Measuring large scale flow structures behind a bluff body using a hot-wire rake

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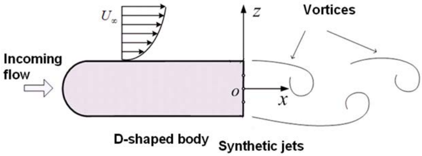
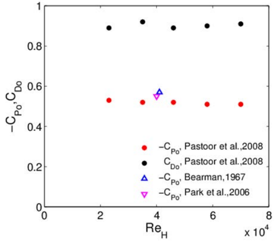
D-shaped bluff body

- Two-dimensional body with a streamlined front and a blunt trailing edge.
- Shear layers separated from upper and lower edges rolled up forming alternating vortices.
- Natural vortex shedding frequency $St_0 \approx 0.23$.

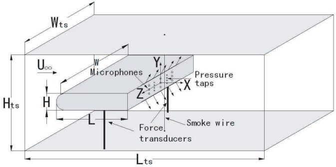


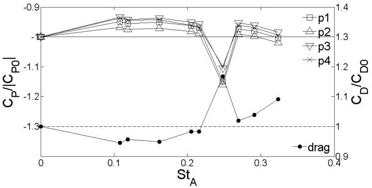


Drag coef. and rear wall pressure coef. in the literature

Active control

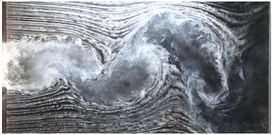
- Pastoor *et al.* (2008) in phase control of the two synthetic jets
  - 15% drag reduction when $St_A \sim 0.16$ and $C_\mu > 0.5\%$
  - Delayed transition from shear layer mode to asymmetric wake mode
- Li *et al.* (2015)
  - 5% drag reduction when $St_A \sim 0.16$ and $C_\mu \sim 0.1\%$, two jets act in phase.





Li et.al(2015)

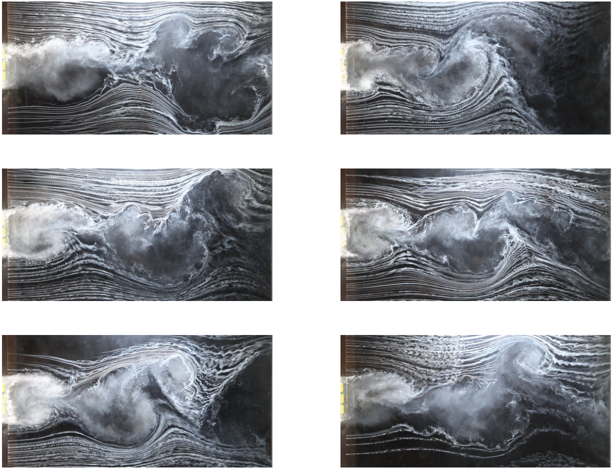
Visualizations for $St_A \sim 0.16$ and $C_\mu \sim 0.1\%$ (Li *et al.*, 2015)



unforced flow

UP: Typical Kármán vortex street of un-forced flow behind a bluff body visualied by smoke wire.

RIGHT: Visualization of many different wake types forced at actuation frequency $St_A \sim 0.16$ and momentum ratio $C_\mu \sim 0.1\%$

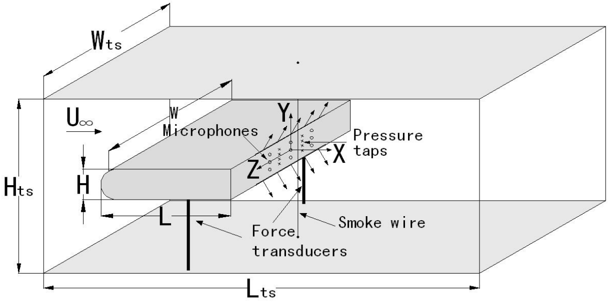


Objective

- Quantitatively determine the changes of wake structures under small amplitude periodic perturbations

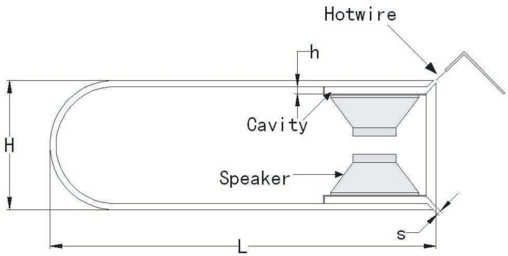
Experimental setup

- Suction type, open loop tunnel, 300x300mm test section;
- Model size $H = 63mm$, $L \sim 3H$, $W \sim 4.5H$;
- Incoming velocity $U_\infty = 9.2m/s$, corrected due to blockage to $U_{\infty,c} = 11.7m/s$, $Re_H = 47000$.



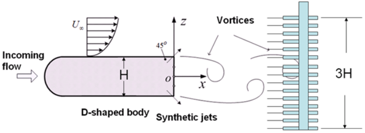
Actuators

- 2x3 array of speakers, $4.5W$, 8Ω,$45mm$, sinusoidal signal from a signal generator: $g_1(t) = Asin(2\pi f_A t)$ and $g_2(t) = Asin(2\pi f_A t + \phi)$
- Strength of actuation characterized using: $C_\mu = 2\frac{S}{H}\frac{u_A^2}{U_{\infty,c}^2}.S = 2mm$
- Parameters
  - Momentum ratio $C_\mu = 0.1\%$
  - Actuation frequency, $St_A(f_A H/U_{\infty,c}) = 0.16$ and 0.24;
  - Two actuators act in phase $\phi = 0$.

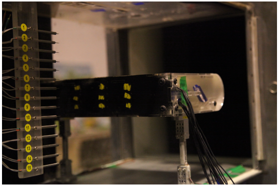


Hot-wire rake

- A rake of 15 single hot-wire probes, in house anemometry system;
- $5\mu m$ tungsten wire, 1.5mm long, calibrated *in-situ*;
- tuned to respond up to 6000Hz;
- 4kHz sampling frequency, sampling time 150s.

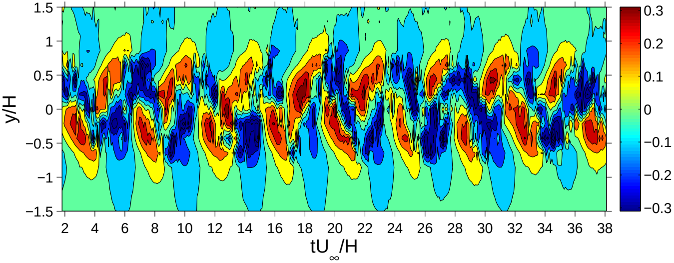


8-channel hotwire anemometry



Hot-wire array

Results The instantaneous velocity for un-forced flow at $x/H = 2$



Proper Orthogonal Decoposition(POD) of velocity signals

- The instantaneous velocity $u(y,t)$ can be decomposed into 15 modes using POD:

$$u(y,t) = \sum_{n=1}^{15} a_n(t)\phi^{(n)}(y)$$

- Coefficients for mode n were obtained by projecting the velocity $u(y,t)$ on to a set of orthogonal basis:

$$a_n(t) = \int_{-1.5H}^{1.5H} u(y,t)\phi^{(n)} dy$$

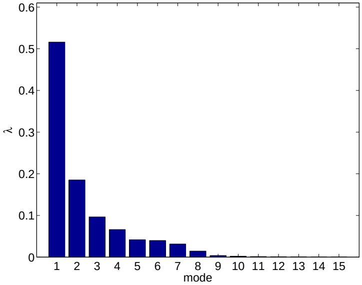
- The orthogonal basis $\phi(n)$ was obtained by computing the eigenvectors of the correlation matrix:

$$\int R_{uu}(y,y',\tau=0)\phi^{(n)}(y')dy' = \Lambda^{(n)}\phi^{(n)}(y)$$

- The motion fot the n-th mode can be re-constructed using $a_n(t)$and$\phi^{(n)}(y)$:

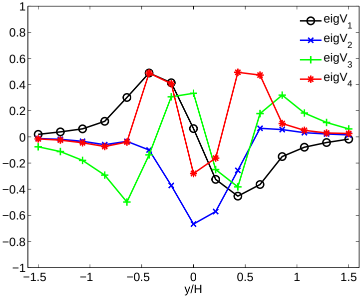
$$u_n(y,t) = a_n(t)\phi^{(n)}(y)$$

Results decomposition of un-forced flow at $x/H = 2$



Λ^n

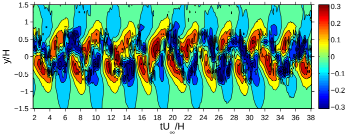
eigenvalues for each mode



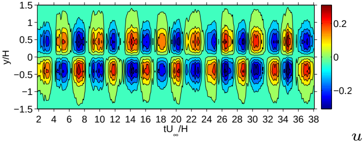
ϕ^n

eigenfunctions for each mode

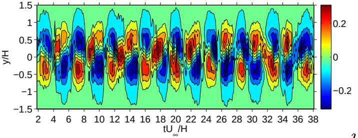
Results re-constructed velocity for un-forced flow at $x/H = 2$



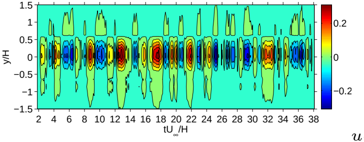
$u(y,t)$



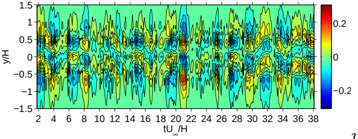
u_1



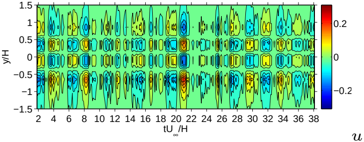
$u_1 + u_2$



u_2

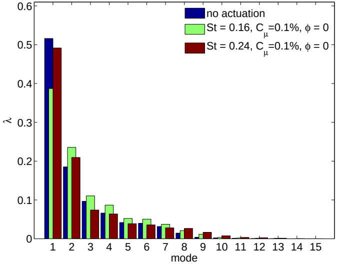


$u_3 + u_4$

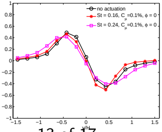


u_3

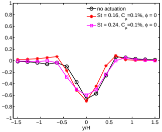
Results effect of forcing frequency on modal energy, $x/H = 2$



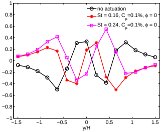
Eigenvalues ($\lambda^{(n)}$) for the three different cases



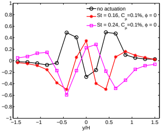
$\phi^{(1)}$



$\phi^{(2)}$



$\phi^{(3)}$



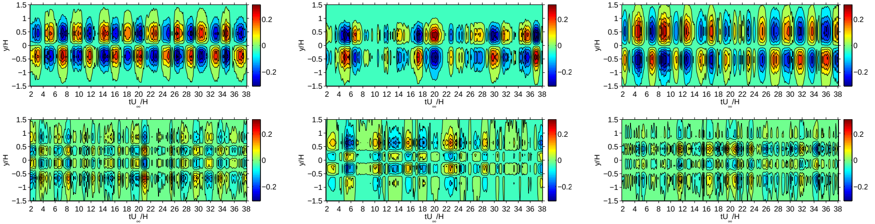
$\phi^{(4)}$

Results re-construction velocity for POD mode 1 (u_1) and mode 3 (u_3), $x/H = 2$

un-forced flow | in-phased forcing($\phi = 0$) with $St_A = 0.16$ | in-phased forcing($\phi = 0$) with $St_A = 0.24$

u_1

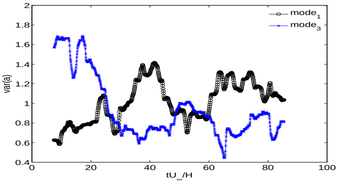
u_3



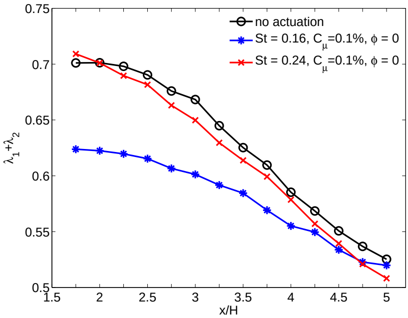
'move box variance'

$$\sum_{t-\Delta T/2}^{t+\Delta T/2} a^{(n)2}(t)/N,$$

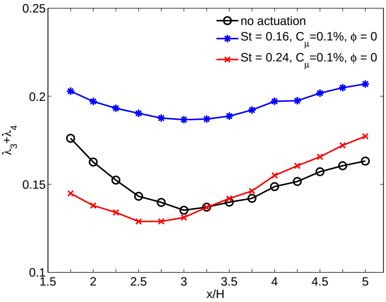
$N = \Delta T \cdot f_{sampling}$, for in-phased forcing($\phi = 0$) with $St_A = 0.16$



Results Evolution of modal energy in the streamwise direction



modal energy $\lambda^{(1)}+\lambda^{(2)}$



modal energy $\lambda^{(3)}+\lambda^{(4)}$

Concluding remarks

- In-phase actuation on the trailing edges of a D-shaped body at $f_A H/U_o = 0.16$ decreased the form drag;
- In-phase actuation at $f_A H/U_o = 0.16$ was found to suppress the anti-symmetric von-Karman vortex (the lower POD modes) and promote the symmetric vortices (higher modes) ;
- the transitions between lower mode motions and higher modes seem to be sporadic, possibilities of higher mode motion were increased by the in-phased actuations at $f_A H/U_o = 0.16$.

Thank you.