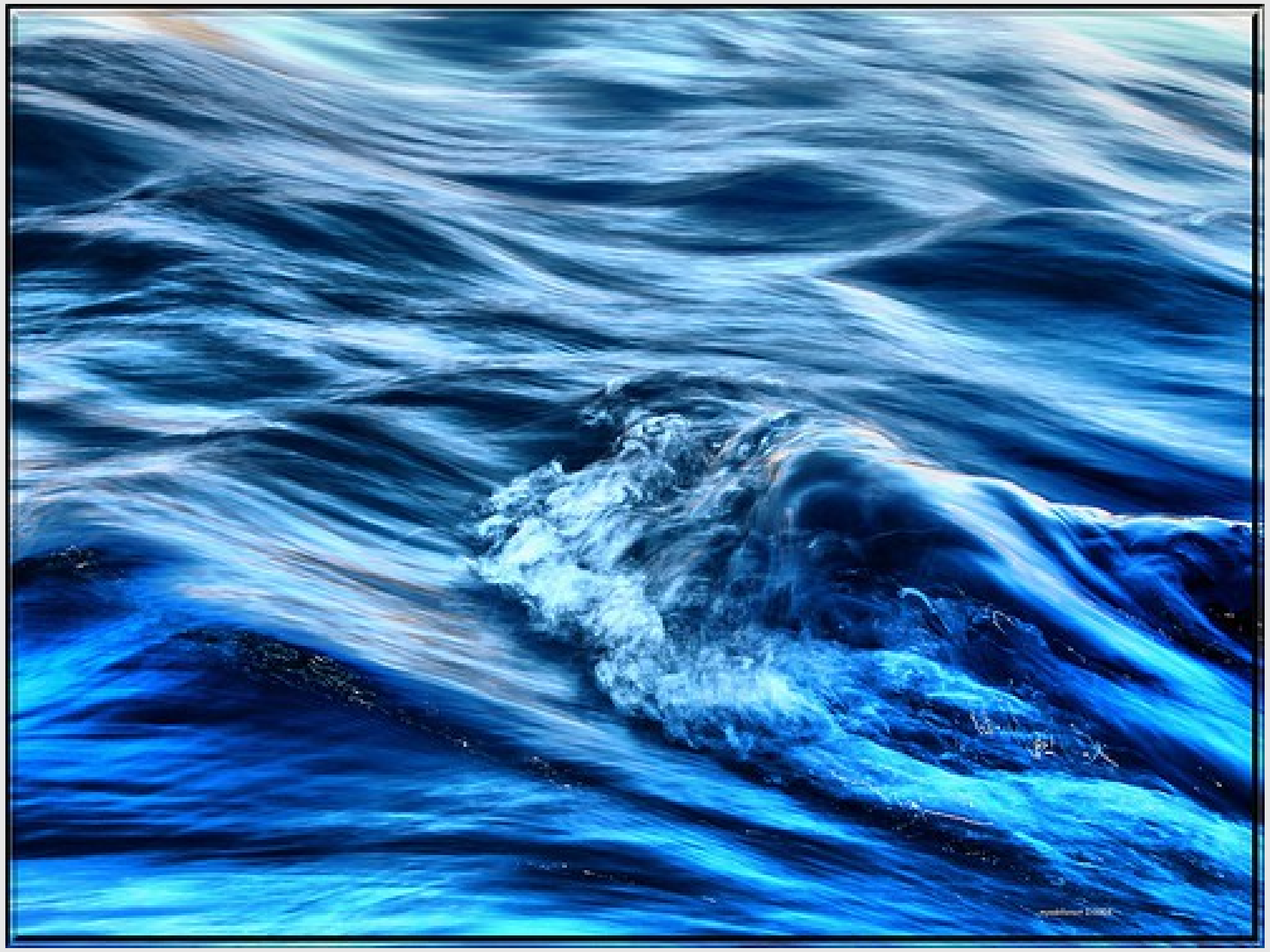
Soft in Flow: a Compliant Flow Sensing Underwater Robot



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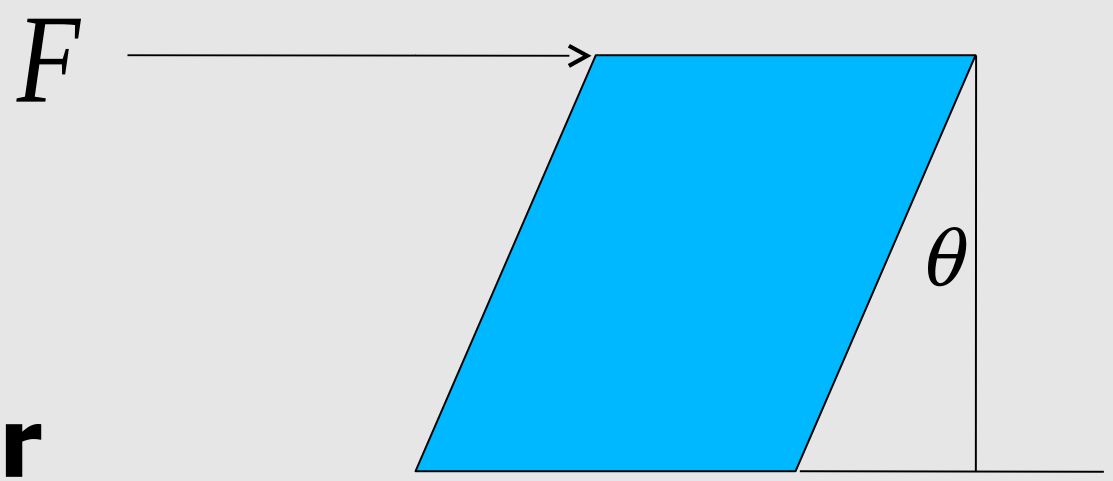
Prof. Maarja Kruusmaa
Tallinna Tehnikaülikool

Fluids

Solids resist shear deformation – shear stress is proportional to shear strain.

$$\frac{F}{S} = G$$



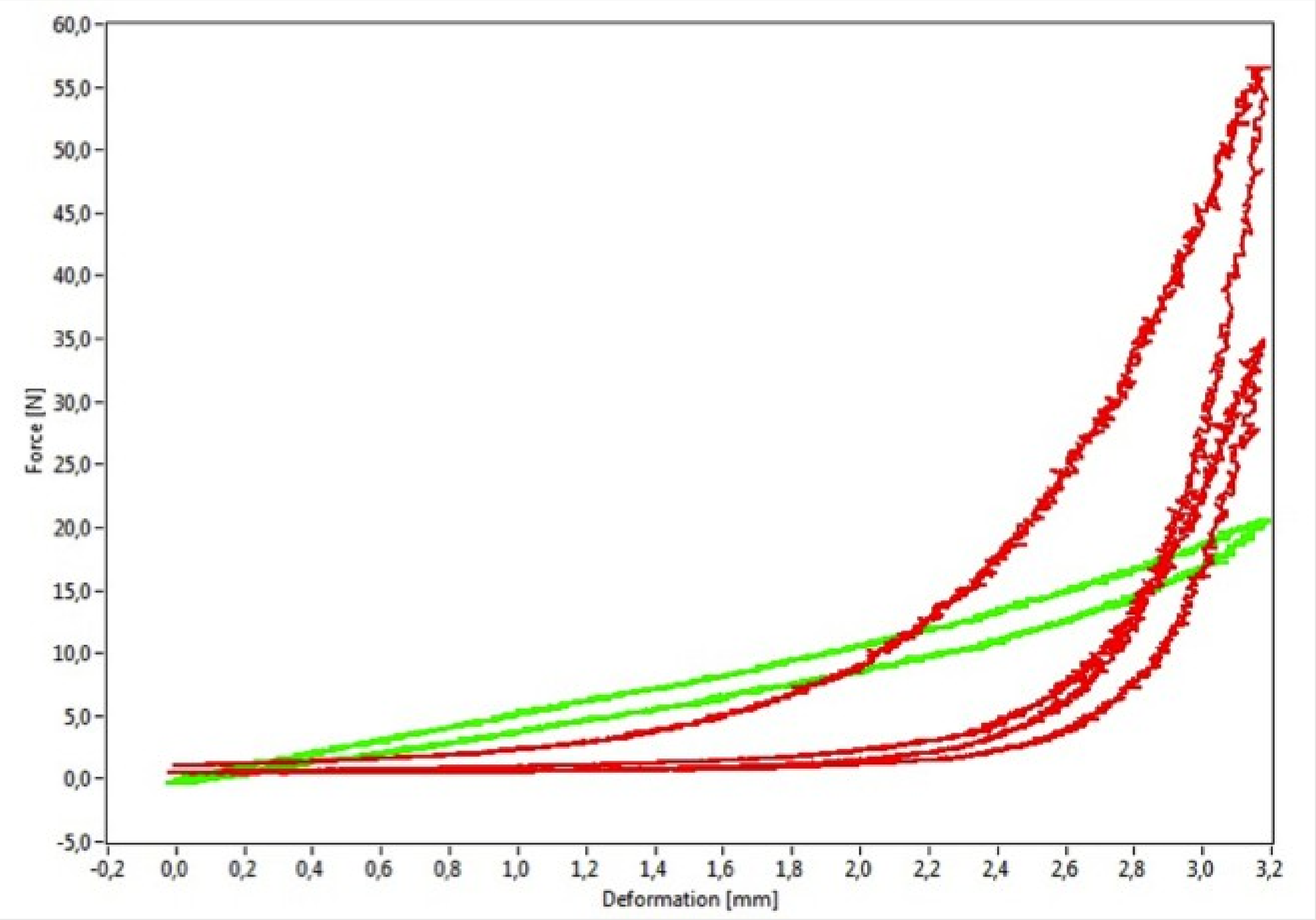
Fluids resist rate of shear

$$\frac{F}{S} = \frac{\quad}{t}$$

$$\tau = \mu \frac{dU}{dz}$$

For Newtonian fluids (dynamic) viscosity $\mu = const.$

Elasticity, viscosity and deformation



Dynamic modulus

Strain $\varepsilon = \varepsilon_0 \sin(t \quad)$

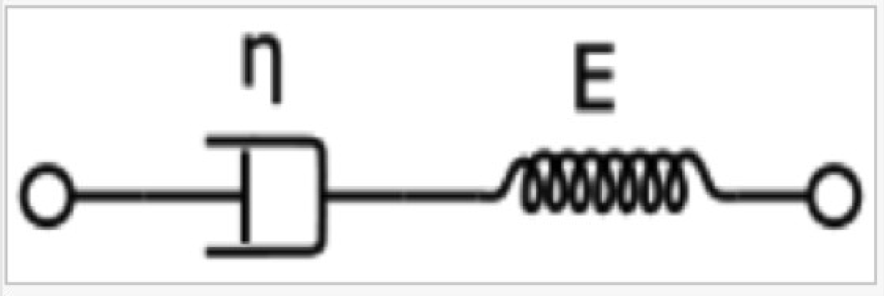
Stress $\sigma = \sigma_0 \sin(t \quad + \quad)$ δ - Phase lag

Elastic materials $\delta = 0$ Viscous materials $\delta = \dfrac{\pi}{2}$

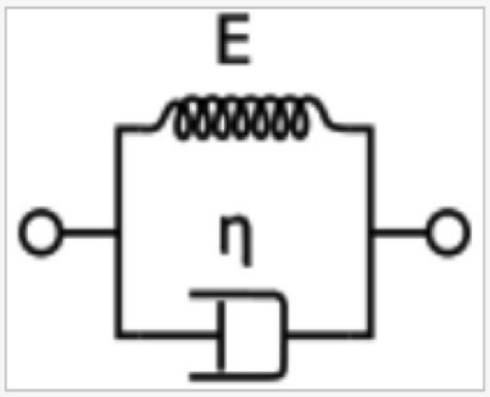
Elasticity : Storage modulus – energy conserved $E' = \dfrac{{}_0}{{}_0}\cos$

Viscosity: Loss modulus – energy dissipated $E'' = \dfrac{{}_0}{{}_0}\sin$

Springs and chock absorbers



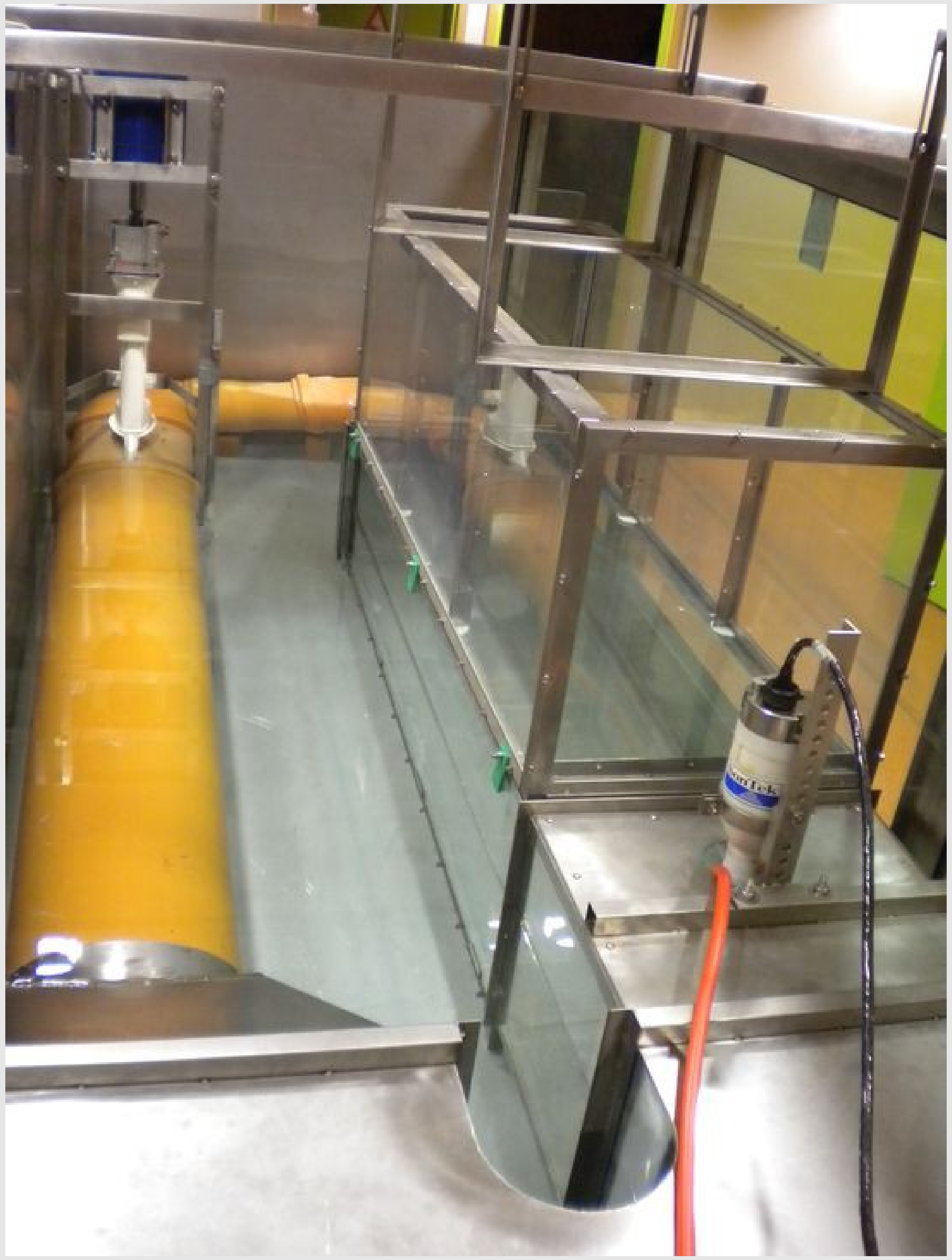
$$\frac{d\epsilon_{Total}}{dt} = \frac{d\epsilon_D}{dt} + \frac{d\epsilon_S}{dt} = \frac{\sigma}{\eta} + \frac{1}{E}\frac{d\sigma}{dt}$$



$$\sigma(t) = E\varepsilon(t) + \eta\frac{d\varepsilon(t)}{dt}$$

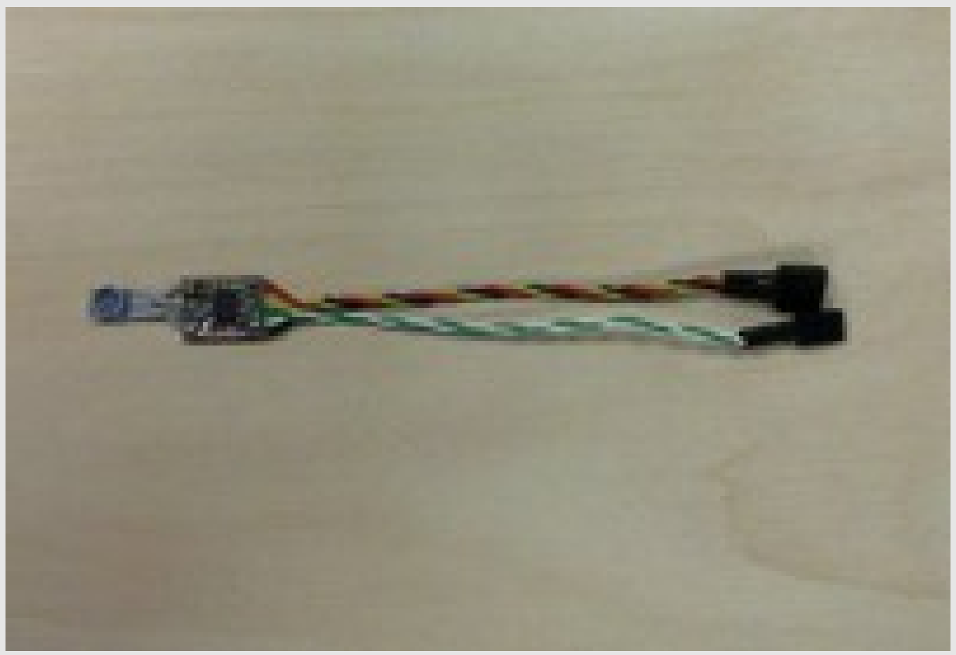
Solids are springs
Fluids are absorbers

How to we measure it?



Stress and pressure

Pressure sensors



$$p + \frac{U^2}{2} + \quad gz = const$$

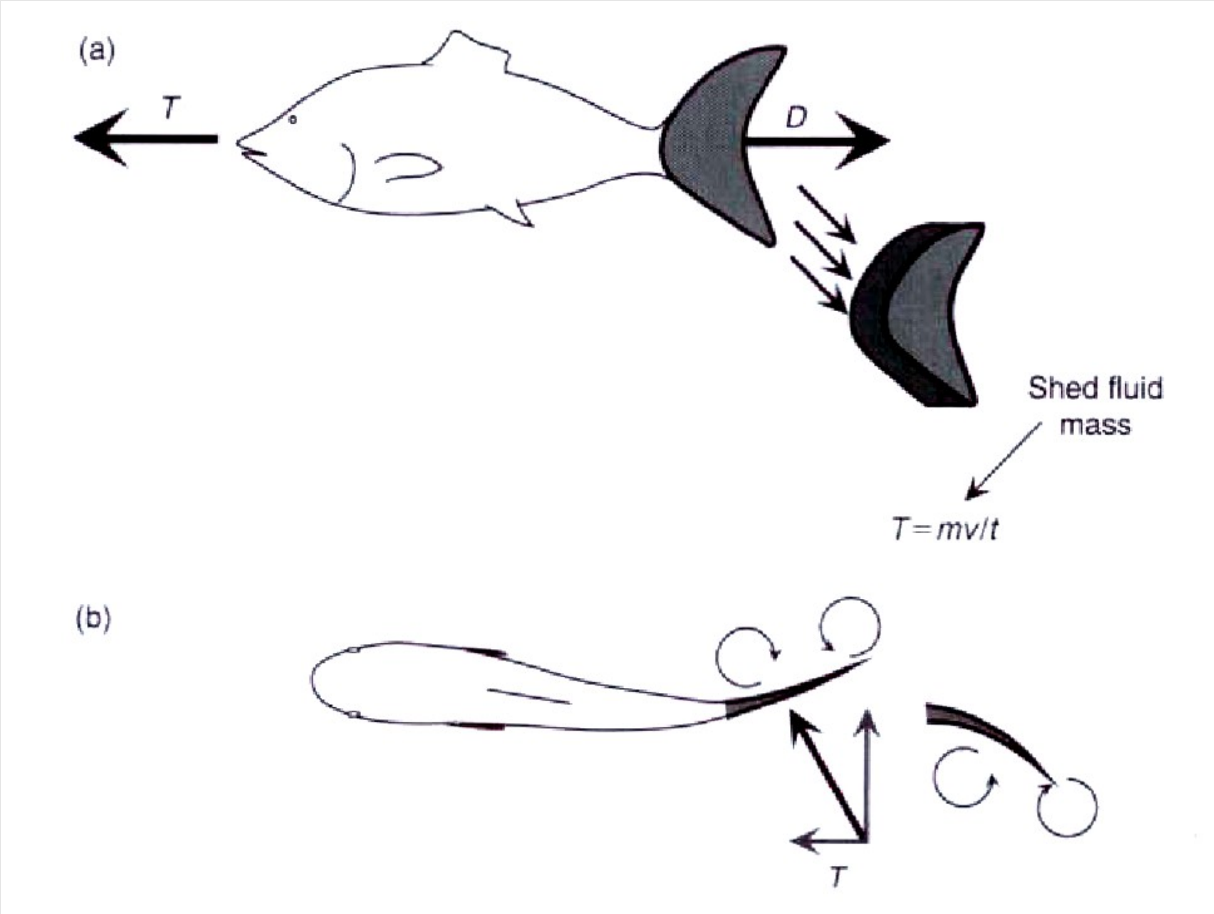
Bernoulli's principle

Momentum, thrust and drag

$$\frac{m}{t} = \rho S U$$

$$\frac{mU}{t} = \rho S U^2$$

$$dF = \rho dS_1 U_1^2 - \rho dS_2 U_2^2$$

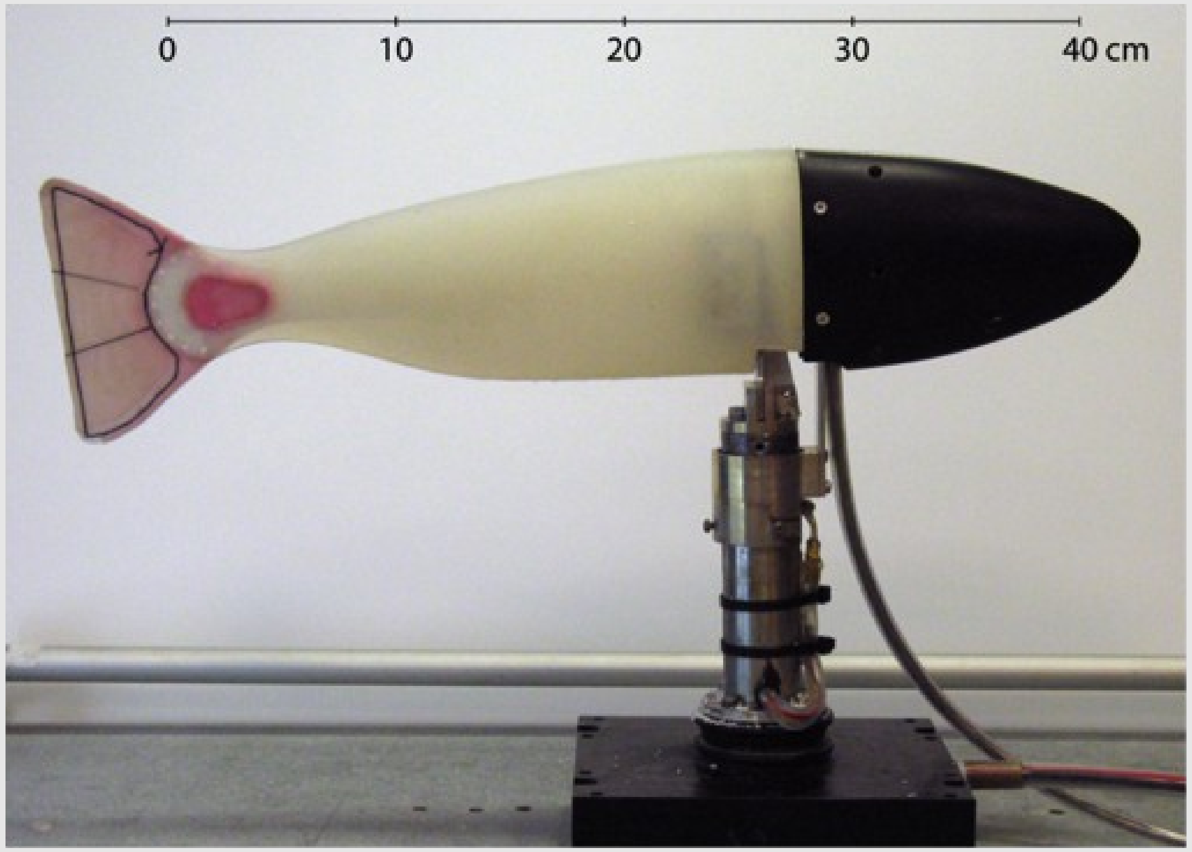


$$C_p = \frac{2\ p}{U^2}$$ Drag coefficient

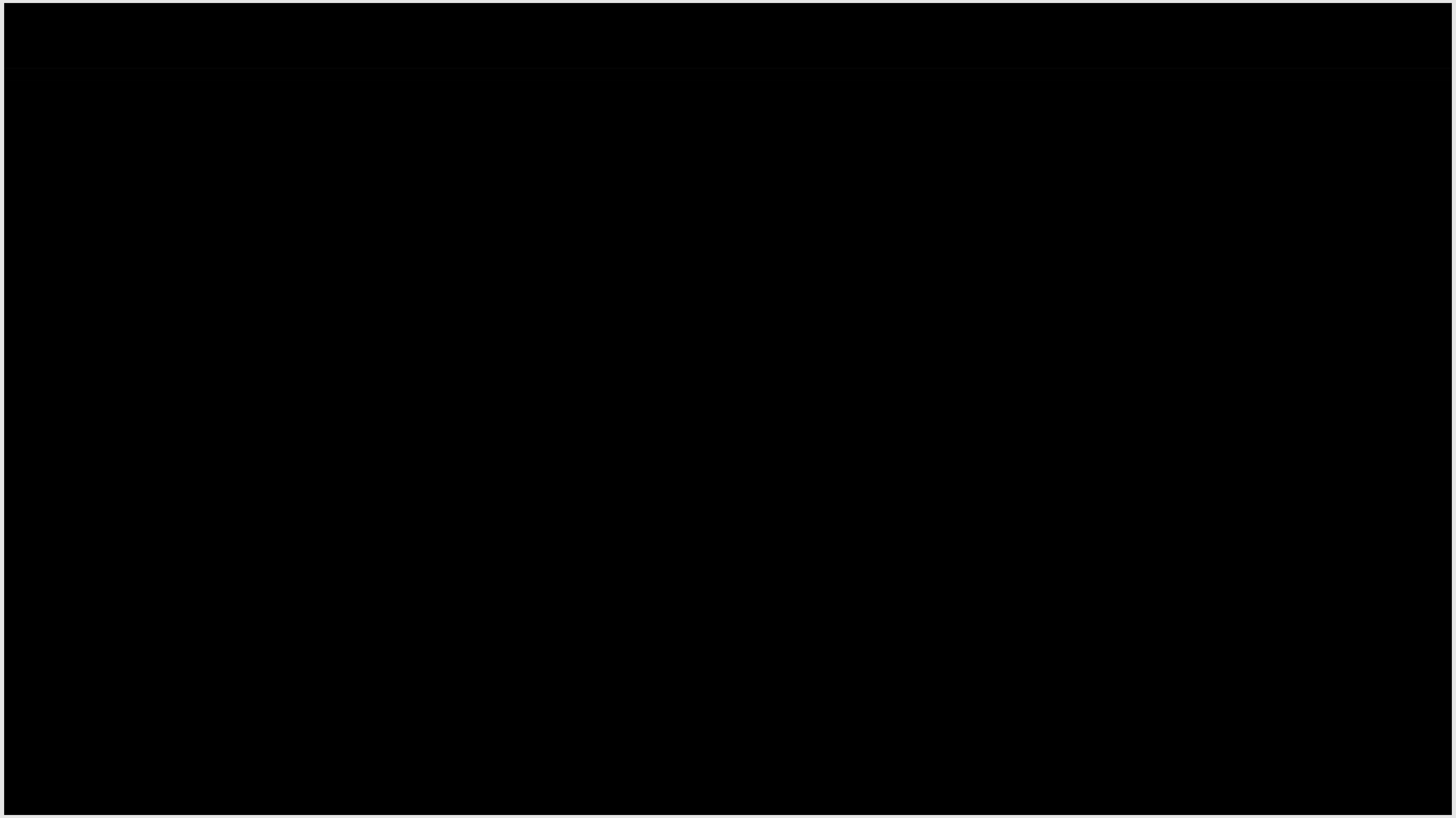
Drag is the removal of the momentum from the moving fluid
Thrust is the addition of the momentum to the moving fluid

How to we measure it?

Measuring forces with force and torque sensors

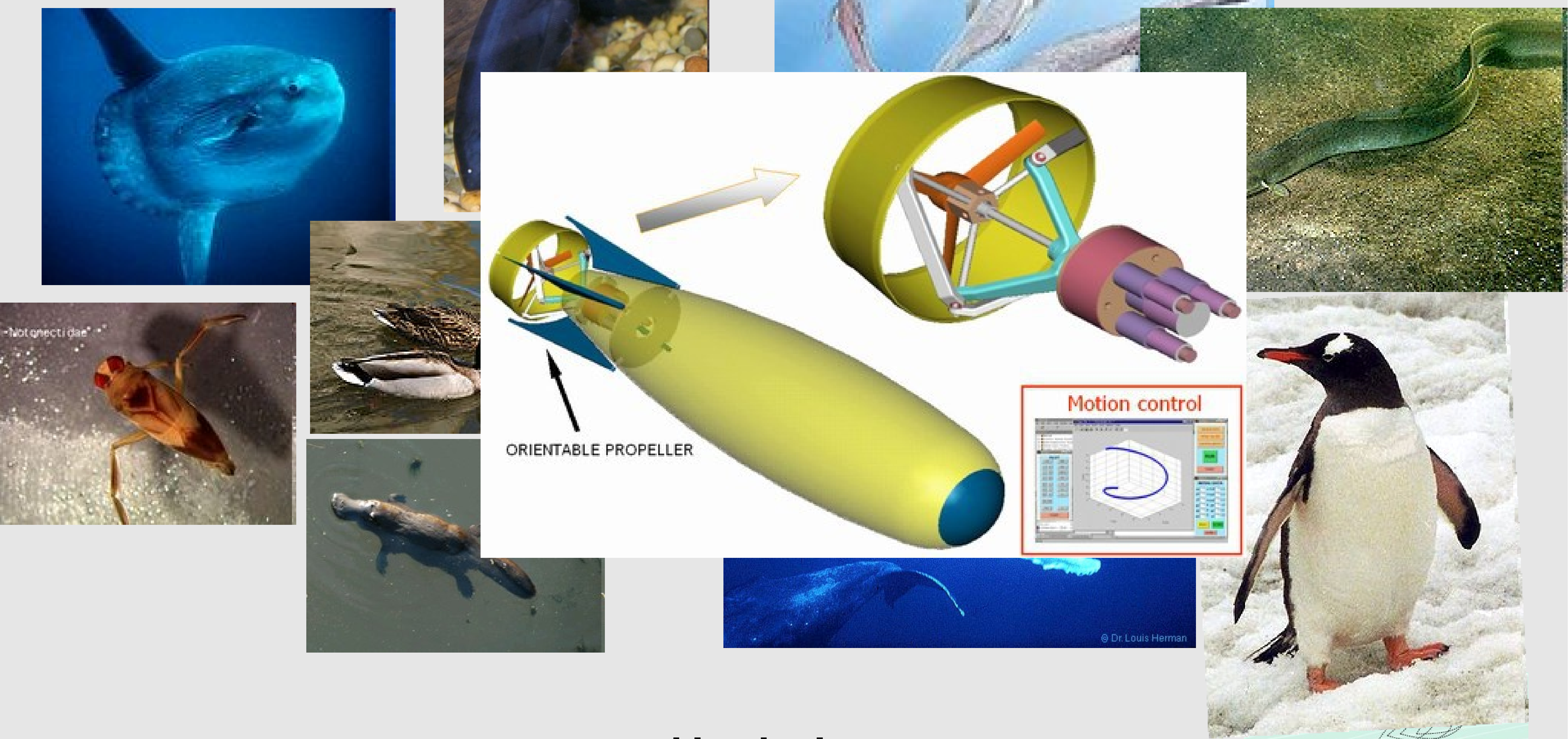


Controlling the speed

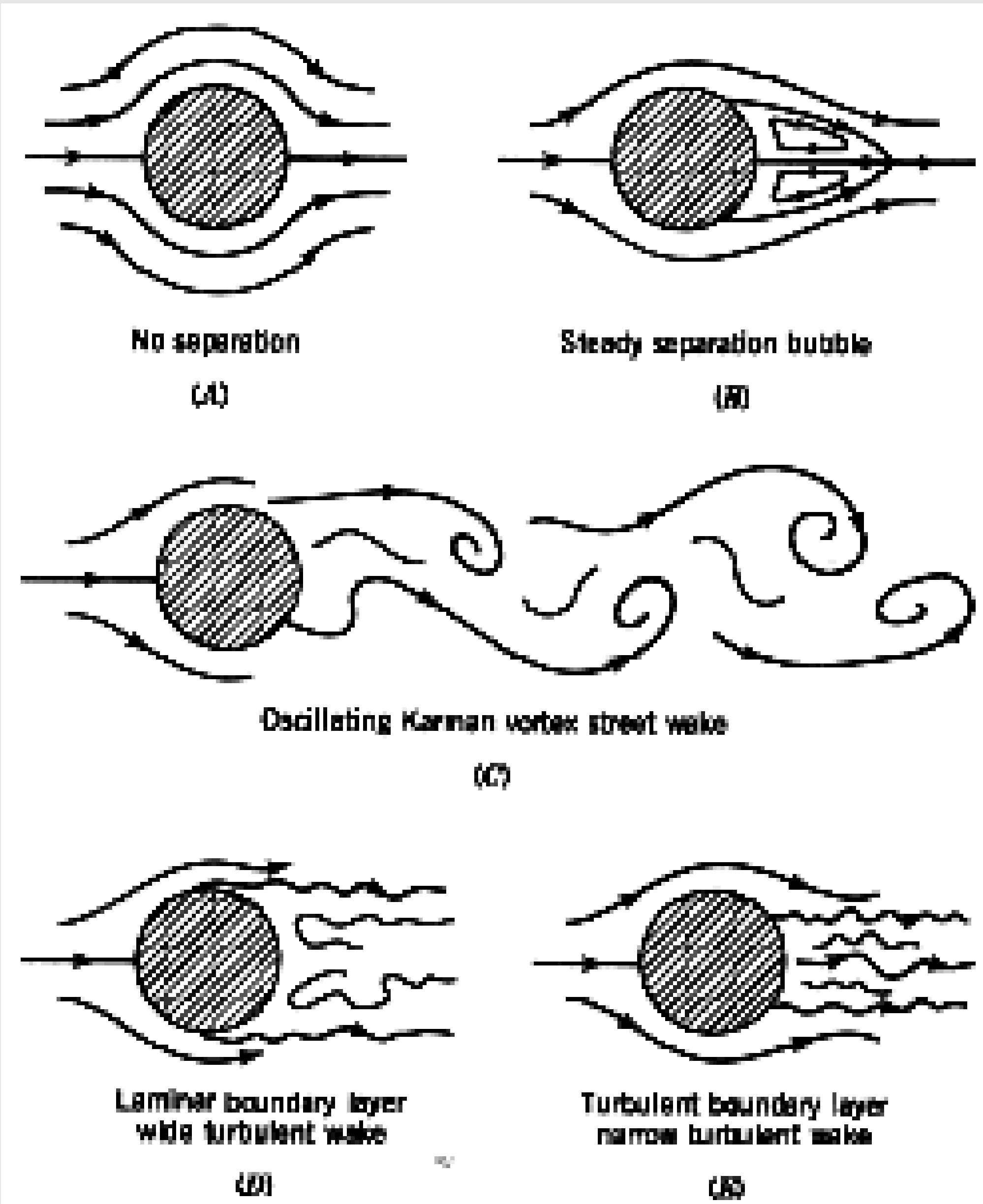


Maarja Kruusmaa, Taavi Salumae, Gert Toming, Andres Ernits, Jaas Ježov, "Swimming Speed Control and on-board Flow Sensing of an Artificial Trout", In Proc. of IEEE Int. Conf. of Robotics and Automation (IEEE ICRA 2011), Shanghai, China, May 9-13, 2011.

How to create thrust?



Reynolds number



$$\mathrm{Re} = \frac{lU}{\ }$$

$$F_I = SU^2$$

$$F_v = \frac{SU}{l}$$

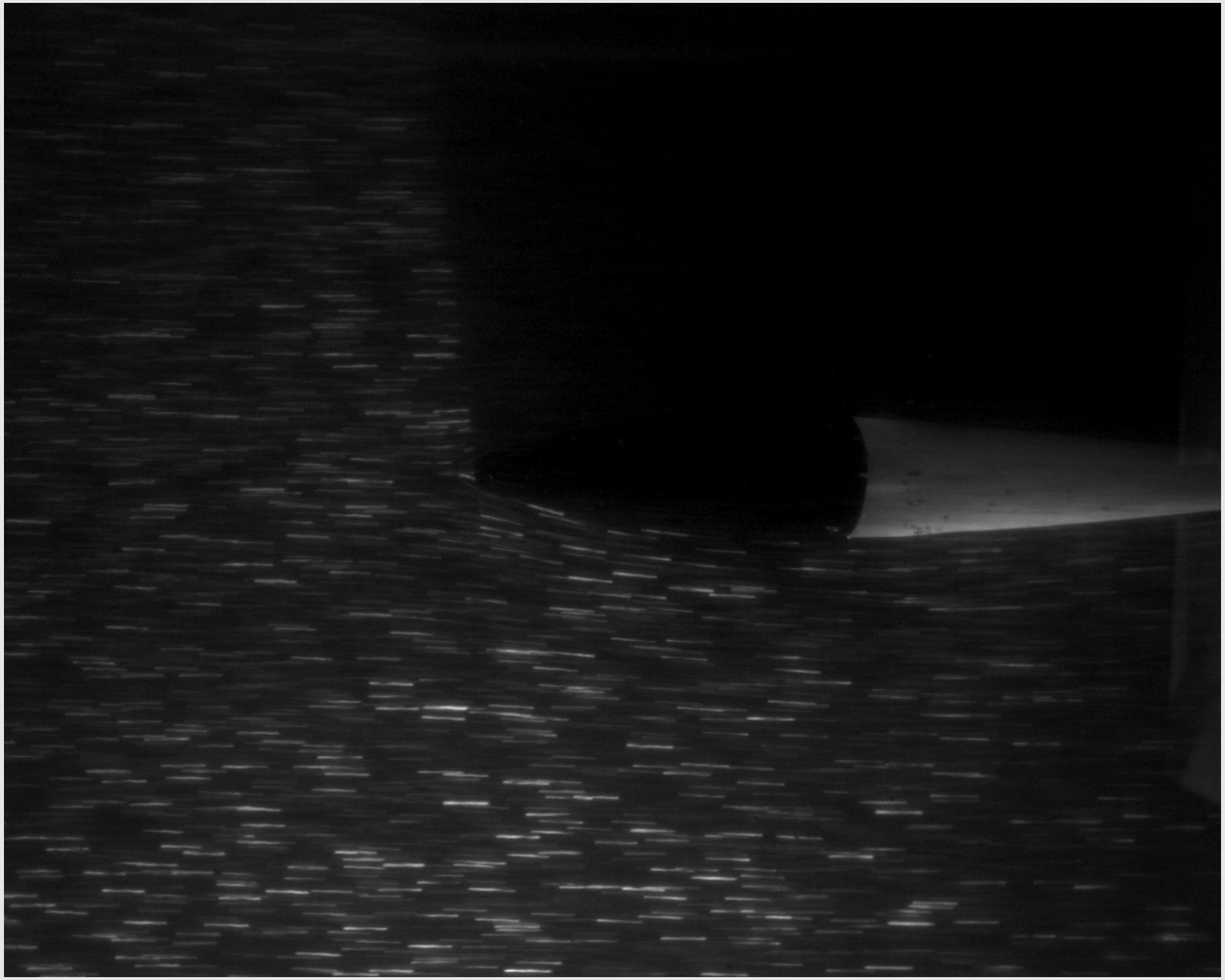
$$\frac{F_l}{F_V} = \frac{SU^2}{SU/l} = \frac{lU}{\ }$$

$$D_d = f(\mathrm{Re}) \qquad D = \frac{1}{2} C_d \ SU^2$$

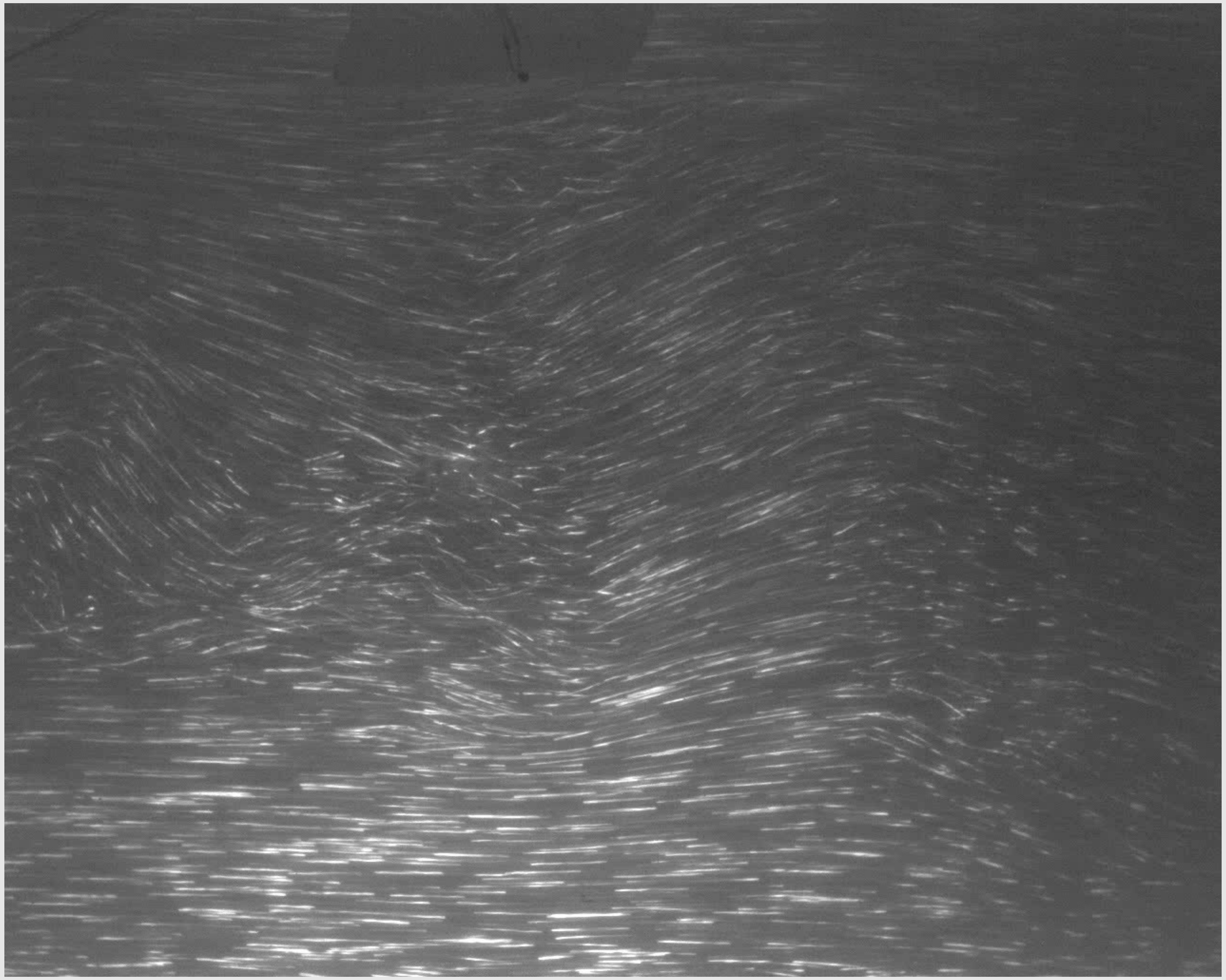
How to we measure it?

Indirect measurements – Digital Particle Image Velocimetry

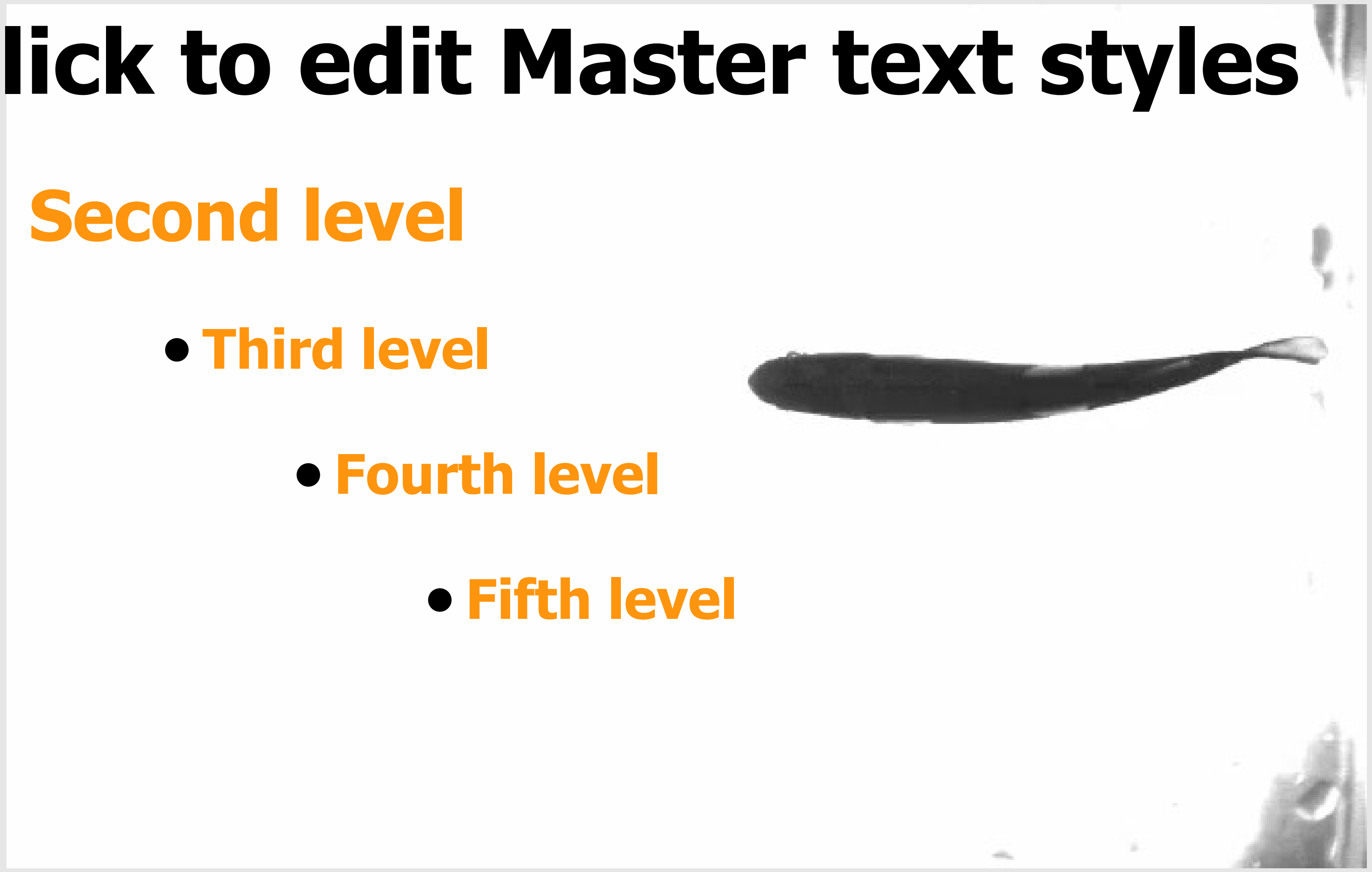
Laminar flow



Von Karman Vortex street



Undulatory swimming



Click to edit Master text styles

Second level

- Third level
  - Fourth level
    - Fifth level

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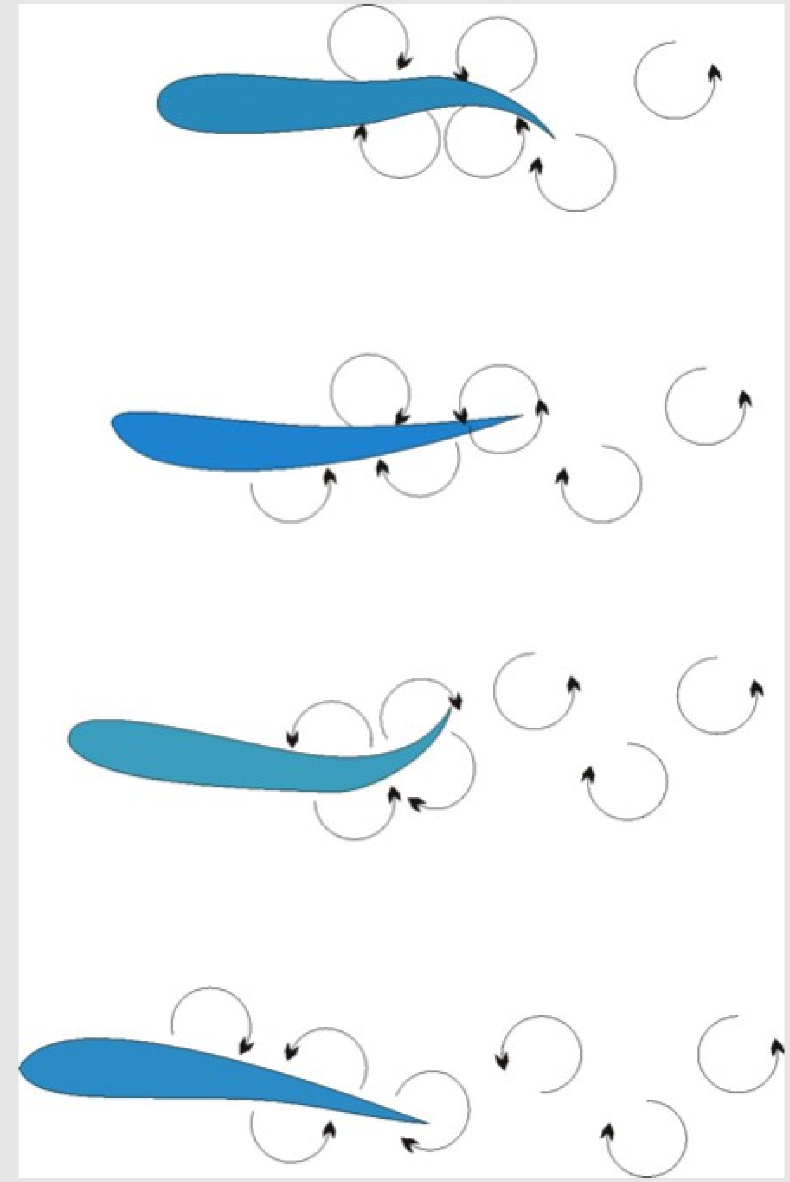
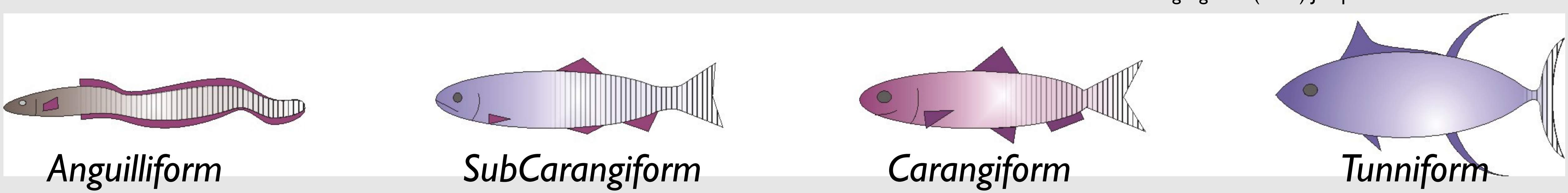
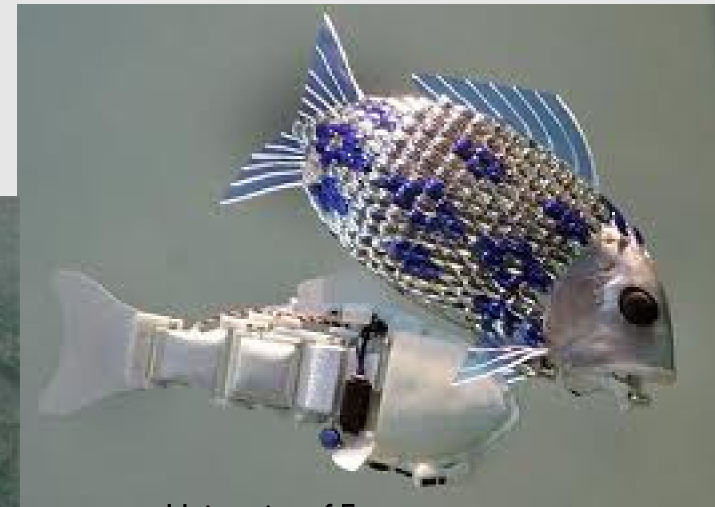


Wolfgang et al (1999) J exp Biol 202



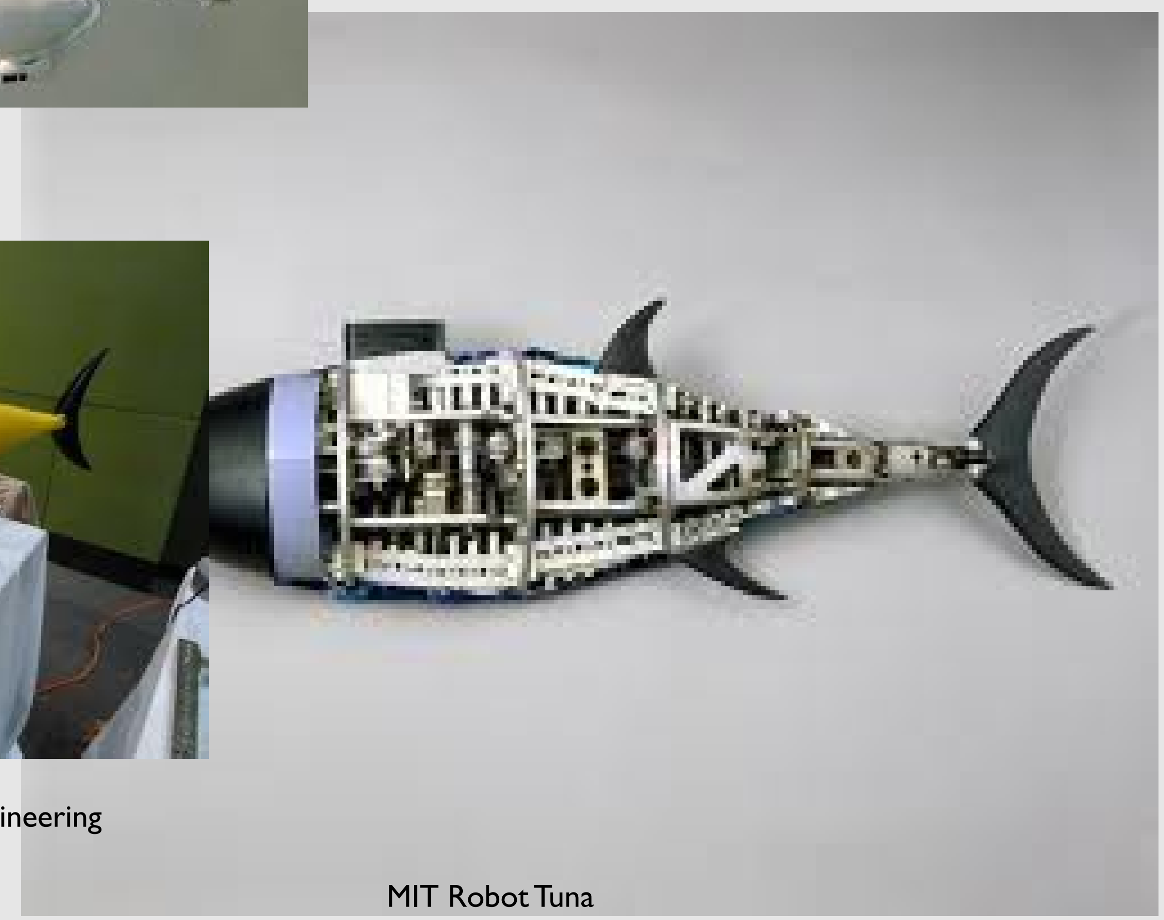
Drag, wake and entropy

Fish robots of the world



University of Essex

Ryomei Engineering, Koi carp rob

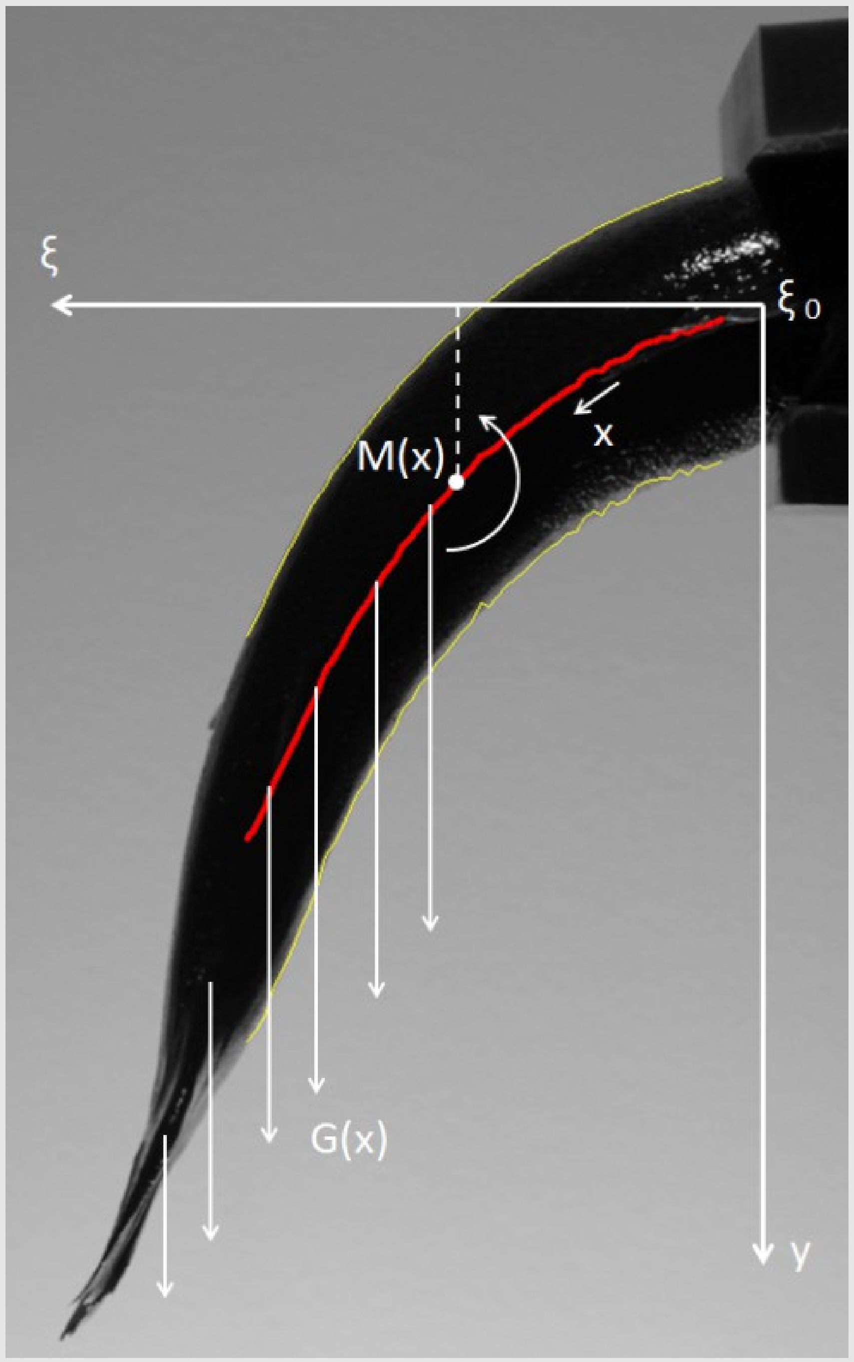


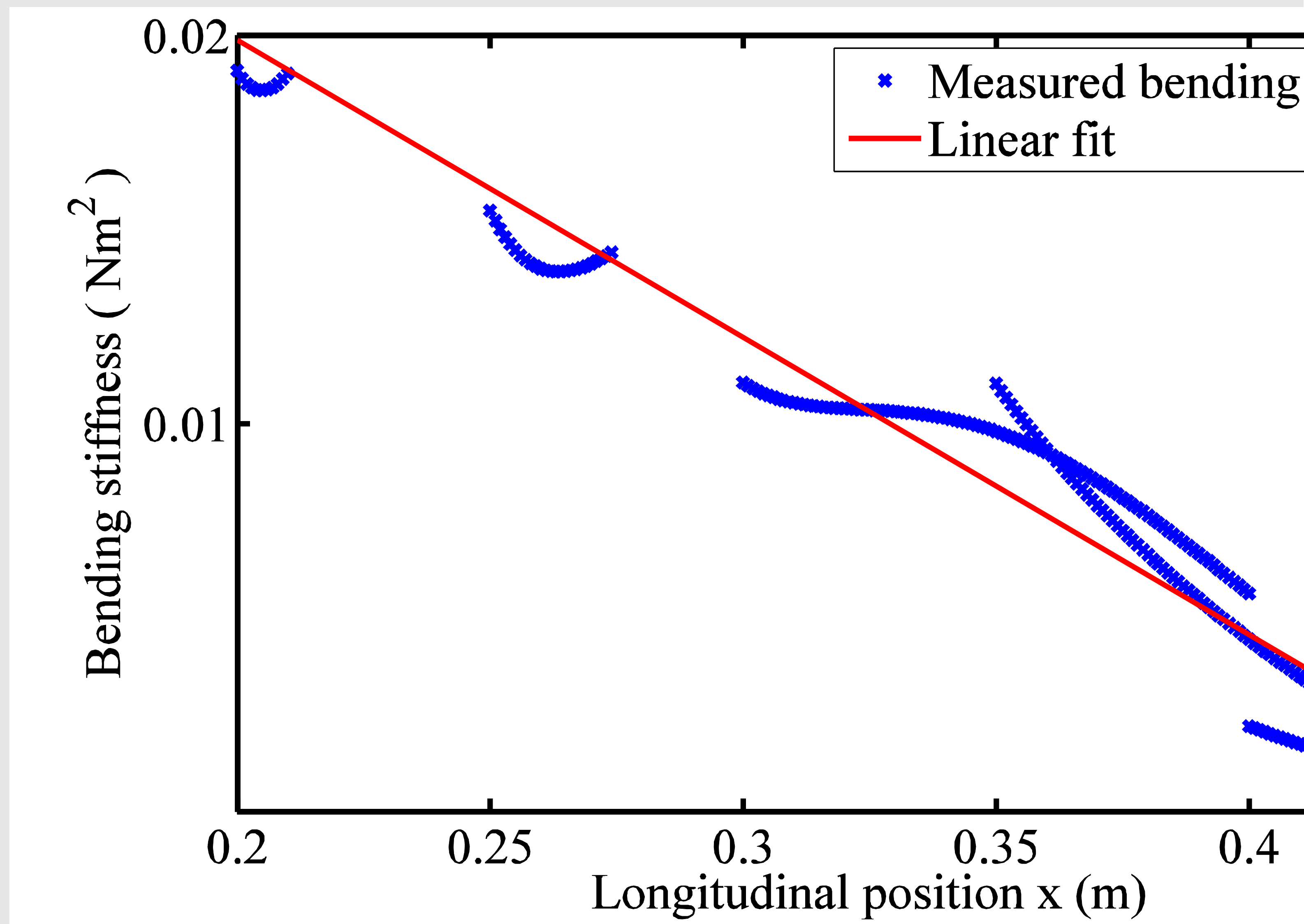
MIT Robot Tuna

Ghost swimmer Boston Engineering

Festo Aqua ray

The role of embodiment – stiffness profile

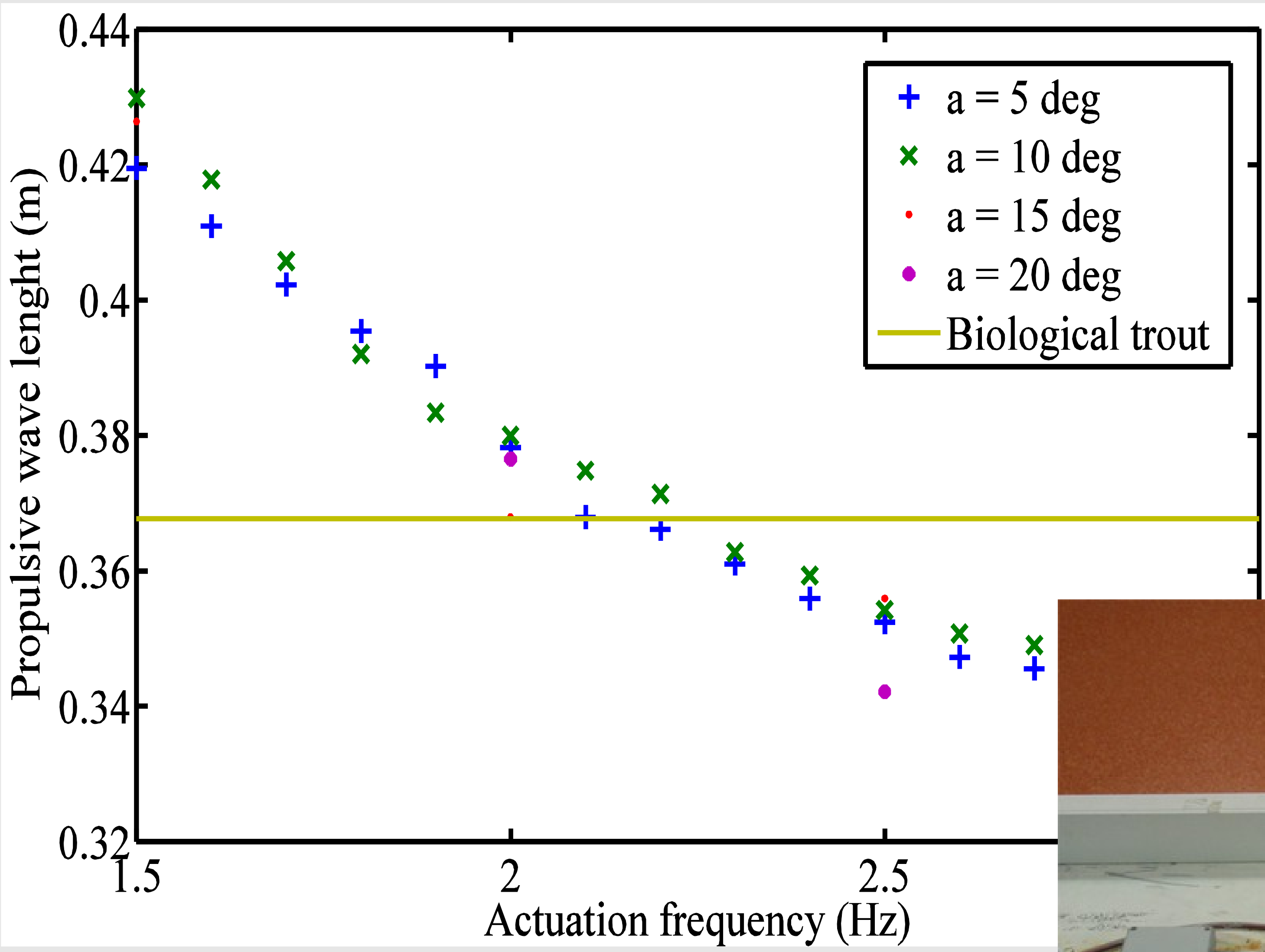


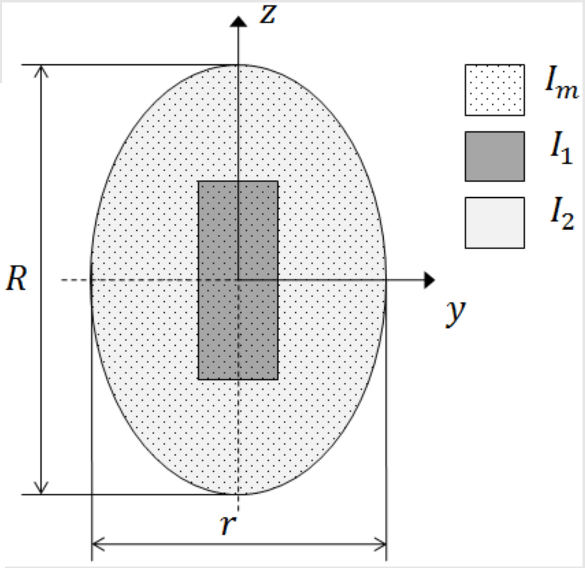


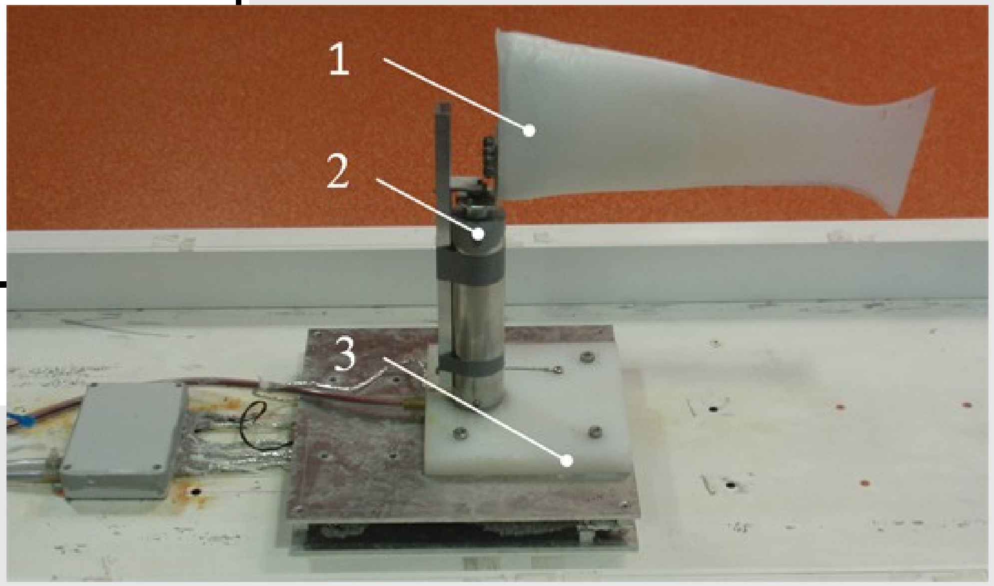
T. Salumäe, M. Kruusmaa, A flexible fin with bio-inspired stiffness profile and geometry", Journal of Bionic Engineering 8.4, Elsevier, 2011, pp. 418-428

Understanding kinematics

Biomimetic stiffness profile produces fish-like kinematics at cruising speeds

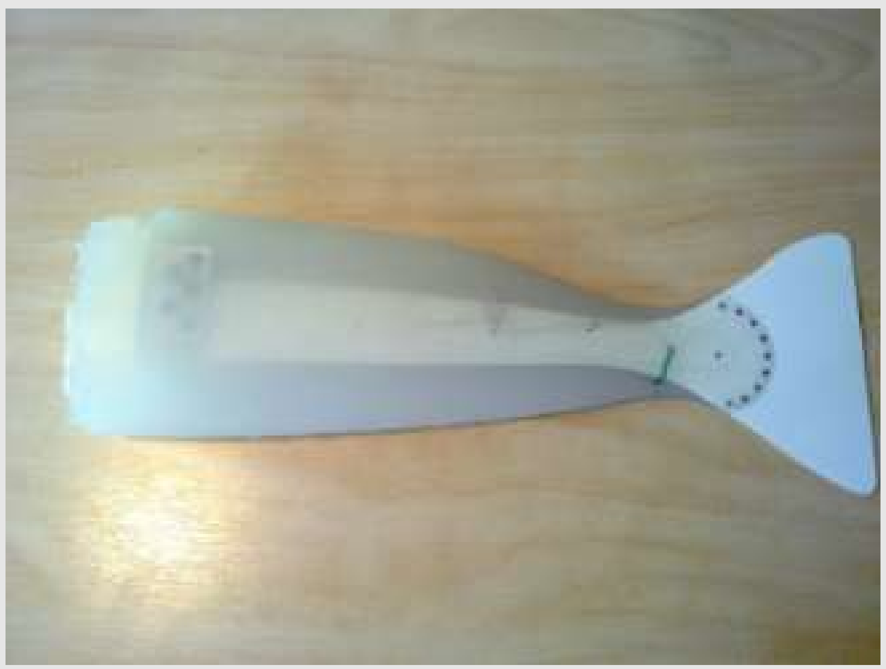


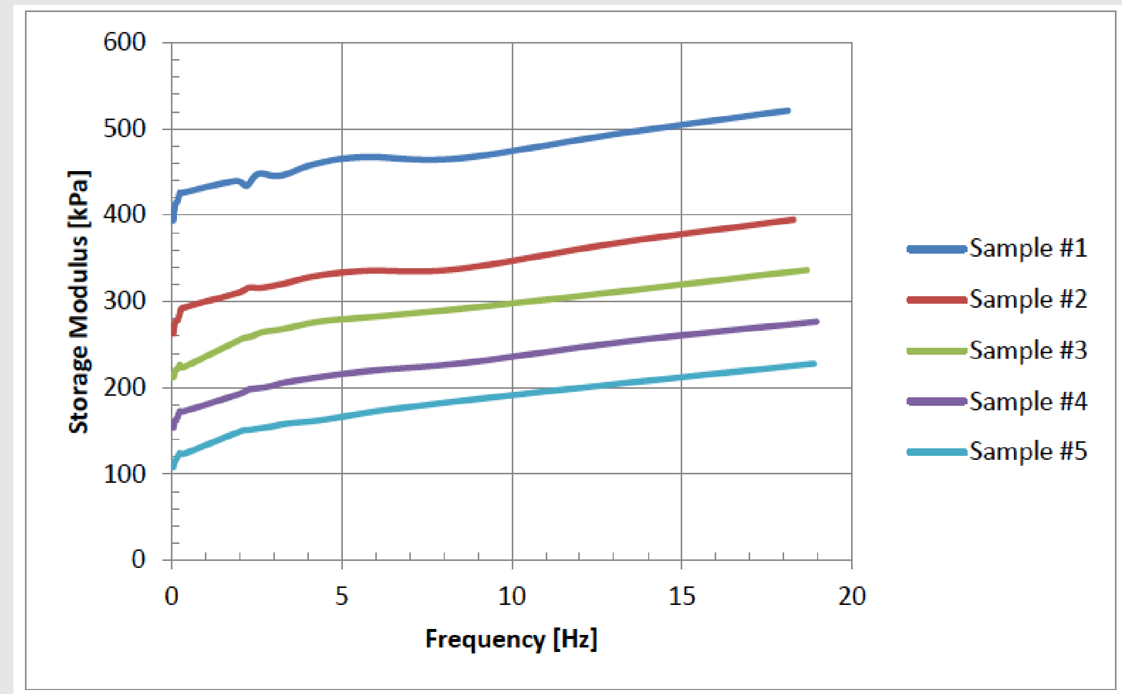


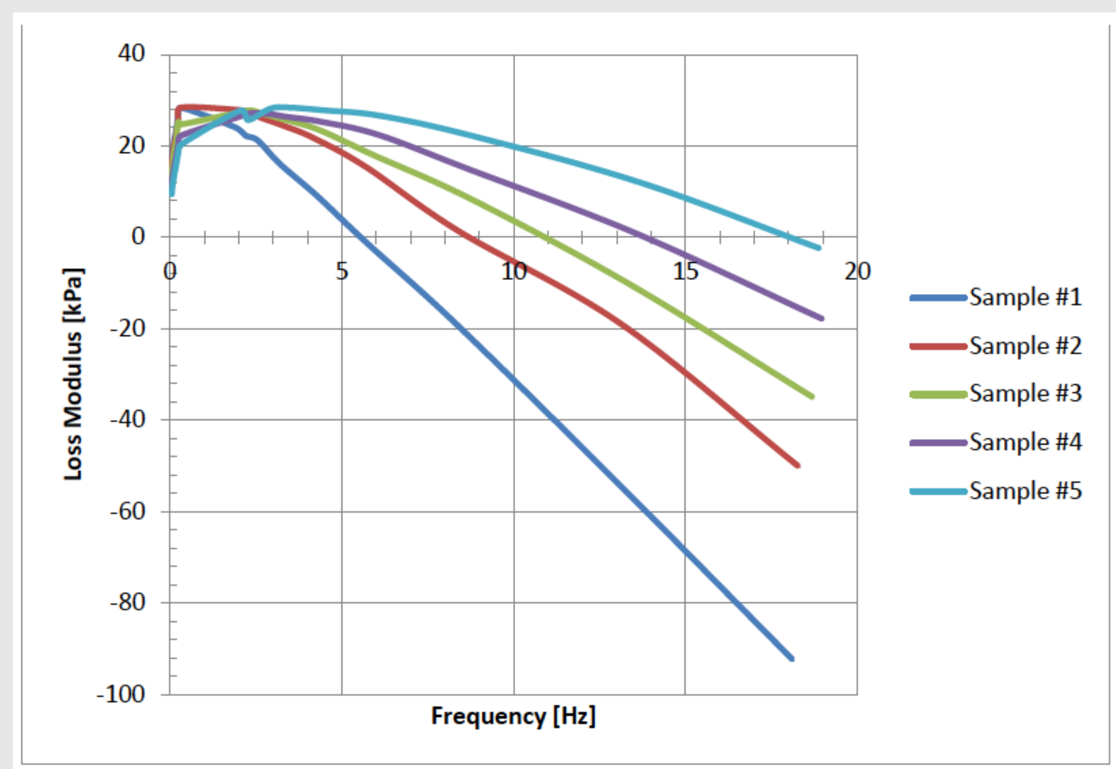


T. Salumäe, M. Kruusmaa, A flexible fin with bio-inspired stiffness profile and geometry", Journal of Bionic Engineering 8.4, Elsevier, 2011, pp. 418-428

Viscoelasticity of the tail

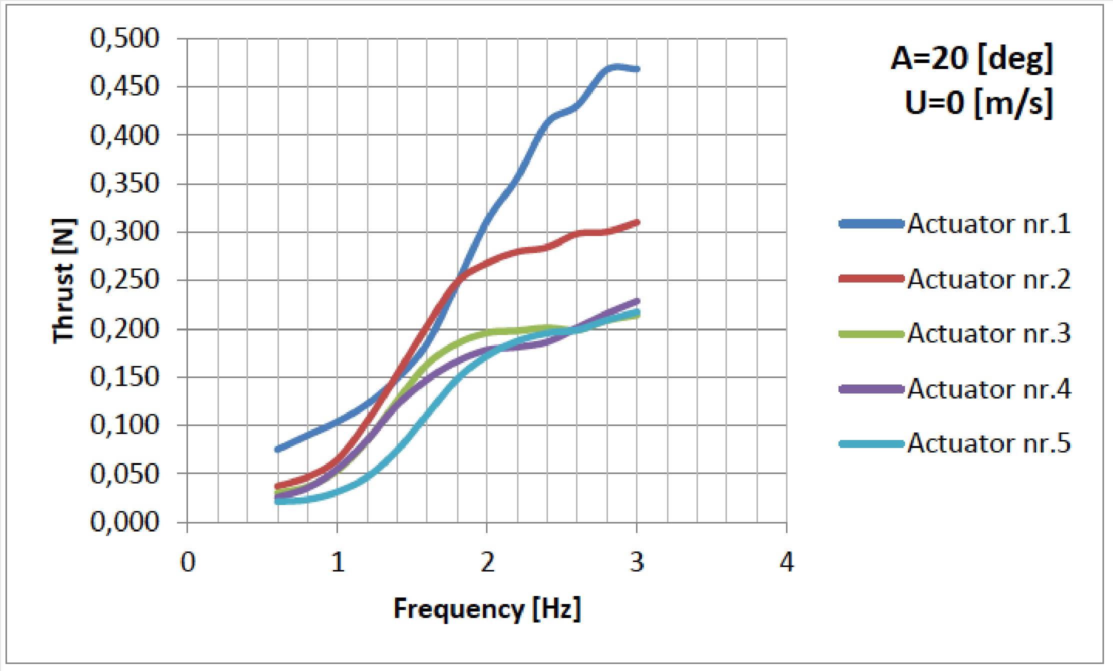


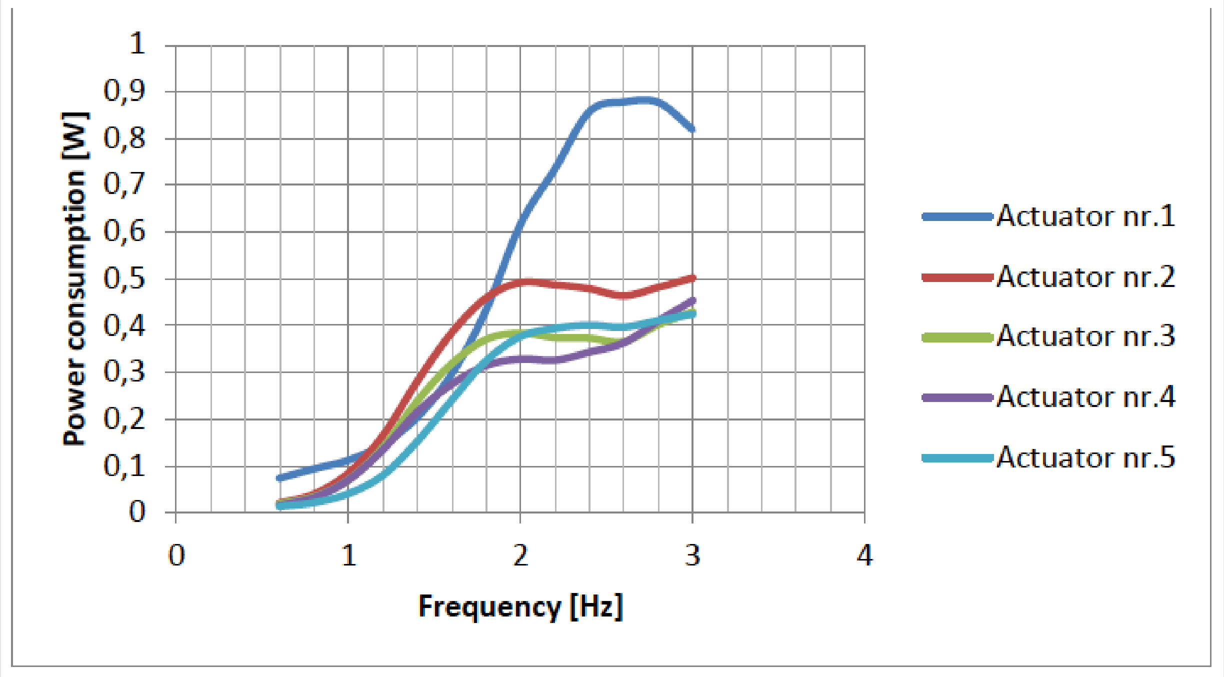




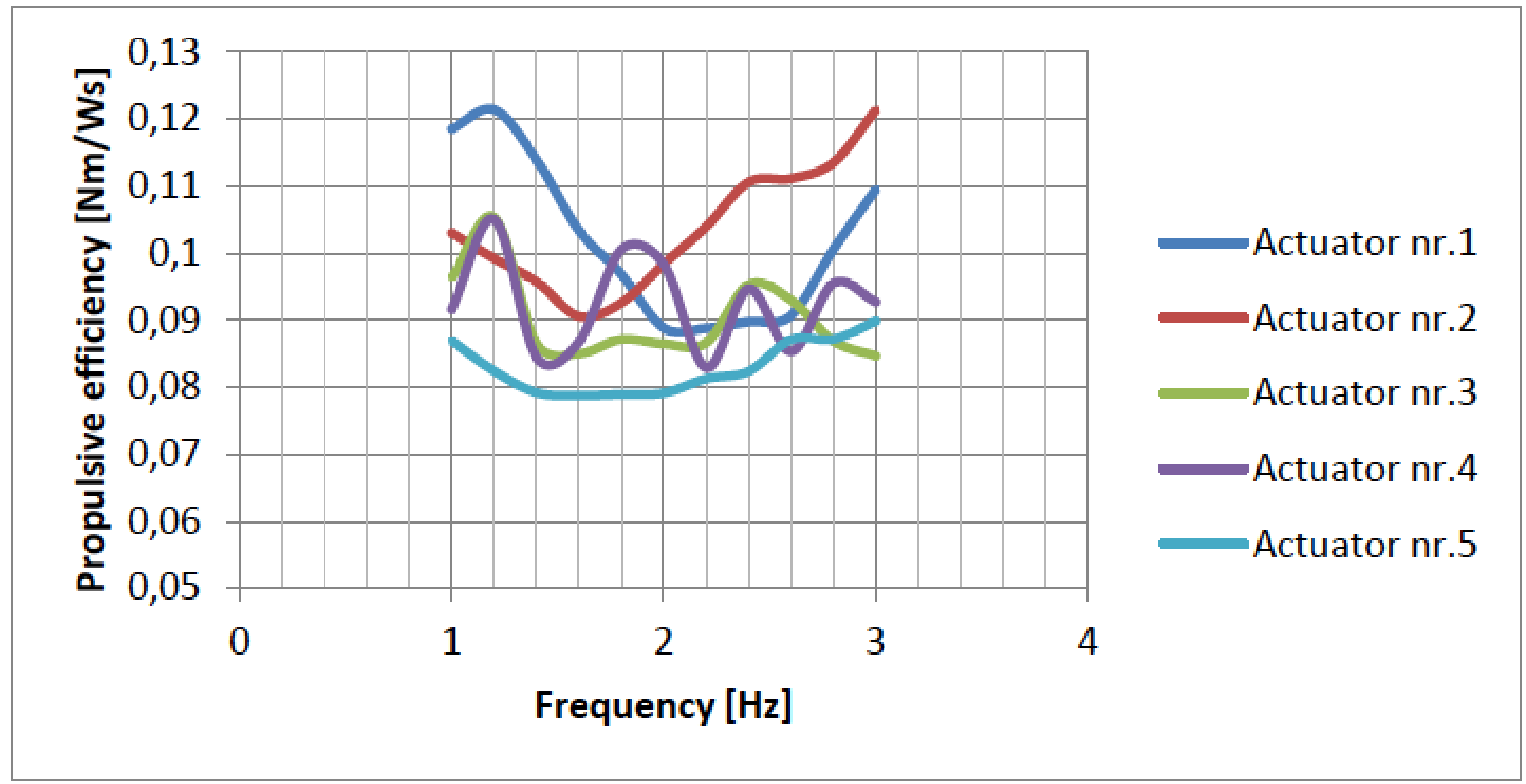
Kaspar Kaarlep. THE EFFECT OF MATERIAL VISCOELASTICITY ON THE PERFORMANCE OF BIOMIMETIC TAIL FIN ACTUATORS.
MSc Thesis, Faculty of Science, Institute of Physics, Tallinn University of Technology, 2012

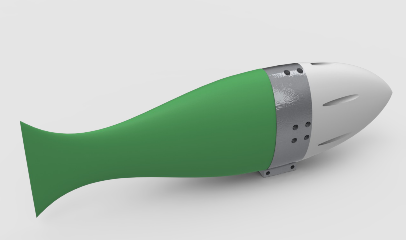
Thrust and viscoelasticity





Efficiency and viscoelasticity



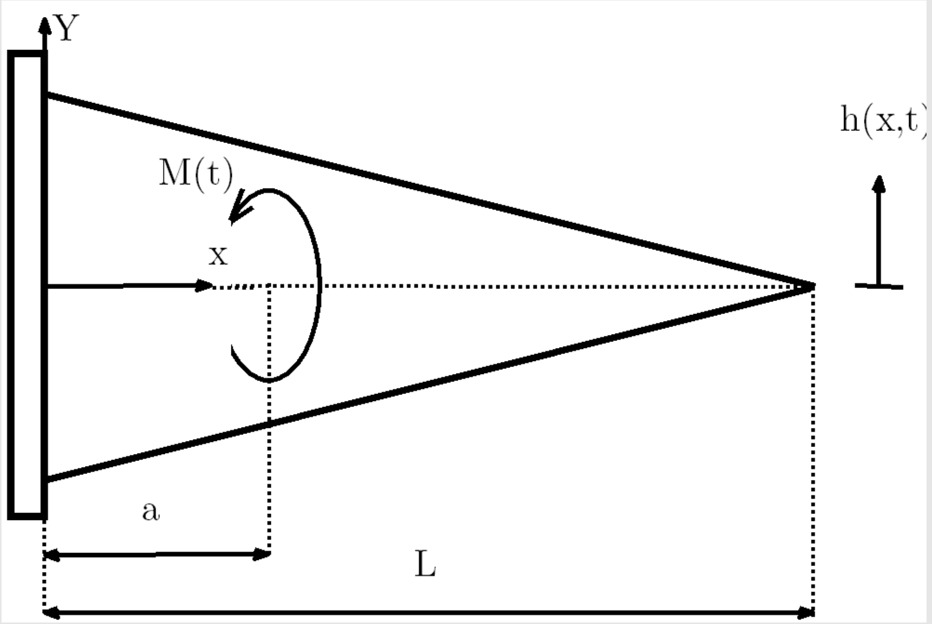


Modelling the tail motion

$$[M]\{\ddot{q}(t)\} + [K]\{q(t)\} = \{Q(t)\}$$

$$m_{ij} = \int_0^l (\mu(x) + \rho_f A(x))\varphi_i(x)\varphi_j(x)dx$$

$$k_{ij} = \int_0^l EI(x)\varphi_i''(x)\varphi_j''(x)dx$$



$$q(t) = ae^{\lambda}(t)$$ $$det(\lambda^2 M + K) = 0$$ $$\lambda_r = -iw_r$$

$$q(t) = U\eta(t)$$ $$U = [a_1\ a_2\ a_3\ a_4\ a_5\ \ldots\ldots\ldots\ a_n]$$ $$a_r^T.M.a_s = \delta_{rs} \qquad a_r^T.K.a_s = w_r^2\delta_{rs}$$

$$\ddot{\eta}(t) + \Lambda\eta(t) = N(t)$$

in which :

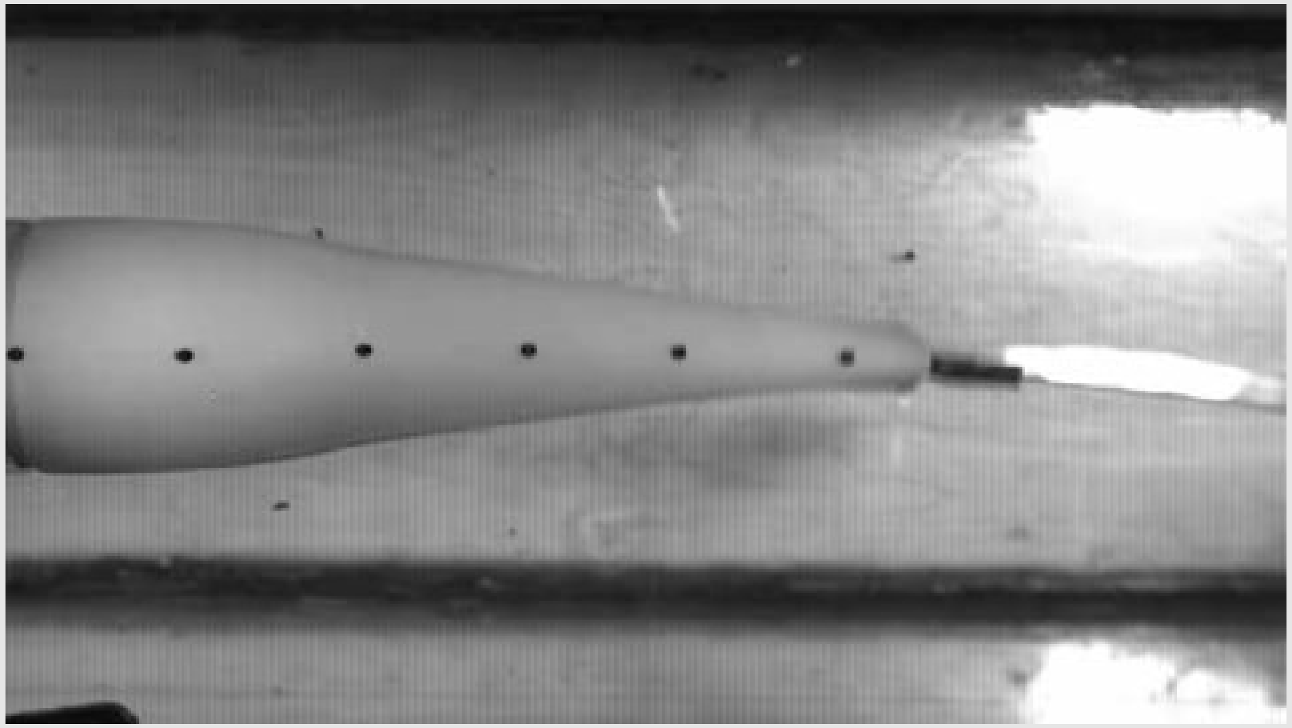
$$\Lambda = diag[w_1^2\ w_2^2\ w_3^2\ w_4^2\ w_5^2\ w_6^2\ \ldots\ldots\ w_n^2]$$

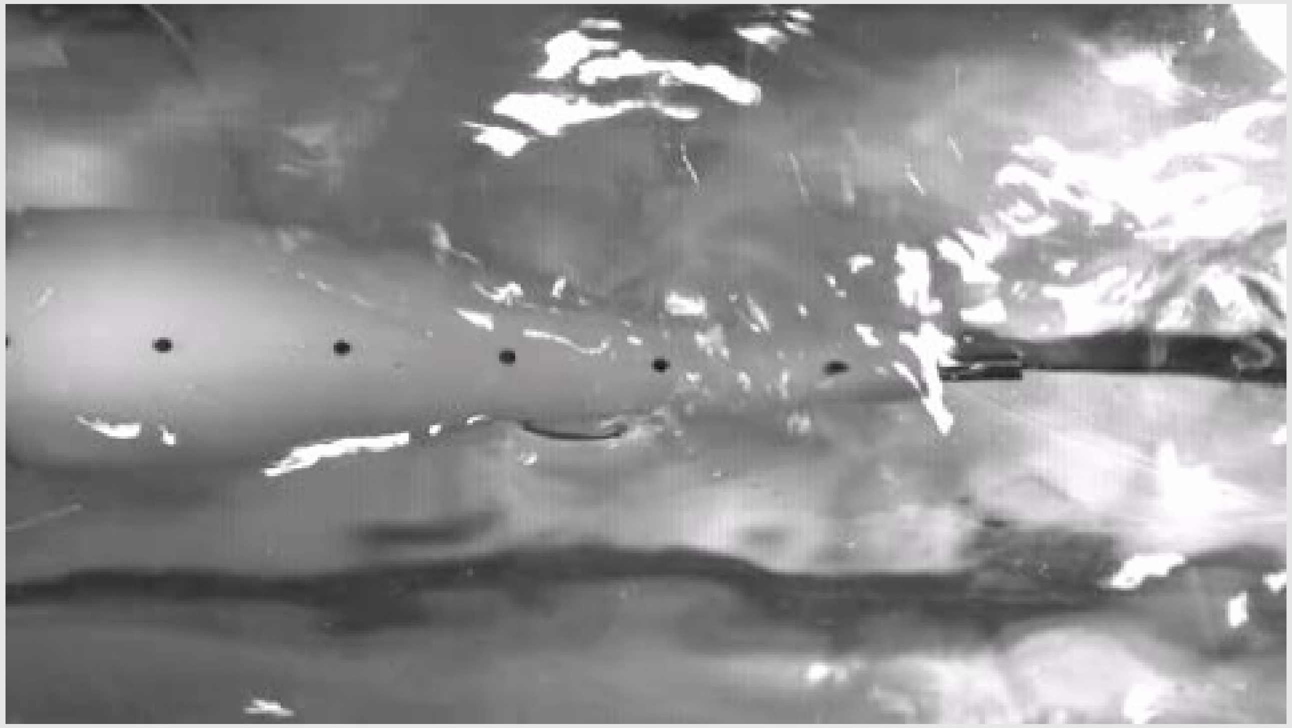
$$N(t) = U^T Q(t)$$ $$\eta_i(t) = \frac{1}{w_i}\int_0^t N_i(t-\tau)sin(w_i\tau)d\tau$$

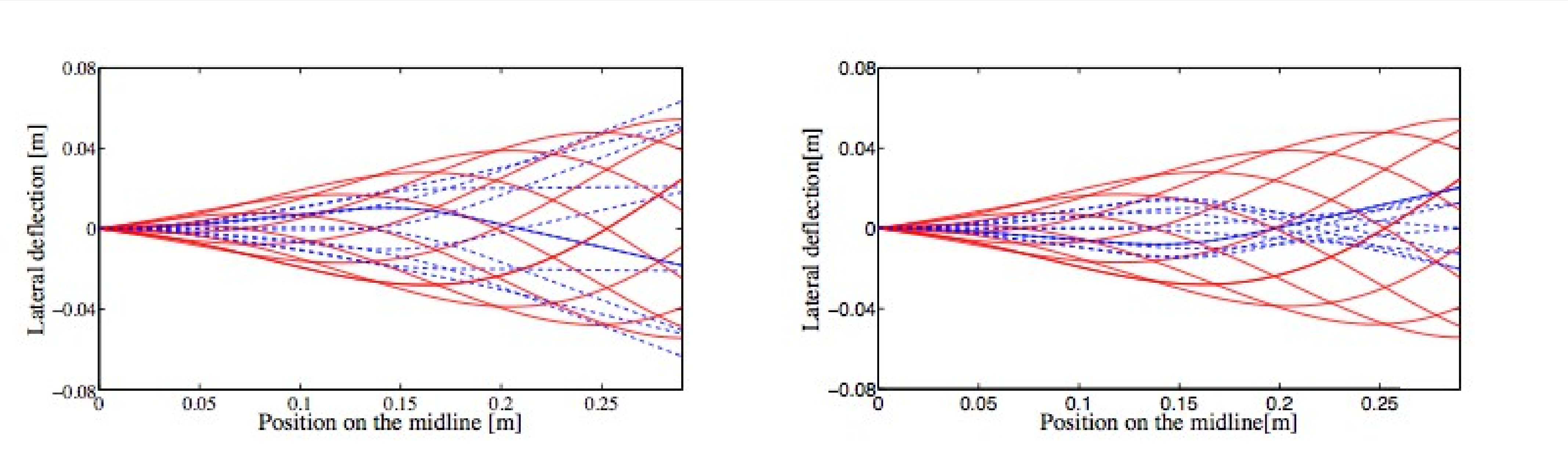
$$h(x,t) = v(x,t)$$ $$M_0 h_1(x,t) = v(x,t)$$

H. El Daou, T. Salumäe, G. Toming, M. Kruusmaa, "Bio-inspired Compliant Robotic Fish: Design and Experiments", IEEE International Conference on Robotics and Automation, St. Paul, USA, May 14-18, 2012.

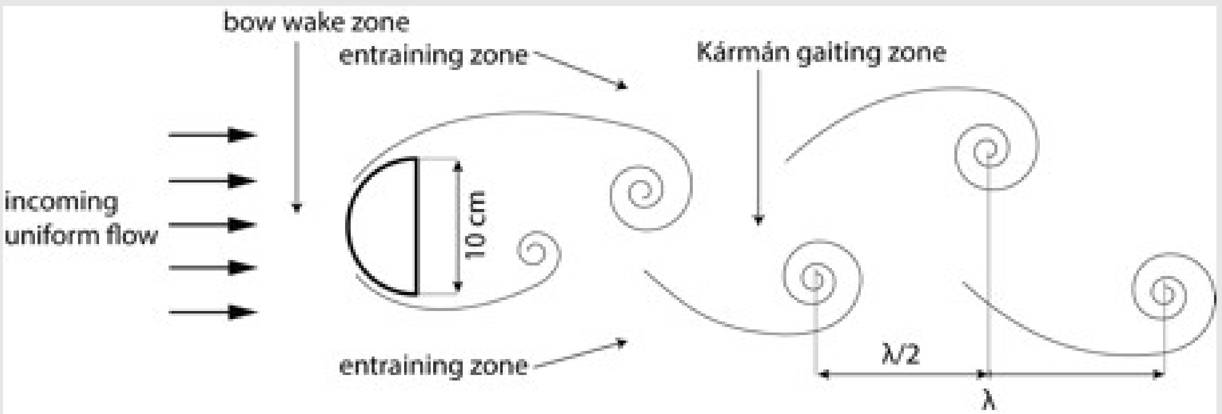
Experimental validation

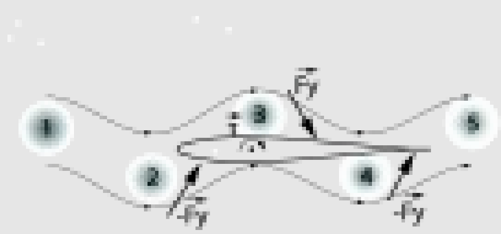






Swimming in von Karman vortex street





Swimming in steady flow and periodic turbulence

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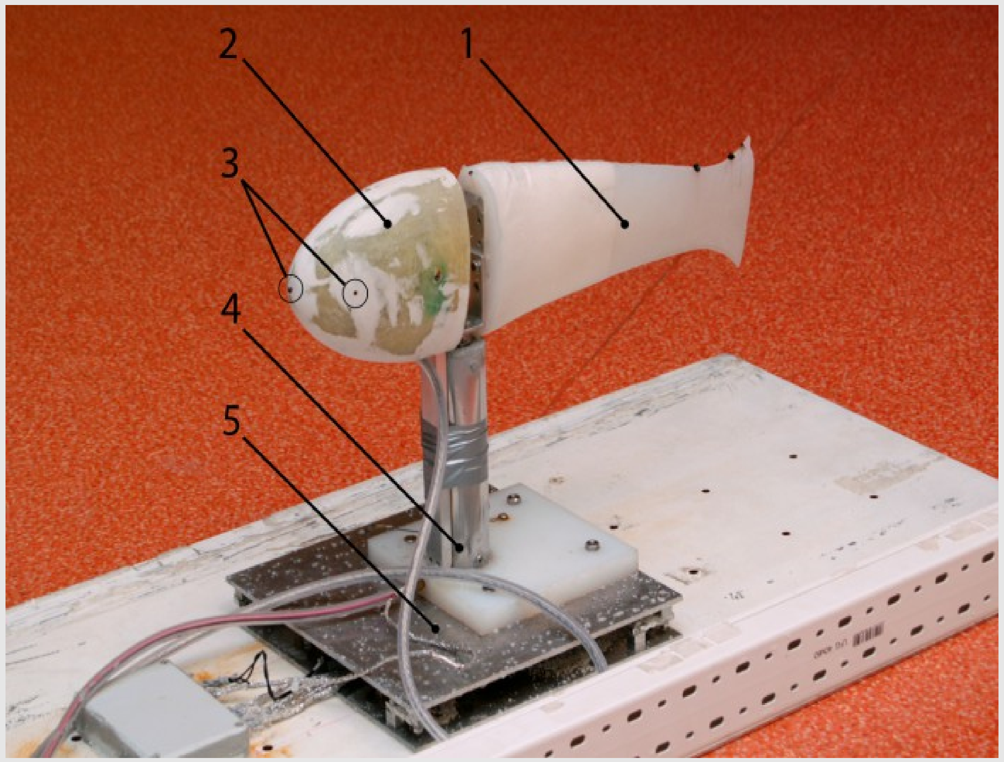
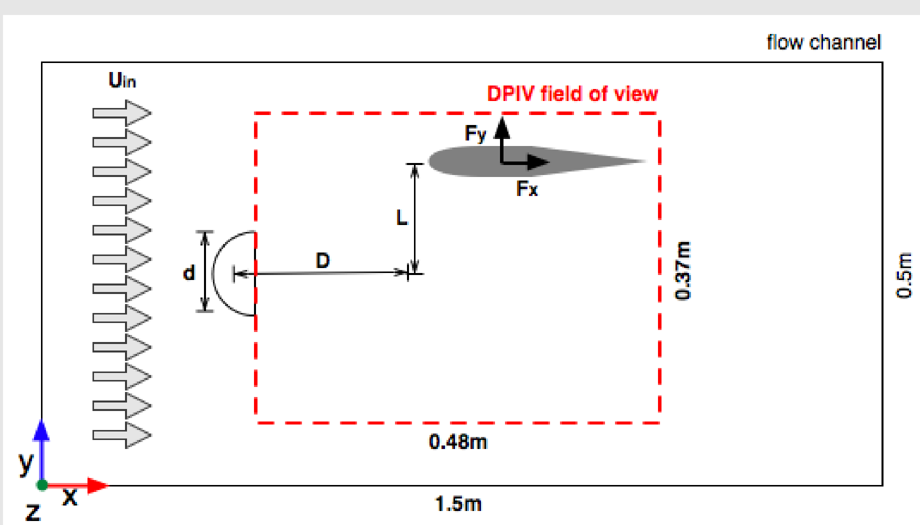
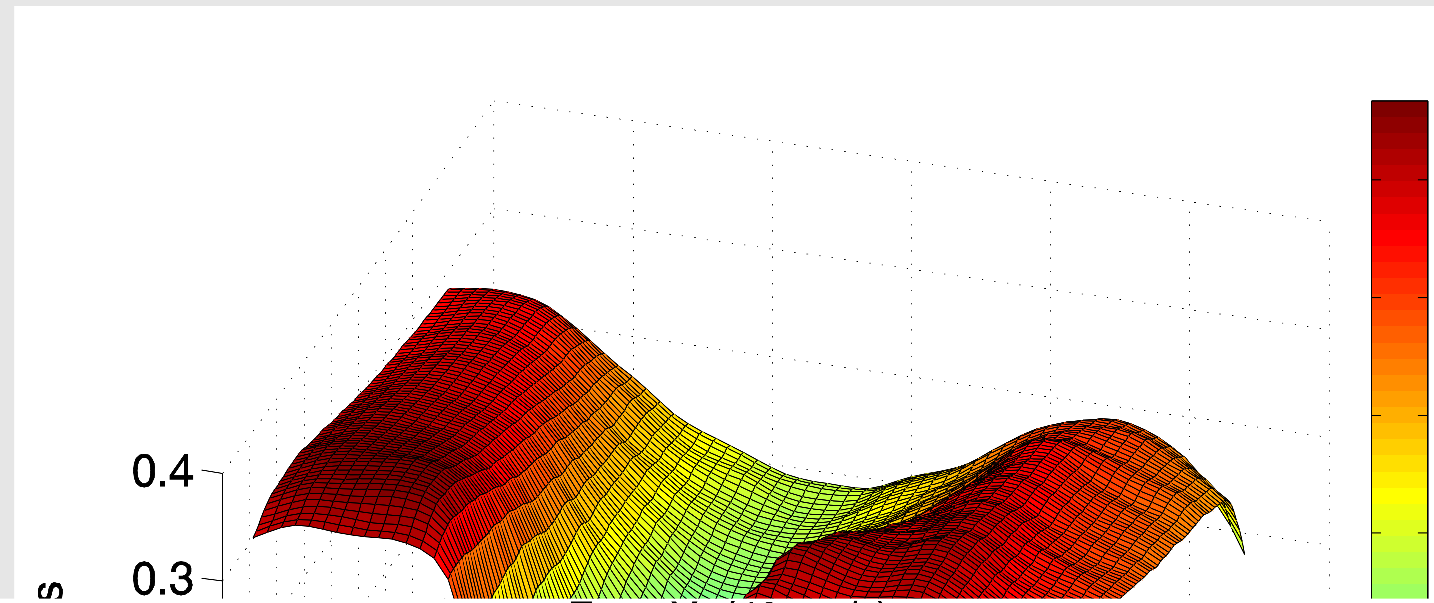
Beyond 100%

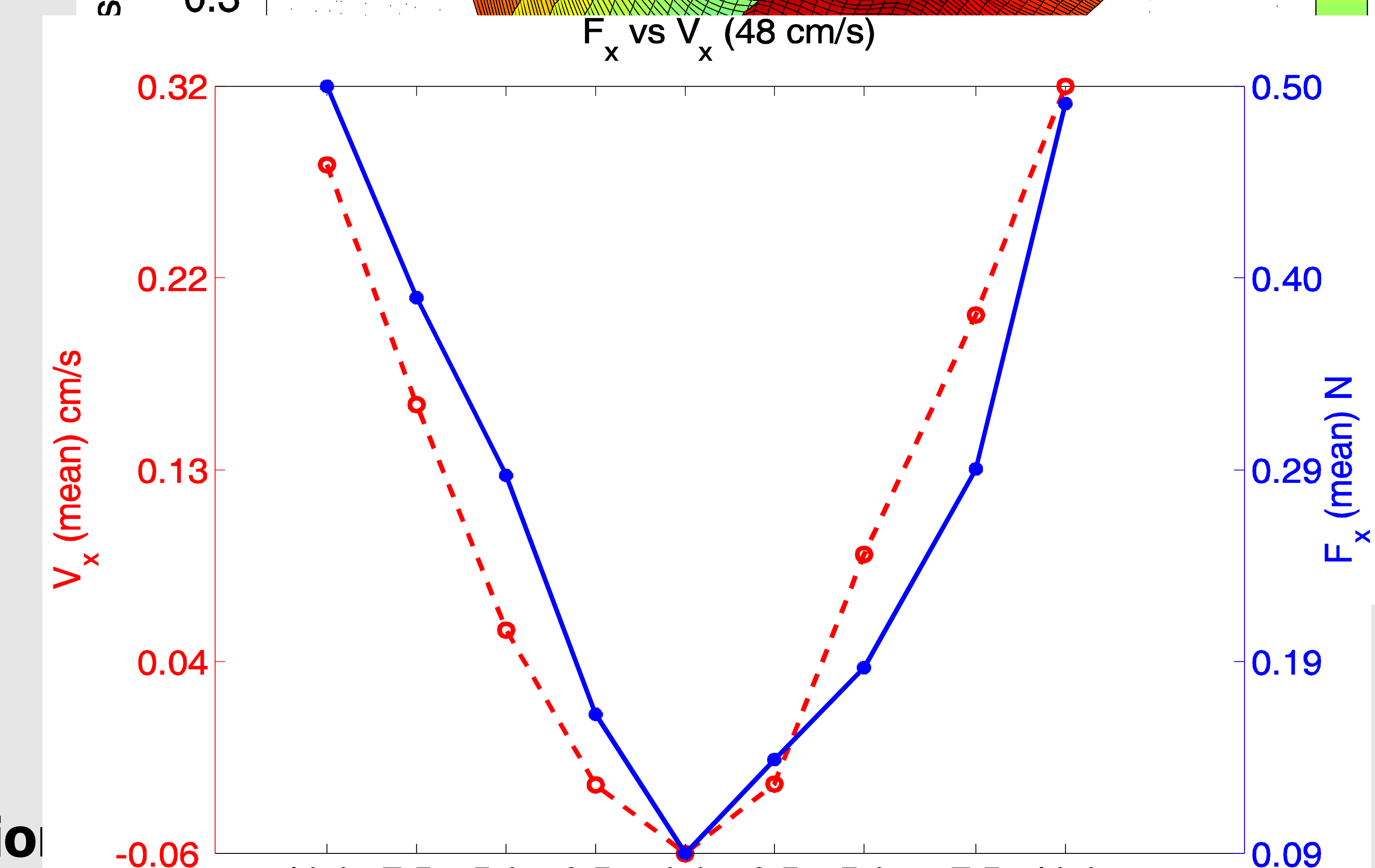
] Liao J. C., Beal D. N., Lauder G.V., Triantafyllou M. S., The Karman gait: novel body kinematics of rainbow trout swimming in a vortex street. Journal of Experimental Biology, vol. 206, 1059 - 1073, 2003.

Passive dynamics in von Karman vortex street



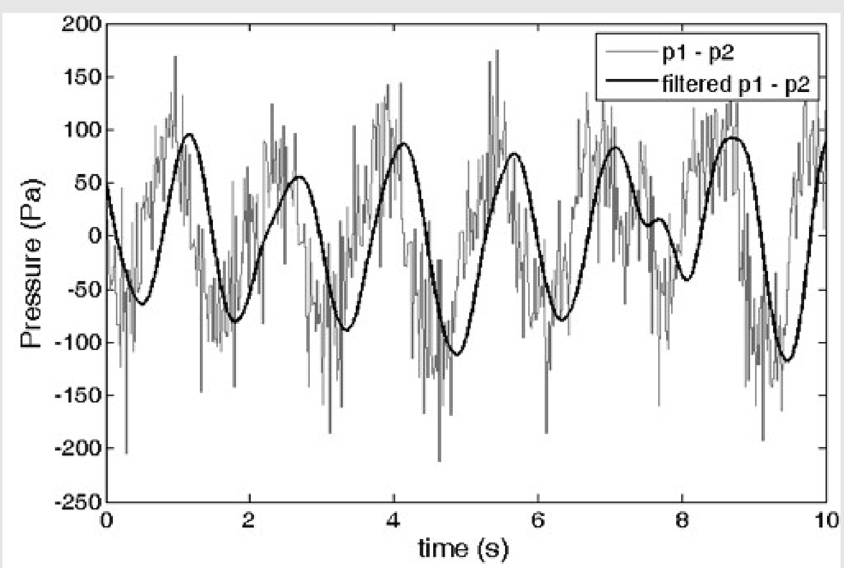


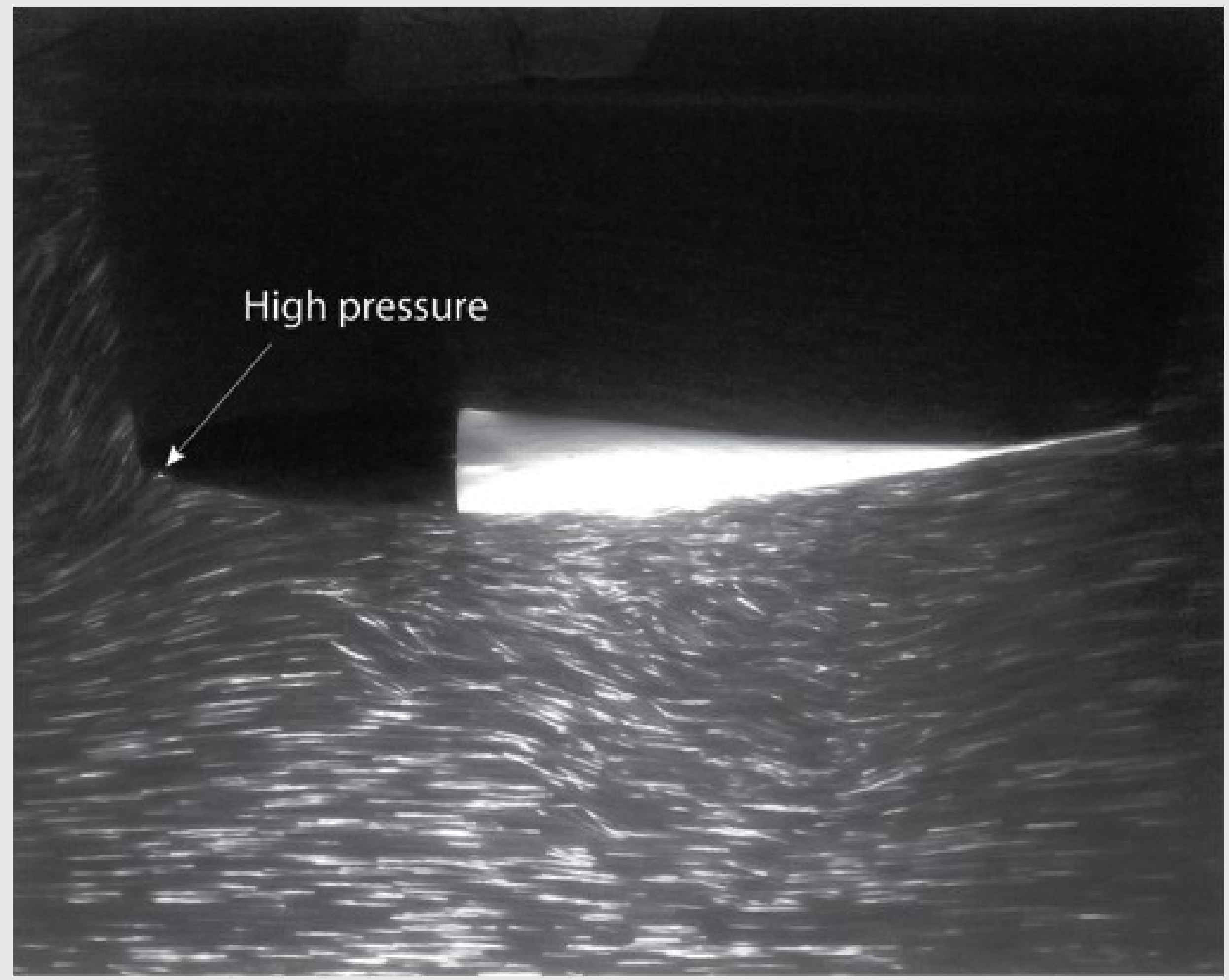




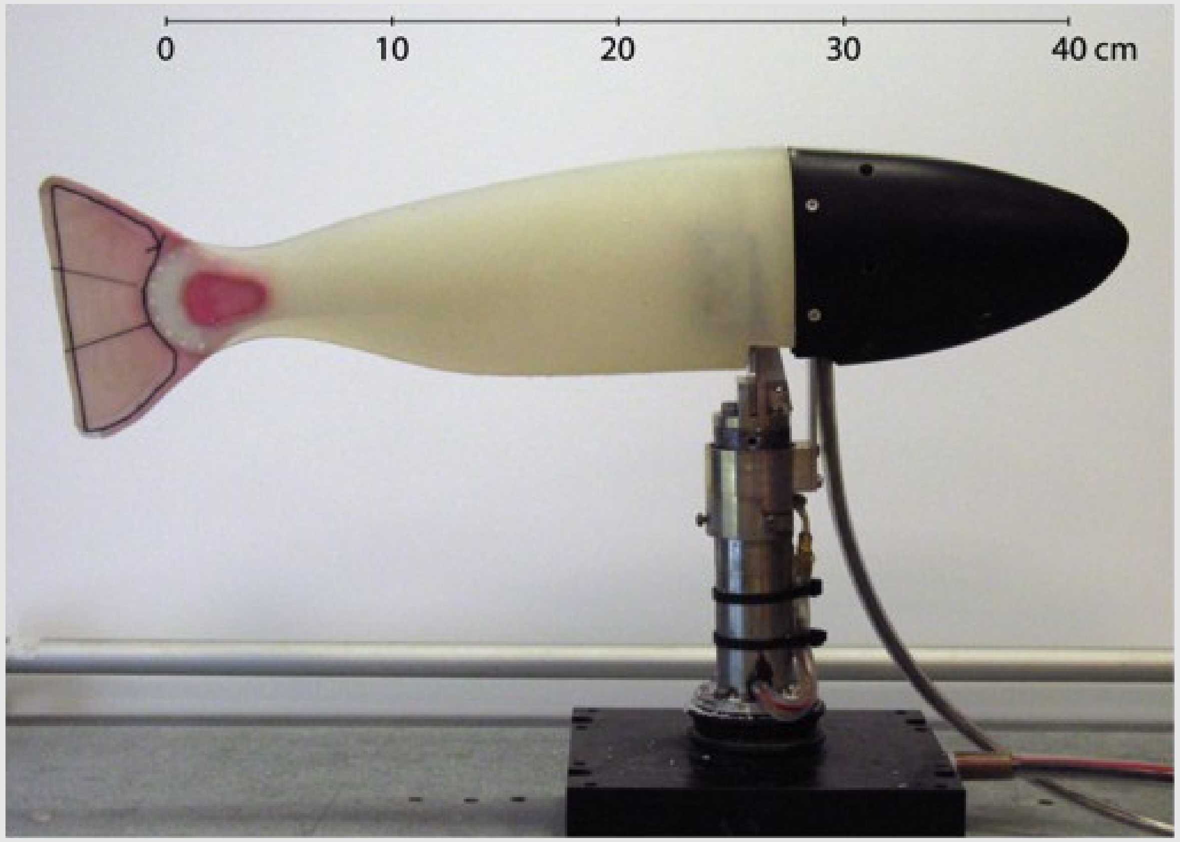
Fish robot in the turbulent flow

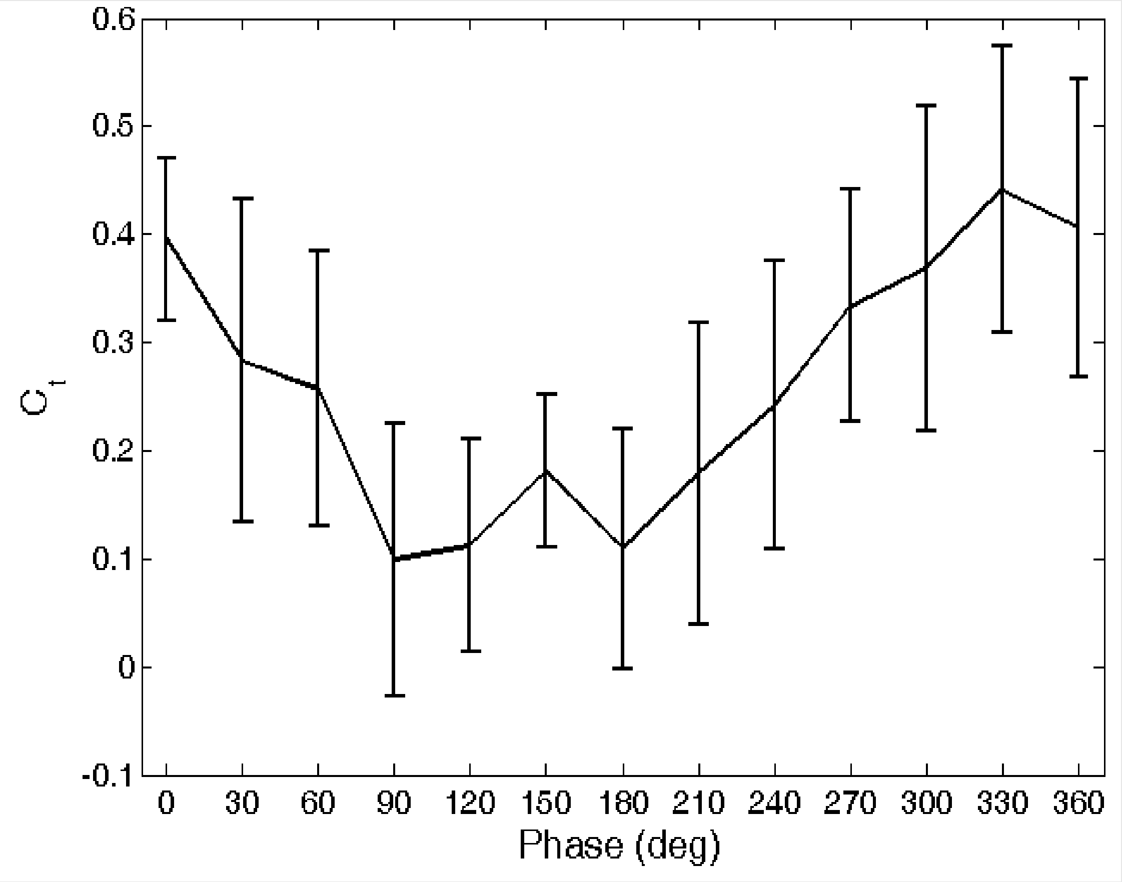
Sensing vorticity





Controlling tail beat timing saves 30% energy

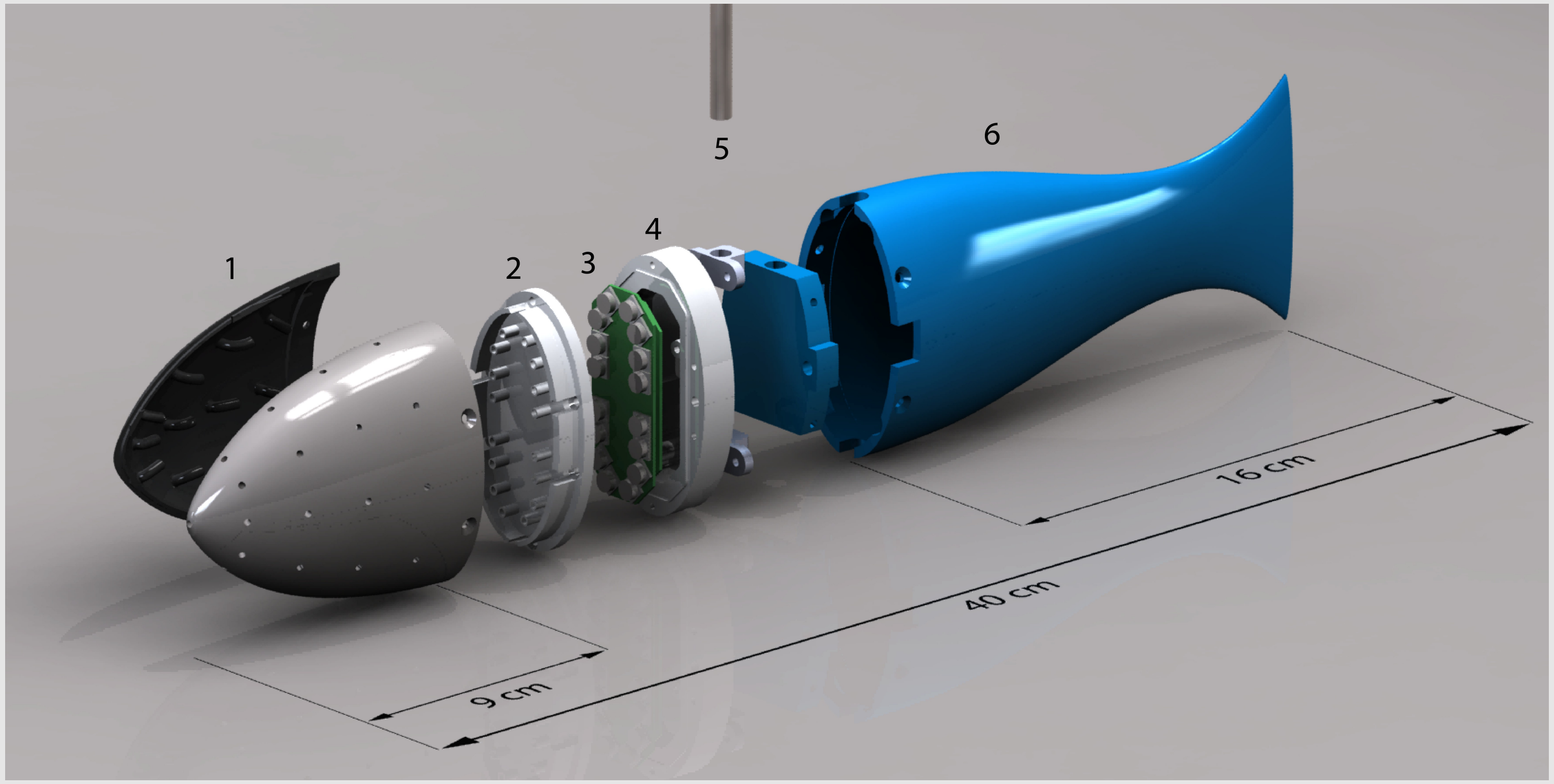




center for biorobotics

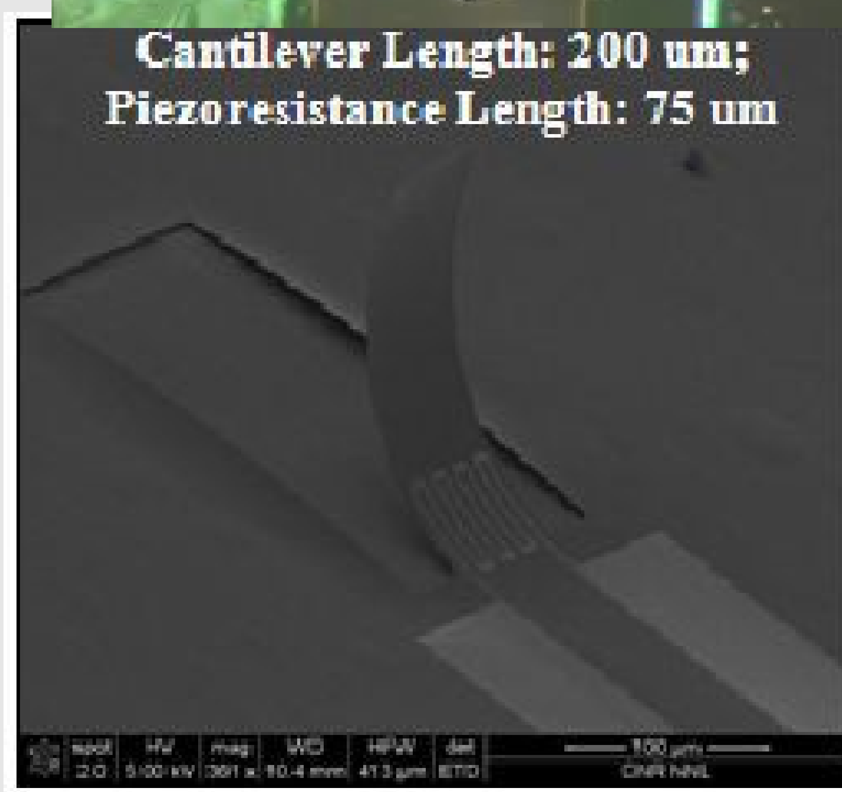
filose

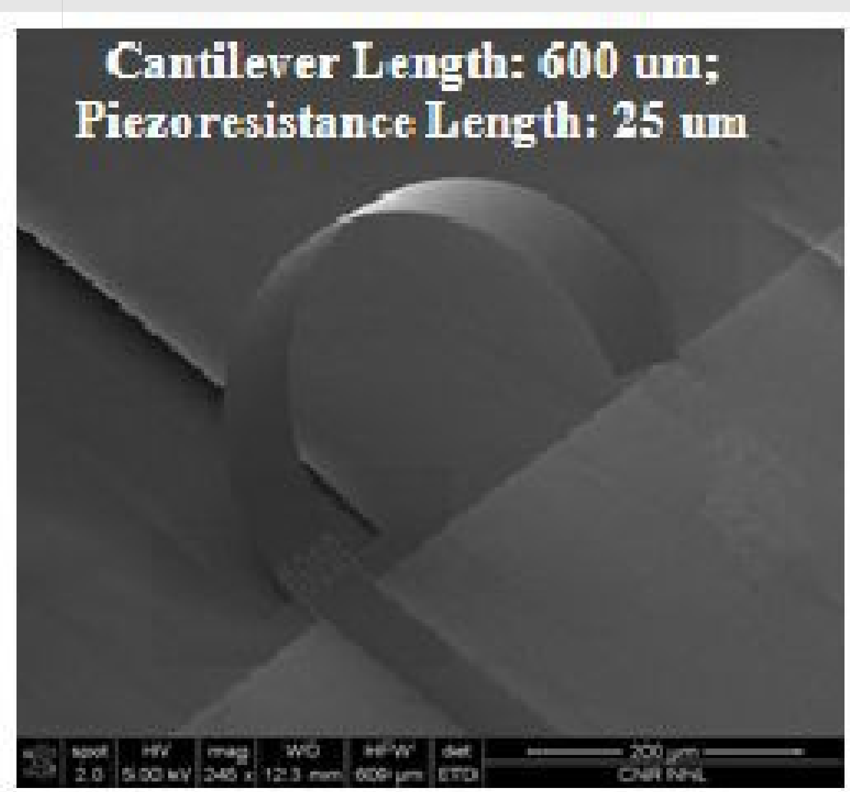
3D flow sensing



Roberto Venturelli, Otar Akanyeti, Francesco Visentin, Jaas Ježov, Lily D Chambers, Gert Toming, Jennifer Brown, Maarja Kruusmaa, William M Megill and Paolo Fiorini, "Hydrodynamic pressure sensing with an artificial lateral line in steady and unsteady flows", Bioinspiration & Biomimetics Volume 7 Number 3

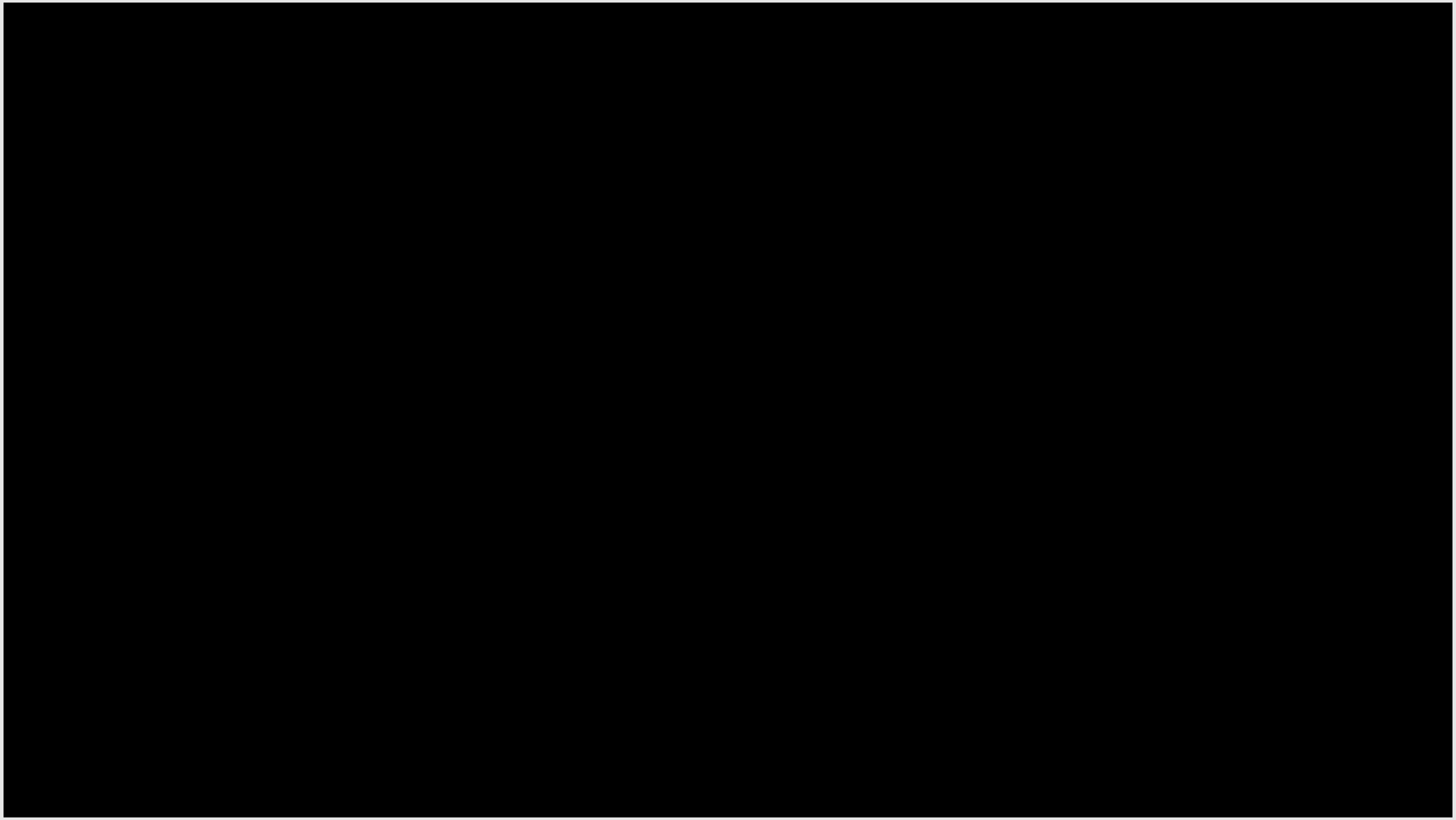
Methods - MEMS Artificial Lateral Line





Antonio Qualtieri; Francesco Rizzi; Maria Teresa Todaro; Adriana Passaseo; Massimo De Vittorio, Stress-driven AlN cantilever-based flow sensor for fish lateral line system. 36th International Conference on Micro and Nano Engineering 19-22 September 2010, Genova, Italy.

Brainteberg fish



T. Salumäe, I. Rano, O. Akanyeti, M. Kruusmaa, "Against the flow: A Braitenberg controller for a fish robot", IEEE International Conference on Robotics and Automation, St. Paul, USA, May 14-18, 2012.

Thanks to…

Steve Vogel, Jimmy Liao, George Lauder, John Long, Thor Fossen, Pablo Alvarado, Otar Akanyeti, Lily Chambers, Joachim Mogdans, William Megill, Rolf Pfeifer, David Lane, Jeff Tuthan, Otar Akanyeti, Massimo de Vittorio, Francesco Rizzi, Hadi el Daou, Mart Anton, Madis Listak, Taavi Salumäe, Gert Toming, Andres Ernits, …….

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