The Journal of Open Source Software

# TurboFlow: Meanline Modelling of Axial Turbines

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**DOI:** 10.21105/joss.07588

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**Submitted:** 26 June 2024
**Published:** 26 June 2025



## Summary

Meanline modeling is a fundamental approach used in the design and analysis of axial turbines (Dixon, 2014). The method simplifies the analysis by assuming a uniform flow and incorporates semi-empirical correlations to estimate performance. This approach allows for a reasonably accurate approximation at low computational cost.

TurboFlow is a Python package for meanline modeling of axial turbines, providing a comprehensive framework for on- and off-design performance analysis and design optimization. It employs an equation-oriented model formulation, making it compatible with gradient-based equation solvers and optimization algorithms for efficient computations. The package features a modular architecture that allows for seamless integration of various submodels, enabling users to select and combine different models for calculating losses, flow angles, choking, and tailoring the analysis to specific needs. The structure also facilitates the implementation of other submodels for these purposes. TurboFlow provides access to advanced equations of state for real gas fluid properties by interfacing to the CoolProp library. The accuracy and computational robustness of the implemented models have been demonstrated through comprehensive validation against experimental data (Anderson et al., 2024).

TurboFlow comes with comprehensive documentation, including installation guides, tutorials, model descriptions, and a complete API reference. This extensive resource ensures that users can easily learn how to use the package and apply it effectively in their projects. For more details, visit the documentation pages. Additionally, the package includes preconfigured examples that demonstrate performance analysis and design optimization. These examples serve as practical guides for users to apply TurboFlow to their own projects. Additionally, these examples showcase the post-processing capabilities, including plotting, logging, and export utilities for result interpretation and analysis.

The package source code is hosted in a GitHub repository (Anderson & Agromayor, 2024). Through GitHub Actions, an automated test suite is included, which checks the functionality of the performance analysis and design optimization, as well as all submodels. It enables continuous integration, ensuring that code changes are systematically tested and validated. This comprehensive testing framework provides confidence that the code works as expected, maintaining the reliability of the package with each update.

With these features, TurboFlow should present a reliable and flexible tool for researchers and engineers within the field of turbomachinery.

## Statement of need

Meanline models are essential for simulating turbomachinery (Dixon, 2014). For design processes, they enable rapid evaluation of design concepts and are used to establish key geometrical parameters. The preliminary design forms the basis for subsequent refined design steps and is crucial for achieving high-efficiency turbomachinery (Macchi & Astolfi, 2017). Furthermore, meanline models offer a method to quickly, yet accurately, predict performance, making them well-suited for system-level analyses involving turbomachines, both at design and off-design conditions.

Despite the importance of these models, there is no established reference meanline tool for turbomachinery modeling available. Although there are several commercial tools available:

- CFturbo (*CFturbo*, n.d.)
- AxSTREAM (*AxSTREAM*, n.d.)
- TURBOdesign Suite (*TURBOdesign Suite*, n.d.)
- Concepts NREC (*Concepts NREC*, n.d.)

These are closed source, limiting the ability to modify, extend, or debug the models.

Several meanline models developed in academic settings also suffer from being closed source:

- zTurbo from TU-Delft (Pini et al., 2013)
- axTur from Politecnico di Milano (Macchi & Astolfi, 2017)
- OTAC from NASA Glenn Research Center (Hendricks, 2016)

The few open-source meanline models that do exist come with significant limitations in terms of programming language, model formulation, and restricted functionality. These models and their features are summarized in the following table:

| Reference | Programming language | Model formulation | Functionalities |
|---|---|---|---|
| (Genrup et al., 2005) | MATLAB (proprietary) | Sequential | Performance analysis |
| (Denton, 2017) | FORTRAN77 (legacy) | Non-iterative | Inverse design |
| (Agromayor & Nord, 2019) | MATLAB (proprietary) | Equation-oriented | Design optimization |
| (Brind, 2024) | Python | Non-iterative | Inverse design |

The use of diverse programming languages, such as MATLAB and FORTRAN77, presents accessibility and compatibility issues. MATLAB-based models, such as those by (Genrup et al., 2005) and (Agromayor & Nord, 2019), are proprietary, which limits their accessibility to those with MATLAB licenses. While legacy languages like FORTRAN77, as used by (Denton, 2017), might be more accessible, they fall short in terms of modern features and extensive community support. Consequently, models developed with these languages are less efficient to develop and less attractive to potential contributors, hampering development and collaboration. Furthermore, models adopting a sequential model formulation solve sets of model equations sequentially through multiple nested iterations. This approach can lead to unreliable convergence and prolonged execution times due to the high number of model equations evaluations required. In contrast, an equation-oriented model formulation solves a larger set of equations simultaneously, enhancing reliability and computational efficiency. Lastly, existing models vary in functionality. The model from (Genrup et al., 2005) is dedicated to performance analysis, whereas (Agromayor & Nord, 2019) focuses on design optimization. On the other hand, (Brind, 2024) and (Denton, 2017) employ an inverse design methodology, where the geometry is derived from specified performance parameters (e.g., flow coefficient, loading coefficient, degree of reaction), rendering them unsuitable for performance prediction for a given geometry. Consequently, no single open-source model currently provides a comprehensive solution that integrates both performance analysis and design optimization.

TurboFlow addresses these gaps with a robust, open-source framework for meanline modeling. It combines performance analysis and design optimization within a flexible, modular architecture, accommodating various submodels seamlessly. This flexibility allows for the integration of new submodels, giving users the option to tailor the analysis for their application. The model adopts an equation-oriented formulation, allowing integration with gradient-based solvers and offering the potential for faster convergence compared to methods based on the sequential model formulation. TurboFlow's open-source framework enables other researchers and industry practitioners to use and contribute to its development, positioning it as the first community-driven effort in turbomachinery meanline modeling. Through a collaborative effort, TurboFlow can be expanded with other types of turbomachinery and features, having a significant potential to advance turbomachinery meanline modeling.

# Acknowledgment

The research leading to the presented work has received funding from the EEA/Norway Grants and the Technology Agency of the Czech Republic within the KAPPA Program. Project code TO01000160. This work also received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 899987. The financial support is gratefully acknowledged.

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