TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Why Excitation and Subsequent Evolution of Wind Waves Can Be Adequately Modeled by Viscous Shear Flow Instability?

INDEED, THEY CAN!

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MOTIVATION

Wave models are based on the energy balance equation for wave action density $N=E/\omega$ (Janssen, The Interaction Ocean Waves and Wind, 2004):

$$\frac{\partial N}{\partial t} + \nabla \cdot (\boldsymbol{c_g} N) = S_{nl} + S_{source} + S_{sink}$$

Here
- S_{nl} term representing nonlinear wave-wave interactions;
- S_{source} energy input by wind
- S_{sink} dissipation (primarily due to wave breaking)
- $\boldsymbol{c_g}$ group velocity, the wave energy propagation velocity vector

In this talk, I will discuss **a simplified model, grounded in experimental evidence**, that can provide both qualitative and quantitative predictions of the initial excitation and subsequent evolution of wind waves in a laboratory setting.

MECHANISMS OF WIND WAVE EXCITATION

Phillips (*JFM*, 1957): Wave Excitation by Turbulent Airflow

- Proposed that waves are excited by **random pressure fluctuations** within the turbulent wind.
- Developed a **nonlinear theory** predicting a **broad spectral distribution** and **directional spreading** of the waves.
- Relied on assumptions that **cannot be directly verified**; the theory remains **experimentally unconfirmed**.

Miles (*JFM* 1957), Valenzuela (*JFM* 1976), Kawai (*JFM* 1979): shear flow instability

- **Miles:** Wind-wave generation as **deterministic linear 2D** shear flow instability (**Rayleigh** equation, inviscid).
- **Valenzuela, Kawai:** Extended Miles' theory by including **viscosity**; waves arise from linear viscous shear flow instability governed by **coupled Orr–Sommerfeld** equations in air and water.

It is accepted that **shear flow instability is the primary mechanism by which wind excites waves**.

Conclusive experimental verification of this theory has remained elusive.

The **empirical** relation by **Plant (*JGR* 1982)** loosely based on Miles' theory is routinely used in models.

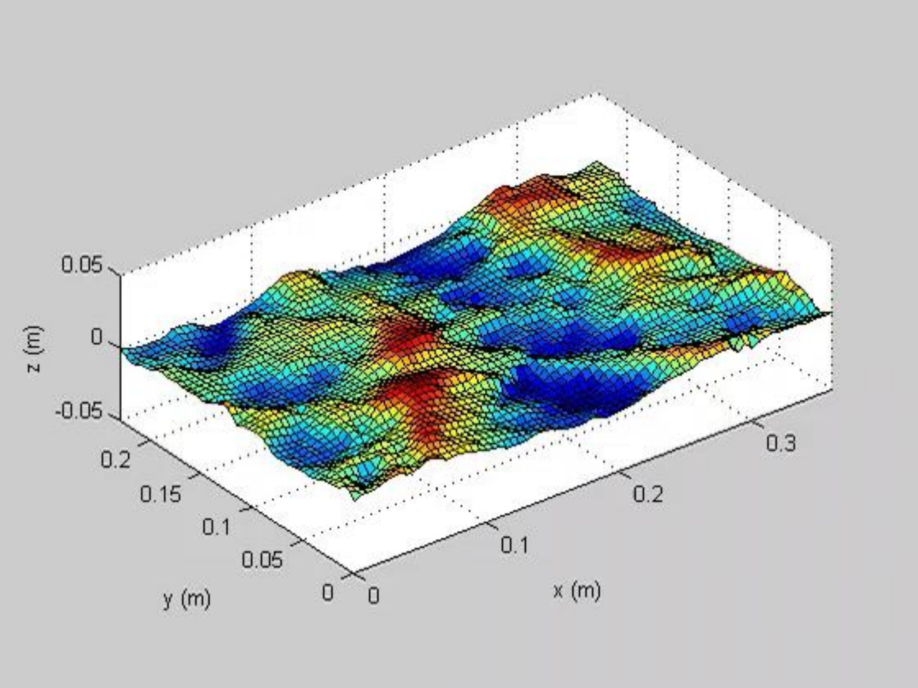
Field experiments lack control over the forcing conditions and cannot provide sufficiently detailed data.

LIMITATIONS OF SHEAR FLOW INSTABILITY AND PHILLIPS THEORIES

- Both theories consider **temporal** evolution of **a spatially uniform** wave field.
- In contrast, most experiments involve **spatial evolution under steady wind** forcing (growth with fetch).
- While Phillips' theory provides valuable physical insight, it does not yield expressions applicable for practical modelling. Consequently, attention has primarily focused on the approach initiated by Miles.
- Linear shear flow instability predicts **exponential temporal growth** of a **single, deterministic, unidirectional** harmonic wave defined by its wavenumber.
- Predictions are highly sensitive to the assumed air and water velocity profiles, especially near the interface (**Zeisel, Stiassnie & Agnon *JFM* 2008**).

WHY SHEAR FLOW INSTABILITY SHOULD NOT BE EXPECTED TO WORK - I

Wind waves are inherently random and spread over a range of frequencies and directions.

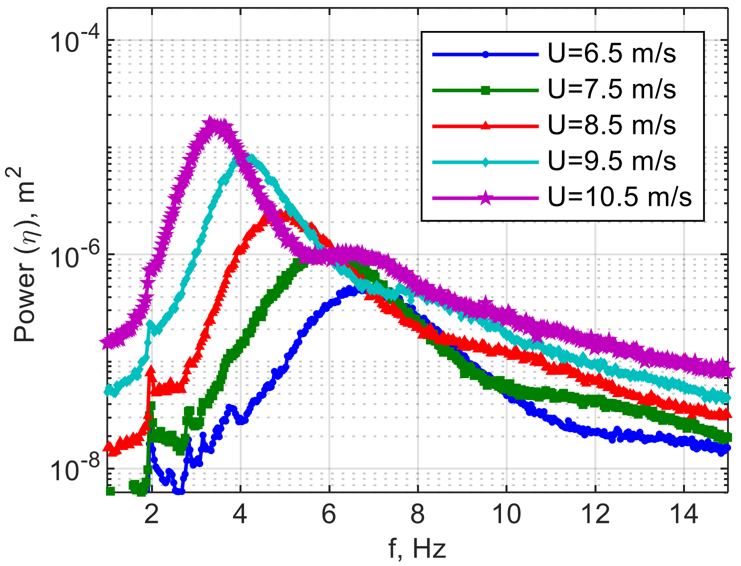


Stereo Video Imaging:
Zavadsky. Benetazzo & Shemer, *Phys. Fluids* 2017

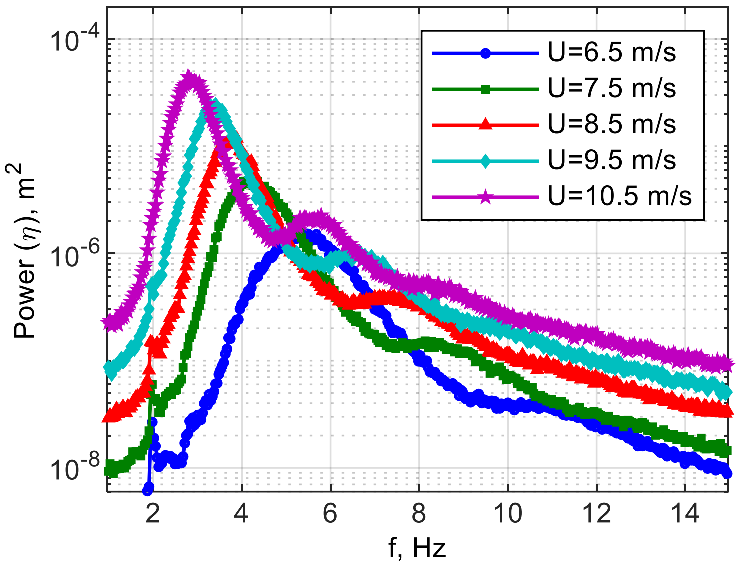
WHY SHEAR FLOW INSTABILITY SHOULD NOT BE EXPECTED TO WORK - II

Under steady wind forcing, **wind waves are not monochromatic** but exhibit **a broad, fetch-dependent spectrum.** The spectral **peak downshifts** to lower frequencies as **fetch *x* and wind velocity *U* increase**

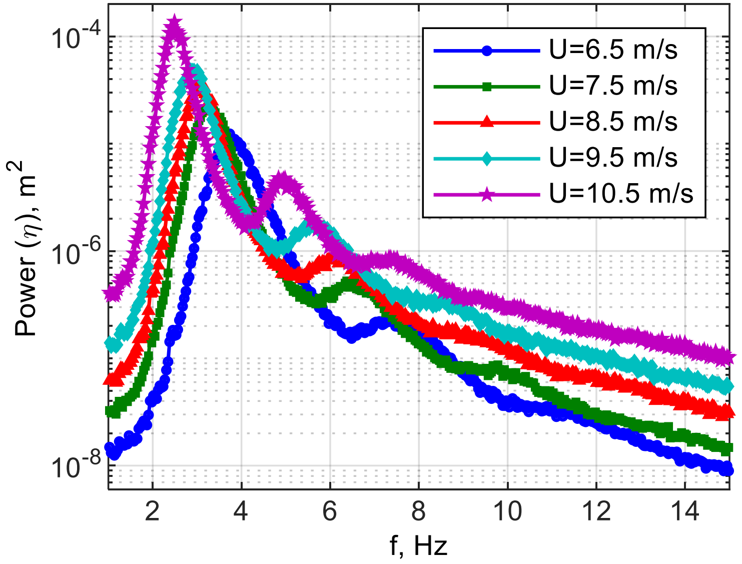
Wind velocity U_a=6.8 m/s



x=120 cm



x=220 cm



x=340 cm

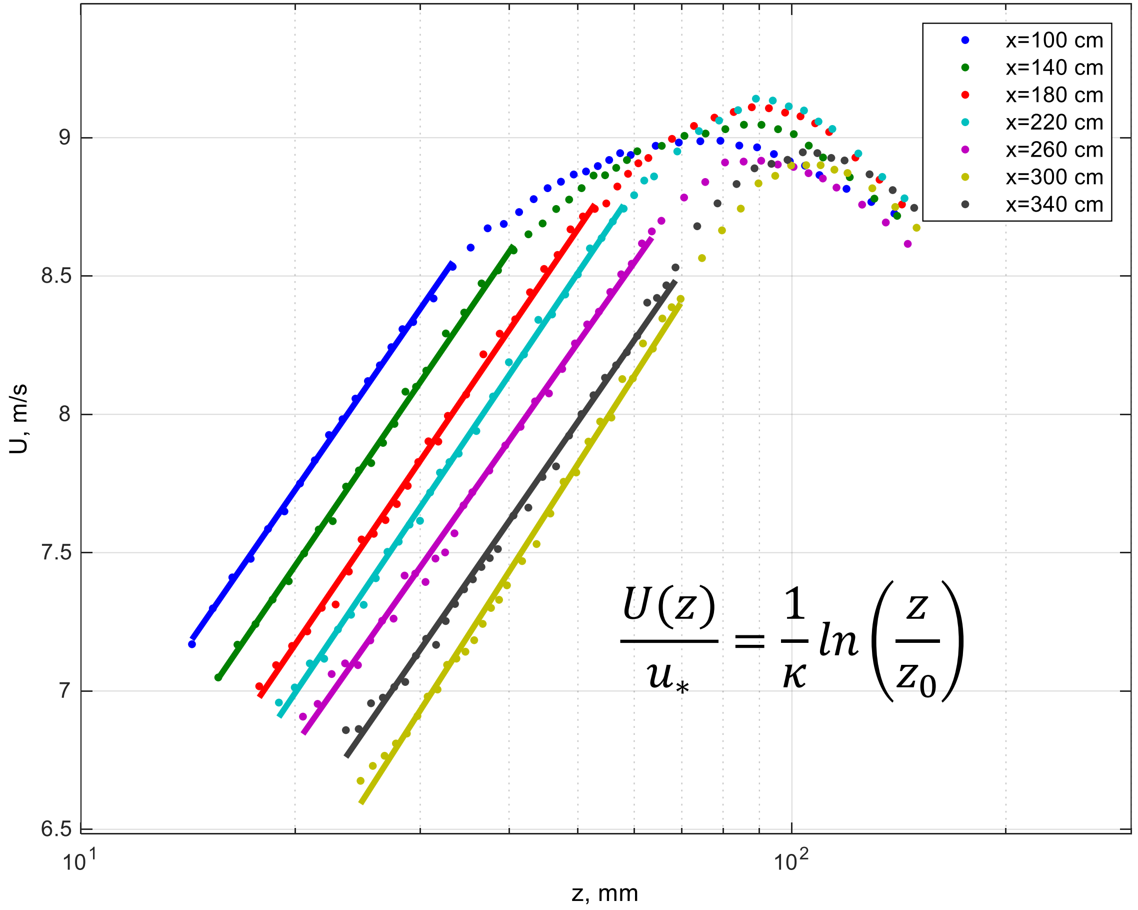
Zavadsky & Shemer, *Phys. Fluids* 2017

WHY SHEAR FLOW INSTABILITY SHOULD NOT BE EXPECTED TO WORK - III

The wind velocity profile also evolves with fetch, adjusting the changing wave field.

The characteristic roughness z_0 increases with fetch x. **Geva & Shemer (*J. Fluid Mech.* 2022)** showed that $z_0 \approx \eta_{rms}/30$.

The slope does not vary with fetch x, so that for a given wind forcing velocity U, the friction velocity u_* remains constant with x.



$$\frac{U(z)}{u_*} = \frac{1}{\kappa} ln\left(\frac{z}{z_0}\right)$$

Zavadsky & Shemer, *J. Geophys. Res.* 2012

These slides show that the fundamental assumptions used in computing shear flow instabilities break down, even in the relatively simple scenario of waves generated by steady wind.

We thus examined how the wind-wave field evolves in time and in space from an initially smooth water surface under impulsively applied wind.

EXPERIMENTS ON WAVES EXCITED BY SUDDEN WIND FORCING

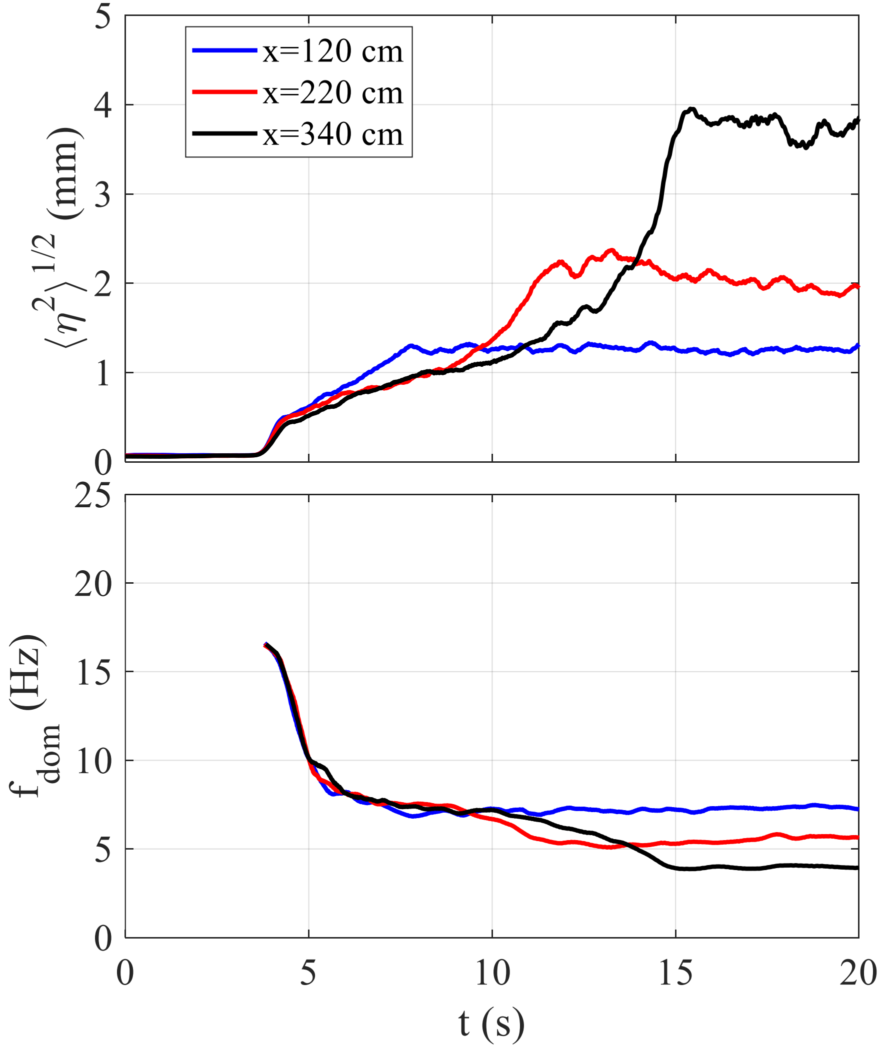
Zavadsky & Shemer *J. Fluid Mech.* 2017

- Measurements were conducted at several wind velocities and fetches.
- For each combination of fetch x and wind velocity *U*, **multiple independent runs** were performed.
- At the start of each run, the test section was windless and the water surface was calm.
- **Instantaneous** dominant frequencies were determined using **wavelet analysis**.
- **Ensemble averaging** across all realizations, as a function of time elapsed since blower initiation, was used to calculate characteristic wave parameters at each fetch and wind velocity.

WHAT DO EXPERIMENTS TELL US ABOUT WATER SURFACE RESPONSE TO IMPULSIVE WIND?

Zavadsky & Shemer *J. Fluid Mech.* 2017

Ensemble-averaged characteristic wave parameters derived from **multiple independent realizations**

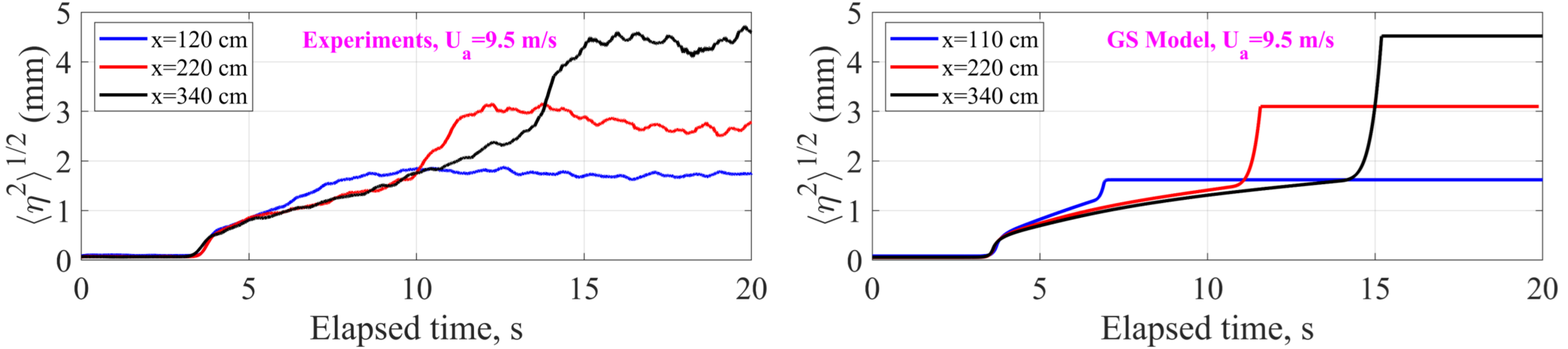


The characteristic wave amplitude η_{rms} at 3 fetches x, U=9.5 m/s

The wavelet-derived dominant wave frequency f_{dom} at 3 fetches x

THE STOCHASTIC VISCOUS SHEAR FLOW INSTABILITY MODEL

Geva & Shemer (*Phys. Rev. Lettr*. 2022)



MODEL ASSUMPTIONS

- Wind wave field consists of **multiple equally probable random harmonics** defined by their wavenumbers k_j.
- All harmonics have identical initial ensemble-averaged energy $E_{j,0}=E(k_j,t=0)=const$, they then grow exponentially at growth rates γ_j determined by solution of the coupled Orr-Sommerfeld equations in air and water, $E_j(k,t)= E_{j,0}\, exp(\gamma_j t)$.
- The exponential growth stage of each harmonic k_j is capped by the wave steepness or by the maximum possible growth duration $\tau_j = x/c_{g,j}$
- The characteristic wave energy $\langle \eta^2(t) \rangle$ and the instantaneous dominant frequency f_{dom}, are evaluated by averaging over ensemble of independent realizations.

EXPERIMENTAL VERIFICATIONS OF THE STOCHASTIC SHEAR-FLOW GS APPROACH TO WIND-WAVE GENERATION

Key Findings:

- The exponential initial growth and the subsequent decay with fetch of individual frequency harmonics in wave field excited by **steadily blowing wind** have been successfully analyzed in the framework of this model: **Kumar & Shemer *J. Fluid Mech.* 984, 2024**.

- The model clarifies the effect of **co- and counter-wind water current** on the spatial evolution of wind-waves, see **Kumar & Shemer *J. Fluid Mech.* 996, 2024**.

- As shown in the previous slide, the model also describes the complex wave field excited by **impulsively applied wind forcing** that **varies in time as well as in space**, as demonstrated in **Geva & Shemer *Phys. Rev. Lettr.* 128, 2022**.

Thus, despite the inherent randomness and directional spreading, the complex spatio-temporal evolution of wind waves under diverse wind forcing conditions can be effectively captured using a unidirectional deterministic model based led Orr–Sommerfeld equations.

However, some aspects of the model still require additional refinement to fully address certain assumptions and their implications. Further work is needed in this regard.

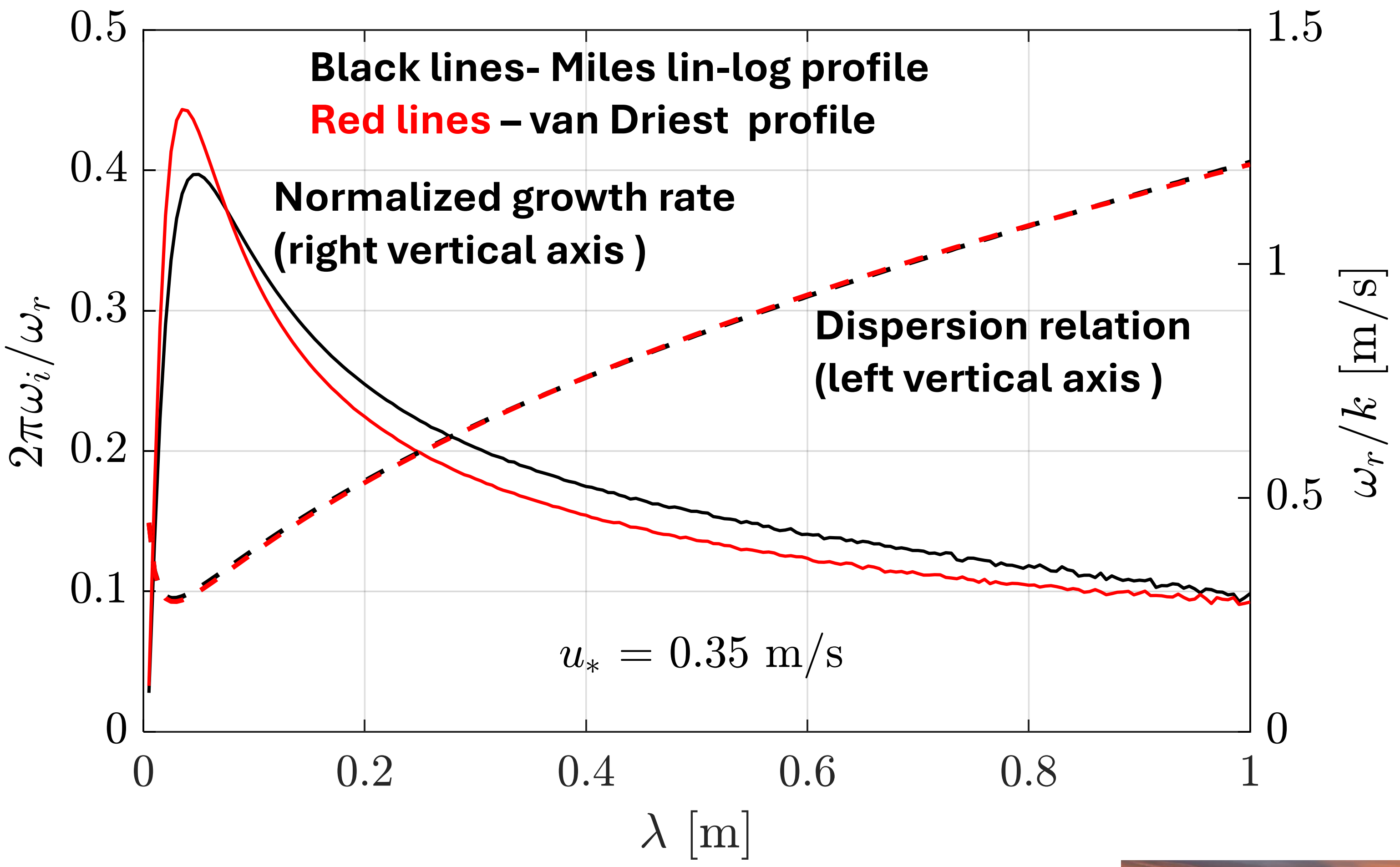
KEY OPEN QUESTIONS ABOUT THE MODEL PERFORMANCE

- **The Geva & Shemer *PRL* 2022 model** employed the **Miles (*J. Aeronaut. Sci.* 1957) lin-log velocity profile** for a **smooth surface** in air and the **Kawai (*JFM* 1979)** exponential velocity profile in water, both assumed to be independent of fetch.
- They **model** assumes **fetch-independent friction velocity** u_* that defines the shear stress at the air-water interface and links the wind-induced **surface drift velocity** U_d to the friction velocity u_*.
- However, the transition between wave evolution stages not fully explained
- Fast-growing short ripples act as **surface roughness**, modifying airflow
- Moreover , viscous instability growth rates determined from the Orr-Sommerfeld equations **depend on velocity profiles near the air-water interface** that defy direct measurements.

Some of those questions are addressed in **Kumar & Shemer,** *Shear flow instability analysis of young wind waves: coupled air–water Orr-Sommerfeld framework guided by experiment* (revised version is currently being prepared for **re-submission to *JFM***)

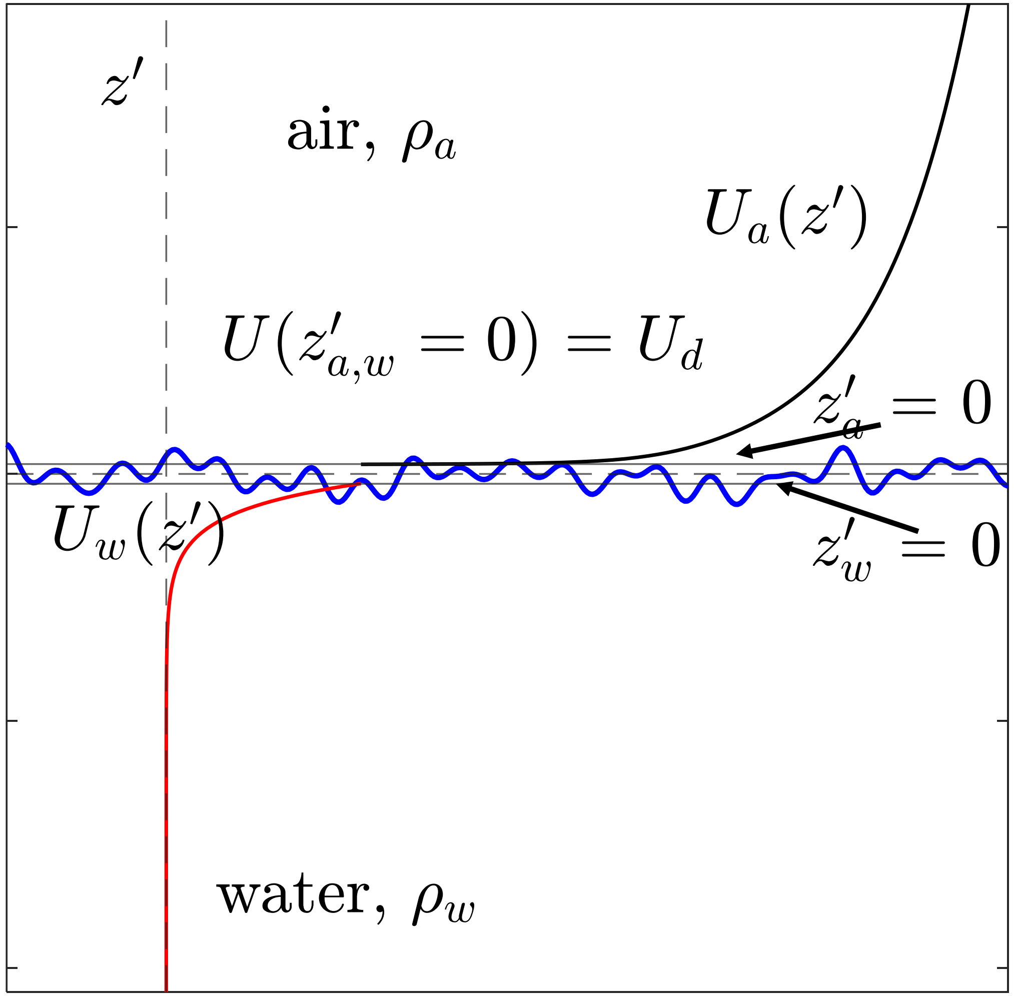
SENSITIVITY OF OS SOLUTIONS TO AIR VELOCITY PROFILE SHAPE

(Kumar & Shemer, submitted to *JFM*)



TREATMENT OF WAVY WATER SURFACE

(Kumar & Shemer, submitted to *JFM*)



Black: air van Driest model for $U_a(z')$ over rough water surface

Virtual origin at $z = \pm d$; $d = 0.8\ \eta_{rms}$ **(Jackson *JFM* 1980, Wu & Piomelli *JFM* 2018)**

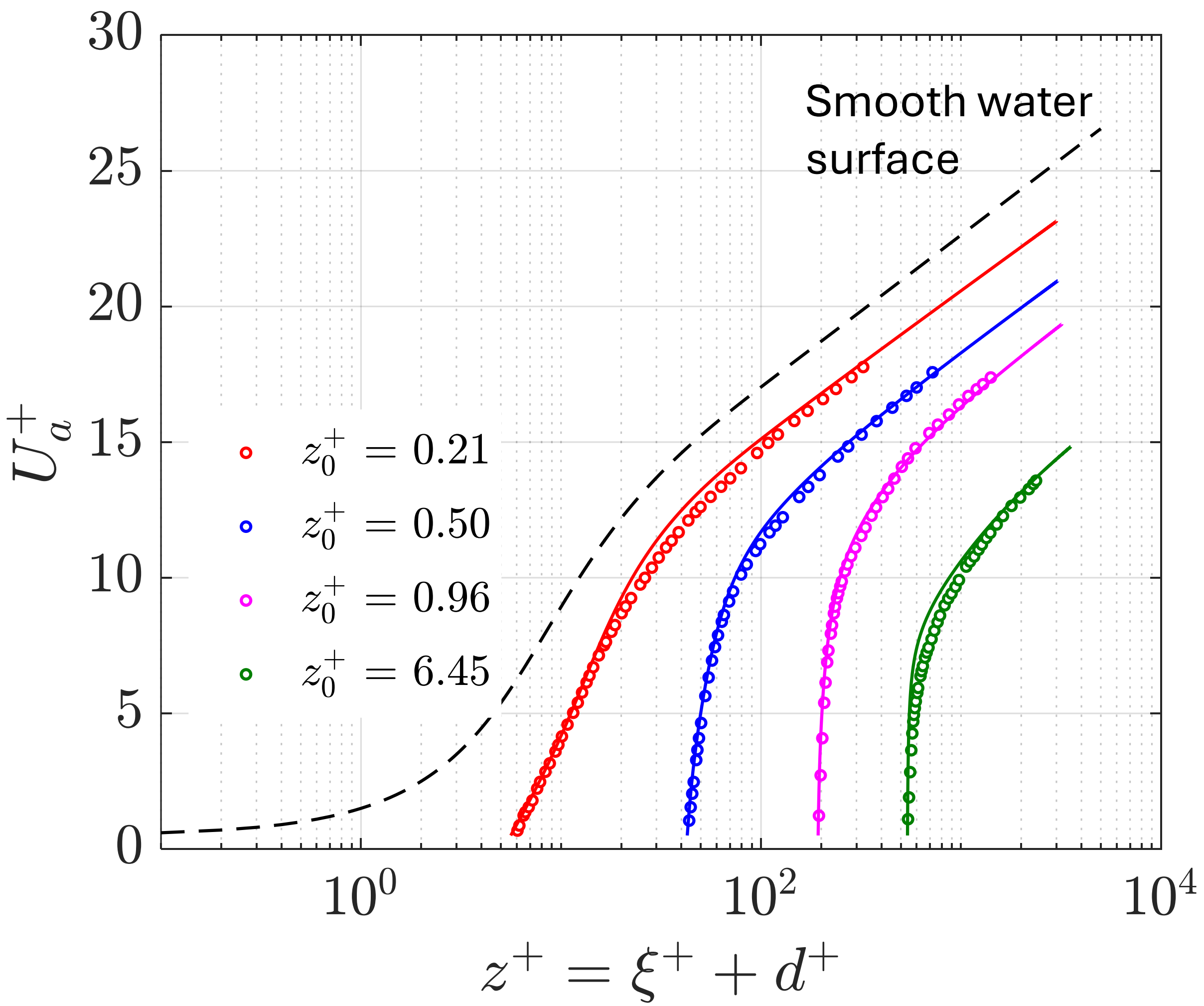
Shifted vertical axis $z' = z + d$ in air and water.

Red: water – exponentially decaying $U_w(z')$

AIR VELOCITY PROFILES

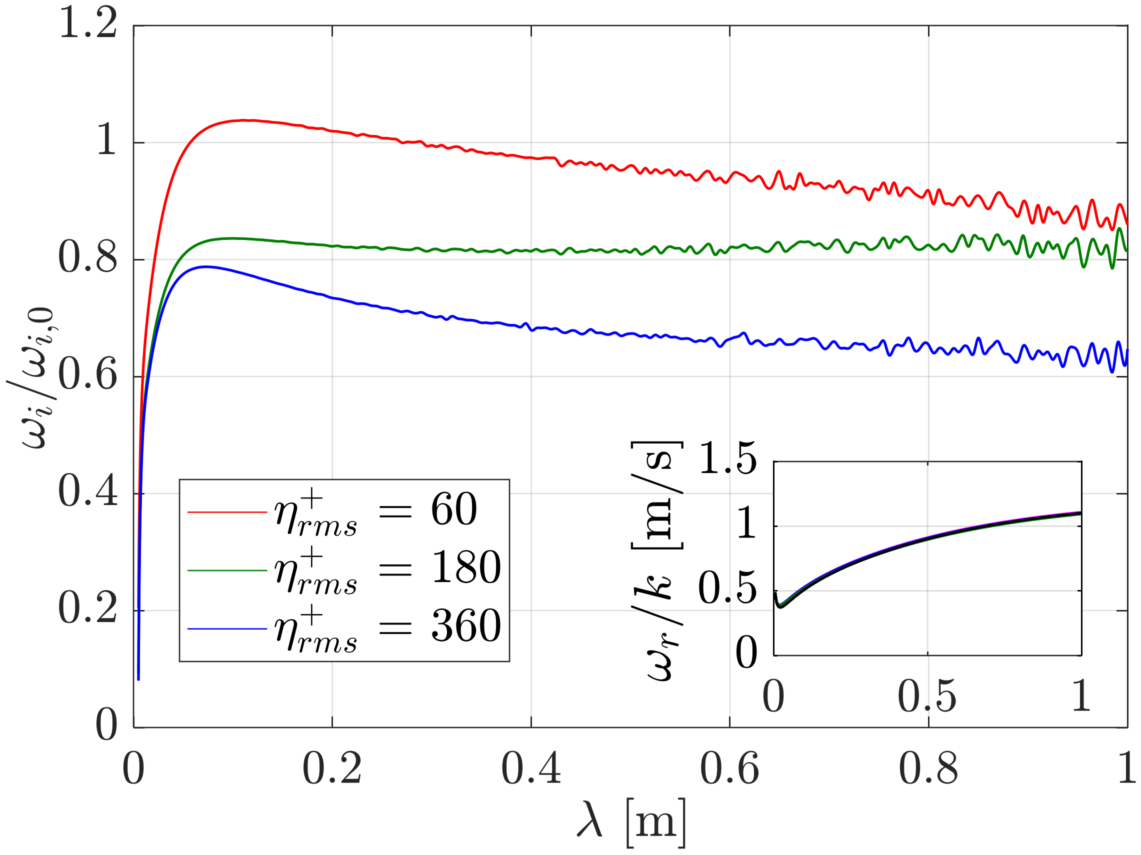
Close water surface (in wall units), either smooth or wavy

Lines – van Driest (*J. Aerospace Sci.* 1956) theory**; Symbols: measurements (Buckley et al. *JFM* 2020)**



EFFECT OF WAVY WATER SURFACE ON O-S SOLUTIONS

(Kumar & Shemer, submitted to *JFM*)



CONCLUSIONS

- Classical shear–flow instability assumptions do not align with experimental reality.
- Yet, Orr–Sommerfeld growth rates depend only weakly on velocity-profile shape or the presence of short ripples.
- Dispersion relation remains essentially unaffected by surface roughness or the air velocity profile, confirming robustness of the viscous shear–flow Orr–Sommerfeld framework.
- Experiments in waves excited by impulsive wind forcing reveal multi-stage, fetch-dependent wave evolution. This behavior is not captured by deterministic single-harmonic theory but is reproduced, both qualitatively and quantitatively, within a stochastic shear–flow framework with multiple random coexisting harmonics and finite spectral width.
- The theory further explains the influence of mean water current on wind-wave evolution.
- We now work on further refinements and extensions of this theory.

Thank you

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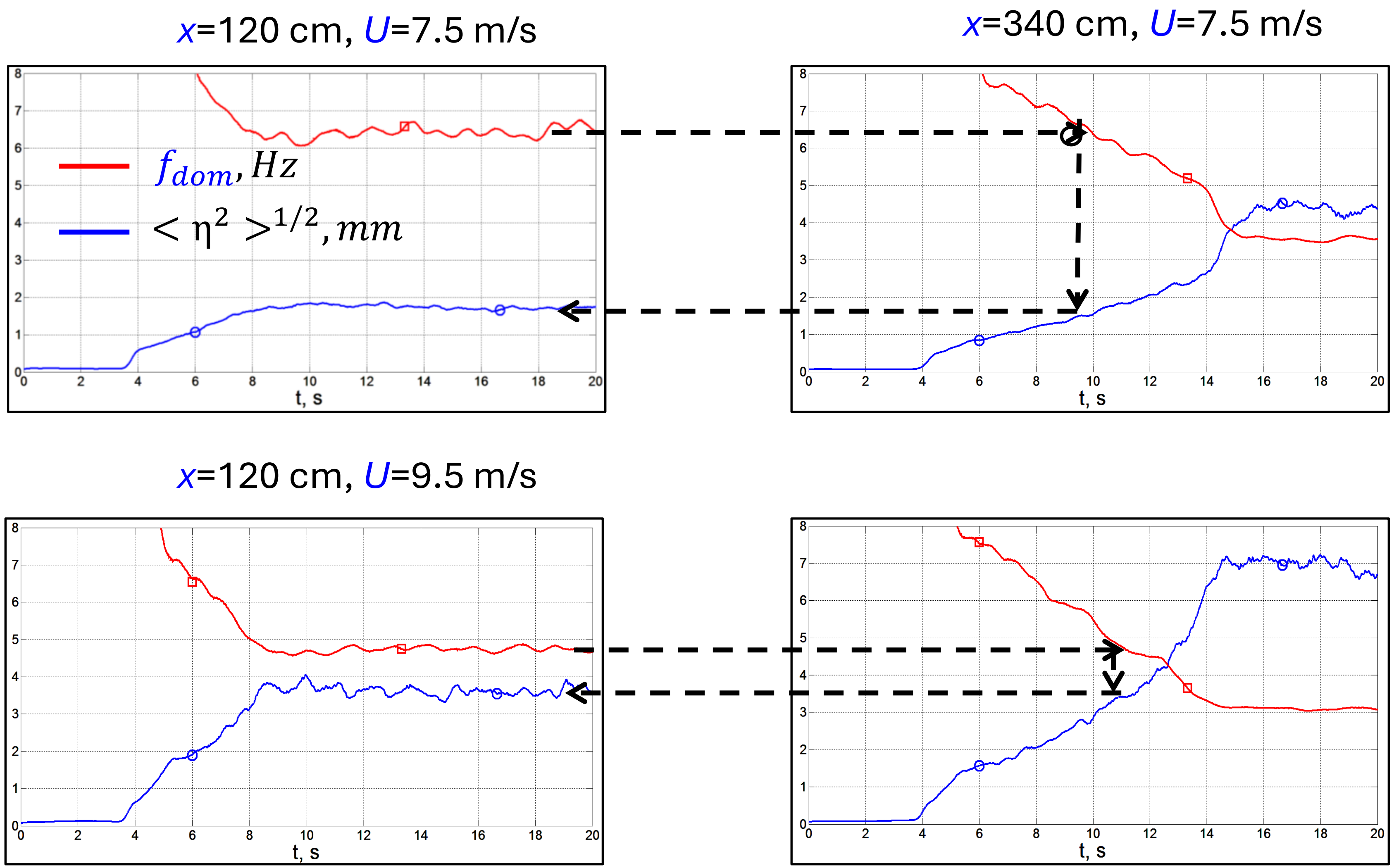
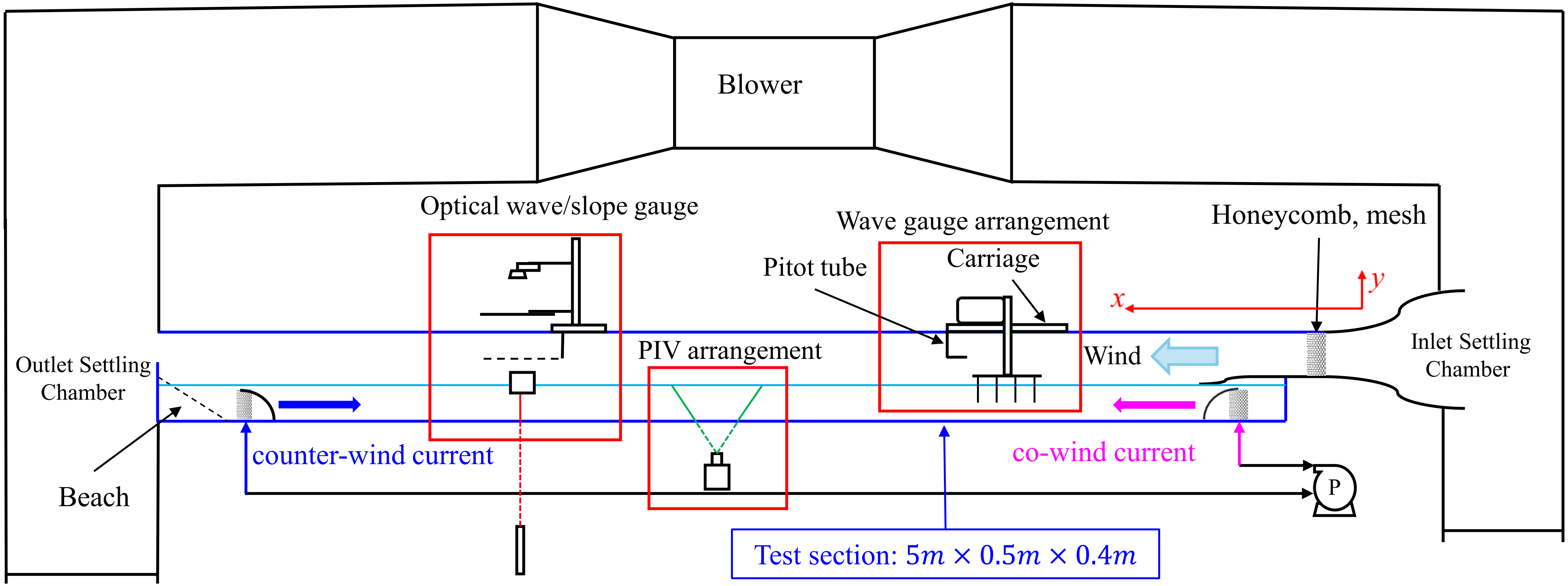
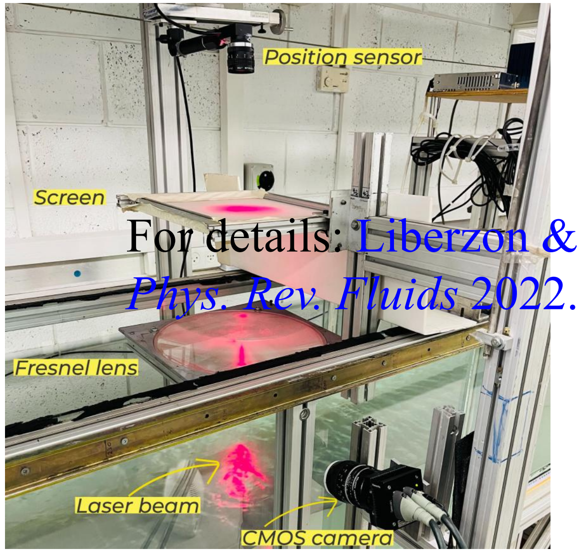
WHAT DO EXPERIMENTS REVEAL ABOUT WAVES EXCITED BY IMPULSIVE WIND FORCING?

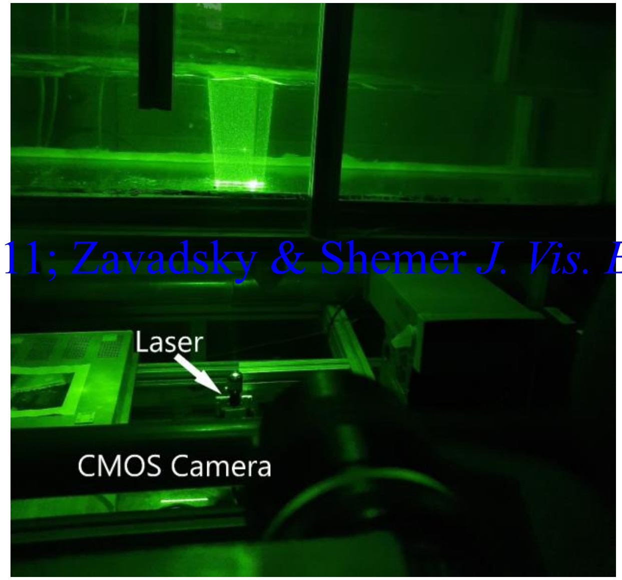


Zavadsky & Shemer, *J. Fluid Mech.* 2017



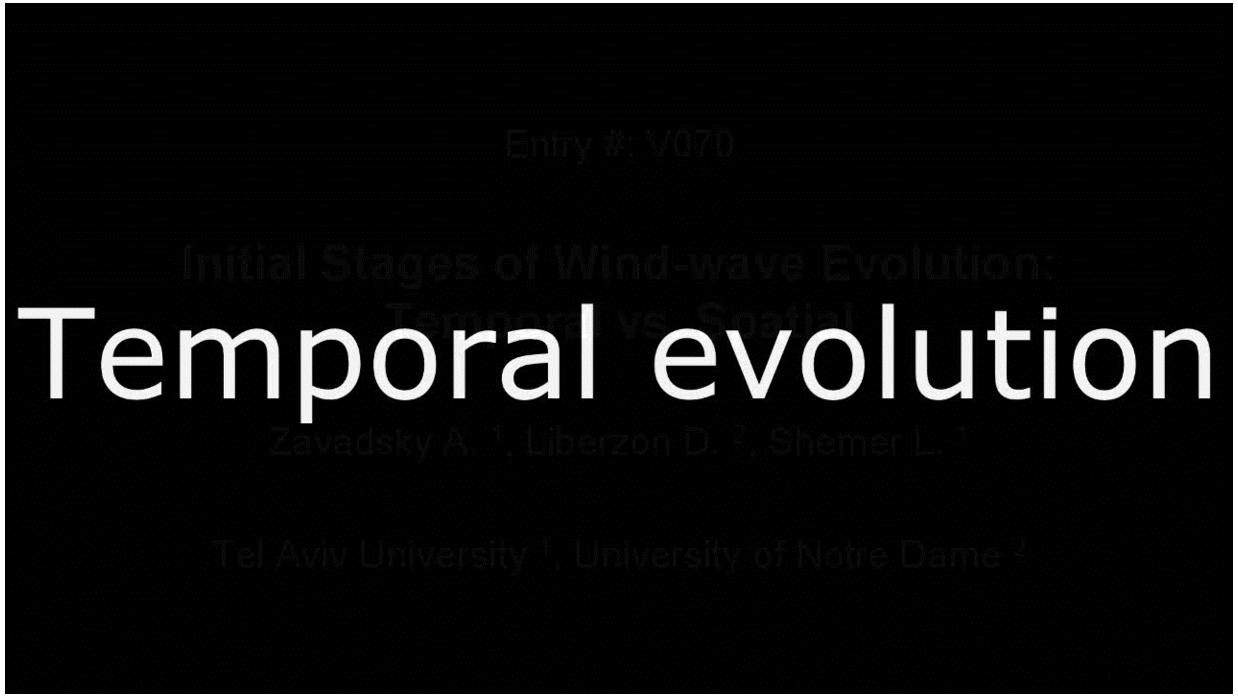
For details: Liberzon & Shemer *JFM* 2011; Zavadsky & Shemer *J. Vis. Exp.* (*JoVE*) 20
Phys. Rev. Fluids 2022.





EVOLUTION OF WIND-WAVES IN TIME

The **existing theoretical models**, as well as numerical simulations, **deal** nearly exclusively with **temporal** (duration-limited) **evolution** of waves that is routinely analyzed **in the wave vector Fourier space**.



Waves are indeed **excited initially everywhere** over the test section; however, the **wave field loses its spatial homogeneity fast.**

The **3-dimensional nature of wind waves** is visible even in an experimental facility of a moderate size.

WAVES UNDER STEADY WIND FORCING

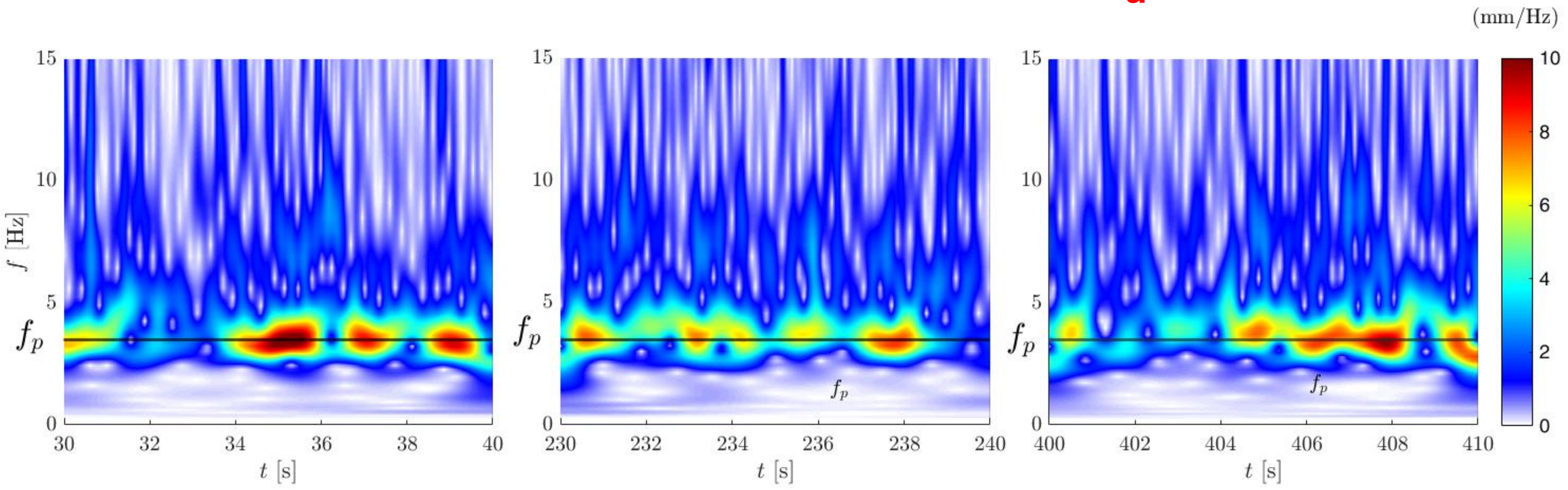
Impulsively excited wind-waves evolve **in TIME and in SPACE**; the wavenumber-based GS model succeeds in a qualitatively correct description of such wave field evolution; the theoretical prediction of the initial spatially homogeneous stages agrees with experiments only quantitatively.

Unlike the dispersive water waves under impulsively-applied wind that are neither spatially homogeneous nor statistically stationary (Shemer *Atmosphere* 2019), waves excited by **steady wind grow with fetch *x*** but are stationary.

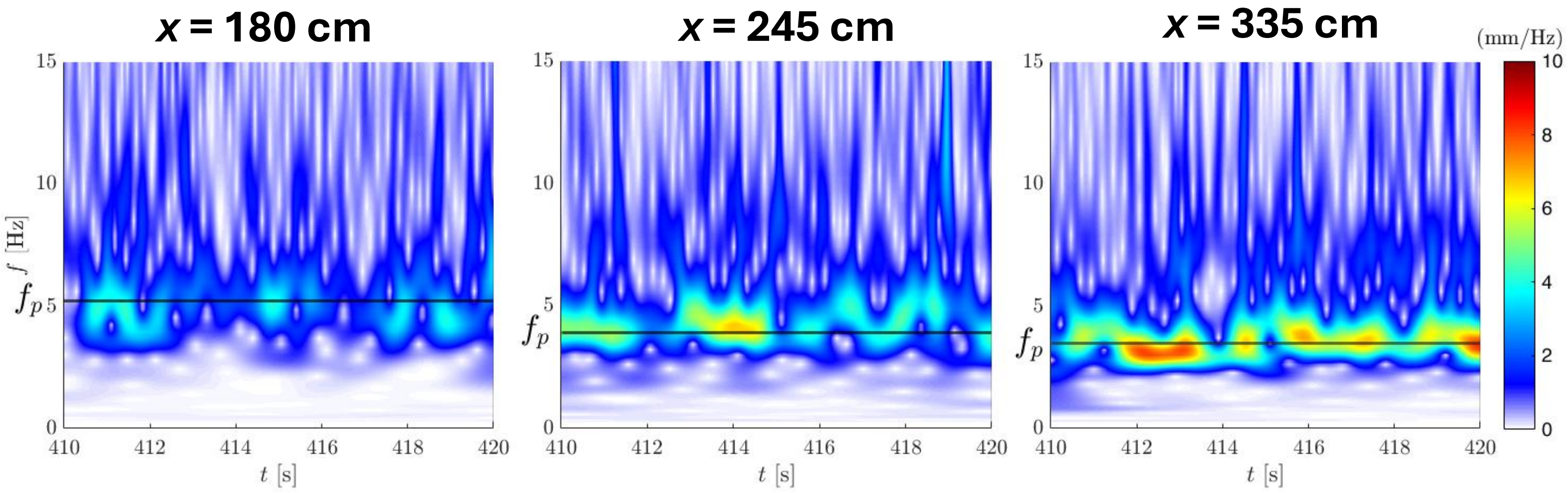
The instantaneous shape of the surface is time-dependent and 3D. Nevertheless, under stead wind forcing, statistically the waves **evolve in the wind direction only, justifying application of temporal Fourier transform.**

THE RANDOM NATURE OF WIND WAVES

Morlet wavelet maps at different instants: U_a = 8.1 m/s, x = 335 cm



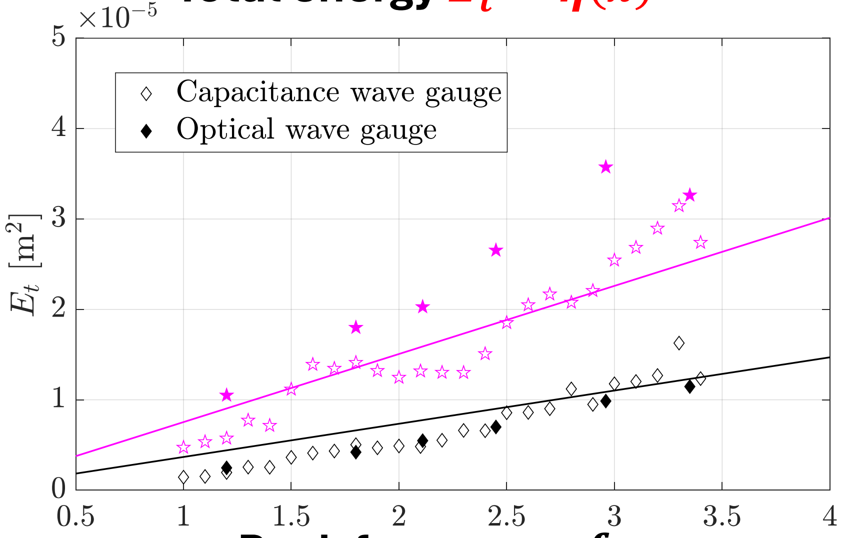
and at various fetches x



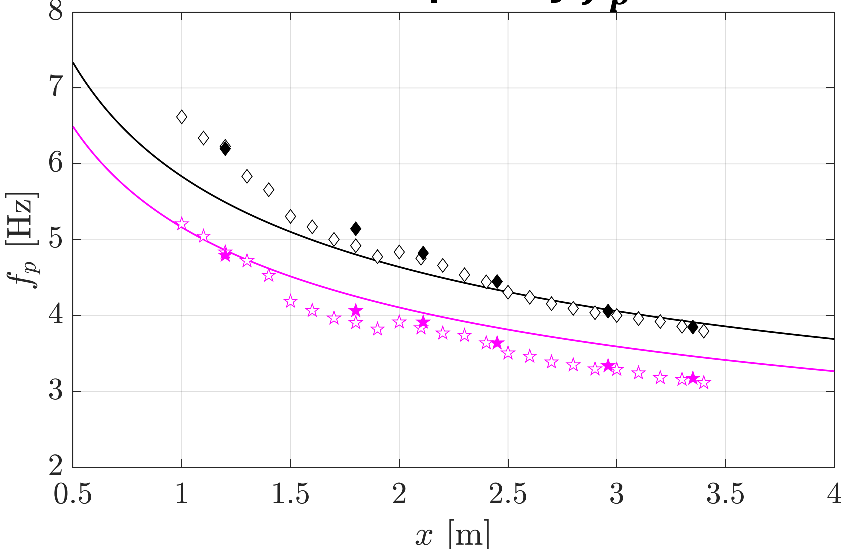
VARIATION WITH FETCH OF INTEGRAL WAVE PARAMETERS

(Kumar & Shemer *JFM* 2024)

Total energy $E_t = \overline{\eta(x)^2}$



Peak frequency f_p



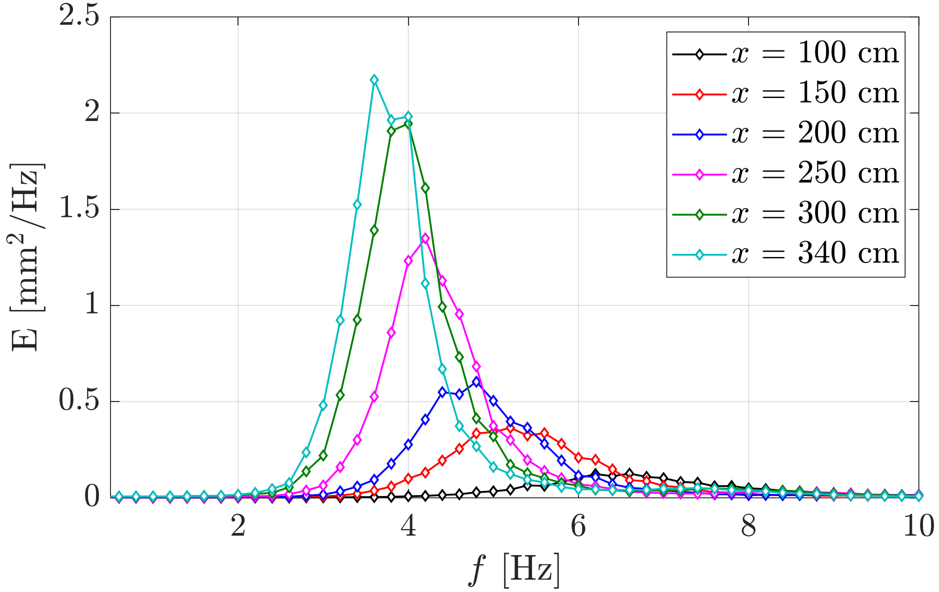
◇ $U = 6.83$ m/s
☆ $U = 9.35$ m/s

Solid lines

$$E = 1.86 \cdot 10^{-4} \left(\frac{x u_*^2}{g}\right)$$

$$f_p = 0.96 \left(\frac{g}{u_*}\right)\left(\frac{gx}{u_*^2}\right)^{-0.33}$$

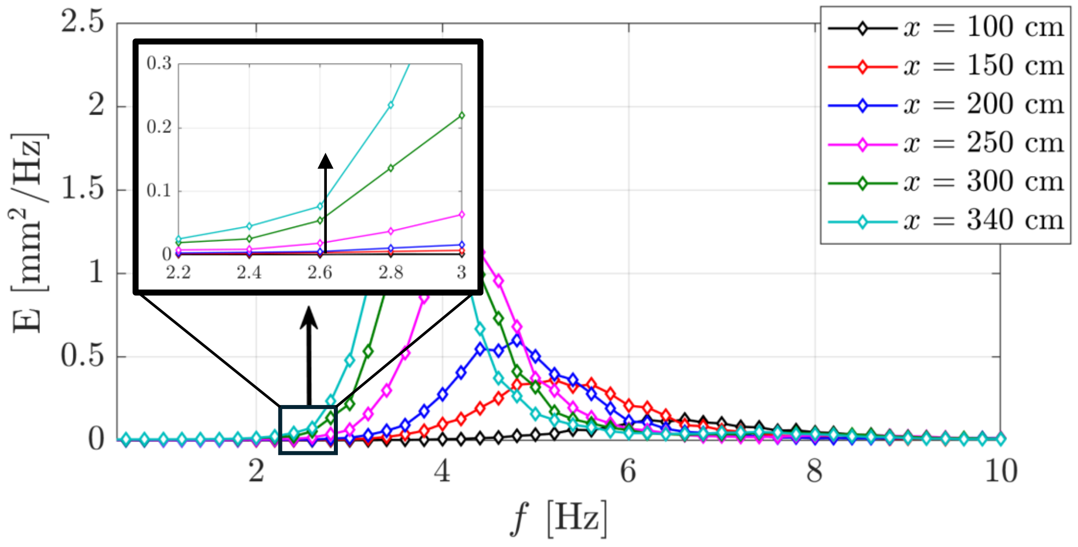
Power Spectra; U_a = 6.83. m/s

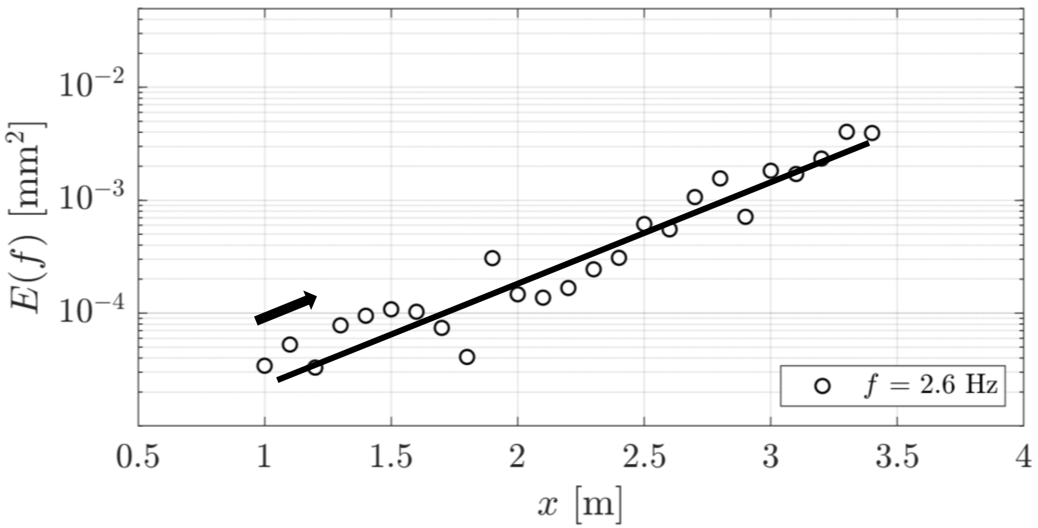


The fits by solid lines are consistent with Mitsuyasu (*Coast. Eng. Jap.* 1970) power laws

EVOLUTION WITH FETCH OF INDIVIDUAL HARMONICS IN THE WIND-WAVE SPECTRUM; $U_a = 6.83$ m/s

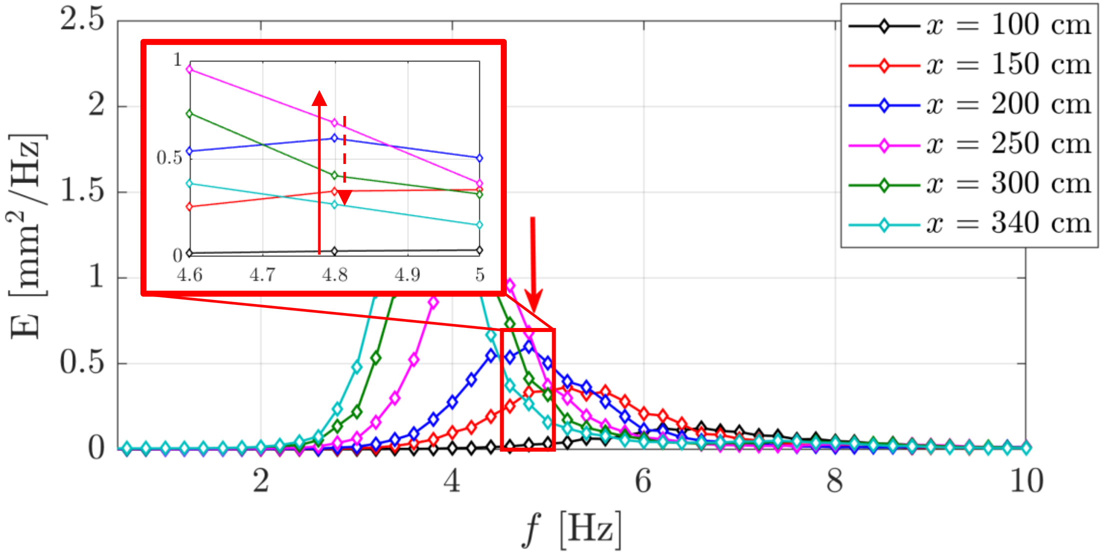
Selected Harmonic: $f = 2.6\ Hz$

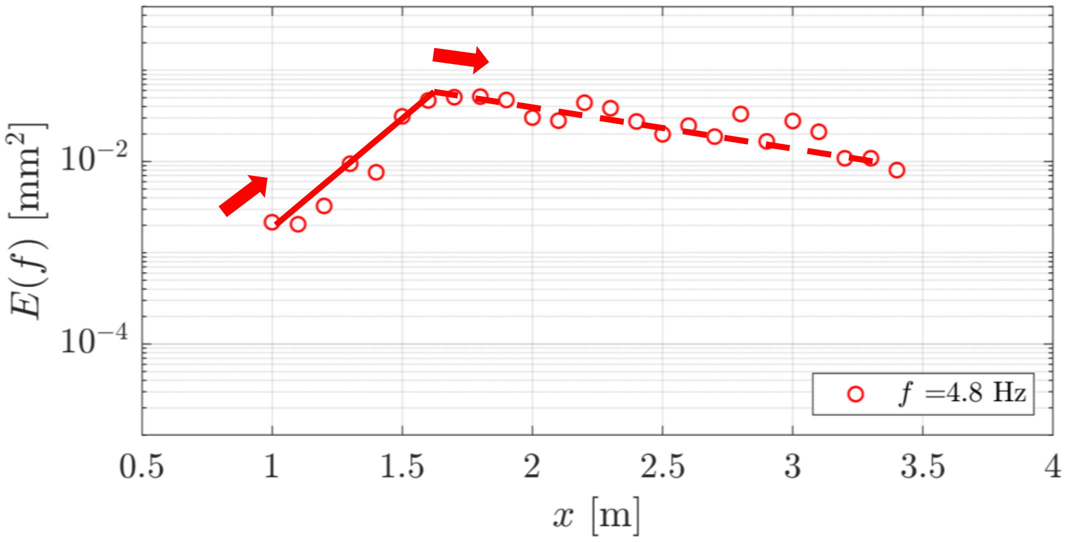




EVOLUTION WITH FETCH OF INDIVIDUAL HARMONICS IN THE WIND-WAVE SPECTRUM; $U_a = 6.83$ m/s

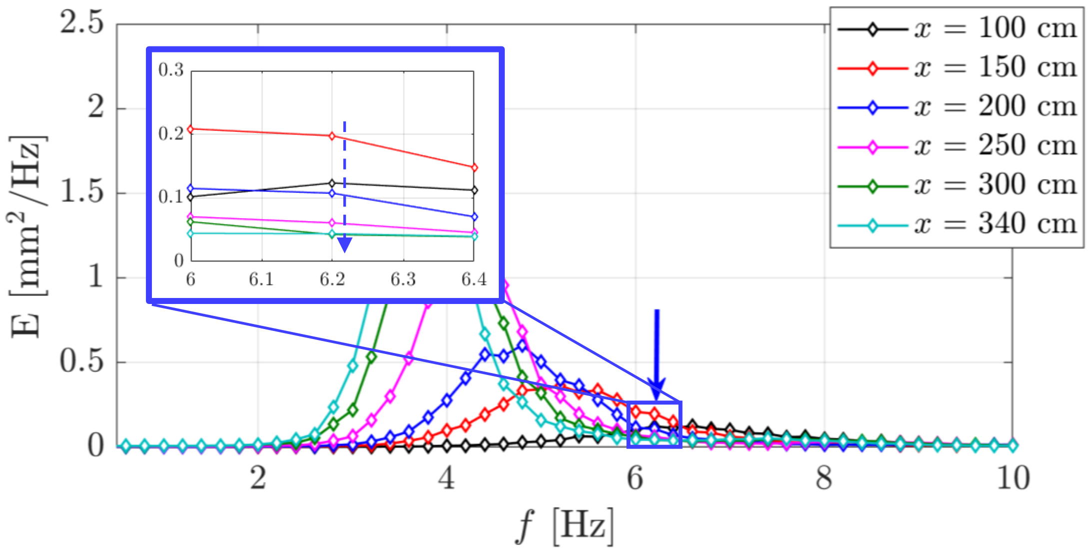
Selected Harmonic: $f = 4.8\ Hz$

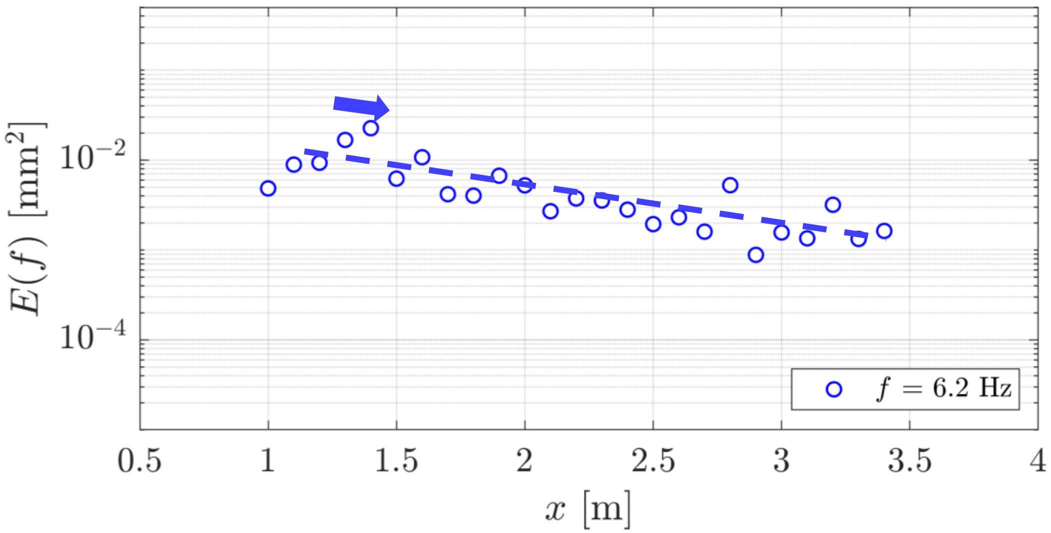




EVOLUTION WITH FETCH OF INDIVIDUAL HARMONICS IN THE WIND-WAVE SPECTRUM; U_a = 6.83 m/s

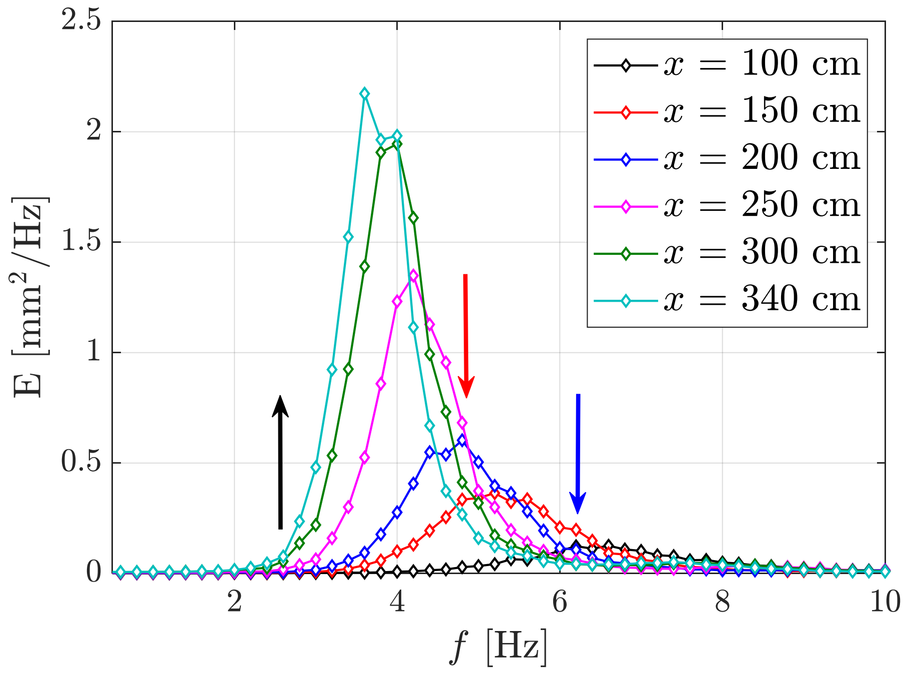
Selected Harmonic: $f = 6.2\ Hz$



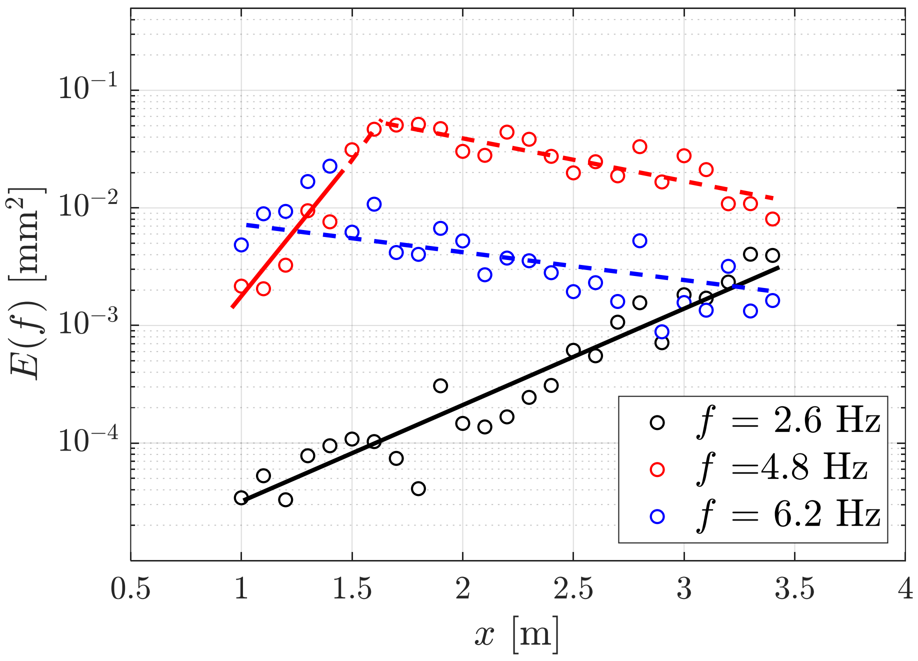


EVOLUTION WITH FETCH OF INDIVIDUAL HARMONICS IN THE WIND-WAVE SPECTRUM; U_a = 6.83 m/s

Power Spectra

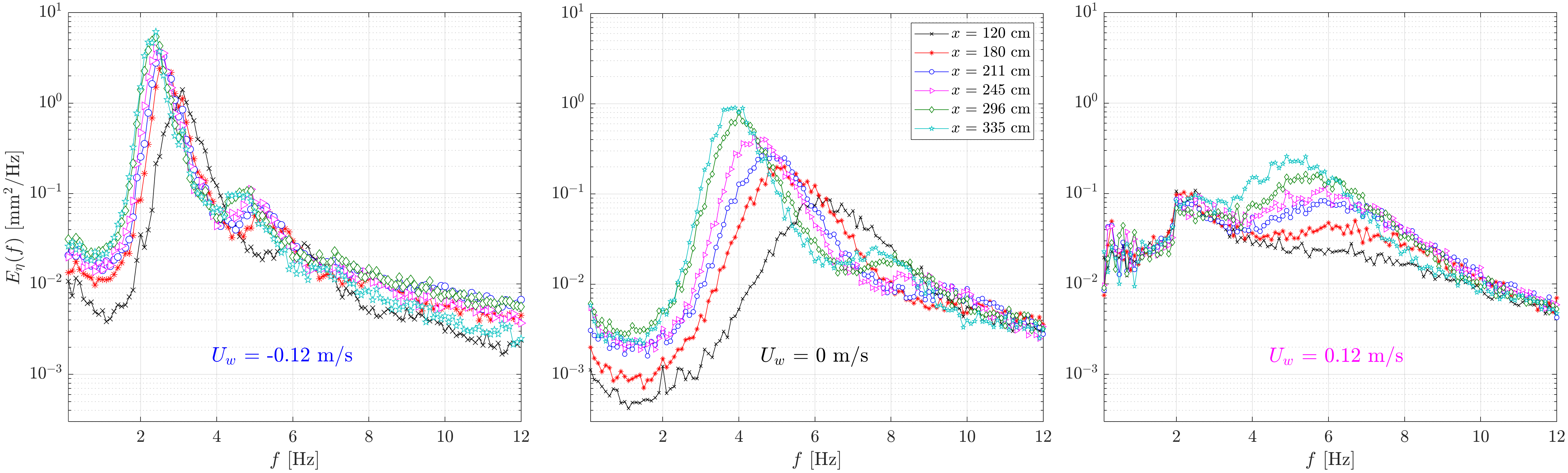


Selected Harmonics



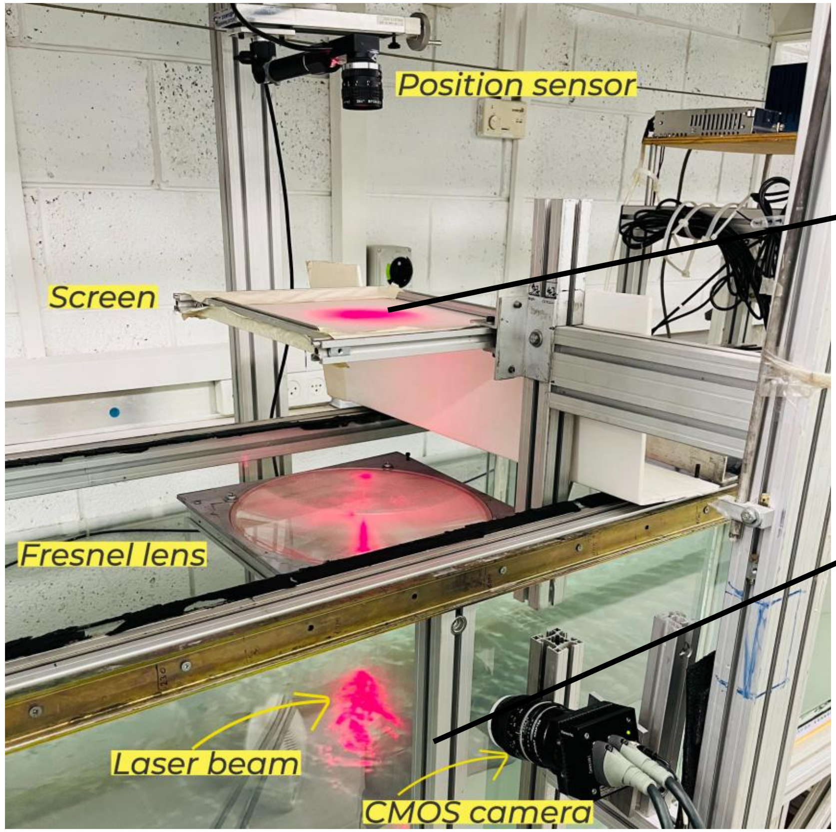
EFFECT OF MEAN WATER CURRENT ON THE SPATIAL EVOLUTION OF WAVE ENERGY SPECTRA

Wind velocity U_a=6.83 m/s

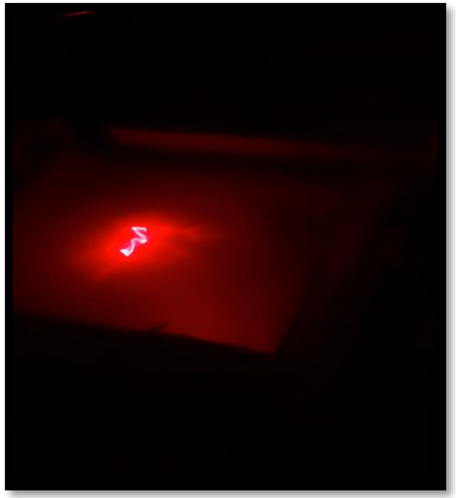


OPTICAL WAVE AND LASER SLOPE GAUGE

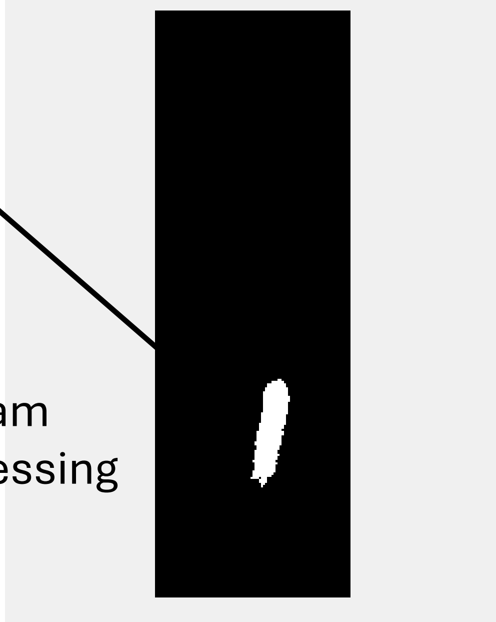
Synchronous measurements of $\eta(t)$ and $\eta_x(t)$



Laser beam on the screen \eta

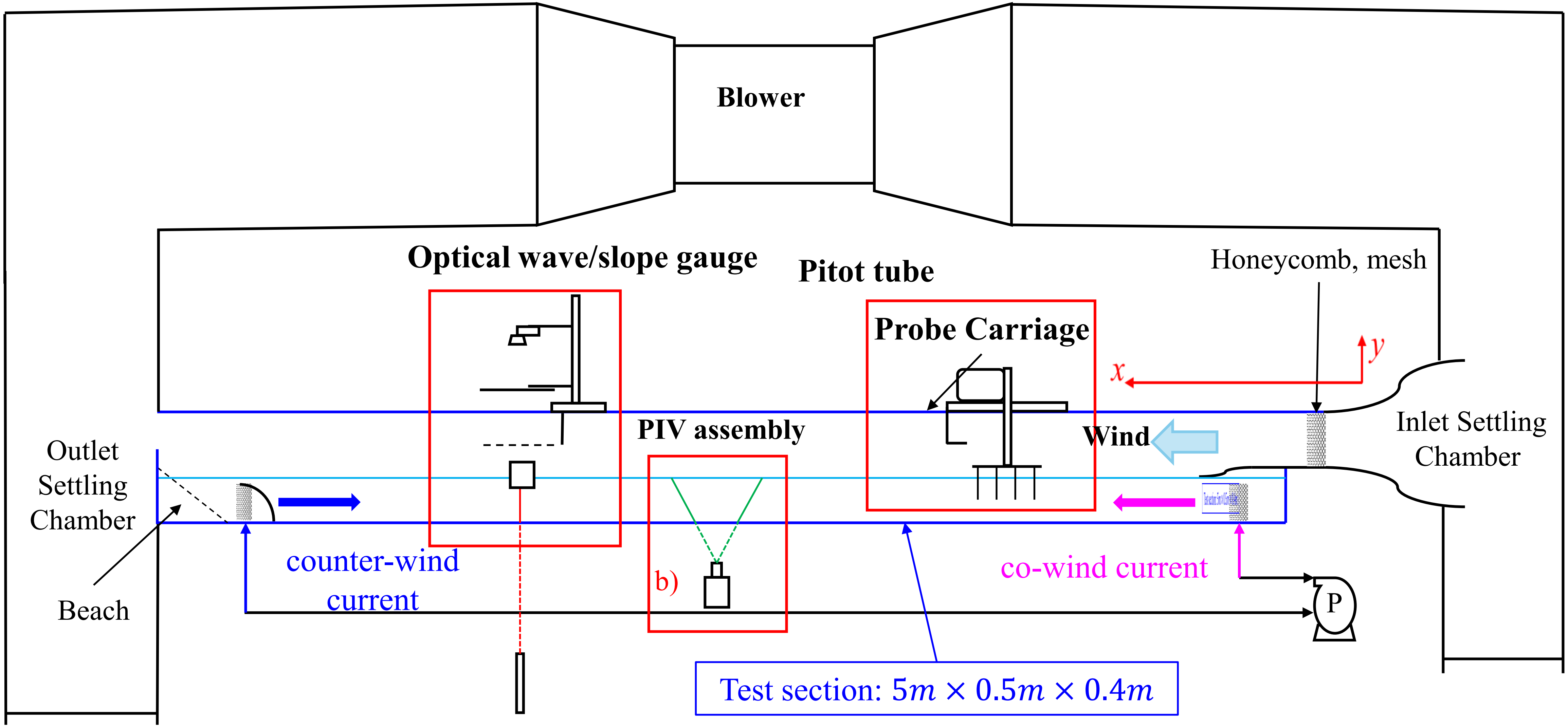


The laser beam as seen by the camera



The laser beam after post-processing

EXPERIMENTAL FACILITY AND METHODS



For details: Liberzon & Shemer *JFM* 2011; Zavadsky & Shemer *J. Vis. Exp.* (*JoVE*) 2018; Kumar, Singh & Shemer *Phys. Rev. Fluids* 2022.