Applied Research Laboratory
The Pennsylvania State University

State-of-the-Art Laboratory Instrumentation Systems

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Session: Field and Laboratory Measurement and Instrumentation
Track: Laboratory Testing Methods

Instrumentation Requirements

Test Goals Drive Instrumentation Needs

- **Low TRL level Proof-of-Concept evaluation**
  - Macroscopic device performance
  - Relaxed spatial and temporal requirements → steady
  - Moderate levels of accuracy

- **Low – Mid TRL Level Concept Development Testing**
  - Macro & microscopic device performance
    - Powering, loads, near-field performance characterization
  - Refined spatial and temporal requirements → steady and dynamic
  - Moderate levels of accuracy

- **Validation & Verification Testing[1-5]**
  - Macro & microscopic device performance
    - near-field performance, far-field boundary conditions
    - Accurate model characterization
  - Refined spatial and temporal resolution → dictated by physics at model scale
    - Steady and dynamic measurements
  - Increased levels of accuracy → documented uncertainty

Measurements

Structural / Mechanical

- Device & component loads
- Device & component motion
- Vibration & radiated sound

Flow

- Flow and velocity
- Pressure
- Cavitation
- Acoustics
- Fluid properties

Invasive vs Non-Invasive Instrumentation

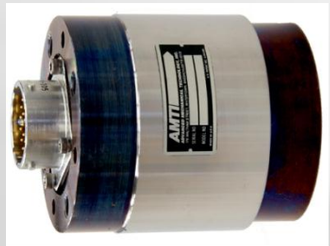
Impact on Performance

- Model integrity → impact of sensor installation on component function
- Flow interference → alter flow field or impact flow measurement
- Noise or vibration source → instrument vibration or elevated background noise

Non – Invasive Instrumentation is Preferred Laboratory Measurement

Instrumentation State of the Art
Structural / Mechanical

- Steady & low frequency loads → strain – gaged based multi-degree of freedom load cells



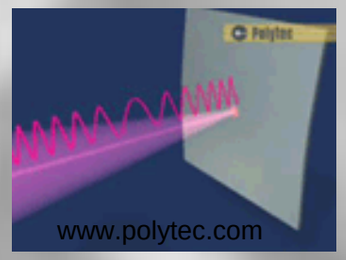
- **6-DOF: F_x, F_y, F_z, M_{xz}, M_{yz}, Torque**
- **Water-proofed & can be rotated**

- Unsteady & high frequency loads → Piezoelectric based sensors

- Device & component motion
  - Shaft rpm → optical and electrical encoders
  - Component and Device motion & deformation → optical systems (non-invasive), acoustic displacement sensors (invasive)

- Component vibration
  - Invasive → strain gages, multi-axis accelerometers
  - Non-invasive → High mag / high speed imaging, laser Doppler Vibrometry[6]

- **Displacement and velocity**
- **Single-point and scanning**
- **Small and large amplitude vibration**
- **Good spatial and temporal resolution**



- Component noise → hydrophones, acoustic arrays, dynamic pressure

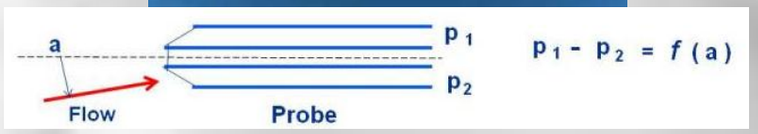
Instrumentation State of the Art
Flow & Velocity

Flow

- Flow → Mass (gas): thermal mass flow meters
  Volume (liquids): magnetic & ultrasonic flow meters

Velocity

- Invasive → Pressure Based: multi-holed Pitot type probes
  - Multi-component, single point
  - Calibration important
  - Directional sensitivity
  - Mean velocity – ~~turbulence~~



- Invasive → Thermal Anemometry[7,8]
  - Multi-component, single point
  - Low noise, high spatial and temporal resolution
  - Calibration important – non-linear
  - Directional & fluid property sensitivity
  - Mean velocity & turbulence
  - Wires ⇒ gases; films ⇒ liquids

Instrumentation State of the Art Velocity

- Invasive → Acoustic: ADV & ADCP[9-11]
  - Measurement acquired off backscattered acoustic signals from dispersed particles
  - Multi-component, single point or line scan
  - Reasonable dynamic range & good accuracy
  - Relatively low sampling rate and large measurement volume
  - Mean velocity, turbulence?
    - Bias errors associated w/ particle sampling(velocity & gradient)
    - Aliasing
    - High noise floor

www.nortekusa.com

ADV

- **Acoustic beams focused onto single volume**
- **Meas. Vol. *O*(0.1 cm^3), F_s *O*(100Hz*)***
- **Deployment can be fixed or moving**
- **Turbulence measurements possible (though spatial averaging & noise still an issue)**
- **Motion compensation**
- **Improved resolution**
- **Improved processing**

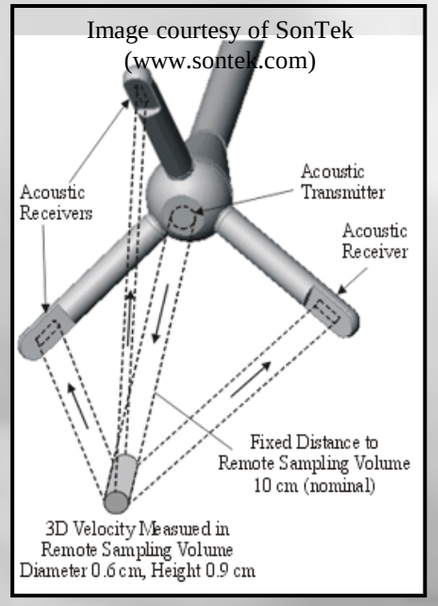


Image courtesy of SonTek (www.sontek.com)

ADCP

- **Acoustic beams (3 or 4) divergent**
- **No single defined meas. volume**
- **Deployment can be fixed or moving**
- **Accurately determine mean velocities through a selected column of water**
- **Wave height**
- **Turbulence?**
  - **Improved turbulence meas.**

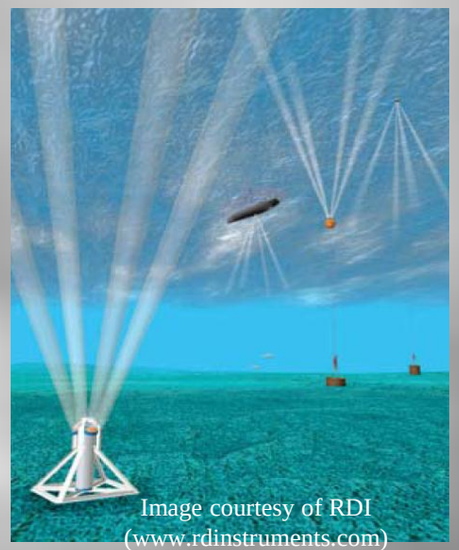
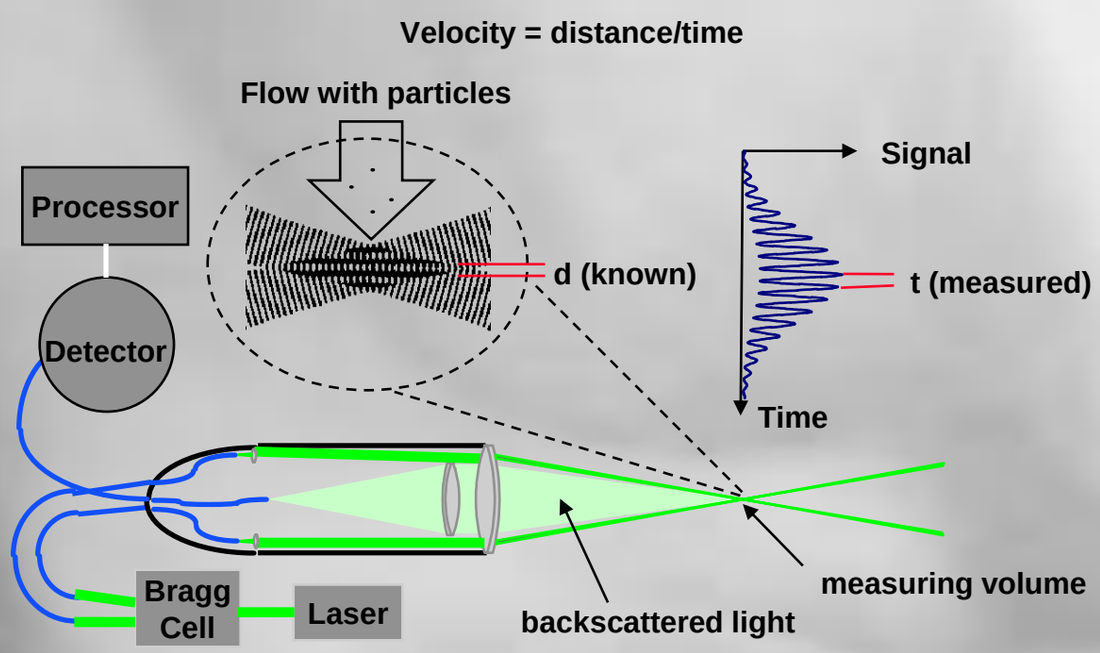


Image courtesy of RDI (www.rdinstruments.com)

Instrumentation State of the Art Velocity

- Non-Invasive → Laser Doppler Velocimetry[12] – ~50 years ⇒ **Gold Standard Meas**.
  - Measurement acquired off scattered light from dispersed particles
  - Multi-component, single point
  - High dynamic range & accuracy
  - High spatial $O(10^{-8} - 10^{-5}\ cm^3)$ & temporal resolution *O(kHz)*
  - Short and long stand-off
  - Mean flow & turbulence
    - ➢ Bias errors associated w/ particle sampling – well known and correctable
    - ➢ Elevated noise floor relative to thermal anemometry

Dantec Inc.



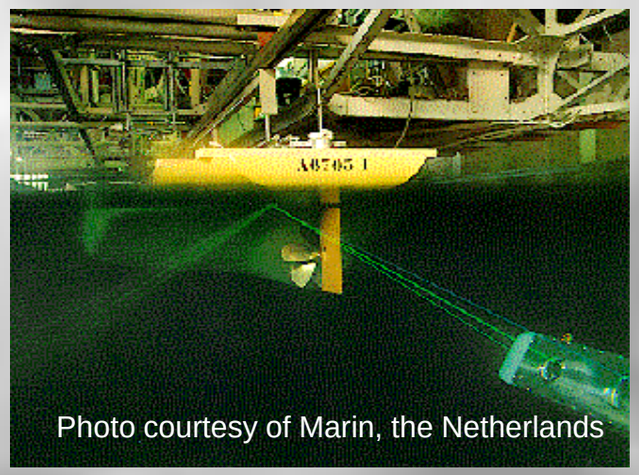
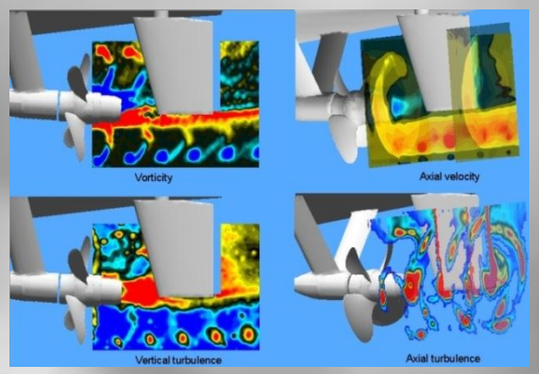


Photo courtesy of Marin, the Netherlands

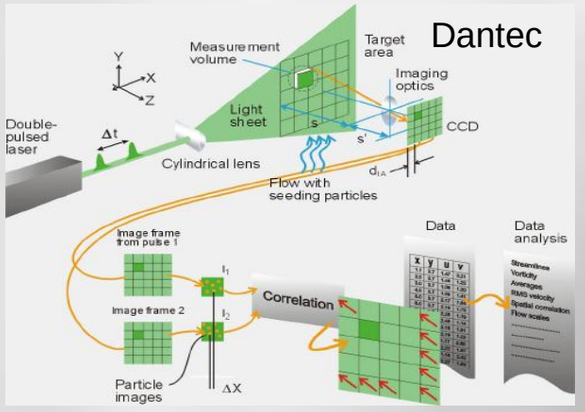


phase-locked LDV Muscari *et al.*[13]

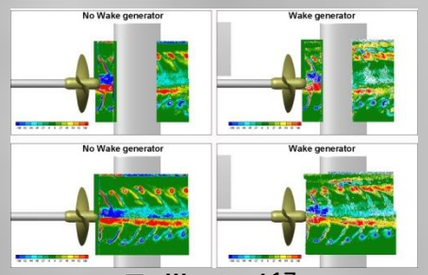
www.TSI.com & WWW.Dantec.com

Instrumentation State of the Art
Velocity

- Non-Invasive → Particle Image[14] and Particle shadow[15] Velocimetry – ~80 years
  - Measurement acquired from imaging dispersed particles or particle shadows
  - Multi-component, multi-point
  - **PSV/PSA[16]: Velocity & Acceleration, FSI**
  - Planar and **volumetric** – Instantaneous snapshot of flow
  - High dynamic range & accuracy
  - Good spatial and temporal resolution (kHz)
  - Mean flow & turbulence
    - ➢ Bias errors associated w/ particle sampling – well known and manageable



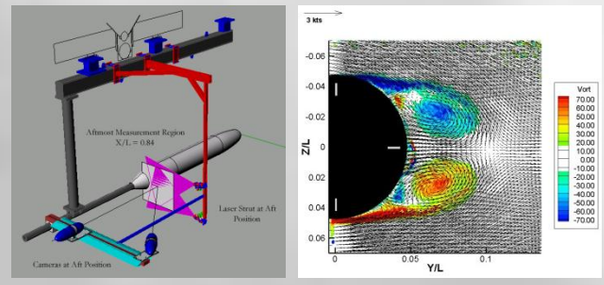
PIV



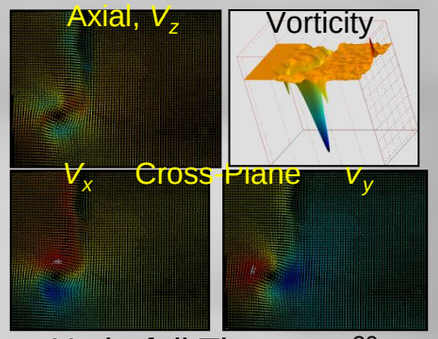
Felli *et al*.[17],

Atsavapranee *et al*.[18]

SPIV

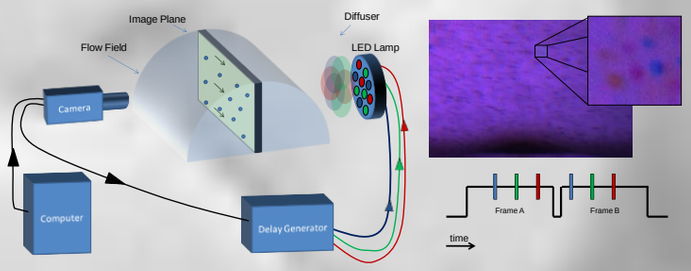


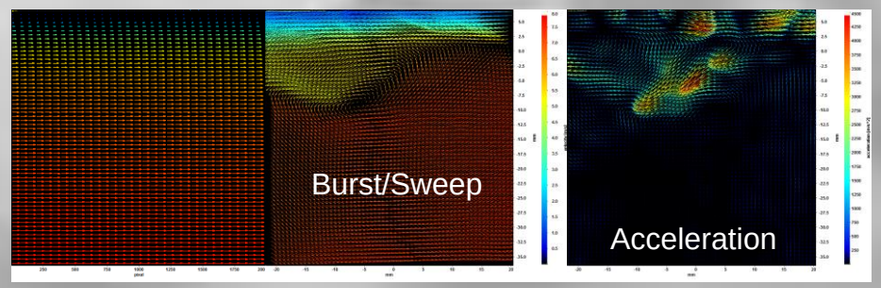
Etebari *et al*. [19]



Hydrofoil Tip vortex[20]

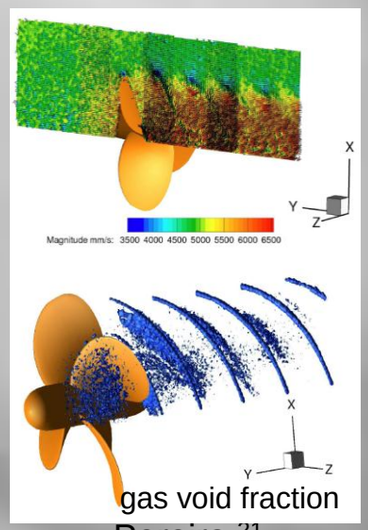
Multi-Color PSV/PSA





Dowell *et al*.[15]

DDPIV

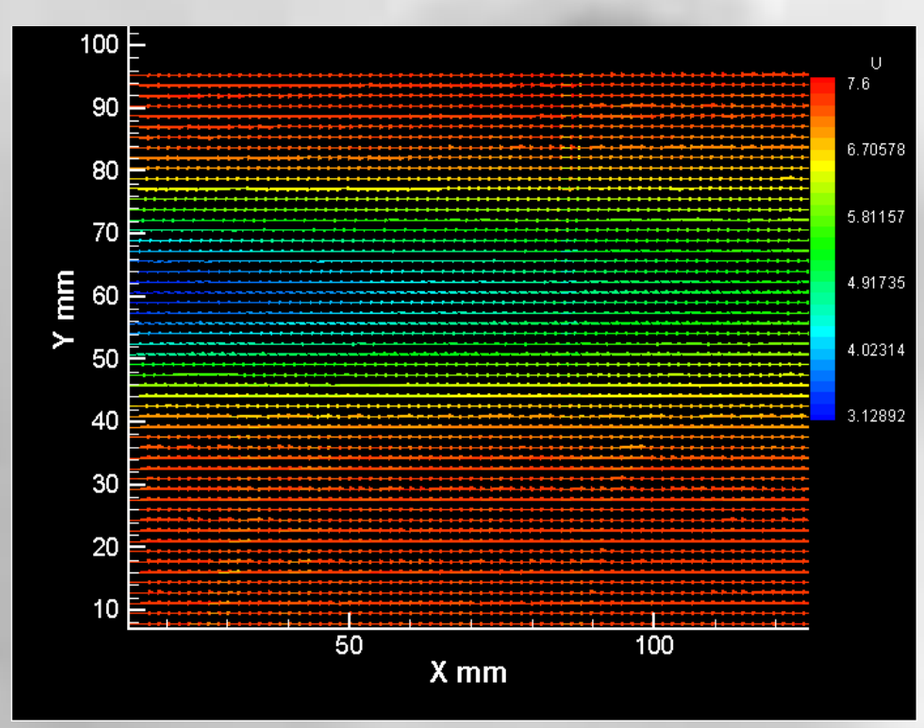


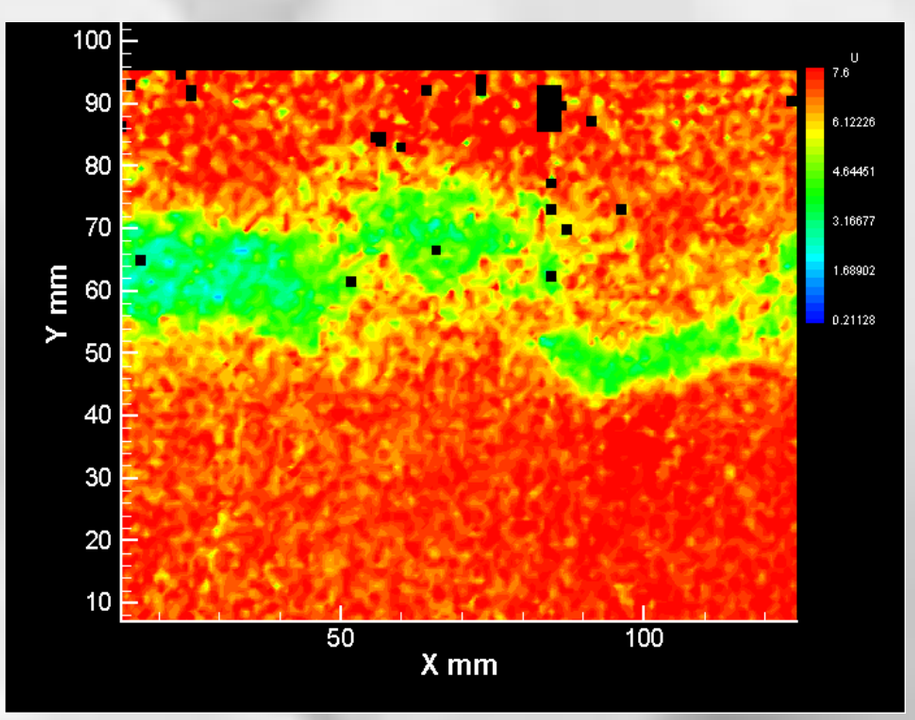
Pereira,[21]

Instrumentation State of the Art
PIV

Wake Structure

Axial Flow





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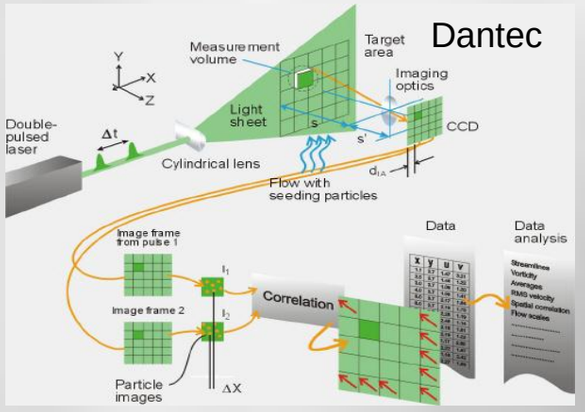

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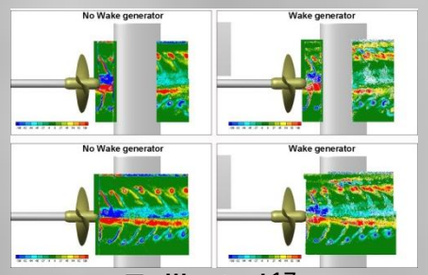

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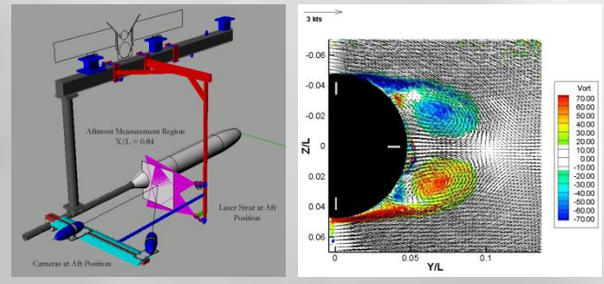

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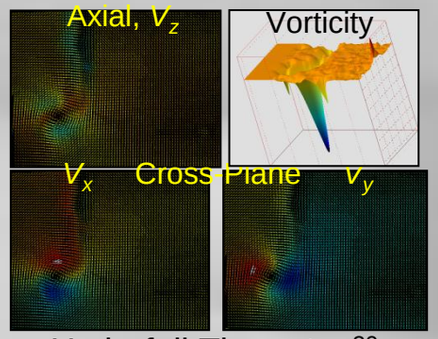

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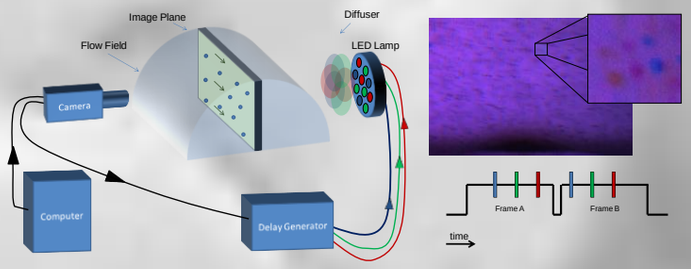
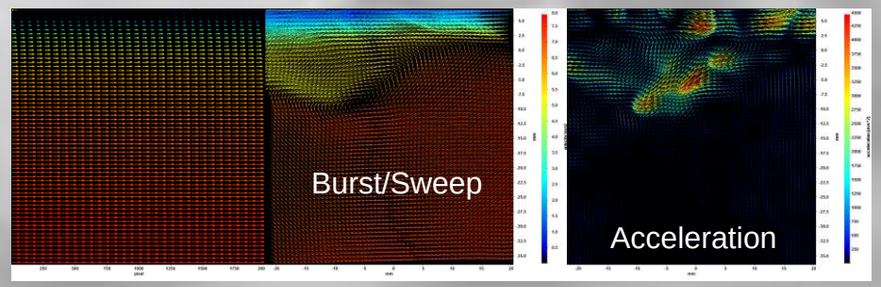
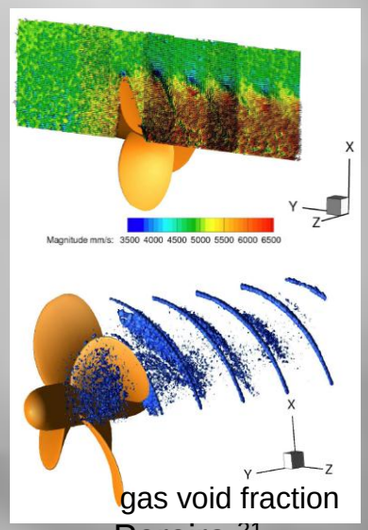




Dowell *et al*.[15]

DDPIV



Pereira,[21]

Instrumentation State of the Art
Pressure, Cavitation & Acoustics

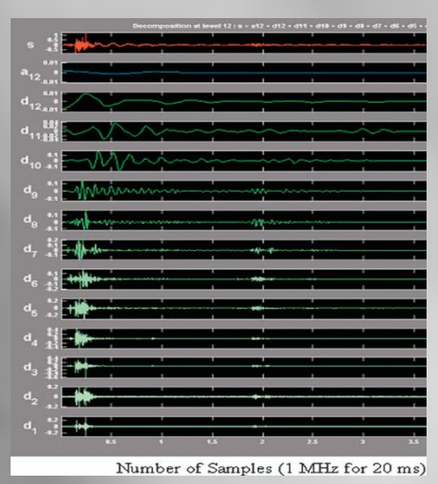
Pressure

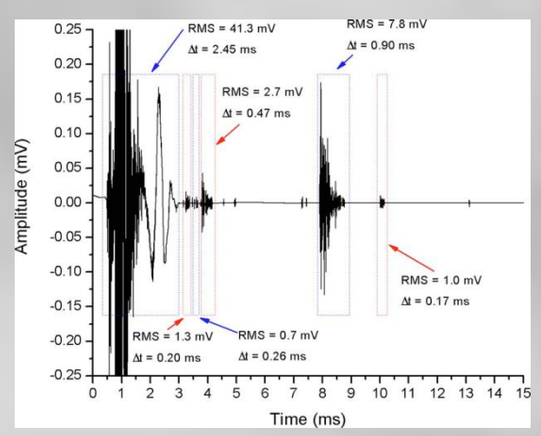
- Dynamic → Piezoelectric & Strain-gaged Bridge
  - Piezo: AC, high frequency, sensitive to vibration
  - Strain: DC to high frequency, vibration compensated.
  - Water-proofing ?

Cavitation

- Visual

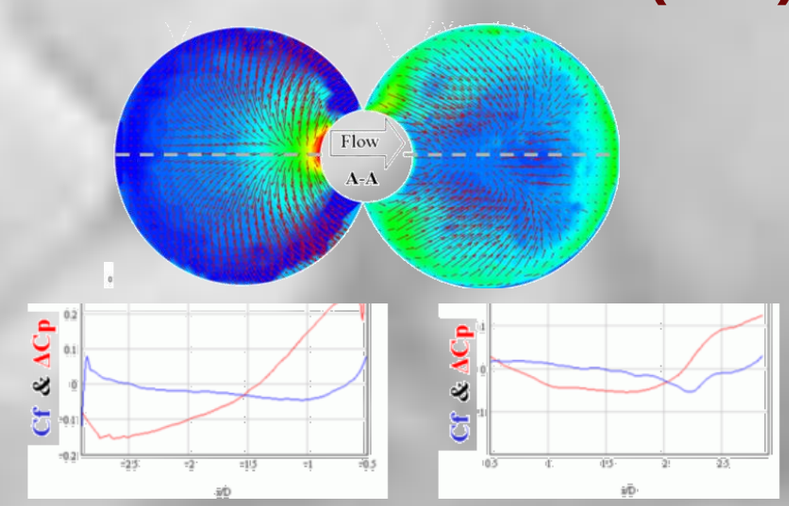
- Acoustic[22, 23] → hydrophone, Dynamic pressure and Accelerometer
  - **Wavelet analyses**





Wall Shear

- Mechanical balances
- Oil films
- Liquid crystals
- Thermal sensors
- Near-wall velocity sensors
- **Surface Stress Sensitive (S3F) films[24]**



Surface Wall Shear & Pressure Gradient

ISSI Inc.

Instrumentation State of the Art
Wave Height

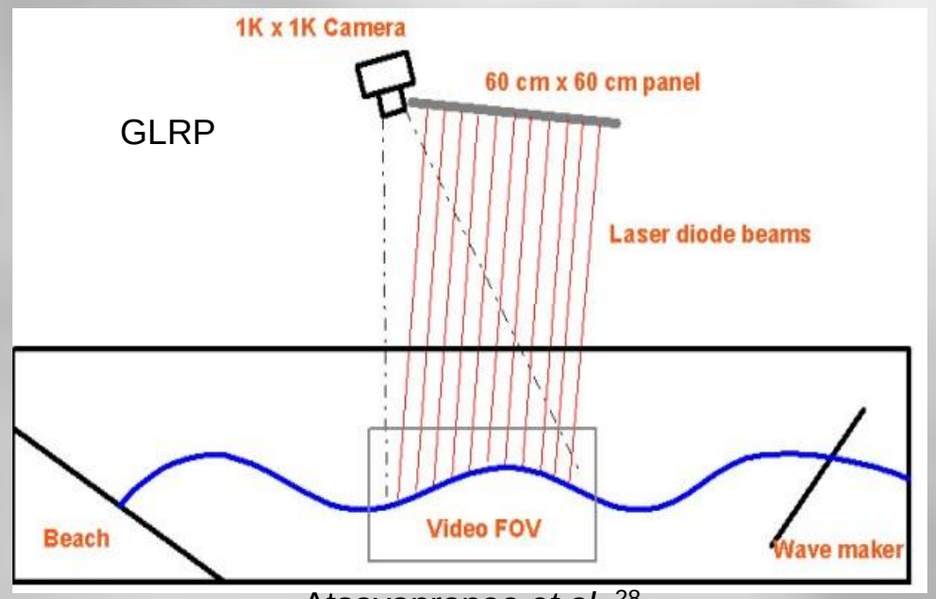
- Intrusive → Resistive, Servo and Capacitive Probes
  - Difficulties can include:
    - Meniscus reversal and wave scattering around probes
    - Fluid loading on probe – vibration
    - Air entrainment due to mean flow separation around probe
    - Non-linear behavior in shallow water
    - Drop-outs

- Non-Intrusive → Ultrasonic and Optical Systems
  - Ultrasonic – typically used in above wave application
    - Good accuracy relative to intrusive.
    - Performance gain with roughened surface increasing diffusive reflection
    - Drop-outs
  - Optical – Imaging based
    - *Automated Trinocular Stereo Imaging System (ATSIS)*- Wanek and Wu[25]
    - Grid projection techniques

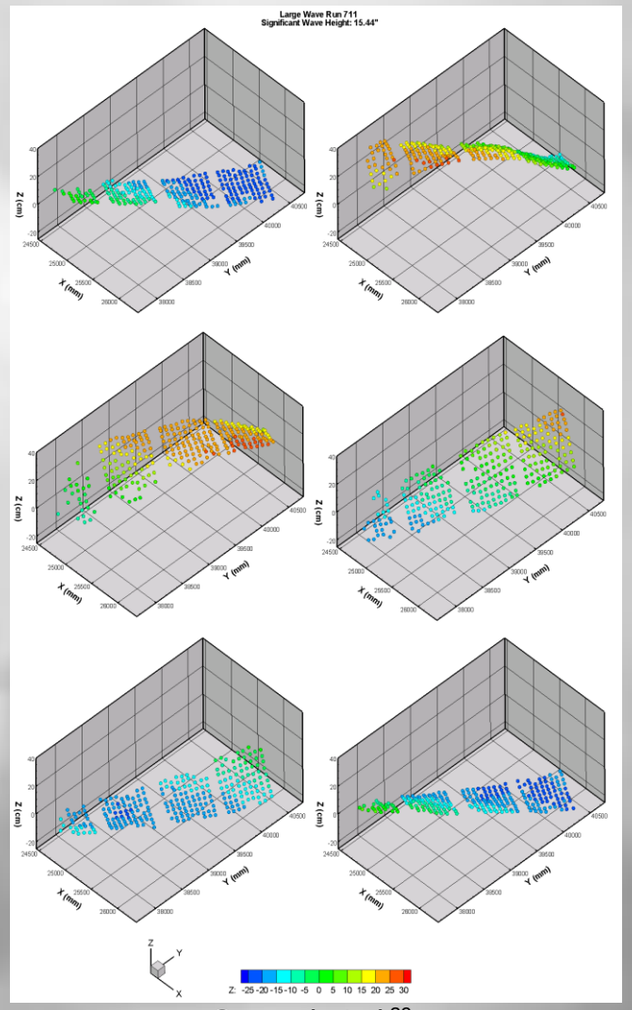
Zhao[26]

Instrumentation State of the Art
Wave Height

- Non-Intrusive → Ultrasonic and Optical Systems
  - Ultrasonic – typically used in above wave application
    - Bottom mounted systems – AWAC[27]
      - 3-beam ADCP with a 4th beam for water surface elevation
  - Optical – laser based
    - Global laser Rangefinder Profilometry (GLRP)[28] – point based
    - Laser light sheet based systems
  - Optical – Imaging based
    - Light Detection and Ranging Systems (LiDaR)[27]



Atsavapranee *et al.* [28]



Carneal *et al.*[29]

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