Επιστημονικό Συνέδριο προς τιμήν του
ομότ. καθηγητή ΕΜΠ κ. Γεράσιμου Α. Αθανασούλη

AUGMENTING SHIP PROPULSION IN WAVES

BY BIOMIMETIC FLAPPING THRUSTERS

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Contents

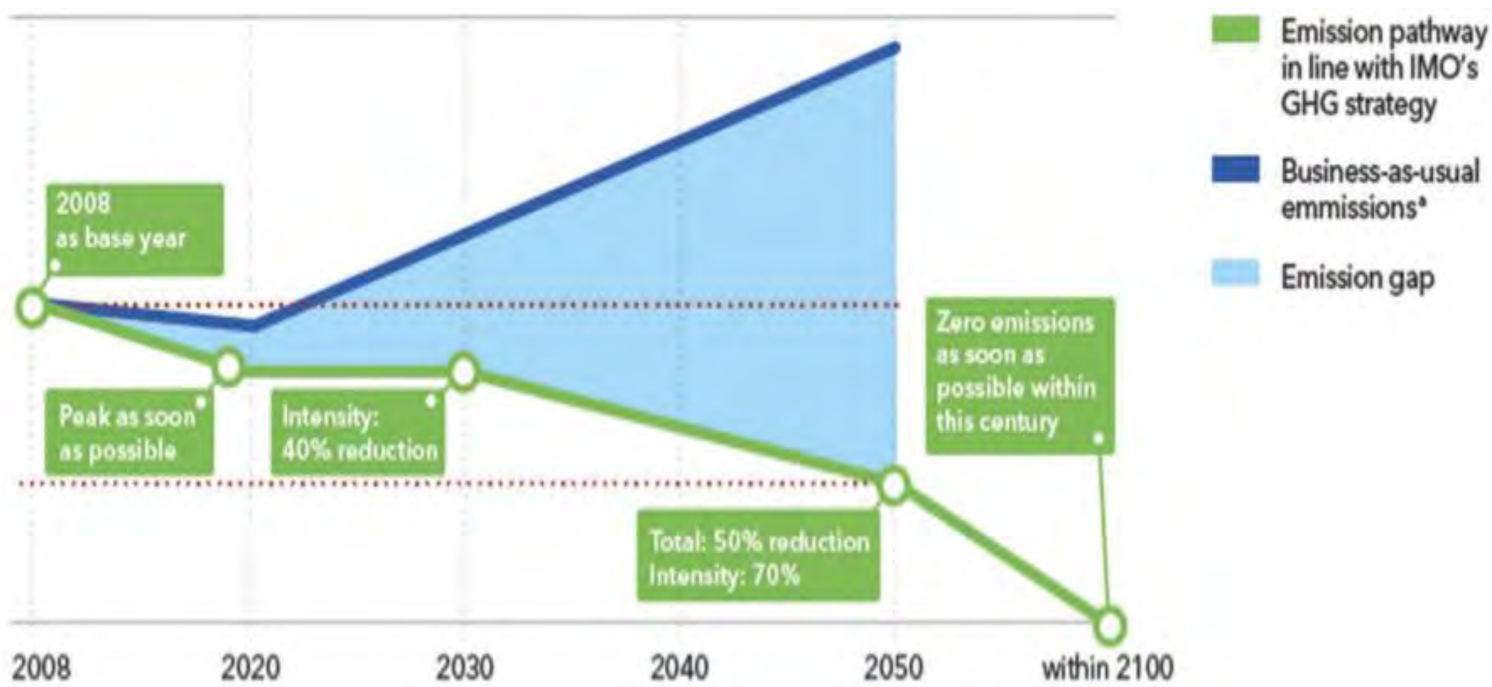
- **Introduction – Motivation for the present work**
- **Flapping foil biomimetic thrusters for augmenting ship propulsion in waves**
- **Numerical models and experimental research for the performance of the considered system**
- **Simulation in irregular waves by means of dynamical systems**
- **Application to a short-sea shipping scenario in the North Sea for a ROPAX ferry ship**
- **Next steps of the research planned for supporting the industrial development of the system**

Introduction

Flapping-foil thrusters arranged below the hull of the ship are examined for the exploitation of energy from wave induced motions by direct conversion to useful propulsive power.

In the framework of EU **Seatech H2020 project** (https://seatech2020.eu/) flapping-foil thruster propulsion innovation is examined, in combination with standard propulsion system based on optimally controlled Dual Fuel engine, aiming at increase in fuel efficiency and radical emission reductions of NOx, SOx, CO_2 and particulate matter.

SEATECH



IMO GHG strategy

EU ZEWT: Develop and demonstrate solutions
to reduce the fuel consumption of waterborne transport
by at least 55% before 2030 compared to 2008

Ship propulsion by flapping thrusters

The superior swimming and maneuvering capabilities of aquatic animals has motivated research on **fish-like propulsion** for many years

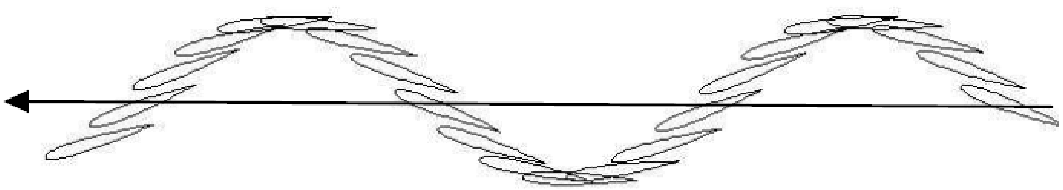
It has been found that **flapping-foil biomimetic systems at optimum conditions** could achieve quite good thrust levels and efficiency.

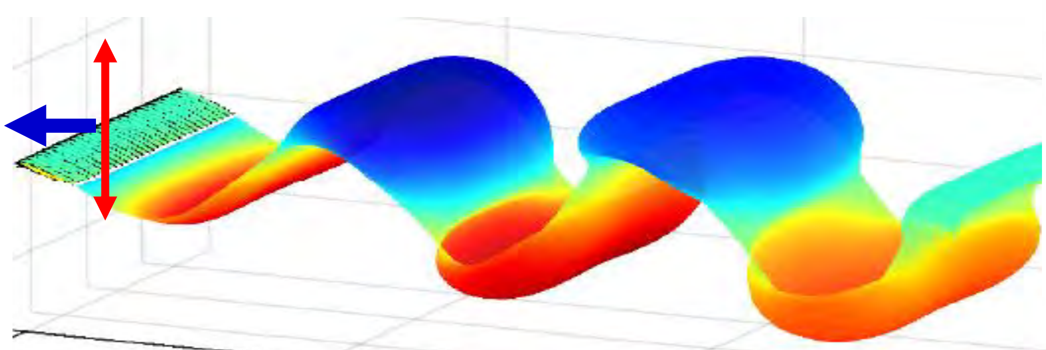
Triantafyllou et al (2000, 2004), von Ellenrieder et al (2008), Taylor et al (2010),… review by Wu et al (OE 2020)

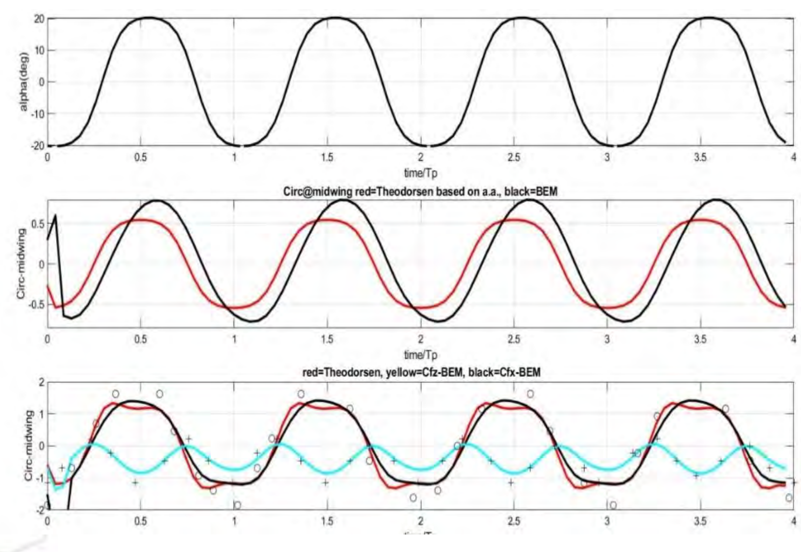
Main difference between biomimetic propulsor and conventional propeller is that the former absorbs its energy by two independent motions:

heaving / pitching or **swaying / rolling** motions

while for the propeller there is only rotational power feeding.







flapping foil as main ship propulsor

Application at inland shipping (O-foil, Ms Triade)

→ **smaller required submergence, reduced fuel consumption, reduced emissions and noise level, increase of capacity**

Biomimetic propulsors are also exploitable for converting sea wave energy to useful thrust

In **real sea conditions**, the ship undergoes

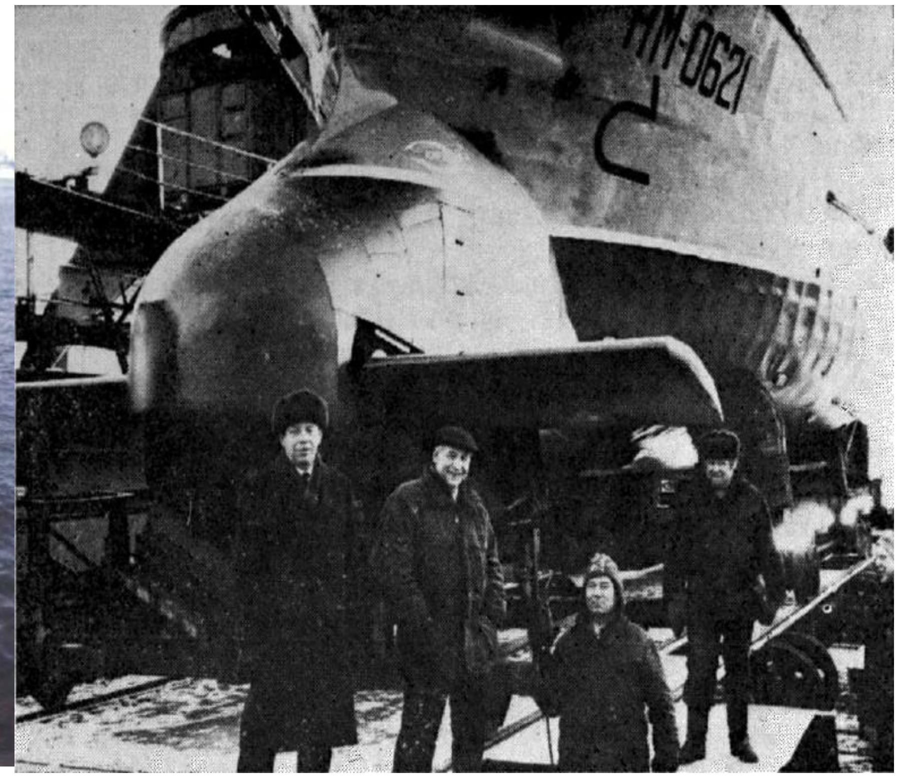
moderate or **higher-amplitude** oscillatory motion due to **waves**, and the **vertical/transverse ship motion** could be **exploited** for providing free of cost one of the modes of combined/complex oscillatory motion of a biomimetic propulsion system.

At the same time, **due to waves added resistance**, wind and other reasons, **ship propulsion energy demand in rough sea is usually increased** well above the corresponding value in calm water for the same speed, especially in the case of bow/quartering seas.

Energy extracted from ship motions → enhancement of stability in rough sea

wave-energy extraction flapping systems

see, e.g., Rozhdestvensky & Ryzhov (2003),
Naito & Isshiki (2005)

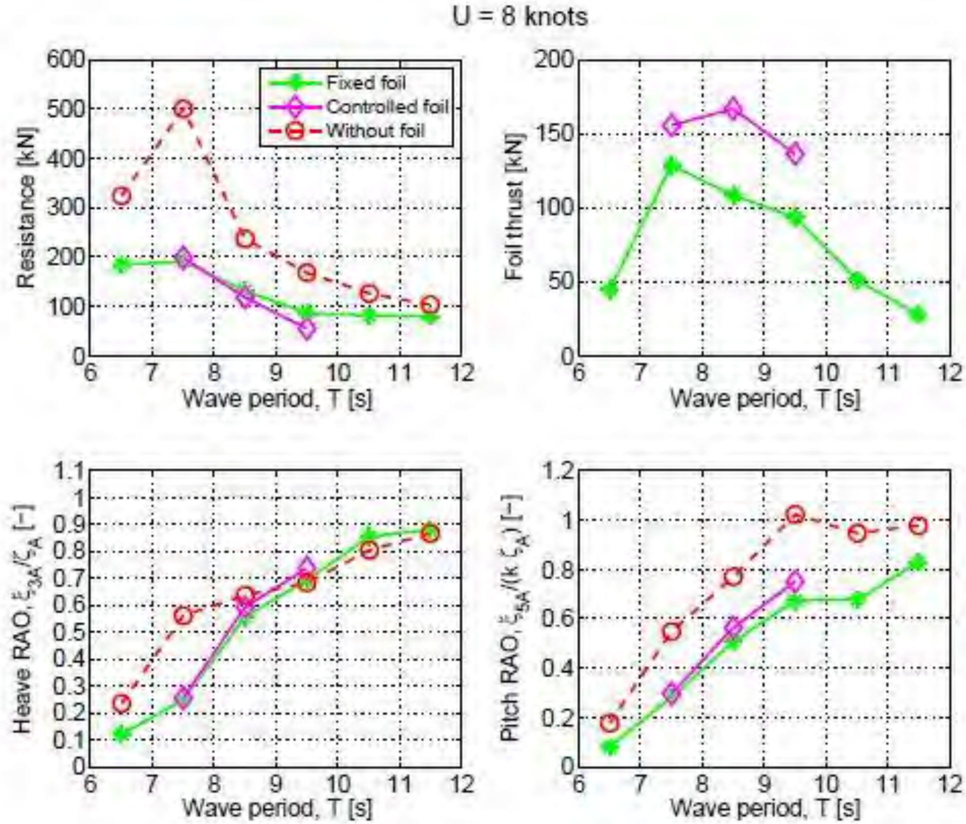


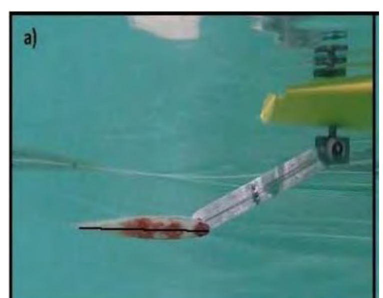
Norwegian ship achieves fuel savings 15-20%
By wave-energy extraction, Jakobsen (1983)

Russian ship with bow-wings,
Nikolaev et al (1995)

wave-energy extraction flapping systems

Experimental study of biomimetic foil on ship propulsion and motions, 67% reduction of resistance in waves, 60% & 50% reduction of heaving & pitching, Bøckmann & Steen (2013,2016)





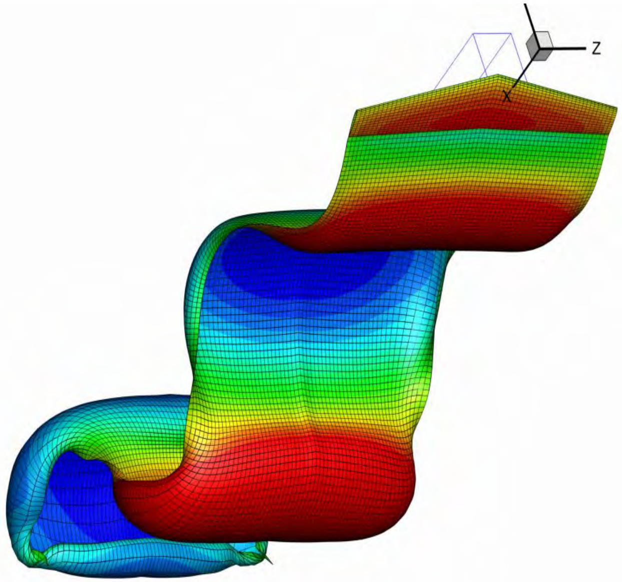
Bowker & Townsend (2018, IEEE 2020) free running and restrained towing tank experiments for :

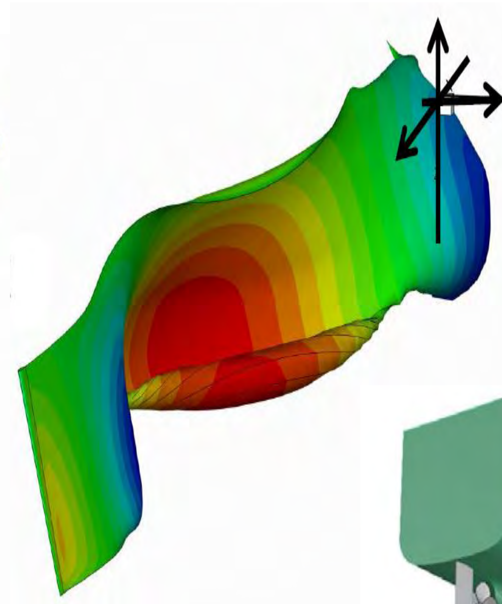
- Wave propulsion

- Energy recovery for onboard power generation

NTUA CFD & EFD research

→ **3D flapping wing thrusters operating beneath the free surface and in waves**



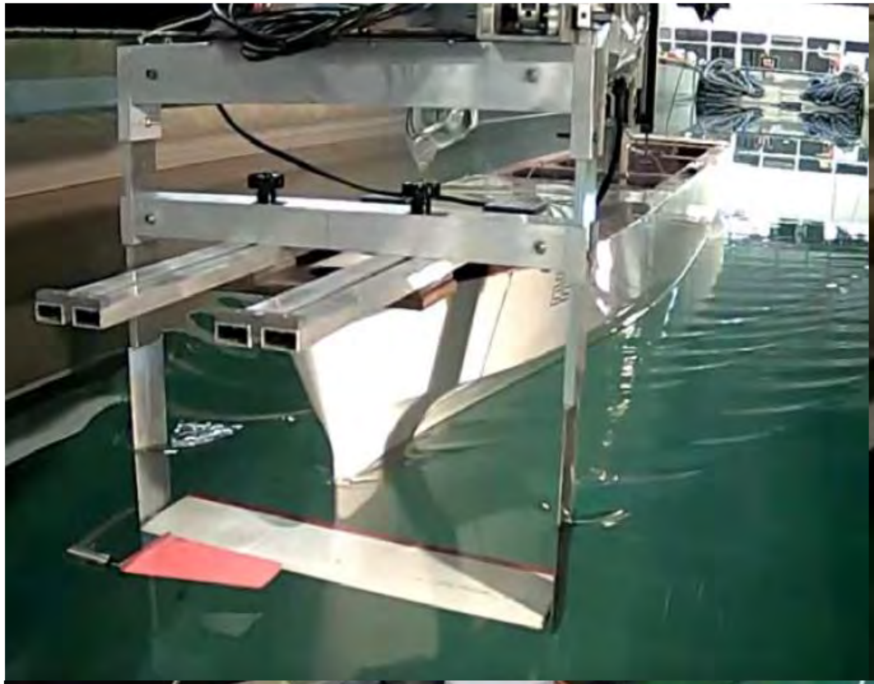


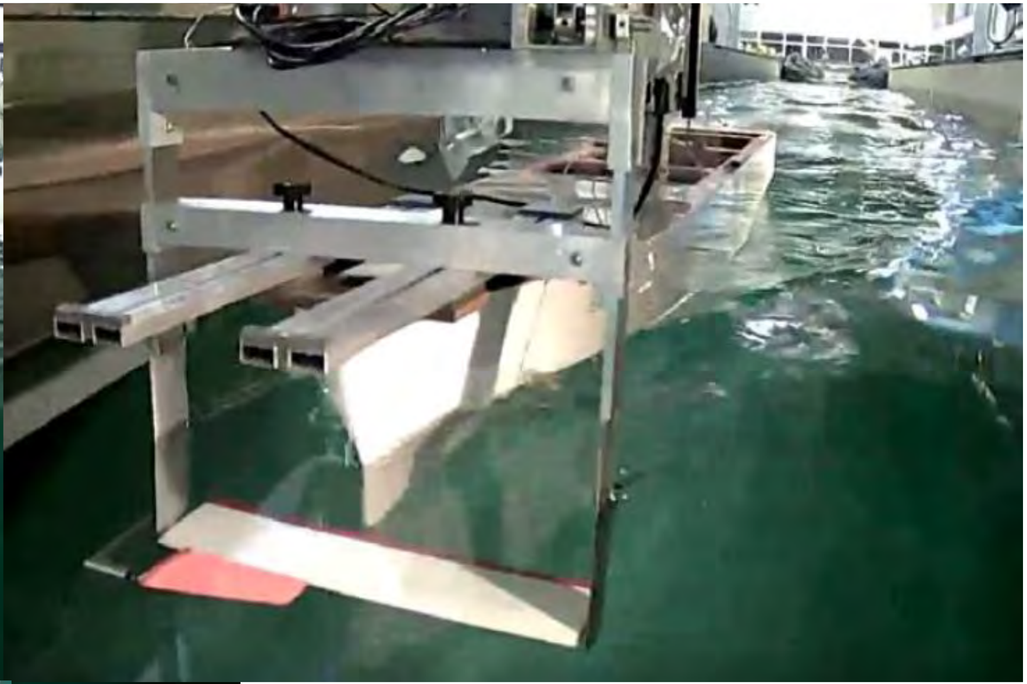
→ **3D wing-hull-free surface interaction multiple flapping wing arrangements**

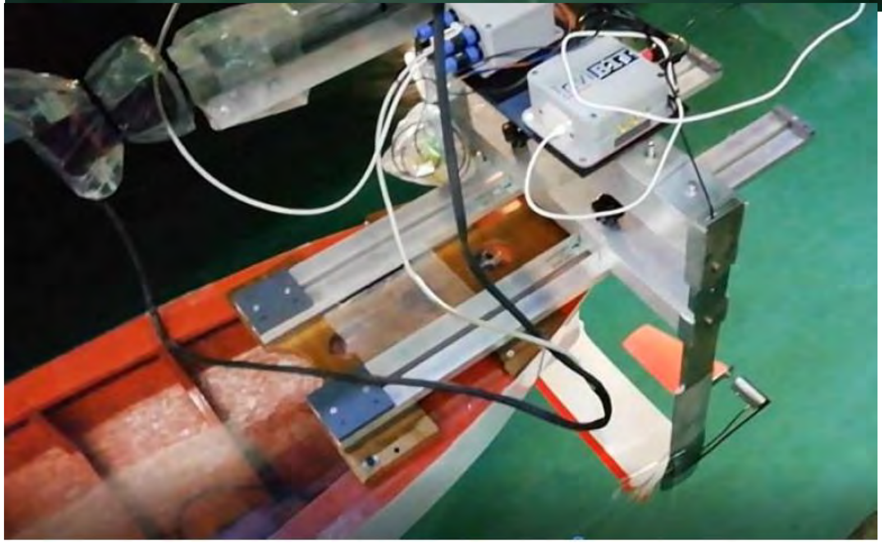
→ **BiopropShip project (2012-2015)**
http://arion.naval.ntua.gr/~biopropship/description_en.html

→ **V.Tsarsitalidis PhD thesis (NTUA 2015), E.Filippas PhD thesis (NTUA 2019)**

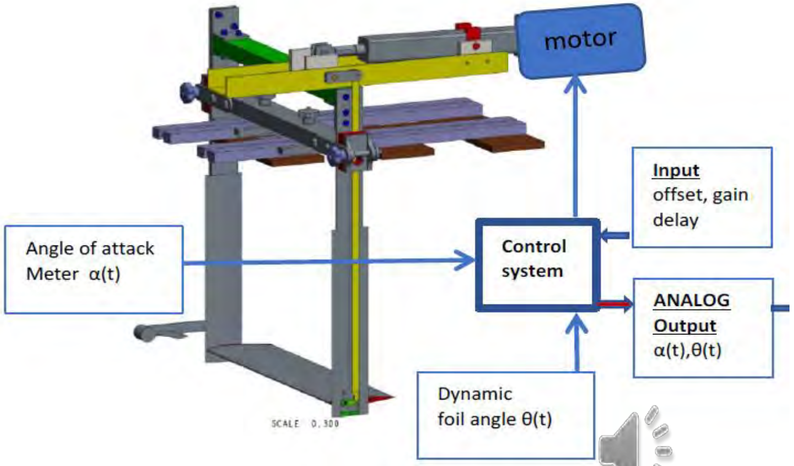
→ running experimental investigation at NTUA







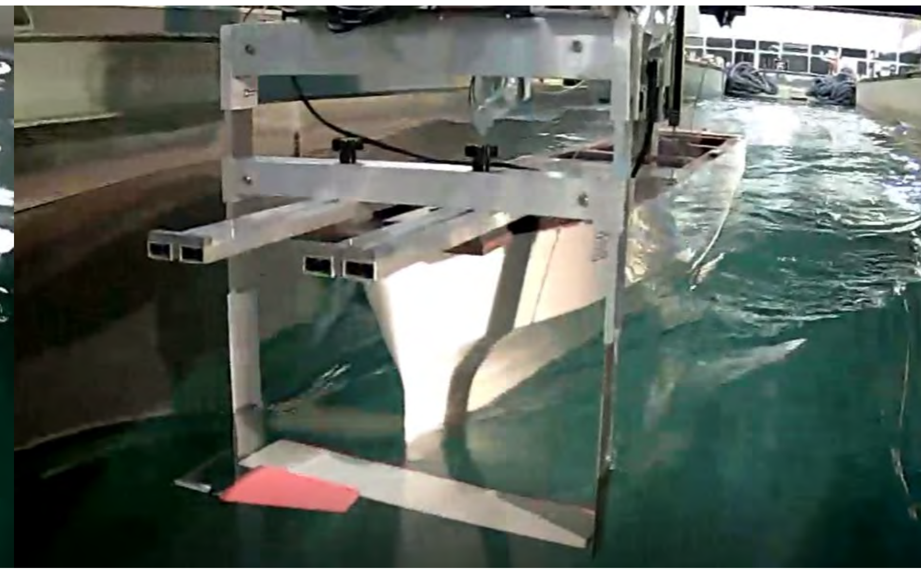
Seatech H2020 project



→ running experimental investigation at NTUA (Seatech)

U=1.42m/s (F=0.25), head waves H=6cm, f=0.67Hz

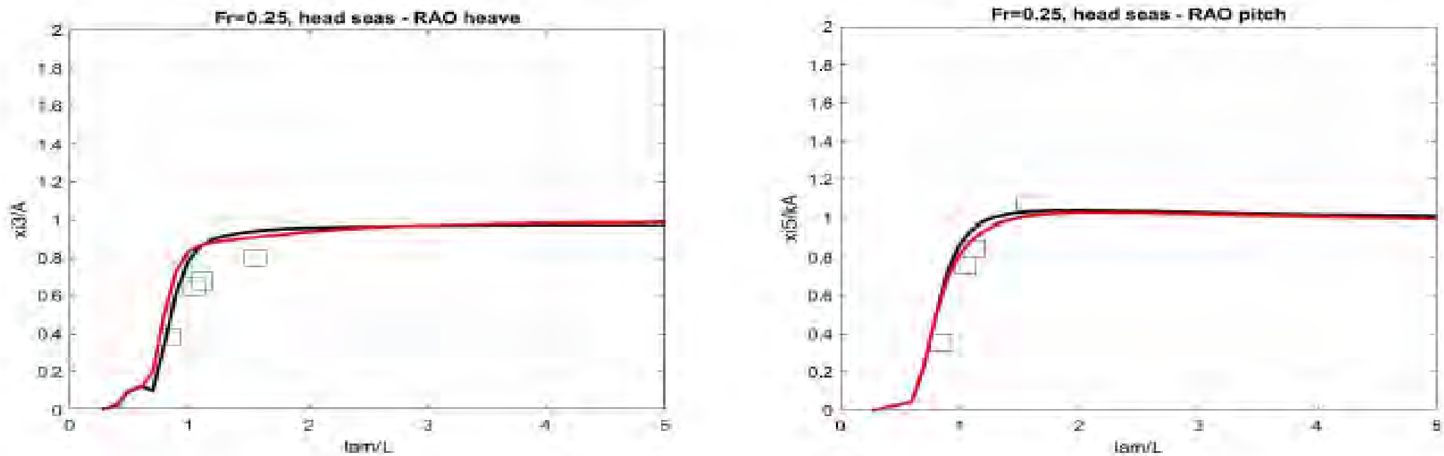
ship responses without foil **with dynamic foil**



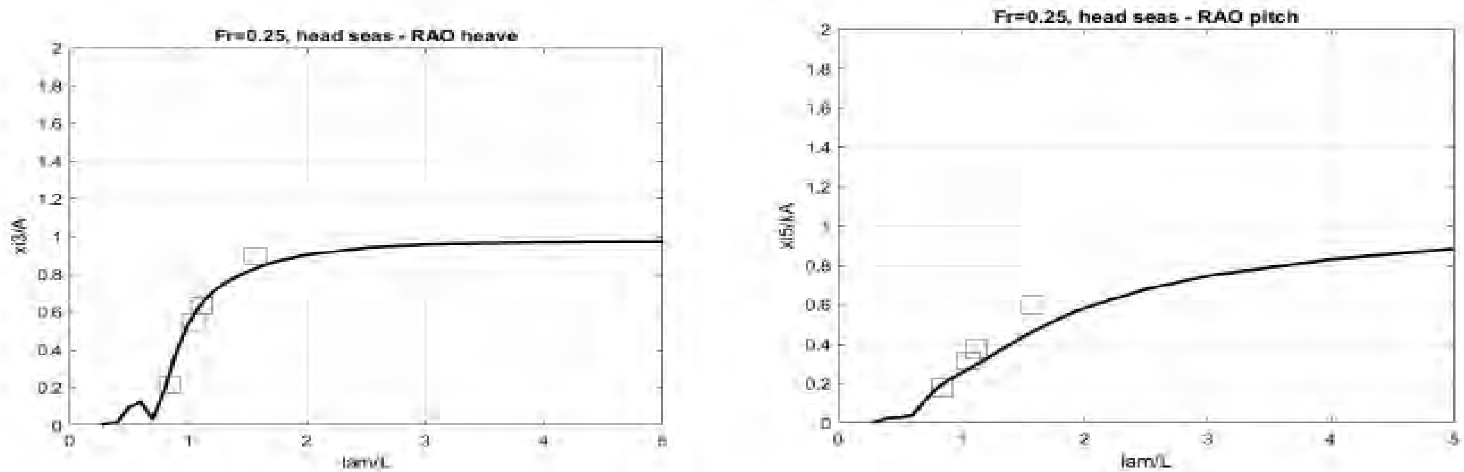
→ results from experimental investigation at NTUA

U=1.42m/s (F=0.25), head waves H=6cm

RESPONSES WITHOUT FOIL



RESPONSES WITH DYNAMIC FOIL



→ results from experimental investigation at NTUA tank

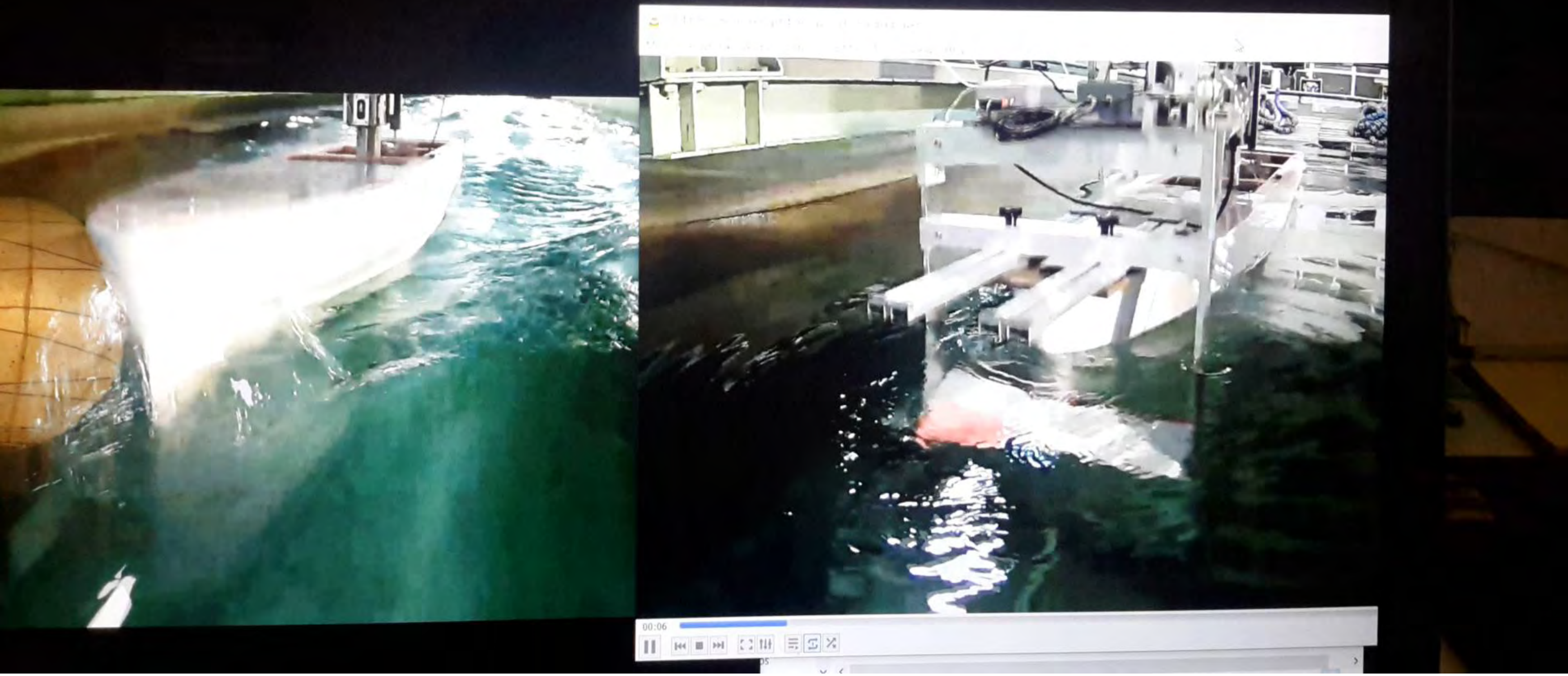
U=1.42m/s (F=0.25), head waves H=6cm

λ/L	G=0 (foil fixed) enhancement %	G=0.5 %	G=-0.25 %	G=-0.25(*) %
1.56	-12	-14	-9	2
1.12	10	4	14	25
1.05	16	6	18	29
0.84	1	-1	4	15

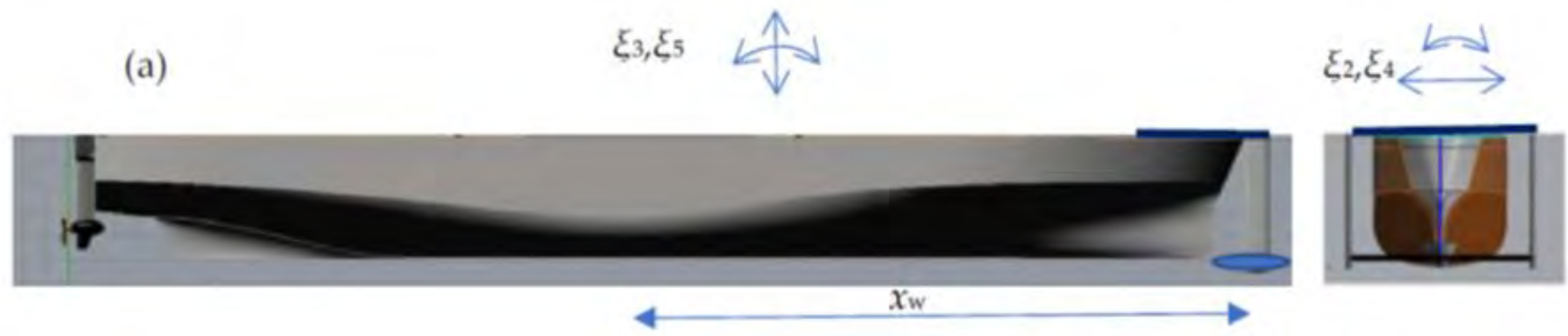
→ running experimental investigation at NTUA (Seatech)

U=1.42m/s (F=0.25), head irregular waves Hs=6cm

responses without foil — with dynamic foil



System (ship and flapping foil) dynamics – time domain



Time domain equations (simplified model)

$$(M + A_{33})\ddot{\xi}_3 + B_{33}\dot{\xi}_3 + C_{33}\xi_3 + A_{35}\ddot{\xi}_5 + B_{35}\dot{\xi}_5 + C_{35}\xi_5 = F_3, \quad F_{3,5}(t;U,\varphi_{INC},\xi,\theta) =$$

$$(I + A_{55})\ddot{\xi}_5 + B_{55}\dot{\xi}_5 + C_{55}\xi_5 + A_{53}\ddot{\xi}_3 + B_{53}\dot{\xi}_3 + C_{53}\xi_3 = F_5, \quad = F_{3,5}^{S}(t) + F_{3,5}^{f}(t)$$

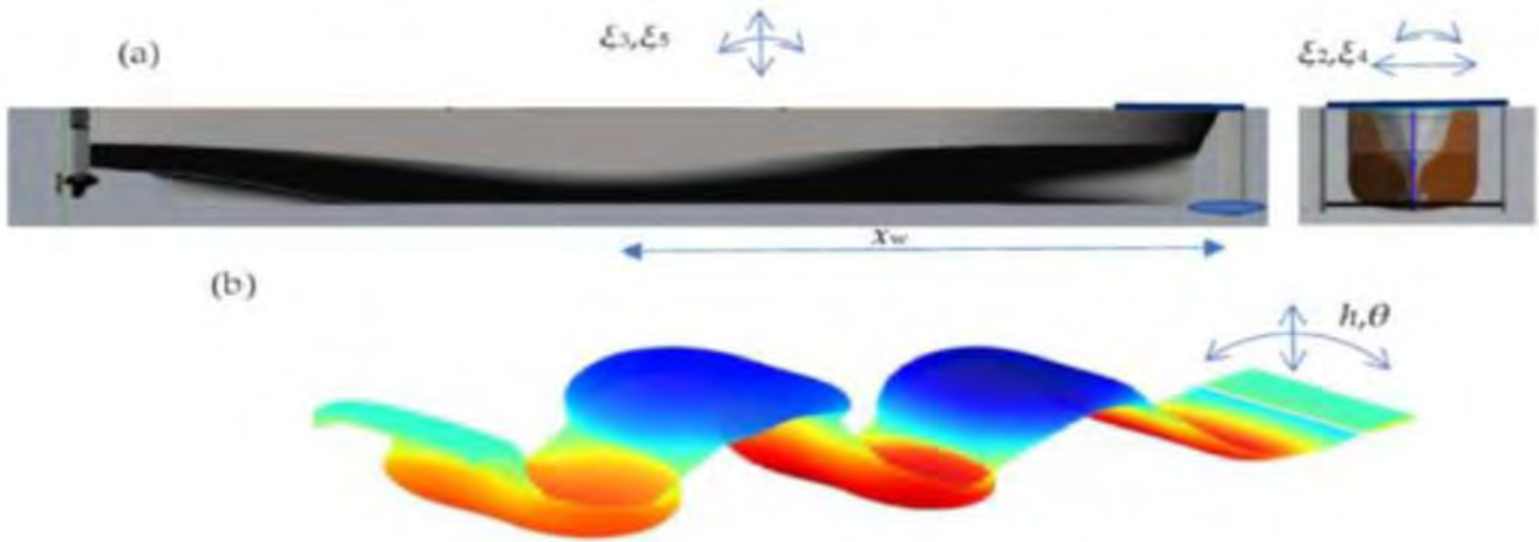
Ship frame of reference with encounter frequency: $\omega = \omega_0 + kU,\ k = \omega_0^2 / g$

Approximation: added mass & damping coefficients at peak period

Calculation of excitation forces from Frequency Response functions:

$$F_{3,5}^{S}(t) = G(t)R\left(\sum_n F_{3,5}(\omega_n)e^{j\omega_n t}\right), \quad F_{3,5}(\omega_n) = FRF_{3,5}^{Fn} A_n$$

Flapping thruster dynamics



Flapping wing forces: $F^{f}_{3,5}(t; U, \xi_3, \xi_5, \varphi_{INC}, \theta)$

$$h_0 = \xi_3 - x_w \xi_5$$

$$\varphi_{INC} = \Lambda \exp(kz + ikx)$$

Dependent on ship oscillatory amplitudes & incoming wave potential

3D BEM models: **Filippas & Belibassakis EABE(2014), Filippas & Belibassakis (OE2022)**

Dynamic foil active control

Foil in irregular head waves

angle of attack:

$$a(t) = -\xi_5(t) + \underbrace{\tan^{-1}\left(\frac{-dh(t)/dt}{-U}\right) + \frac{\partial \varphi_{INC}}{U\,\partial z}}_{\Phi(t)} - \theta(t)$$

heaving motion of the hydrofoil:

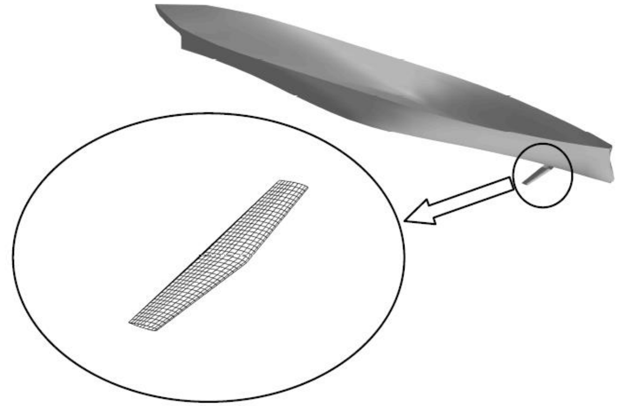
$$h(t) = \xi_3(t) - x_{wing}\,\xi_5(t)$$

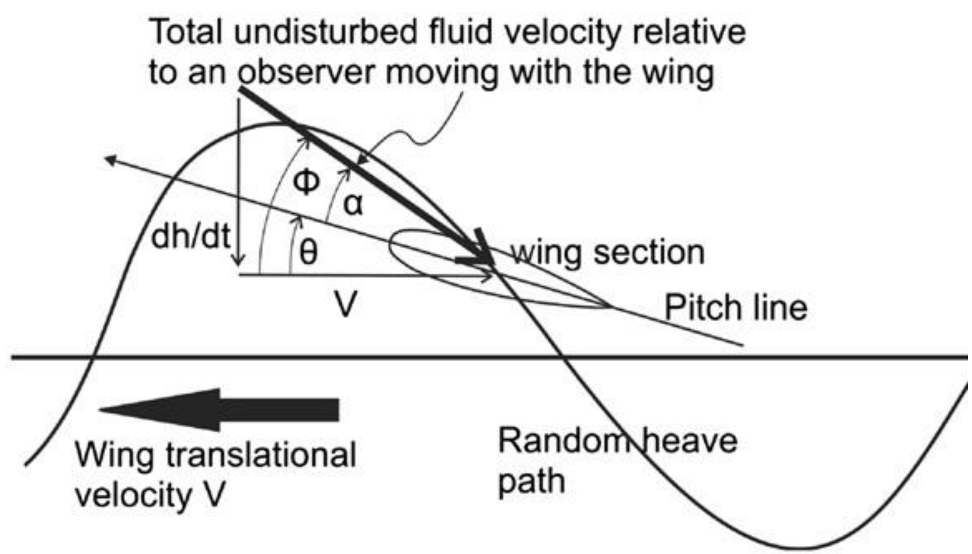
active pitch (θ) control:

$$\theta(t) = w\Phi(\mathrm{t})$$

dynamic angle of attack:

$$a(t) = (1-w)\tan^{-1}\left(\frac{-dh(t)/dt}{-U}\right) - \xi_5(t)$$





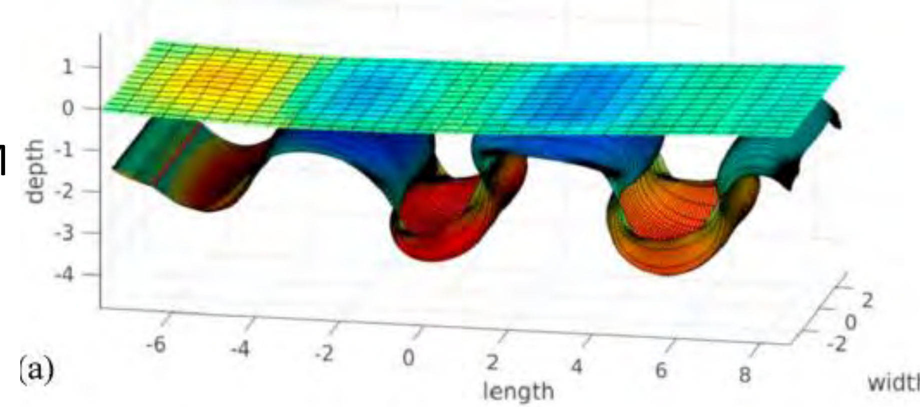
Belibassakis & Politis (OE 2013)

BEM & CFD modelling

- BEM: 88 seconds in a GPU
  with 2560 single precision cores

Filippas &Belibassakis (OE 2022)

BEM

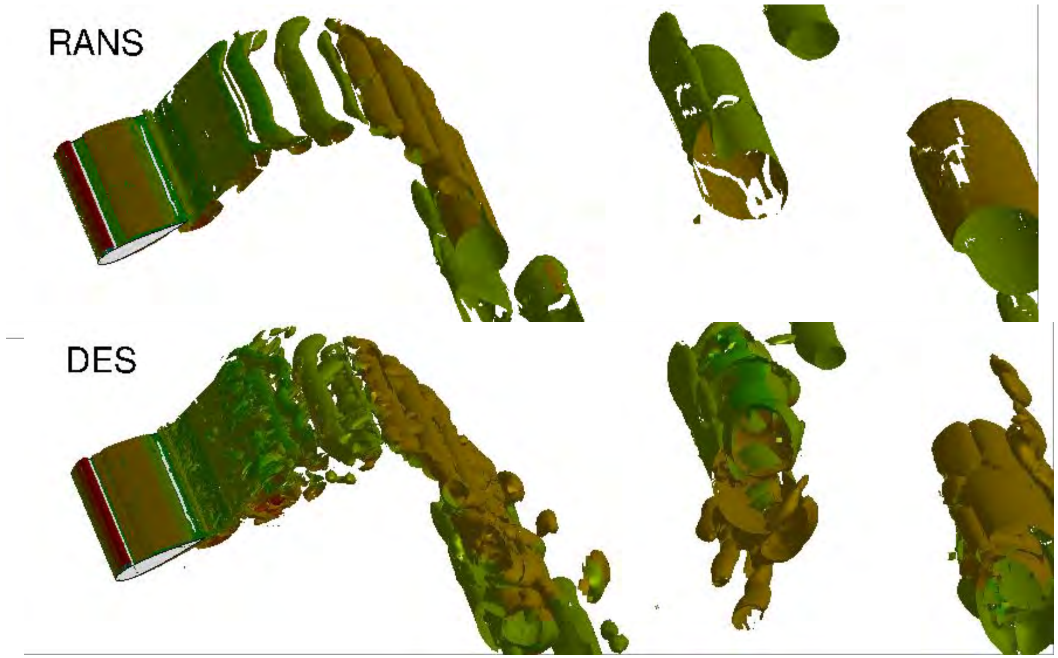


- RANS: 5 hours in 120 CPU cores

- DES: 12 hours in 1000 CPU cores

Filippas et al (JMSE2021),

Ntouras et al (JMSE 2022)



Surge motion dynamics

Forward motion dynamics: $(1-t)N_pT_p + T_{foil} + R_{AW} + F_{FK} = (M_B + A_{11})\ddot{\xi}_1 + B_{11}\dot{\xi}_1$

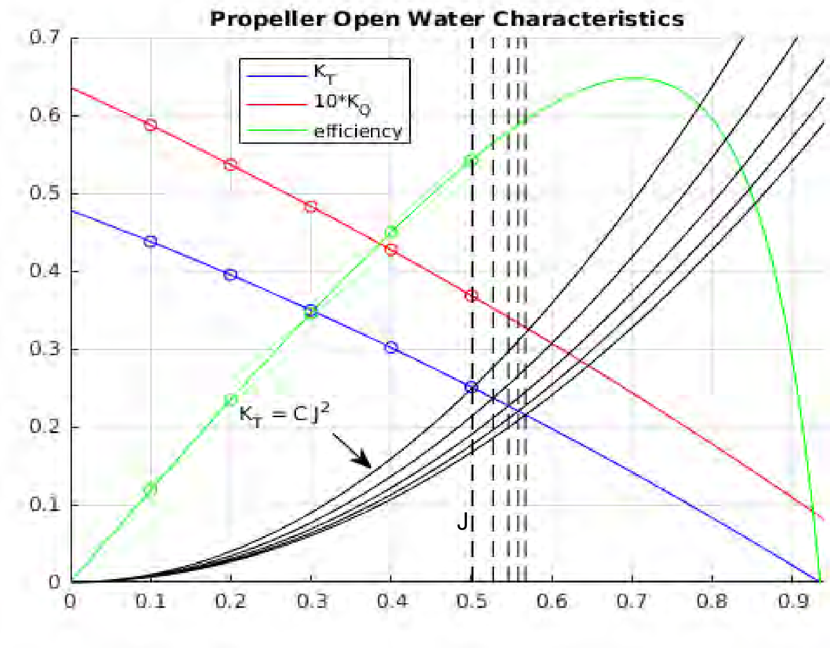
Calculation of propeller loads and RPM (n_p)

$$T_p = \rho n_p^2 D^4 K_T(J;P/D)$$

$$Q_p = \rho n_p^2 D^5 K_Q(J;P/D),\ \eta_p = \eta_p(J;P/D)$$

$$\frac{K_T}{J^2} = \frac{R + R_{AW}}{\rho(1-t)(1-w)^2(U+|\dot{\eta}_1|)^2 D^2}$$

$$\Rightarrow \quad T_p(t),\ n_p(t) = (1-w)U/(JD)$$

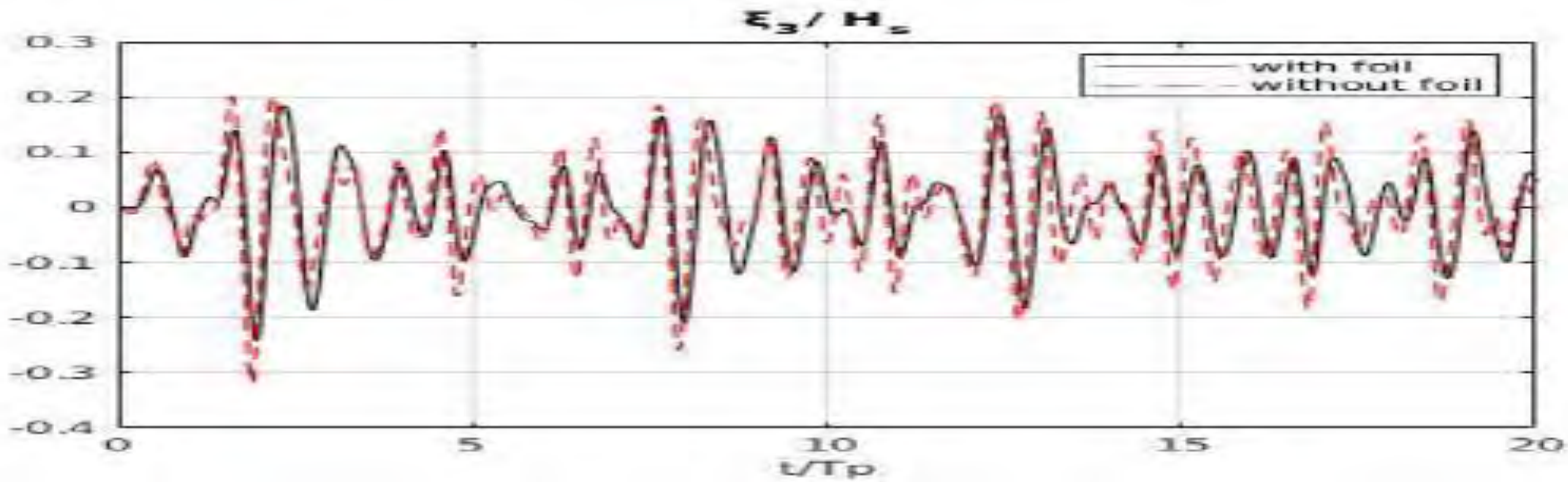


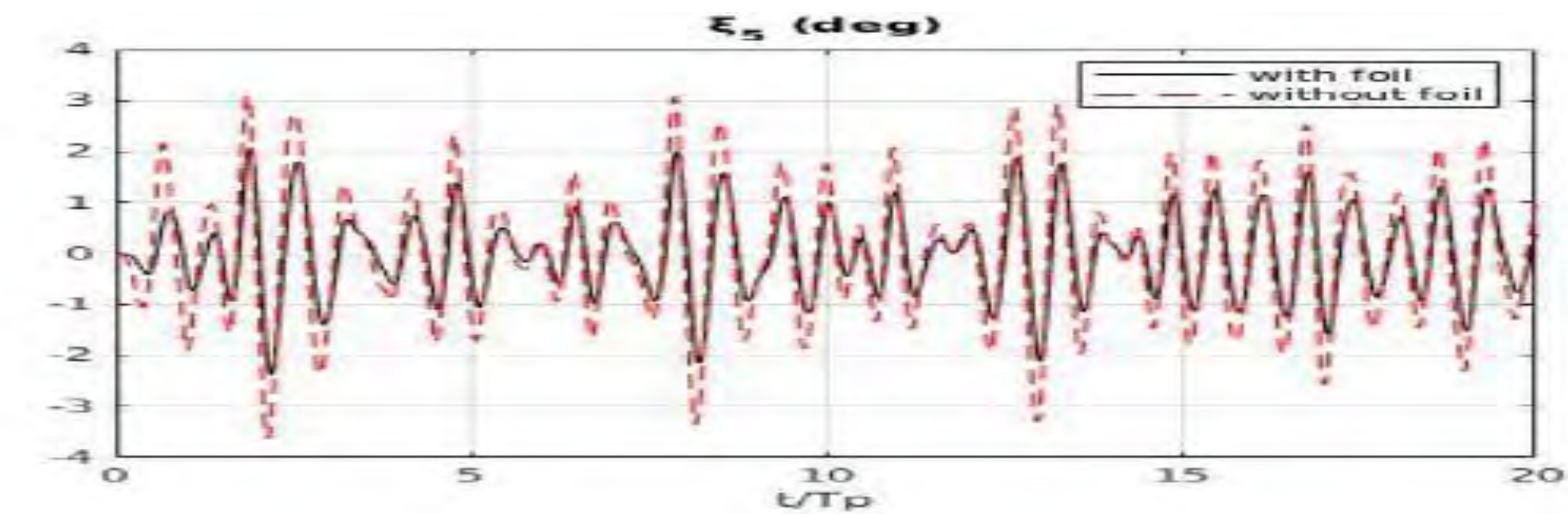
Added wave resistance

$$R_{AW} = \frac{1}{2}\frac{\omega^3}{g}\left[\left(B_{33} + \frac{L_c}{U}\right)\xi_3^{\ 2} + \left(B_{55} + \frac{L_c x_f^{\ 2}}{U}\right)\xi_5^{\ 2} - 2\left(B_{35} + \frac{L_c x_f}{U}\right)\xi_3\xi_5\right]$$

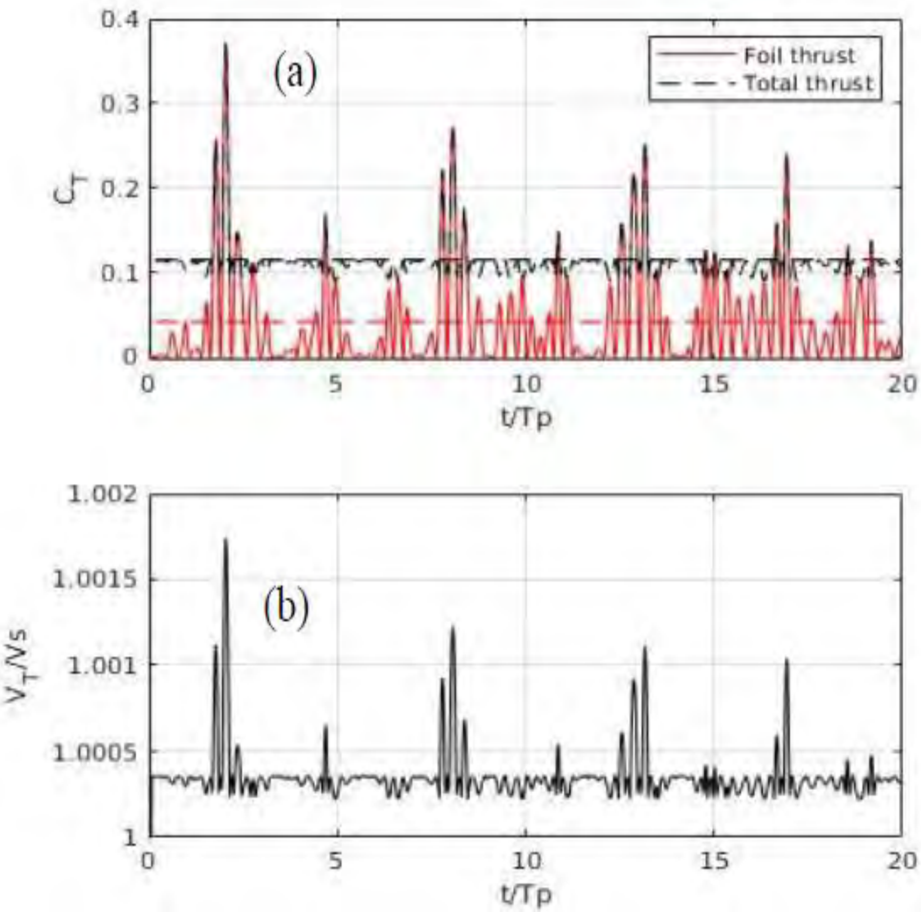
and hydrodynamic damping $\quad B_{11} = \frac{dR_T}{d\dot{\xi}_1} = \frac{d(R_{SW} + R_{AW} + D)}{d\dot{\xi}_1}$

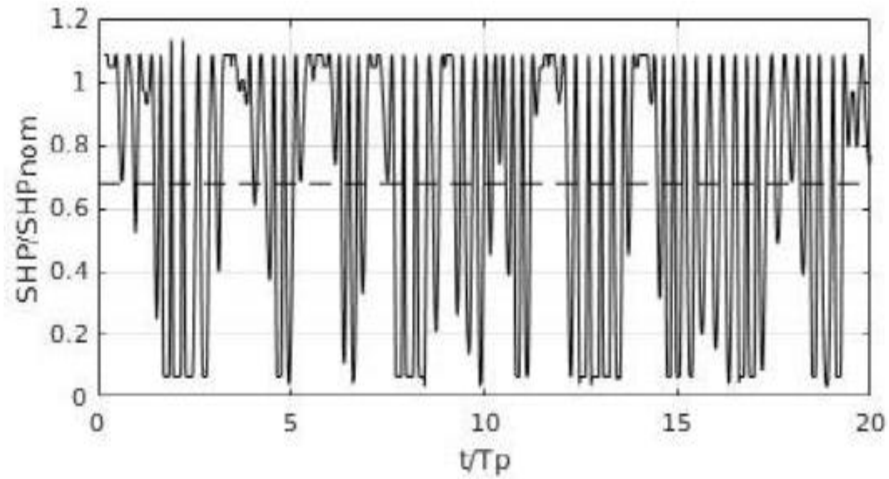
Ship responses without &with the dynamic foil



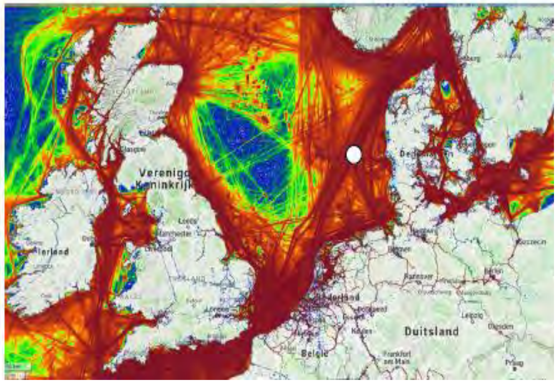


Flapping thruster performance and responses in irregular waves

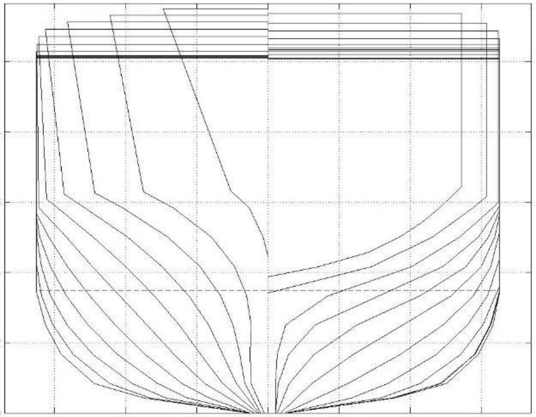


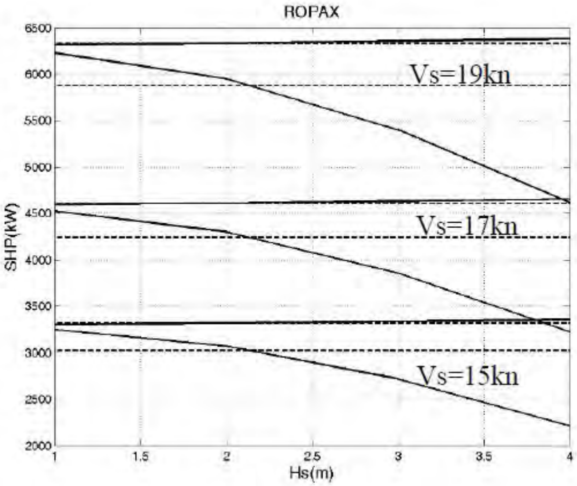


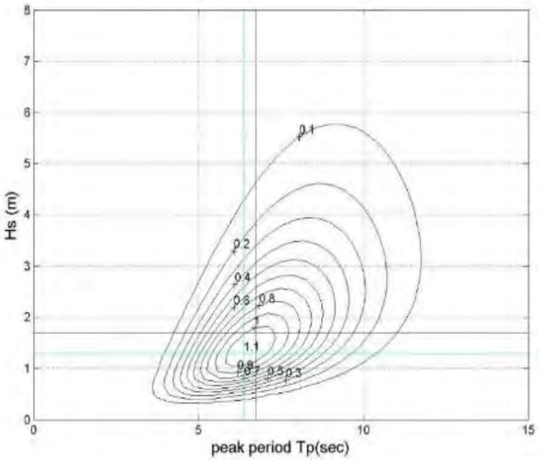
Combined performance calculations for a ferry ship based on North Sea climatological data

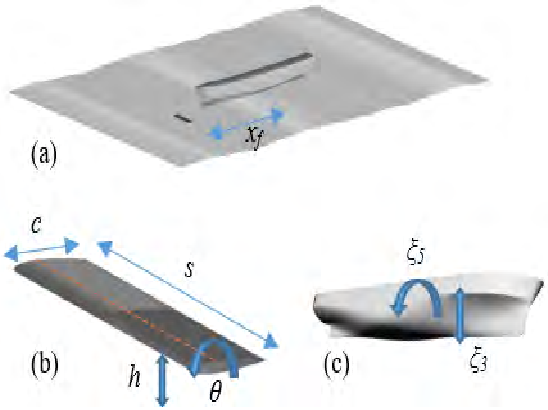


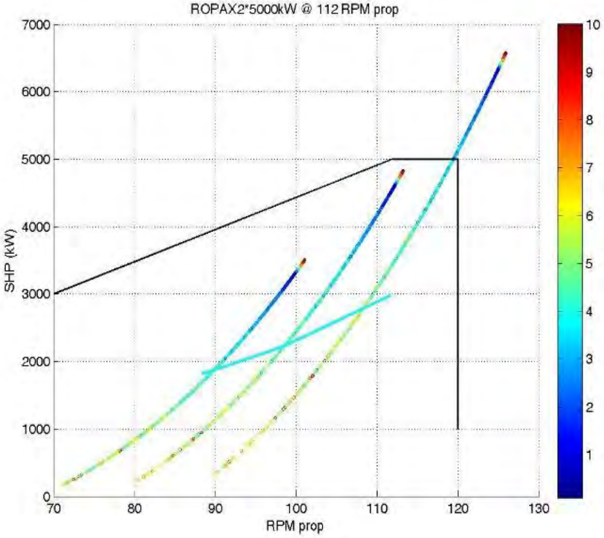
ROPAX 140m











Conclusions

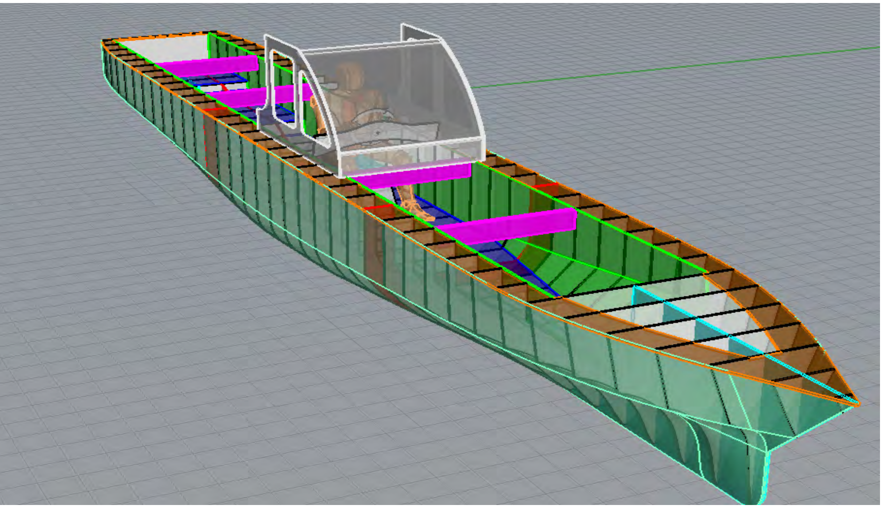
Flapping foil thrusters arranged at the bow of a ship are exploited for **augmenting the overall propulsion in waves** by directly converting kinetic energy from ship motions to thrust and improving dynamic stability.

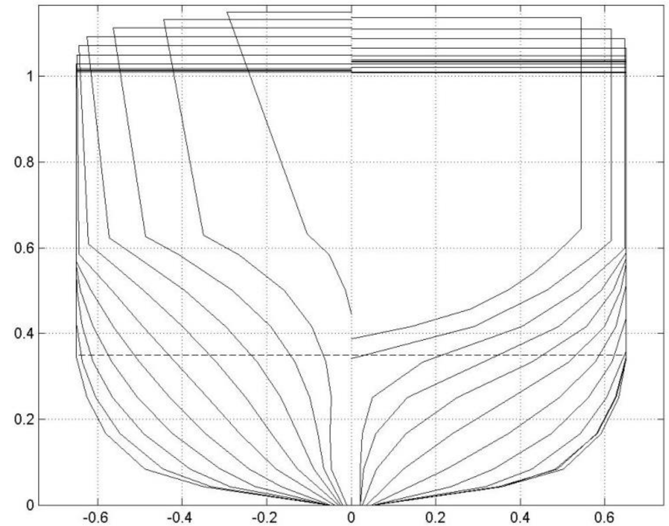
A dynamical model is presented and applied to a ferry ship model illustrating the **complementary nature of dynamic wing and engine innovations.**

Results show that the **additional thrust generated by the dynamic wing** enables the engine to operate in part-load without compromising vessel speed, resulting in an additional positive effect on its emission profile.

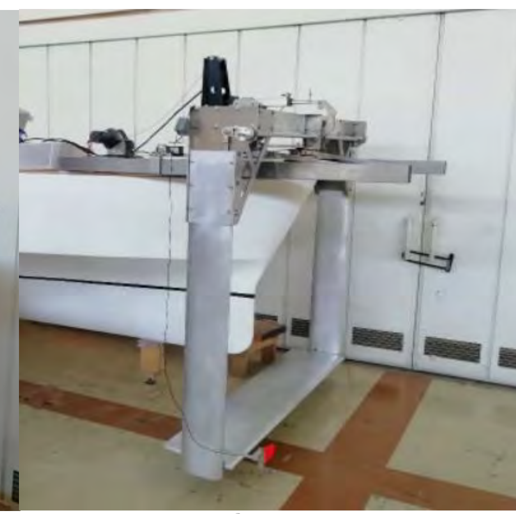
Future work is planned towards the development of **more accurate methods for the prediction of short- and long-time combined dynamics of ship engine – biomimetic thruster performance in waves** for a variety of ship types.

Next Steps: large-scale 10m self-propelled model
with dynamic wing at the bow - construction & testing at sea





L=10m
B=1.3m
D=1.0m
T=0.35m
Δ=2100kp
Cb=0.45
V=1.5-2.5m/s



Parallel/Next steps: ADAF for performance & LCCA Design for full scale ship

Advanced Data Analytics Framework to quantify the performance under calm water and various sea states in relation to fuel types.

Design of the wing for full-size ship including strength, fatigue and service-life considerations.

Mechanical wing-retractability concept for calm and heavy weather conditions, including elevator systems installed on deck for placing the dynamic wing in water and retract it out of the water in calm seas.

Evaluation of retrofitability and maintainability of both innovations at full scale for short-sea vessels.

"Μοναξιά"
Σάββατο 17/11/90

ΚΥΜΑΤΑ, ΠΙΘΑΝΟΤΗΤΕΣ ΚΑΙ ΑΝΑΜΝΗΣΕΙΣ









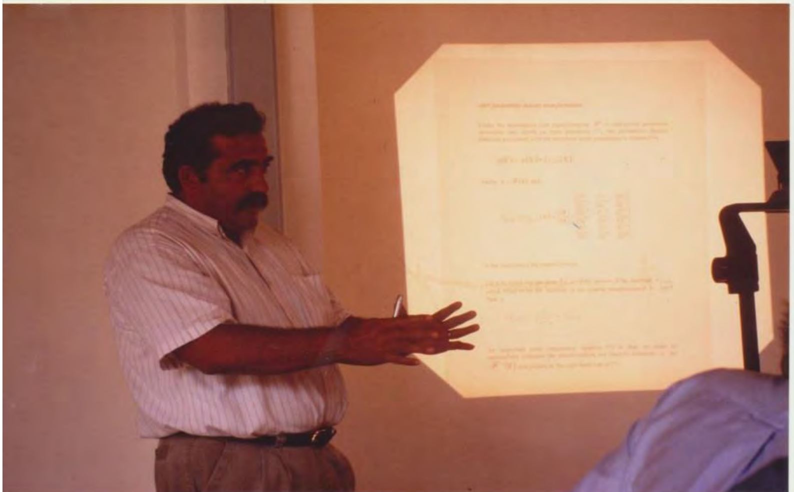


Δείπνο στο σπίτι
του D. Euvrard

16 Απριλίου 1991
(Παρίσι)

Σάββατο 21/12/91

Τέλος Αθηναϊκής
φάσεως του Σεμιναρί-
ου θαλάσσιας Τεχνο-
λογίας της Κρήτης



After a hard-working day....

πολιτιστικο
κεντρο
Αγιας Ευφημιας