Calibrating cavitation sensors

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NPL Cavitation Roadmap

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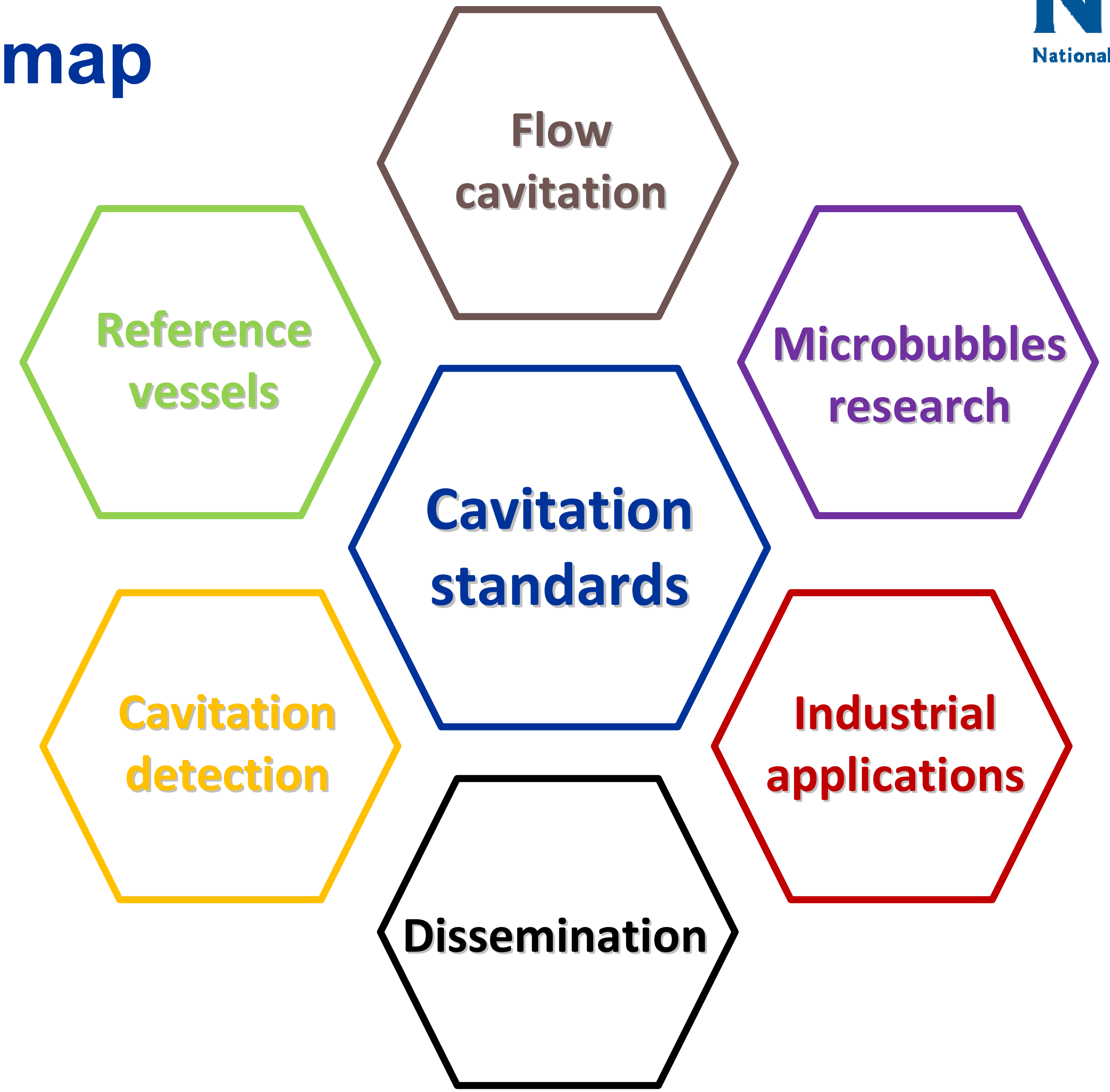

NPL Cavitation Roadmap

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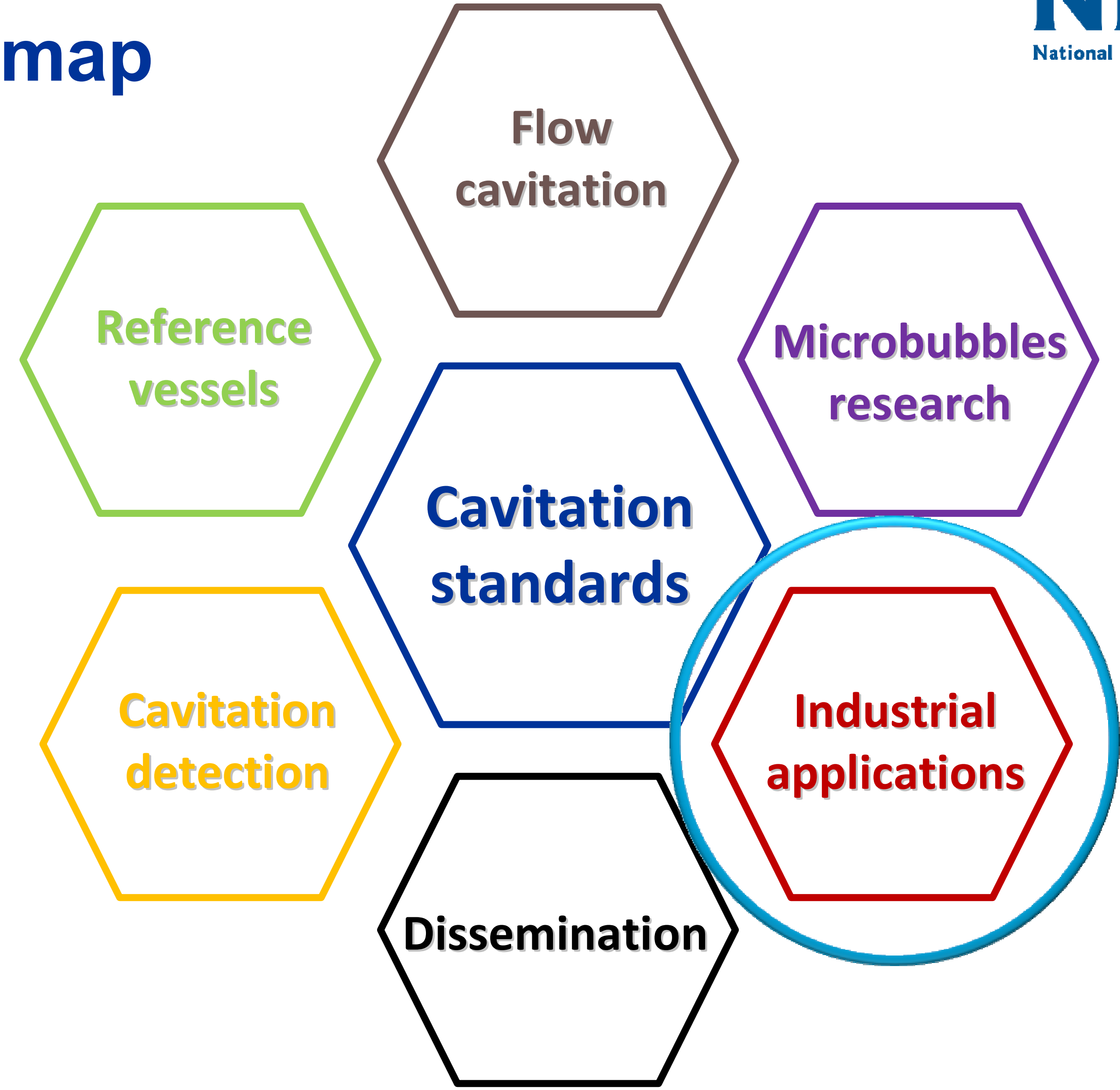


Why measure cavitation?

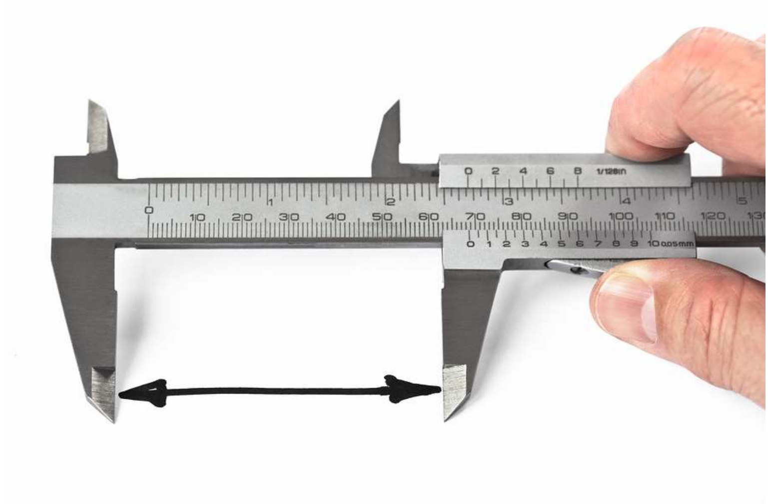
- To enable the application of cavitation technology on a robust metrological basis, by developing cavitating systems and sensors which enable the development, consensus and take up of standards (through IEC)

But then, why measure anything?

Magna Carta - 1215

“There is to be one measure of wine and ale and corn within the realm, namely the London quarter, and one breadth of cloth, and it is to be the same with weights.”

How can we measure cavitation?



- Sound
- Light
- Chemistry
- Damage

http://www.mondolithic.com/wp-content/uploads/2011/10/Focus-Italy_Cavitation-Bubble.jpg
http://leaderchat.files.wordpress.com/2013/12/bigstock-measurement-with-caliper-44942719.jpg

What's the best way to measure cavitation?

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There isn't one.

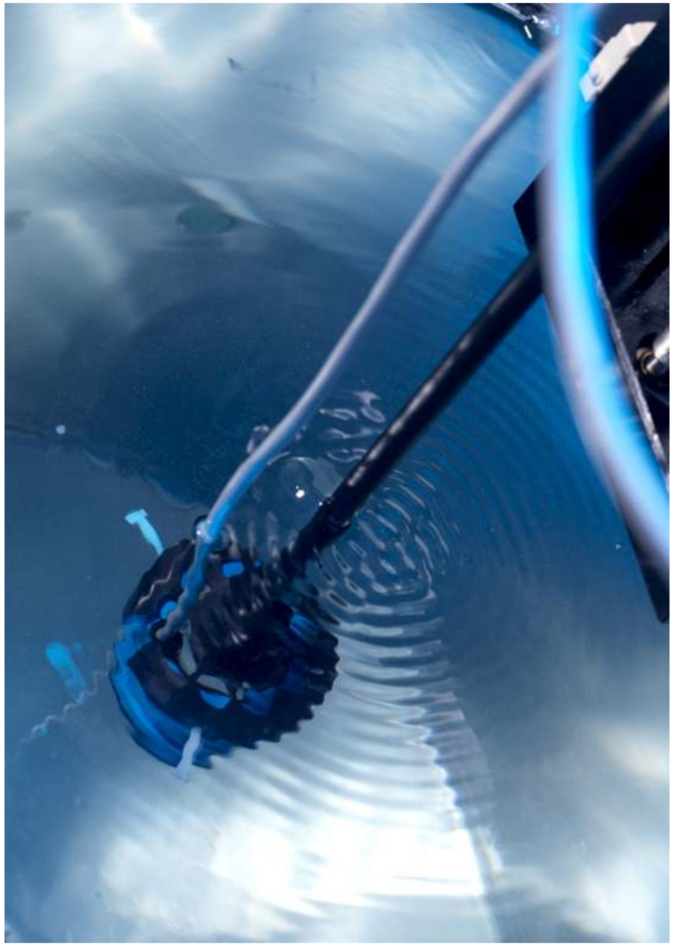
(yet)

www.lapetitebrique.com

What's the most versatile way to measure cavitation?

Acoustic emission, we think.

NPL CaviSensor



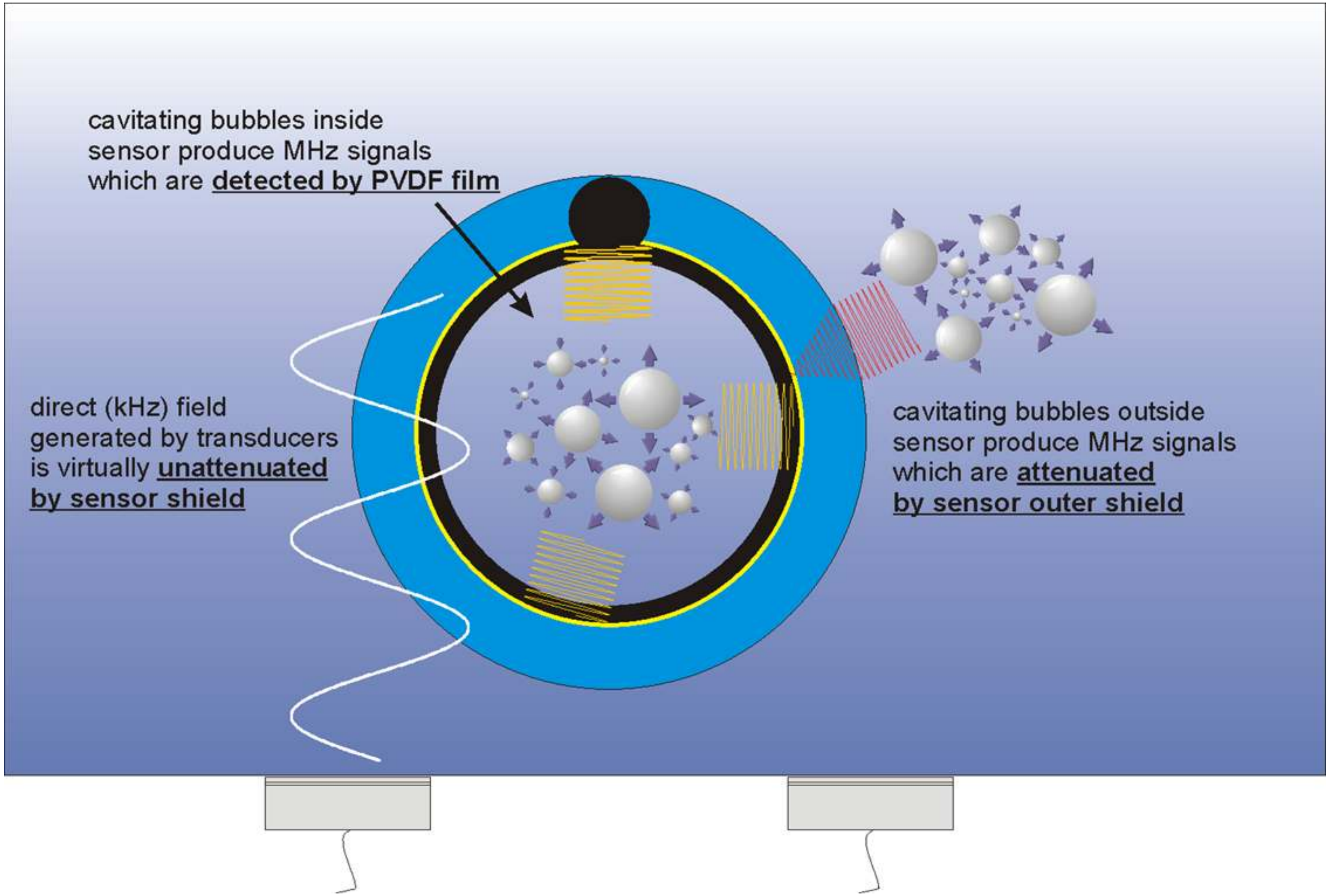
B Zeqiri, PN Gélat, M Hodnett, ND Lee. A novel sensor for monitoring acoustic cavitation. Part I: Concept, theory and prototype development. IEEE Trans. UFFC, 50, October 2003, 1342 – 1350

NPL CaviMeter

- Two signal processing channels
  - peak notch detection up to 130 kHz
  - broadband integration from 1.5 to 7 MHz
- Enables discrimination of driving field and resulting inertial cavitation
- Broadband acoustic emission demonstrated to correlate with erosion

M Hodnett and B Zeqiri. Towards a reference ultrasonic cavitation vessel. Part 2 - Investigating the spatial variation and acoustic pressure threshold of inertial cavitation in a 25 kHz ultrasound field IEEE Trans. UFFC 55, pp 1809-1822 (2008)

Cavitation sensor concept



Cavitation sensors

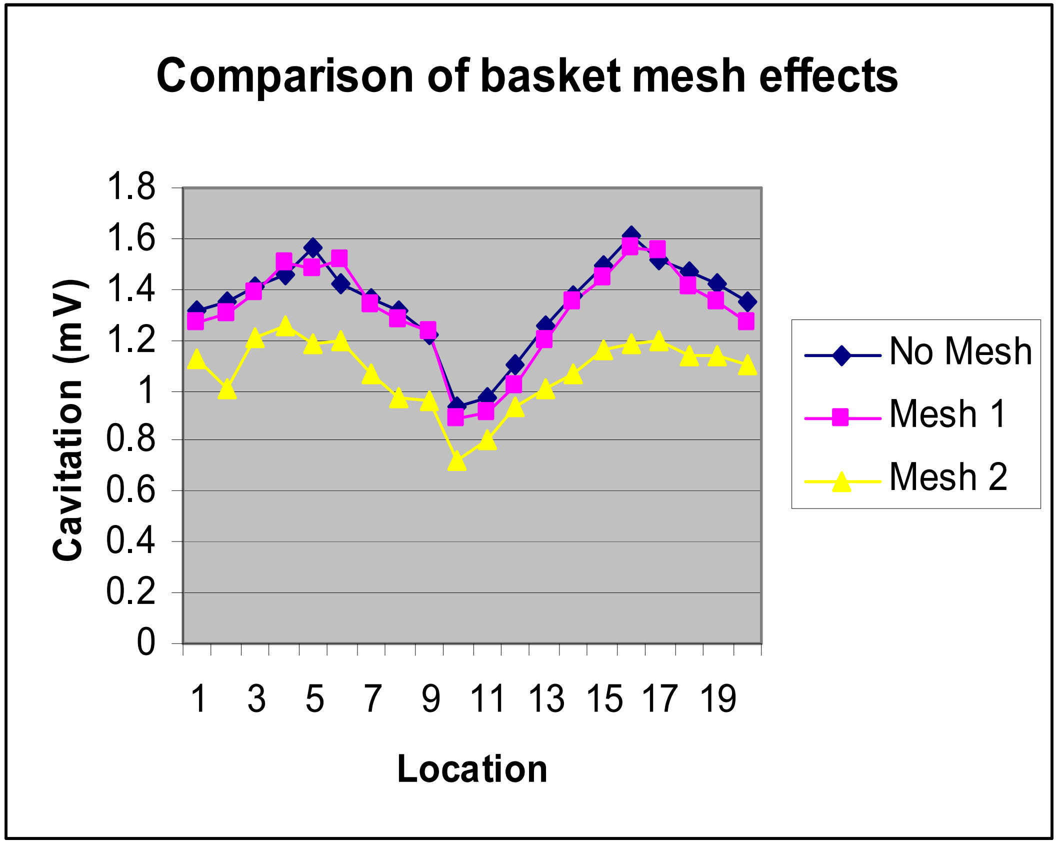
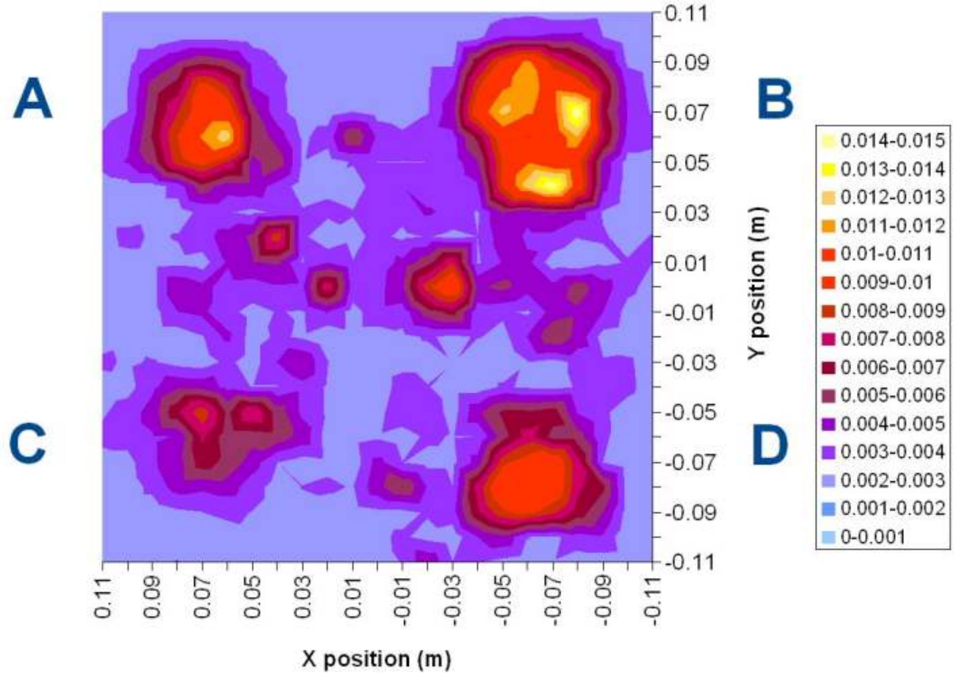
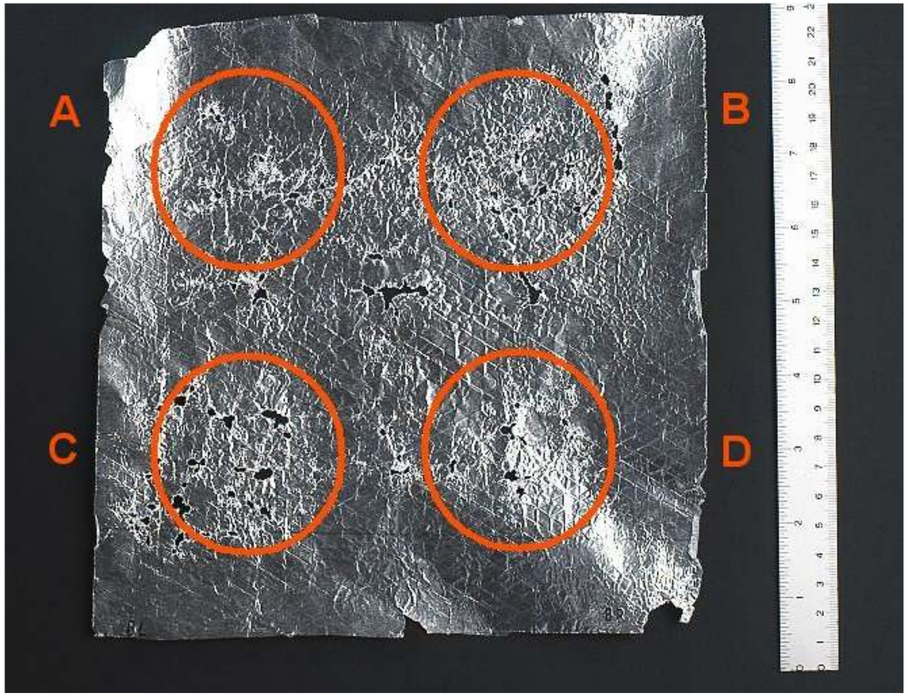


Figure (3): Effect of wire baskets on inertial cavitation.

Broadband acoustic emission vs erosion





B Zeqiri, M Hodnett & A Carroll, Studies of a novel sensor for assessing the spatial distribution of cavitation activity within ultrasonic cleaning vessels. Ultrasonics, Vol.44, January 2006, 73-82.

Motivation

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- To write standards within international frameworks, we need to have calibrated sensors, and make measurements which are traceable to accepted quantities

➢ The acoustic Pascal

Motivation

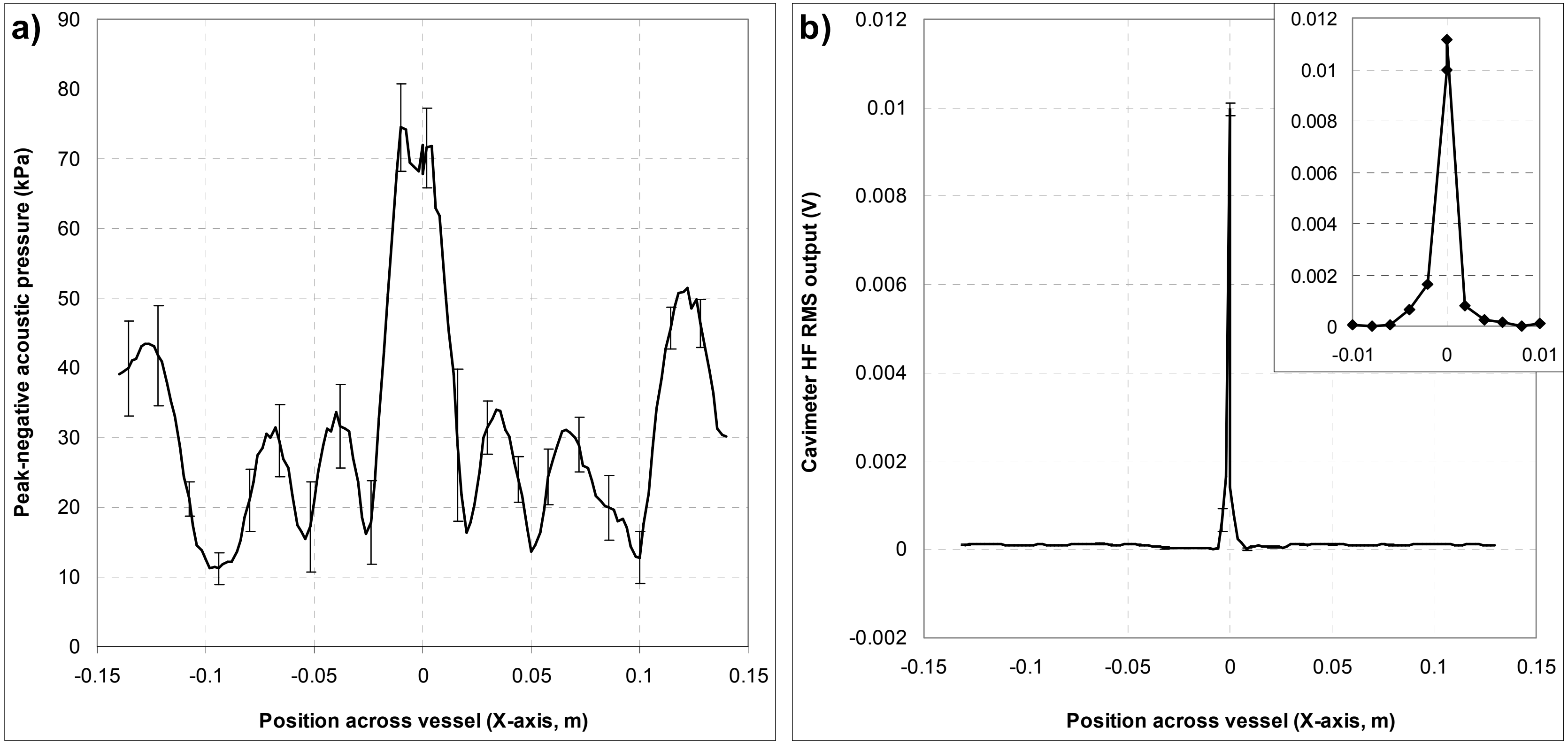
- This is already carried out at the kHz frequencies typical of ultrasonic cleaners and processors, and can give absolute acoustic pressures of the driving field

Reson TC4038

Brüel and Kjær 8103

Motivation

- But measuring acoustic emissions from inertial cavitation requires sensors that can perform at, and be calibrated at, MHz frequencies



Goal

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- Design a method to generate a stable, repeatable source of signals representative of inertial cavitation emissions, and calibrate the CaviSensor as a cavitation measurement device

SIGNAL SOURCE DESIGN

Design concept

- Previous theoretical modelling of the CaviSensor has shown it responds to in-phase arrivals of acoustic signals occurring along its axis, with a frequency-dependent radius of around 3mm
- Considering the typical frequencies detected from inertial cavitation emissions during measurements of ultrasonic cleaners/processors, select a mid-range value of 2.5 MHz
- Design and manufacture an approximately 6mm diameter cylindrical transducer, to be positioned within the cavitation sensor, to generate a planar (non-cavitating) field

Transducer considerations

- CaviSensors range in height from 6 – 24 mm (active element size)
- Manufacturing challenges in manufacturing ceramic piezoelectric elements exceeding a 1:1 aspect ratio at MHz frequencies
- Multi-element design, built up from 6mm high units: two devices made (2x and 5x)

Two-element transducer

- ABS casing, epoxy-backed, internal matching network
- Overall casing height 35 mm, 8 mm diameter
- MCX connector to a base support
- Can be driven (short burst mode) up to 100Vp-p, with a peak response at 2.45 MHz

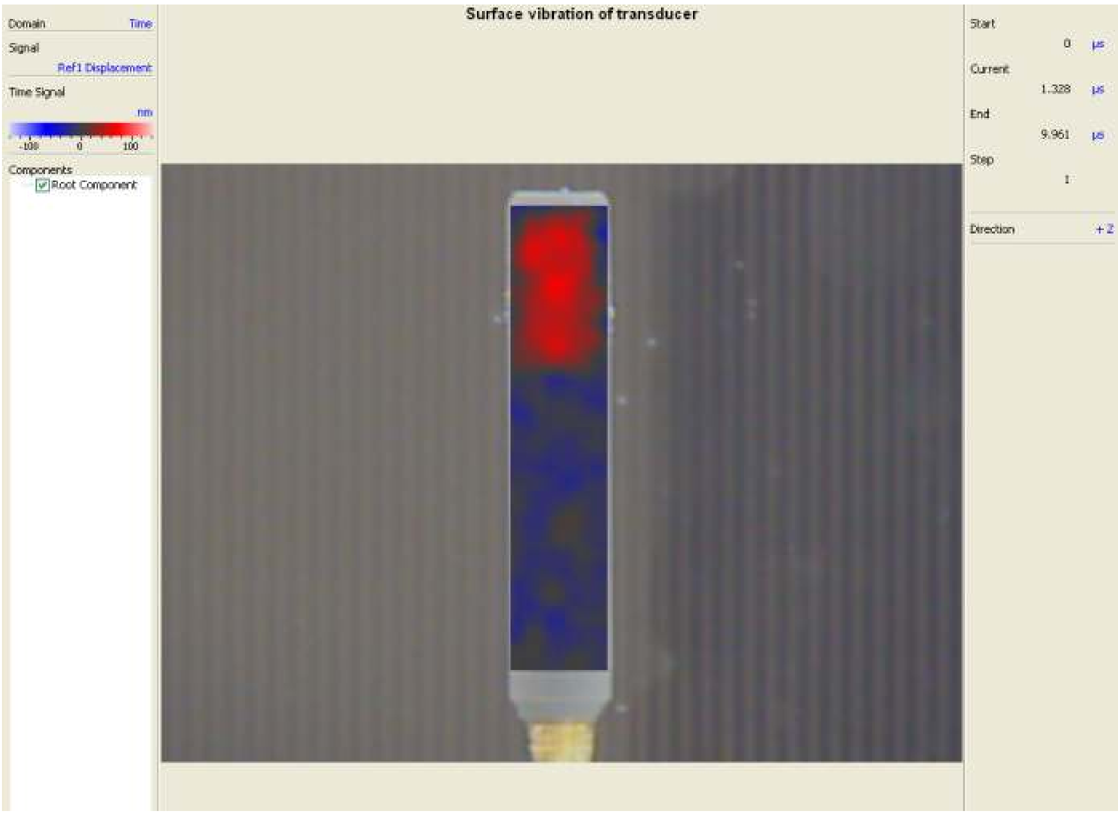
TRANSDUCER MEASUREMENTS

Beam characterisation tests (1/4)

- Objective of design was to have a cylindrical wavefront as uniform as possible over the transducer height, to generate an in-phase signal

➢ *Surface vibration characterised using a Polytec PSV-400 scanning laser vibrometer*

➢ *Some suggestion of the two elements, but uniformity looks promising*

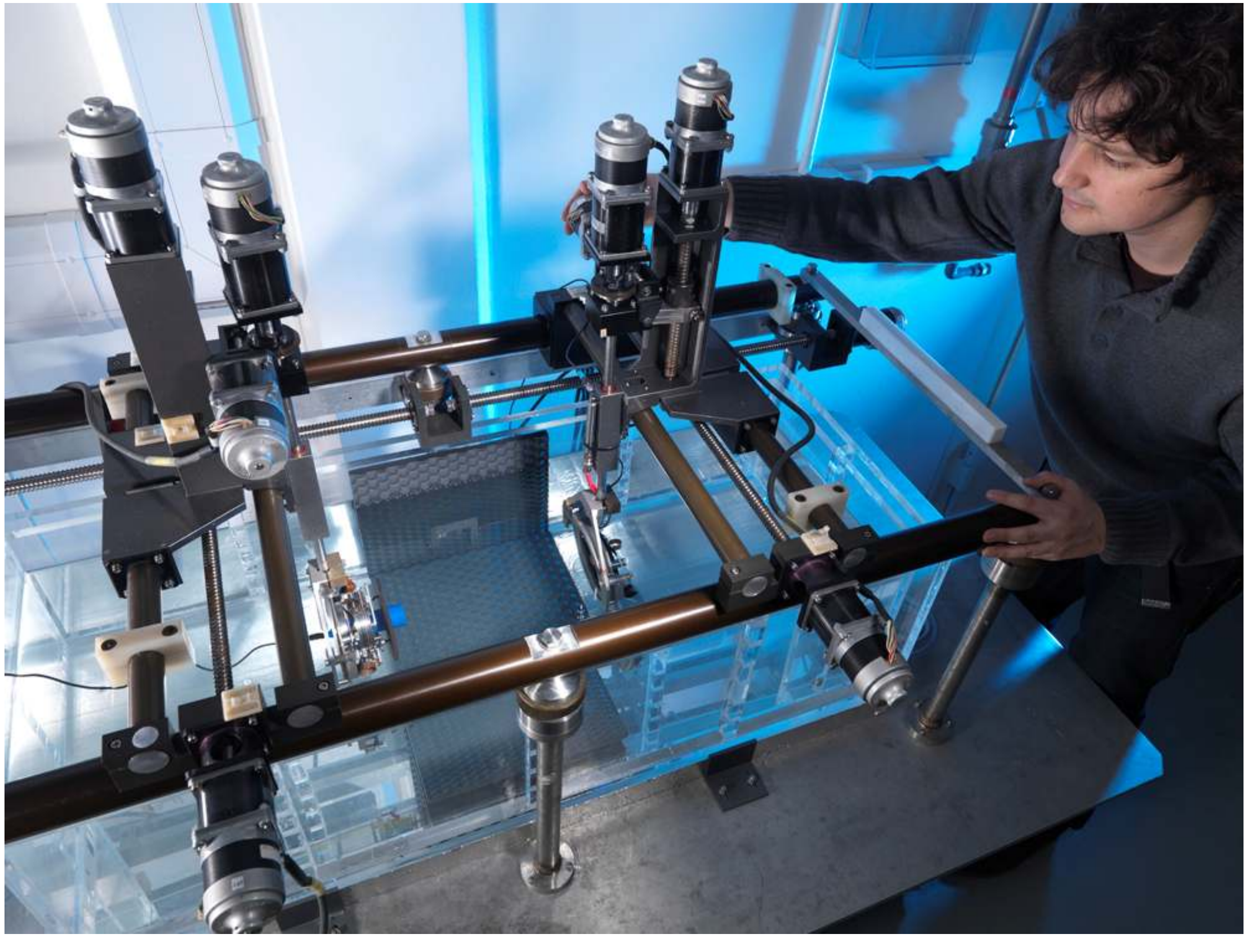


Beam characterisation tests (2/4)

- Calibration of the CaviSensor requires derivation of its sensitivity in terms of V/Pa
- So, use a conventional hydrophone to characterise the acoustic pressure distribution at the distance corresponding to the position of the CaviSensor receiving element (11 mm stand-off)

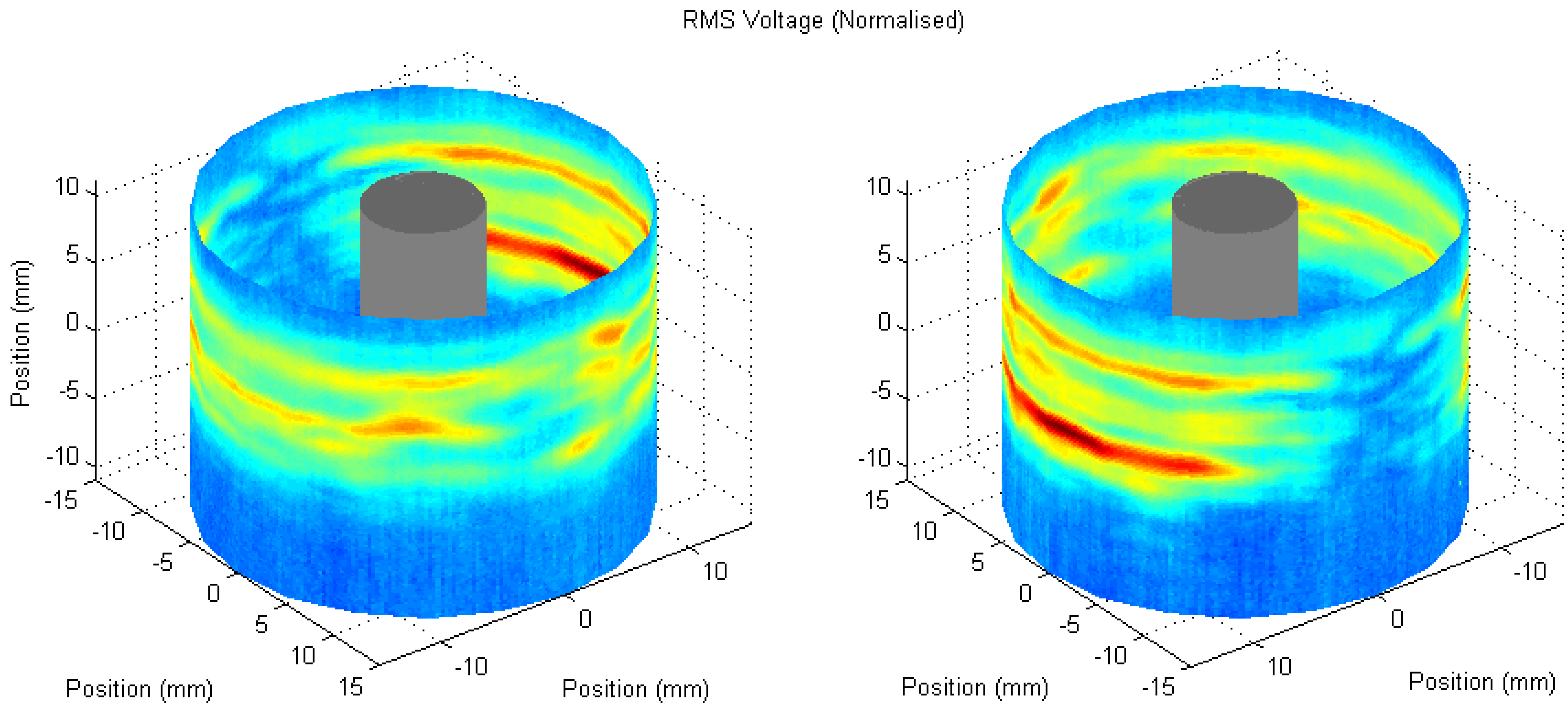
➢ NPL Beam-Plotting Facility

Beam characterisation tests (3/4)



- Onda GL0200 hydrophone and preamplifier, located at 11mm separation from vertically-mounted transducer
- Line scans along transducer axis
- 1 degree rotational steps
- ➢ Map of acoustic pressure over conceptual cylindrical surface

Beam characterisation tests (4/4)



- Shows active region of transducer, and also the complex structure within near field

Sensor measurements (1/2)

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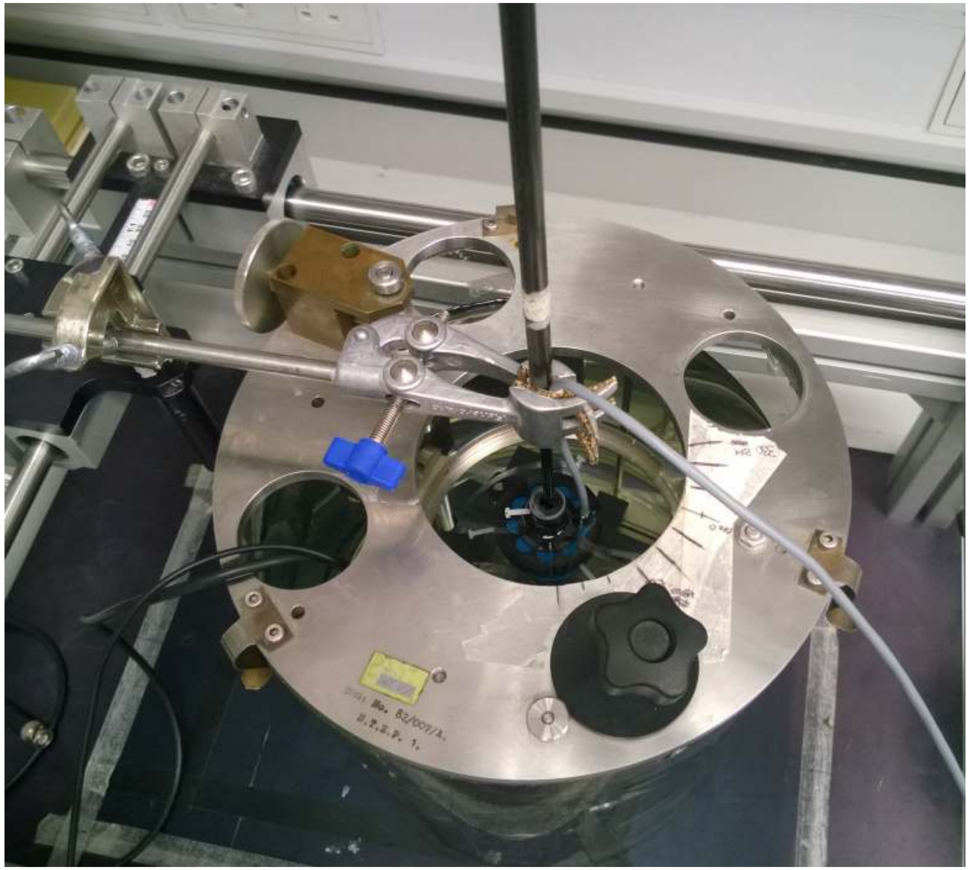
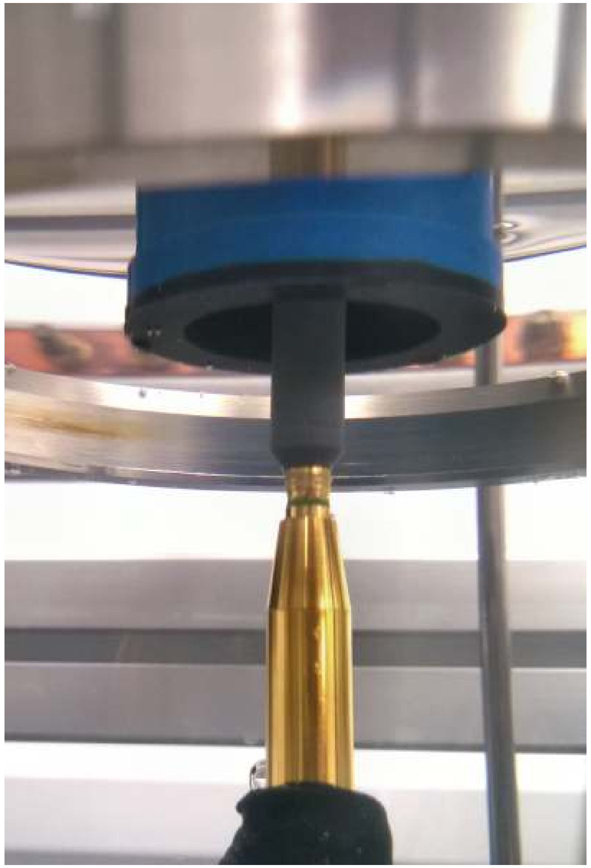
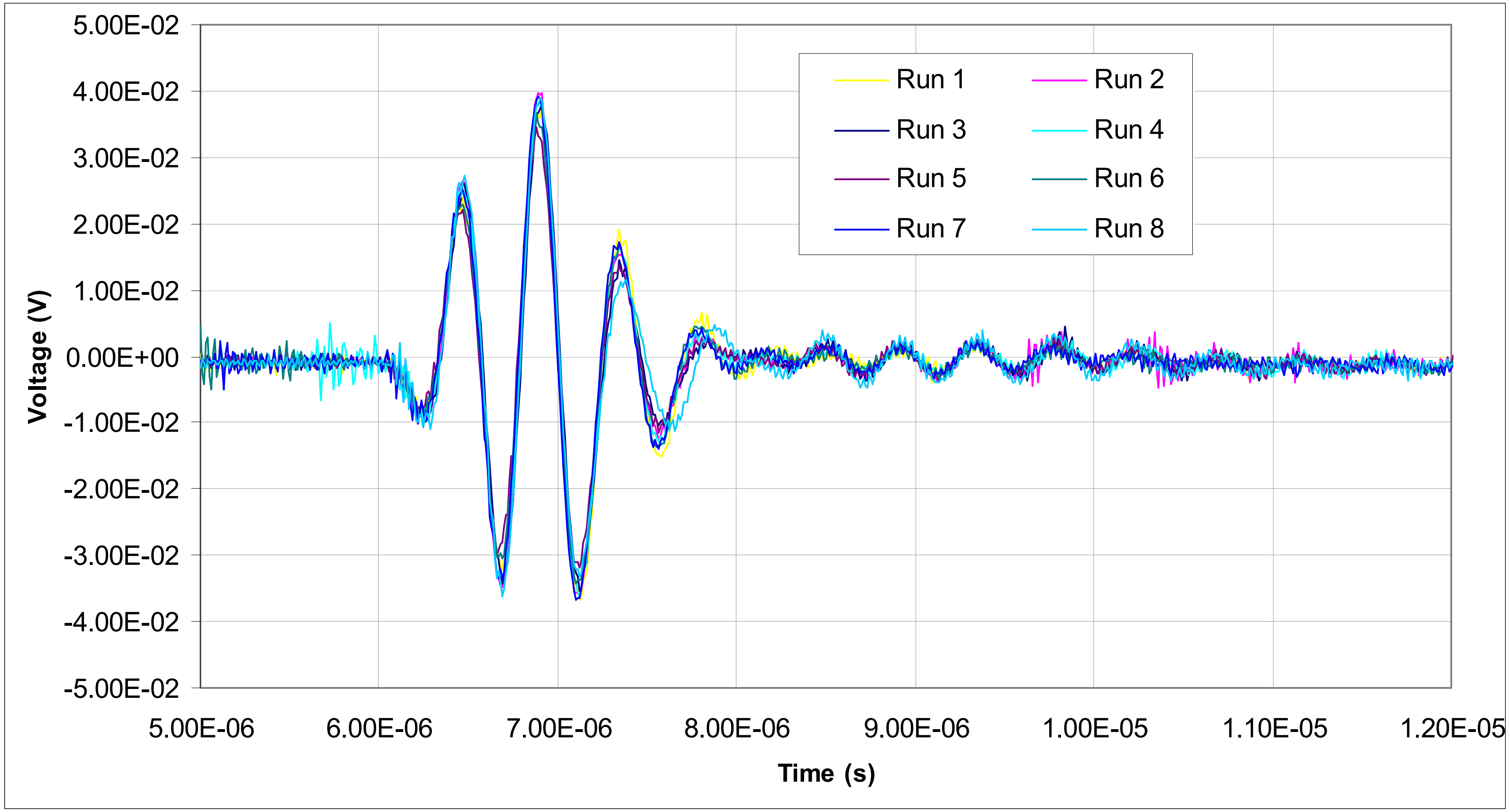
- Using the same transducer excitation conditions as used for the beam profiling measurements, measure the CaviSensor output





Sensor measurements (2/2)



- Sensor rotated at 45º steps, two complete rotations
- 10 $V_{p\text{-}p}$, 2 cycles, 2.45 MHz, 1 ms repetition period

Measurement system calibration

- HF channel of CaviMeter is an RMS value (integrated over the range 1.5 – 7 MHz)
- With CaviSensor connected to CaviMeter (at specific gain settings), and the cylindrical transducer co-aligned, compare average RMS pressure values determined from beam plotting measurements, with displayed CaviMeter values
- System sensitivity = **19 mV/Pa @ 2.45 MHz**

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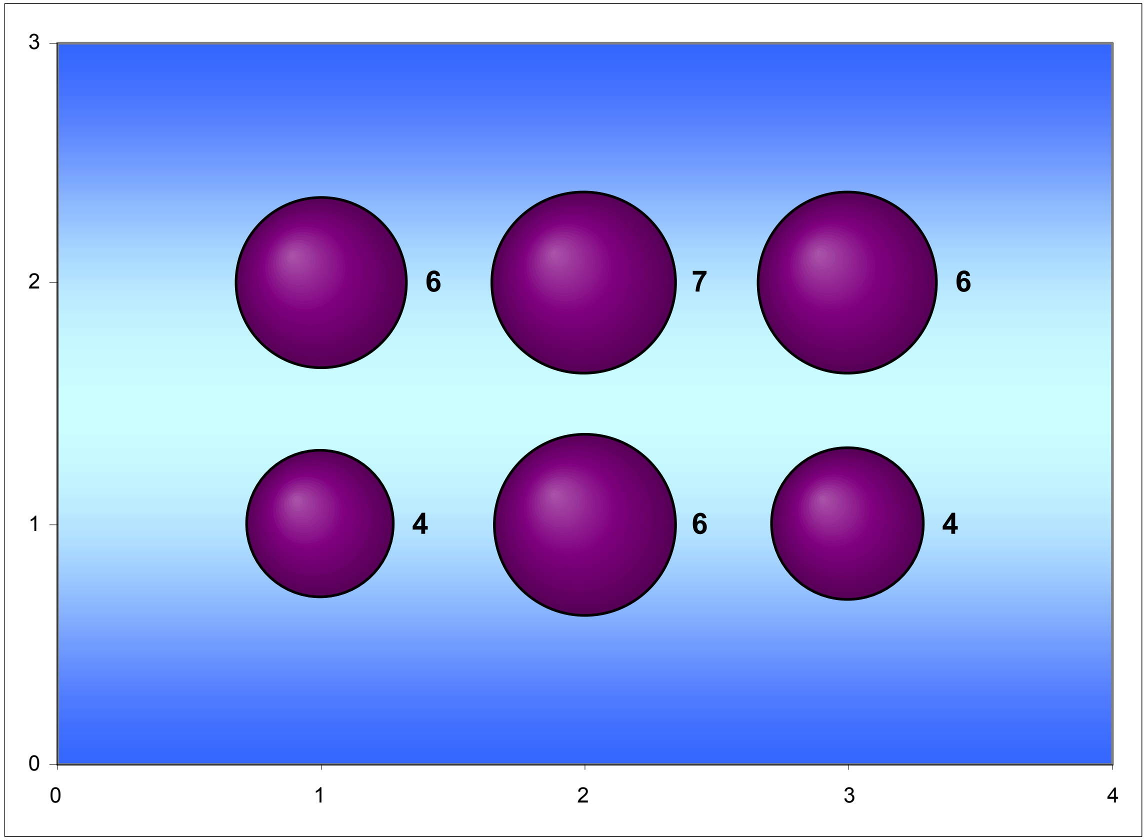
CAVITATION MEASUREMENTS

Cleaning vessel measurements (1/2)

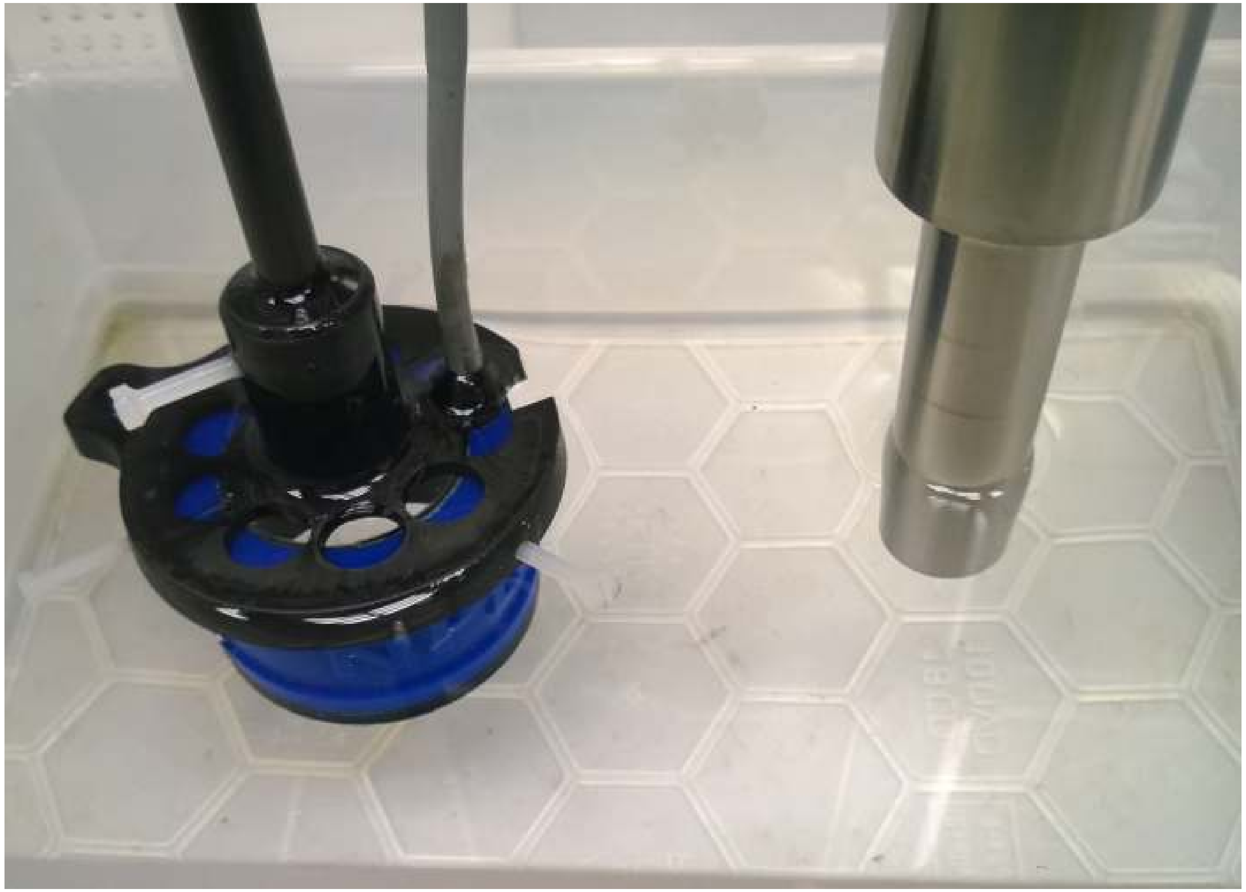
- Ultrawave 36 kHz six-transducer bath
- Fixed output
- Calibrated sensor located 4 cm from base, each transducer measured, four repeats on each

Cleaning vessel measurements (2/2)



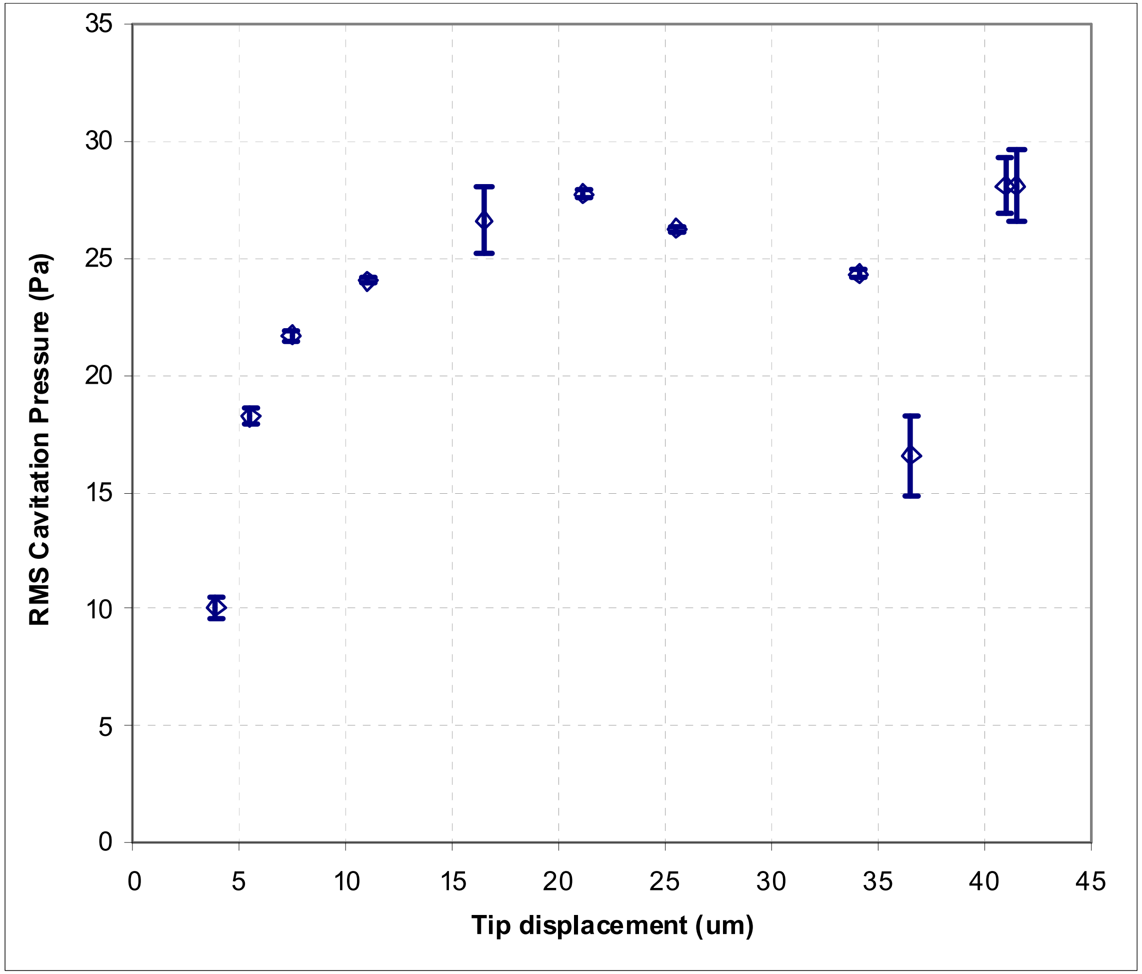
Transducer	RMS cavitation pressure
1	6 Pa ± 2%
2	7 Pa ± 16%
3	6 Pa ± 10%
4	4 Pa ± 3%
5	6 Pa ± 5%
6	4 Pa ± 3%

Sonotrode measurements (1/2)



- Sonic Systems P100, 20 kHz, with 12.7 mm diameter tip horn
- CaviSensor placed 8 cm adjacent, in a 3 litre rectangular water tank

Sonotrode measurements (2/2)



- Strong nonlinearity with increasing TD, due to local bubble shielding restricting effective acoustic transmission into fluid volume
- Error bars are Type A (random) evaluations
- Would expect measurements to increase by at least a factor of 4 for sensor directly beneath tip

Summary and conclusions

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- We've designed, built and characterised a bespoke cylindrical transducer, operating at low MHz frequencies under linear conditions
- We've used it to test the response of our CaviSensor and CaviMeter
- We now have a spatially-sensitive cavitation sensor that determines the average RMS acoustic pressures emitted by multi-bubble inertial cavitation
- We've measured a cleaner and a sonotrode, and shown the latter generates RMS cavitation pressures around a factor of 4 higher

We’re not there quite yet….

- ‘First approximation’ calibration, as it so far doesn’t account for:
  - Variation in the measured acoustic field over the conceptual cylinder, which itself includes a fundamental difference in the directionality of the hydrophone vs CaviSensor
  - Variation in the inherent CaviSensor film sensitivity over its surface
  - Variation in the CaviSensor frequency response over the 1.5 – 7 MHz band, although this is small, and believed to be less than 10%

Next steps

- Theoretical modelling: spatial and temporal deconvolution of respective sensor responses
- Improvements to cylindrical transducer, possibly moving to a bespoke piezocomposite device with better uniformity and a higher power output
- Discussing findings within IEC TC 87 WG3 (High Power Transducers) to supplement current work on ultrasonic cleaner characterisation

Acknowledgements

- The authors acknowledge the financial and technical support of:
  - The UK National Measurement System (DBIS)
  - NPL Strategic Research

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Thank you!