Floating Wind Turbines

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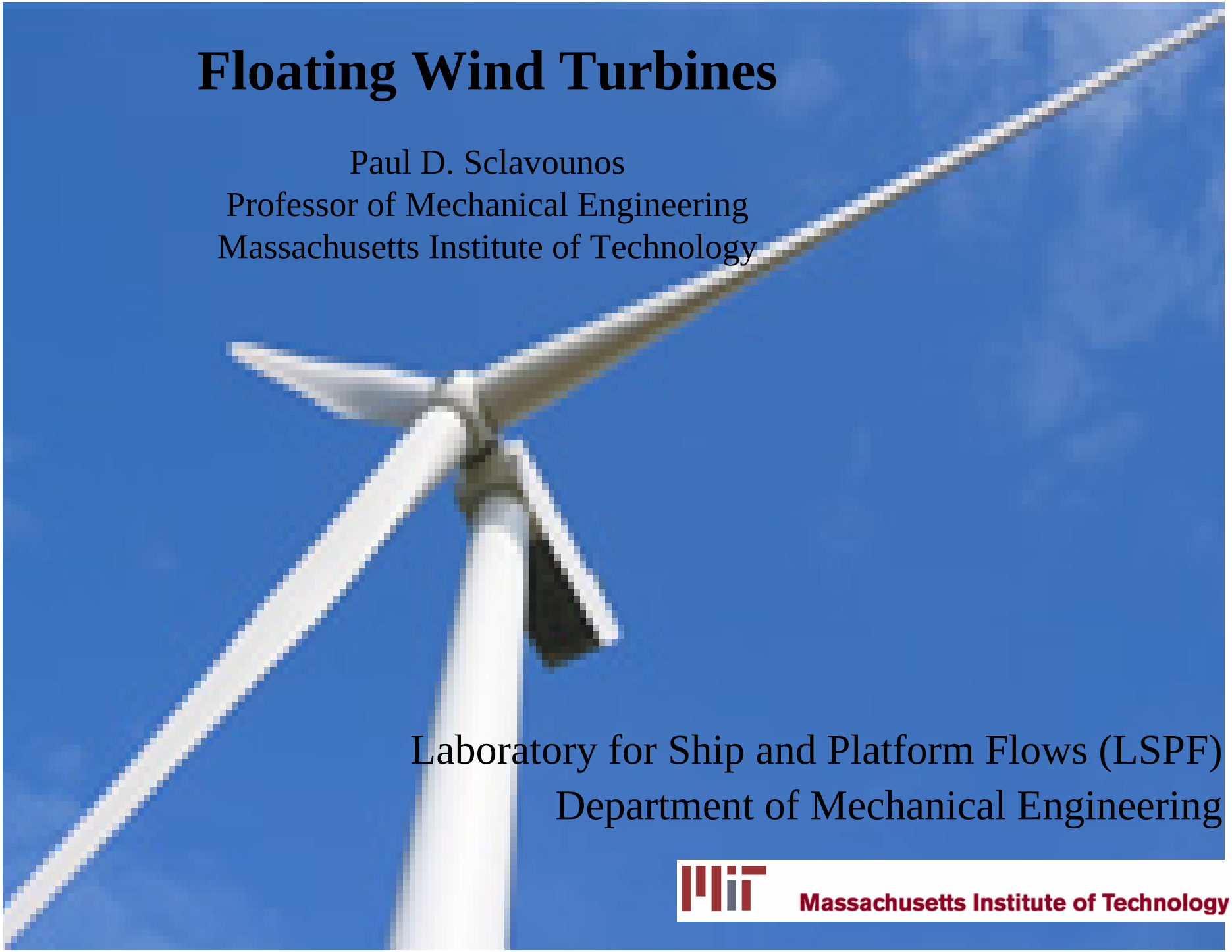
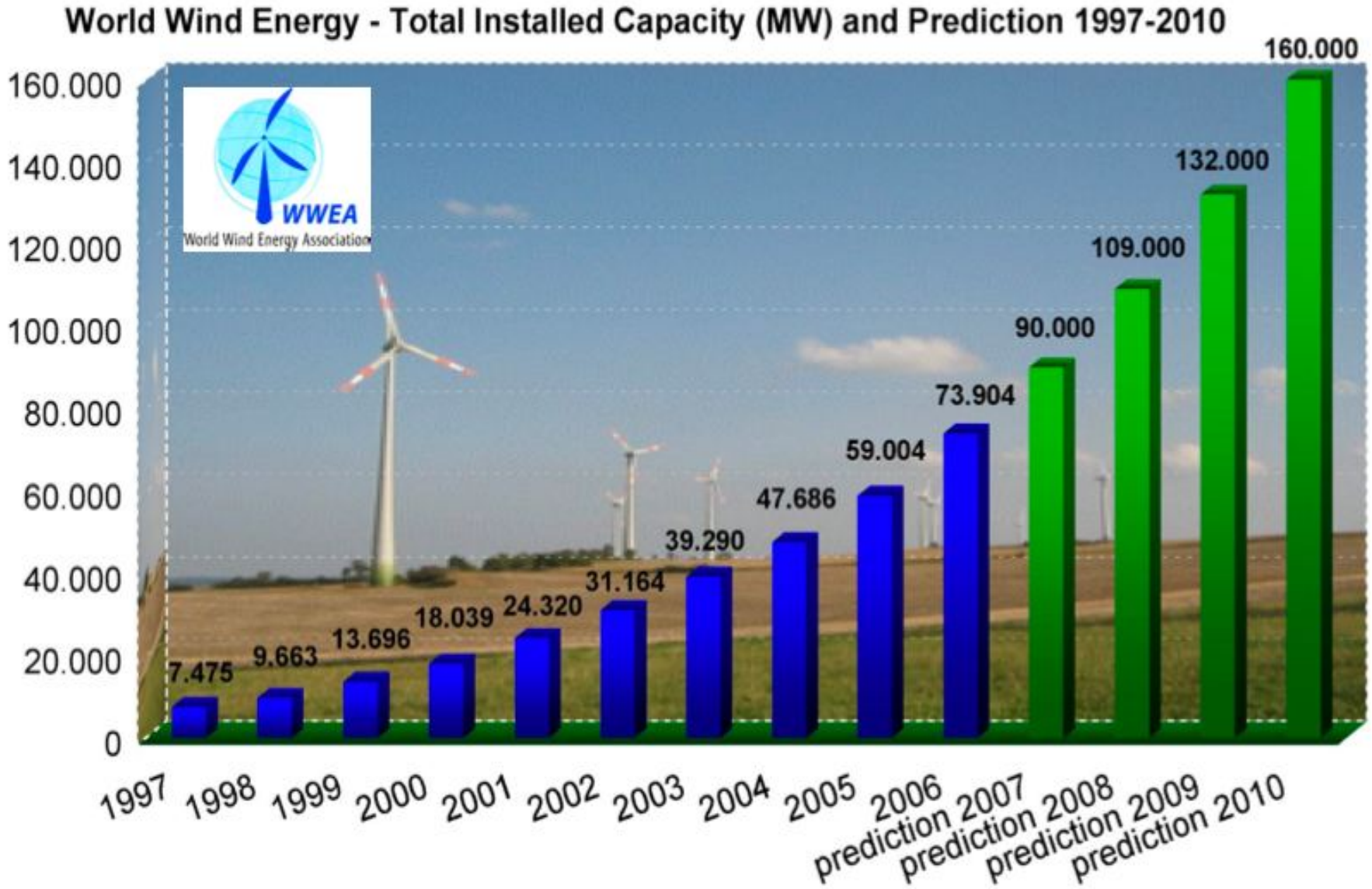


Laboratory for Ship and Platform Flows (LSPF)
Department of Mechanical Engineering

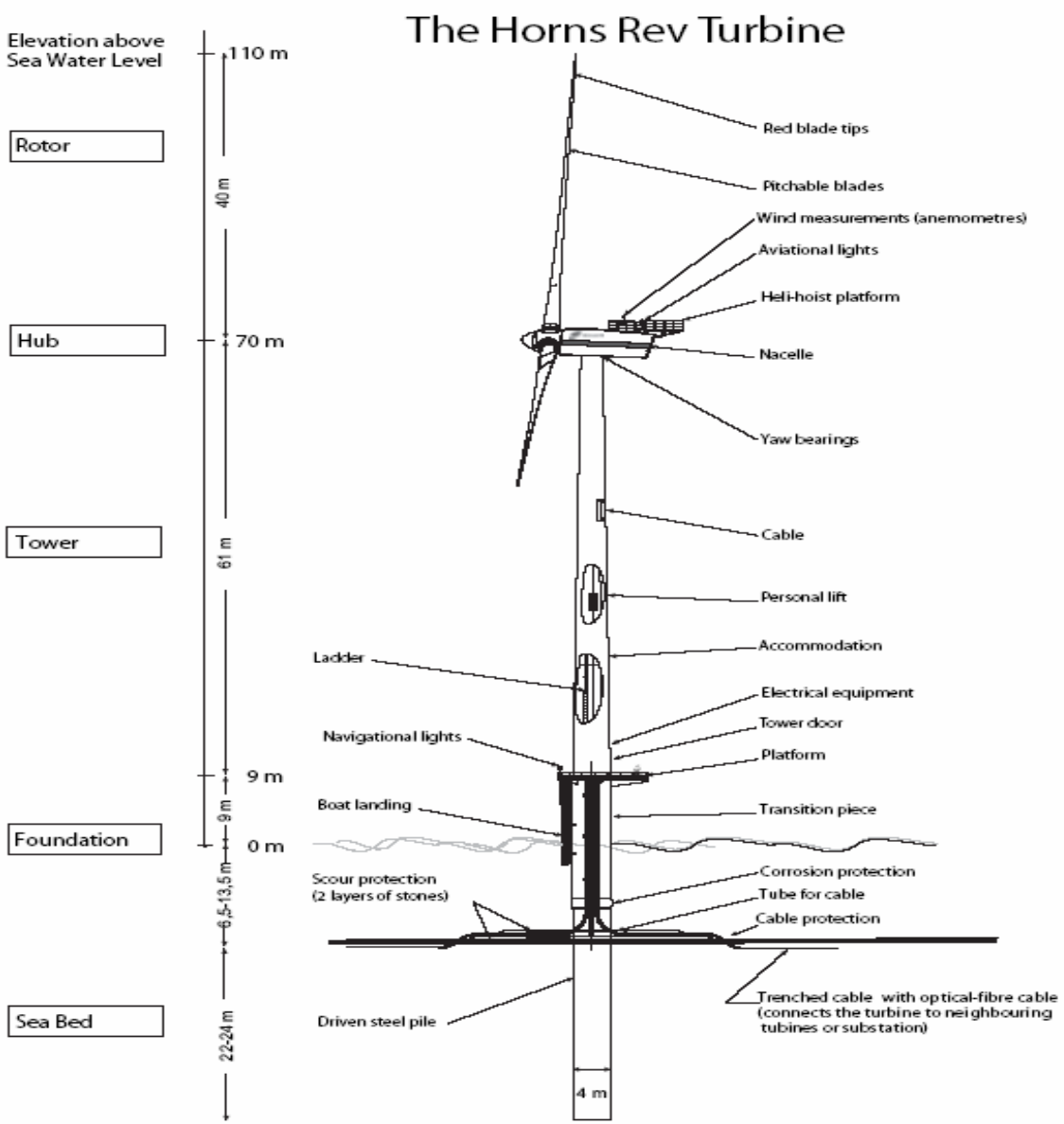
Massachusetts Institute of Technology


World Wind Energy - Total Installed Capacity (MW) and Prediction 1997-2010
WWEA
World Wind Energy Association
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
7.475
9.663
13.696
18.039
24.320
31.164
39.290
47.686
59.004
73.904
90.000
109.000
132.000
160.000
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
prediction 2007
prediction 2008
prediction 2009
prediction 2010

Advantages of Floating Offshore Wind Farms

- **Wind a Rapidly Growing, Free, Inexhaustible, Environmentally Friendly, Utility Scale and Cost Effective Energy Source**
- **Vast Offshore Wind Resources with Higher and Steadier Wind Speeds**
- **Over 75% of Worldwide Power Demand From Coastal Areas**
- **Power Increases with Cube of Wind Speed ~ 50% Higher Offshore**
- **Lower Offshore Wind Turbulence – Longer Farm Life ~ 25-30 Years**
- **Connection to Electric Grid by Sub Sea AC or HVDC Cables**
- **Experience of Oil Industry Essential for the Development of Safe and Cost Effective Spar, TLP and Hybrid Wind Turbine Floaters**

Horns Rev Wind Farm (Denmark) - Rated Power 160 MW – Water Depth 10-15m

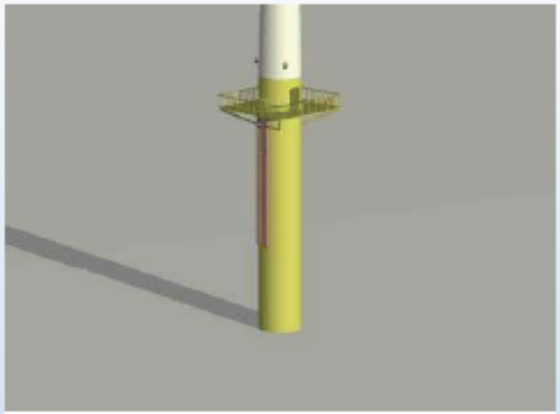


Principal Components and Dimensions of an Offshore Wind Turbine

Graphic courtesy of Horns Rev wind project, Denmark (http://www.hornsrev.dk). Copyright Elsam A/S.

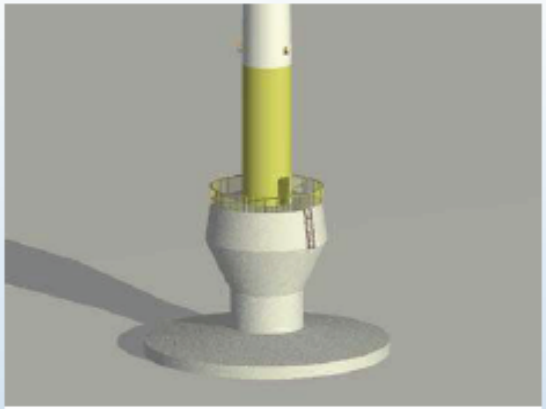
Fixed Bottom Substructure Technology

Proven Designs



Monopile Foundation

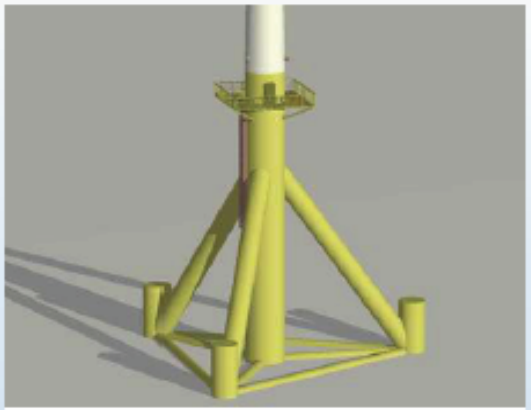
- Most Common Type
- Minimal Footprint
- Depth Limit 25-m
- Low stiffness



Gravity Foundation

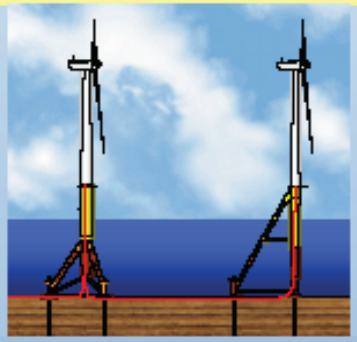
- Larger Footprint
- Stiff
- heavy

Future



Tripod/Truss Foundation

- No wind experience
- Oil and gas to 450-m
- Larger footprint
- Talisman project



NREL National Renewable Energy Laboratory

Graphics source: http://www.offshorewindenergy.org/

Expensive Installation Process for Seafloor Mounted Turbines

Installation must be low cost and weather tollerant.

Floating Wind Turbine Attributes

- **Water depths of 30 – 1000 m**
- **5-MW Wind Turbine: 1 GW Floating Wind Farm (200 Units)**
- **Flexible installation process:**
  - **Full Assembly at a Coastal Facility**
  - **Ballasted Mini TLPs, Spar Buoys and Hybrids**
  - **Floater Size Independent of Water Depth**
  - **Tow Stably Floating Units Offshore**
  - **Floating Wind Turbine Movable for Major Maintenance**
  - **Gravity Anchors for Tethers and Mooring Lines**
  - **Conventional and Synthetic Catenaries**
- **Attractive Economic and Financial Attributes**

Coastal Zone of Visual Influence (ZVI)

- L Distance from Shore for Turbine to be Invisible
- H Max Height of Turbine Blade Tip (90 + 65=155 m)
- R Earth Radius (~ 6,370,000 m)

$$L = \sqrt{2\,H\,R}$$

- L = 28 miles (45 Km) (H=155m - Blade Tip)
- L = 21 miles (34 Km) (H=90m - Hub)

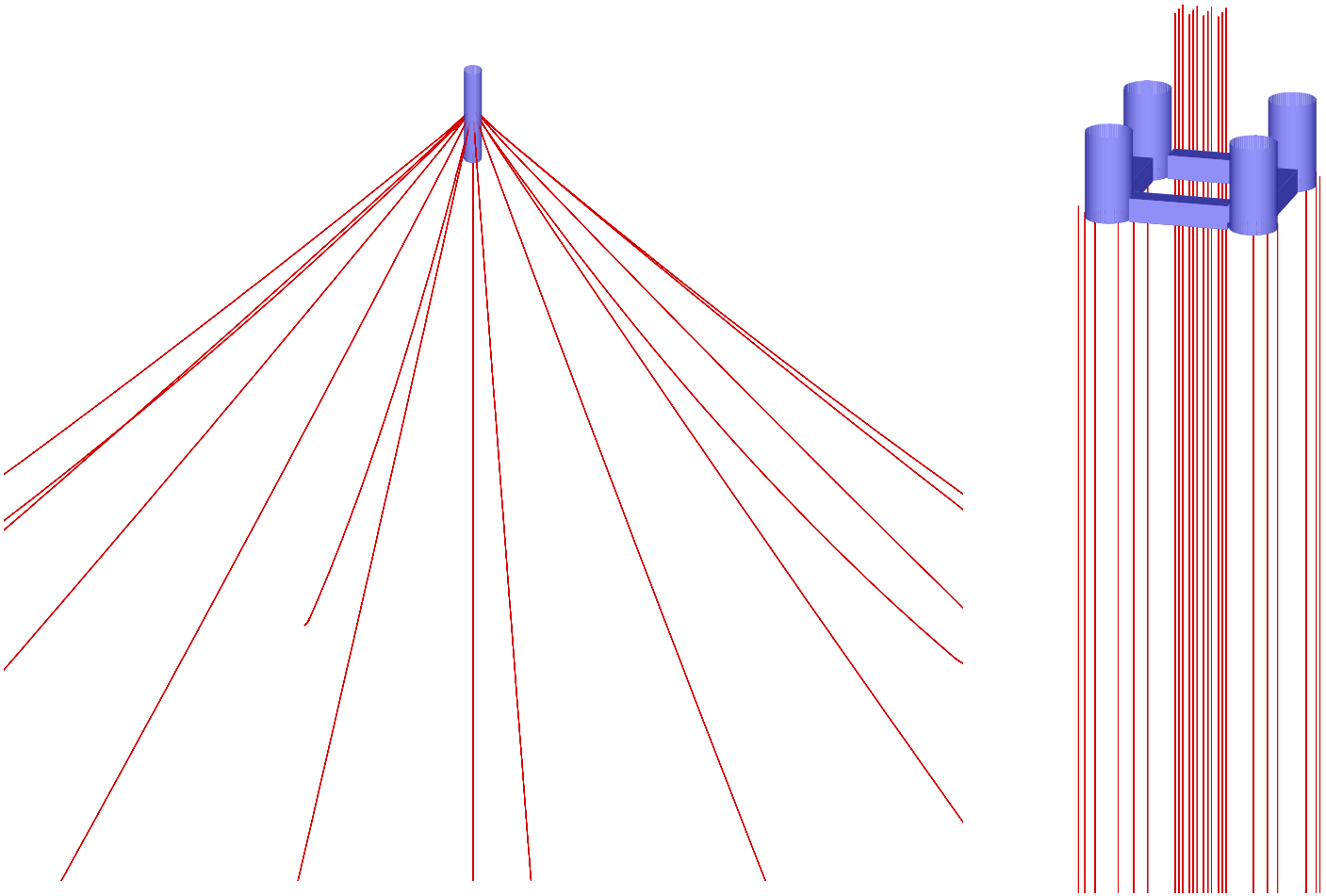
Deep Water Offshore Platforms for Oil and Gas Exploration

Tension Leg Platform

Taut-Moored Spar

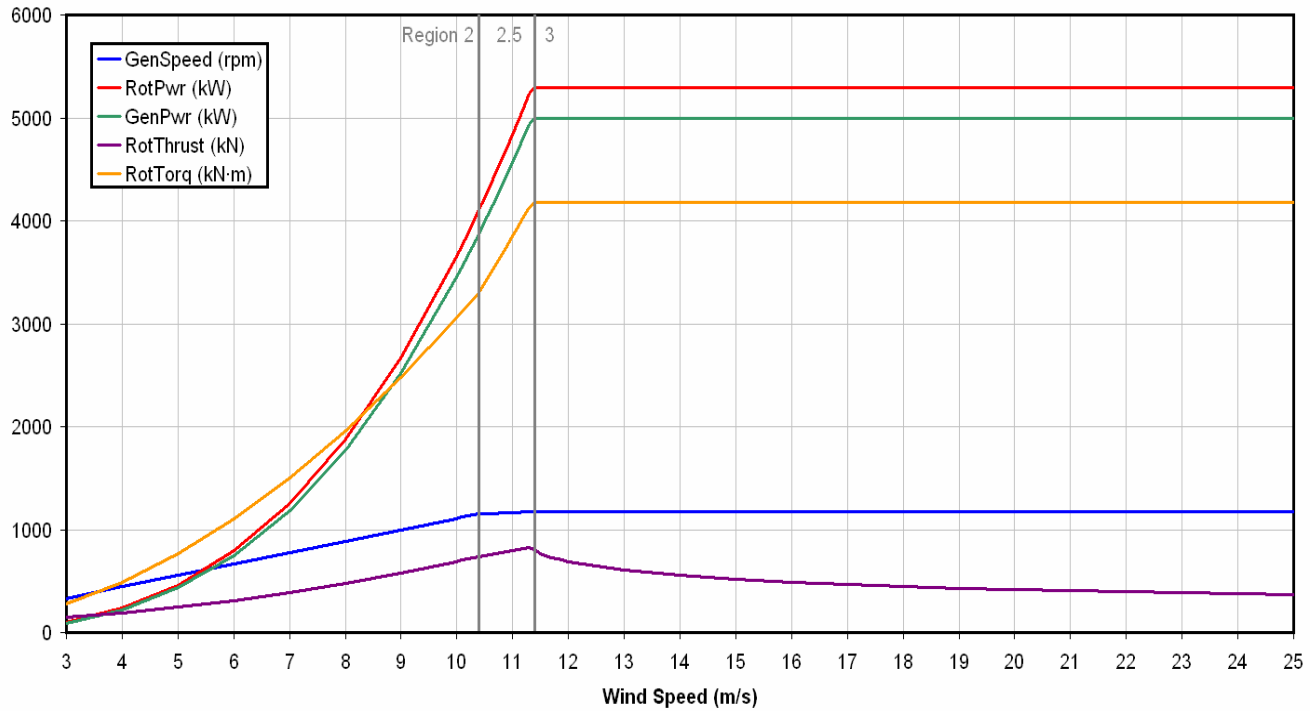
Catenary-Moored Semi-Submersible

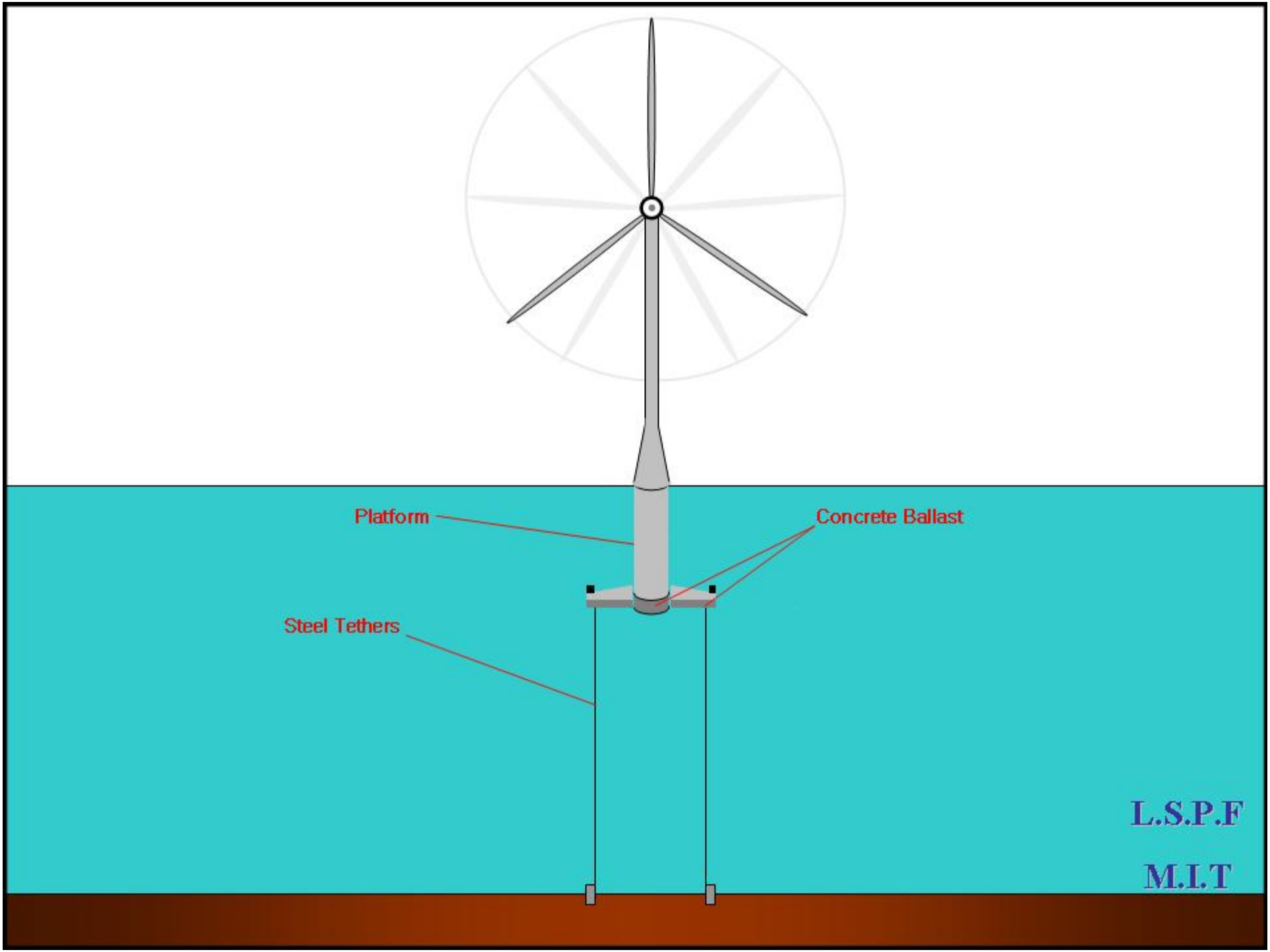
Spar and TLP SML Simulation Models of MIT Laboratory for Ship and Platform Flows

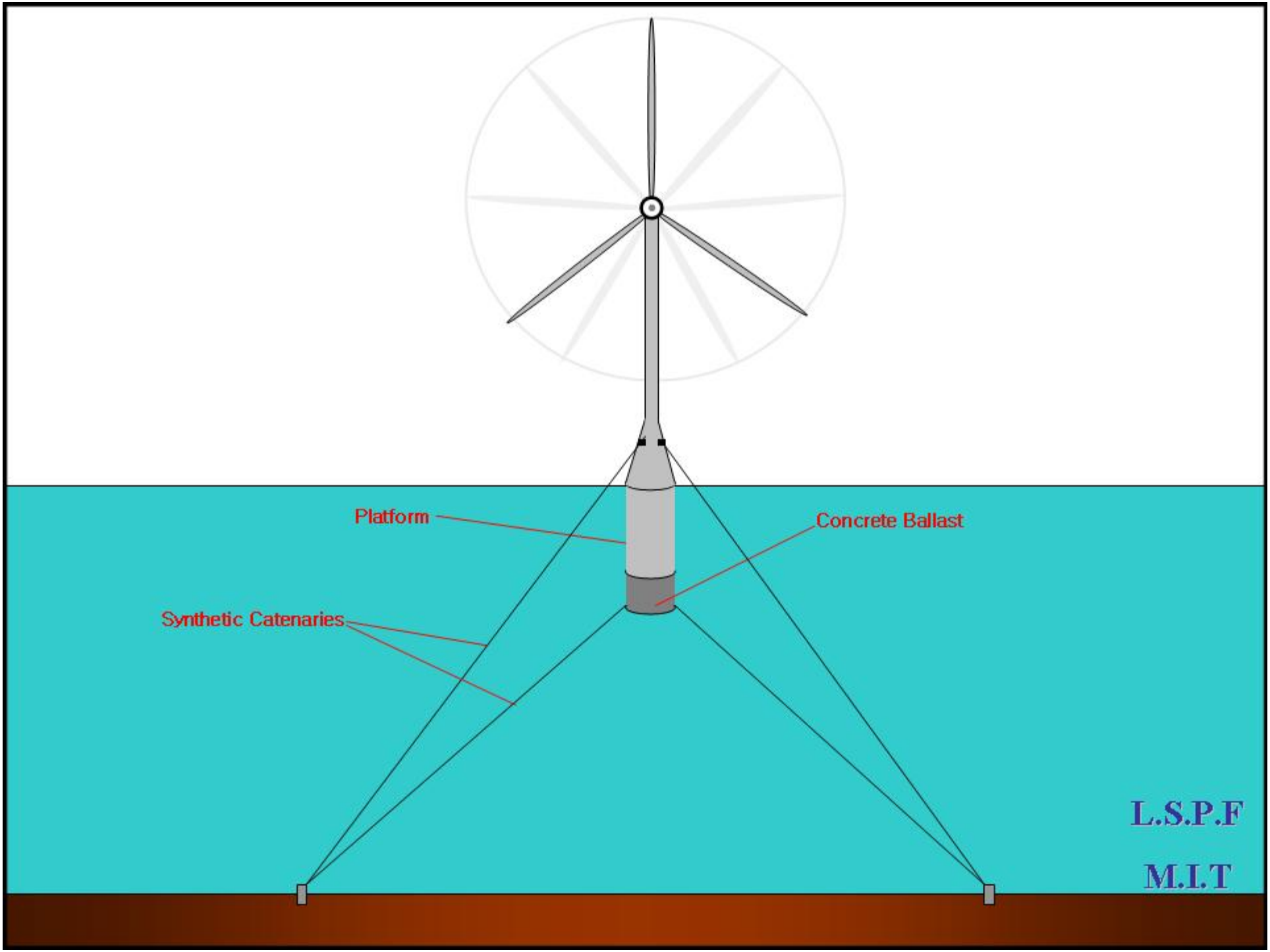


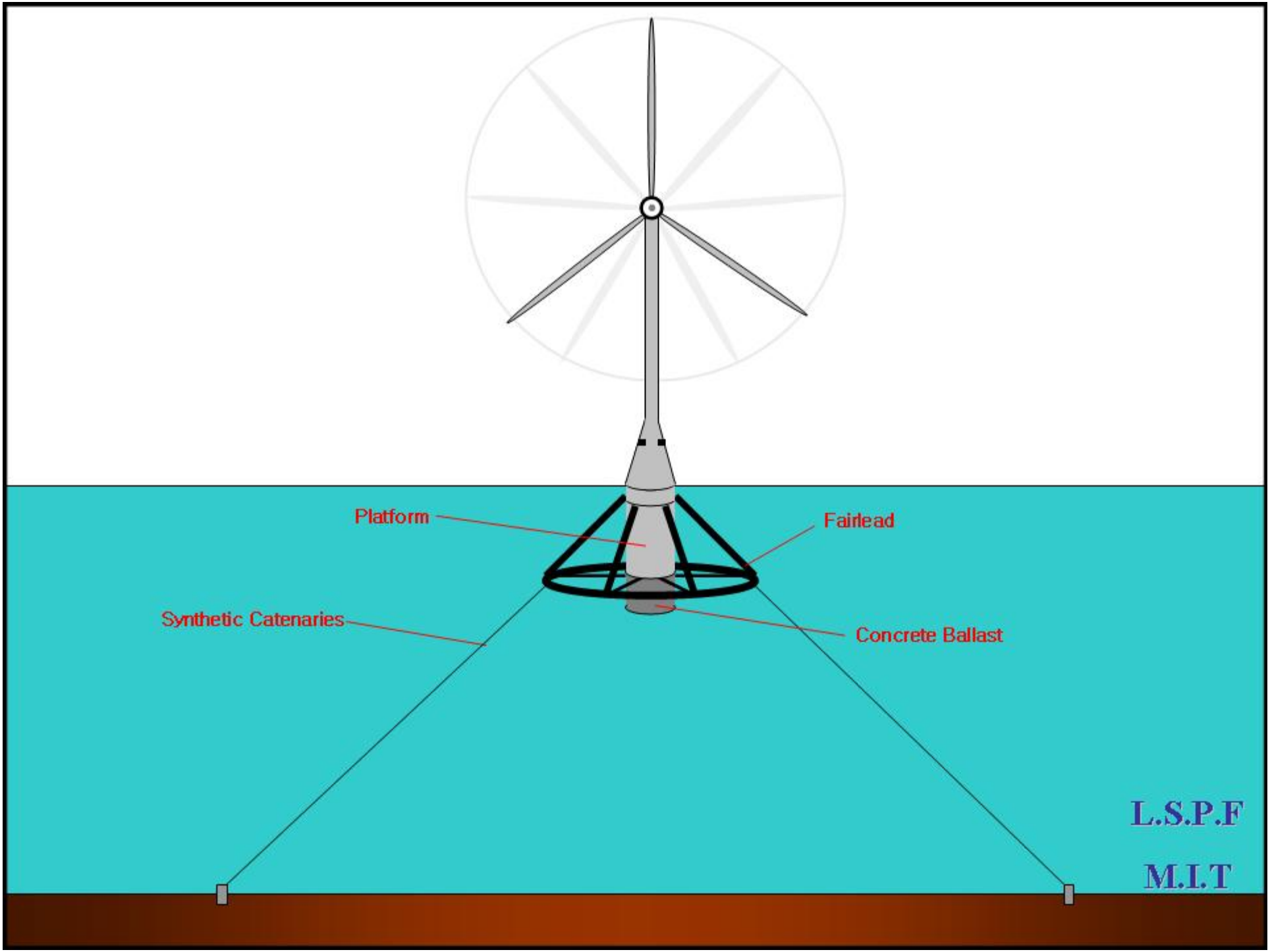
5 MW Wind Turbine

Rotor Orientation	Upwind	
Control	Variable Speed, Collective Pitch	
Rotor Diameter/Hub Diameter	126 m/3 m	
Hub Height	90 m	
Max Rotor/Generator Speed	12.1 rpm/1,173.7 rpm	
Maximum Tip Speed	80 m/s	
Overhang/Shaft Tilt/Precone	5 m/ 5°/ -2.5°	
Rotor Mass	110,000 kg	Overall c.g. location:
Nacelle Mass	240,000 kg	$(x,y,z)_t$ = (-.2,0,64)m
Tower Mass	347,460 kg	

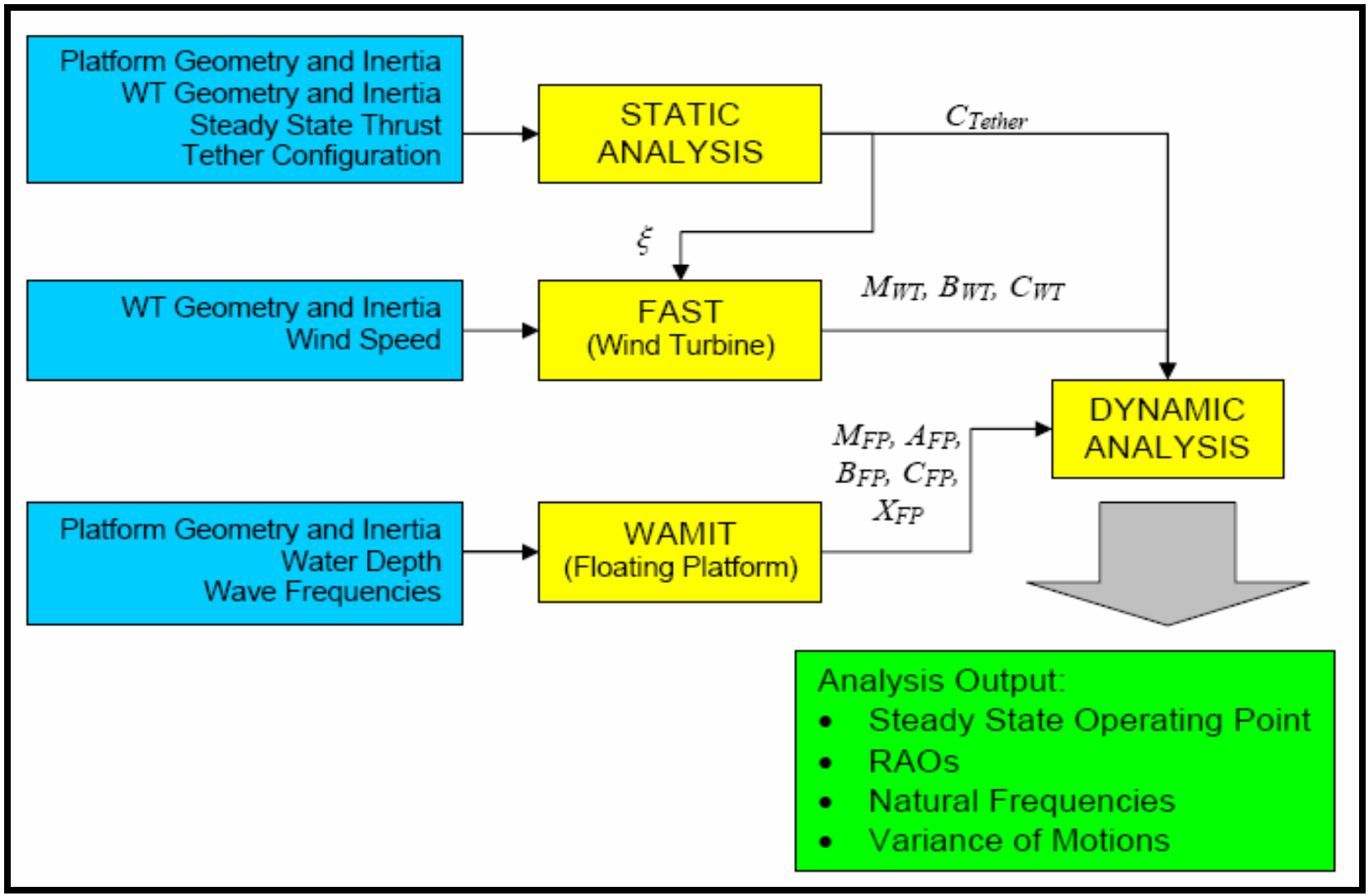



Platform
Concrete Ballast
Steel Tethers
L.S.P.F
M.I.T

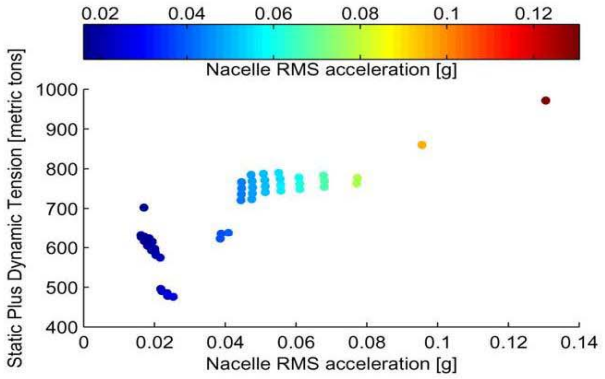

Platform
Concrete Ballast
Synthetic Catenaries
L.S.P.F
M.I.T

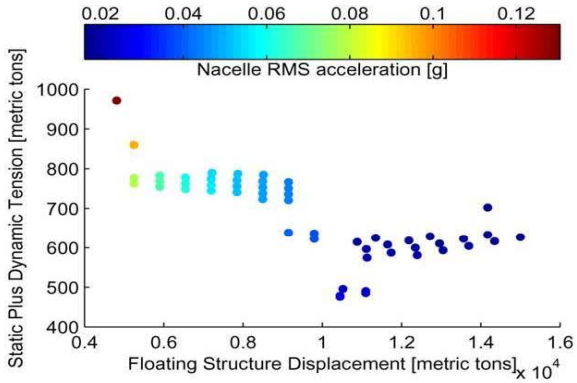

Platform
Fairlead
Synthetic Catenaries
Concrete Ballast
L.S.P.F
M.I.T

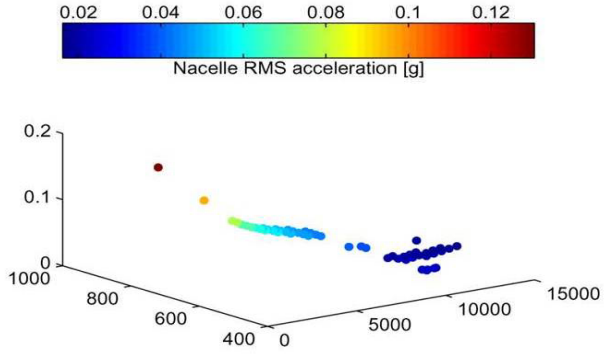
Coupled Dynamic Analysis

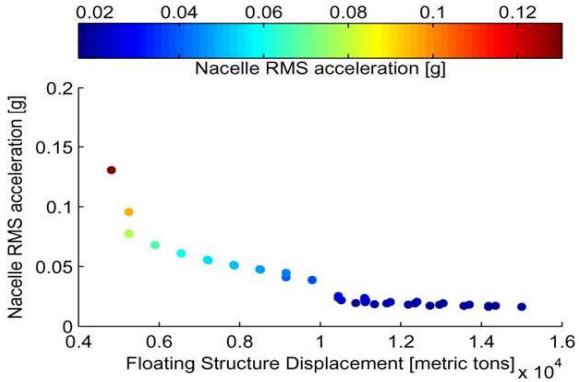


TLP Water depth = 200 m; Seastate H=10m Pareto Fronts

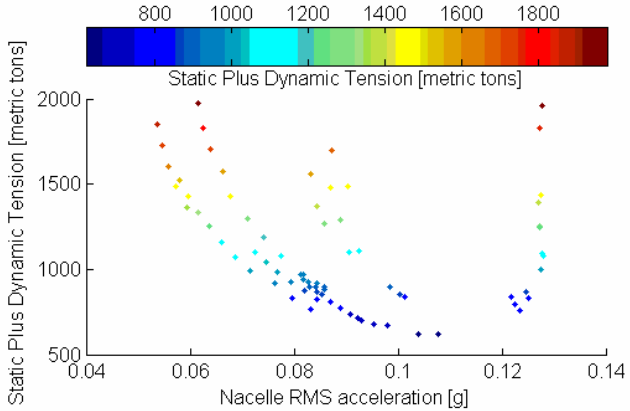


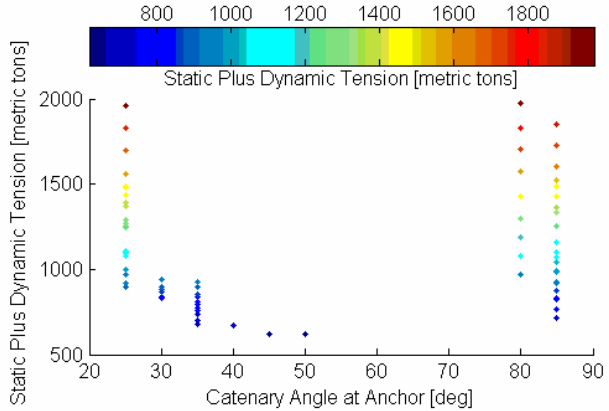


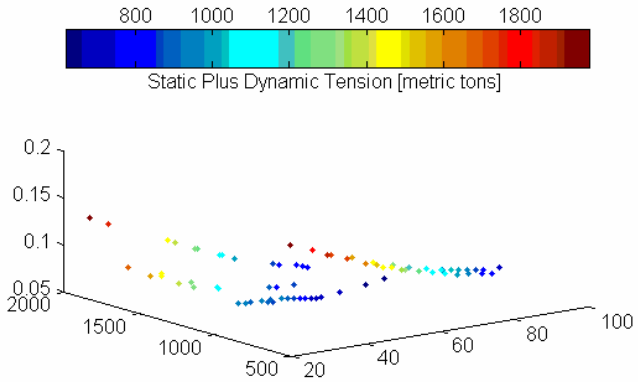


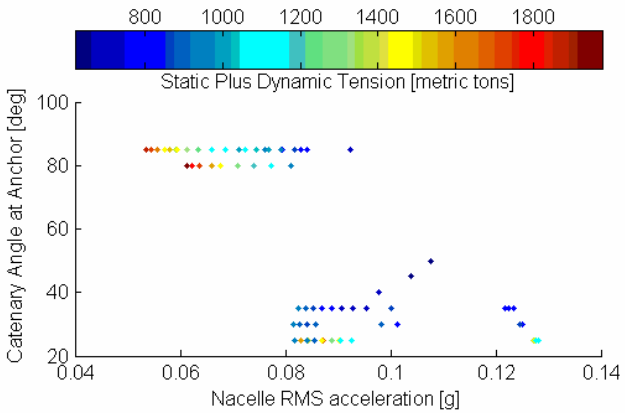


Spar Buoy Optimization
Pareto Fronts









Floating Wind Farm Financial Attributes

- **Annual Revenues of 1 GW Farm (200 Units) @ 40% Capacity Factor and @10 cents/KWh: ~ $400 Million**
- **Breakeven Cost vs CCGT ~ $ 3 M/MW: Based on Natural Gas Price Projections $9-15/MMBtu from 2010-2029**
- **Breakeven Cost per Floating Unit: $15 M; 1GW Wind Farm: $3 B**
- **O&M: Unit Ballasted & Towed to Shore – On Site Routine Maintenance**
- **Interconnection Costs ~ 15-20% of Capital Costs**
- **AC Subsea Cables for up to 120 km. HVDC Technology - No Distance Limits**
- **Coal Plant Emits ~ 1 ton CO2/MWh; Combined Cycle Gas Turbine Emits ~ 300 Kg CO2/MWh**
- **At $50/ton of CO2 – Emissions Credit ~ 5 cents/KWh**

Conclusions

- **Design of Hybrid TLP / Spar Buoy Floaters and Mooring System Optimized for Water Depth, Wave and Wind Environment**
- **Low Nacelle Accelerations – Initial Use of Marinized Onshore Wind Turbines**
- **Longer Term – Two Bladed Downwind Turbines with 10-20 MW Generators Designed for Smart Offshore Electric Grids**
- **Attractive Economic Fundamentals – Scalable Investment**
- **Carbon Emissions Credits**
- **Non Recourse Project Finance for Utility Scale Offshore Wind Farms**