Characterization Toolbox User Guide

Version 1.1

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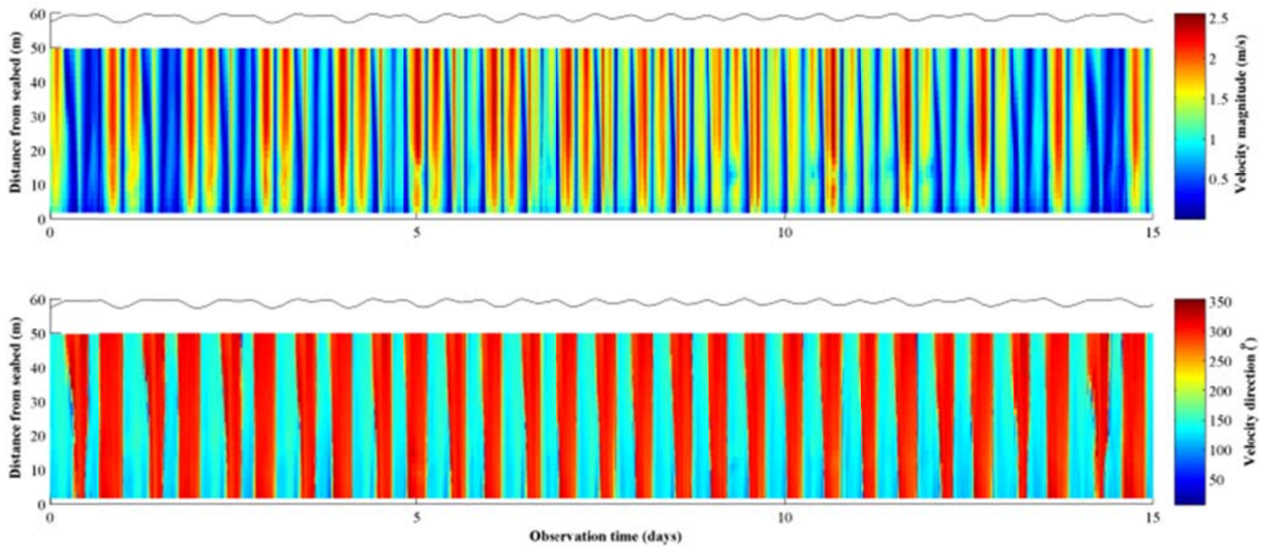

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Change Log

11/20/11 – Initial release

12/23/11 – Documentation of additional outputs from `characterize_operation.m`

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1 Introduction

This toolbox is intended to provide users with a set of pre-defined functions for investigating ADCP data collected at tidal energy sites. The toolbox has two components: a set of routines focused on characterizing the tidal resource independent of device parameters and a set of routines focused on estimating the performance of a horizontal axis turbine deployed at a particular location. Both components are designed to operate on batches of data, enabling scenario analysis and facilitating the application of new characterizations to broad data sets.

These routines are coded for Matlab and require the Statistics Toolbox to execute.

All routines in the toolbox are "research grade" and are not intended to supersede international standards for resource characterization that are currently under development. The code has been tested on multiple data sets from sites around Puget Sound, but it is possible that there are some gremlins still lurking that will be brought to light by broader use. Error handling is crude – if you do feed the code data that cannot be processed, expect Matlab to toss an error. As such, no warranty on the accuracy of results produced by these routines is intended or implied. Bug fixes will be listed on the NNMREC website (http://depts.washington.edu/nnmrec/characterization.html) as they are made.

In general, the code is well-documented and inputs/outputs from individual subroutines are not repeated here.

2 Calculating Resource Characteristics

2.1 Characteristics Evaluated

Resource characteristics are calculated from ADCP data collected at tidal energy sites. The following resource characteristics are evaluated as part of the program flow:

- Current Direction
  - Principal axis direction
  - Standard deviation of flow direction relative to the principal axis – implications for power output from devices that do not have yaw control
  - Directional asymmetry between ebb and flood – similar implications
- Current Velocity
  - Mean velocity on ebb and flood
  - Maximum velocity on ebb and flood – as described in Polagye and Thomson (*submitted*), this metric should not be used to directly set design loads
  - Vertical profiles – generalized fits to the vertical velocity profile of the form:
    - Power law: $u(z)=u_0\left(\frac{z}{z_0}\right)^{1/\alpha}$ - suitable for evaluating power production potential at a site
    - Log layer law: $u(z)=\frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right)$ – suitable for evaluating shear stress, roughness, and bottom drag coefficient. This may be helpful for evaluating acoustic measurements or tuning model parameters.
  - Vertical shear
  - Probability distributions – velocity and joint velocity/direction
  - Residual currents – helpful for identifying the magnitude of estuarine circulation
- Kinetic Power Density
  - Mean kinetic power density on ebb and flood
  - Power density asymmetry between ebb and flood
- Mean free surface elevation
- Resource Statistics
  - Current ellipses
  - Duration, direction, and maximum amplitude of ebb and flood tides

2.2 Running the Program

Program execution is controlled by spreadsheet and Matlab code inputs.

1. Specify ADCP file details on spreadsheet `Data_Resource.xlsx`
   a. Column 1: File ID: integer sequence from 1:N
   b. Column 2: Input file name: .mat format ADCP data
   c. Column 3: File path name: path for input and output files
   d. Column 4: Output file name: .mat format metrics file produced by program

e. Column 5: Maximum bin: normally set to 0, which causes the program to process all bins. *For AWAC data with waves*, set this to the maximum good bin, otherwise, all bins will fail the automated QA check for number of gaps.
f. Column 6: Latitude of deployment
g. Column 7: Longitude of deployment
h. Column 8-M: Descriptive information not referenced by code. Use for comments, organization, etc.

2. In `BatchResource.m` specify:
   a. `char_proc`: indices from `Data_Resource.xlsx` to process
   b. `t_ens`: ensemble duration (300 seconds recommended)
   c. `bins`: range of bins to process (empty entry recommended, which will process all depths)
   d. `options`: various controls for characterization algorithms. Options that are not set will be initialized to their default values, as specified in `functions/set_defaults.m.`
3. For each data file being processed, `BatchResource.m` calls `functions/characterize_resource.m`.
4. `characterize_resource.m` calls a series of functions (described in the code comments) to generate resource metrics. The results are stored in the file structure specified in `Data_Resource.xlsx`.

2.3 Input Data

Input data files must be in "standard" NNMREC format:

- `t` rows (each corresponding to an equally spaced time index)
- `z` columns (each corresponding to a specific depth bin)
- `time.mtime` (t) - start time for ensemble
- `data.bins` (z,1) – vertical bin centers (m) relative to seabed
- `data.dir_vel` (t,z) - direction of velocity ensembles (north = 0 degrees, cw positive)
- `data.north_vel` (t,z) - north-south component of ensemble velocity
- `data.east_vel` (t,z) - east-west component of ensemble velocity
- `data.vert_vel` (t,z) - vertical component of ensemble velocity
- `data.mag_signed_vel` (t,z) - signed speed ensembles (ebb negative, flood positive) (optional - if not present, user will be prompted to assign the approximate flood direction and this information will be automatically generated)
- `pres.surf` (t) - free surface elevation (m) (optional - if not present, mean water depth set to zero)

2.4 Output Data

Output data is contained in a series of structures, most with entries for each vertical bin analyzed:

- `all`
  - `d_mean`: mean direction over all tidal cycles
  - `d_sigma`: standard deviation from principal axes over all tidal cycles
  - `d_asym`: asymmetry between mean ebb and flood directions

    - s_mean: mean speed over all tidal cycles (m/s)
    - s_max: maximum speed over all tidal cycles (m/s)
    - s_asym: asymmetry between mean ebb and flood speed
    - ds_dz: mean vertical shear (m/s per m) over all tidal cycles
    - P_mean: mean kinetic power density over all tidal cycles (kW/m^2)
    - P_asym: asymmetry between ebb and flood power density
    - h: mean water depth over deployment
- ebb, flood
    - Same as for all, excepting asymmetry metrics
- bins: bin numbers included in output data
- cycle: histograms of duration, velocity, and direction for each ebb or flood cycle
- ellipse: tidal ellipses for the first *N* ebb/flood cycles
- ens_d: ensemble averaged current direction
- ens_da_PA: ensemble averaged current direction corrected for 0/360^{o} phase ambiguity
- ens_h: ensemble averaged water depth (m)
- ens_s: ensemble averaged horizontal velocity (m/s)
- ens_t: starting time for ensemble average
- ens_u: ensemble averaged east velocity (m/s)
- ens_v: ensemble averaged north velocity (m/s)
- ens_w: ensemble averaged vertical velocity (m/s)
- jpdf_vd: joint probability distribution of horizontal velocity and direction
- pdf_v: probability distribution of horizontal velocity
- profile_log: log-layer profile fits for all ensembles. Calculated for all possible depth profiles (e.g., starting from 10 m from seabed, calculated at each depth up to surface)
    - s: depth-average velocity for profile (m/s)
    - z0: bottom roughness from fit (m)
    - ushear: shear velocity from fit (m/s)
    - R2: coefficient of determination for fit
    - tau: shear stress (Pa)
    - z_log: height of log layer for each fit
    - exit_flag: 1 = fit converged, 0 = not converged
- profile_power: power law profile fits for all ensembles.
    - s: depth-averaged velocity for profile (m/s)
    - exp: inverse of power law exponent (e.g., exp = 7 corresponds to 1/7 fit)
    - R2: coefficient of determination for fit
- res_s: residual current information
    - t: time index (matlab time)
    - s: unfiltered horizontal velocity (m/s)
    - s_filter: filtered horizontal velocity (m/s)
- slack_t: times for slack water
- t_ens: input value for duration of ensemble average

- `v_bins`: velocity bins used for probability distributions (m/s)
- `d_bins`: direction bins used for probability distributions (degress)
- `z`: vertical bin centers for output data (m)

3 Visualizing Resource Characteristics

A number of plotting routines are included to visualize resource characteristics for a single deployment. All of these can be accessed through `PlotResource.m`. To run the visualization routine, specify:

1. `z_target`: for plots at a single depth, the depth desired to plot. If `z_target` is less than 1, this will be interpreted as a normalized depth in the water column, relative to mean water depth. If `z_target` is greater than 1, this will be interpreted as an absolute distance from the seabed (m).
2. `plot_case`: the file index to be plotted, corresponding to the index notation in `Data_Resource.xlsx`.
3. Plots to be created.

Available visualizations include:

- `plot_current`: a trace of current velocity at hub height, with optional color coding for vertical velocity
- `plot_ellipse`: tidal ellipses for first N tidal cycles, with optional color coding for vertical velocity – potentially helpful to identify vertical velocity variations associated with elliptical motion.
- `plot_cycle_histogram`: histograms of cycle duration, amplitude, and direction
- `plot_residual`: color plot of residual currents
- `plot_pdf`: plot a number of probability and joint probability distributions for velocity and direction
- `plot_rose`: (beta) a compass rose of resource characteristics
- `plot_profiles`: ebb, flood, and all vertical profiles for key metrics
- `plot_power_law_stats`: details of power law fits as a function of horizontal velocity
- `plot_log_law_stats`: details of log law fit as a function of horizontal velocity
- `plot_pcolor`: color plot of horizontal velocity and direction over all depths

In addition to graphical visualization, multiple sites can be compared by generating a resource characteristics table using `ResourceTable.m`. To generate the table, specify:

1. `z_target`: for plots at a single depth, the depth desired to plot. If `z_target` is less than 1, this will be interpreted as a normalized depth in the water column, relative to mean water depth. If `z_target` is greater than 1, this will be interpreted as an absolute distance from the seabed (m).
2. `char_proc`: cases to include in table, as referenced to the indices in `BatchResource.xlsx`.
3. Values to include in table, as hardwired in the code.

4 Calculating Performance Characteristics

4.1 Performance Model

The performance model is a relatively simple one, as described in Polagye and Thomson (2012). The model presumes a horizontal axis turbine where power output (P) depends on a modified horizontal velocity, as

$$
\begin{array}{ll}
P = 0 & \left|U_h \cos\gamma\right| < U_{\text{cut-in}} \\
P = \tfrac{1}{2}\rho\left|U_h \cos\gamma\right|^3\left(\dfrac{\pi D^2}{4}\right)\eta_p\eta_e & U_{\text{cut-in}} \le \left|U_h \cos\gamma\right| \le U_{\text{rated}} \\
P = \tfrac{1}{2}\rho {U_{\text{rated}}}^3\left(\dfrac{\pi D^2}{4}\right)\eta_p\eta_e & \left|U_h \cos\gamma\right| > U_{\text{rated}}
\end{array}
$$

where U_h is the horizontal velocity, γ is the angle between the rotor swept area and incident flow, ρ is the density of seawater, D is the turbine diameter, η_p and η_e are the rotor and power train efficiencies (respectively), $U_{\text{cut-in}}$ is the speed the rotor begins to turned, and U_{rated} is the rated velocity. Horizontal velocity and direction are evaluated based on the joint probability distribution of velocity and direction generated by the resource characterization routine.

The program evaluates devices on the basis of power generation and operation:

- Power generation
  - Average power generated (MW)
  - Maximum power generated (MW)
  - Capacity factor: ratio of average power to maximum power
  - Probability distribution function of energy generated as a function of horizontal velocity
- Operation
  - Fraction of time in operation (i.e., velocity greater than $U_{\text{cut-in}}$)
  - Probability distribution of operating and idle durations

Future enhancements to the code may include handling for vertical axis (or cross flow) turbines and variable efficiencies as a function of current velocity or rated power.

4.2 Running the Program

As for resource characterization, operation characterization code is controlled by spreadsheet and user input to a matlab routine. The code can be used to investigate the performance a particular device in a range of tidal resources or the significance of varying device parameters in a particular resource (e.g., what is the implication of fixed versus active/passive yaw?).

To execute the routine:

1. Specify turbine parameters on `Data_Operation.xlsx`.
   a. Column 1: Case ID: integer sequence from 1:N
   b. Column 2: Site ID: site identifier from `Data_Resource.xlsx`
   c. Column 3: Hub height: turbine hub height (m) – the routine will operate on the bin closest to hub height (assumes hub height velocities are indicative of averages over rotor swept area)

    d. Column 4: Diameter: horizontal axis turbine rotor diameter (m)
    e. Column 5: Efficiency: water-to-wire turbine efficiency
    f. Column 6: Cut-in: velocity at which turbine begins to rotate
    g. Column 7: Rated: velocity at which turbine power output levels off
    h. Column 8: Yaw
        i. 0 = passive yaw: γ will be 0 for any velocity direction
        ii. -999 = fixed, optimized yaw: routine will choose the turbine orientation that maximizes power output
        iii. > 0 = fixed yaw angle: user-specified yaw angle
    i. Columns 9-N: output storage, comments, etc. – not used by matlab routines
2. In `BatchOperation.m`, specify:
    a. `operation_proc`: cases to execute, as specified in `Data_Operation.xlsx`.
    b. `out_path`: file path for results
    c. `prop.rho`: seawater density (kg/m^3)
3. For each case, `BatchOperation.m` calls `functions/characterize_resource.m`.
4. If yaw optimization is specified, the code first determines the yaw angle that maximizes power generation and then calculates operation metrics.
5. Output is stored in the directory specified by `out_path`.

4.3 Input Data

`BatchOperation.m` operates on the files generated by `BatchResource.m`. Specifically, the joint probability distribution of velocity with direction serves as an input to the performance model.

4.4 Output Data

The following variables are stored for each case:

- `generation`: structure containing statistics about power generation
    - `power_avg`: average power generation (MW)
    - `cf`: capacity factor
    - `power_max`: maximum power generation (MW)
    - `energy_vpdf`: probability distribution of energy generation as a function of current velocity
    - `energy_spdf`: same as `energy_vpdf`, but for speed (e.g., no ebb/flood differentiation)
- `operation`: structure containing statistics about turbine operation
    - `windows`: (:,1) – duration of state, (:,2) – state (1=on, 0=off)
    - `f_op`: fraction of time operation
    - `f_on`: probability distribution of operating durations
    - `f_off`: probability distribution of idle durations
    - `T_bins`: duration bins for `f_on` and `f_off`
- `s_bins`: horizontal speed bins for probability distributions
- `v_bins`: horizontal velocity bins for probability distributions
- `d_bins`: horizontal velocity direction bins for probability distributions

- z: hub height relative to seabed (m)
- bin: hub height bin
- turbine: structure containing turbine properties
    - yaw: if specified, the yaw angle the maximizes power generation
- s: horizontal velocity series underlying probability distribution
- t: time series associated with s
- d: direction time series associated with s
- P: time series of turbine power output
- pdf_v: probability distribution of horizontal velocity
- pdf_s: probability distribution of horizontal speed
- jpdf_vd: joint probability distribution of horizontal velocity and direction used to estimate turbine performance

5 Visualizing Performance Characteristics

Plotting routines used to visualize turbine operation can be accessed through `PlotOperation.m`. To run the visualization routine, specify:

1. `plot_case`: the file index to be plotted, corresponding to the case index in `Data_Operation.xlsx`.
2. `file_path`: output directory for `BatchOperation.m`.
3. Plots to be created.

Available visualizations include:

- `plot_operation_period`: a trace of current velocity at hub height with shading denoting operating and idle periods
- `plot_operation_CDF`: cumulative distribution of horizontal velocity and power generated.

In addition to graphical visualization, multiple cases can be compared by generating a operating characteristics table using `OperationTable.m`. To generate the table, specify:

1. `operation_proc`: cases to include in table, as referenced to the indices in `Data_Operation.xlsx`.
2. `file_path`: output directory for `BatchOperation.m`.
3. Values to include in table, as hardwired in the code. The default output can be used to populate the blue-shaded columns in `Data_Operation.xlsx`.

6 References

Polagye, B. and J. Thomson (*submitted*) Tidal energy resource characterization: methodology and field study in Admiralty Inlet, Puget Sound, US. *Submitted to IMechE Part A: J. Power and Energy.*