WTSoftwareUtilitiesShare

Wind Tunnel Analysis Software Package

Repository Structure and Usage Guide

Analysis Documentation

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Contents

1 Repository Overview **2**

1.1 Repository Structure 2

2 Main Workflows and Example Files **3**

2.1 Example_PointConc_Analysis_200325_stepByStep (Learning) 3

2.1.1 Processing Steps 3

2.2 Example_Flow_Analysis (Flow Field Analysis) 5

2.3 Example_PointConc_Analysis_200325_Analysis_deploy 5

3 Physical Equations for Concentration Analysis **6**

3.1 Model Scale Mass Flow Rate 6

3.2 Net Concentration 6

3.3 Dimensionless Concentration (C^*) 6

3.4 Full-Scale Concentration 7

4 Parameter File Structure **9**

4.1 Example CSV Format 9

5 Software Usage **10**

5.1 Quick Start for Students (Jupyter Server) 10

5.2 Local Installation (Windows) 10

5.3 Manual Installation (Linux/Mac) 10

6 Conclusion **10**

1 Repository Overview

The `WTSoftwareUtilitiesShare` repository provides a comprehensive Python package for wind tunnel measurement analysis, focusing on point concentration measurements and flow analysis. The software enables automated data processing, dimensionalization, and visualization of wind tunnel experimental data.

1.1 Repository Structure

- **Main Package:** `windtunnel/` – Core Python package containing analysis modules
  - `concentration/` – Point and puff concentration analysis
  - `flow/` – Flow statistics and turbulence analysis
  - `plots/` – Visualization tools
  - `grid/` – Grid manipulation tools
- **Jupyter Notebooks:**
  - `Example_PointConc_Analysis_200325_stepByStep.ipynb` – Tutorial notebook
  - `Example_PointConc_Analysis_200325_Analysis_deploy.ipynb` – Deployment version
  - `Example_PointConc_Analysis_200325_Analysis.ipynb` – Full analysis workflow
  - `Example_Flow_Analysis.ipynb` – Flow field analysis
- **Data Structure:**
  - `Data/InputData/` – Raw measurement time series
  - `Data/ParameterFiles/` – CSV files with ambient conditions
  - `Results/` – Processed output data
  - `ExampleData/` – Example datasets for testing
- **Deployment:**
  - `deploy_config.py` – Setup functions for Jupyter server deployment
  - `windows_deploy/` – Windows batch scripts for environment setup
  - `requirements.txt` – Python dependencies

2 Main Workflows and Example Files

2.1 Example_PointConc_Analysis_200325_stepByStep (Learning)

This notebook provides a detailed step-by-step walkthrough of the concentration analysis workflow. It is designed for learning and understanding the underlying processes.

2.1.1 Processing Steps

1. **Data Import and Initialization**
   - Import `windtunnel` package and required libraries
   - Define paths to input data and output directories
   - Specify measurement file prefixes (namelist)
   - Define CSV parameter file location
2. **Read Ambient Conditions**
   - Load ambient conditions from CSV file for each time series
   - Extract source location ($x_{\text{source}}, y_{\text{source}}, z_{\text{source}}$)
   - Extract measurement location ($x_{\text{measure}}, y_{\text{measure}}, z_{\text{measure}}$)
   - Read environmental parameters (pressure, temperature)
   - Read mass flow controller settings and calibration data
   - Read scaling information (model scale, reference lengths)
   - Read tracer gas properties (molecular weight, gas factor)
   - Read full-scale transformation parameters
3. **Initialize PointConcentration Objects**
   - Create dictionary structure for all measurement files
   - Load raw time series data using `PointConcentration.from_file()`
   - Each file contains: time, wtref, slow_FID, fast_FID, open_rate
   - Store data in nested dictionaries: `conc_ts[name][file]`
4. **Set Ambient Conditions**
   - Apply ambient conditions to each `PointConcentration` object
   - Store source and measurement positions
   - Store pressure (p) and temperature (T)
   - Store mass flow controller settings
   - Calculate relative measurement position: $x = x_{\text{measure}} - x_{\text{source}}$
5. **Set Scaling Information**
   - Define model to reality scale factor
   - Set reference length L_{ref} (model scale)
   - Set reference height H_{ref}
   - Define scaling factor for wtref adjustment
   - Calculate full-scale reference length: $L_{\text{ref,fs}} = \text{scale} \cdot L_{\text{ref}}$

6. **Set Tracer Gas Information**
   - Define gas name (e.g., C12, N_2)
   - Set molecular weight M [g/mol]
   - Set gas correction factor (for different gases)
7. **Set Full-Scale Information**
   - Define full-scale reference wind speed $U_{\text{ref,fs}}$ [m/s]
   - Define full-scale mass flow rate $\dot{Q}_{\text{fs}}$ [kg/s]
   - Set full-scale ambient temperature T_{fs} [°C]
   - Set full-scale ambient pressure p_{fs} [Pa]
8. **Temperature Conversion**
   - Convert ambient temperature to Kelvin: $T_K = T + 273.15$
   - Convert full-scale temperature: $T_{\text{fs,K}} = T_{\text{fs}} + 273.15$
   - Store standard conditions: $T_{\text{std,K}} = 273.15$ K, $p_{\text{std}} = 101325$ Pa
9. **Calculate Mean Wind Tunnel Reference Speed**
   - Calculate mean of wtref time series
   - Apply scaling factor: $\overline{U}_{\text{ref,ms}} = \text{scaling\_factor} \cdot \text{mean(wtref)}$
10. **Calculate Model Scale Mass Flow Rate**
    - Account for controller settings and open_rate
    - Apply gas correction factor
    - Correct for ambient conditions (temperature and pressure)
    - Apply calibration (if specified)
    - **See Equation 1 for details**
11. **Calculate Net Concentration**
    - Subtract background concentration from total concentration
    - $C_{\text{net}} = \text{fast\_FID} - \text{slow\_FID}$ [ppmV]
12. **Calculate Dimensionless Concentration (C^*)**
    - Normalize concentration by flow rate and reference wind speed
    - **See Equation 3 for details**
13. **Calculate Full-Scale Concentration**
    - Transform C^* to full-scale conditions
    - Account for full-scale flow rate and wind speed
    - **See Equation 5 for details**
14. **Optional: Transform to Full Scale or Non-Dimensional**
    - `full_scale='ms'`: Keep model scale values
    - `full_scale='fs'`: Convert all quantities to full scale
    - `full_scale='nd'`: Convert all quantities to non-dimensional

15. **Save Processed Data**
    - Save time series with all calculated quantities
    - Save averaged values (time-averaged statistics)
    - Save statistical measures (mean, percentiles, peak-to-mean ratio)
    - Create combined CSV file with all measurement points
16. **Visualization and Analysis**
    - Plot time series of concentrations
    - Generate statistical plots (histograms, PDFs, CDFs)
    - Create comparison plots between different measurement locations
    - Analyze concentration fluctuations and intermittency
    - Plot power spectral density of concentration fluctuations

2.2 Example_Flow_Analysis (Flow Field Analysis)

This notebook analyzes velocity measurements from wind tunnel experiments:

- **Vertical/Horizontal Wind Profiles**: Analysis of mean velocity and turbulence intensity
- **Turbulence Statistics**: Calculate turbulence intensities (I_u, I_v, I_w), Reynolds stresses
- **Integral Length Scales**: Calculate L_{ux} from autocorrelation
- **Spectral Analysis**: Power spectral density of velocity fluctuations
- **Convergence Tests**: Bandwidth analysis for different averaging intervals
- **Boundary Layer Fitting**: Power law exponent α and roughness length z_0

2.3 Example_PointConc_Analysis_200325_Analysis_deploy

Streamlined deployment version for Jupyter server environments:

- Automatic package installation from GitHub
- Automatic folder structure creation
- Example data download
- Simplified configuration for students/users

3 Physical Equations for Concentration Analysis

3.1 Model Scale Mass Flow Rate

The mass flow rate at model scale is calculated accounting for ambient conditions, controller settings, and gas properties:

$$\boxed{\dot{Q}_{\mathrm{amb}} = \frac{\mathrm{open\_rate} \cdot 10 \cdot f_{\mathrm{gas}} \cdot \dot{Q}_{\mathrm{controller}}}{100} \cdot \frac{T_K \cdot p_{\mathrm{std}}}{p \cdot T_{\mathrm{std,K}}}} \tag{1}$$

where:

- $\dot{Q}_{\mathrm{amb}}$ – ambient mass flow rate [l/h]
- open_rate – valve opening [0-10], multiplied by 10 to get percentage
- f_{gas} – gas correction factor [-] (e.g., for different tracer gases)
- $\dot{Q}_{\mathrm{controller}}$ – maximum flow rate of mass flow controller [l/h]
- T_K – ambient temperature [K]
- p – ambient pressure [Pa]
- $T_{\mathrm{std,K}}$ – standard temperature = 273.15 K
- p_{std} – standard pressure = 101325 Pa

Note on Mass Flow Controller: The mass flow controller unit represents the maximum flow rate capacity of the device (e.g., 150 l/h). This value is calibrated at standard conditions and must be corrected for ambient temperature and pressure. The actual flow rate is then determined by the valve opening (open_rate) which controls the percentage of this maximum flow that passes through.

3.2 Net Concentration

The net concentration is obtained by subtracting the background concentration (slow FID) from the total measured concentration (fast FID):

$$\boxed{C_{\mathrm{net}} = \mathrm{fast\_FID} - \mathrm{slow\_FID}} \tag{2}$$

where:

- C_{net} – net tracer concentration [ppmV]
- fast_FID – total concentration measured by fast flame ionization detector [ppmV]
- slow_FID – background concentration [ppmV]

3.3 Dimensionless Concentration (C^*)

The dimensionless concentration is the fundamental scaling parameter for comparing measurements at different scales and conditions:

$$\boxed{C^* = \frac{C_{\mathrm{net}} \cdot \overline{U}_{\mathrm{ref}} \cdot L_{\mathrm{ref}}^2}{\dot{Q}_{\mathrm{amb}}}} \tag{3}$$

In computational form (with unit conversions):

$$C^* = \frac{\left(\frac{C_{\text{net}}}{10^6}\right) \cdot \overline{U}_{\text{ref}} \cdot L_{\text{ref}}^2}{\left(\frac{\dot{Q}_{\text{amb}}}{1000 \cdot 3600}\right)} \tag{4}$$

where:

- C^* – dimensionless concentration [-]
- C_{net} – net concentration [ppmV], converted to volume fraction by 10^{-6}
- $\overline{U}_{\text{ref}}$ – mean reference wind speed [m/s]
- L_{ref} – reference length (model scale) [m]
- $\dot{Q}_{\text{amb}}$ – ambient flow rate [l/h], converted to [m^3/s] by $(1000 \cdot 3600)^{-1}$

Physical Interpretation: C^* represents the normalized concentration field. It is scale-invariant, meaning identical C^* values at different scales indicate similar dispersion physics (assuming geometric and dynamic similarity).

3.4 Full-Scale Concentration

To predict concentrations at full scale, the dimensionless concentration is rescaled using full-scale parameters:

$$\boxed{C_{\text{fs}} = C^* \cdot \frac{\dot{Q}_{\text{fs,vol}}}{L_{\text{ref,fs}}^2 \cdot U_{\text{ref,fs}}} \cdot 10^6} \tag{5}$$

where the full-scale volumetric flow rate is calculated from the mass flow rate:

$$\dot{Q}_{\text{fs,vol}} = \dot{Q}_{\text{fs,mass}} \cdot \frac{R \cdot T_{\text{fs,K}}}{p_{\text{fs}} \cdot M \cdot 10^{-3}} \tag{6}$$

Combined:

$$\boxed{C_{\text{fs}} = C^* \cdot \frac{\dot{Q}_{\text{fs,mass}} \cdot R \cdot T_{\text{fs,K}}}{p_{\text{fs}} \cdot M \cdot 10^{-3} \cdot L_{\text{ref,fs}}^2 \cdot U_{\text{ref,fs}}} \cdot 10^6} \tag{7}$$

where:

- C_{fs} – full-scale concentration [ppmV]
- $\dot{Q}_{\text{fs,mass}}$ – full-scale mass flow rate [kg/s]
- $\dot{Q}_{\text{fs,vol}}$ – full-scale volumetric flow rate [m^3/s]
- R – universal gas constant = 8.3144621 J/(mol·K)
- $T_{\text{fs,K}}$ – full-scale ambient temperature [K]
- p_{fs} – full-scale ambient pressure [Pa]
- M – molecular weight of air [g/mol], converted to [kg/mol] by 10^{-3}
- $L_{\text{ref,fs}}$ – full-scale reference length [m] = scale $\cdot\, L_{\text{ref}}$
- $U_{\text{ref,fs}}$ – full-scale reference wind speed [m/s]

Physical Interpretation: This transformation accounts for:

- Geometric scaling ($L^2_{\mathrm{ref,fs}}$ vs L^2_{ref})
- Kinematic scaling ($U_{\mathrm{ref,fs}}$ vs $\overline{U}_{\mathrm{ref}}$)
- Source strength scaling ($\dot{Q}_{\mathrm{fs,vol}}$ vs $\dot{Q}_{\mathrm{amb}}$)
- Thermodynamic conditions (via ideal gas law)

4 Parameter File Structure

The ambient conditions are stored in CSV files with the following structure:

4.1 Example CSV Format

```
,file1.ts#0,file2.ts#1,file3.ts#2
x_source,0.0,0.0,0.0
y_source,0.0,0.0,0.0
z_source,0.0,0.0,0.0
x_measure,37.5,50.0,62.5
y_measure,0.0,0.0,0.0
z_measure,10.0,10.0,10.0
pressure,101768,101768,101768
temperature,23.0,23.0,23.0
mass_flow_controller,0.300,0.300,0.300
calibration_curve,None,None,None
calibration_factor,1,1,1
scale,200,200,200
ref_length,0.005,0.005,0.005
gas_name,C12,C12,C12
mol_weight,28.97,28.97,28.97
gas_factor,1.0,1.0,1.0
full_scale_wtref,5.0,5.0,5.0
full_scale_flow_rate,0.5,0.5,0.5
full_scale_temp,20,20,20
full_scale_pressure,101325,101325,101325
config_name,test,test,test
```

5 Software Usage

5.1 Quick Start for Students (Jupyter Server)

1. Upload `Example_PointConc_Analysis_200325_Analysis_deploy.ipynb` and `deploy_config.py` to Jupyter server

2. Open the notebook and run Cell 1 – the software automatically:

   - Installs the `windtunnel` package
   - Creates folder structure (`Data/`, `Results/`)
   - Downloads example data

3. Run subsequent cells to perform analysis

4. To use your own data: Upload files to `Data/InputData/` and `Data/ParameterFiles/`, then modify Cell 2

5.2 Local Installation (Windows)

For users who want to work locally with full repository access:

1. Clone or download the repository

2. Run `windows_deploy/setup_WTConc2.bat` (creates virtual environment)

3. Run `windows_deploy/Start_WTConc2_Notebook.bat` to start Jupyter

4. Open any notebook from the browser interface

5.3 Manual Installation (Linux/Mac)

```
git clone https://github.com/se04ber/WTSoftwareUtilitiesShare.git
cd WTSoftwareUtilitiesShare
python -m venv WTConc2
source WTConc2/bin/activate  # On Windows: WTConc2\Scripts\activate
pip install -r requirements.txt
jupyter notebook
```

6 Conclusion

The `WTSoftwareUtilitiesShare` package provides a comprehensive framework for wind tunnel data analysis. The modular structure allows users to:

- Process raw concentration and velocity measurements
- Apply proper scaling transformations
- Perform statistical analysis of turbulent concentration fields
- Generate publication-quality visualizations
- Scale results between model and full scale

The software implements rigorous physical models accounting for:

- Ambient condition corrections (temperature, pressure)

- Mass flow controller calibrations
- Geometric scaling (model to full scale)
- Kinematic scaling (velocity matching)
- Thermodynamic transformations (ideal gas law)

For questions or issues, contact: `Sabrina.ebert@proton.me`

Table 1: Ambient Conditions Parameter File Structure

Parameter	Unit	Description	Importance
x_source	[mm]	X-coordinate of tracer gas source	Defines source position
y_source	[mm]	Y-coordinate of tracer gas source	Defines source position
z_source	[mm]	Z-coordinate of tracer gas source (height)	Defines source position
x_measure	[mm]	X-coordinate of measurement point	Defines measurement location
y_measure	[mm]	Y-coordinate of measurement point	Defines measurement location
z_measure	[mm]	Z-coordinate of measurement point (height)	Defines measurement location
pressure	[Pa]	Ambient atmospheric pressure	Critical for mass flow rate calculation
temperature	[°C]	Ambient temperature	Critical for mass flow rate calculation
mass_flow_controller	[l/h]	Maximum flow rate capacity of controller	Defines maximum source strength
calibration_curve	[-]	Linear calibration coefficient	Corrects controller output
calibration_factor	[-]	Calibration offset	Corrects controller output
scale	[-]	Model to full-scale ratio (e.g., 1:200)	Required for scaling
scaling_factor	[-]	Wind speed correction factor	Adjusts wtref to reference position
ref_length	[m]	Reference length in model scale	Fundamental scaling parameter
ref_height	[m]	Reference height (if applicable)	Boundary layer scaling
gas_name	-	Tracer gas identifier (e.g., C12, N_2)	Documentation
mol_weight	[g/mol]	Molecular weight of air	Used in ideal gas law
gas_factor	[-]	Correction factor for different gases	Adjusts for tracer properties
full_scale_wtref	[m/s]	Full-scale reference wind speed	Target full-scale velocity
full_scale_flow_rate	[kg/s]	Full-scale source emission rate	Target full-scale source strength
full_scale_temp	[°C]	Full-scale ambient temperature	Full-scale ambient conditions
full_scale_pressure	[Pa]	Full-scale ambient pressure	Full-scale ambient conditions
config_name	-	Configuration identifier	Labels different test conditions