An Overview of the MOTSTRÖM Project: Motståndsminskning för Strömningsytor i Kompressor

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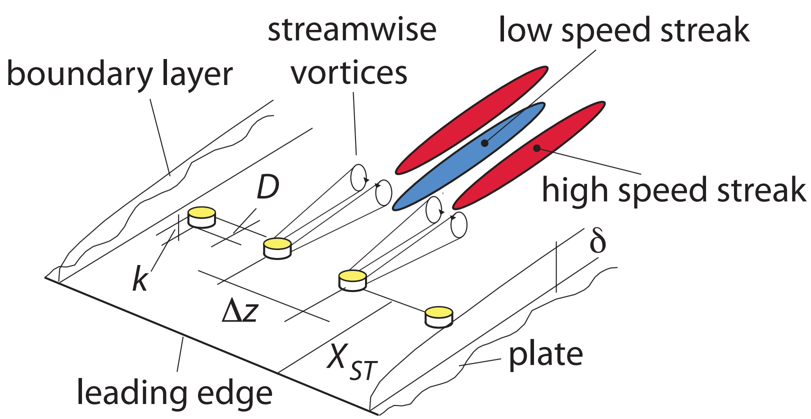
Outline

- Background: surface roughness and transition
- Miniature vortex generators (MVGs) as laminar flow control devices
- Experimental setup: pressure gradients and MVG selection
- Results: boundary-layer streak development
- Results: transition study in adverse pressure gradient boundary layer
- Conclusions

Surface roughness and transition

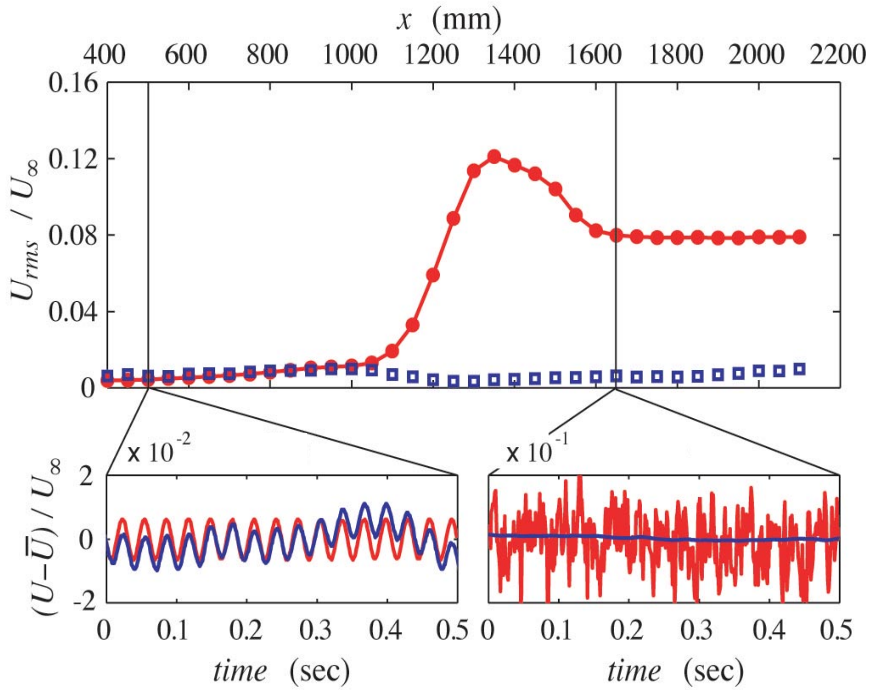
Previous experiments have shown that transition delay in a flat plate boundary layer may be accomplished by modulating the boundary layer in the spanwise direction (Fransson *et al*. 2006 *Phys. Rev. Lett.*)



Experimental setup with array of cylindrical surface roughness

Transition measurement:

- Forced TS waves (red)



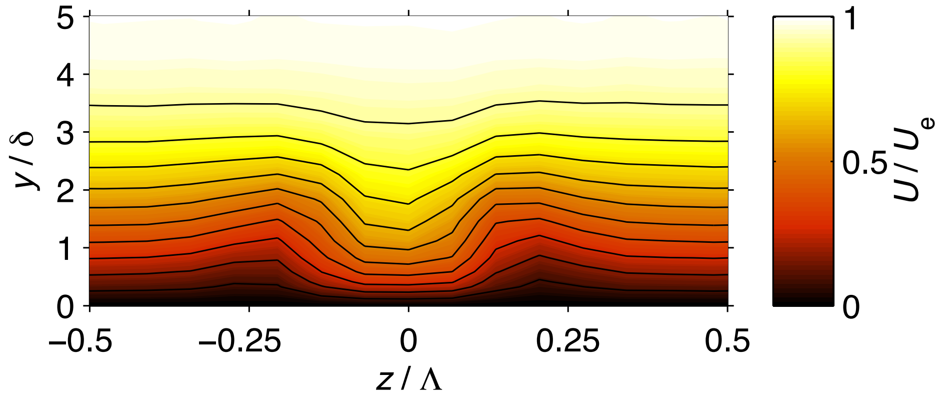
Streak amplitude measurement

To quantify boundary-layer distortion by MVGs, an integral measure of velocity streak amplitude is computed from measured flow fields at each streamwise location:

$$A_{\mathrm{ST}}^{\mathrm{int}} = \frac{1}{U_e(x)} \int_{-0.5}^{0.5} \int_{0}^{\eta=9} \Big| U(x,\eta,\zeta) - U^z(x,\eta) \Big| \mathrm{d}\eta \mathrm{d}\zeta$$

$$\eta = y/\delta, \quad \zeta = z/\Lambda$$

Streak amplitude is a key indicator of disturbance attenuation effectiveness, with optimal values near 30% of U_e.



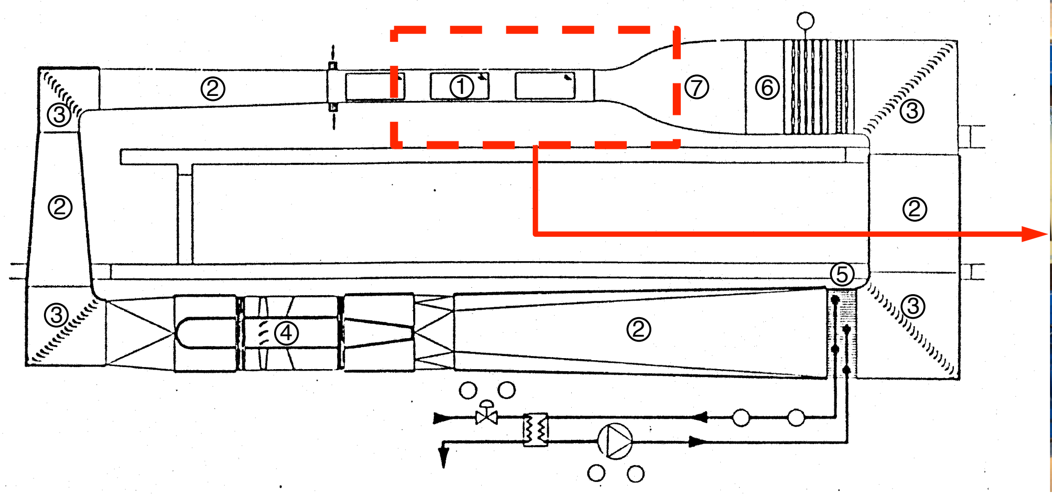
MOTSTRÖM program

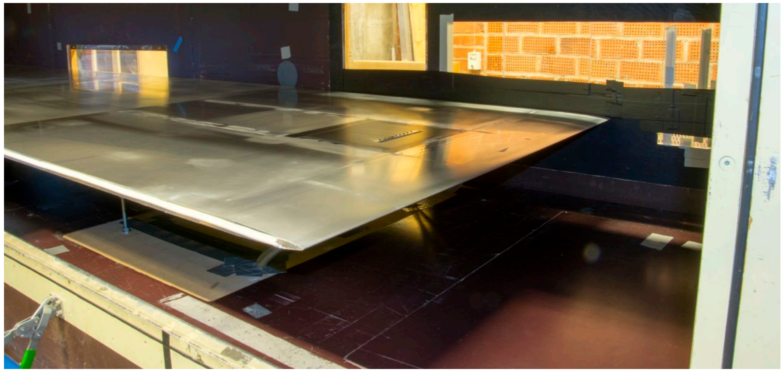
MOTSTRÖM (Motståndsminskning för strömningsytor i kompressor) is an ongoing collaboration involving

- KTH Royal Institute of Technology,
- GKN Aerospace Sweden AB, and
- Chalmers University of Technology (future project phases).

Goal: develop and extend current LFC methods to reduce drag in flows over compressor components.

Experiments in MTL wind tunnel





Minimum Turbulence Level (MTL) wind tunnel at KTH

Tu_u = 0.025%, $Tu_{v,w}$ = 0.035%

0.8 m × 1.2 m test section

0 – 70 m/s (empty test section)

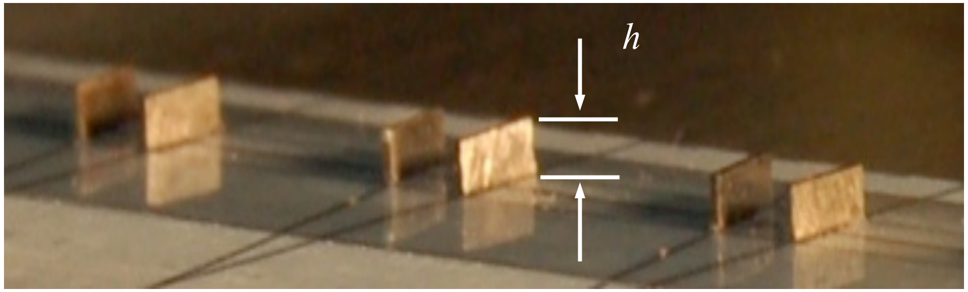
Temperature controlled within ±0.1°C

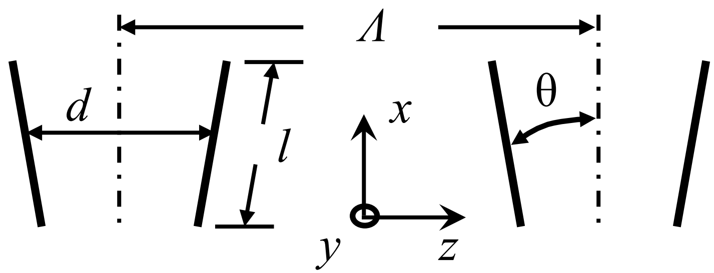
Miniature vortex generators

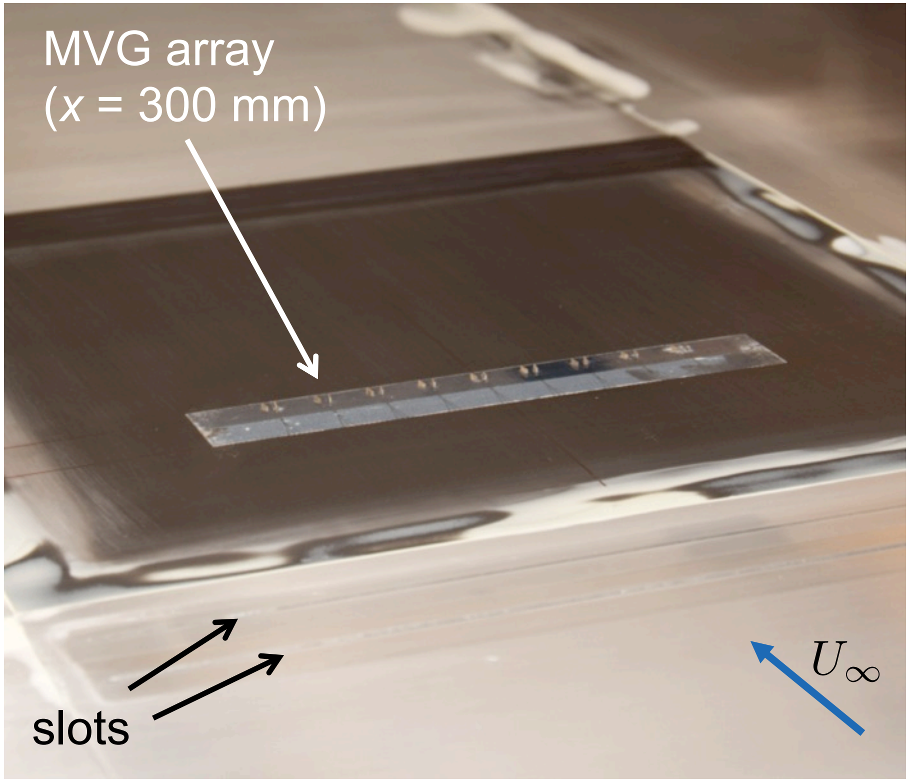
MVG array composed of rectangular blades

- inclined at $\theta = 9°$
- spanwise spacing between pairs
  $\Lambda = 14.63$ mm
- fixed length, blade separation $l = d = 3.25$ mm
- heights h from 1.1 mm to 1.5 mm

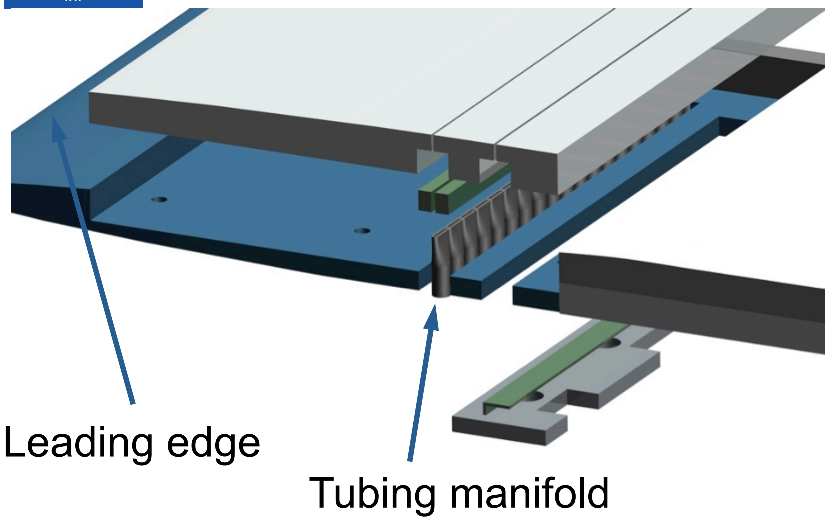
U and h tuned to give $Re_{hh} = \frac{U(h)h}{\nu} = 309$

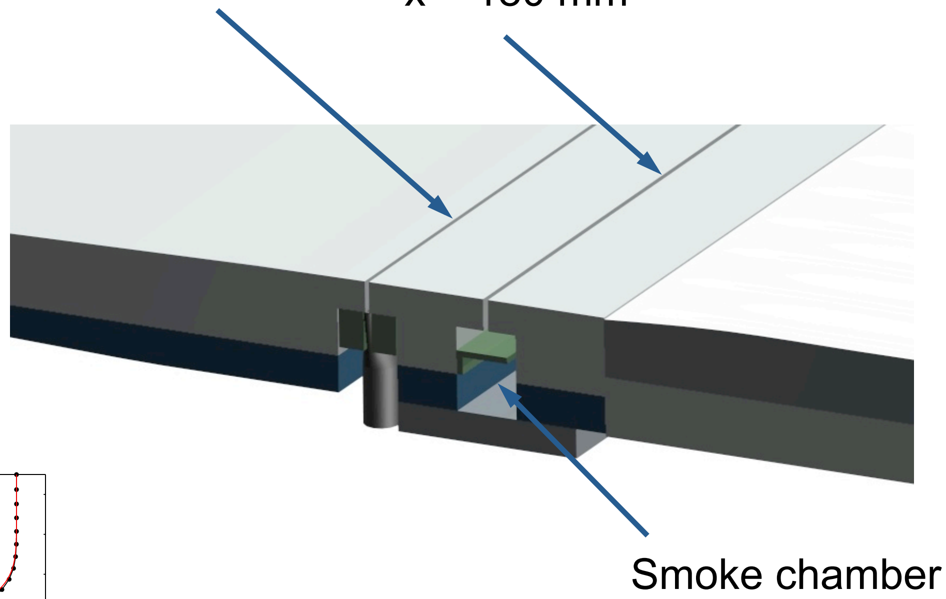


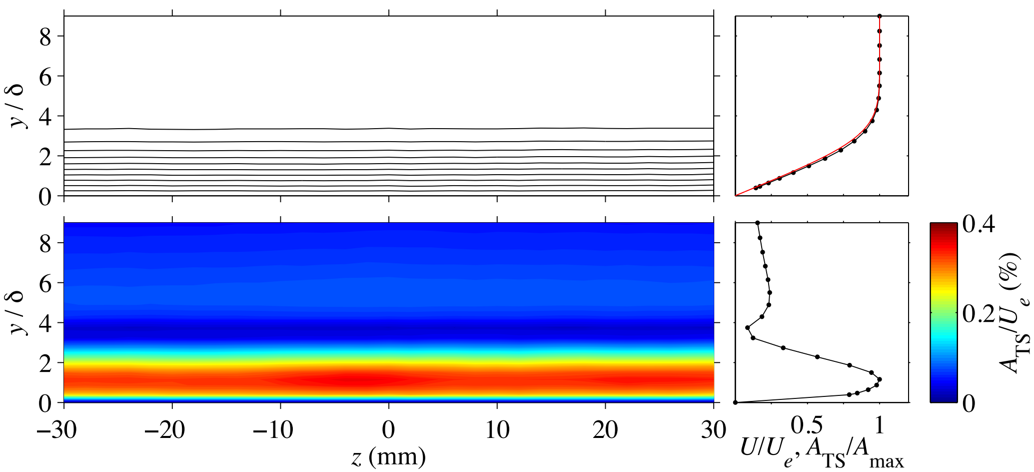




TS-wave forcing



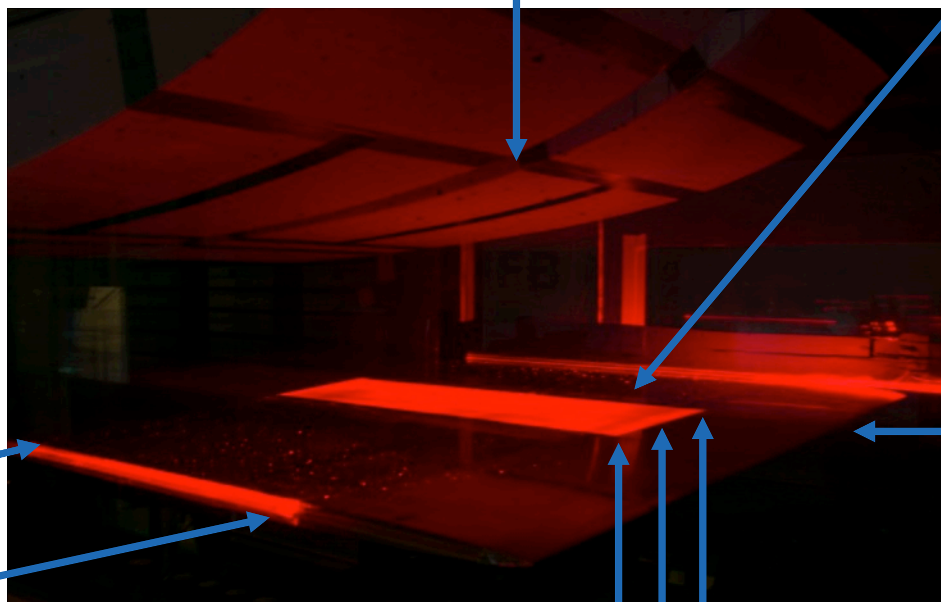




Flow visualization apparatus

Camera

illuminated smoke sheet

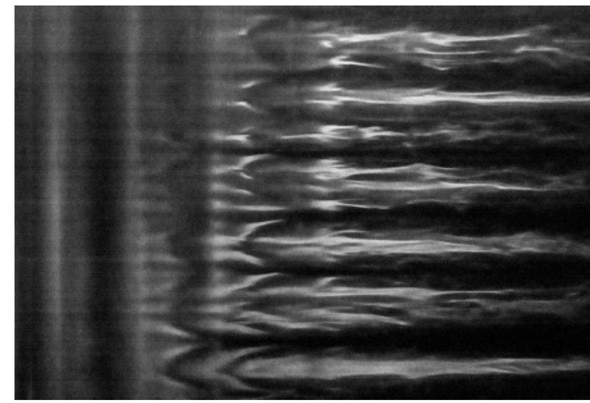


U_∞

0.5 W laser sheet

smoke injection

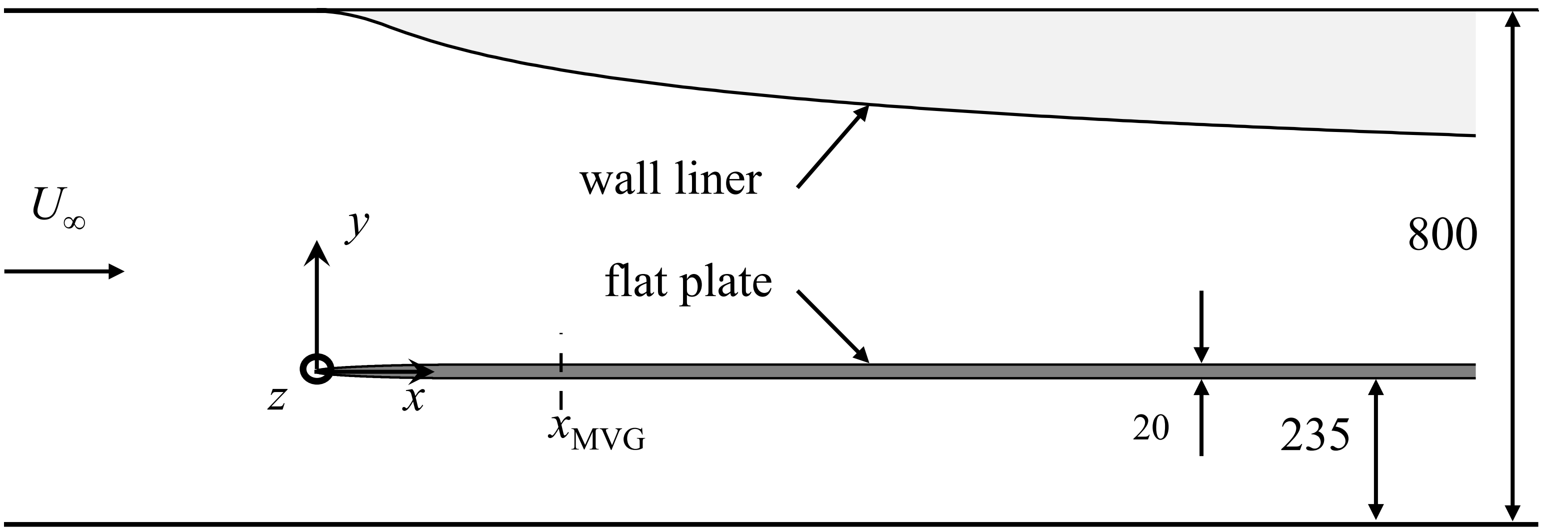
U_∞



Example image
252 × 168 mm
(flow direction reversed)

Pressure gradients

Streamwise pressure gradients are imposed with contoured wall bumps installed on the test section ceiling.

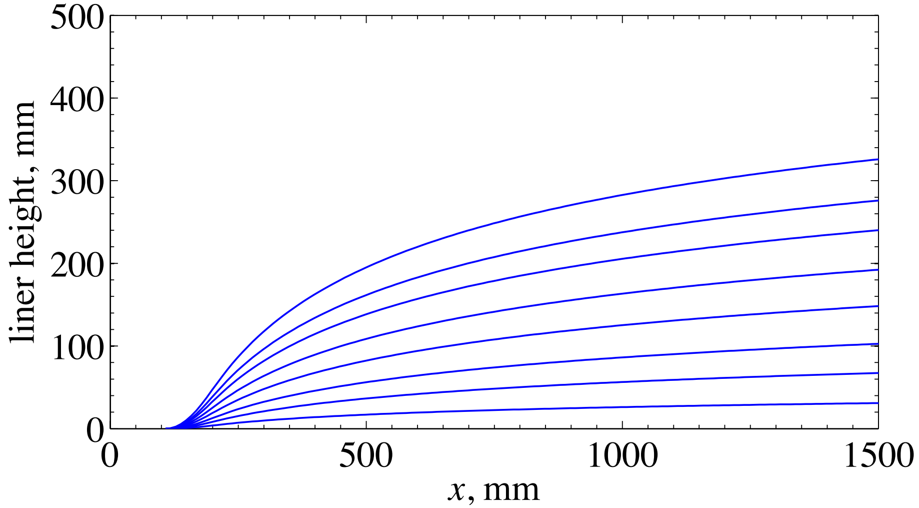


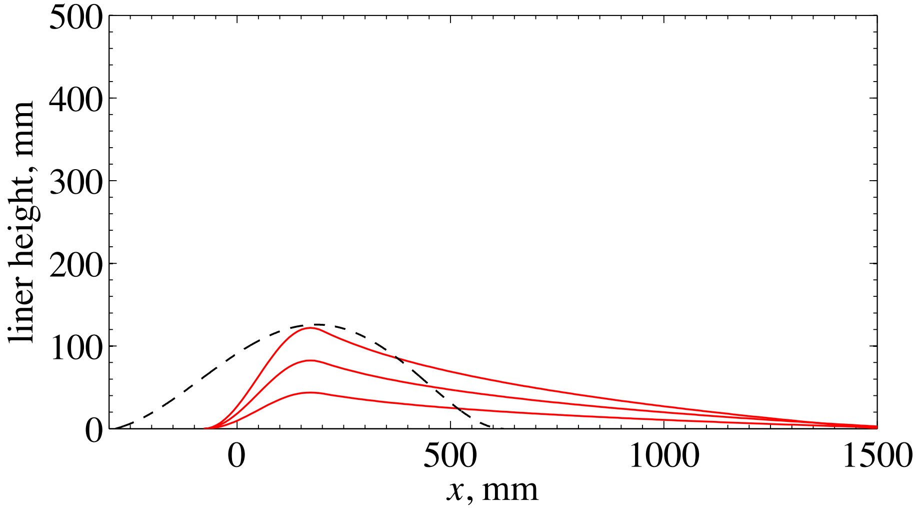
Pressure gradients

Bump shapes are designed to produce freestream velocities following the expression: $U_\infty(x) = ax^m$

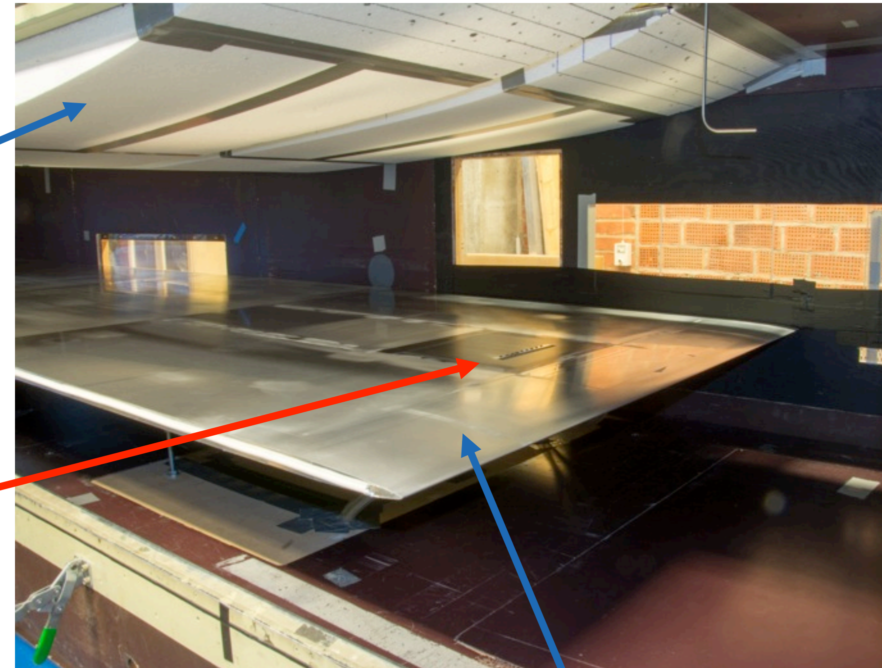
The imposed freestream velocity distributions produce boundary layers following the family of Falkner–Skan similarity solutions, characterized by the exponent *m*:

$$m \begin{cases} < 0 & \rightarrow \frac{\mathrm{d}p}{\mathrm{d}x} > 0, \text{ adverse} \\ = 0 & \rightarrow \frac{\mathrm{d}p}{\mathrm{d}x} = 0, \text{ Blasius} \\ > 0 & \rightarrow \frac{\mathrm{d}p}{\mathrm{d}x} < 0, \text{ favorable} \end{cases}$$





Pressure gradients



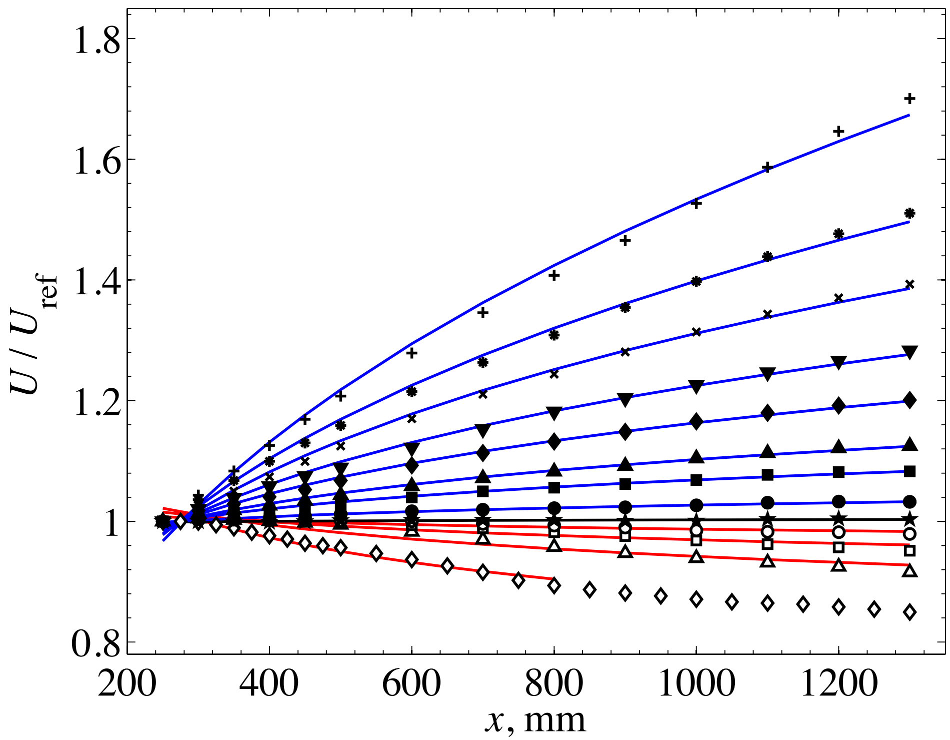
Wall liners

Insert with MVGs

Plate

Pressure gradients

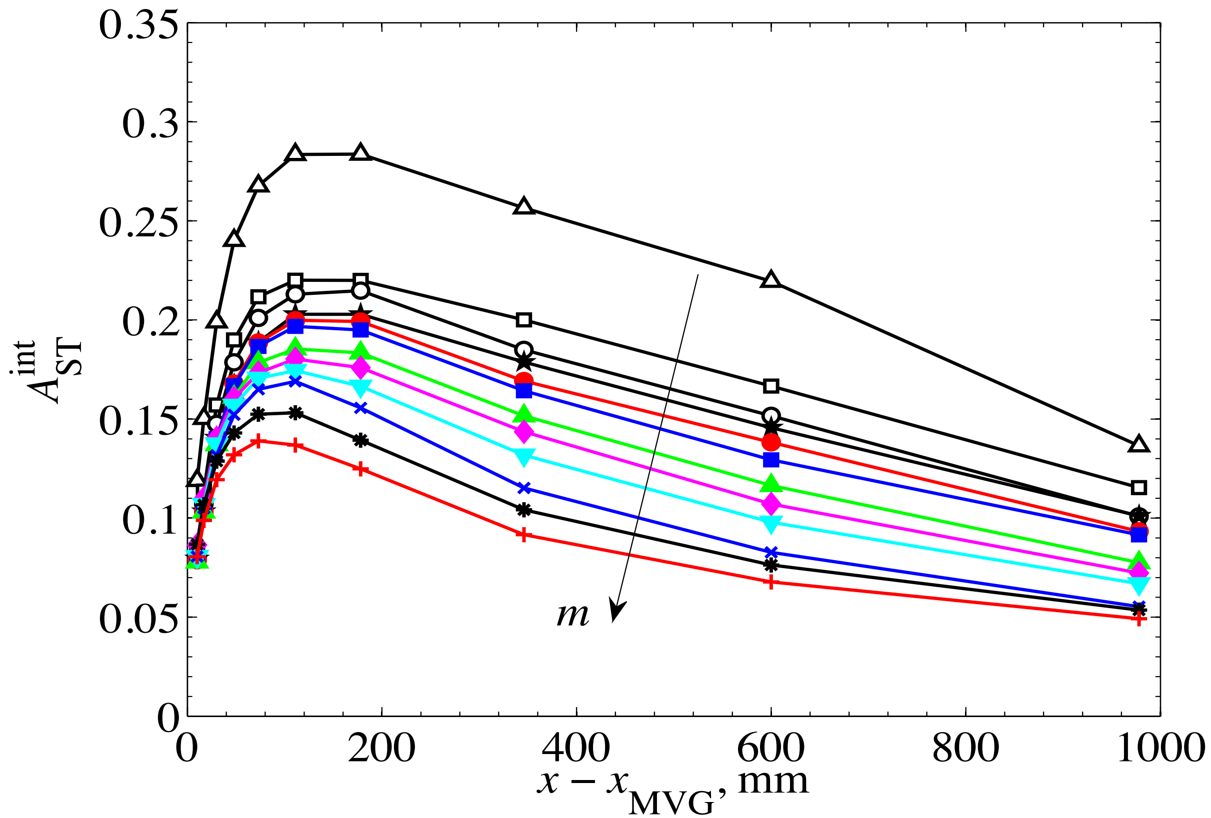
Case	m	$U_{e,MVG}$ (m/s)	h (mm)	Re_{hh}
1	0.0025	5.98	1.4	314.3
2	0.0207	5.89	1.4	309.5
3	0.0501	5.80	1.4	309.1
4	0.0746	5.74	1.4	313.1
5	0.116	6.10	1.3	311.9
6	0.1569	5.92	1.3	311.5
7	0.2103	5.71	1.3	306.2
8	0.2582	6.72	1.1	309.0
9	0.3324	5.80	1.2	303.5
10	-0.0149	6.25	1.4	307.0
11	-0.0333	6.19	1.4	308.7
12	-0.0586	5.98	1.4	307.4
13	-0.1055	6.25	1.5	307.7



Solid lines represent curve fits to theoretical velocity distribution.

- adverse (APG)
- nominal zero (ZPG)
- favorable (FPG)

Pressure gradient effects: A_{ST}

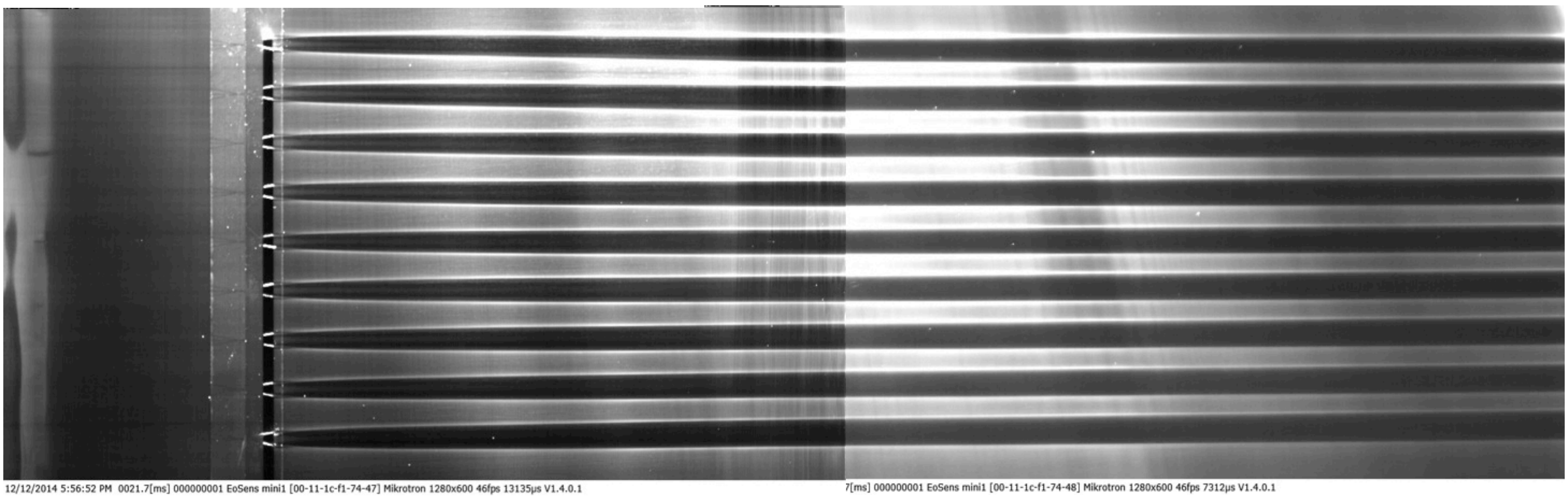


As streamwise pressure gradient is decreased from adverse to favorable, streak amplitude growth is attenuated and peak location occurs further upstream.

For $m = -0.11$ case (not shown), flow separation and turbulent reattachment prematurely destroys velocity streaks.

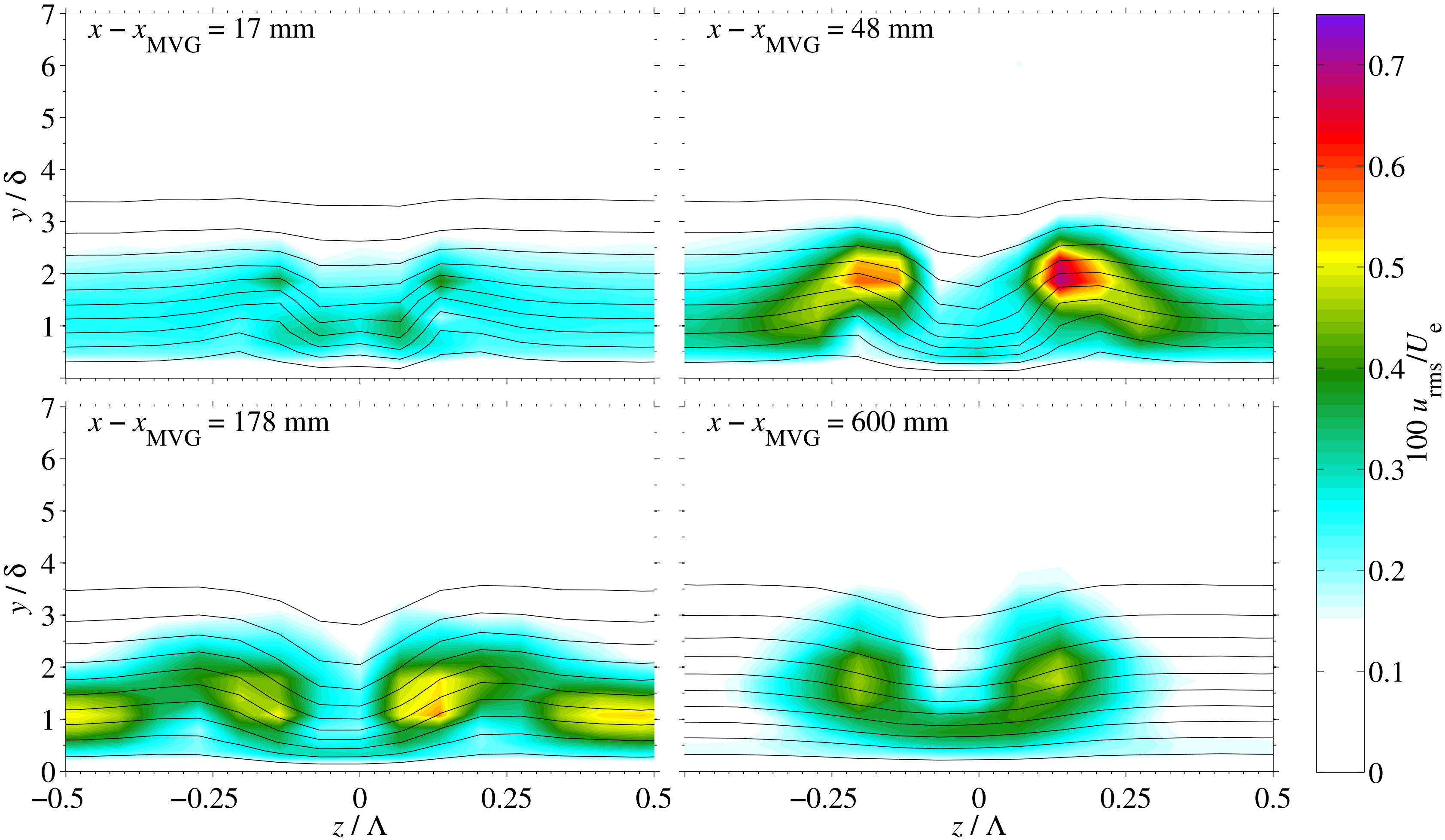
Flow visualization: FPG

m = 0.332, h = 1.2 mm MVGs, composite image from 2 cameras is 550 x 140 mm



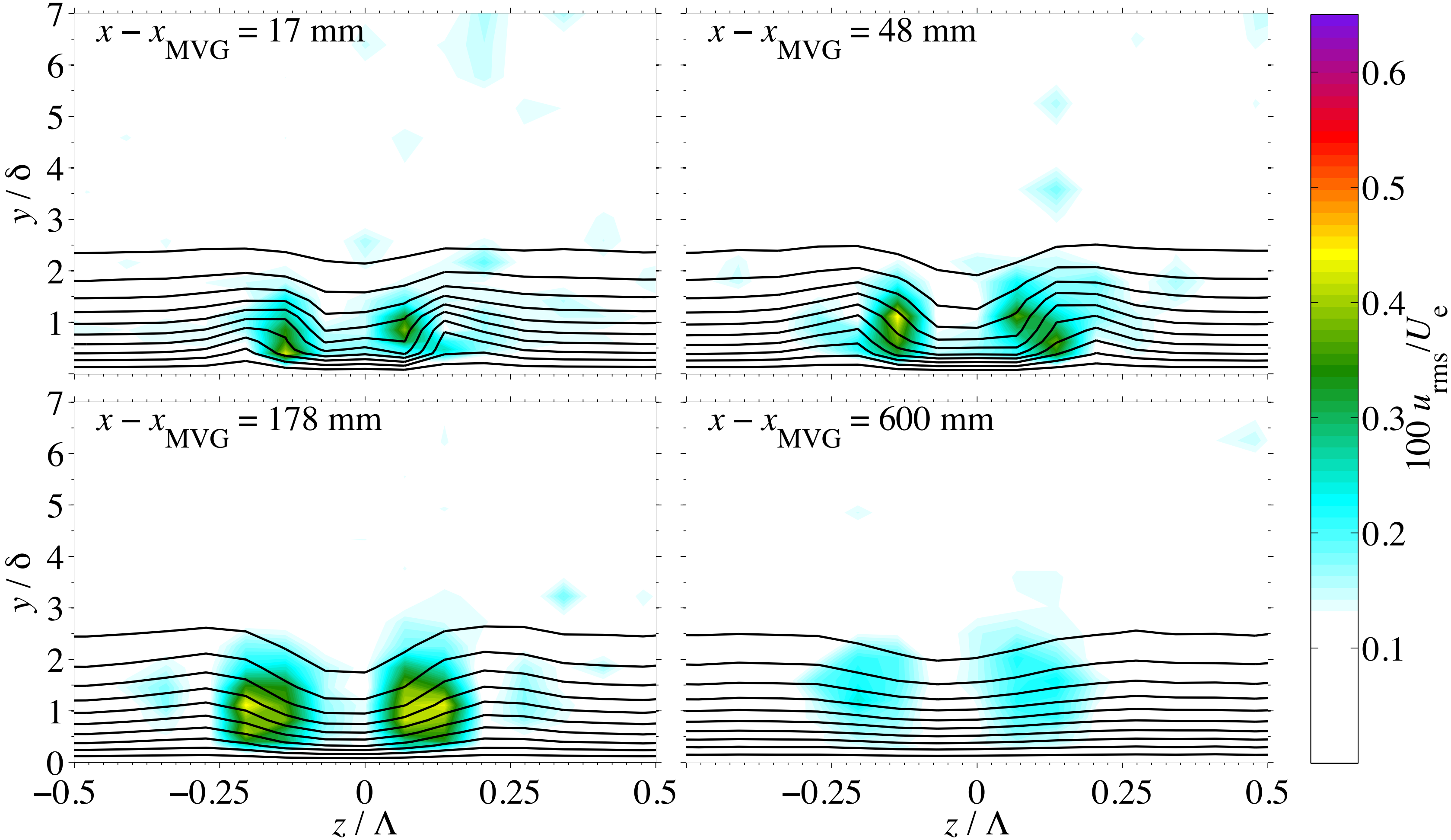
Flow contours: ZPG

Mean flow contours (lines), u_{rms} contours (color map) at $m = 0.002$



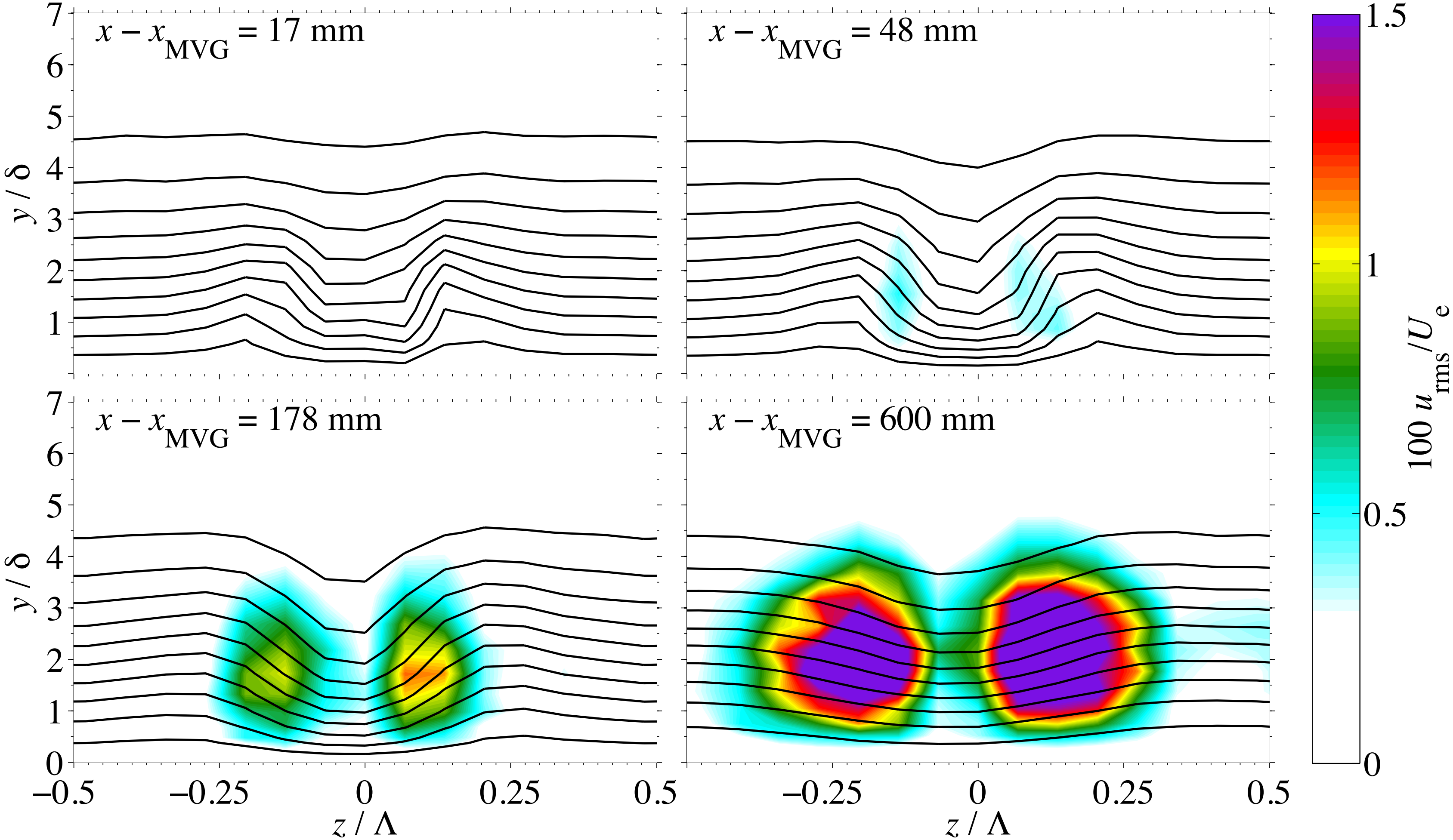
Flow contours: FPG

Mean flow contours (lines), u_{rms} contours (color map) at m = 0.26



Flow contours: APG

Mean flow contours (lines), u_{rms} contours (color map) at $m = -0.06$

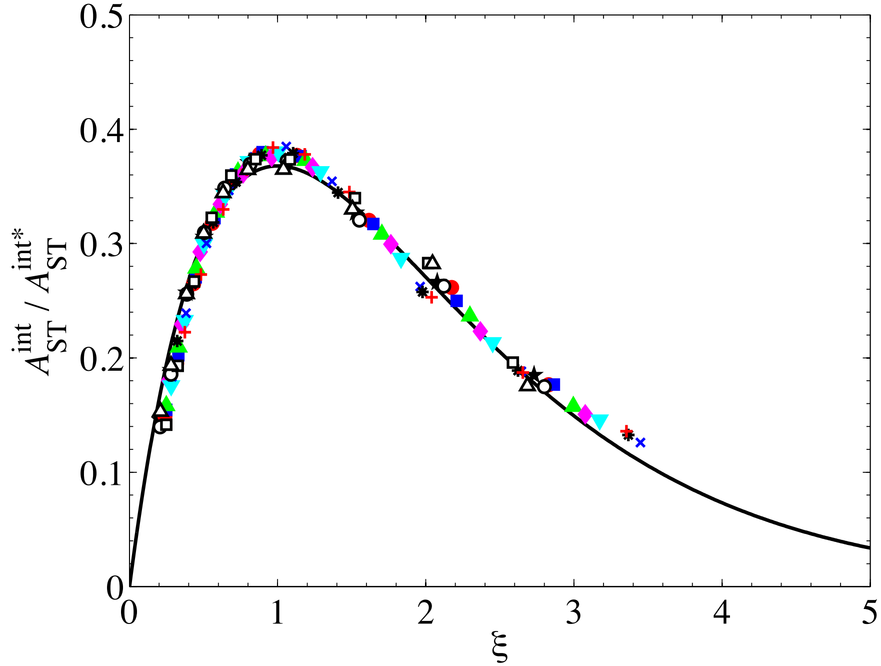


Scaling of streak amplitudes

To describe pressure gradient effects on streak development, an empirical scaling is sought based on the ansatz:

$$\frac{A_{\mathrm{ST}}^{\mathrm{int}}}{A_{\mathrm{ST}}^{\mathrm{int}*}} = \xi \mathrm{e}^{-\xi},$$

$$\xi = \left[C_\xi^i \left(\frac{x}{x_{\mathrm{MVG}}} - 1 \right) \right]^{C_\xi^{ii}}$$



where

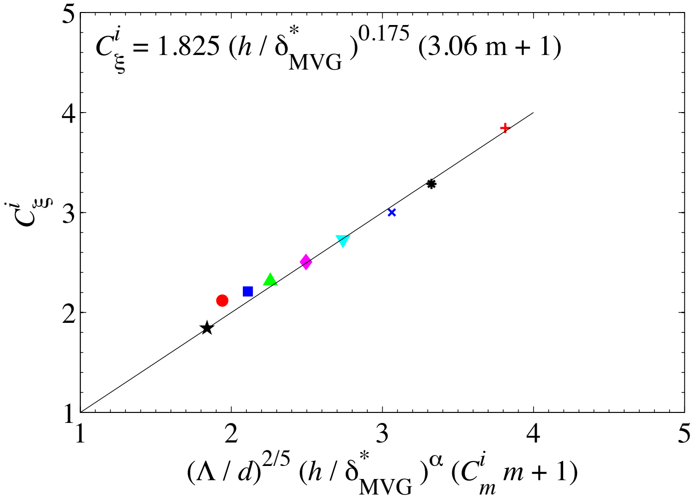
$$C_\xi^i = \left(\frac{\Lambda}{d} \right)^{2/5} \left(\frac{h}{\delta_{\mathrm{MVG}}^*} \right)^{\alpha} \left(C_m^i \, m + 1 \right) = 1.825 \left(\frac{h}{\delta_{\mathrm{MVG}}^*} \right)^{\alpha} \left(C_m^i \, m + 1 \right)$$

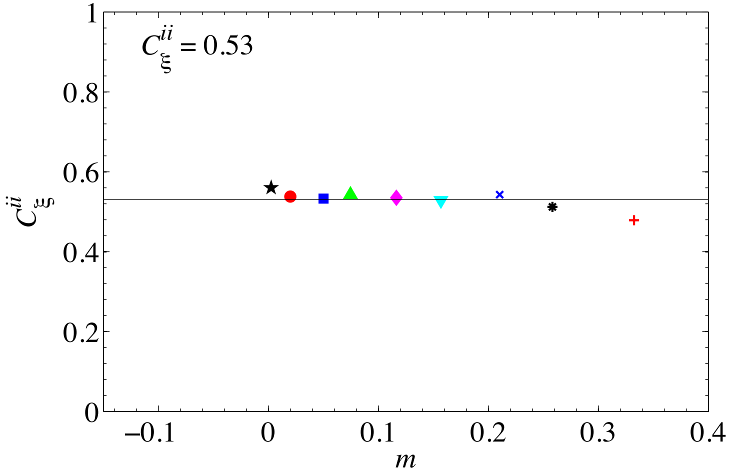
$$A_{\mathrm{ST}}^{\mathrm{int}*} = C_A f(\theta) f(\Lambda/d) f(Re) f(m) = C_A \times 0.156 \times 1.051 Re_h^2 \left(C_m^{ii} \, m + 1 \right)$$

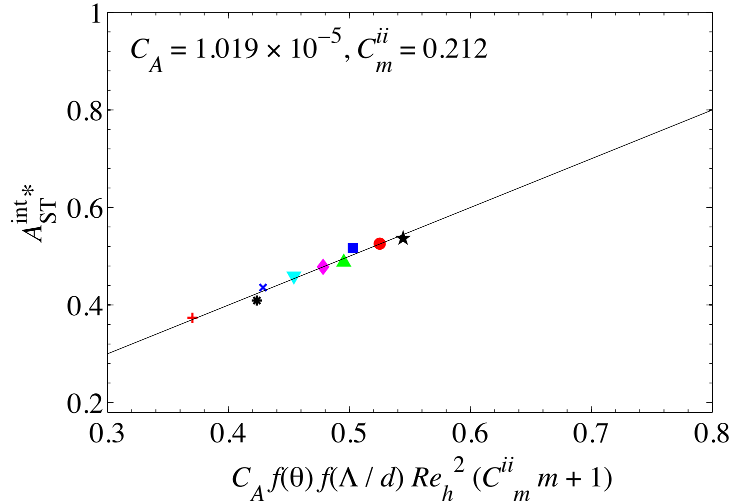
Performing separate optimizations to determine individual coefficient values for each set of *m* data shows that all cases follow this form.

Scaling of streak amplitudes

Scaling parameter optimizations for **FPG** data: $m \geq 0.003$

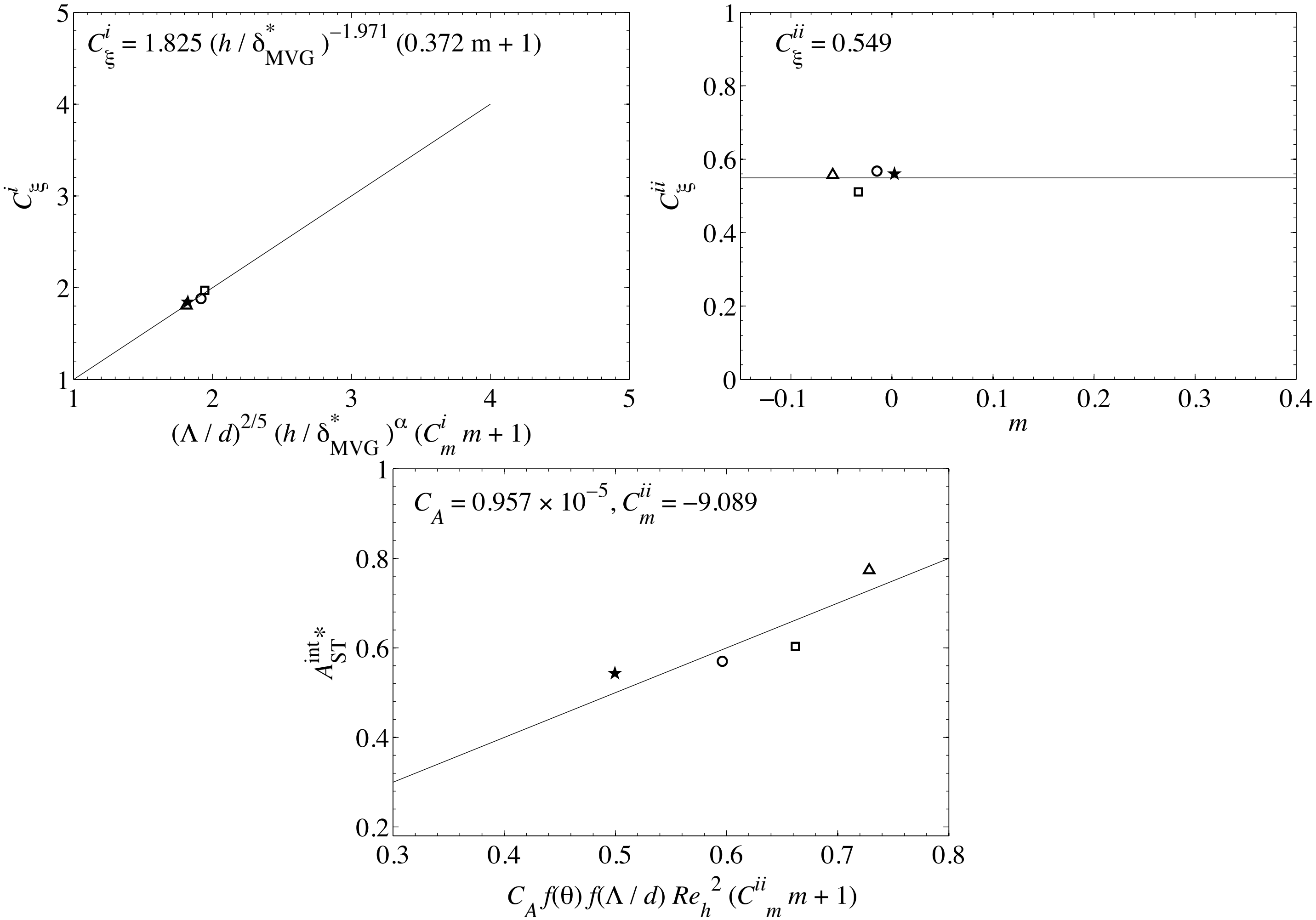






Scaling of streak amplitudes

Scaling parameter optimizations for **APG** data: *m* ≤ 0.003



Scaling of streak amplitudes

Scaled streak amplitudes based on two sets of fitting parameters: APG and FPG.

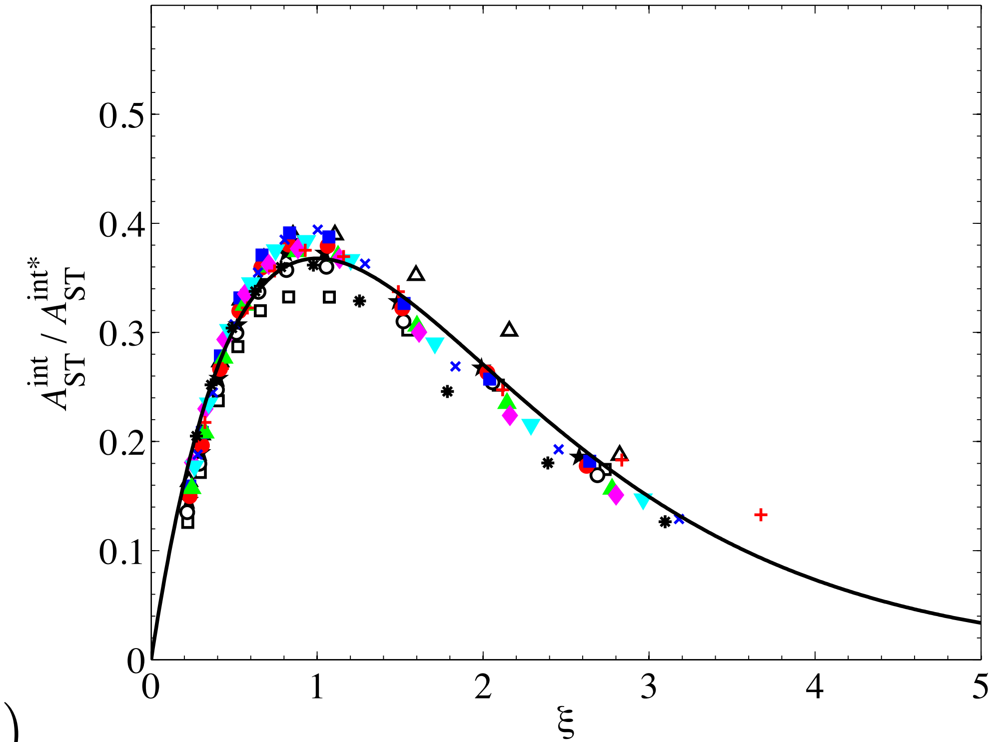
Fitting functions:

$$\frac{A_{\mathrm{ST}}^{\mathrm{int}}}{A_{\mathrm{ST}}^{\mathrm{int}*}} = \xi \mathrm{e}^{-\xi},$$

$$\xi = \left[C_\xi^i \left(\frac{x}{x_{\mathrm{MVG}}} - 1 \right) \right]^{C_\xi^{ii}}$$

$$C_\xi^i = 1.825 \left(\frac{h}{\delta^*_{\mathrm{MVG}}} \right)^{\alpha} \left(C_m^i \, m + 1 \right)$$

$$A_{\mathrm{ST}}^{\mathrm{int}*} = C_A \times 0.156 \times 1.051 Re_h^2 \left(C_m^{ii} \, m + 1 \right)$$



	α	C_m^i	C_ξ^{ii}	C_A	C_m^{ii}
$m \geq 0$	0.157	3.060	0.530	1.019×10^{-5}	0.212
$m < 0$	-1.971	0.372	0.549	0.957×10^{-5}	-9.089

Transition study: TS waves in APG

Laminar flow control via imposition of spanwise mean velocity gradients (SVG) in ZPG boundary layers has been demonstrated for TS-wave induced transition.

An application of this flow control method is now sought for the case of a boundary layer developing in a more realistic non-zero pressure gradient flow.

The following test conditions are used:

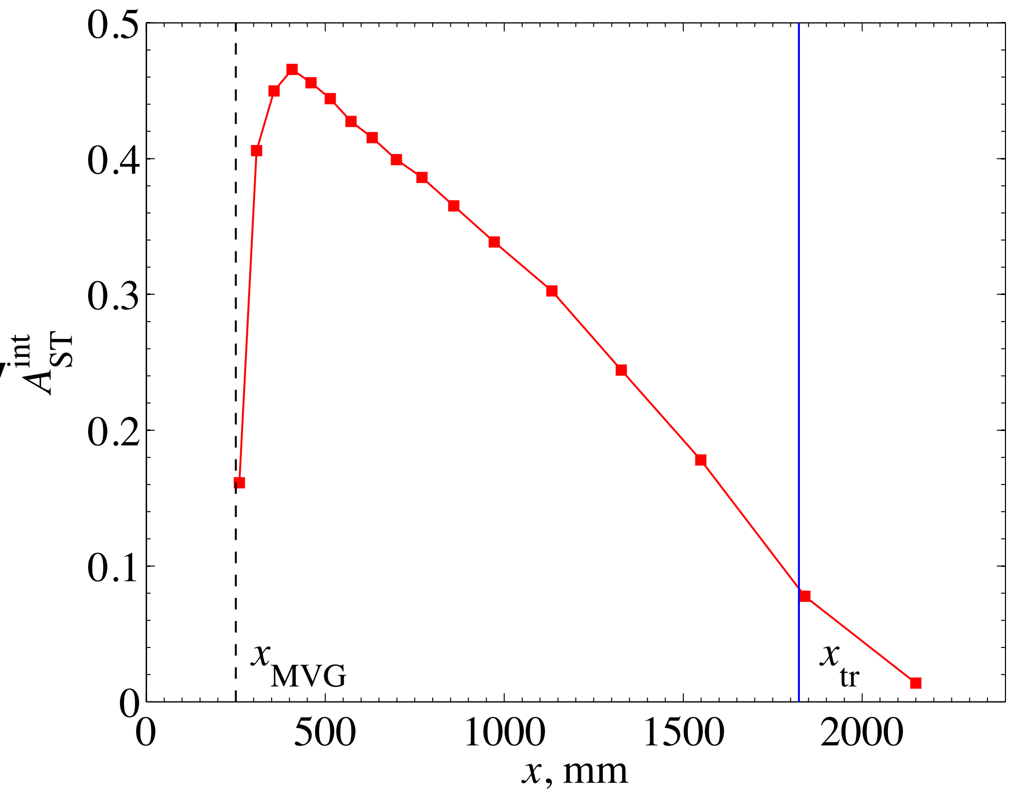
$$m = -0.054$$
$$x_{\mathrm{MVG}} = 250 \text{ mm}$$
$$U_{e,\mathrm{MVG}} = 7.5 \text{ m/s}$$
$$Re_{hh} = 440$$

TS waves are excited at $f = 72$ Hz ($F_{\mathrm{MVG}} = 122$).

MVG selection for APG transition study

To contend with higher growth rates of disturbances in APG boundary layer, MVG array is moved upstream and Re_{hh} is increased.

The maximum streak amplitude is measured as $A^{int}_{ST} = 0.47$.



Dimensions of MVG array at x_{MVG} = 250 mm:

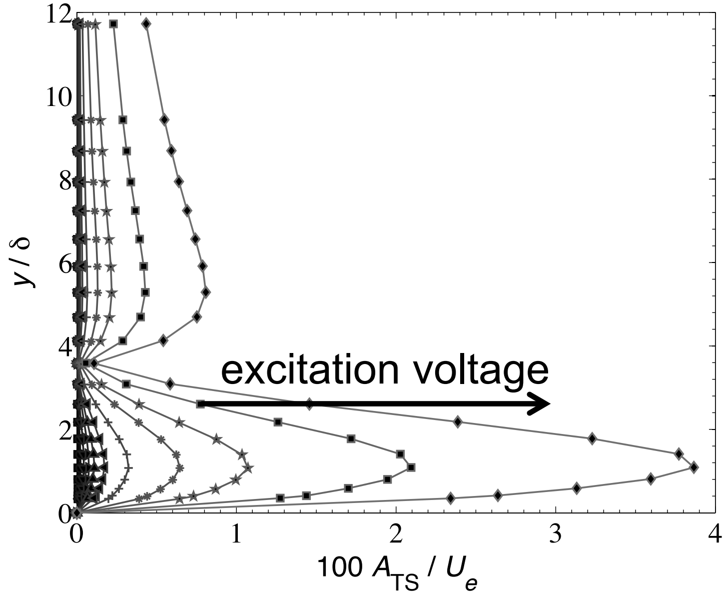
h = 1.4 mm

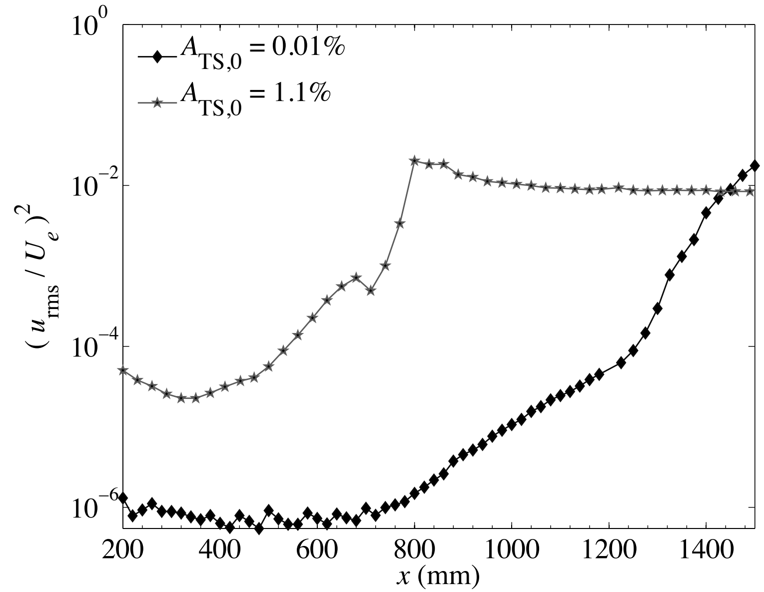
Λ = 14.63 mm

$d = l$ = 3.25 mm

$\theta = 9°$

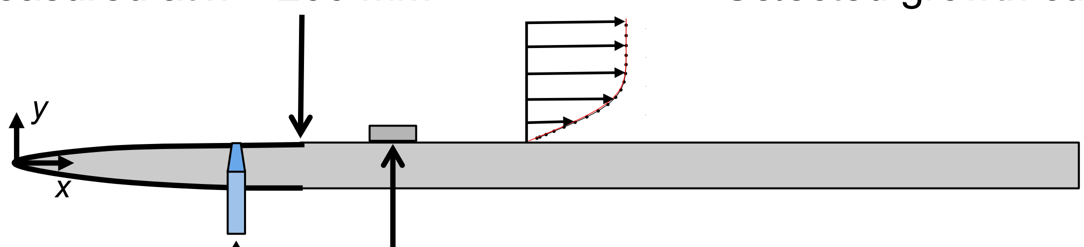
TS-wave growth: APG





Initial TS-wave profiles measured at x = 200 mm

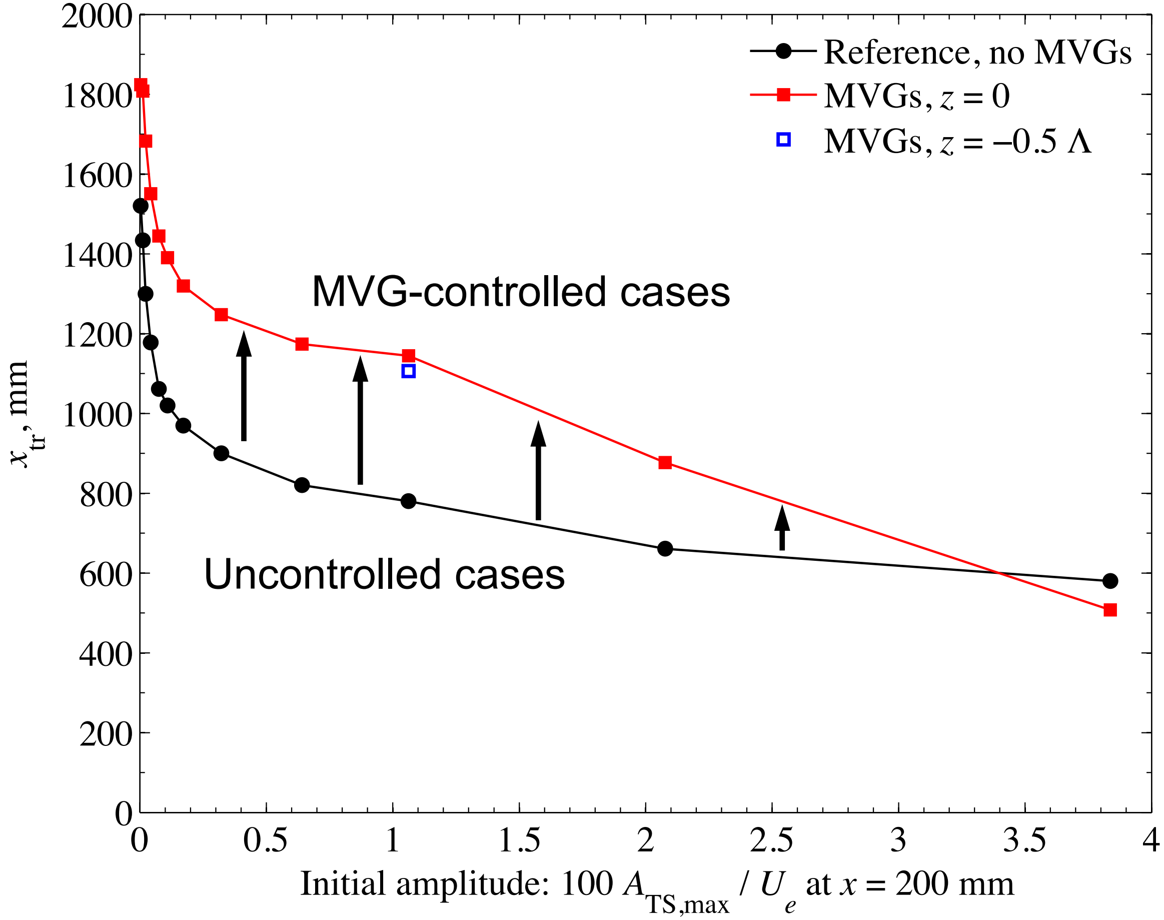
Selected growth curves



MVG array installed at x = 250 mm

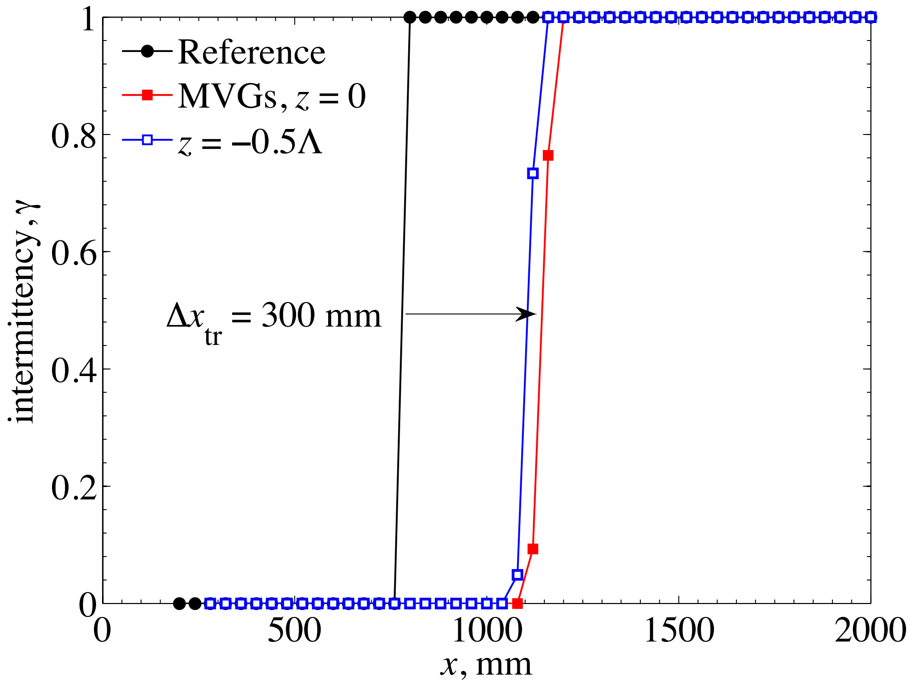
TS-wave excitation at x = 160 mm

Parameter study: TS-wave amplitude

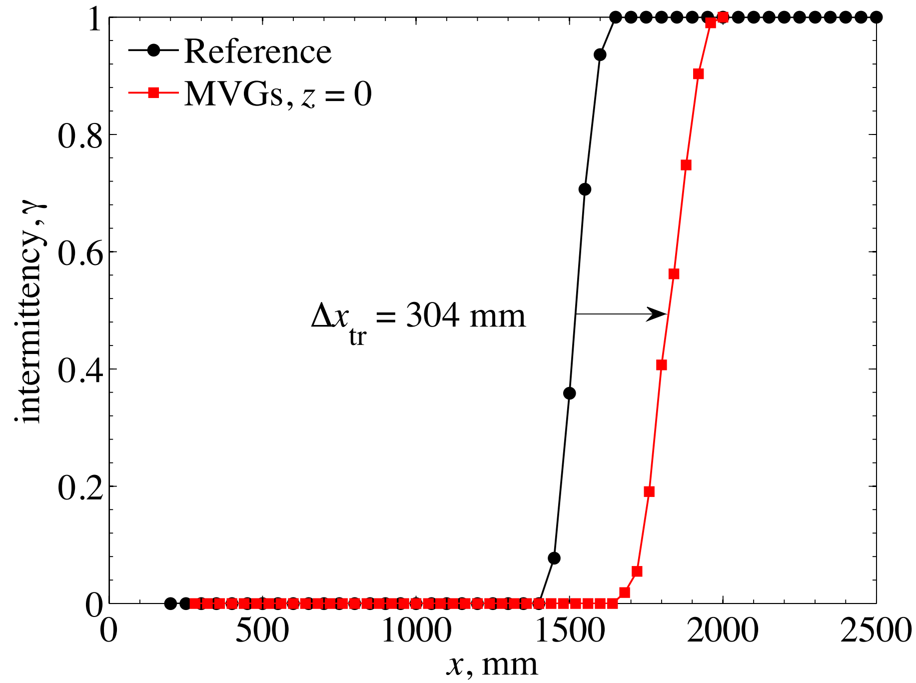


Transition locations measured across a range of initial TS-wave amplitudes show moderate delays when MVG array is installed.

Transition measurements



Forcing: $A_{TS,0}$ = 1.1%



No TS-wave forcing (natural transition)

$u_{rms,0}$ = 0.09%

Intermittency distributions measured at $y = \delta^*$ demonstrate delays in transition onset of 20 – 30% at these conditions.

Conclusions

- Favorable pressure gradients contribute to faster streak dissipation whereas adverse pressure gradients allow streaks to grow larger and persist over longer distances.
- An empirical scaling can be used to describe streak development in non-zero pressure gradient boundary layers.
- Laminar flow control via the spanwise velocity gradient (SVG) method with MVGs is possible in flow characterized by moderately adverse pressure gradient; in these experiments the extent of laminar flow was increased on the order of 20%.