# Response of turbulent fluctuations to the periodic perturbations in a flow over a backward facing step

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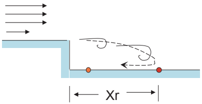
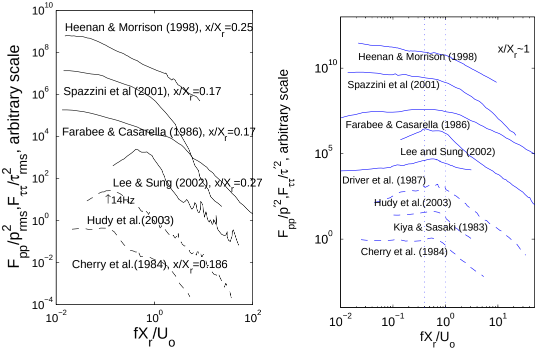
# Background

Flow over a backward facing step:

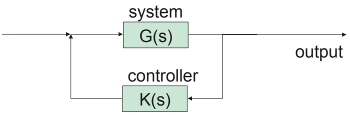
- time-averaged reattachment length $X_r/H \approx 4$ to 7;
- at $x/X_r = 1/4$, low frequency fluctuations $fX_r/U_o \approx 0.1$, 'flapping' (Heenan & Morrison, 1998);
- at $x/X_r = 1$, high frequency $fX_r/U_o \approx 1$ 'shedding' (Simpson, 1989);

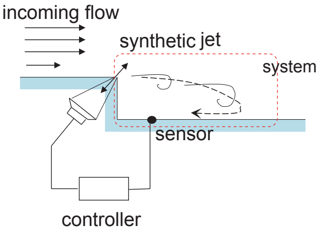



Spectra of wall pressure/skin friction from literature

# Objectives



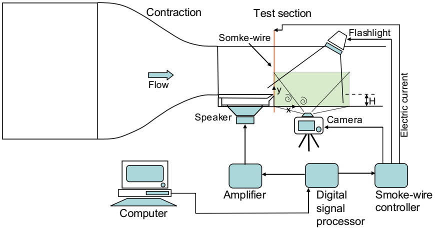




Schematics of a feedback control system

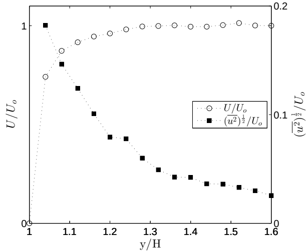
- Feedback control based on linear control theory to increase the pressure in the separated region (*e.g.* Dahan *et al.*, 2012);
- Construct a functional controller requires accurate linear model of system;
- 'Black-box model' approach to found the linear model for a separated flow, *i.e.* examine the response of flow parameter (*e.g.* wall pressure ) to the acutation
- current investigation focuses the size of the peak in wall pressure spectra to the actuation strength

$$F_{pp}(f = f_A) \sim u'$$

# Experiment Facility




Schematics of the test rig

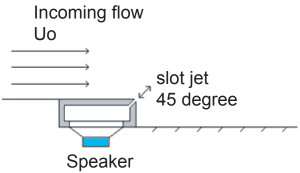



Mean and r.m.s. velocities at $x/H = -0.1$

- Step height $H = 0.025m$;
- Free-stream velocity $U_o = 5.7m/s$, $Re = 9100$ ;
- Boundary layer thickness $\delta/H = 0.24$, $\theta/H = 0.02$;
- Free-stream turbulence intensity 2.0%.

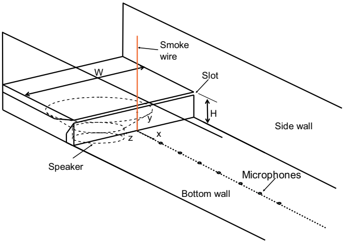
# Experimental Facility

- $0.22 * 0.08 * 0.02m$ box with a speaker (20cm diameter, 8Ω, 150W) and an $1mm$ wide slot;
- jet directed at a $45^o$ to the free-stream;
- forcing frequency: $St_A = fH/U_o = 0.04 - 0.4$;
- forcing strength: $u'/U_o = 0.1 - 0.4$, $u'$ standard deviation of the jet velocity, measured using a single hotwire 1mm downstream of the jet centerline;



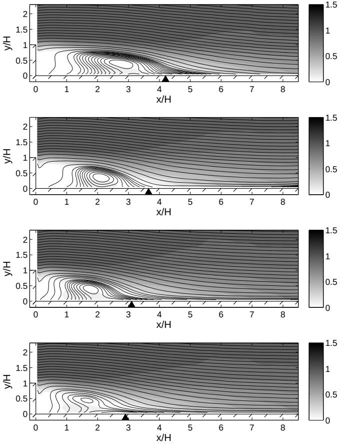
# Experimental Facility

- Lavision 2D PIV, 49Hz, 2000 realizations
- Smoke-wire visualization, 0.1mm diameter steel wire, liquid paraffin
- Wall pressure measurement, 20 Panasonic WB61A microphones embedded in the bottom wall at $x/H = 0.5 - 10$, $\Delta x = 0.5H$




Schematics of the actuator and test rig

# Effect of forcing frequency $St_A$ on the mean flow



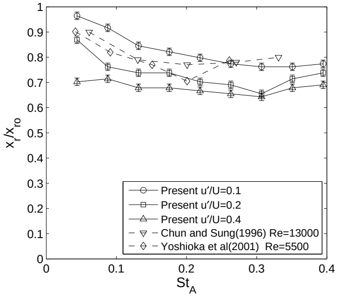

*Unactuated*

$St_A = 0.04$

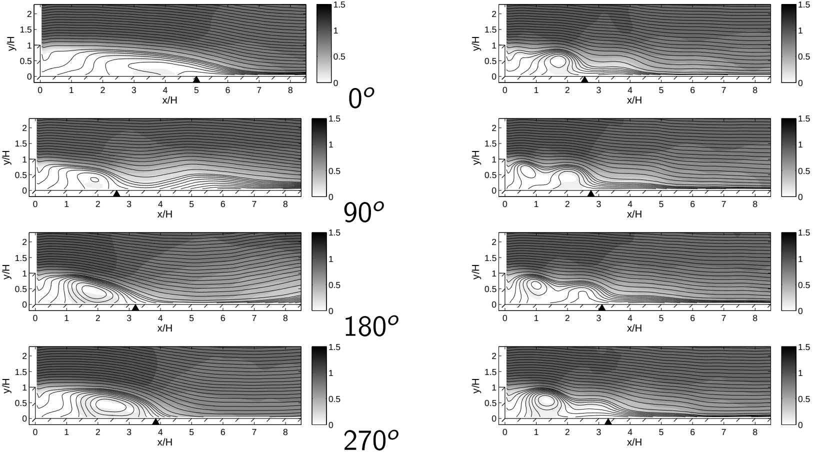
$St_A = 0.18$

$St_A = 0.26$

$\sqrt{U^2 + V^2}/U_o$ for actuation strength $u'/U_o = 0.2$

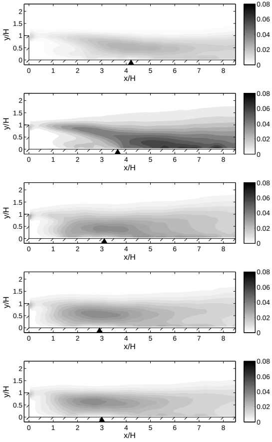


# Phase averaged streamlines for different $St_A$

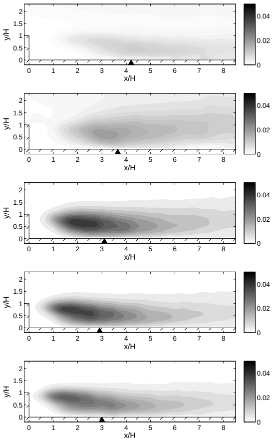



$St_A = 0.04$ $St_A = 0.26$

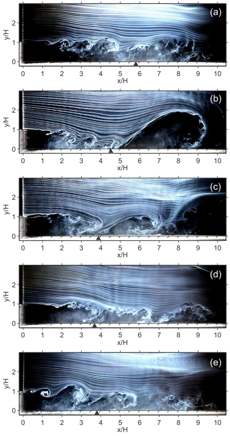
# Effect of forcing frequency $St_A$ on the shear layer



$\overline{u^2}/U_o^2$



$\overline{v^2}/U_o^2$ for $u'/U_o = 0.2$



Smoke-wire visualize

*Unactuated*

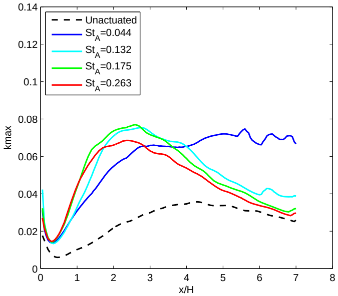
$St_A = 0.04$

$St_A = 0.18$

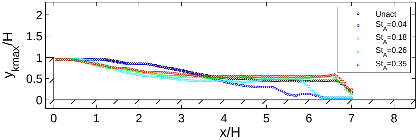
$St_A = 0.26$

$St_A = 0.35$

# Effect of forcing frequency $St_A$ on the shear layer

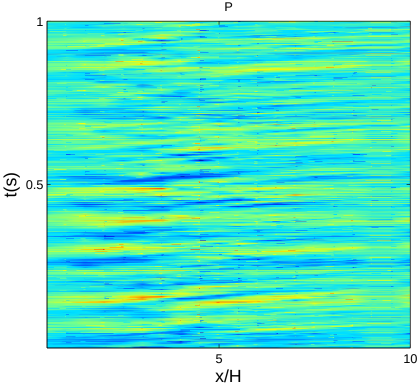



max. local turbulent kinetic energy $k = \overline{u^2} + \overline{v^2}$




location of the max. local kinetic energy

# Surface pressure for the un-controlled flow




- Proper Orthogonal Decomposition (POD) to separate acoustic pressure ($p_a$) and hydrodynamic pressure ($p_h$)

$$p(t) = p_a(t) + p_h(t)$$

- A total of N=20 sensors, $p$ decomposed into N modes ($p_n$)

$$p(x,t) = \sum_{n=1}^{N} p_n(x,t) = \sum_{n=1}^{N} a_n(t)\phi^{(n)}(x)$$

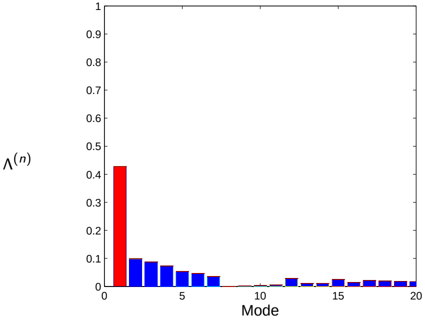
where

$$a_n(t) = \int p(x,t)\phi^{(n)} dx$$

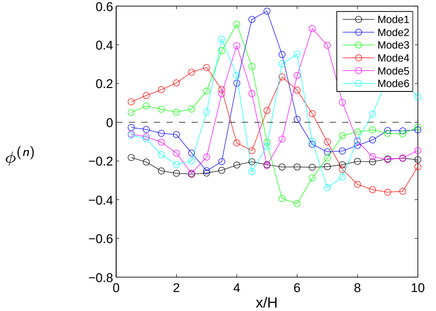
The orthogonal basis $\phi(n)$ was obtained by computing the eigenvectors of the correlation matrix:

$$\int R(x, x', \tau = 0)\phi^{(n)}(x')dx' = \Lambda^{(n)}\phi^{(n)}(x)$$

# Decomposition of surface pressure for the un-controlled flow

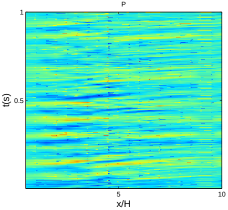



Eigenvalues for each mode

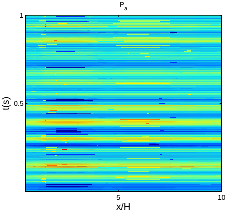



Eigenfunctions for each mode

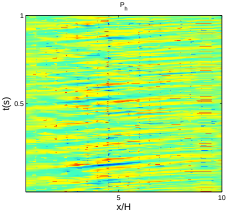
# Re-construction of surface pressure for the un-controlled flow




$=$




$+$




$+$ other modes

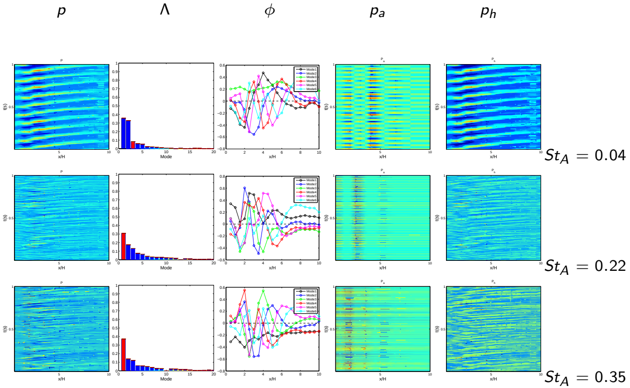
Original

mode 1, $p_1(x, t)$
acoustic pressure $p_a$

mode 2&3, $p_2(x, t) + p_3(x, t)$
hydrodynamic pressure $p_h$

$$p_n(x, t) = a_n(t)\phi^{(n)}(x)$$

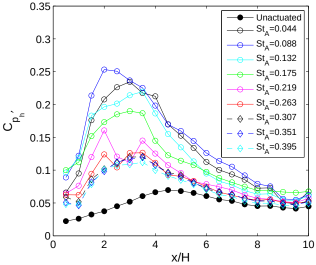
# POD for cases with different forcing frequencies $St_A$



# Effect forcing frequency $St_A$ on wall pressure fluctuations

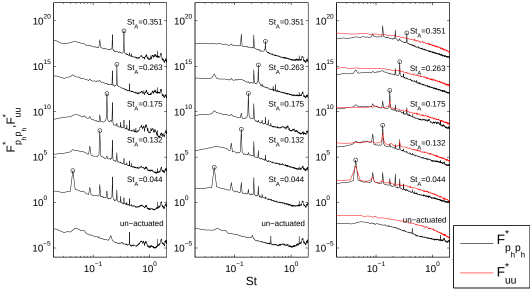
Coef. of the fluctuating wall pressure

$$C_{p_h'} = \frac{(\overline{p_h^2})^{\frac{1}{2}}}{1/2\rho U_o^2}$$




$u'/U_o = 0.2$

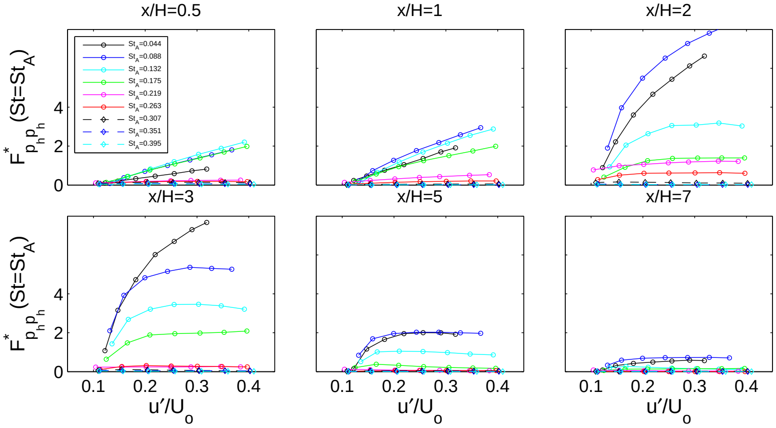
# Pressure and velocity Spectra




$x/H = 0.5$ $x/H = 1$ $x/H = 3$

hot-wire probe location at $y/H = 0.2$ above the microphones

# Effect of forcing strength $u'/U_o$ on the peak in spectrum



# Conclusion

- Forcing the shear layer at the 'flapping' frequency ($St_A = 0.04$) caused very large scale vortical motion, $p'$ increases significantly;
- forcing the flow at the 'shedding' frequency ($St_A \approx 0.2$) caused turbulent kinetic energy grow fast, $X_r$ becomes very small;
- wall pressure at $x/H \leq 1.0$ changes linearly to the actuation at $St = St_A$ when $u'/U_o \leq 0.4$ in magnitude;
- phase will be examined in the future.