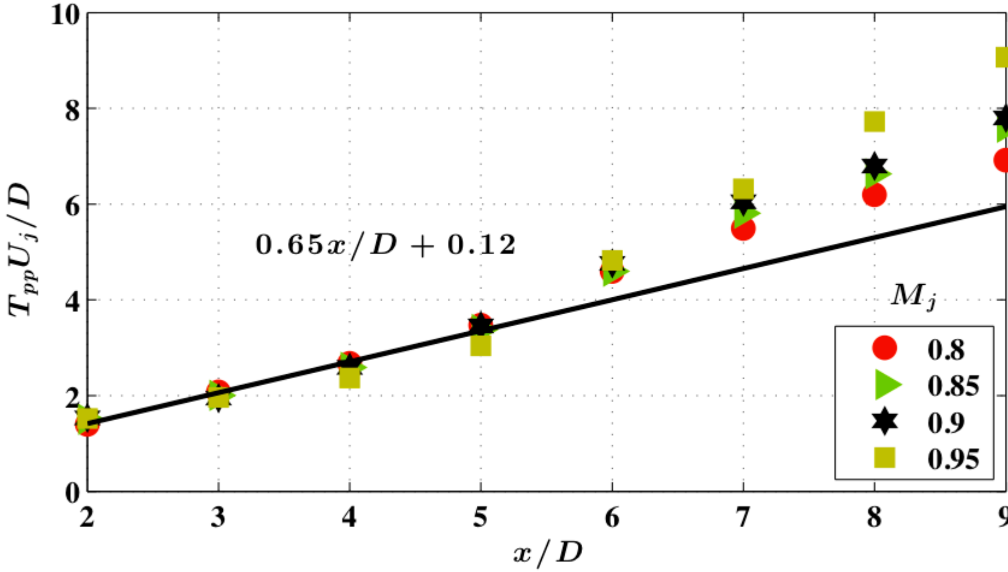
- Compact signature time scale << Forcing period => Impulse response
- Scaling indicates the involvement of large scale structures
- Peak-to-peak amplitude ~ 10 x p_{RMS} (unforced)

Impulse Response – Streamwise Evolution of Vortex Rings

M_j = 0.9, D = 1”



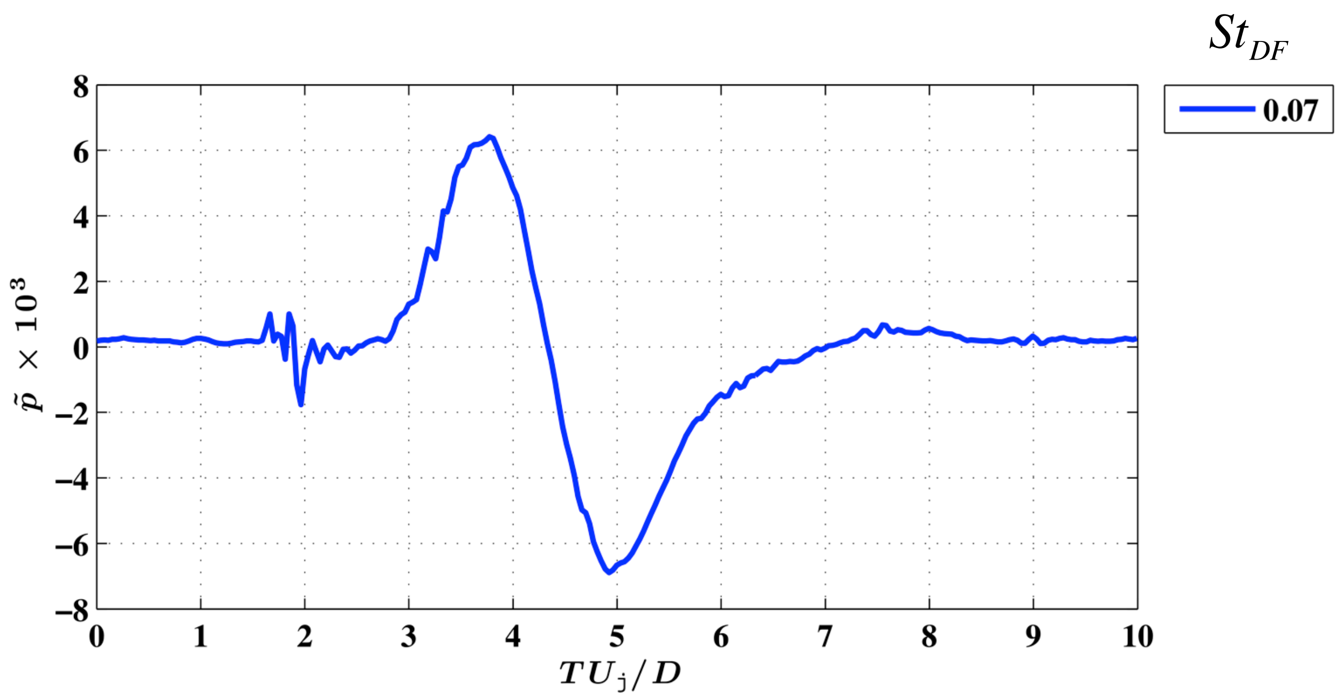
Temporal scale of vortex ring



- Linear increase of T_{pp} (temporal scale of impulse response) mirrors $1/St_D^{max}$ of unforced jet
- Further confirmation that each impulse is seeding a large scale structure that develops as in unforced jet

Wave Pressure (Vortex Ring Signature): Impulse Response

Frequency Sweep

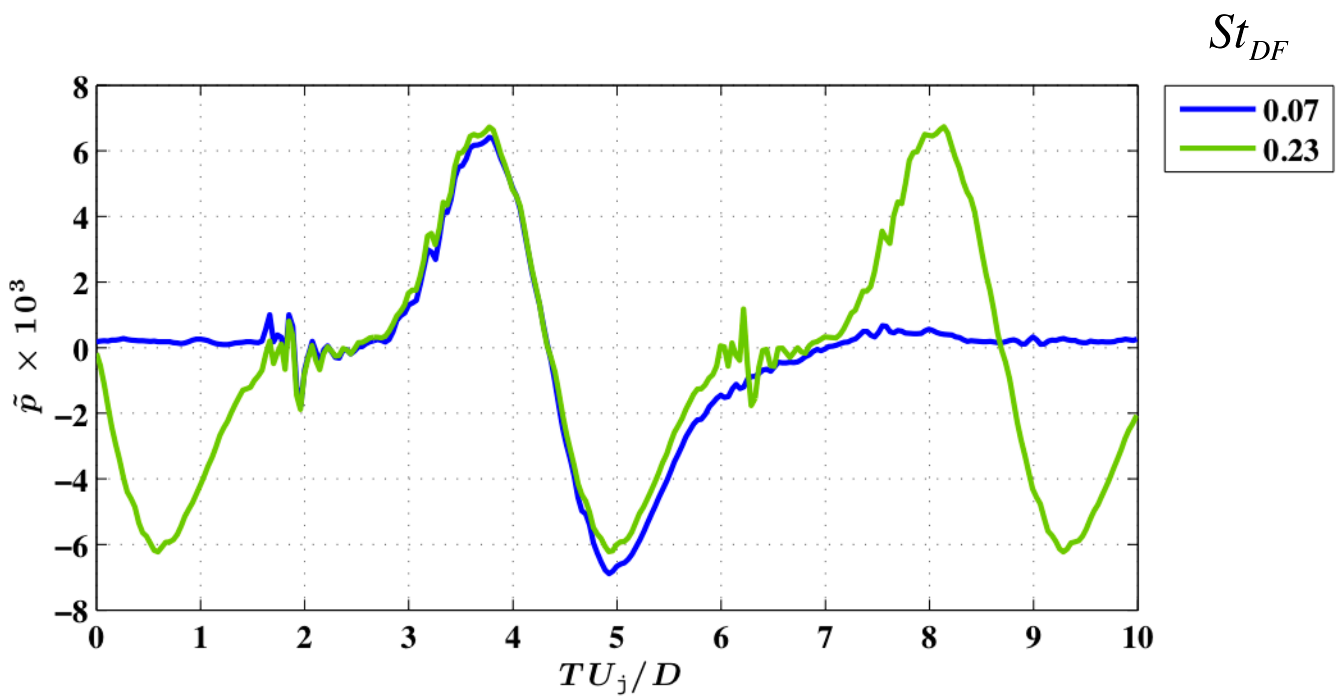


Operating conditions: M_j = 0.9, D = 1.5”

Probe location: x = 2 D, r = 1.35 D

Wave Pressure (Vortex Ring Signature): Impulse Response

Frequency Sweep



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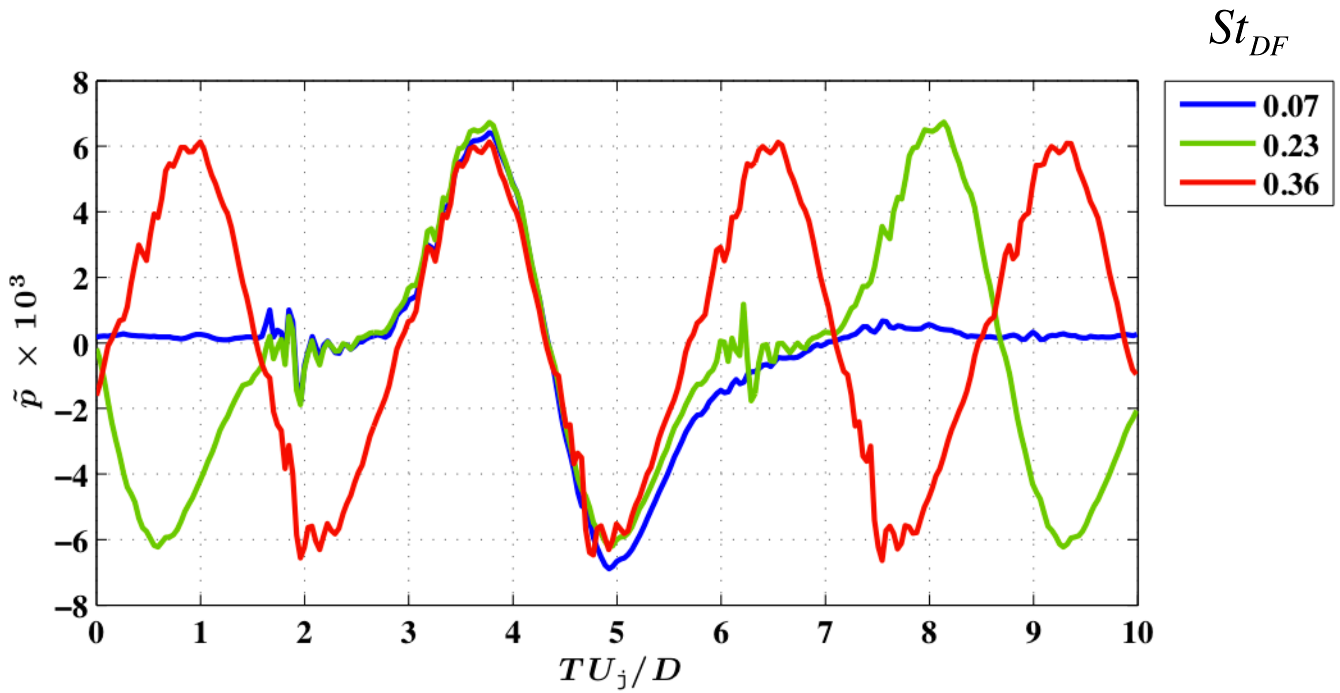
Wave Pressure (Vortex Ring Signature): Impulse Response

Frequency Sweep

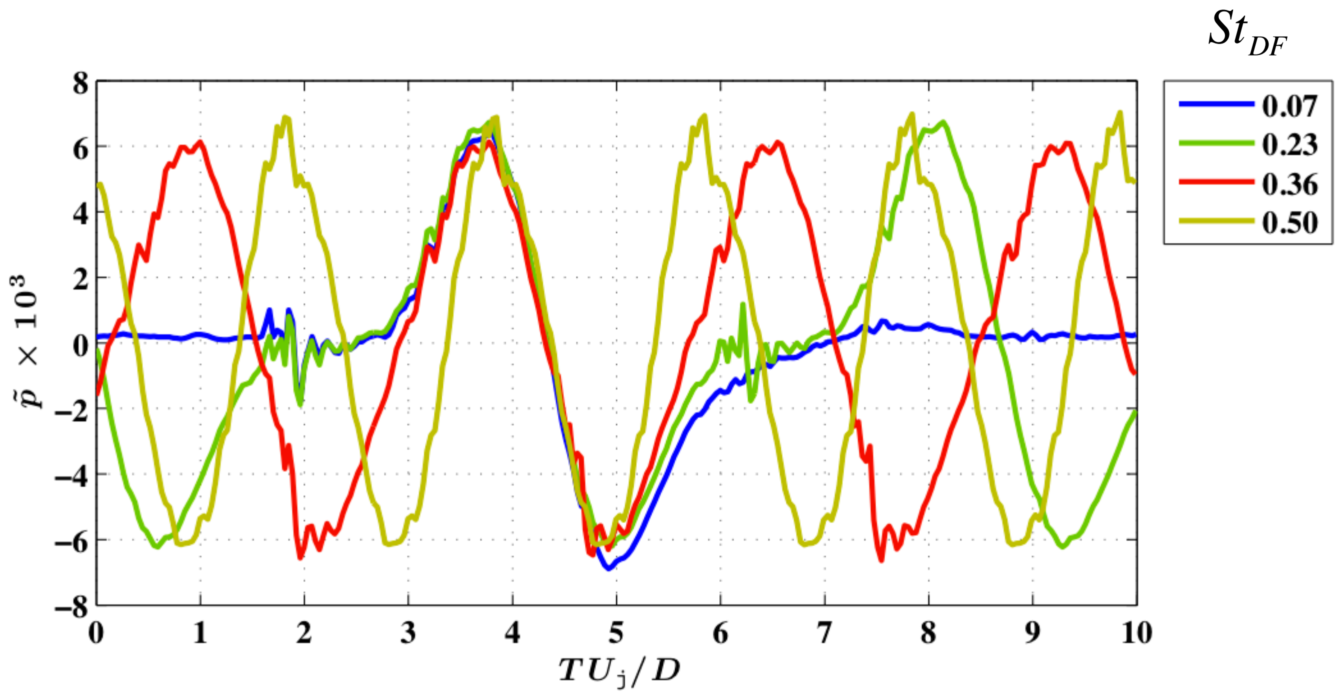


Operating conditions: $M_j = 0.9$, $D = 1.5''$

Probe location: $x = 2\ D$, $r = 1.35\ D$

Wave Pressure (Vortex Ring Signature): Impulse Response

Frequency Sweep

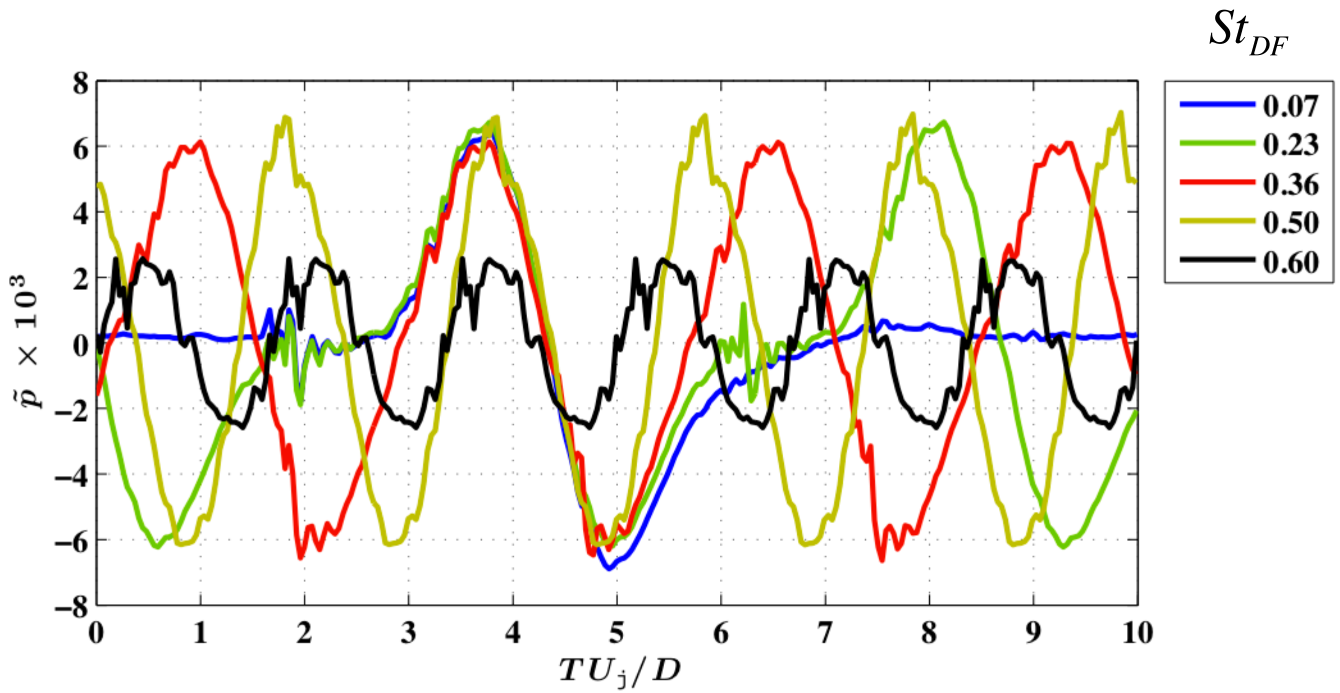


Operating conditions: M_j = 0.9, D = 1.5”

Probe location: x = 2 D, r = 1.35 D

Wave Pressure (Vortex Ring Signature): Impulse Response

Frequency Sweep

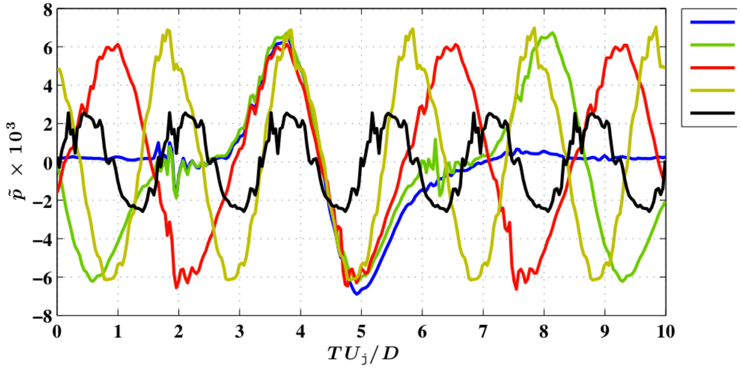


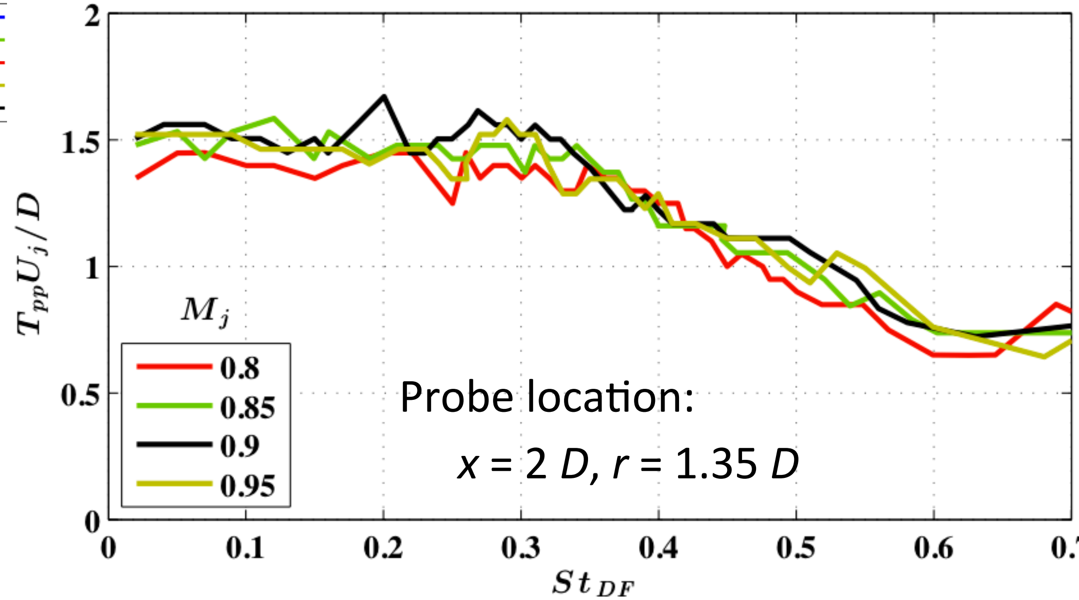
Operating conditions: M_j = 0.9, D = 1.5”

Probe location: x = 2 D, r = 1.35 D

Impulse & Harmonic Response

Vortex Ring Time-Scale - Peak-to-Peak Time, T_{pp}





- Seeded vortex rings do not interact at low St_{DF}'s - ***impulse response***
- Beyond $St_{DF} \sim St_D^{\max}$, the interaction manifests in reducing T_{pp} – ***quasi-linear interaction***
- St_{DF} x $(T_{pp}U_j/D) \approx 0.5$ in harmonic response (sinusoidal symmetry) – beyond which we get ***non-linear interaction***

Future Work on Jet Noise

- We have developed a tool to thoroughly investigate, in a well controlled environment, the flow field, irrotational near-field, and far-field of
  - A single vortex ring (of various kind),
  - Quasi-linear interacting vortex rings (of various kind), and
  - Non-linearly interacting vortex rings (of various kind)

Outstanding Scientific Research Issues

- Jet noise
  - *Dynamics of large scale structures and their relation to jet noise*
  - *Effective control of jet noise*
- Shock/boundary layer interaction
  - *Mechanism and structure of low frequency oscillations in the interaction region*