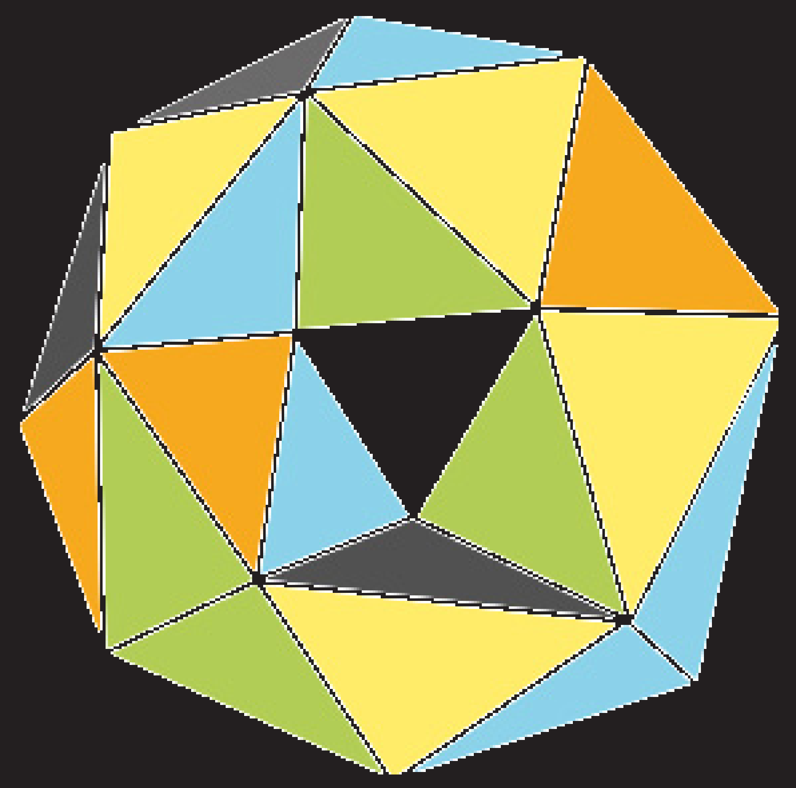
Controls Co-design

ARPA-e, July 2018



Saul Griffith
www.otherlab.com

no-control

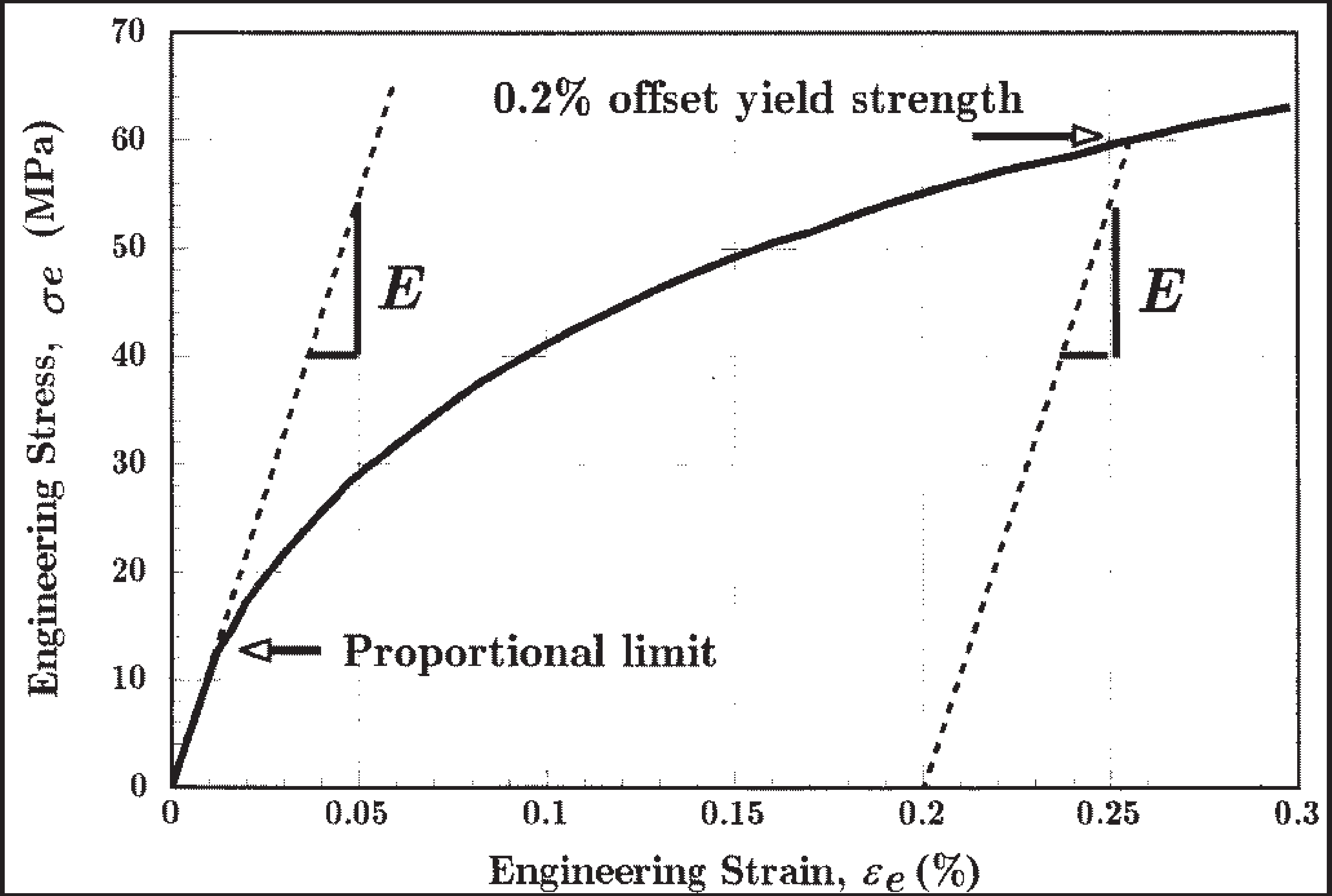
~control

Controls
Computation
Compliance

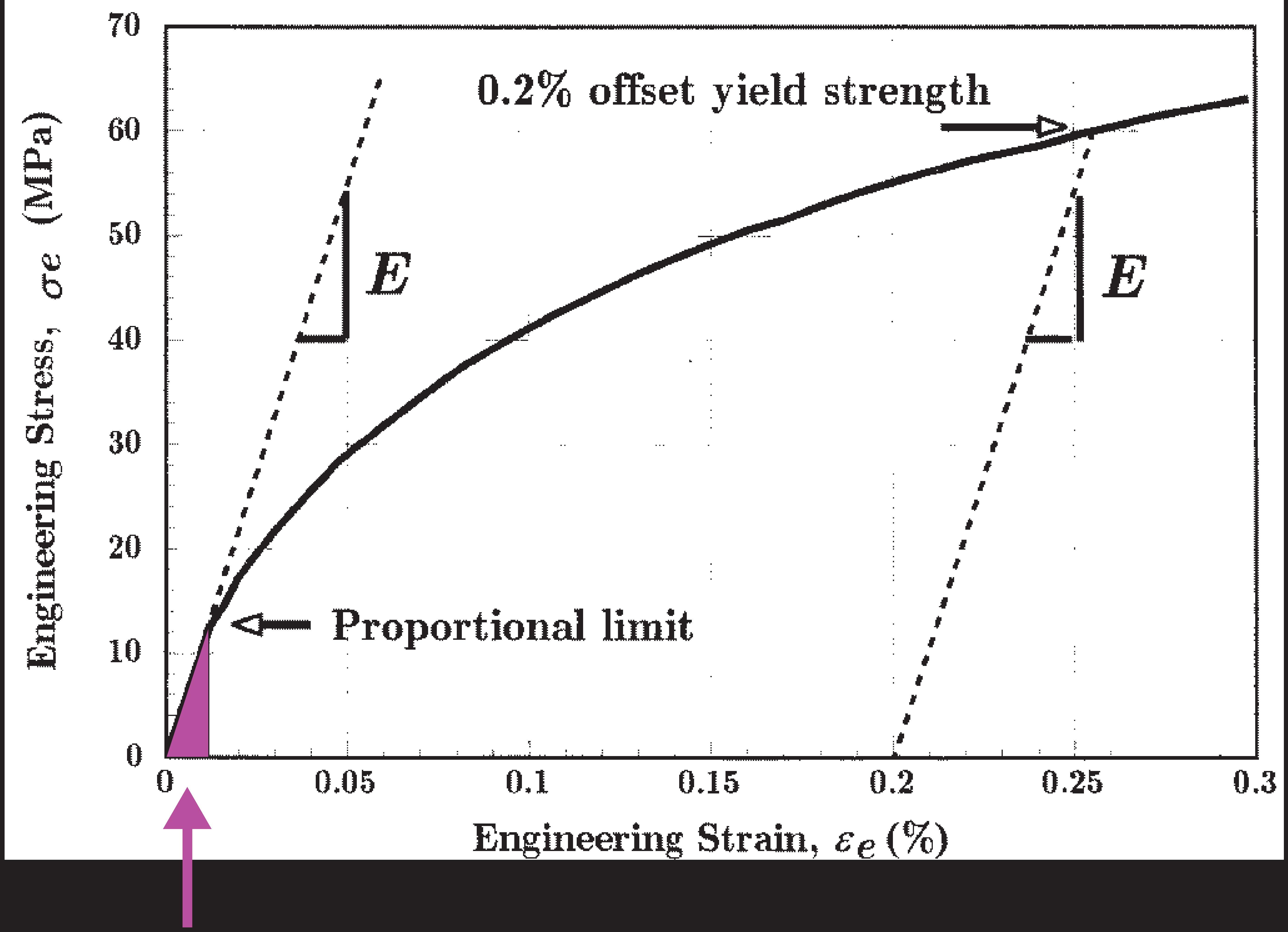

ROBERT HOOKE
1635~1703
Engineer

1660, Hooke's Law

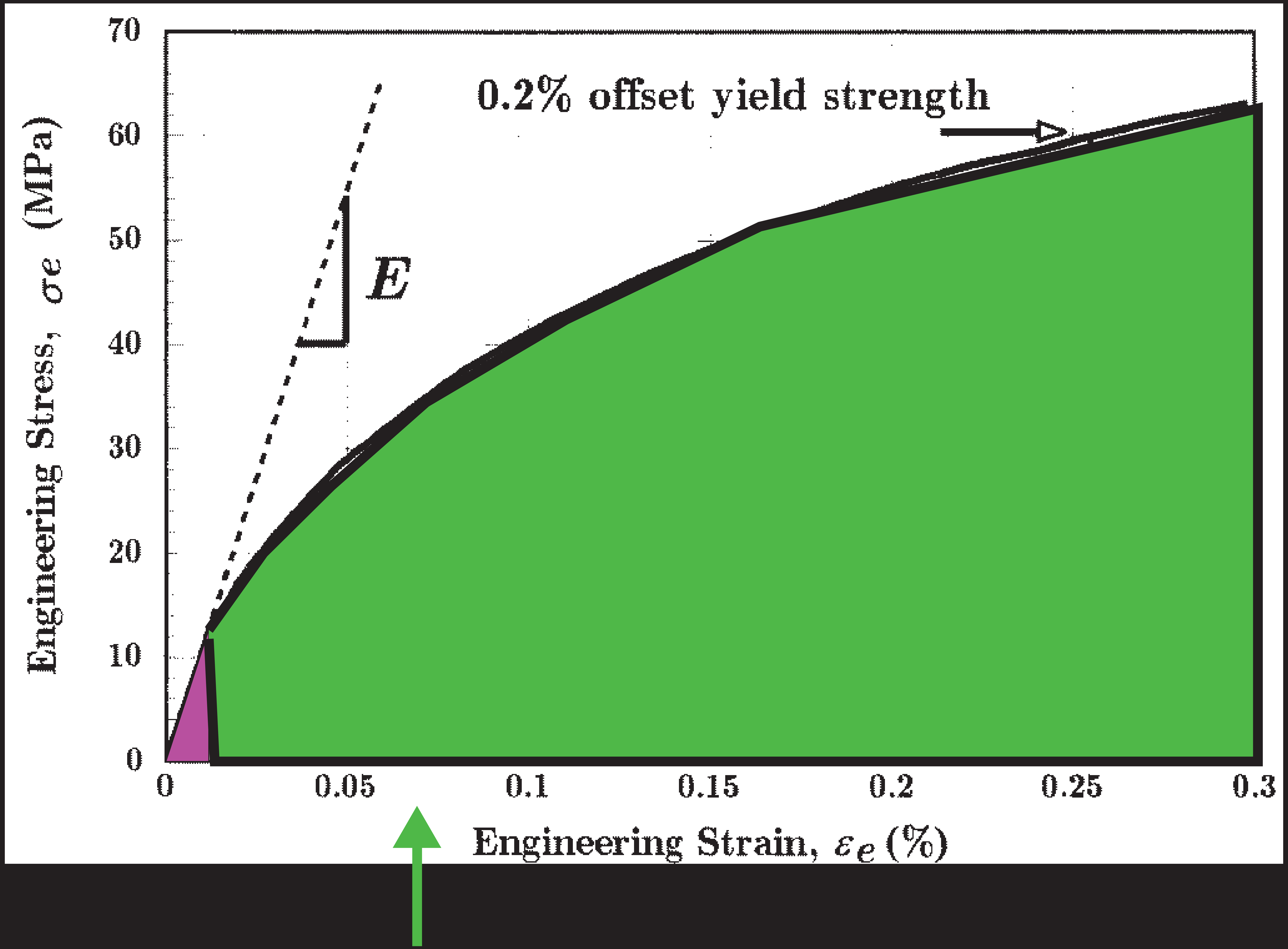
$$F = -k.x$$



$$E = \sigma_e / \epsilon_e$$



WE ONLY USE THIS BIT



BECAUSE WE ARE SCARED OF THIS BIT.

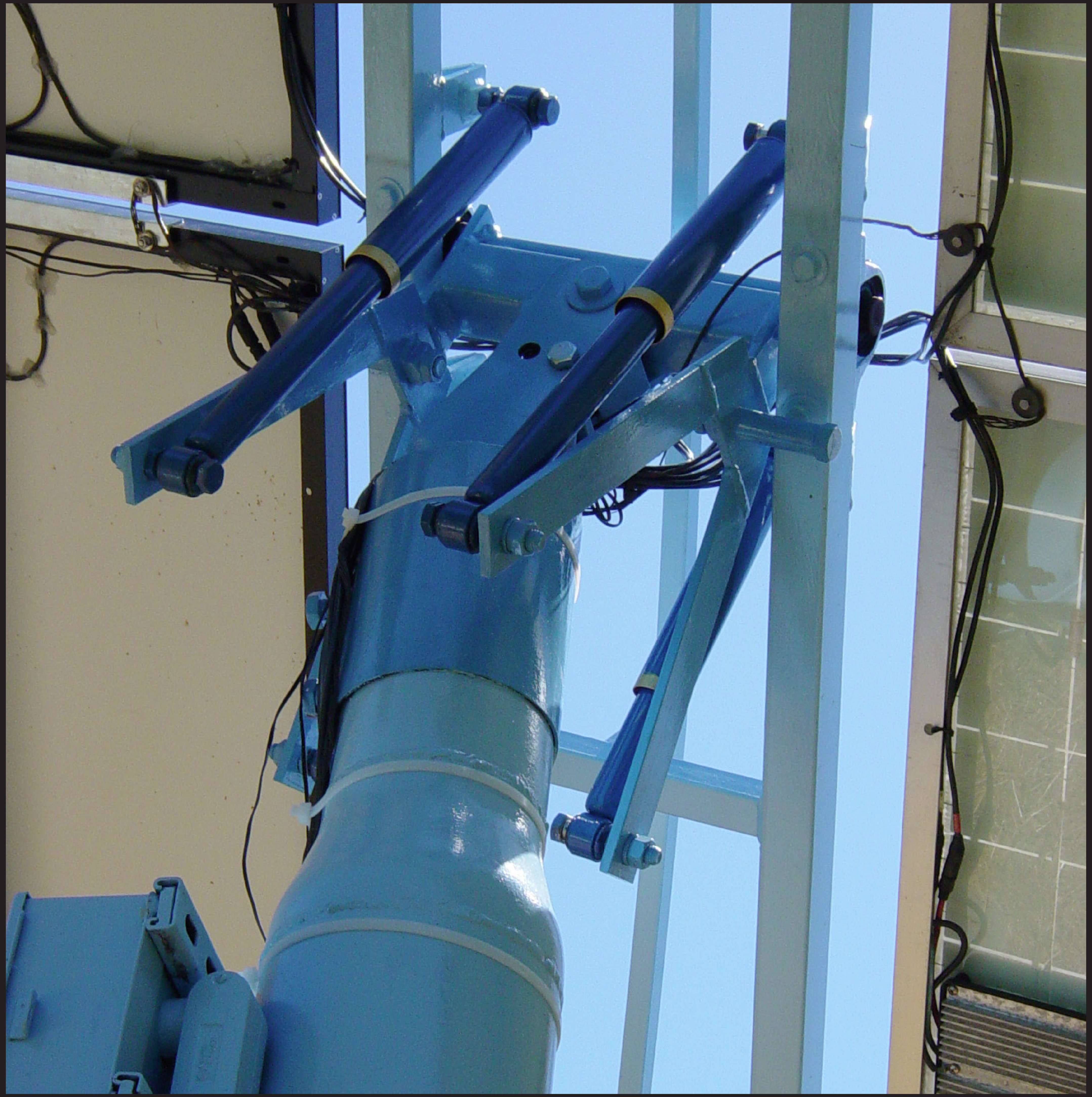
no control

control

no-control

control

rigid - no control



compliant - passive control

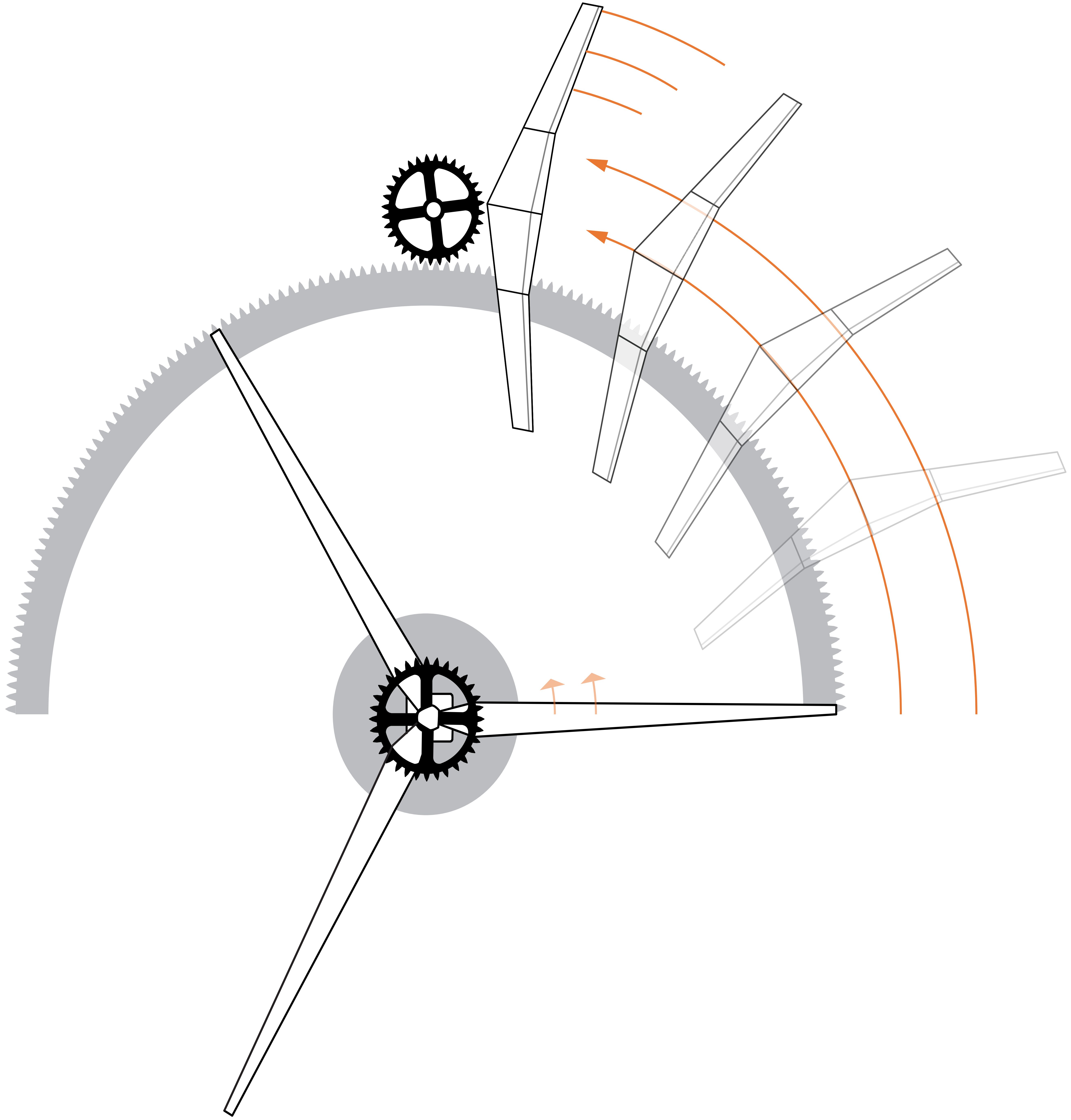
sunfolding video

control

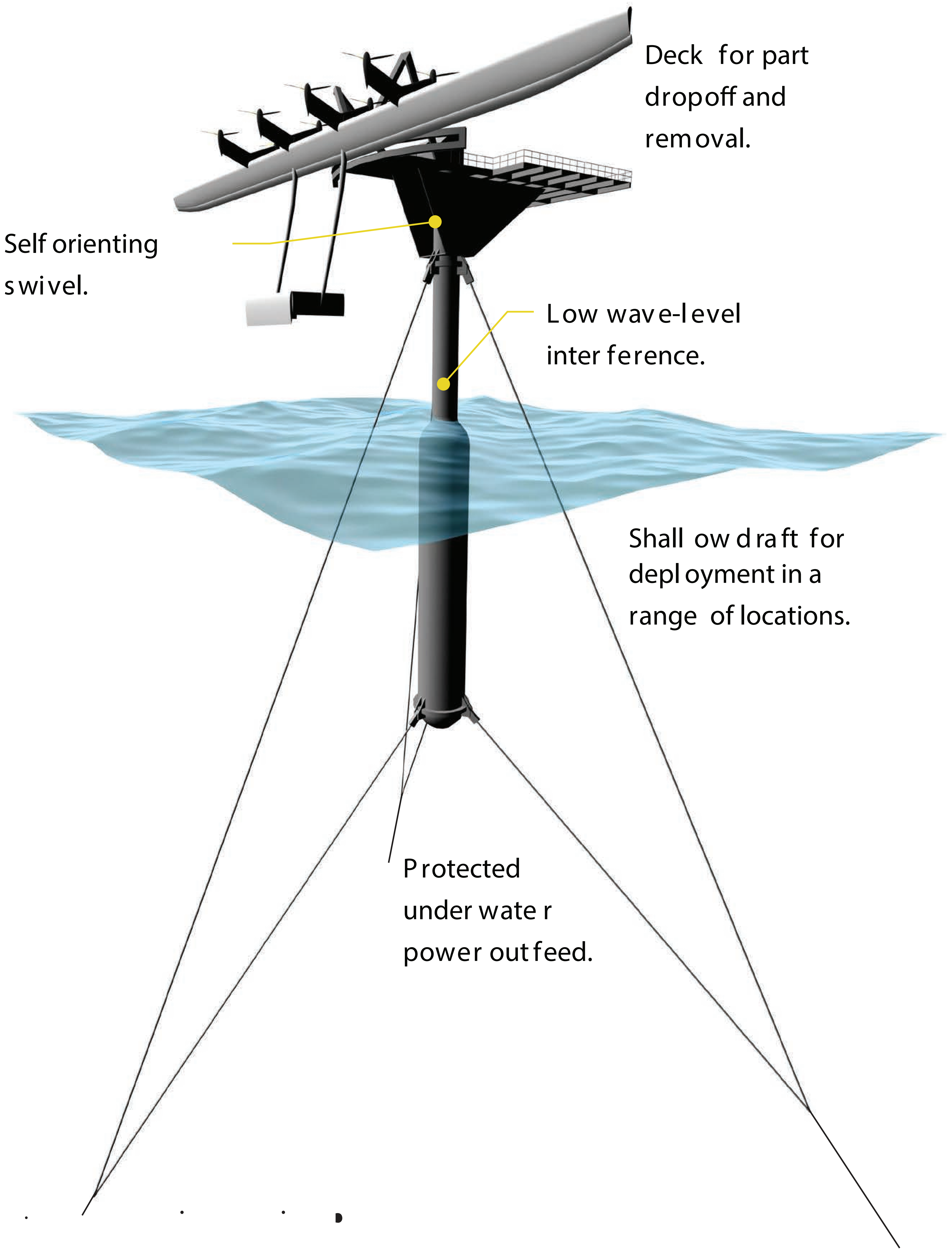
more control

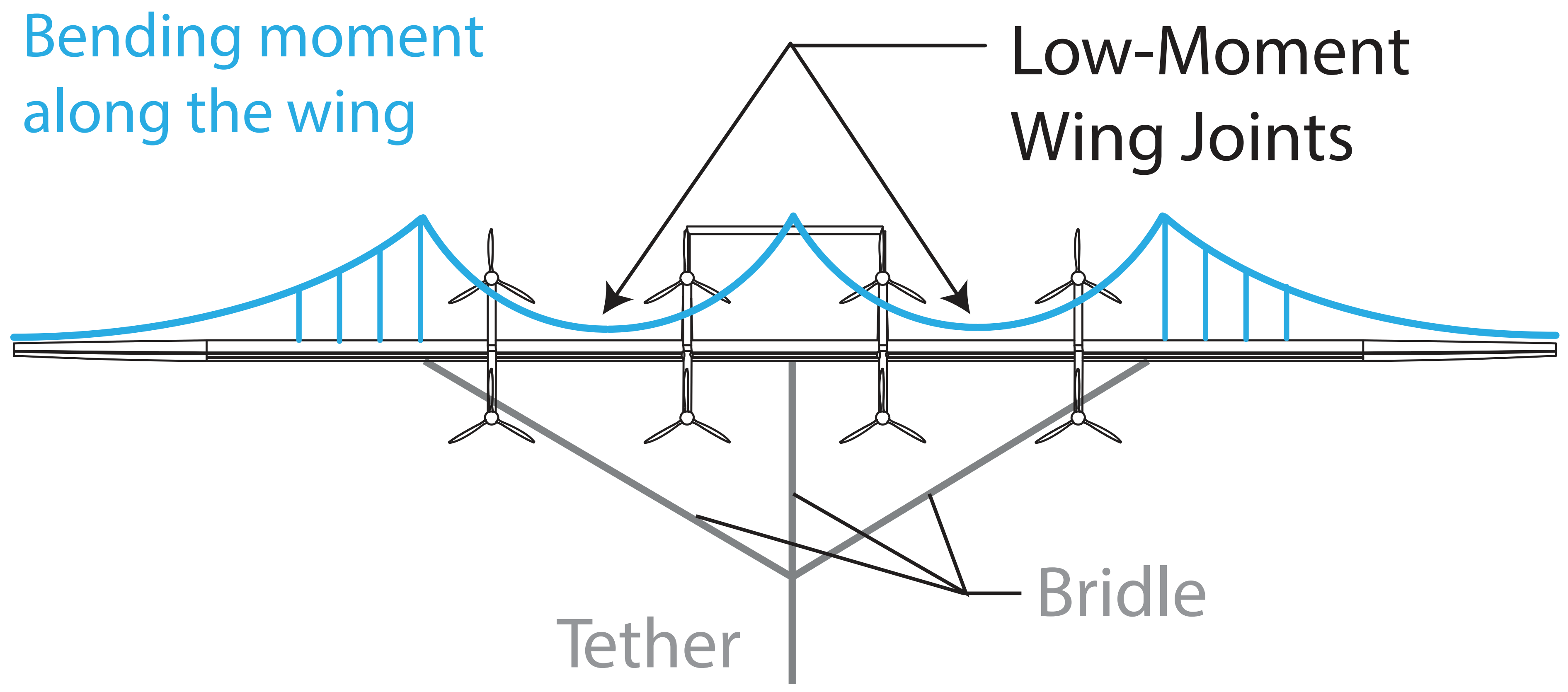
substituting control for material : lighter = cheaper

makani video



Hybrid Floating Platform





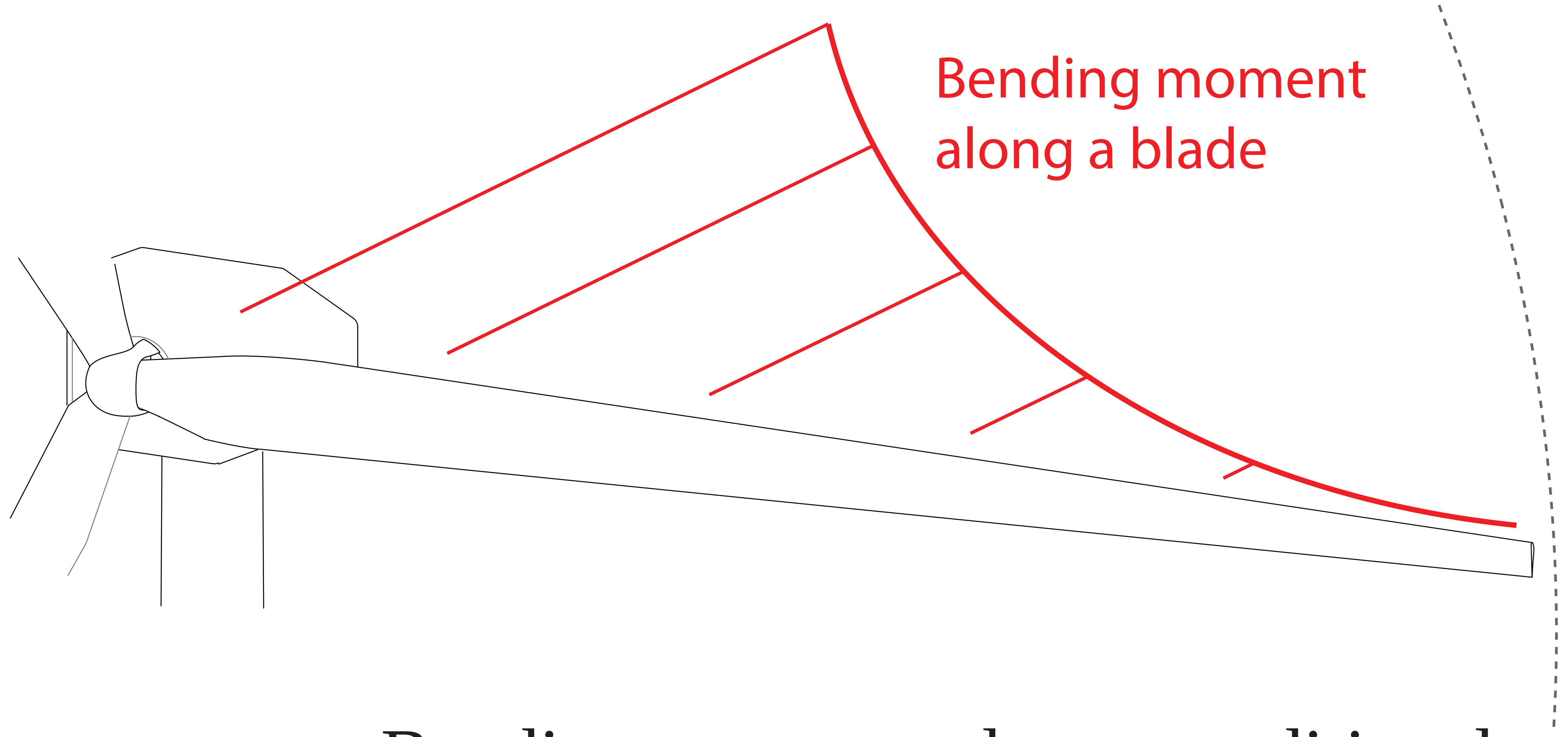
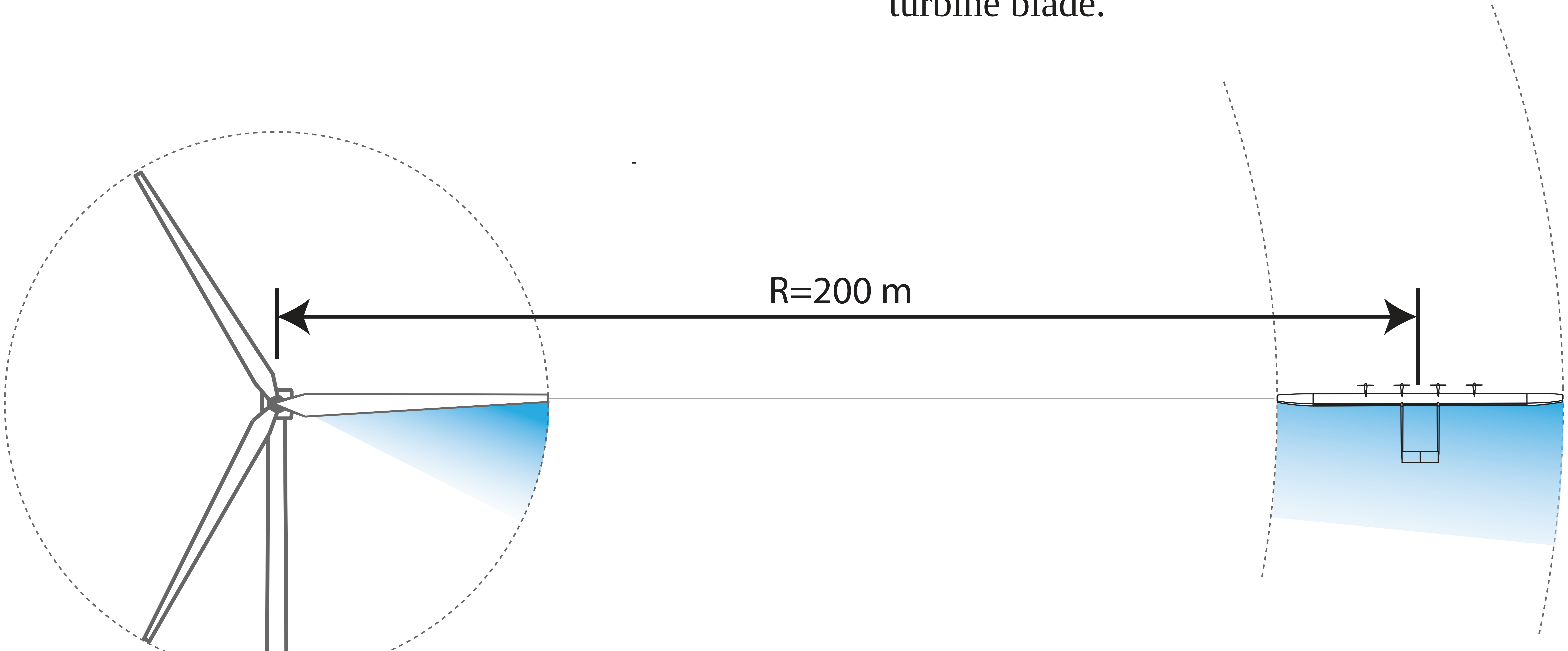
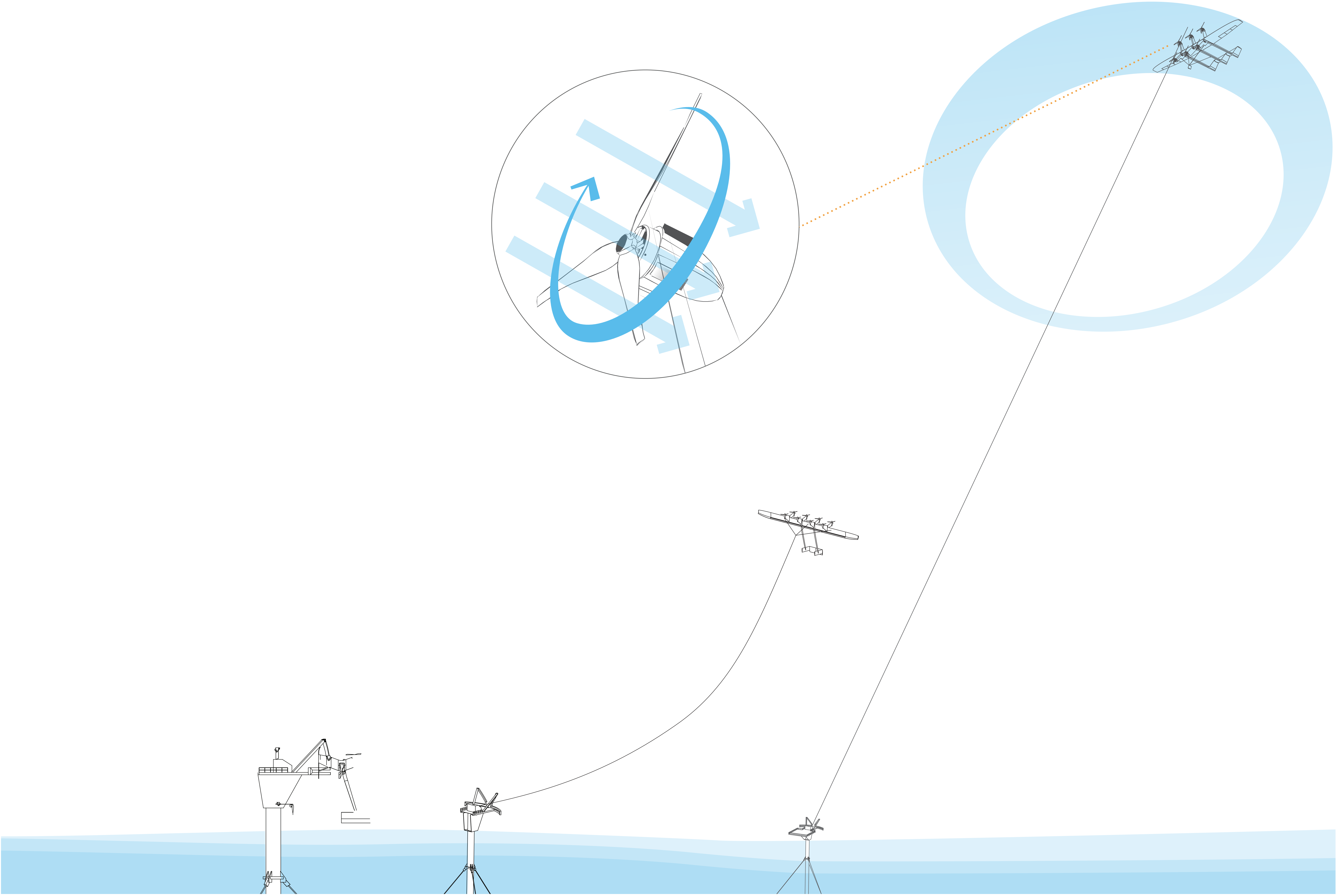


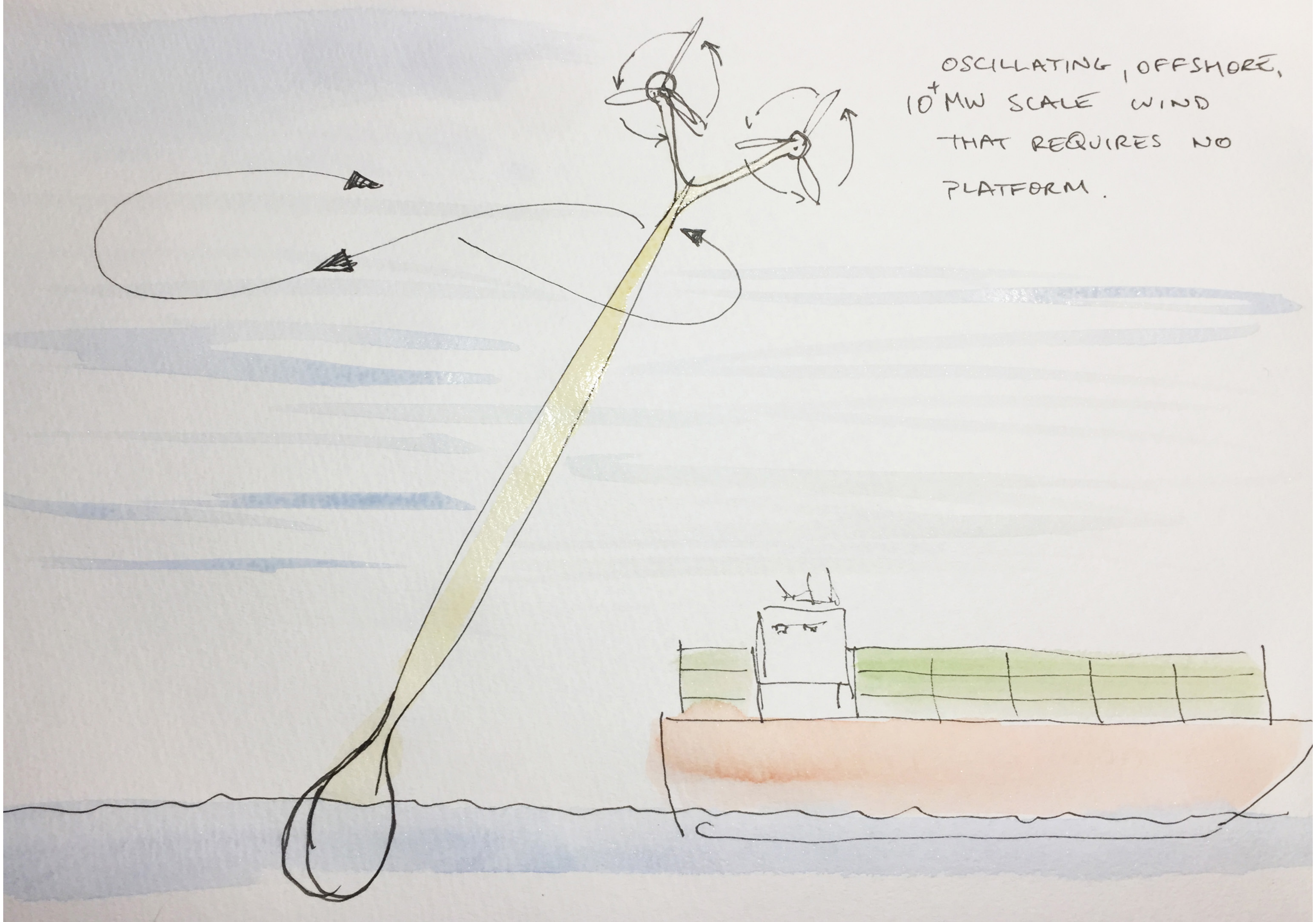
Figure 3. Bending moments along a traditional turbine blade.





Some new concepts in hydrokinetic and wind energy extraction enabled by control co-design..

“Seagrass”


OSCILLATING, OFFSHORE,
10+ MW SCALE WIND
THAT REQUIRES NO
PLATFORM.


CF 8202 KM
NALANI

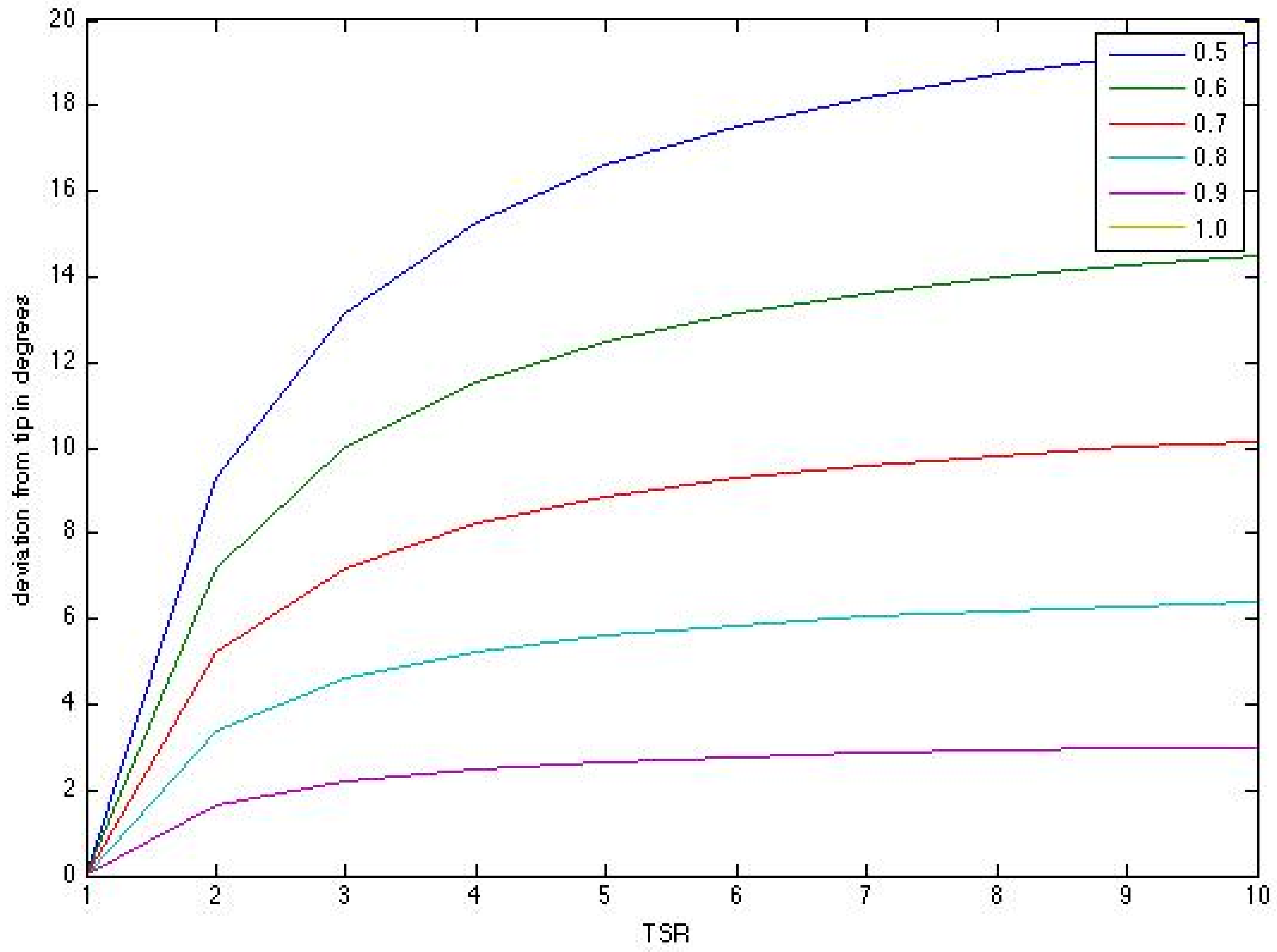


FIGURE 3. The maximum variation of angle of attack (AoA) with that at the tip over a sinusoidal stroke, assuming no induced drag, plotted against TSR for various nondimensional blade radii. AoA variation is measured against the AoA at the blade tip. If we wish to maintain usable airfoil area over the outer half of the blade, this shows we are limited to a maximum tip speed ratio of around 4-5, assuming we do not use a highly flexible spar. Higher TSRs also have a large impact on acceleration loading, as is discussed later.

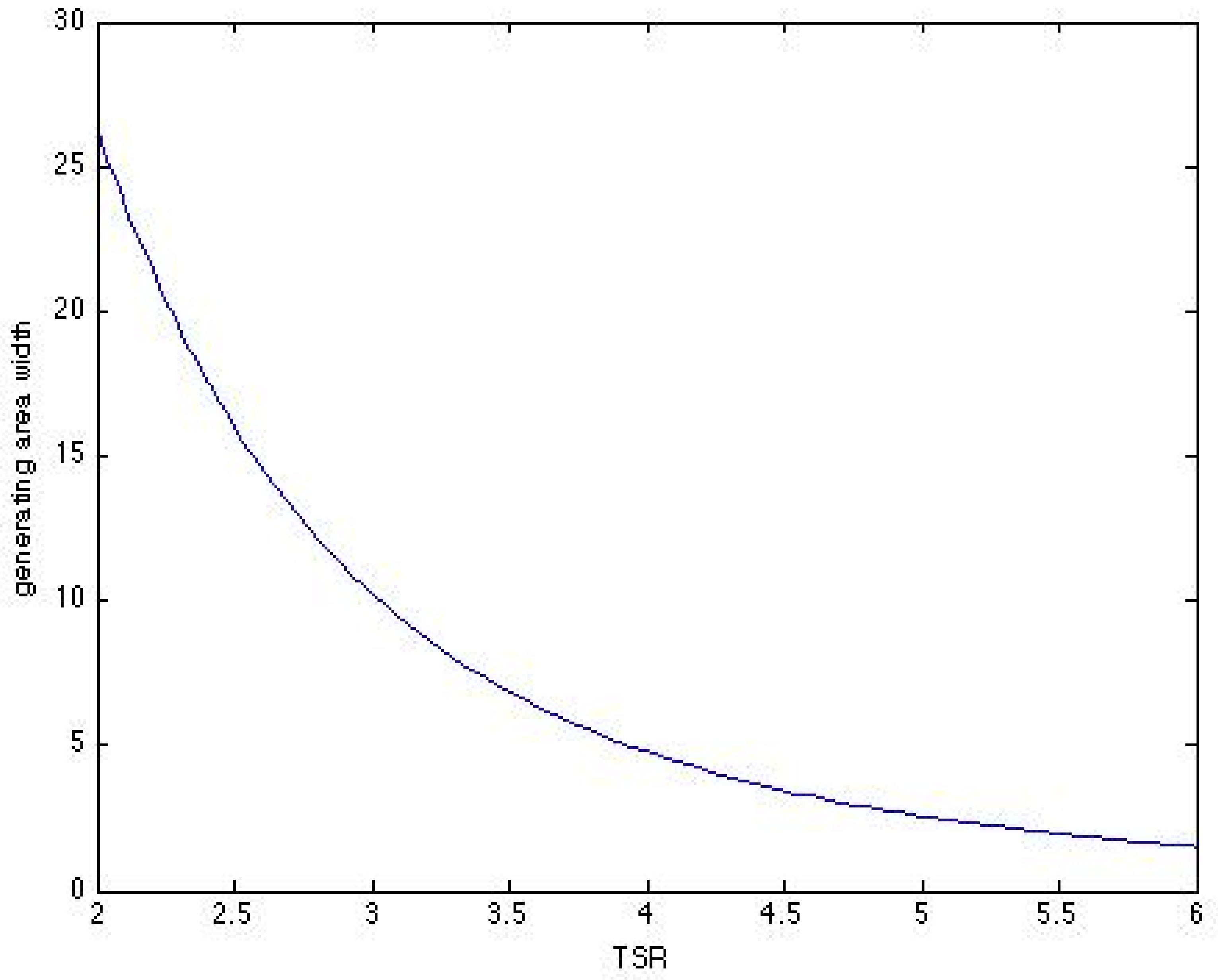


FIGURE 4. If the top 20 meters of a 70 meter tall 1MW Seagrass unit is covered with wind turbines operating at 80% of Betz efficiency, this is the width of generating area needed to generate that power, supposing that we are trying to pack circular swept areas in a square box. Thus, at a TSR of about 2.2, we can use one turbine of 10 meter radius. At a TSR of about about 3, we need two turbines of 5 meter radius, at a TSR of 4 we can use four turbines with a 2.5 meter radius. Thus we see a TSR of 3-4 is about the lower limit of what we might be able to get away with when considering the (large) gyroscopic effects on these blades, and the relative cost of the generation turbine versus that of the Seagrass unit.

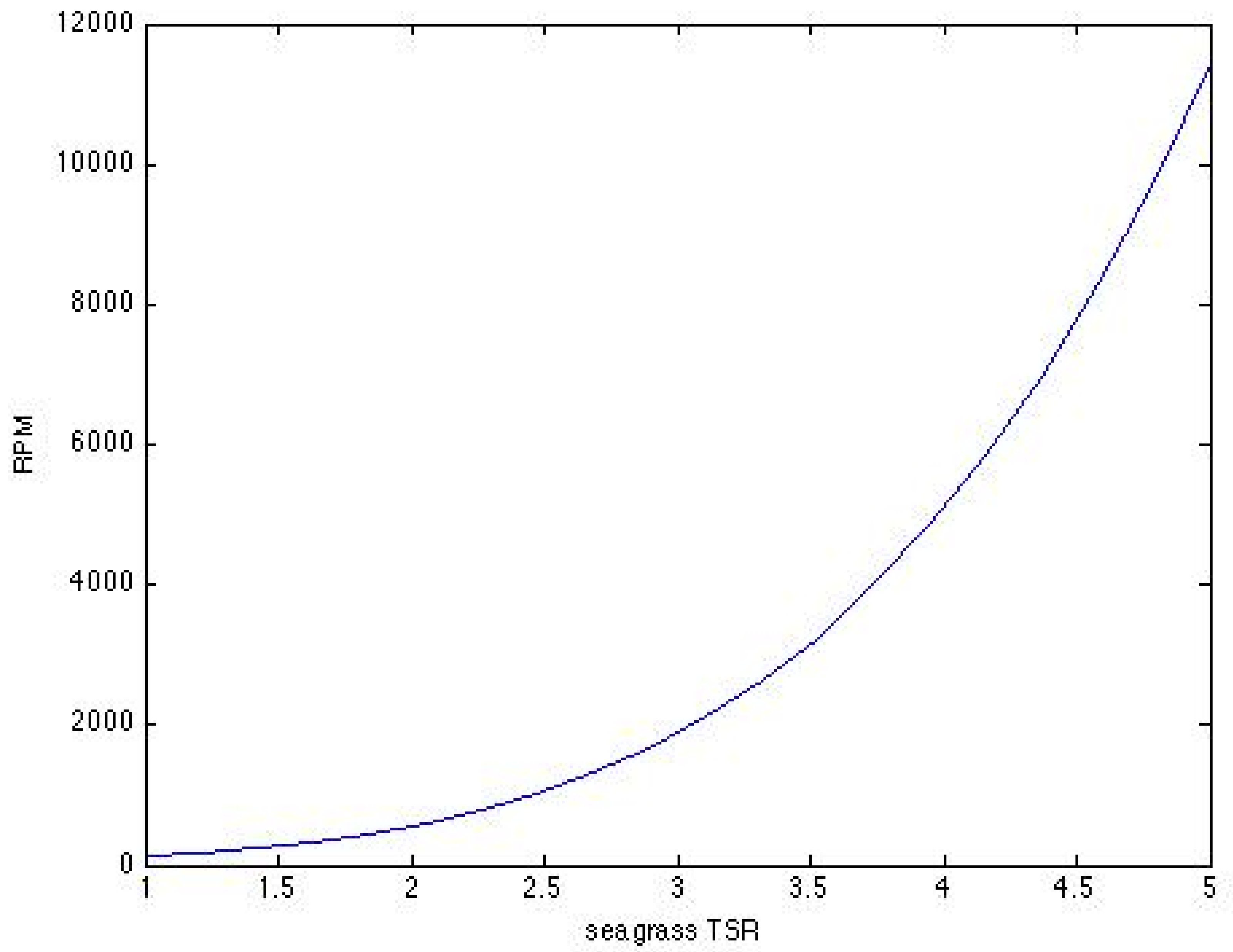


Figure 5. A Seagrass unit consists of a big blade swining back and forth, with a smaller turbine or set of turbines near the tip. A higher-end TSR for a wind turbine is generally around $\frac{22}{n_{blades}}$, so the highest RPM design without large teeter issues is a two blade turbine, for which we will assume a turbine TSR of 11. In this plot we see the time-average RPMs of turbines of sufficient diameter (see figure 4) to produce 1MW of power on a 70 meter Seagrass unit when placed on the outer 20 meters of blade, as a function of TSR. Rotor RPMs of above 1000 are desirable, though much can be done with motor design to optimize for lower angular rates. A two-bladed turbine is also preferable as more can be done with use of a teeter axis to provide automatic correction for angle of attack while yawing, much like a model helicopter blade.

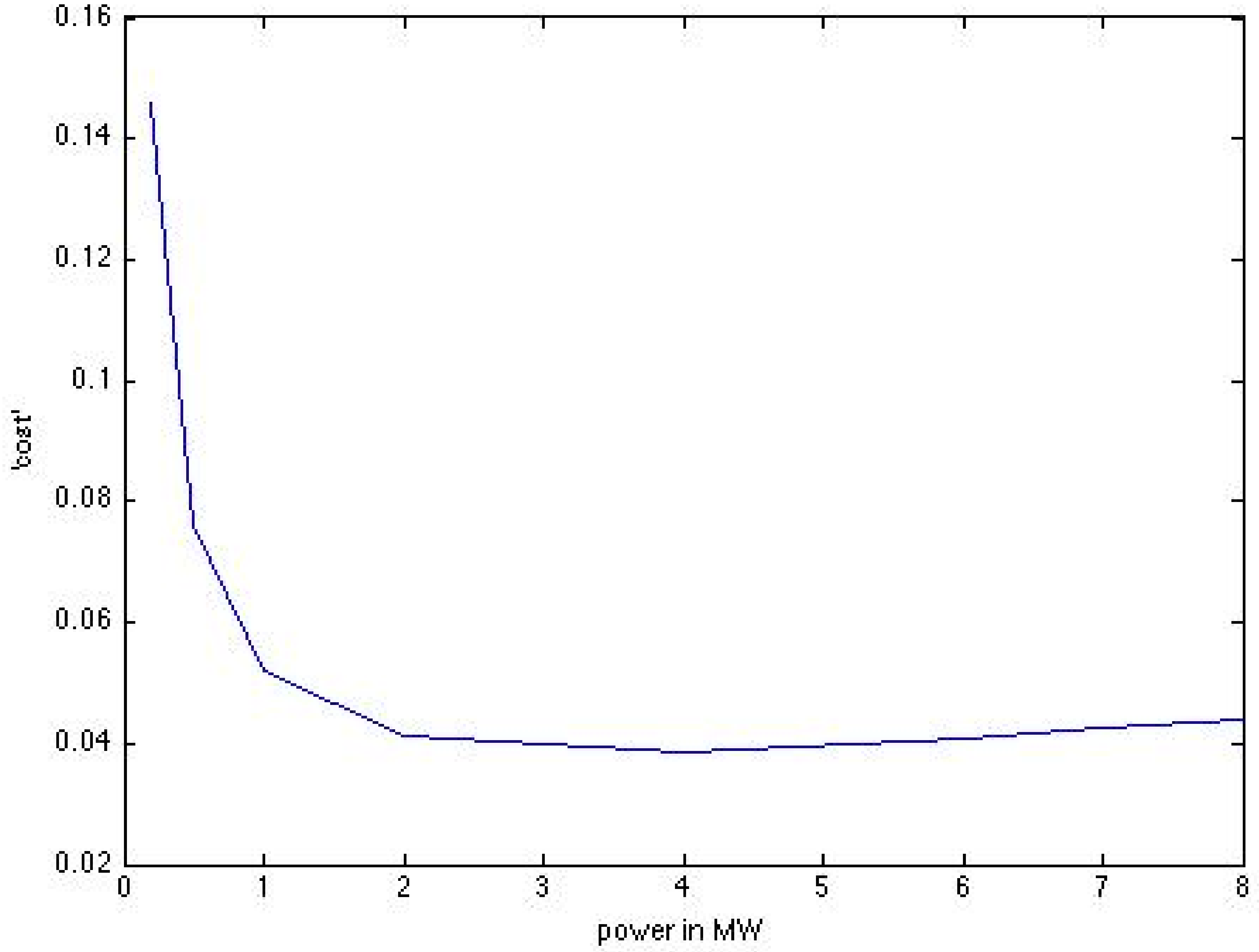
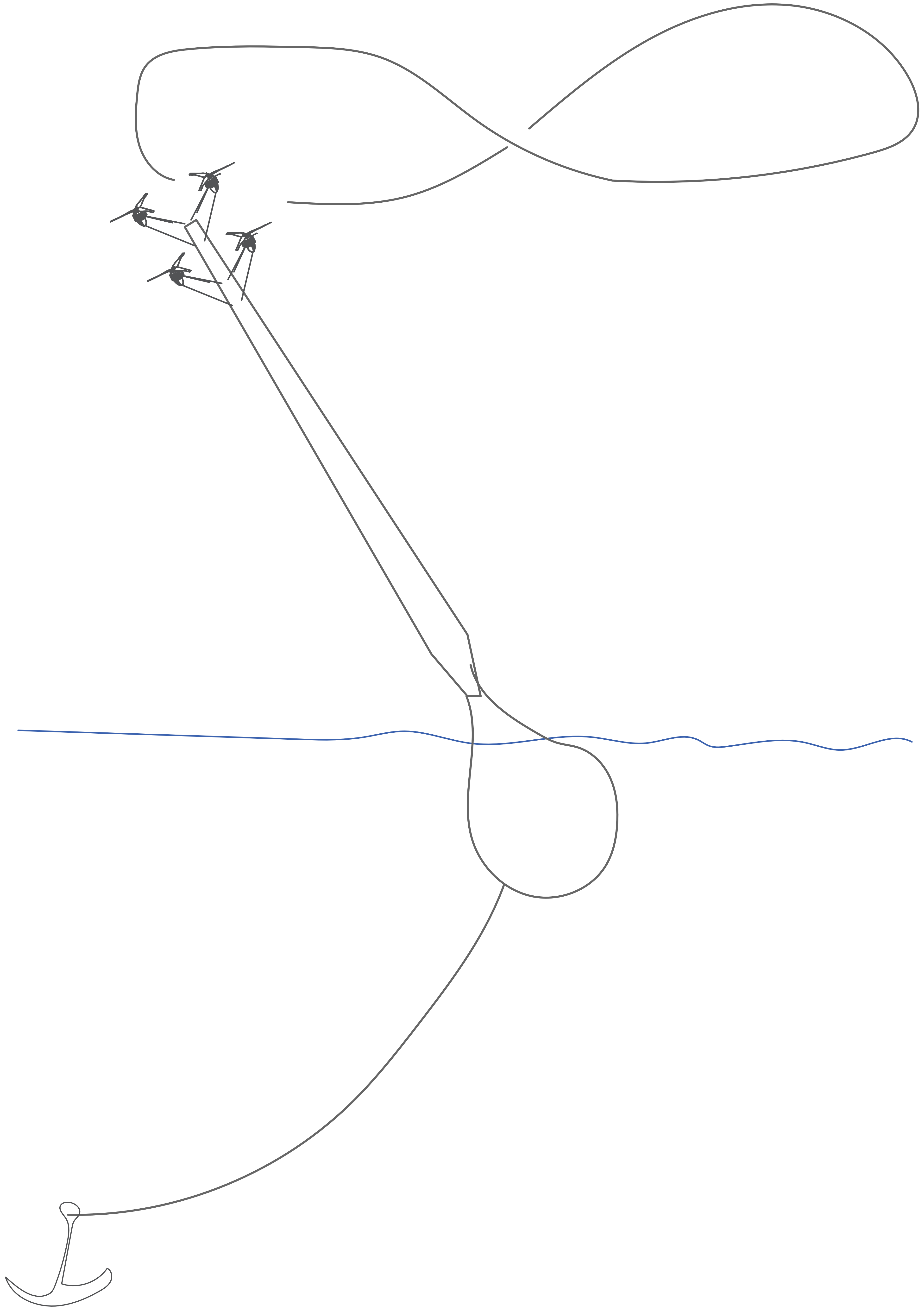


FIGURE 8. The cost per watt of power produced, as a function of rated power, for a slenderness of 10. This cost is based only on the relative prices of concrete and polyester, priced at $\$5/Kg$ of polyester, and $\$0.09/Kg$ for concrete. The minimum cost occurs very near to 4MW. In this plot, concrete cost dominates on the low-power side, while polyester cost slowly starts to dominate on the high-power side. If we were to account for the high cost of bearings or floats to support this amount of concrete, the plot would skew further towards the high-power side.



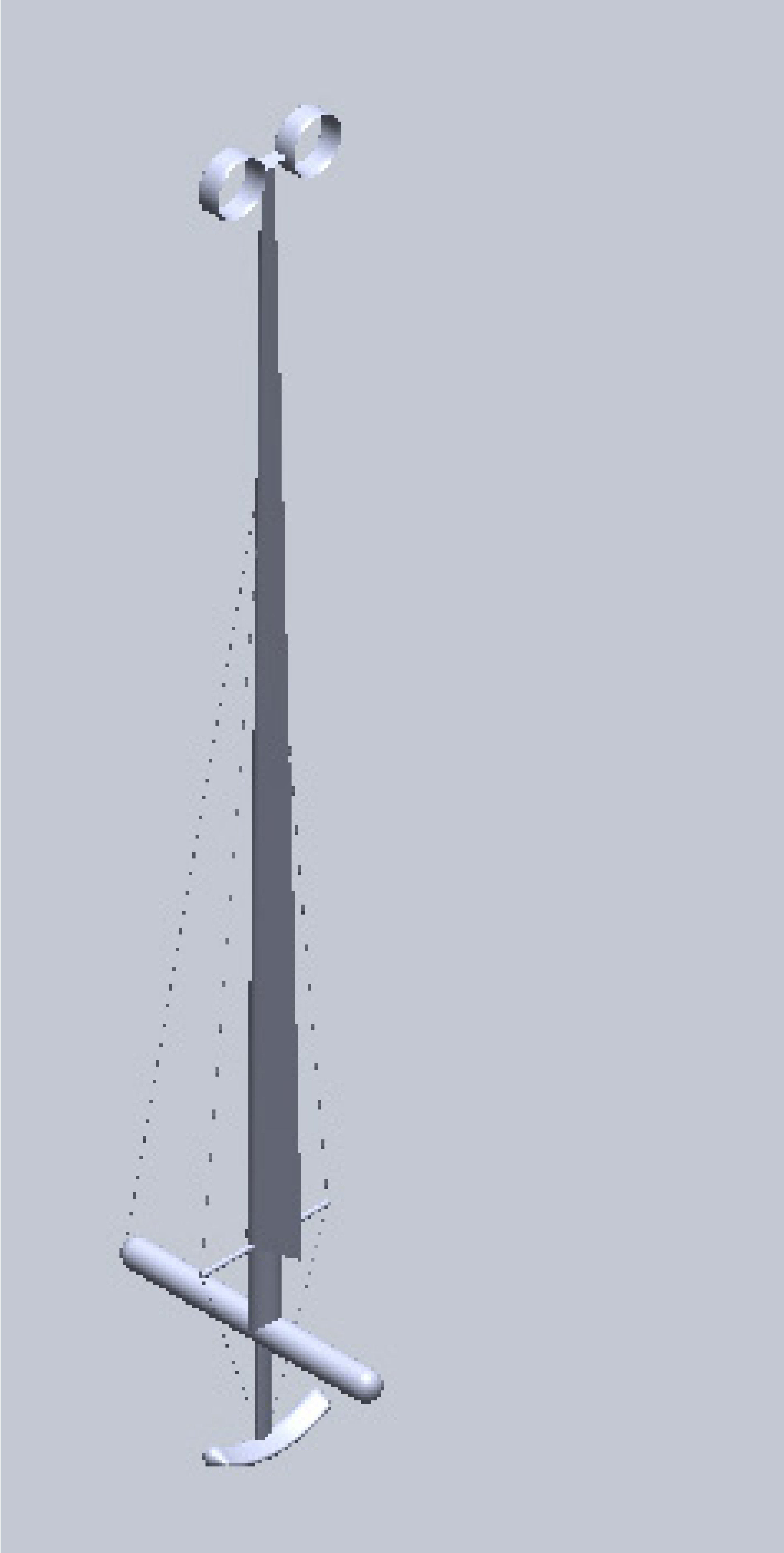
May be a good idea :

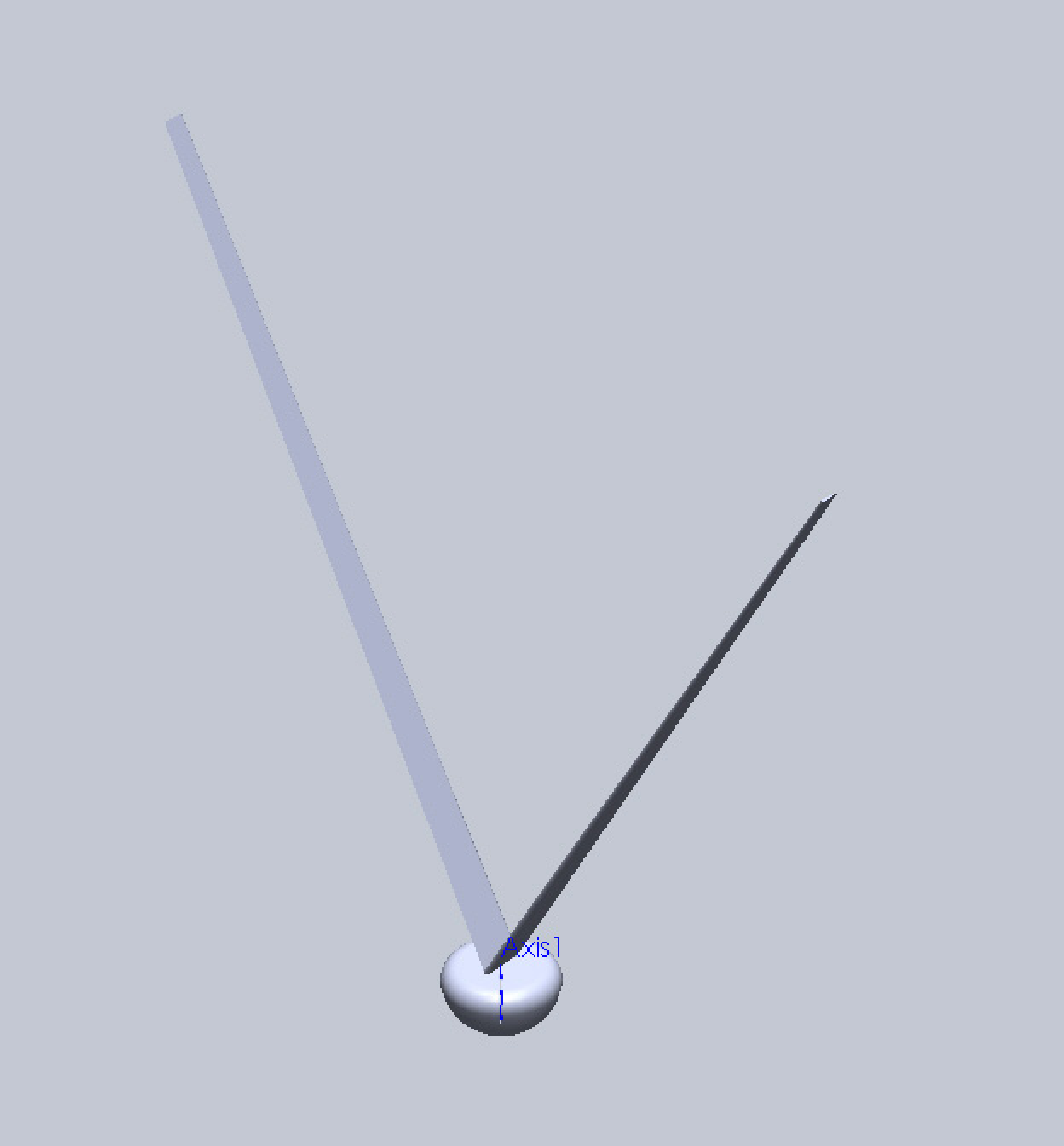
Low mass
No gearboxes
Single mooring line
No platform
5c/kWh ?? cost uncertainty goes from materials to O&M and controls reliability.

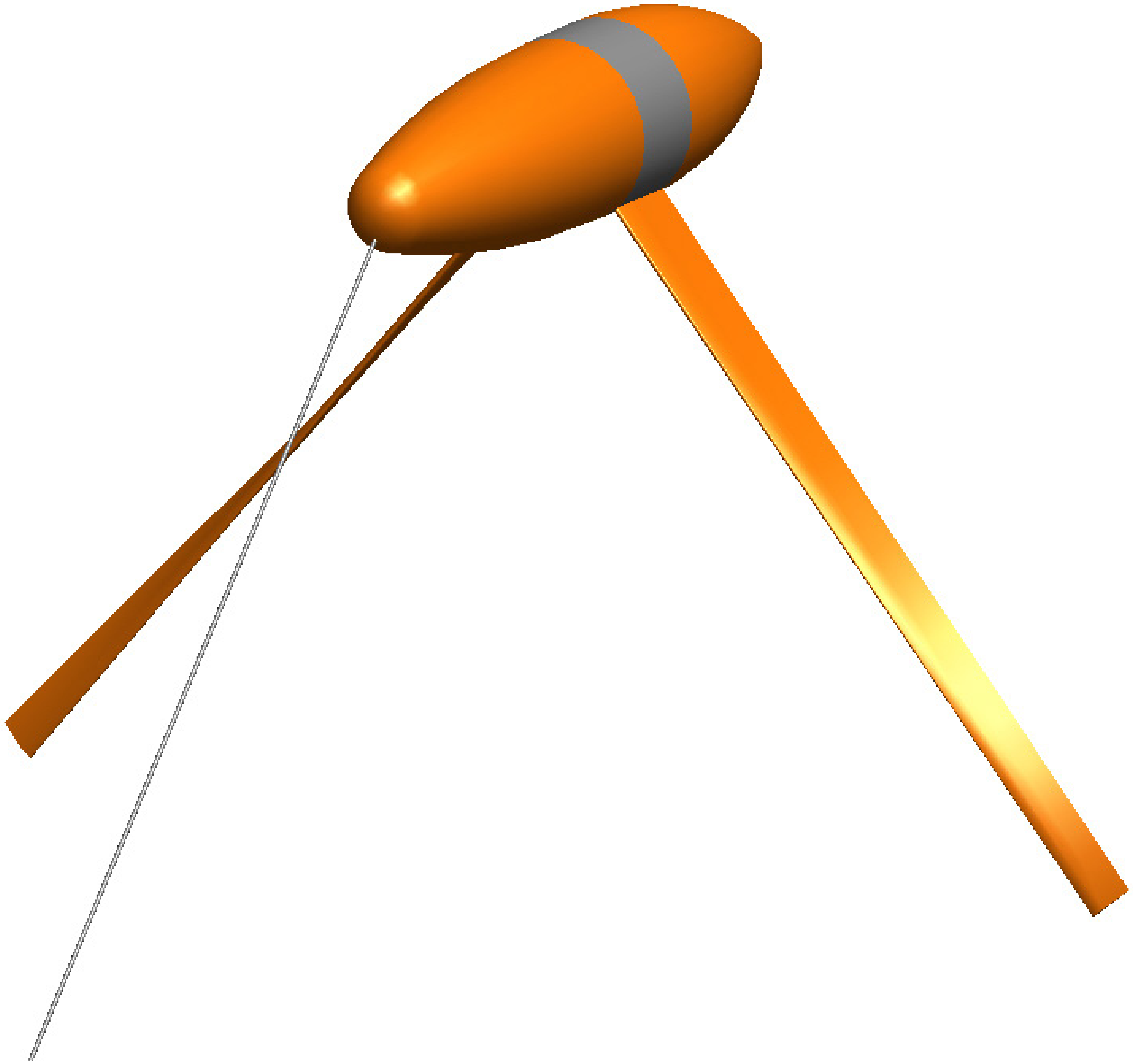
May be a bad idea :

Torques and accelerations
Cost and time to market
Mass of counter-weight

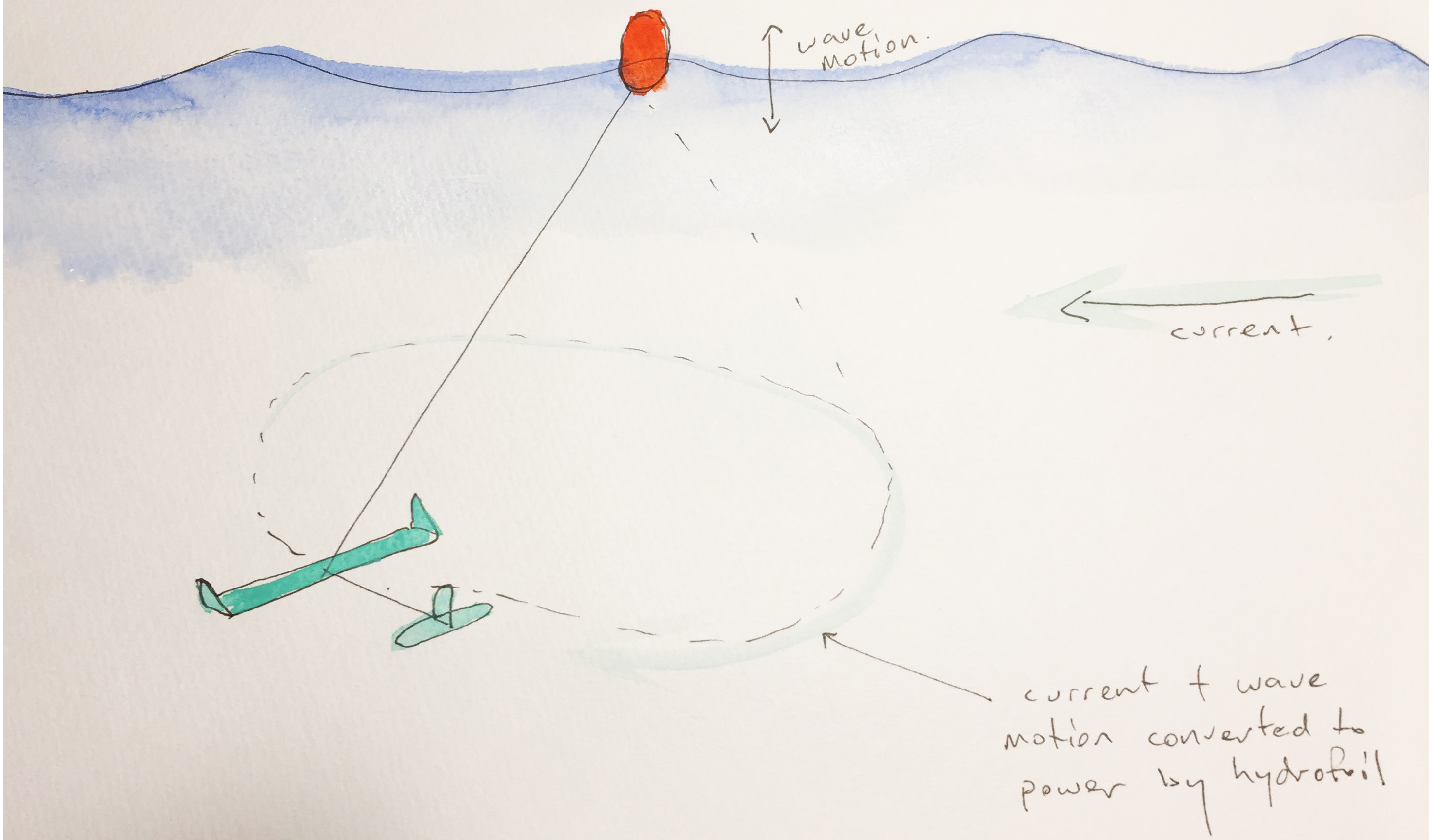
Other ideas.

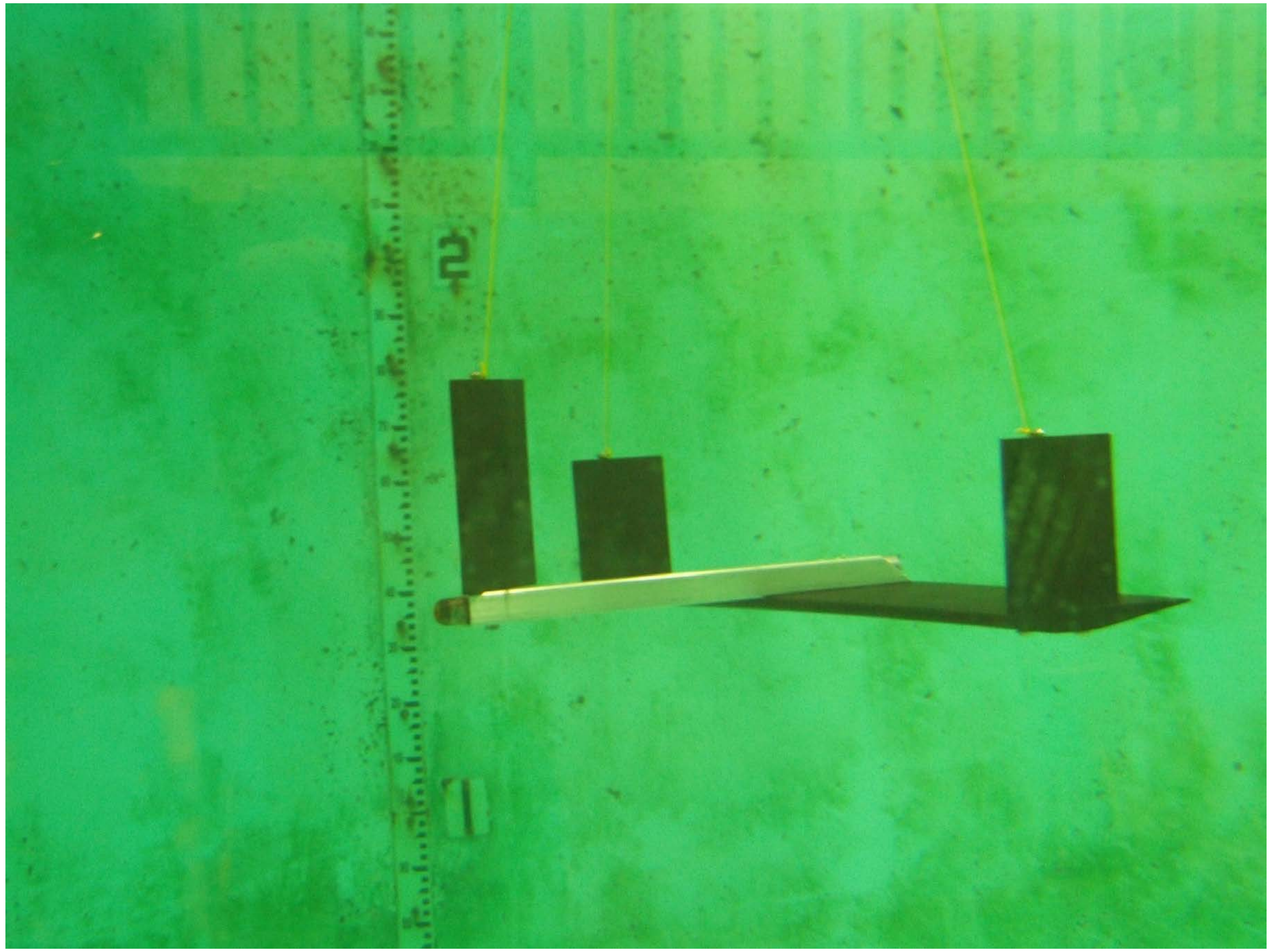


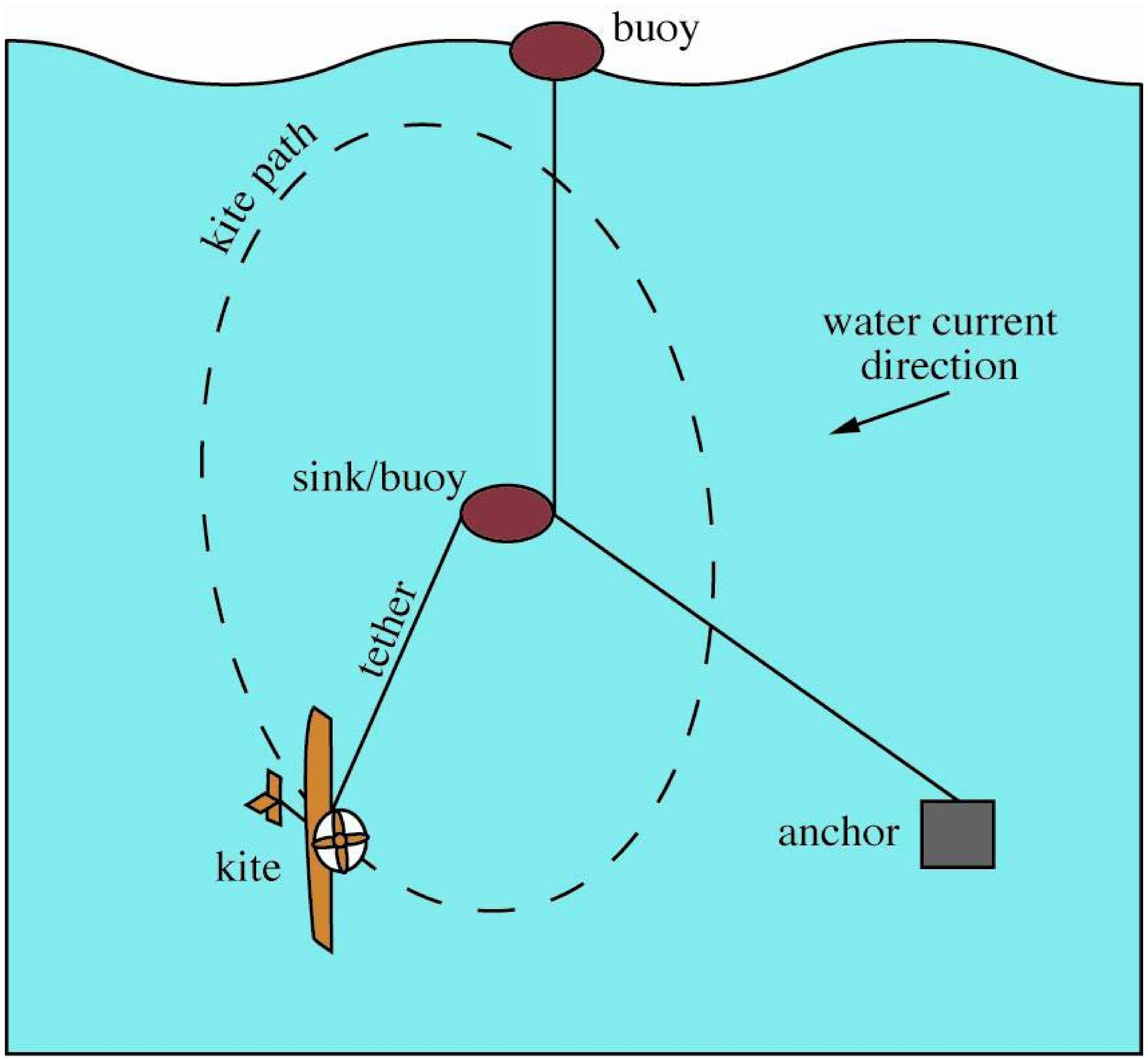

Axis1

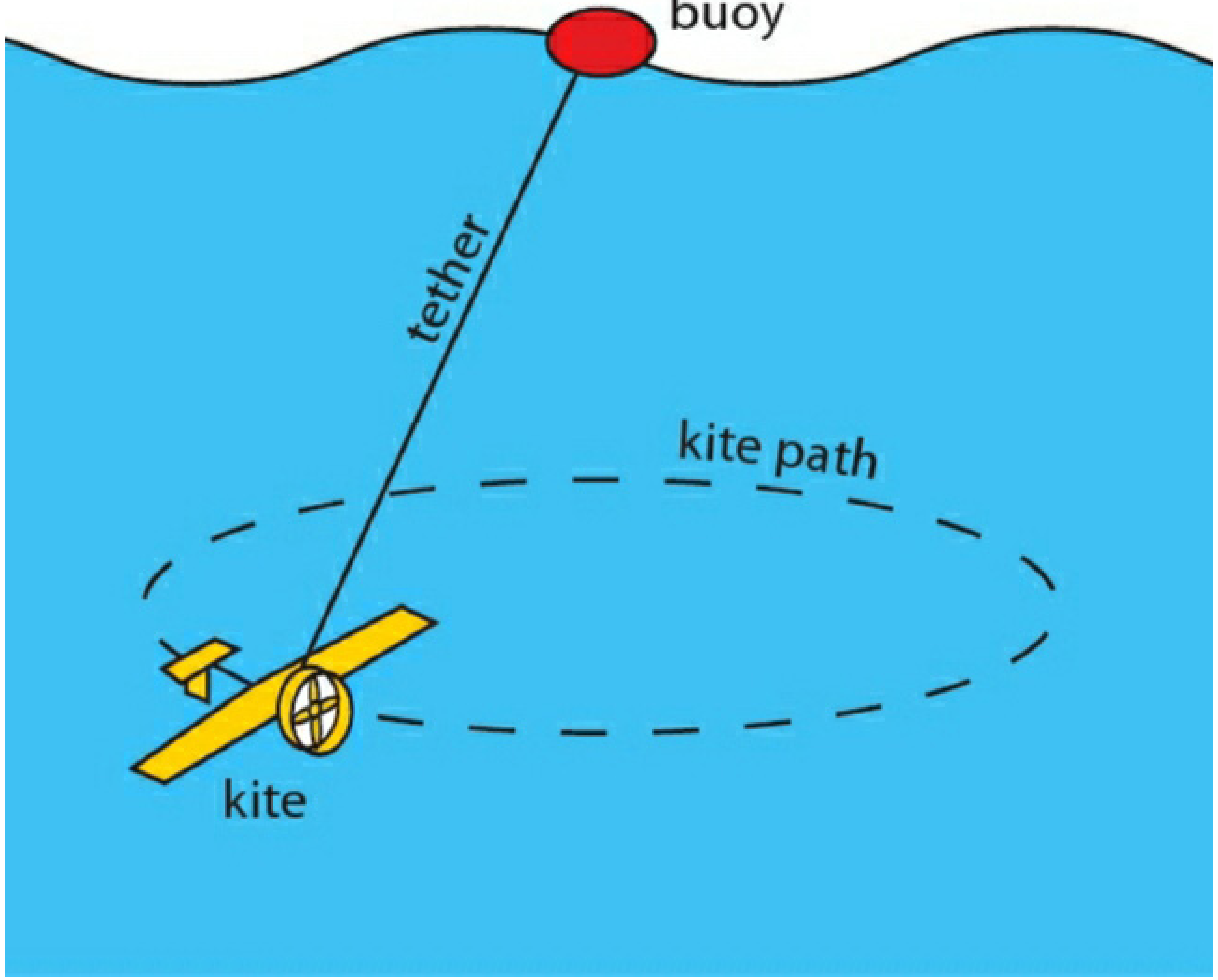


PUMPED HYDROFOIL HYBRID WAVE & CURRENT POWER

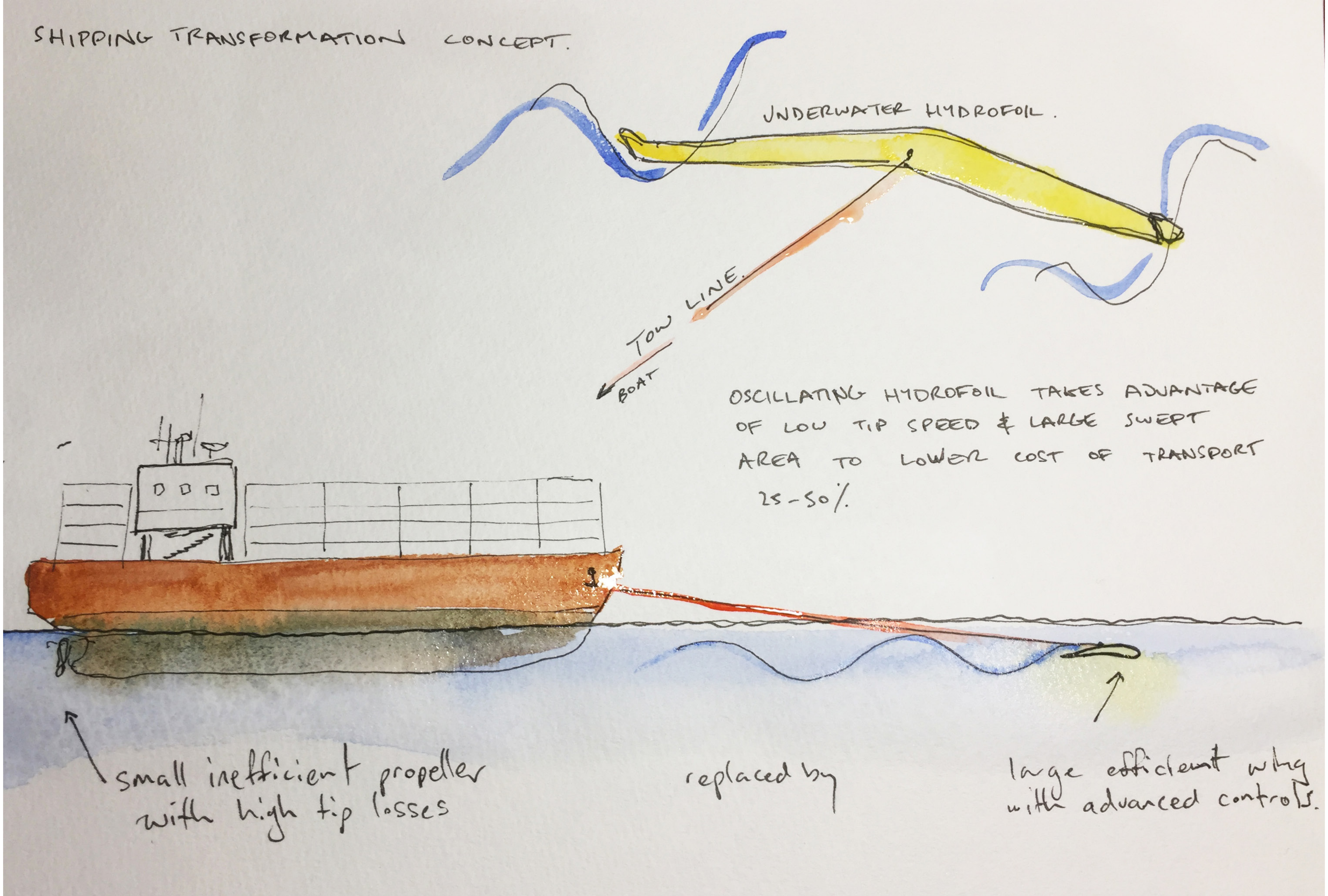


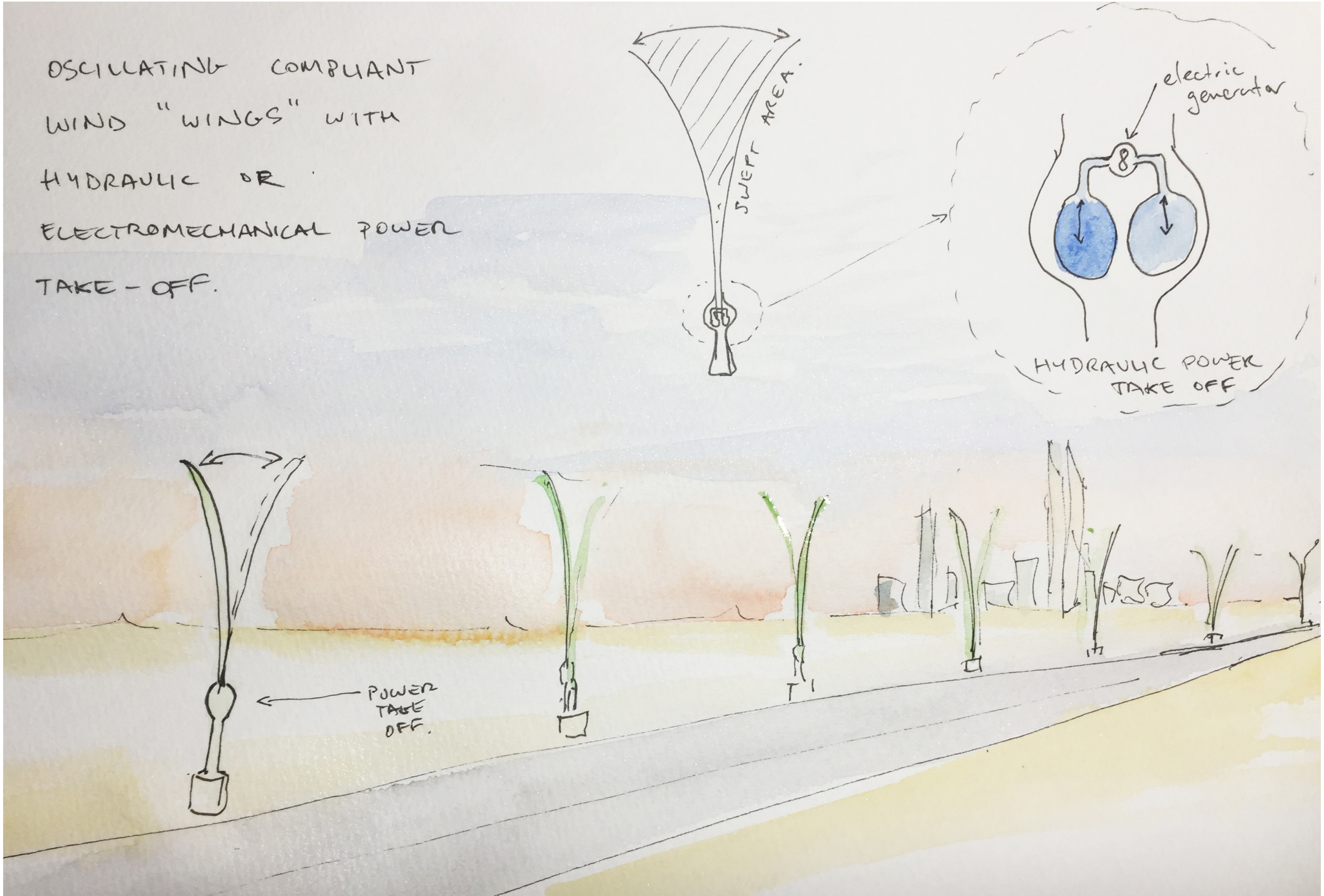



buoy
kite path
water current
direction
sink/buoy
tether
kite
anchor


buoy
tether
kite path
kite

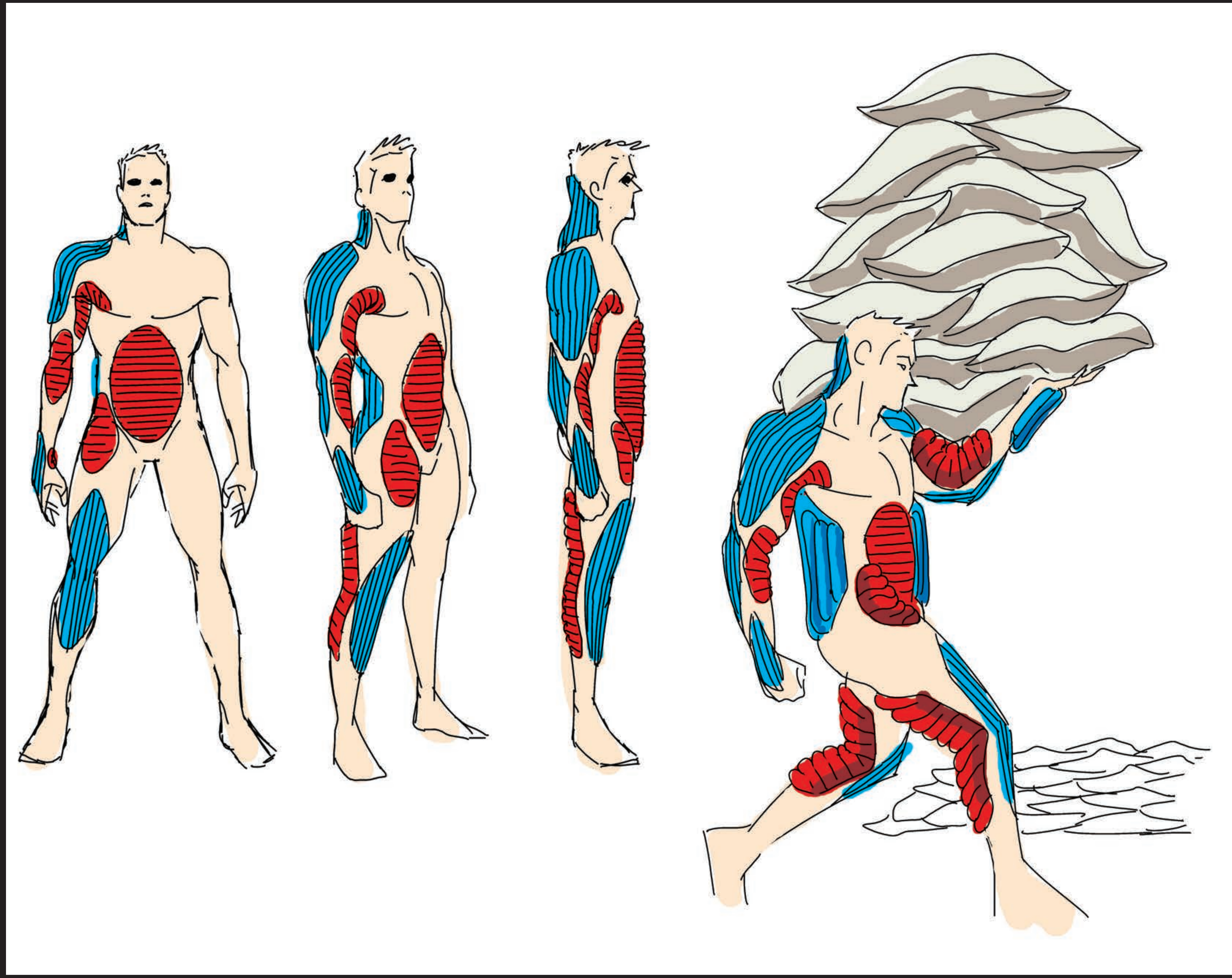
Hydrofoil video


SHIPPING TRANSFORMATION CONCEPT.
UNDERWATER HYDROFOIL.
TOW LINE.
BOAT
OSCILLATING HYDROFOIL TAKES ADVANTAGE OF LOW TIP SPEED & LARGE SWEPT AREA TO LOWER COST OF TRANSPORT 25-50%.
small inefficient propeller with high tip losses
replaced by
large efficient wing with advanced controls.


OSCILLATING COMPLIANT WIND "WINGS" WITH HYDRAULIC OR ELECTROMECHANICAL POWER TAKE-OFF.
SWEPT AREA.
electric generator
HYDRAULIC POWER TAKE OFF
POWER TAKE OFF.

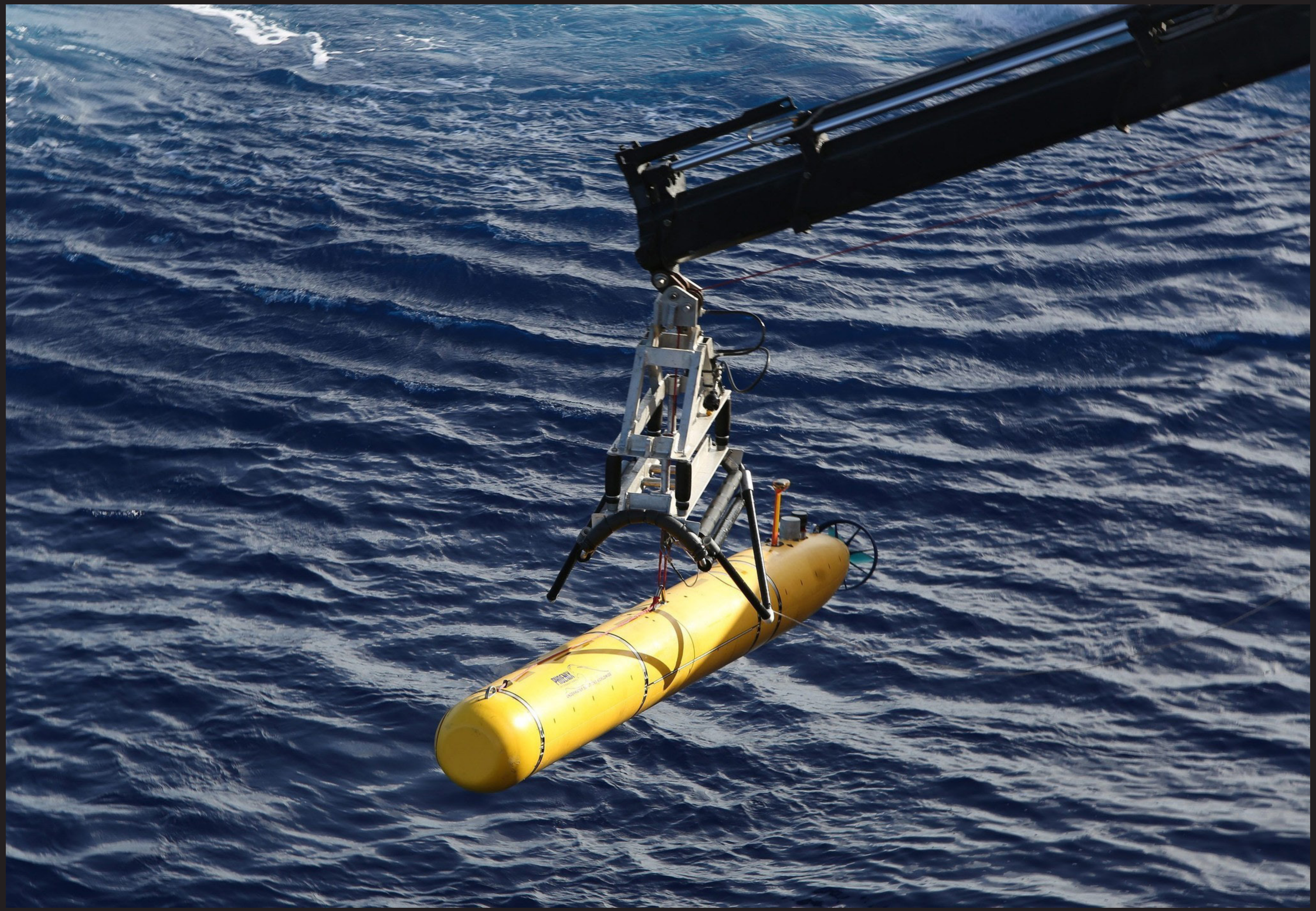
solid

un:solid

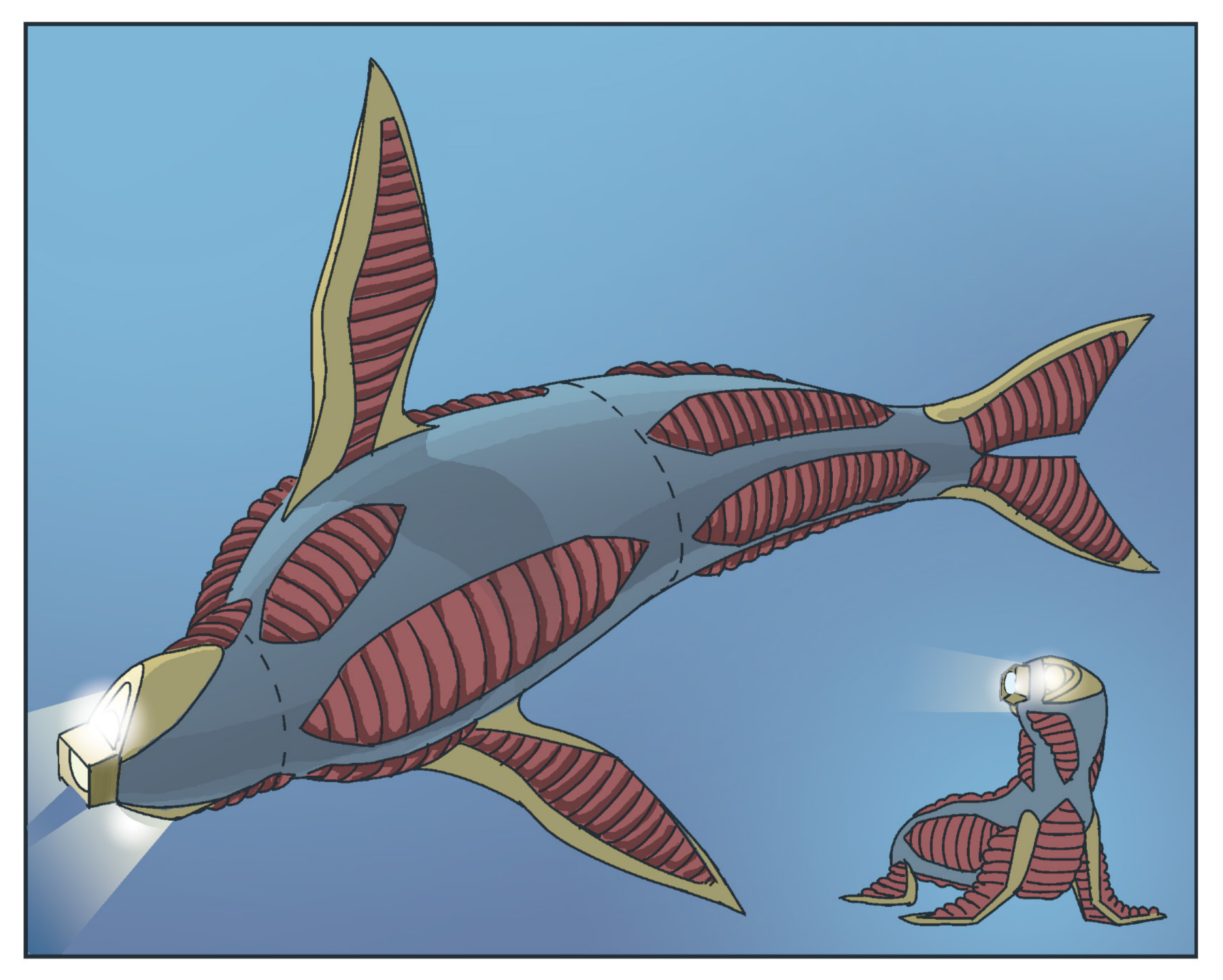


orthotics 1,2

solid



un:solid



solid

un:solid

solid

un:solid