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Non-contact acoustic characterisation of the dynamic patterns at the free surface of shallow turbulent flows

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Remote monitoring of shallow turbulent flows

Remote measurements:

- Lower cost.
- Safer access.
- Less risk of fouling.
- Reliability?

Free surface patterns in shallow flows


(Brocchini and Peregrine, 2001 JFM)


(Chanson, 2000 WRR)

- Turbulent 'boils'.
- Gravity-capillary waves.

Surface patterns

Effects of surface waves on unseeded LSPIV

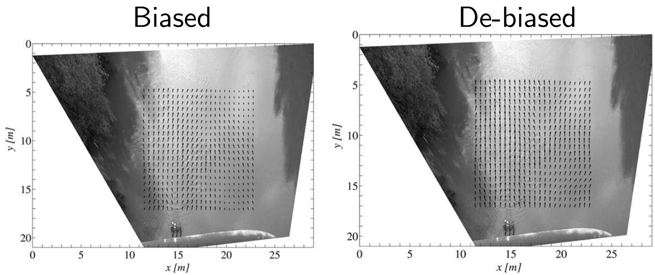


Fig. 11 Experiment 3: surface velocity field averaged over 40 s obtained applying standard unseeded LSPIV without clustering and correction (*left panel*), and applying clustering-correction unseeded LSPIV (*right panel*)

(Benetazzo *et al.*, 2017 RFAL)

Effects of surface waves on unseeded LSPIV

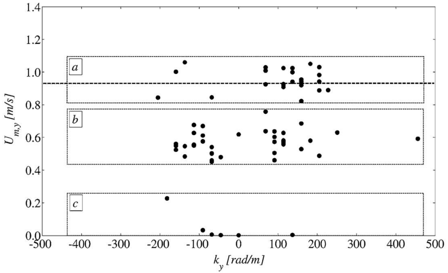
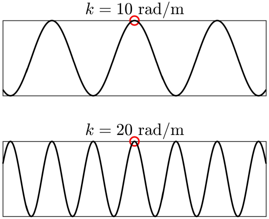


Fig. 5 Results of unseeded LSPIV. Example (*black dots*) of stream-

- $30 - 40\%$ error in low flow conditions.
- Generally underestimation caused by upstream-propagating waves.
- Affects the average velocity.

(Benetazzo *et al.*, 2017 RFAL)

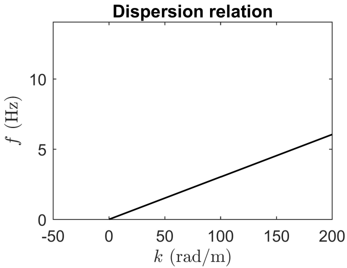
Dispersion relations



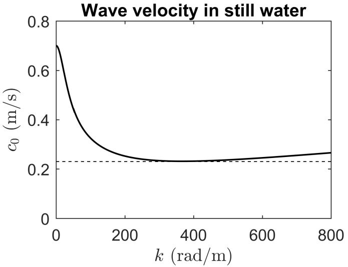
Wavenumber: $k = 2\pi/\lambda$
Frequency: $f = kc/2\pi$

Mean surface velocity: U_0

Non-dispersive waves:
$c = U_0$



Downstream gravity-capillary waves

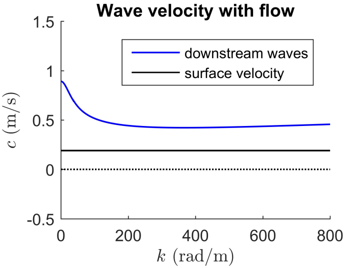


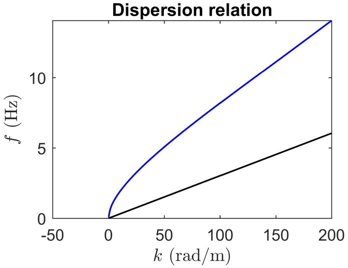
Non-dispersive waves:

$$c = U_0$$

Downstream G-CW

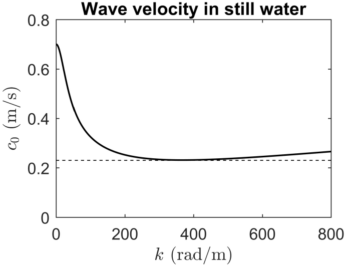
$$c \approx U_0 + c_0$$





Upstream gravity-capillary waves

$$U_0 < c_0 \approx 0.23 \text{ m/s}$$



Non-dispersive waves:

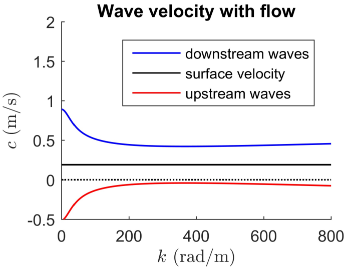
$$c = U_0$$

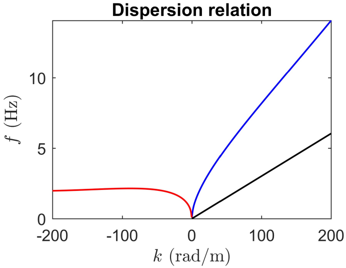
Downstream G-CW:

$$c \approx U_0 + c_0$$

Upstream G-CW:

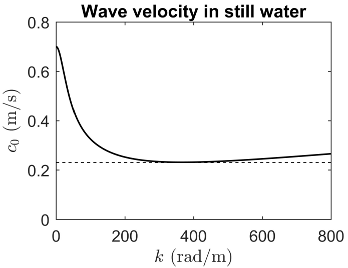
$$c \approx U_0 - c_0$$





Upstream gravity-capillary waves

$$U_0 > c_0 \approx 0.23 \text{ m/s}$$



Non-dispersive waves:

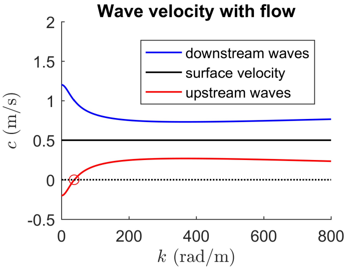
$$c = U_0$$

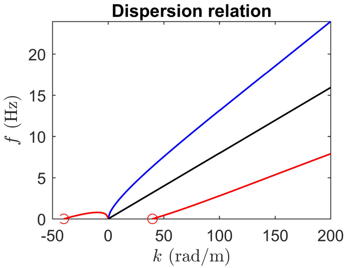
Downstream G-CW:

$$c \approx U_0 + c_0$$

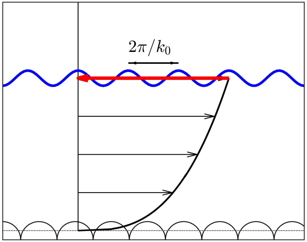
Upstream G-CW:

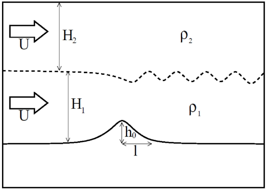
$$c \approx U_0 - c_0$$





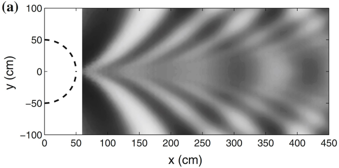
Stationary waves





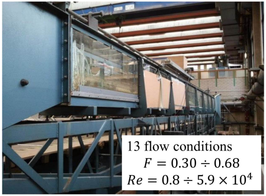
(Teixeira *et al.*, 2017 JAtSc)

Isolated bed topography



(Lacaze *et al.*, 2013 ExpF)

Experiments in a laboratory flume



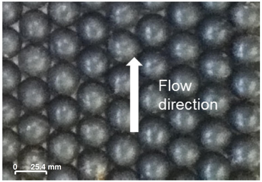
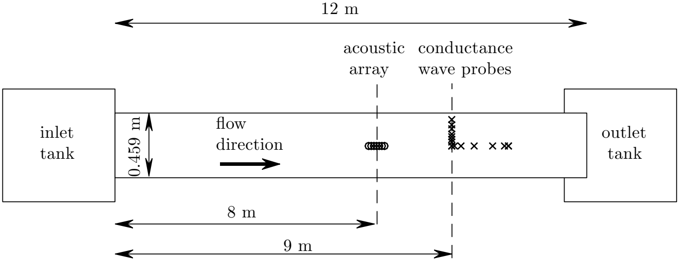
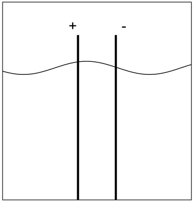


Figure 4.2: A photograph of the flume bed.

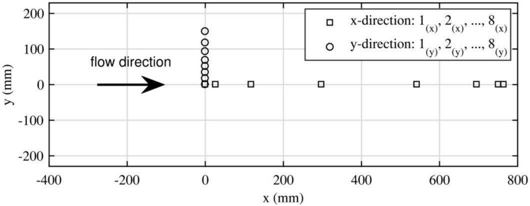


Analysis procedure

conductance wave probe



arrays of probes



- Two arrays of conductance wave probes.
- Space-time Fourier transform:

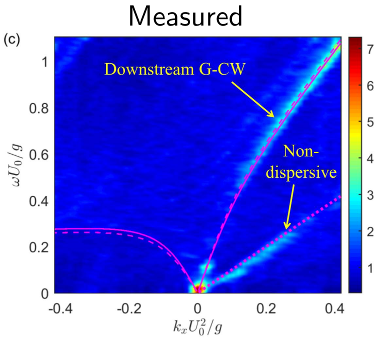
$$S(k,f) = \int\int < z(x,t) z(x+r, t+\tau) > e^{\mathrm{i}(kr - 2\pi f \tau)} dr d\tau$$

- Sinc-based reconstruction for non-equidistant arrays.

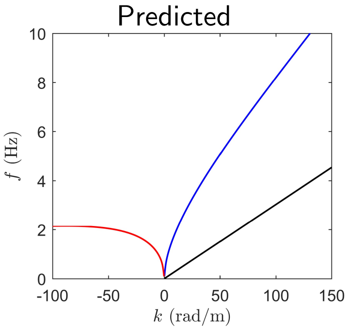
(Dolcetti *et al.*, 2016 PoF)

$U_0 < 0.23$ m/s

Streamwise frequency-wavenumber spectrum



(Dolcetti *et al.*, 2016 PoF)

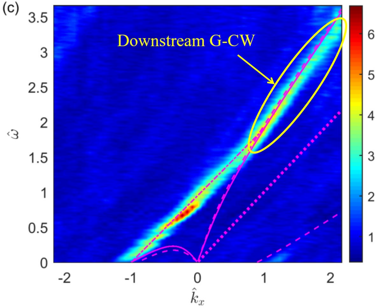


- Downstream G-CW.
- Non-dispersive waves (turbulence-generated?).

$U_0 > 0.23$ m/s

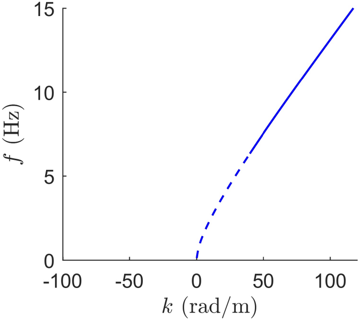
Streamwise frequency-wavenumber spectrum

Measured



(Dolcetti *et al.*, 2016 PoF)

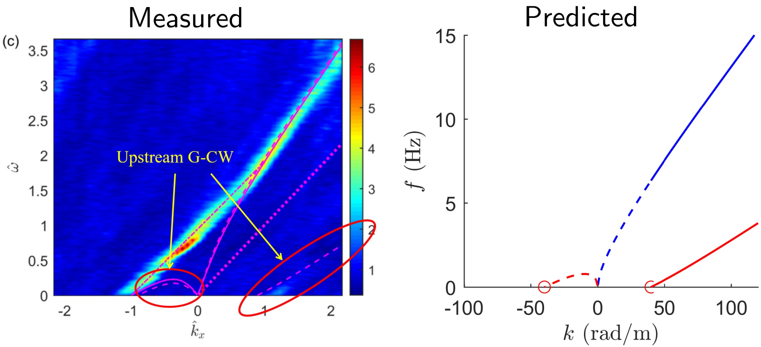
Predicted



- Downstream G-CW.

$U_0 > 0.23$ m/s

Streamwise frequency-wavenumber spectrum



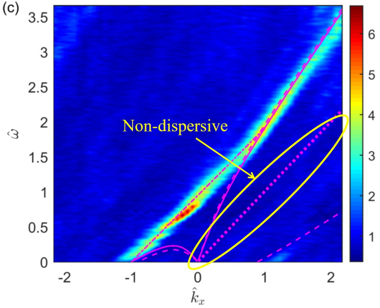
(Dolcetti *et al.*, 2016 PoF)

- Downstream G-CW.
- Upstream G-CW.

$U_0 > 0.23$ m/s

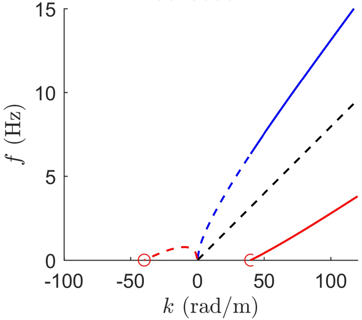
Streamwise frequency-wavenumber spectrum

Measured



(Dolcetti *et al.*, 2016 PoF)

Predicted

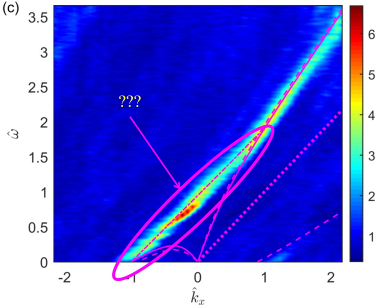


- Downstream G-CW.
- Upstream G-CW.
- Only dispersive G-CW.

$U_0 > 0.23$ m/s

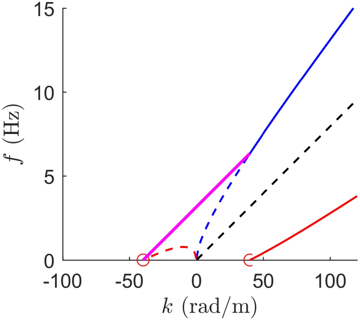
Streamwise frequency-wavenumber spectrum

Measured



(Dolcetti *et al.*, 2016 PoF)

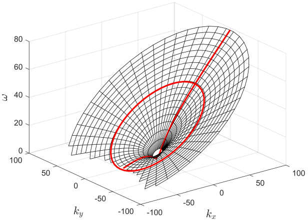
Predicted



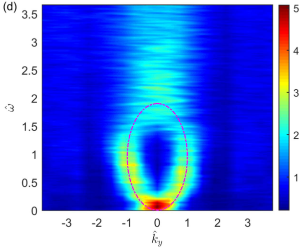
- Downstream G-CW.
- Upstream G-CW.
- Only dispersive G-CW.

Three-dimensional patterns

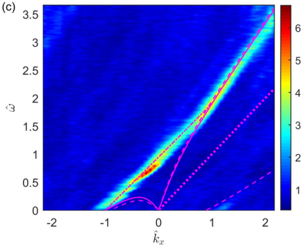
3-D dispersion shell



Transverse spectrum

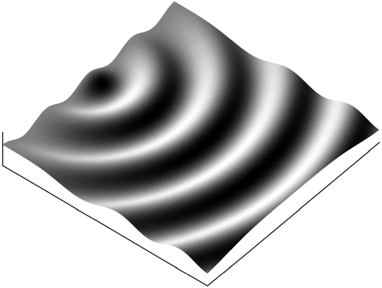


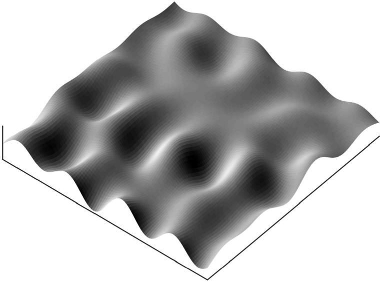
Streamwise spectrum



- Waves in all directions with same wavenumber k_0.
- Stationary waves dominate the pattern.

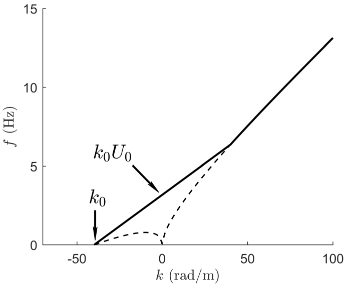
Radial pattern of waves





Relation with the flow quantities

- Characteristic spatial scale: $2\pi/k_0$.
- Characteristic temporal scale: $k_0 U_0$.



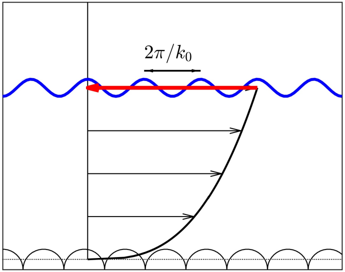
Irrotational flow:

$$k_0 U_0 = \sqrt{\left(g + \frac{\gamma}{\rho} k_0^2\right) k_0 \tanh(k_0 H)}$$

k_0: wavenumber of stationary waves
H: mean depth
U_0: mean surface velocity
γ: surface tension
ρ: density

Relation with the flow quantities

- Characteristic spatial scale: $2\pi/k_0$.
- Characteristic temporal scale: $k_0 U_0$.



$$U(z) = U_0(z/H)^n$$

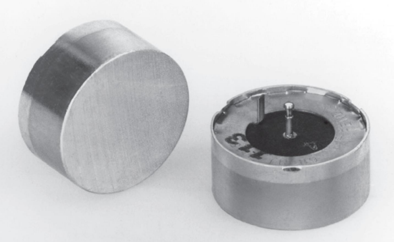
Power function profile:

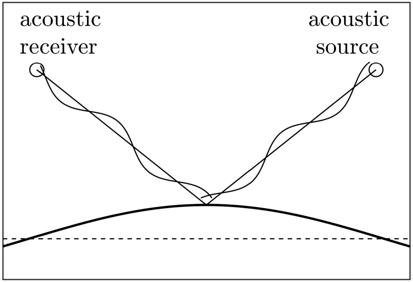
$$k_0 \frac{I_{-1/2-n}(k_0 H)}{I_{1/2-n}(k_0 H)} = \frac{g + \frac{\gamma}{\rho} k_0^2}{U_0^2}$$

k_0: wavenumber of stationary waves
H: mean depth
U_0: mean surface velocity
γ: surface tension
ρ: density

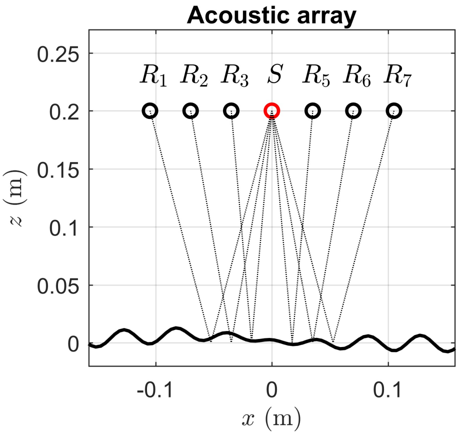
(Burns, 1953 MPCam; Fenton, 1976 IMA JAM)

Acoustic measurements - basic principle





Acoustic measurements - array of sensors

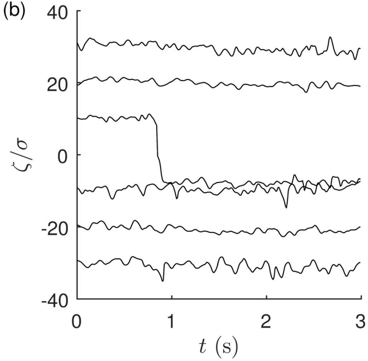


- 1 Source.
- 6 Receivers.
- Horiz. resolution 17.5 mm.
- Max. wavelength 105 mm.

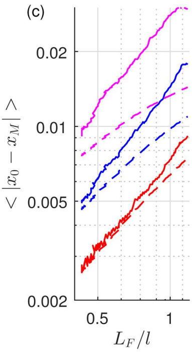
$$\zeta(x_i, t) \rightarrow S(k, f)$$
$$= \int\int < z(x_i, t) z(x_j, t + \tau) > e^{-\mathrm{i}(kr_{ij} - 2\pi f \tau)} dr d\tau$$

Acoustic measurements - accuracy of the reconstruction

Failure of reconstruction



Reconstruction error



Limited range of flow conditions

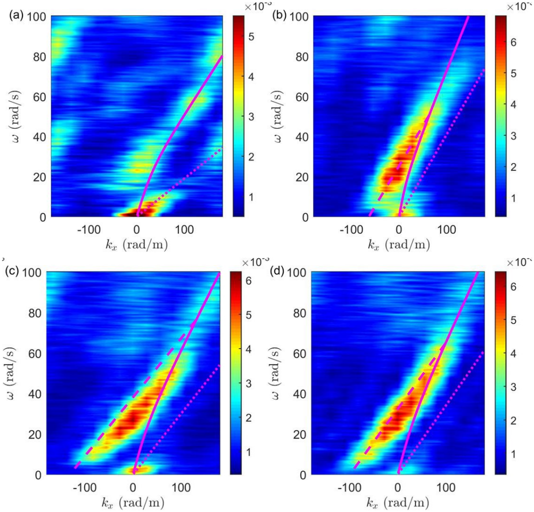
$F = 0.30 - 0.52$

$\sigma = 0.05 - 2.05$ mm

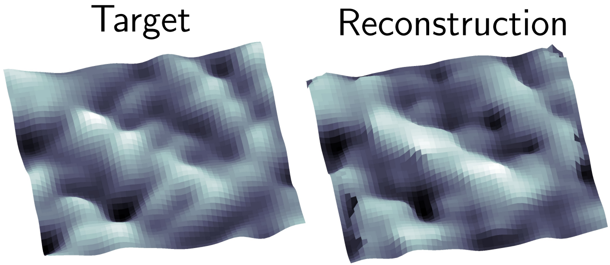
$\lambda_0 = 48 - 139$ mm

Results - frequency-wavenumber spectra

Acoustic streamwise spectra



Current work



- 3-D dynamic surface reconstruction based on acoustic holography.
- Multiple arrays of ultrasonic transducers and sources.
- Improved resolution and range of application.

(Krynkin *et al.*, 2016 RSI; Dolcetti *et al.*, 2016 JASA)

Thank you.