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

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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 Dinerwig turbine UK [1, 2001]



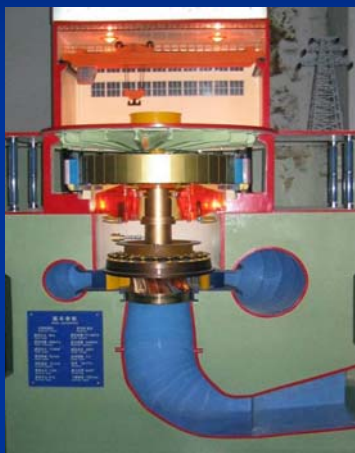
Site inspection (19th March 2006) with Chief Engineer (CTGPC) Prof Dai Jiang

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

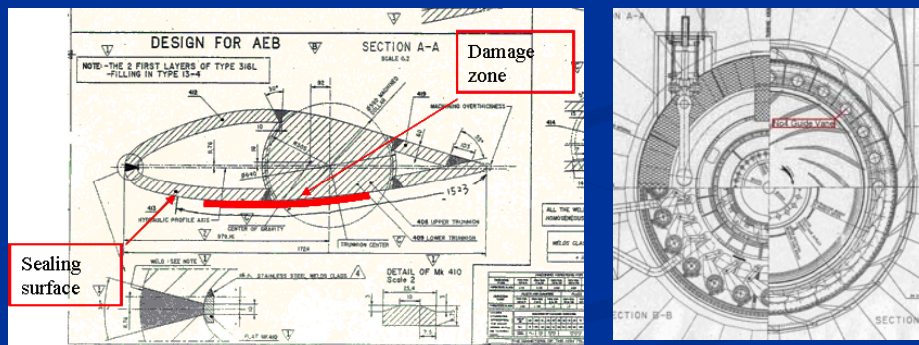
* Note:

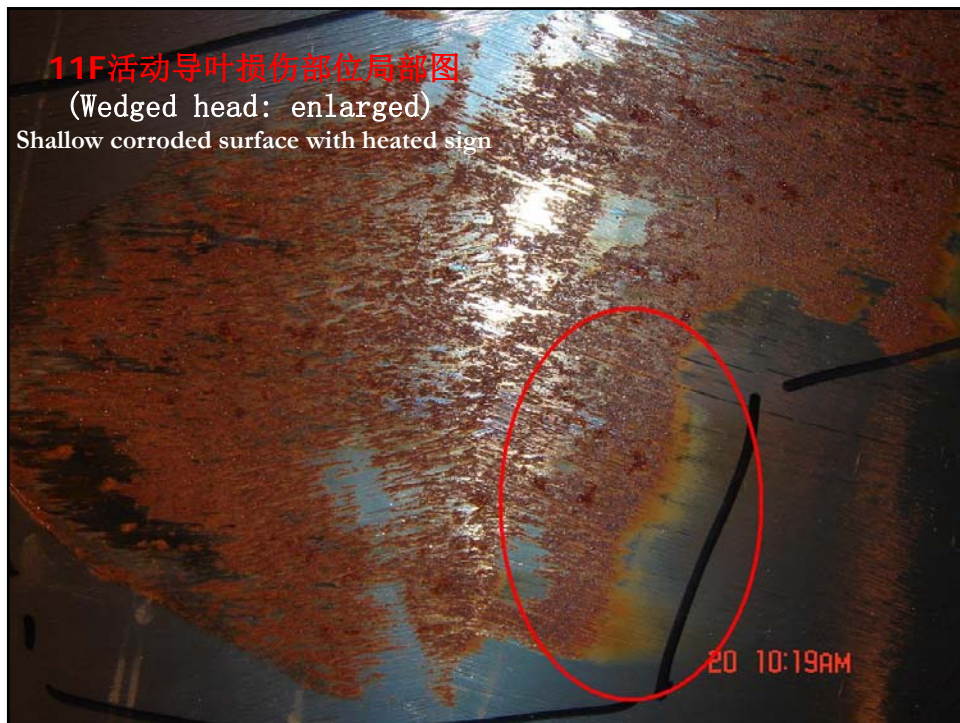
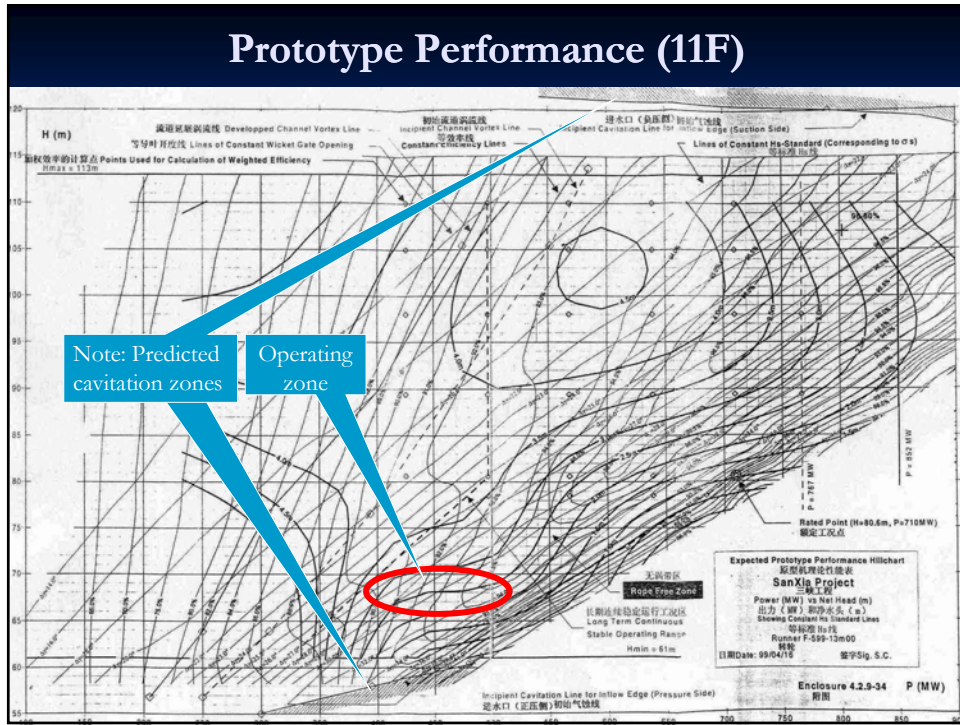
Heads of No 1 & 18 has been sanded off by the manufacturer representative.

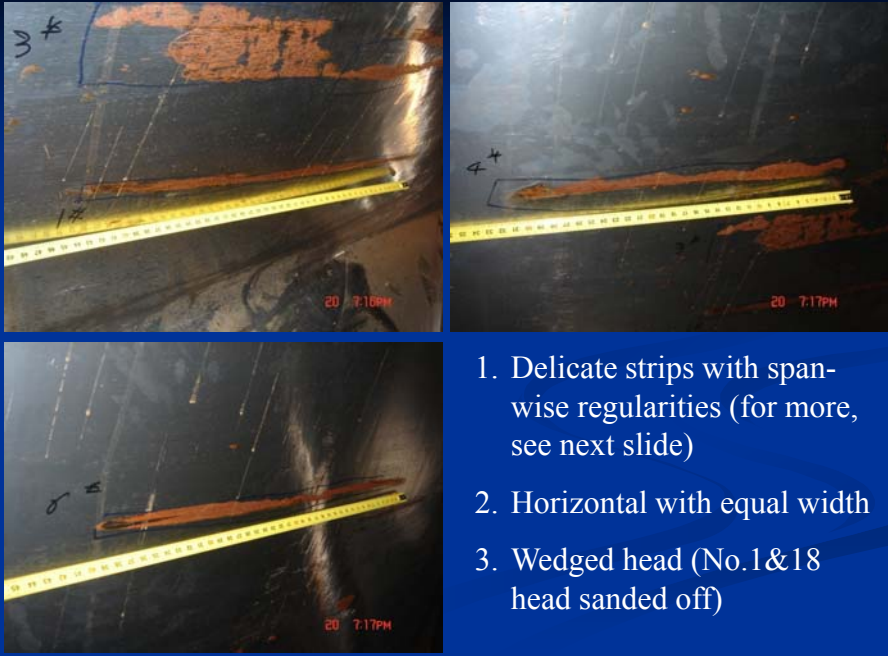


Number 4 guide vane of 11F

- Pattern of damage: representative
- Positively curved hydrofoil







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



Location	Area	Color	Notes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

- 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

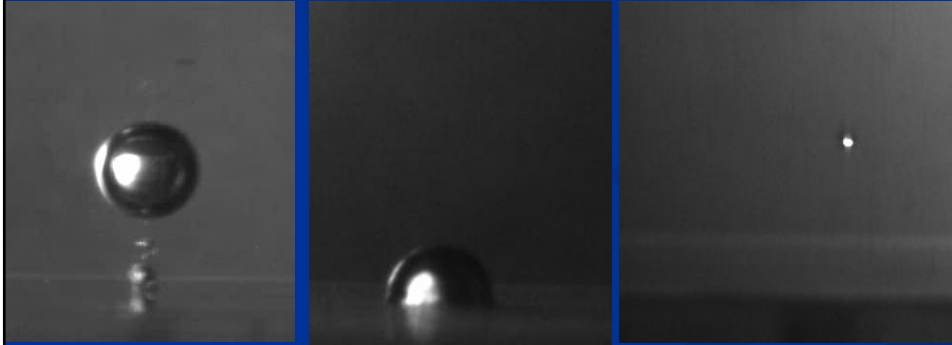
- The colour zone suggests a temperature around 250°C - 600°C for 'bluing').
- A typical case of coating (steel) sheets with a film of bluish-black oxide is obtained by exposure to dry steam or air about 538°C [Simons Rolling Forming Co].

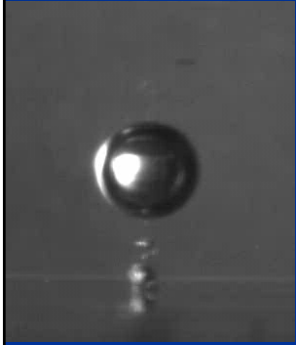
Bluing: coating steels with a thin, even film of coloured oxide from bluish-black to purple brown shade, obtained by exposure to an atmosphere of dry steam or air, at certain temperature subject to the material as well as the colour.

Heat Source


- Cavitation is the only possible heat-source
- The experimentally proven temperature that a collapsing single bubble could generate is about 6000°C ~ 7000°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]

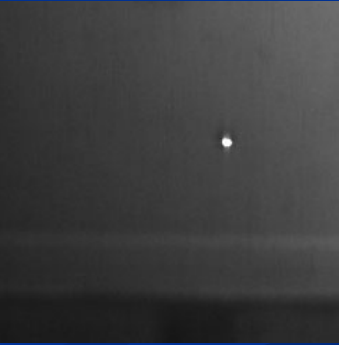




In still water



On wall surface



In flowing water

Heat Source
Multi-Bubble Collapse (hydrodynamic)
 [S Li, Z Zuo, P Dunkley et al, 2004]

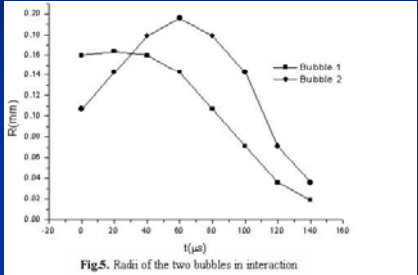
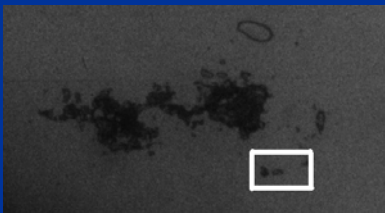
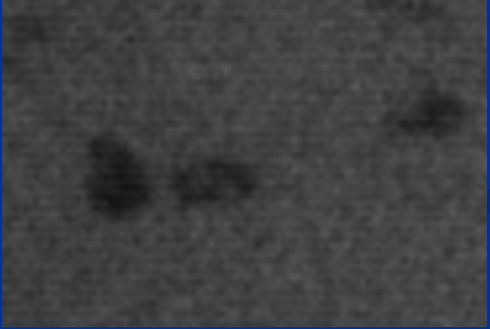


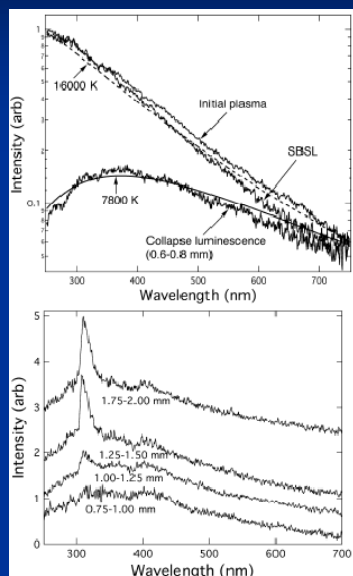
Fig.5. Radii of the two bubbles in interaction

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]

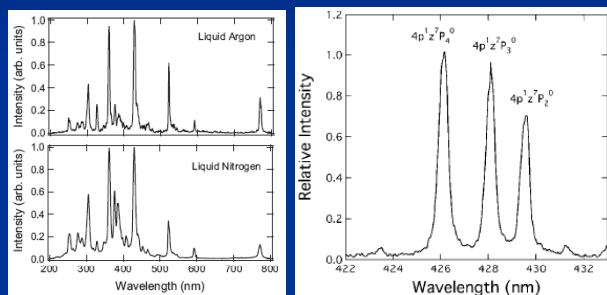


- Spectral intensity vs wavelength (small bubbles, $R_{max} = 0.6-0.8$ mm), from the initial laser-induced plasma, and from an SBSL.
- Spectra of luminescence vs. bubble size, showing the growth of the OH* band at 310 nm.
- Comparison with black body's spectra gives the temperature values as marked on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

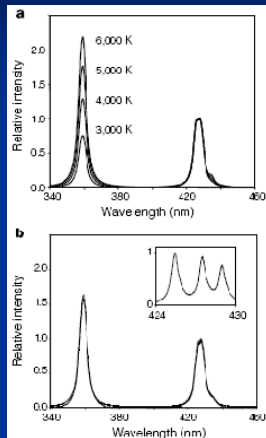
Planck's law

$$E = h\nu$$

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

Temperature of Cavitation 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

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

g : degeneracy of the electronic state;

A : Einstein transition probability,

λ : wavelength;

E : energy of the electronic state;

T_e : electronic (approx. bubble) temperature.

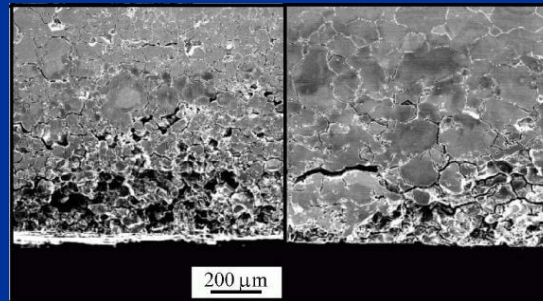
Multi-bubble sonoluminescence (MBSL) emission from excited states of Cr atoms. **a**, Calculated spectra as a function of temperature. **b**, The observed emission spectrum compared to the best-fit calculated spectrum (4,700 K). Inset, observed spectrum at higher resolution, which resolves the individual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

Why Corroded?

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

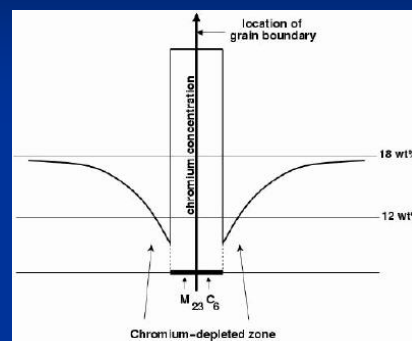
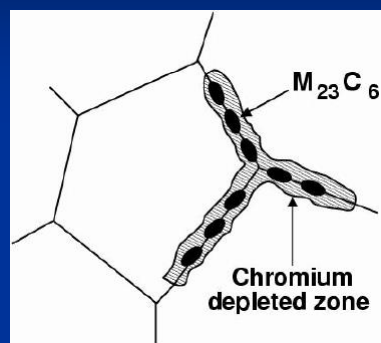
Inter-granular Corrosion

- 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

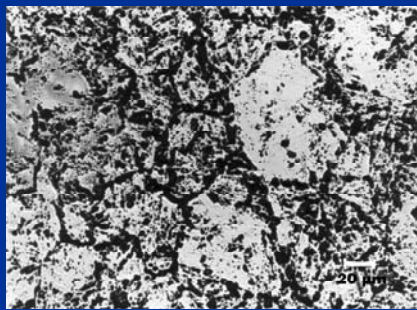
Martensitic: Temper Treatment

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

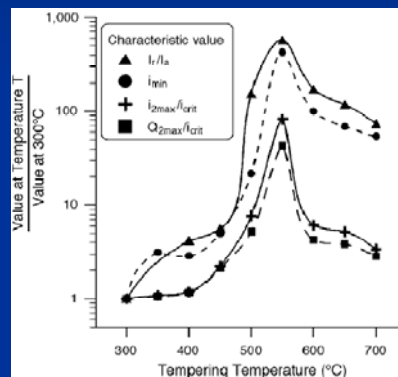
- at 350° C, higher strength and moderate toughness
- at 650° C, moderate strength and high toughness
- **avoid 500° C**, temper embrittlement (i.e. sensitisation) and minimum toughness.

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

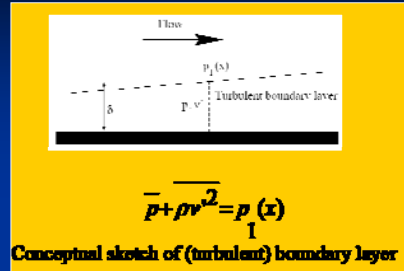
Implications of Heated Sign

- Blue (plus other spectra of colors) indicates a similar heat treatment including the most susceptible range of 500° C to 600° 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) $\omega_b = 3 \cdot \frac{p_0}{\rho \delta} - \frac{2p_0}{\rho \delta^2}$ 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]



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

$$\text{If } \frac{u_{rms}^2}{v^2} T_B < 1 \text{ for smooth wall;}$$

$$\frac{u_{rms}^2}{h} T_B < 1 \text{ for rough wall,}$$

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]

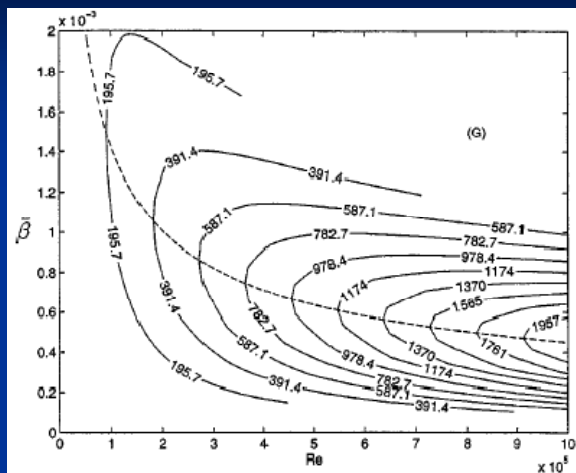


FIG. 4. Contour plots of maximum transient growth vs $\bar{\beta}$ and Reynolds number. The dashed line describes $\bar{\beta}$ for which the maximum transient growth occurs given a specific Reynolds number. Here $x_0=0$.

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;

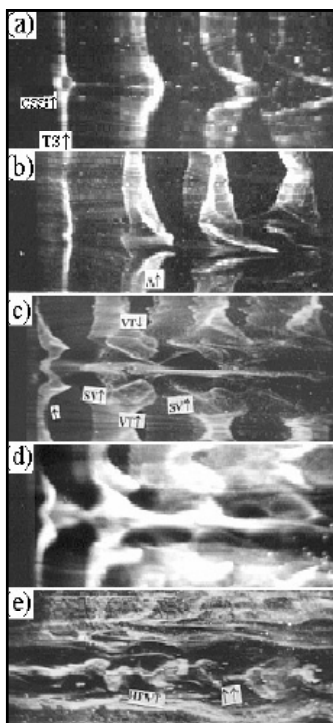
$\|u_{out}\|$: output disturbance energy at a fixed x_f

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

$$Re = U_\infty l / \nu$$

l : fixed distance

β^* : dimensional span-wise wave number



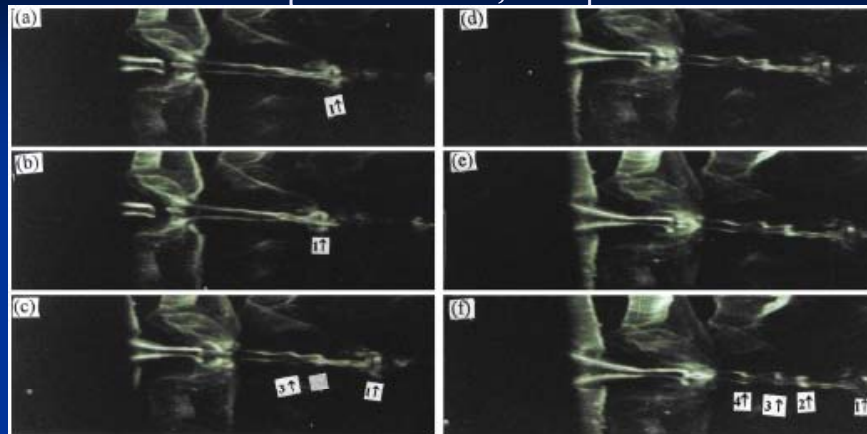
Stream-wise Vortices

[Lee and Chen, 2005]

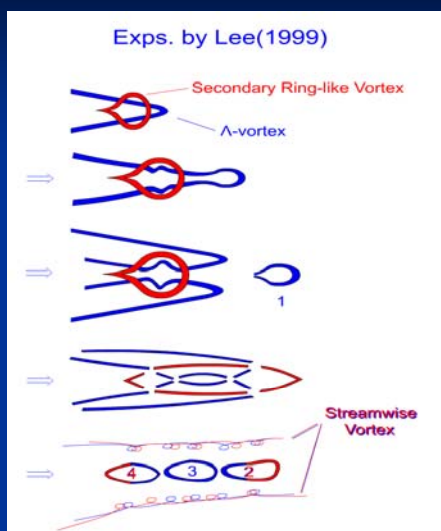
- (a) T-S wave and SCS (CSS in the picture). The hydrogen bubble wire was at $x = 250\text{mm}$ and $y = 0.75\text{mm}$;
- (b) The Λ -vortex structure. The wire was positioned at $x = 300\text{mm}$ and $y = 0.75\text{mm}$;
- (c) Development of the Λ -vortex and the long streak. The wire was at $x = 350\text{mm}$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

Chain of Ring Vortices

[Lee and Chen, 2005]



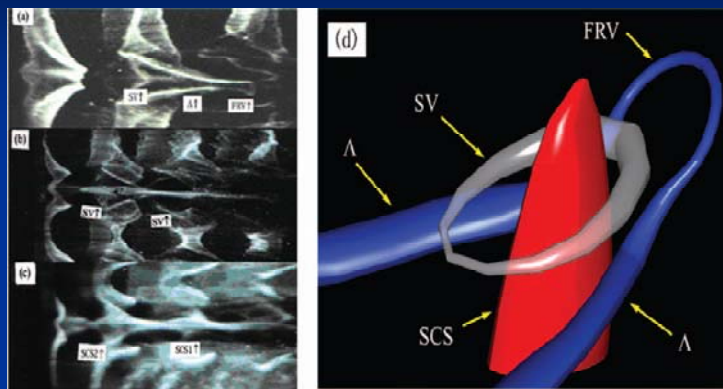
Plan view of the chain of ring vortices (\uparrow) associated with a Λ -vortex ($A \uparrow$) (the wire was at $x = 360$ mm and $y = 1.75$ mm) (Lee, 2001a). The first ring vortex propagated downstream ($1 \uparrow$) while the other three ($2 \uparrow$, $3 \uparrow$ and $4 \uparrow$) appeared at nearly 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. Bristol 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

[Watmuff J H, 2004]

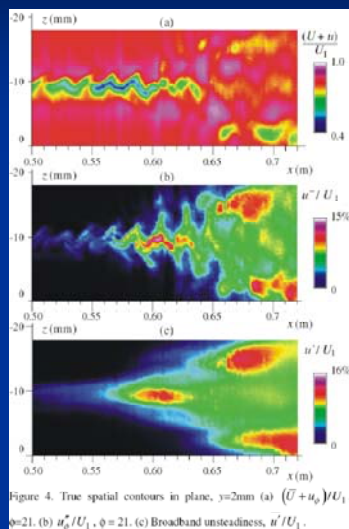


Figure 4. True spatial contours in plane, $y=2\text{mm}$ (a) $(\bar{U}+u_x)/U_1$, $\phi=21$. (b) u'_x/U_1 , $\phi=21$. (c) Broadband unsteadiness, u'/U_1 .

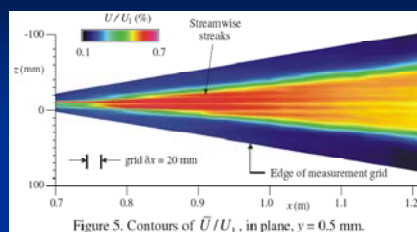
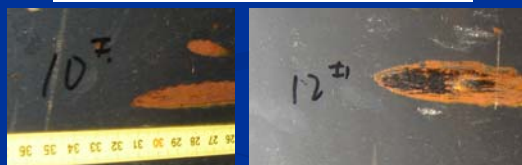


Figure 5. Contours of \bar{U}/U_1 , in plane, $y=0.5\text{ mm}$.



- 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,

$$\delta^* = \frac{1.7208 L}{\sqrt{\text{Re}_l}}$$

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

$\text{Re}_l = 5.2 \times 10^6$ (based on $U_\infty \approx 12.4$ m/s), and $\delta^* = 0.43 \times 10^{-3}$ m,

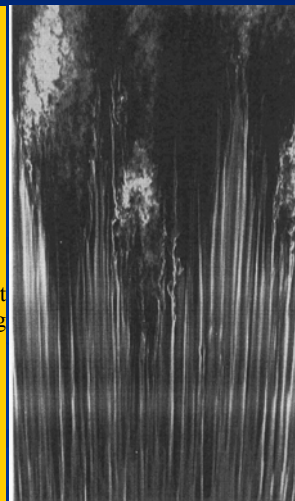
$$\lambda^* \approx 4.3 \times 10^{-3} \text{ m}$$

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

$$\lambda_{spot}^* \approx 86 \times 10^{-3} \sim 129 \times 10^{-3} \text{ m}$$

Agrees well with the observed strip spacing λ_{strip}^* (≈ 0.100 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

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

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

Impossible. For prototype, $Re_{,p} \approx 4.6 \times 10^7$ at $Q_{opt} = 718 \text{ m}^3/\text{s}$, 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

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

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 !