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Periodic Forcing of a Turbulent Axisymmetric Wake

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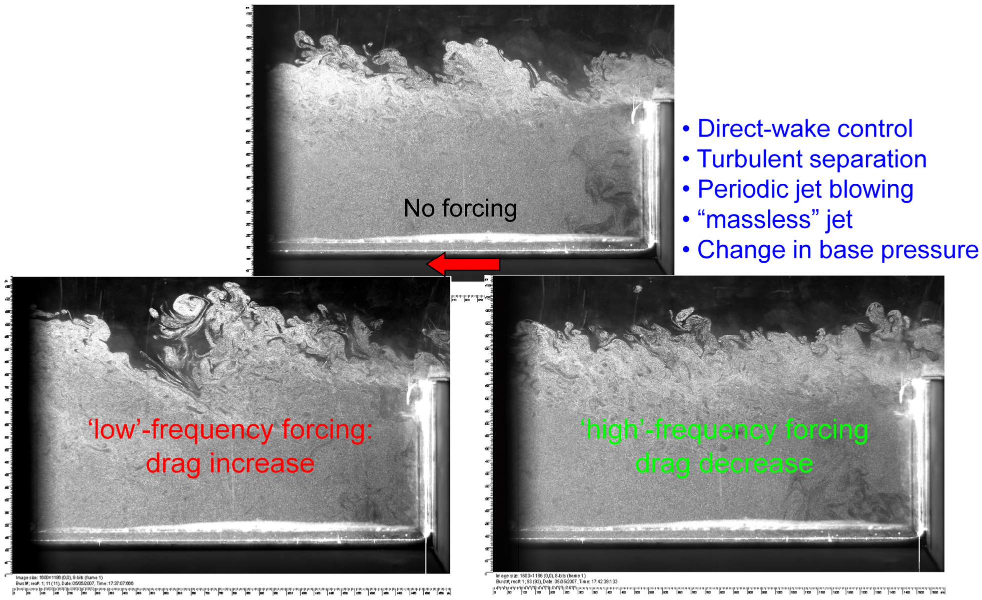
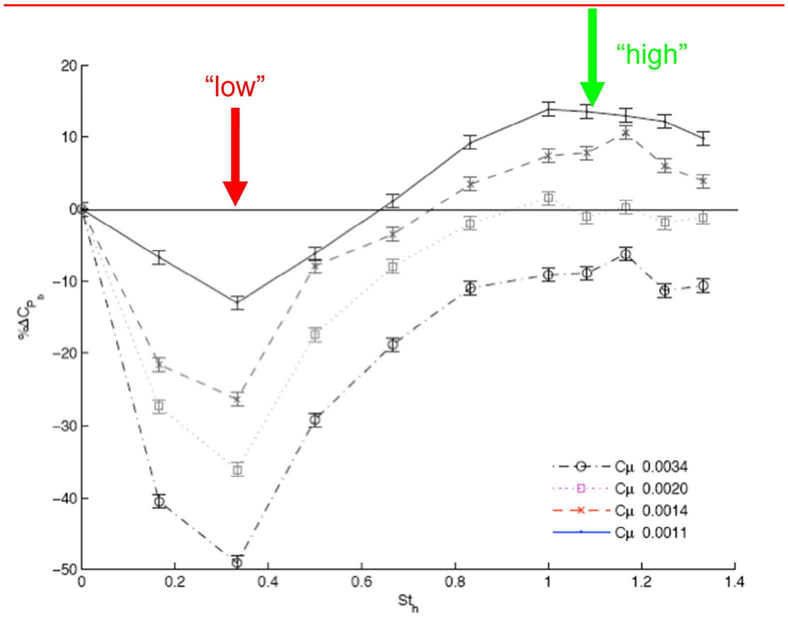
Backward-facing step: two-dimensional separation



Backward-facing step: change in base pressure



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Initial Observations

- Plane mixing layer difficult to control
  - ► growth rate dominated by turbulence (unlike jet)
  - ► receptivity arguments require the super-imposing of a fixed f, λ and φ but it is hard to see how these conditions can be met
- Here flow has both convective and absolute instability
- Globally unstable – natural feedback, upstream convection, pressure fluctuations
- Why is this flow controllable?

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Synopsis

- Effects of variable-frequency forcing
- Relation to linear theory
- Effects of three-dimensional forcing
- Relation between instability mechanisms
- Future work:
  1. Open-loop control
  2. Feedback control

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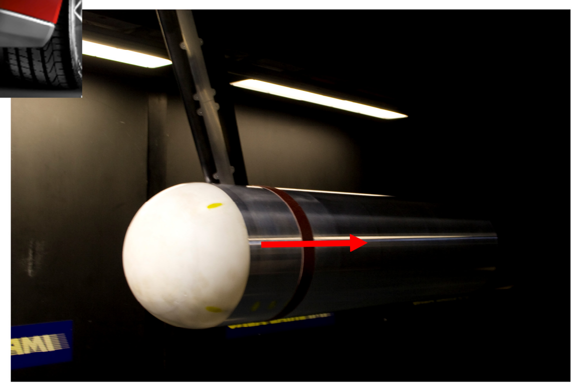
From fast cars…

To a representative shape…



Axisymmetric separation

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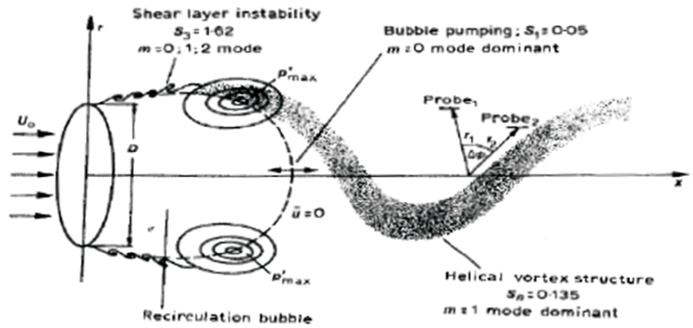

Berger *et al.* 1990

Azimuthal Decomposition into Fourier Modes:

- Shear Layer Instability: dominant mode shape axisymmetric, dominates near-wake
- Helical Instability: antisymmetric, forms past rear stagnation point
- Low-frequency "pumping mode": varicose/axisymmetric

Berger *et al.*:

Forced disk in nutation: lock on to helical instability

- pumping mode not affected
- shear layer mode not affected, not investigated

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Certainly many other works but this is a good summary

Experimental Setup

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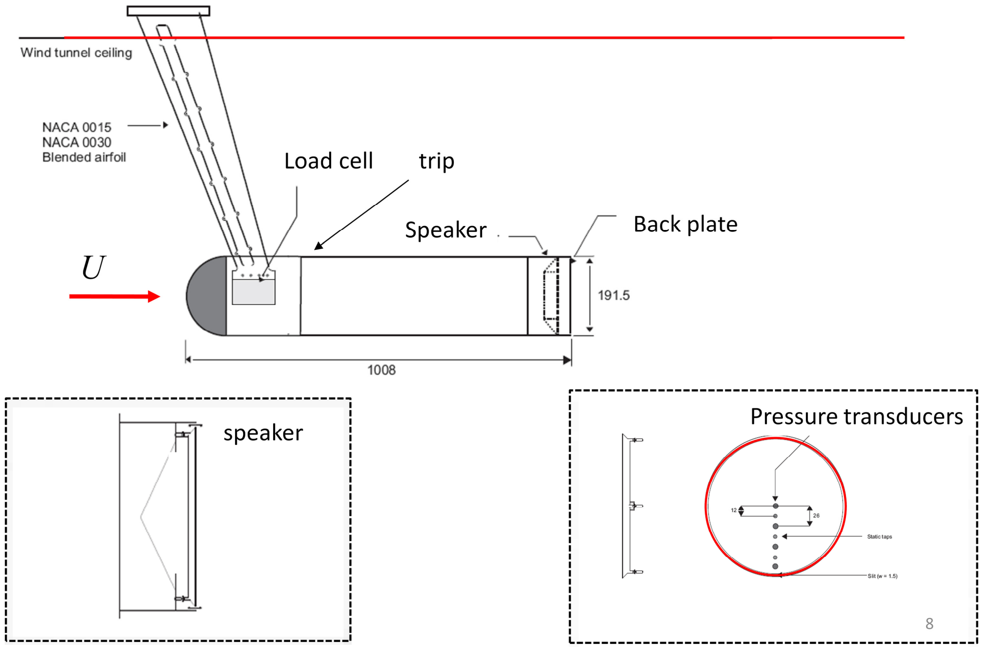

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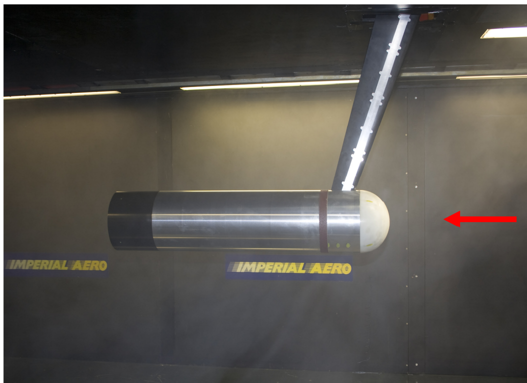
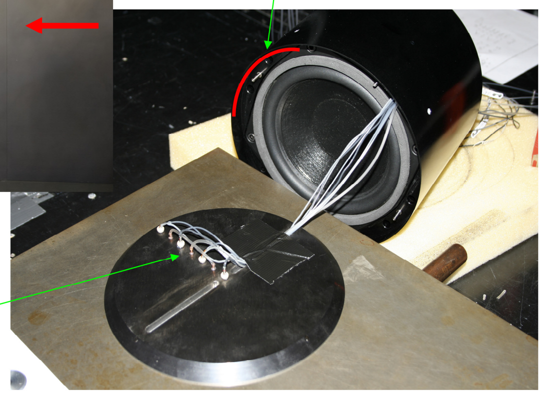
Separation from a sharp edge





Re_D = 1.9 x 10^5
D = 0.19 m
δ/D = 0.11

Actuator – massless jet

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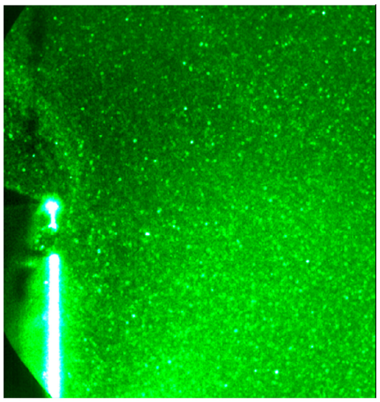
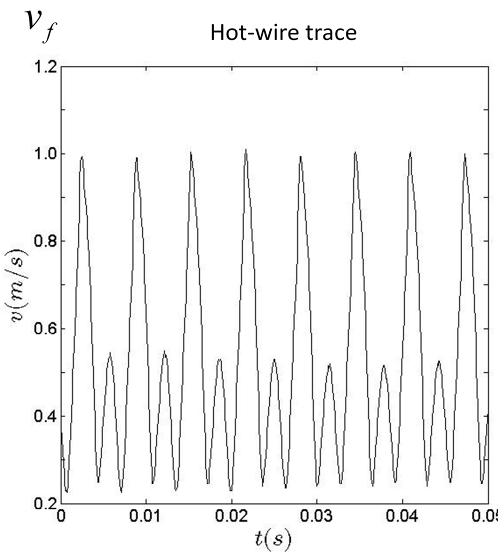
Quiescent:





Time-Resolved Flow Vis:
260 Hz at V_f = *0.27U*
Slit width = 1.5 mm

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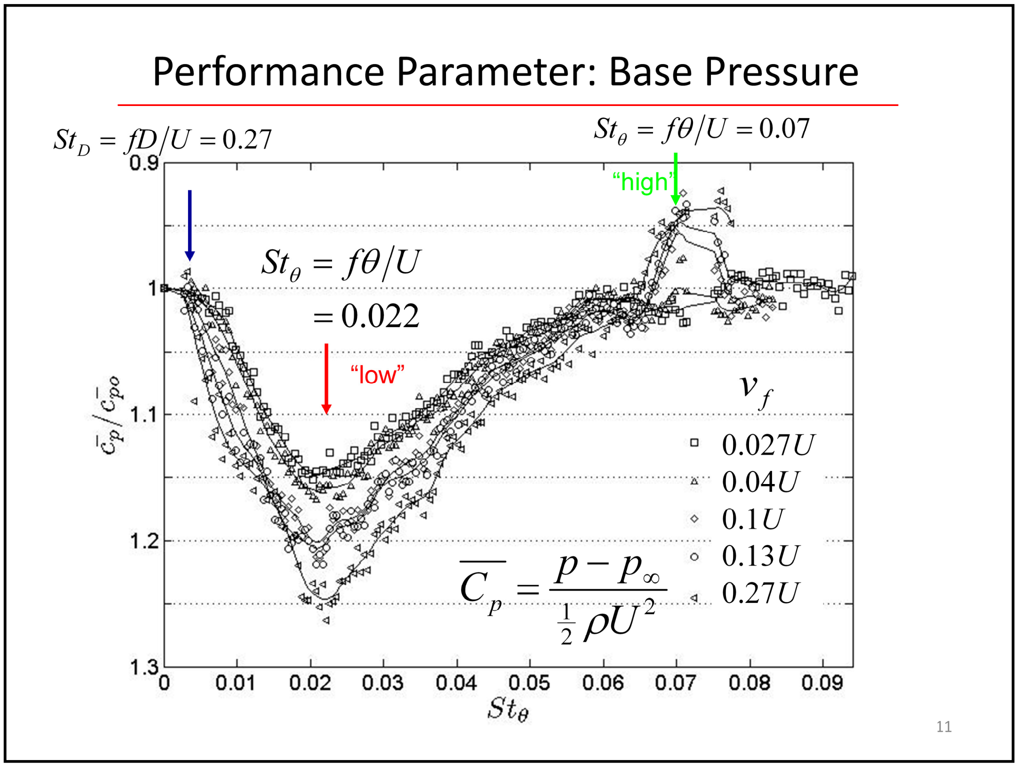
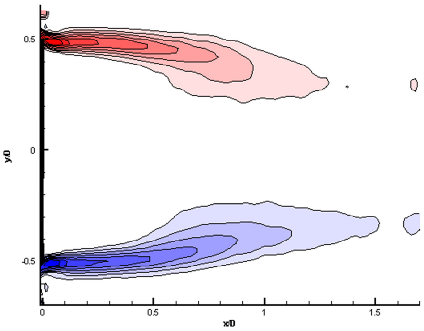
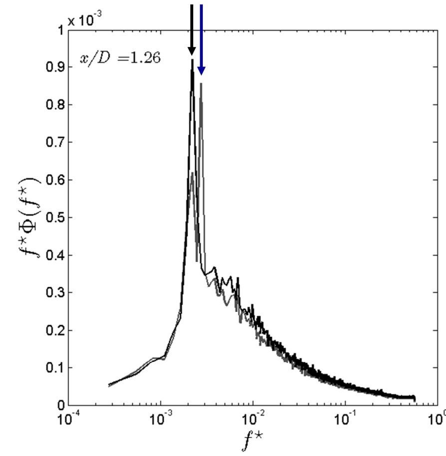


Talk about susceptibility to amplitude
First peak scales with the helix structures

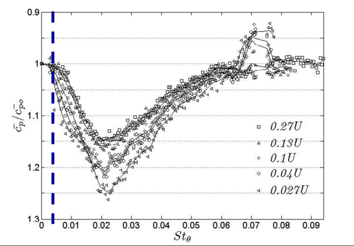
$St_D = 0.27$





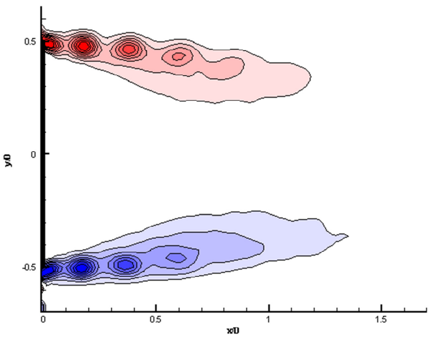
Phase-averaged vorticity, $\delta\varphi = \pi/4$; $v_f = 0.27U$

Beat coupling:
Detuned frequency – slightly higher than that of natural helical shedding $St_D \approx 0.23$
Bubble pumping at $St_D \approx 0.18$

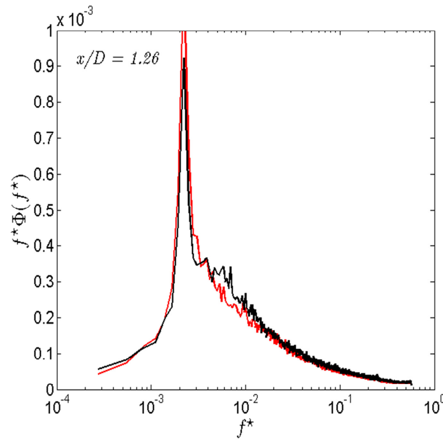


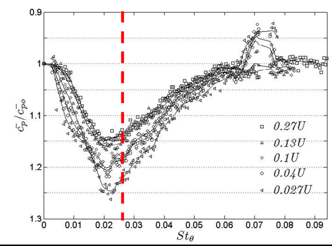
Do not see helical peak at x/D less than 0.6 .

$St_\theta = 0.024$



$v_f = 0.27U$

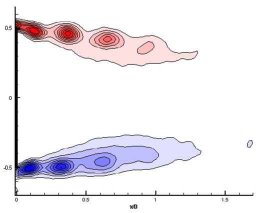




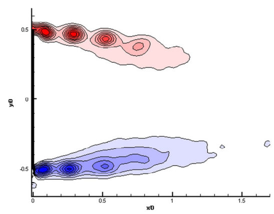
Helix not affected

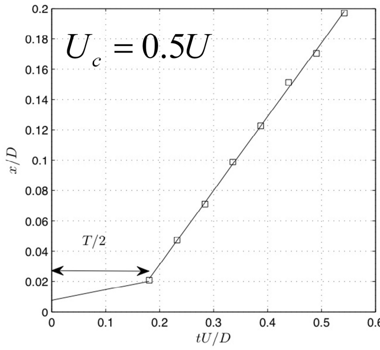
Phase velocity $U_c = f\lambda$

St 0.017

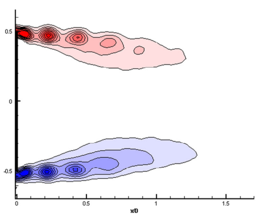


St 0.020

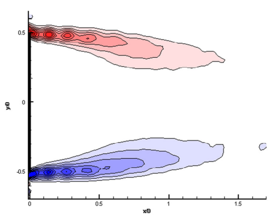


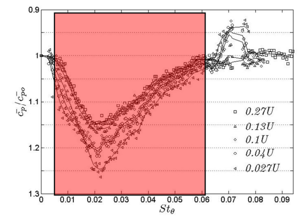


St 0.025



St 0.036





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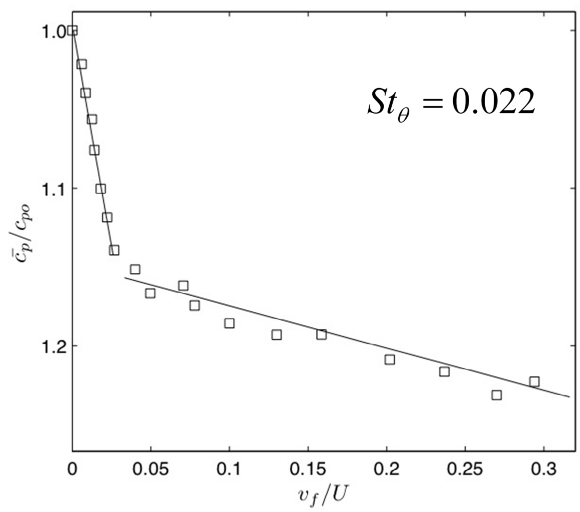
Change in base pressure with forcing amplitude



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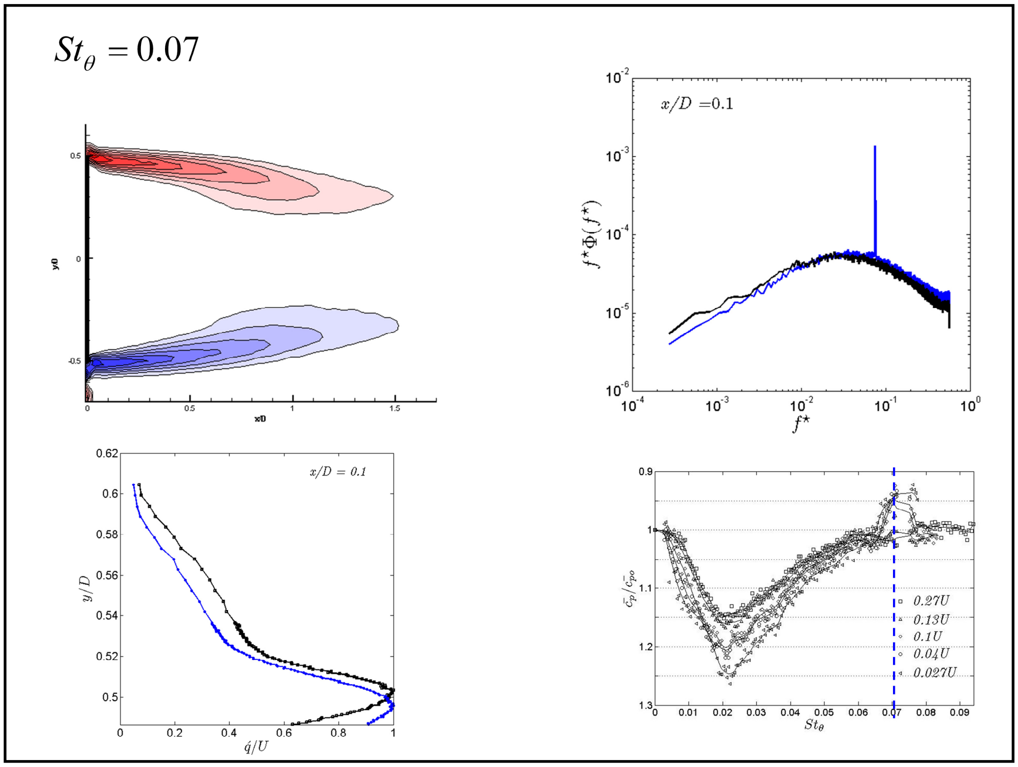
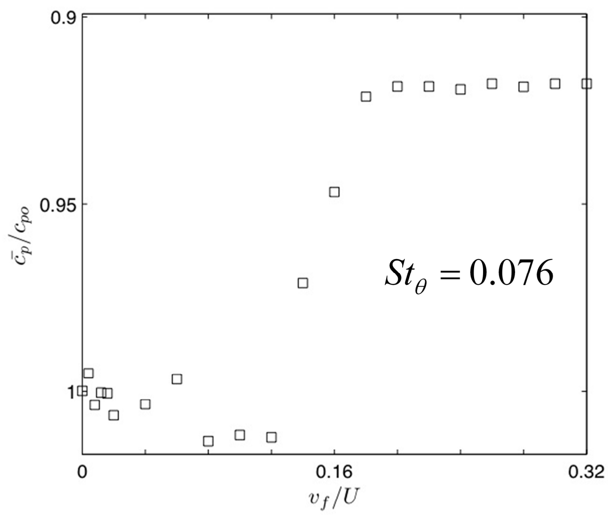
Helix not affected



Helix not affected

Change in base pressure with forcing amplitude



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Helix not affected

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Conclusions

- First time shear layer mode of axisymmetric body investigated using symmetric forcing.
- Variable – frequency axisymmetric forcing shown to both reduce and increase base pressure.
- The momentum thickness at separation important length scale for axisymmetric body.
- Optimum frequency (shear layer mode) close to that predicted by linear stability analysis of laminar mixing layer (Ho & Huerre 1984) and very similar to prediction for turbulent base flow (Morris & Foss 2003) $St_{\theta} = 0.022$
- Helical mode not synchronized at forcing frequencies except St_D=0.27: "beat coupling" at boundaries of lock-in region. Helical shedding only forms downstream of the recirculation bubble.
- Increase in base pressure by forcing small scales of shear layer directly (e.g., Wiltse & Glezer 1998).

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Future Work

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- Most receptive shear-layer frequency predicted by linear theory: suggests usefulness of linear feedback control.
- High-frequency forcing appears to be nonlinear: inhibits entrainment leading to base-pressure recovery – annular "virtual spoiler".
- Low-frequency forcing: use as an "virtual air brake".
- These results appear to be relevant to 2D planar geometry.
- Require two-dimensional or axisymmetric, annular jet: 3D-forcing does not reproduce base-pressure recovery.

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Aerodynamic Steering?

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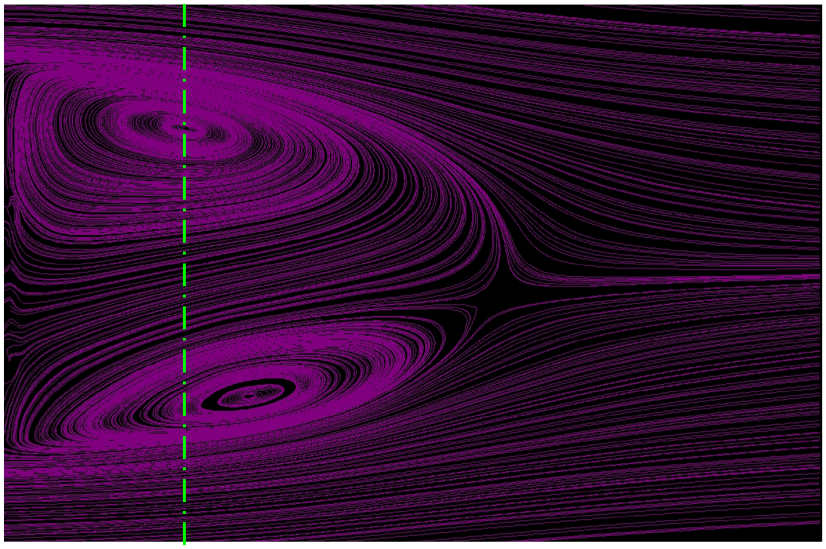

Asymmetry creates forces perpendicular to direction of travel

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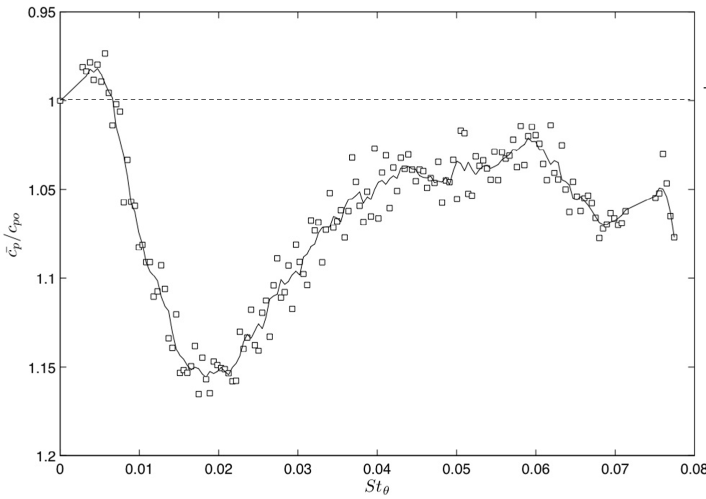
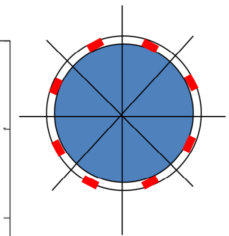
3D Forcing





$v_f/U = 0.27$

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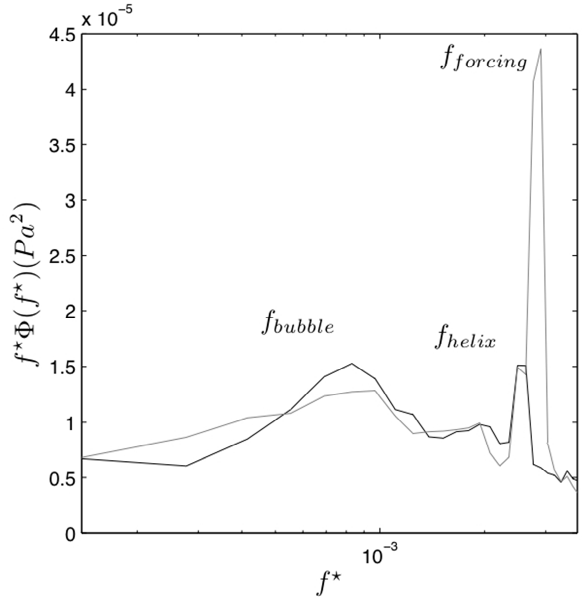
VLF Base-pressure spectra



$St_\theta = 0.003$

$v_f / U = 0.27$

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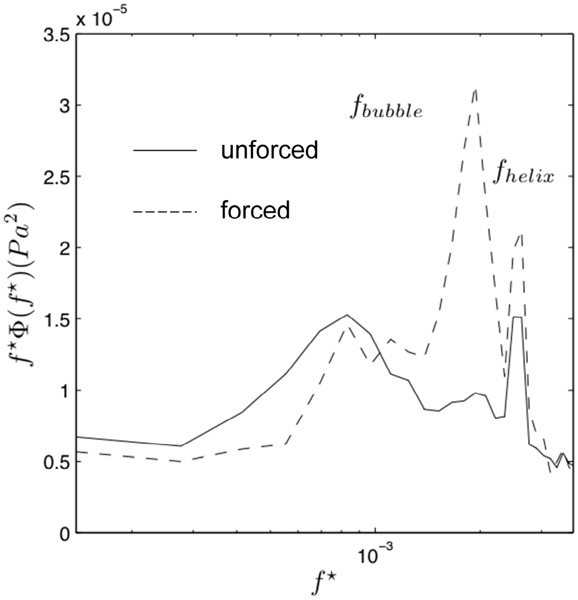
LF Base-pressure spectra



$St_{\theta} = 0.025$

$v_f / U = 0.27$

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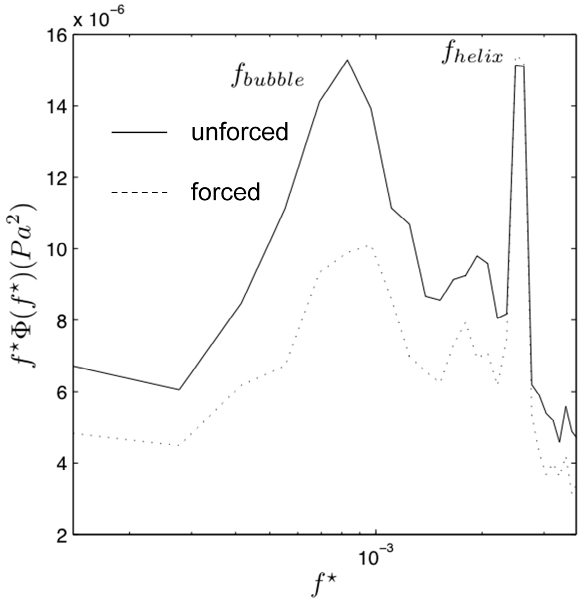
HF Base-pressure spectra



$St_\theta = 0.076$
$v_f / U = 0.27$

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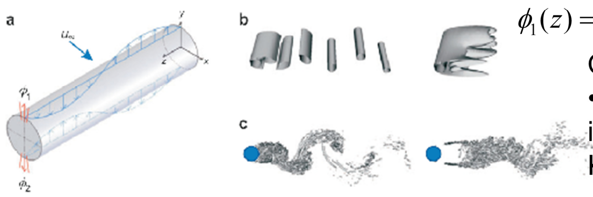
2D Bluff bodies: direct-wake control

1.

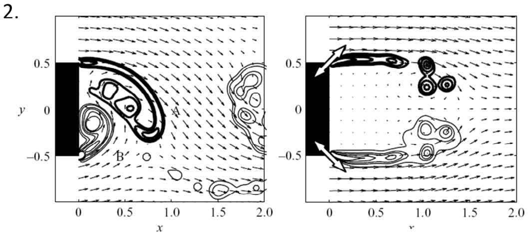


$$\phi_1(z) = \phi_2(z) = \phi_0 \sin(2\pi z / \lambda)$$

Open-loop control:

- upper/lower blowing/suction in antiphase “annihilates” von Kármán shedding

2.



Open- and closed-loop control:

- Synchronization of shedding of top and bottom shear layers
- Effective forcing frequencies close to those of von Kármán shedding
- Decoupling of upper & lower vortex formation

1. *Kim & Choi 2005*
2. *Pastoor et al. 2008*

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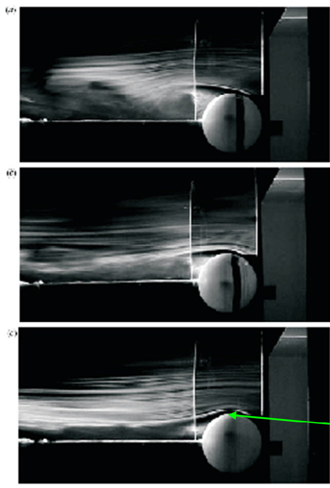
Mention the push to reduce drag talk about application reynolds number absolutely unstable, high frequency effective but not as efficient, different strategies

Axisymmetric bluff body: delay of separation



Basic

Basic+trip

Forced

Drag Reduction Strategy:
Separation delay and reattaching boundary layer.

Boundary layer instability
$Re_D \leq 2x10^5$

High-frequency, time-periodic blowing through axisymmetric slit: St_D=4.95

1. *Jeon et al. 2004*

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