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Cavitation (damage) Strips with Span-wise Regularity Identified from Three Gorges Turbines

Shengcai Li （李胜才）
英国华威大学流体动力学研究中心
Cavitation Research Group, Warwick University, Coventry CV4 7AL, UK;
State Key Lab of Hydroscience & Engineering, Tsinghua University, China;
Hebei University of Engineering, China
S.Li@warwick.ac.uk

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A NEW TYPE OF CAVITATION (DAMAGE) IDENTIFIED FROM THREE GORGES TURBINES

Plenary speeches at international conferences

From the Editor(2007) (No1 subscription in the field)
I meant to ask, out of interest, how the actual turbine manufacturers at Three Gorges reacted to the damage illustrated in your paper… You'll be pleased to note I've mentioned to a few people about the article and everyone is very interested to read. Should get a great response from the readers!

Three Gorge Turbines
Corrosion ?
Galvanic erosion ?
Particle impacts ?
Material defects ?
…

Cavitation Dinorwig turbine UK) [Li, 2001]

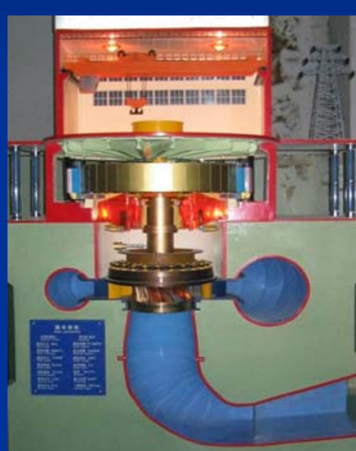
Site inspection (19th March 2006) with Chief Engineer (CTGPC) Prof Dai Jiang

CONTENTS

- Features
  - Highly unusual: puzzles professionals
  - Neither seen nor reported before
- Analysis
  - Multidisciplinary approach (fluids & metallurgy)
- Remarks

BASIC INFORMATION

14 machines (left-plant) made by 2 consortiums



(Courtesy of Harbin Electric Works)

Specifications (11F):

- Rated power 710 MW
- Max efficiency, 96.26%
- Rated head 80.6 M
- Min head 61.0 M
- Max head 113.0 M
- Rated speed 75 rpm
- Run away <150 rpm

Brief Information of Damages
机组表面损伤的基本情况

	Man'ture	Material	Comm'ed	Discovered	Op'ting hours
11F		X3CrNiMo13-4 (EN-1088)	27/07/04 04年 7月 27日	14/10/05 05年10月14日	10245.78 小时
10F		S41500 (ASTM A240)	07/04/04 04年4月7日	27/12/05 05年12月27日	11924.55 小时
9F		GX5CrNi13-4	11/09/05 05年9月11日	11/12/05 100天后整顿检修 (05年12月11日)	2328.41 小时

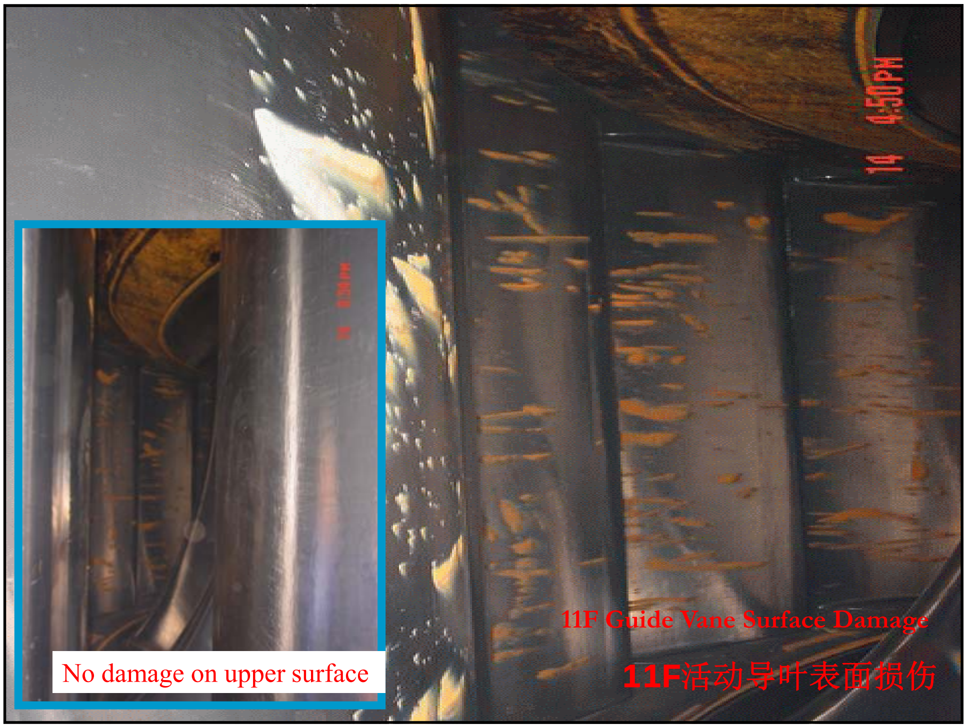
Operating condition: upstream 135-139 m; downstream 64-70 m
运行工况：上游水位：135 - 139米，下游水位：64 - 70米；

FEATURES

- On foil's lower surface only (low head operation)
- Horizontal strips, starting in FPG into APG, mostly around changeover zone
- Wedged head*
- Span-wise intervals showing regularities
- Virtually same width with shallow damage and corrosion surface
- 'Bluing (烧蓝)' appearance

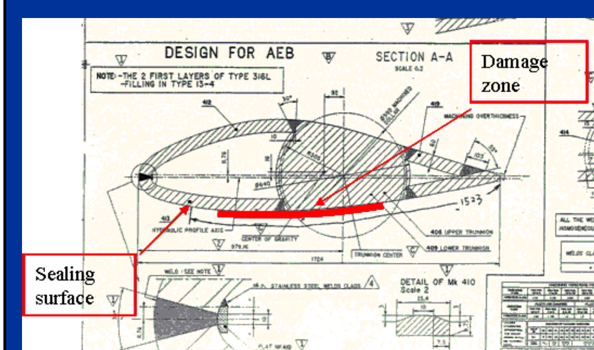
* Note:

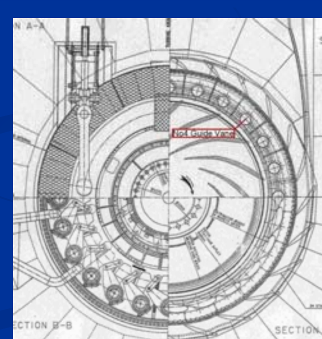
Heads of No 1 & 18 has been sanded off by the manufacturer representative.



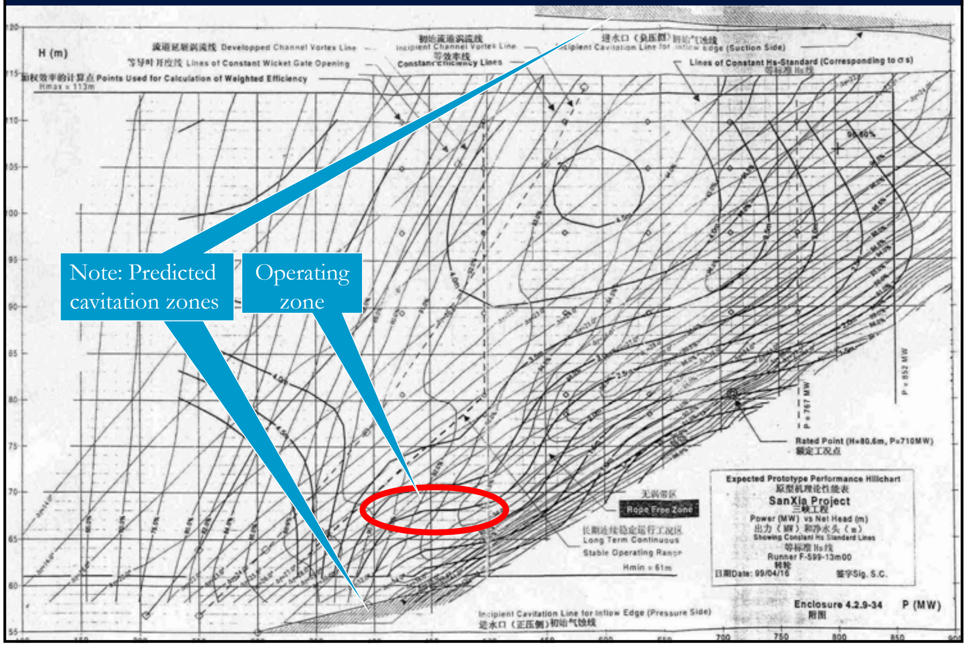
Number 4 guide vane of 11F

- Pattern of damage: representative
- Positively curved hydrofoil



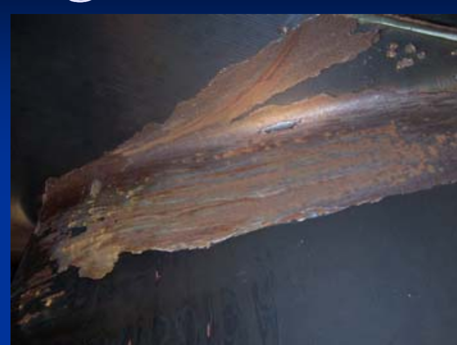


Prototype Performance (11F)



1. Delicate strips with span-wise regularities (for more, see next slide)
2. Horizontal with equal width
3. Wedged head (No.1&18 head sanded off)

Span-wise regularities



- Virtually 2-D (most damages);
- Span-wise space regularity (average space 100 mm);
- 3-D shown at fillet of stay vane: directly attacked by large cavitating flow structure (vortice)

Bluing

- Heated tail
- Heated tails at joints
- Approximately in flow direction
- Puzzles: (circled one) not at flow direction

Corrosion Appearance

- Corrosion + very shallow damage depth tempts to think: **is corrosion a responsible cause for the damage?**
- More appropriate to think:

  Corrosion is a consequence of cavitation damage.

Why?

Analysis of Multi-Sciences

- Metallurgical analysis
  - Heating & Bluing (heat effect from cavitation bubble collapses)
  - Corrosion (sensitisation)
- Fluid Analysis
  - Cavitation inception
  - Free-stream turbulence level (guide plate?)
  - Boundary-layer turbulent production

Metallurgical Analysis

Heating & Bluing

- The colour zone suggests a temperature around 250º C-600º C for 'bluing').
- A typical case of coating (steel) sheets with a film of bluish-black oxide is obtained by exposure to dry steam or air about 538º C [Simons Rolling Forming Co].

Bluing: coating steels with a thin, even film of coloured oxide from bluish-black to purple brown shade, obtained by exposure to an atmosphere of dry steam or air, at certain temperature subject to the material as well as the colour.

Heat Source

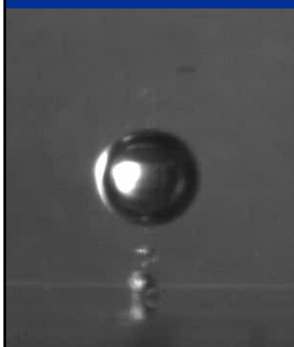
- Cavitation is the only possible heat-source
- The experimentally proven temperature that a collapsing single bubble could generate is about 6000º C~7000º C (comparing with black body's spectra)
- Multi-bubble collapses produce even higher temperature (bubble-bubble interaction)
- See following slides for more information…

Heat Source

Bubble Collapses

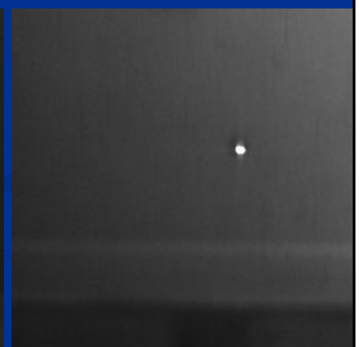
(Laser Induced Bubbles)

[S C Li, Z Zuo, P Dunkley et al, 2004]



In still water

On wall surface



In flowing water

Heat Source

Multi-Bubble Collapse (hydrodynamic)

[S Li, Z Zuo, P Dunkley et al, 2004]

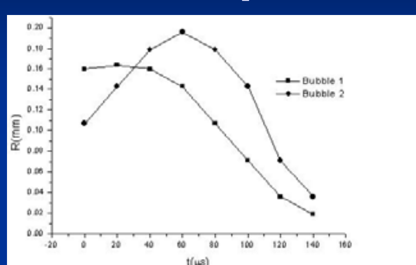
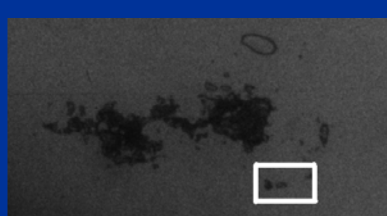


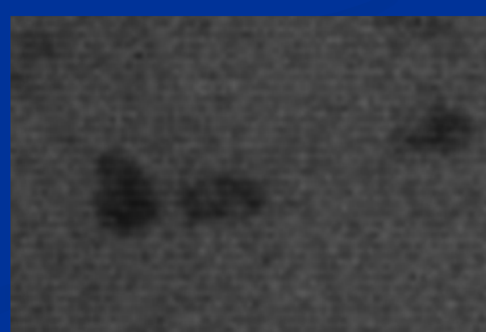
Fig.5. Radii of the two bubbles in interaction

Bubble-bubble interaction

[for detail, see Li, 2001]

Exposure time:100ns; frame interval:20us

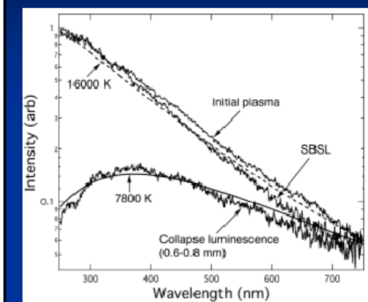


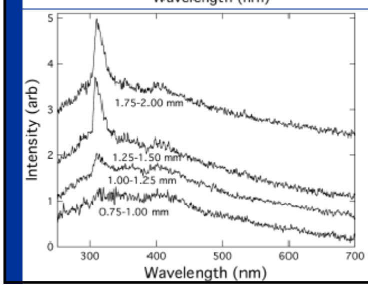


Heat Source

Temperature of Bubble Collapses

[O Baghdassarian, G A Williams, Cav2001]





- Spectral intensity vs wavelength (small bubbles, Rmax =0.6-0.8 mm), from the initial laser-induced plasma, and from an SBSL.
- Spectra of luminescence vs. bubble size, showing the growth of the OH* band at 310 nm.
- Comparison with black body's spectra gives the temperature values as marked on the curves

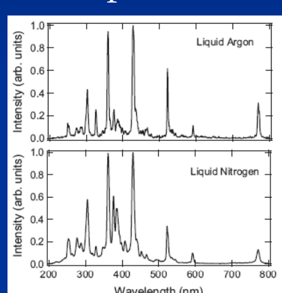
(MBSL & SBSL: Multi-bubble and single-bubble sono-luminescence)

Most Recent Evidence

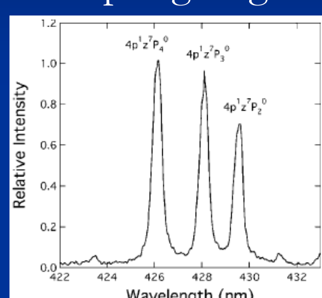
'Error' or 'insignificance', UCLA (USA)

[Gary A. Williams et' al, *PHYSICAL REVIEW E* **75**, 2007]

Temperatures in collapsing single bubble: 4500 K.



Spectrum of the collapse luminescence in liquid nitrogen T=66 K, p=4 bar and liquid argon T=84 K, p=4.5 bar.



Higher-resolution spectra of the chromium triplet lines around 428 nm in liquid nitrogen, showing the excited-state atomic configurations.

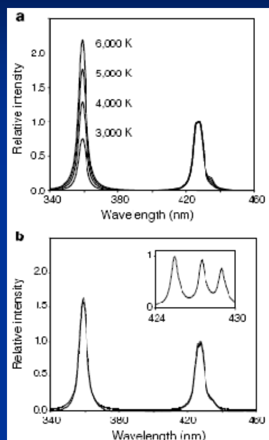
Planck's law

$E = h\nu$

E: photon energy;
ν: frequency at which spectral line occurs;
h: Plank constant.

Temperature of Cavitational Bubble

[MacNamara et'al, *Nature* **401**, 1999]



Relative integrated intensities (I_1/I_2) of two atomic lines from different excited states of same metal atom

$$\frac{I_1}{I_2} = \left(\frac{g_1 A_1 \lambda_2}{g_2 A_2 \lambda_1}\right)^{\left|(E_1 - E_2)/kT_e\right|}$$

g: degeneracy of the electronic state;
A: Einstein transition probability,
λ : wavelength;
E: energy of the electronic state;
T_e **: electronic (approx. bubble) temperature.**

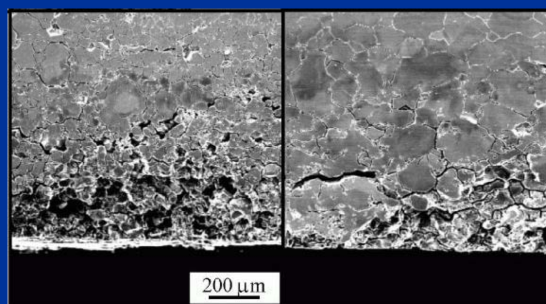
Multi-bubble sonoluminescence (MBSL) emission from excited states of Cr atoms. **a**, Calculated spectra as a function of temperature. **b**, The observed emission spectrum compared to the best-fit calculated spectrum (4,700 K). Inset, observed spectrum at higher resolution, which resolves the individual atomic emission lines.

Why Corroded?

- *Stainless* character occurs if Cr>12 wt%.
- Then why all have corrosion features?

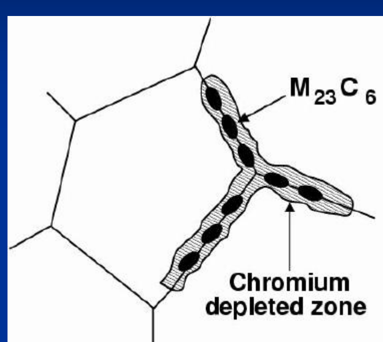
Inter-granular Corrosion

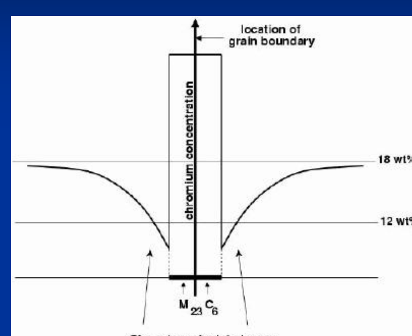
- A wide spread problem for Austenite S S, owing to *sensitization* (for mechanism see following slides)
- A well-known phenomenon of heat effect



Grain de-cohesion due to inter-granular corrosion
Shimada M et al, 2002

Mechanism of Sensitisation





Conceptual sketch of sensitisation [Sourmail T and Bhadeshia H K D H]
(a) Chromium depleted zone susceptible to inter-granular corrosion
(b) Chromium distribution across grain boundary

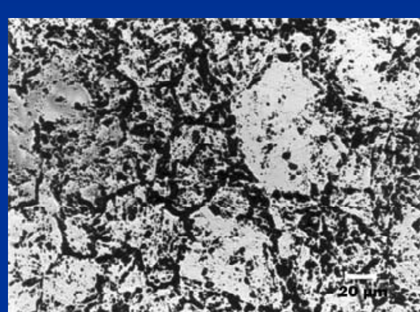
Martensitic: Temper Treatment

For Martensitic S S used for fabrication, both strength and toughness are requested and achieved through **temper**:

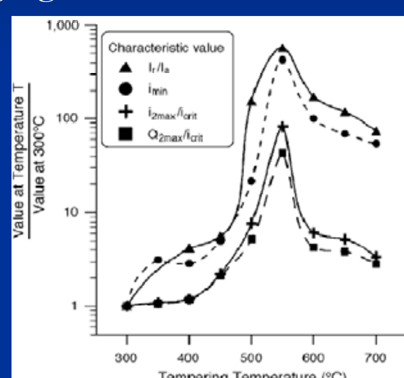
- at 350° C, higher strength and moderate toughness
- at 650° C, moderate strength and high toughness
- **avoid 500° C**, temper embrittlement (i.e. sensitisation) and minimum toughness.

A Typical Case (UNS S41000)

A zone of high sensitization-susceptibility is indicated clearly for temperature ranging from 500° C to 600° C



Optical micrographs of UNS S41000 steel specimens after oxalic acid etch test: tempered at 550° C



Comparison among electrochemical tests to discriminate degrees of sensitization for different tempering temperatures

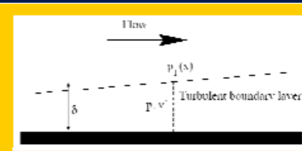
Implications of Heated Sign

- Blue (plus other spectra of colors) indicates a similar heat treatment including the most susceptible range of 500º C to 600º C
- An ideal environment for sensitization, leading to inter-granular corrosion
- **Corrosion formed as a consequence of cavitation attack**

Fluid Dynamics Analysis

Inception within Boundary Layer

- Turbulence (pressure-fluctuation intensity and duration) dominates the statistical characteristics of the micro-bubbles inception performance.
- Tollmien-Schlichting wave prior to transition is 5 kHz (a reference time of 0.2 msec for growth); Bubble life-time (0.1 msec) $\omega_B^2 = 3\gamma \frac{p_0}{\rho_l R_0^2} - \frac{2\sigma}{\rho_l R_0^3}$ observed [Arakari & Acosta, 1981]
- Mostly Favorable Spot for Inception [Daily & Johnson, 1956]: Lowest mean pressure locates at the locations where turbulence is highest
- Kolmogorov Theory: Temporal Pressure Field with Cavitation inception [Arndt & George, 1979]



$$\bar{p}+\rho\overline{v'^2}=p_1(x)$$

Conceptual sketch of (turbulent) boundary layer

Correlating temporal pressure field to cavitation inception (fully developed boundary layer flow).

$$\text{If } \begin{cases} \left(\frac{u_*^2}{\nu}\right) T_B < 1 & \text{for smooth wall;} \\ \left(\frac{u_*^2}{h}\right) T_B < 1 & \text{for rough wall,} \end{cases}$$

The nuclei will have enough time to respond to the **entire spectrum**. Otherwise only a fraction below the frequency of T_B is sensed by the micro-bubbles.

So, damaged surface (spots) is more prone to cavitation and could well serve as the origin of subsequent cavitation !

Possible By-pass Route

Klebanoff Instability

Subject to High FS Turbulence

[Wu X & Luo J, 2001]

- Algebraic growth without wavy pattern
- Resulting in span-wise-dependent but essentially unidirectional flow
- Contributing to secondary instabilities & by-pass transition.
- Interaction with T-S wave, entering nonlinear regime (patches of streak oscillation) and causing breakdown into turbulent spots.

Optimal Disturbance for Klebanoff Instabilities

[Anderson P, 1999]

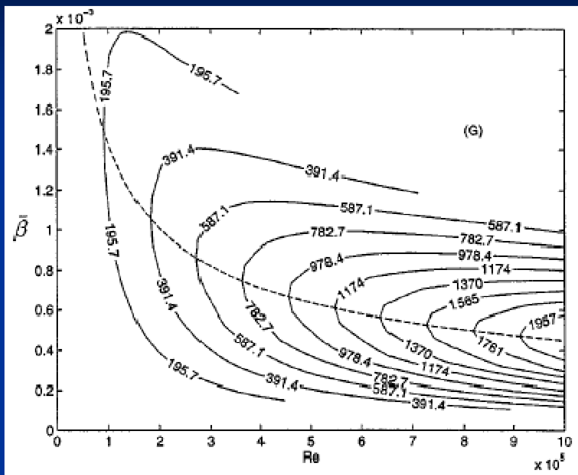


FIG. 4. Contour plots of maximum transient growth vs $\bar{\beta}$ and Reynolds number. The dashed line describes $\bar{\beta}$ for which the maximum transient growth occurs given a specific Reynolds number. Here $x_0 = 0$.

Maximum spatial transient growth (dot line):

$$G(x_f) = \max_{\|u_{in}\| = \|\beta q\| = 1} \|u_{out}(x_f)\|^2$$

$\|u_{in}\|$: input disturbance energy;

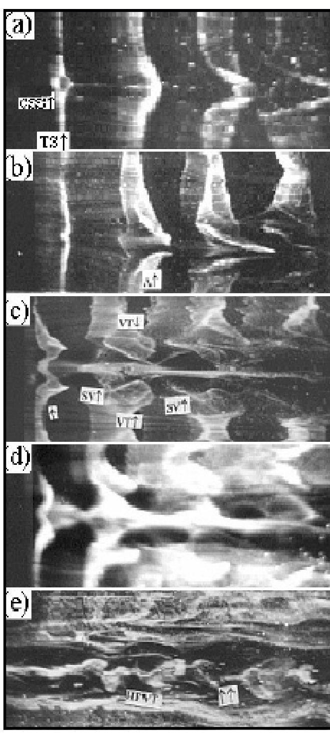
$\|u_{out}\|$:output disturbance energy at a fixed x_f

$$\bar{\beta} = \beta^* \frac{\nu}{U_\infty} = \frac{\beta}{\sqrt{\mathrm{Re}}}$$

$\mathrm{Re} = U_\infty l / \nu$

l: fixed distance

β^*: dimensional span-wise wave number



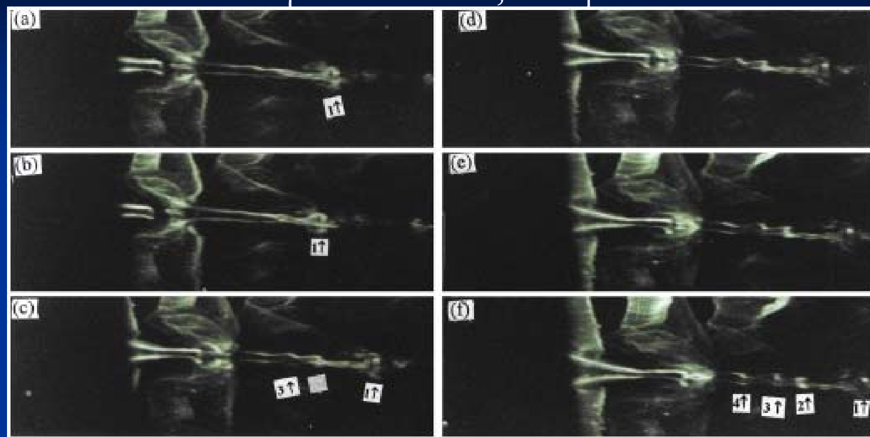
Stream-wise Vortices

[Lee and Chen, 2005]

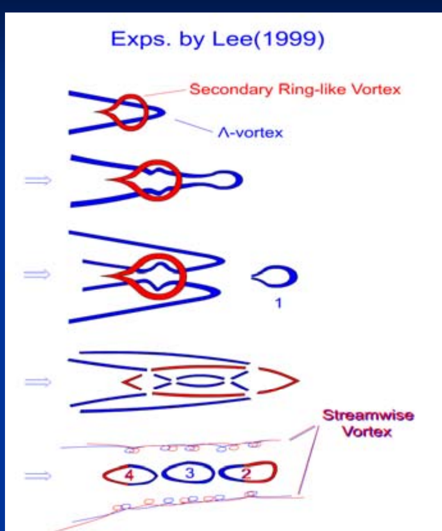
(a) T–S wave and SCS (CSS in the picture). The hydrogen bubble wire was at x = 250mm and y = 0.75mm;
(b) The Λ-vortex structure. The wire was positioned at x = 300mm and y = 0.75mm;
(c) Development of the Λ-vortex and the long streak. The wire was at x = 350mm and y = 0.75mm;
(d) The long streak is composed of several CS-solitons and the wire was at x = 450mm and y = 0.5mm;
(e) Breakdown of a long streak. The wire was at x = 550mm and y = 0.75 mm.

Chain of Ring Vortices

[Lee and Chen, 2005]



Plan view of the chain of ring vortices (↑) associated with a Λ-vortex (A ↑) (the wire was at x = 360 mm and y = 1.75 mm) (Lee, 2001a). The first ring vortex propagated downstream (1 ↑) while the other three (2 ↑ , 3 ↑ and 4 ↑) appeared at nearly the same time. The time interval between successive pictures was 1/24 s. (a) shows the first ring vortex. (b) to (e) show the other three ring vortices.

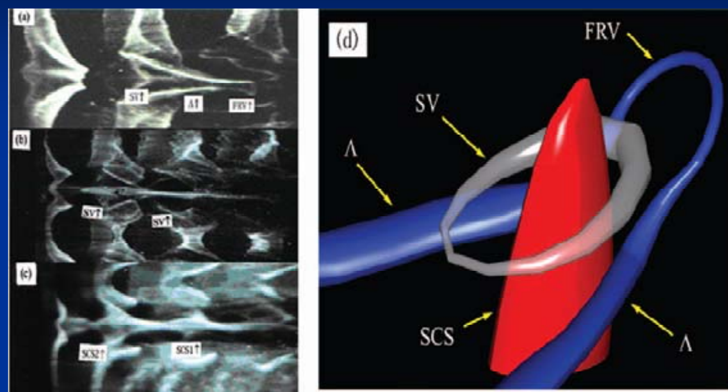


More information on co-rotating & count-rotating unequal pairs etc,

[e.g. Bristal et' al, *JFM,* 2004 **517** pp331-358]

Proposed Structure

[Lee & Wu, 2008]



Left column:

typical hydrogen-bubble photos of complex flow structures illuminated by laser sheet at different horizontal heights. SCS the soliton-like coherent structures; SV the secondary closed vortex and FRV the first ring vortex

Right column:

3-D structure reconstructed from the photos on the left column

Evolution of Turbulence Wedge from Stream-wise Steaks

[Watmuft J H, 2004]

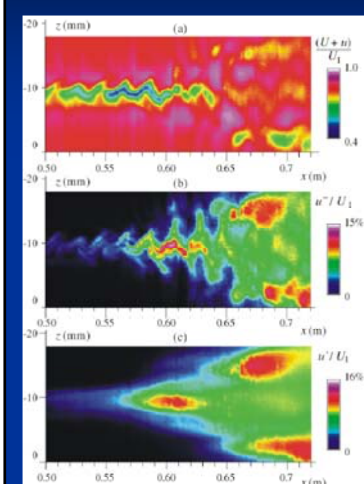


Figure 4. True spatial contours in plane, y=2mm (a) $(\bar{U}+u_{\phi})/U_1$, ϕ=21. (b) u^{*}_{ϕ}/U_1, ϕ = 21. (c) Broadband unsteadiness, $\tilde{u}'/U_1$.

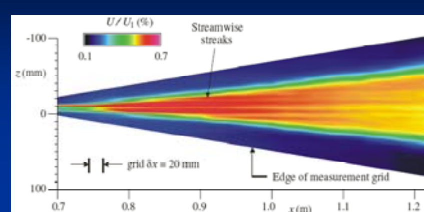
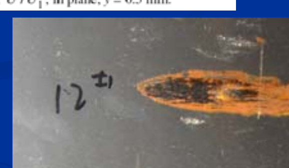


Figure 5. Contours of $\bar{U}/U_1$, in plane, y = 0.5 mm.



- Steady streak excited by a harmonic source, 265 Hz
- Breakdown on the centreline and formation of two regions of highly unsteady flow on either side of streak
- Resemble to the wedged head of damage pattern

High Turbulence in F S

The last piece of the puzzle !!

Span-wise wave-length (spacing) of laminar streaks or Klebanoff wave,

$$\lambda^* = 10\,\delta^*$$

Here, δ^* is the displacement thickness,

$$\delta^* = \frac{1.7208\,L}{\sqrt{\mathrm{Re}_{,l}}}$$

For a typical damage strip, $L = 0.550$ m ,

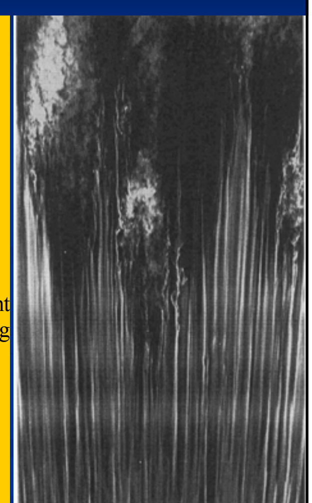
$\mathrm{Re}_{,l} = 5.2\times10^6$ (based on $U_\infty \approx 12.4$ m/s) , and $\delta^* = 0.43\times10^{-3}$ m ,

$$\lambda^* \approx 4.3\times10^{-3}\ \mathrm{m}$$

Transition region characterised by a random appearance of turbulent spots, each generated from 20-30 such streaks, giving the spacing λ^*_{spot} of the turbulent spots

$$\lambda^*_{spot} \approx 86\times10^{-3} \sim 129\times10^{-3}\ \mathrm{m}$$

Agrees well with the observed strip spacing λ^*_{strip} $(\approx 0.100\ \mathrm{m})$.



A Grand Challenge
Why Can't Be Predicted By Model Study?

Violation of dynamic similarities owing to increasingly large model-prototype ratio (28 for Three Gorge)

For free-stream turbulence similarity,
Reynolds number equality would have required, that is

$$\frac{H_m}{H_p} = \left(\frac{D_{1,p}}{D_{1,m}}\right)^2 ,$$

$$\frac{H_m}{H_p} \approx 784, \text{ i.e. } H_m \approx 47{,}824 \square 88{,}592\ m$$

Impossible. For prototype, $Re_{,p} \approx 4.6\times10^7$ at $Q_{opt} = 718\ m^3/s$, while for models, it might be $10^2 \square 10^3$ smaller.
Much higher level of free-stream turbulence for prototype.

For boundary-layer similarity,

1. Similarity of free-stream turbulence;
2. Equality of boundary-layer based Reynolds number, $Re_l = \frac{L \cdot U_\infty}{\nu}$;
3. Equality of Strouhal number (i.e. n_1'),

Leading to

$$\frac{(Re_l)_m}{(Re_l)_p} = \left(\frac{D_{1,m}}{D_{1,p}}\right)\left(\frac{H_m}{H_p}\right)^{1/2} = 1$$

That is,

$$H_m = 784\, H_p$$

This is impossible in reality, the real value of the ratio of the boundary-layer based Reynolds numbers equal to

$$\frac{(Re_l)_m}{(Re_l)_p} = \frac{1}{28}\left(\frac{H_m}{H_p}\right)^{\frac{1}{2}}$$

REMARKS: Challenge & Opportunity

- **Cavitation mechanism**: Span-wise regularities of damage strips thus must relate to the span-wise structure of K-wave breakdown & turbulence production!
- **Turbine technologies**: Similarity laws and design theorems;
- **Multidisciplinary & International effort**: Being investigated at Warwick University at international level.

Thank you !