Renewable Ocean Energy Technologies

- The oceans cover more than 70% of the earth’s surface => enormous renewable energy sources
- **Moving water resources** – *focus of this talk*
  - Ocean waves, tides, ocean and river currents
- Other resources – *will not be covered here*
  - Offshore wind
  - Offshore solar
  - Ocean thermal
  - Geothermal
  - Salinity gradient
  - Marine biomass
**DOE directed to establish marine and hydrokinetic technology program**

- **Energy Independence and Security Act of 2007, Subtitle C**
  - Sec. 633. Marine and Hydrokinetic Renewable Energy Research and Development:
    
    "The Secretary…shall establish a program of research, development, demonstration, and commercial application to expand marine and hydrokinetic renewable energy production…"

- Sept 18, 2008: Announced awards up to $7.3 million for R&D clean technology water power projects:
  - Technology development – up to $600k
  - Market acceleration – up to $500k
  - National Marine Energy Centers – up to $1.25 million
    - Oregon State University, University of Washington
    - University of Hawaii

**Definition of ‘Marine and Hydrokinetic renewable energy’ under EISA**

(1) waves, tides, and currents in oceans, estuaries, and tidal areas;
(2) free flowing water in rivers, lakes, and streams;
(3) free flowing water in man-made channels; and
(4) differentials in ocean temperature (ocean thermal energy conversion).

Explicitly excludes “energy from any source that uses a dam, diversionary structure, or impoundment for electric power purposes.”
Overview

- Renewable ocean energy conversion systems
  - Waves
    - Terminators, attenuators, point absorbers
  - Ocean currents, river currents, tides
    - Horizontal & vertical axis turbines, others
- Horizontal axis turbines
  - What are the differences between wind and marine turbines?
  - How do we analyze/design marine turbines?
  - What are the existing challenges for the design of marine (and wind) turbines?

Renewable Ocean Energy Technologies

Ocean Wave Energy

- Force reverses every 4-20 seconds
- Driven primarily by winds
- Can be predicted to days ahead
- Diverse range of kinetic or potential energy devices
- Global electricity potential ~ 8-80,000 TWh/year (IEA-OES, 2006)
Renewable Ocean Energy Technology
Ocean Wave Energy – Terminators & Attenuators

Sea Dragon
Wave Dragaon ApS

Pelamis “Sea Snake”
Pelamis Wave Power LTD

Renewable Ocean Energy Technology
Ocean Wave Energy – Point Obsorbers

PowerBuoy
Ocean Power Technologies, NJ

AquaBuOY
Finavera Renewables

Smart system that monitors wave conditions and controls power
Renewable Ocean Energy Technologies

Ocean Current Energy

- Relatively steady, unidirectional gulf stream with high-velocity core
- Driven by wind and solar heating of the water near the equator, and deeper currents by density and salinity variation gradients.
- Typical energy conversion device: *underwater turbine*
- Global electricity potential ~ 50 TWh/year (Radkey, 1980)

River Current Energy

- Governed by precipitation
- Stochastic in nature
- Large sediment loads
- Debris and ice impact
- Difficult to schedule maintenance since there are no predictable slack water
- Uni-directional flow
- Typical energy conversion device: *underwater turbine*
- US electricity potential ~110 TWh/year (Miller, 1996)

Roosevelt Island tidal energy project by Verdant Power at East River, NY
Renewable Ocean Energy Technologies

Tidal Energy

- Produced by centrifugal force caused by the earth’s rotation and gravitational attraction of the moon (primary) and the sun (secondary).
- Bi-directional flow due to flood and ebb tide
- Can be reliably predicted years to centuries ahead
- Typical energy conversion device: tidal barrages and underwater turbines
- Global electricity potential ~ 1800 TWh/year

Global Tidal Distribution

North American Tidal Energy Potential
(Electric Power Research Institute, 2007)

Current Energy Conversion Devices

- Horizontal axis turbines
- Vertical axis turbines
- Alternative devices
**Horizontal Axis Turbines**

**Advantages**
- Can borrow from advanced wind energy technology
- Generally self starting & more efficient
- Can be supported from the top or bottom

**Disadvantages**
- Need yawing mechanism to face flow (for tides)

---

**Vertical Axis Turbines**

**Advantages**
- Omni-directional
  - No need for yawing mechanism
- Can be mounted at the base or at the top
  - Top mounted: does not require support tower and generator can be located above waterline
  - Simpler installation and maintenance so reduce overall cost.

**Disadvantages**
- Poor self-starting capabilities
- Less efficient compared to horizontal axis turbine with the same capture area.
- Have not been shown to be commercially successful in the wind industry (typically base mounted for easy of installation & maintenance, but poor wind due to boundary layer effect)

---

*Images: Diagrams of horizontal and vertical axis turbines, illustrating their designs and components.*
Alternative Devices
Many designs, but few has made it to full scale

Stingray Tidal Stream Generator
IHC Engineering Business Ltd. (US)

• Lift/flutter vanes (oscillating hydrofoil)
• 500KW power rating

VIVACE
University of Michigan

Successfully tested at V=0.823m/s

Vortex Induced Vibration for Aquatic Clearn Energy

Industry Learning Curve

• Takes 5-10 years to turn conceptual devices into commercial application
• Two decades ago, wind energy’s cost of electricity started at 20 cents/kWh, today it is \(~4\) cents/kWh (utility scale turbines).
• Marine/tidal energy is entering the market at a cheaper Cost of Electricity, largely due to the advanced state and experience of wind technology.
Evolution of Commercial U.S. Wind Turbines

- Current objectives: reduce the COE produced by an additional 30% by 2012

20% Wind Energy by 2030

Annual and cumulative wind installations needed to meet 20% wind energy scenario by 2030
What are the differences between a wind and a water turbine?
### Wind Turbine vs Water Turbine

<table>
<thead>
<tr>
<th>Wind turbine (land-base)</th>
<th>Water turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid density, $\rho$</td>
<td>1.223 kg/m³</td>
</tr>
<tr>
<td>Flow speed, $V$</td>
<td>10-15 m/s</td>
</tr>
<tr>
<td>Power coefficient, $C_p$</td>
<td>0.35</td>
</tr>
<tr>
<td>Power density, $P/A=0.5pV^3C_p$</td>
<td>214 - 722 W/m²</td>
</tr>
<tr>
<td>Induction factor, $a$</td>
<td>0.626</td>
</tr>
<tr>
<td>Diameter, $d$</td>
<td>50 m</td>
</tr>
<tr>
<td>Power, $P$</td>
<td>420 kW - 1.4 MW</td>
</tr>
<tr>
<td>Drag, $D=0.5pV^2<em>4a(1-a)</em>\pi d^2/4$</td>
<td>112 kN - 253kN</td>
</tr>
</tbody>
</table>

### Pros and Cons of Marine/Tidal Turbines

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
<th>Uncertain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly predictable</td>
<td>Technically challenging (blades, controller, gear box, generator, support structure)</td>
<td>Resource dependent (undersea cables, grid connection, network stability, regulations)</td>
</tr>
<tr>
<td>High power density</td>
<td>Site selection and turbine design are both technically challenging</td>
<td>Field performance, support structure, deployment, O&amp;M, cost</td>
</tr>
<tr>
<td>Lower visual impact</td>
<td>Harsh sea environment, slow permit process, high initial cost</td>
<td>Market acceptance, impact on environment and marine life</td>
</tr>
<tr>
<td>Tremendous crossover potential from wind turbines</td>
<td>More challenging (much higher loads, bi-directional flow, harsh sea environment, cavitation)</td>
<td>Vessel impact, interaction with surface waves, 3D bathymetry, mobile bed.</td>
</tr>
</tbody>
</table>
Marine Current Turbines Ltd. (UK based)
SeaGen Project

- First commercial-scale tidal turbine
  - Northern Ireland (initially generated 150kW into the grid, but once fully operation will generate 1.2 MW)
  - Strangford Lough, 400m from shoreline
- Twin horizontal axis turbine on a monopole foundation
- Variable pitched contra-rotating blades
- 10-15 rpm; 15-20m diameter
- Life-cycle unit cost
  - Strangford: 16.8 cents/kWh
  - Anglesey Skerries when fully developed: 5.2 cents/kWh
Verdant Power (US based)
Roosevelt Island Tidal Energy Project

- 5m rotor diameter
- Pylon mounted
- Yaw bearings allow pivot to follow flow
- 7000 operation hours (45MWh to NYC grid) between 12/06-06/07
- 6 turbine, 200 kW array installed May 2007, all were taken offline for repairs and redesign (inadequate strength)
- New blades are solid cast AlMag
- Preliminary permit for 30 turbines accepted by DOE in Dec 2008

Challenges of Marine/Tidal Turbines

- High hydrodynamic forces ($\rho_{\text{water}} \sim 840 \rho_{\text{air}}$)
  - System strength, fatigue, vibration, and stability issues
- Bi-directional current (flood and ebb tide), tidal boundary layer, and interaction with waves, bathymetry, and adjacent structures
  - Spatial and temporal variation in inflow
  - Need active (and passive) blade pitch control
- Harsh sea environment
  - Corrosion, barnacles, seaweed, sediments, debris, etc.
  - Vessel and ice impact
- Hydrodynamic cavitation
  - Intermittent, can occur on both sides of the blade surface
  - Performance decay, blade surface erosion, noise, and vibration
Hydrodynamic Cavitation

- High frequency (~MHz) & high amplitude (~20-60ksi) pressure waves
- Microjet velocities up to 1000 m/s
- Material fatigue, pits, erosion, noise

Mixed sheet & cloud cavitation

Cavitation tunnel testing: 800mm turbine at TSR=7.5, σ=0.64, V=1.4 m/s
How do we analyze/design marine turbines?

Momentum Theory

Classic Momentum Theory
- Betz (1926)
- Estimates of optimal power output, but cannot determine optimal rotor shape

Blade Element Momentum Theory
- Uses momentum theory to calculate axial and circumferential velocities
- Use blade element method to calculate sectional (2-D) lift and drag coefficients
- Integrate stripwise to estimate total drag (thrust) and power.

$\frac{\Delta V}{V_o} = \frac{V_s - V_o}{V_o}$

$C_D = \frac{D}{0.5 \rho V_o^2 (\pi R^2)}$

$C_{pow} = \frac{\text{useful power}}{\text{available power}}$

$C_{pow} = \frac{DV_s}{0.5 \rho \pi R^2 V_o^3}$

$C_{pow_{max}} = 0.593$ (Betz’s Limit)
Lifting Line, Lifting Surface or Vortex-Lattice Methods

- **2-D Lifting Line Theory**
  - rotor blade is reduced to a single vortex line and wake is represented as a single vortex sheet (Prandtl 1918)

- **3-D Lifting Surface Theory/Vortex-Lattice Methods**
  - accounts for finite chord length using a distributions of vortices, but not thickness effects (Weissinger 1947)
  - Can account for blade shape and capture 3-D flow characteristics
  - Employ linear approximations
  - Very fast
  - Breaks down at leading edge and tip

Boundary Element or Panel Methods

- Distributes singularities (vortices, sources, doublets) to represent blade and wake surfaces (e.g. Hess 1972, van Gent 1975 for propellers, but only recently begun for turbines).
  - More time consuming
  - Accounts for nonlinear thickness-loading coupling
  - Can capture details at the leading edge and tip.
CFD Methods

- Unsteady, turbulent flow condition
- Rotating blades and hub.
- Transient cavitation (multiphase flow)
- Very time consuming!!! Not practical for the design stage.

How about the structural response?

- Excessive blade loads may lead to blade strength failure.
- Blade deflections and vibrations interact with hydrodynamic forces, which may increase blade loads, and lead to system fatigue and instability issues (resonance, flutter, divergence, et.)
A coupled BEM-FEM for the transient hydroelastic analysis of marine (and wind) turbines

\[ v_{\text{total}} = v_{\text{effective inflow}} + v_{\text{potential velocity induced by the rotor}} \]

\[ v_{\text{effective inflow}} = v_{\text{inflow in absence of rotor (nominal)}} + v_{\text{vortical interaction between rotor and flow field}} \]

Numerical Modeling
Potential-Based Boundary Element Method

- Complex, turbulent, non-uniform flow field
- Vorticity in the flow field interacts with the action of the rotor
3D Governing Equations
(in blade-fixed coordinate)

- Governing eqns for incompressive, inviscid fluid
  \[ \frac{Dv}{Dt} = -\nabla \left( \frac{P}{\rho} \right) + g - \Omega \times (\Omega \times x) - 2\Omega \times v, \]
  \[ \nabla \cdot v = 0 \]

- Total velocity
  \[ v_t(x,t) = v_{in}(x,t) + \nabla \phi(x,t) \]

- Inflow velocity
  \[ v_{in}(x,t) = v_e(x_s,r_s,\theta_s) - \Omega \times x \]

Boundary Element Method
Green’s Third Identity

\[ \nabla^2 \phi = 0 \]
\[ \left\{ \begin{array}{l}
  2\pi \phi_p(t) \\
  4\pi \phi^*_p(t)
\end{array} \right\} = \left\{ \begin{array}{l}
  0 \\
  \pm 2\pi \Delta \phi_p(t)
\end{array} \right\} + \int_{S_B(t)} \left[ \phi_q(t) \frac{\partial G(p;q)}{\partial n_q(t)} - G(p;q) \frac{\partial \phi_q(t)}{\partial n_q(t)} \right] ds \\
  - \int_{S_{CW}(t)} \left[ \frac{\partial \phi_w(t)}{\partial n} G(p;q) \right] ds \\
  + \int_{S_{CW}(t) \cup S_W(t)} \Delta \phi_w(r_q,\theta_q,t) \frac{\partial G(p;q)}{\partial n_q(t)} ds \\
\]

The mixed boundary value problem can be solved using a potential-based BEM with constant strength (source and dipole) hyperboloidal panels; \( G = 1/R_{pq} \)
Boundary Conditions

Dynamic Boundary Condition
\[ p = p_v \]

Kinematic Boundary Condition (flow tangency condition)
\[ v_t \]

Cavity detachment point
\[ h(s) \]

Foil LE
\[ V_{in} \]

\[ \alpha \]

Foil TE
\[ V_c \]

Kutta Condition
\[ s \]

Cavity Closure Condition
\[ l \]

Search for the cavity planform

1/28/09
Effect of cavity on the lift and drag

Initial and converged cavity shapes and pressure distributions on a 3D foil

Marine Current Turbine

**Turbine:**
- Diameter=800mm
- No. of blades=3
- Hub radius=80mm
- NACA 63-815 blade section
- Adjustable pitch

**Cavitation Tunnel:**
- Length=5m
- Breadth=2.4m
- Height=1.2m
- Max flow speed=8m/s
- Pressure range=0.2-1.2atm

**Towing Tank:**
- Length=60m
- Breadth=3.7m
- Depth=1.8m
- Max carriage speed=4.5m/s
Marine Current Turbine
Predicted (BEM) vs. Measured Performance

\[ TSR = \frac{\Omega R}{V} = \frac{\pi}{J} \; ; \; \phi = \text{pitch angle at hub} \]

\[ C_P = \frac{P}{0.5 \rho AV^3} \; ; \; C_T = \frac{T}{0.5 \rho AV^2} \]

Power coefficient

Thrust coefficient

Marine Current Turbine
Predicted vs. Observed Cavitation Pattern

\[ TSR = \frac{\Omega R}{V} = \frac{\pi}{J} = 7.5 \]

\[ \sigma_s = \frac{p_e - p_v}{0.5 \rho AV^2} = 3.9 \]

\[ -C_{pres} = \frac{p - p_v}{0.5 \rho AV^2} \]

Looking from upstream

Wetted (suction)

Cavitation (suction)

Prof. Young, Princeton University
23
Marine Current Turbine
Performance Decay Due to Cavitation

\[ TSР = \frac{ΩR}{V} = \frac{π}{J} \]
\[ C_Р = \frac{P}{0.5ρAV^3} \]
\[ C_T = \frac{T}{0.5ρAV^2} \]

Hydroelastic Formulation
(with fluid-structure interaction)

- **Decomposition of perturbation potentials**
  \[ v_i(x,t) = v_{in}(x,t) + \nabla \phi(x,t); \quad \phi(x,t) = \phi(x,t) + \Phi(x,t); \quad \nabla^2 \Phi = 0 \]
  \[ \phi = \text{potential due to rigid blade rotation} \]
  \[ \Phi = \text{potential due to elastic blade deformation} \]

- **Decomposition of pressure**
  \[ P = P_t + P_v = \text{total pressure} \]
  \[ P_t = P_v + \rho \left[ \frac{1}{2} |v_{in}|^2 - \frac{∂φ}{∂t} - \frac{1}{2} |v_{in} + \nabla \phi|^2 \right] \] (rigid blade rotation)
  \[ P_v = \rho \left[ -\frac{∂\Phi}{∂t} - v_{in} \cdot \nabla \Phi \right] \] (elastic blade deformation)
Hydroelastic Formulation

Solid equation of motion in blade-fixed coordinates

\[ [M] \{ \ddot{u} \} + [C] \{ \dot{u} \} + [K] \{ u \} = \{ F_h \} + \{ F_{ce} \} + \{ F_{co} \} \]

\[ [M] = \int \rho_s [N]^T [N] \, dV; \quad [C] = \int c [N]^T \dot{[N]} \, dV; \quad [K] = \int [B]^T [D] [B] \, dV \]

\[ \{ F_h \} = \int [N]^T \{ P_r + P_v \} \, dS \]

\[ \int [N]^T \{ P_r \} \, dS = - \rho \int [N]^T \{ \dot{H} \} \, dS \{ \ddot{u} \} \]

\[ \int [N]^T \{ P_v \} \, dS = - \rho \int [N]^T \{ \dot{V}_{in} \cdot \nabla H \} \, dS \{ \ddot{u} \} \]

\[ [M + M_H] \{ \ddot{u} \} + [C + C_H] \{ \dot{u} \} + [K] \{ u \} = \left( \int [N]^T \{ P_r \} \, dS \right) + \{ F_{ce} \} + \{ F_{co} \} \]

\[ \{ F_{ce} \} = \int \rho_s [N]^T \{-2 \Omega \times (\Omega \times (x + u))\} \, dV; \]

\[ \{ F_{co} \} = \int \rho_s [N]^T \{-2 \Omega \times \dot{u}\} \, dV \]

Marine Current Turbine

D=20 m, TSR=6, n=14.32 rpm

Need high-strength, corrosion resistant alloy!
**Marine Current Turbine**

Modal Characteristics – frequencies significantly decrease in water due to added mass effects

- **Mode 1**
  - $f_{dry} = 2.86 \text{ Hz}$
  - $f_{wet} = 1.68 \text{ Hz}$

- **Mode 2**
  - $f_{dry} = 10.57 \text{ Hz}$
  - $f_{wet} = 6.58 \text{ Hz}$

- **Mode 3**
  - $f_{dry} = 17.0 \text{ Hz}$
  - $f_{wet} = 15.0 \text{ Hz}$

**Unsteady analysis – tidal boundary layer flow**

- $V_{hub\ axis} = 2.5 \text{ m/s}$
Marine Current Turbine
Tidal boundary layer flow – pressure distributions

Marine Current Turbine
Tidal boundary layer flow – unsteady performance

<table>
<thead>
<tr>
<th></th>
<th>STEADY mean</th>
<th>UNSTEADY mean</th>
<th>1st harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{xs}$ (kN)</td>
<td>771.02</td>
<td>768.31</td>
<td>1.07</td>
</tr>
<tr>
<td>$F_{ys}$ (kN)</td>
<td>0.00</td>
<td>5.38</td>
<td>0.71</td>
</tr>
<tr>
<td>$F_{zs}$ (kN)</td>
<td>0.00</td>
<td>36.75</td>
<td>0.76</td>
</tr>
<tr>
<td>$M_{xs}$ (kNm)</td>
<td>751.49</td>
<td>768.31</td>
<td>2.06</td>
</tr>
<tr>
<td>$M_{ys}$ (kNm)</td>
<td>0.00</td>
<td>20.00</td>
<td>23.93</td>
</tr>
<tr>
<td>$M_{zs}$ (kNm)</td>
<td>0.00</td>
<td>227.13</td>
<td>25.80</td>
</tr>
<tr>
<td>Power (MW)</td>
<td>1.125</td>
<td>1.112</td>
<td></td>
</tr>
</tbody>
</table>
Marine Current Turbine
Tidal boundary layer flow – stresses and deflections

Power Output for a Variable-Speed Design
Controller system changes the pitch to control the rotor speed, and to limit power output
How would it perform at the San Francisco Golden Gate Bridge Site?

- Based on site velocity data from EPRI (2006)
- \( \eta_{\text{drive train}} \times \eta_{\text{generator}} \times \eta_{\text{power conditioning}} = 0.89 \)

**Graph:**
- **Annual Power:** 2752 MWh per each 20m turbine
- **Electric Power Output (kW):**
  - Frequency (Hz)
  - Total Power (kWh)

**Future Design Needs (wind & water turbines):**

- Blade design
- Site selection
- Advance passive control strategies
- Support structure
- Extreme loads
- Durability in harsh sea conditions
- Impact
- Noise

- Advance embedded sensors
- Environmental and structural health monitoring (to reduce maintenance cost)

**Hydroelasticity:**
- Hydrodynamics + structural dynamics

**Sensors**

**Control**

- Advance active control strategies (gear box, generator, controller)
- Fatigue & power issues
- Grid connection

- Increase system efficiency, reliability, and robustness
- Reduce total cost
- Reduce impact to wild life and environment
- Reduce noise

1/28/09
Thank You!

This research is supported by ONR Grant Nos. N00014-07-1-0491 and N00014-08-1-0475 managed by Dr. Ki-Han Kim.