Advancing gas-bearing turbocompressor design: a robust and integrated multi-objective optimization via surrogate modeling

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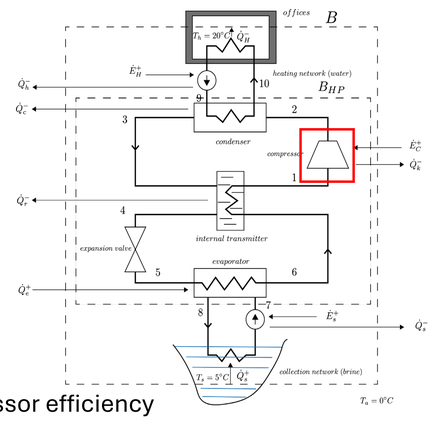
Summary

- Innovative Engineering Design: Robust against manufacturing variations; optimized for multidisciplinary contexts
- Ensemble Neural Networks: Accelerates computations, driving efficiency
- Non-dominated Sorting Genetic Algorithm III: Facilitates effective multi-objective optimization for superior design solutions
- Turbocompressor Focus: Tackles sensitivity issues in bearing clearances, enhancing system stability
- Comprehensive Integration: Harmonizes components from aerodynamics to dynamics and loss analysis
- Proven Results: Matches university cluster performance using desktop-grade GPU

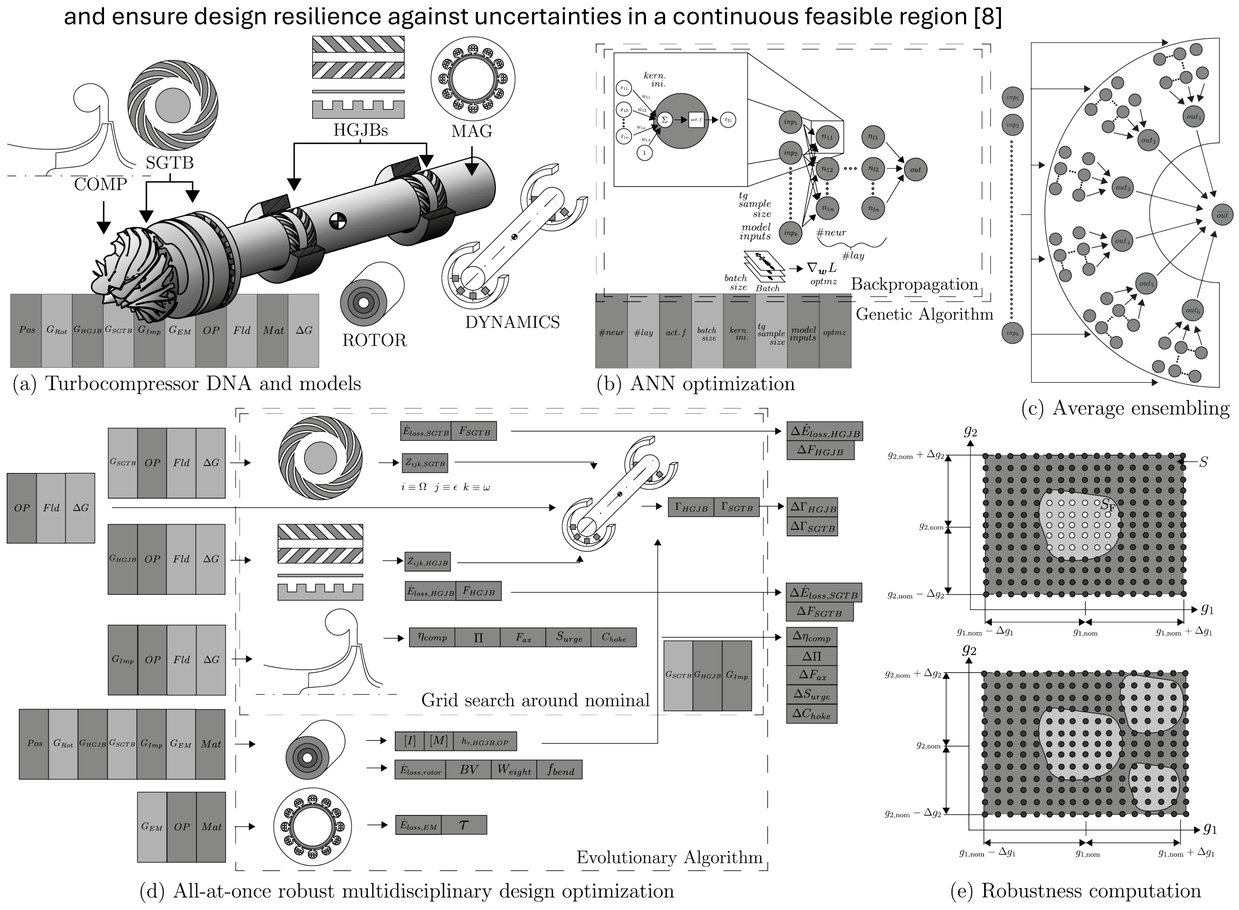
Motivation

- Small-scale turbocompressor system design involves multiple disciplines at various scales with strong component interaction
- Individual component optimizations yield suboptimal solutions
- Maximizing performance metrics may not lead to design robustness or safety margin towards manufacturing imperfection
- Integrated optimization approaches coupled with design robustness require very fast models to identify competing design objectives
- Increasing heat-pump cycle efficiency requires increasing compressor efficiency



Architecture of the Framework

- **(a) Turbocompressor DNA and Models** to predict compressor efficiency, rotordynamic behavior and mechanical losses
- **(b) ANN Hyperparameter Identification** via genetic algorithm-based optimization [2]
- **(c) Average Ensembling** of six ANNs with same hyperparameters but initialized differently to enhance reliability in extrapolation and reduce prediction error [3,4,5,6]
- **(d) All-at-Once Robust Multidisciplinary Design Optimization (AAO-RMDO)** ensures simultaneous consideration of all subsystems interdependencies [1,7]
- **(e) Robustness Computation** uses hypervolume $\overline{HV}$ and signal-to-noise ratio $\overline{S/N}$ metrics to assess and ensure design resilience against uncertainties in a continuous feasible region [8]



(a) Turbocompressor DNA and models

(b) ANN optimization

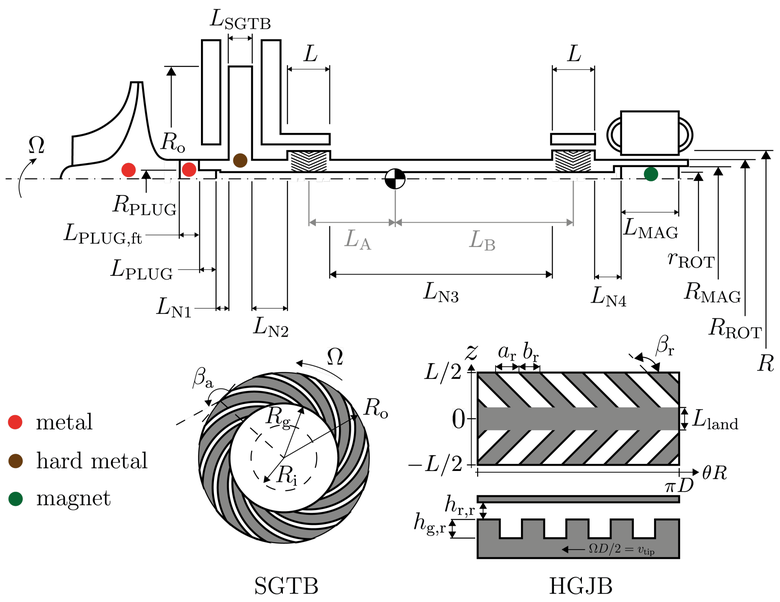
(c) Average ensembling

(d) All-at-once robust multidisciplinary design optimization

(e) Robustness computation

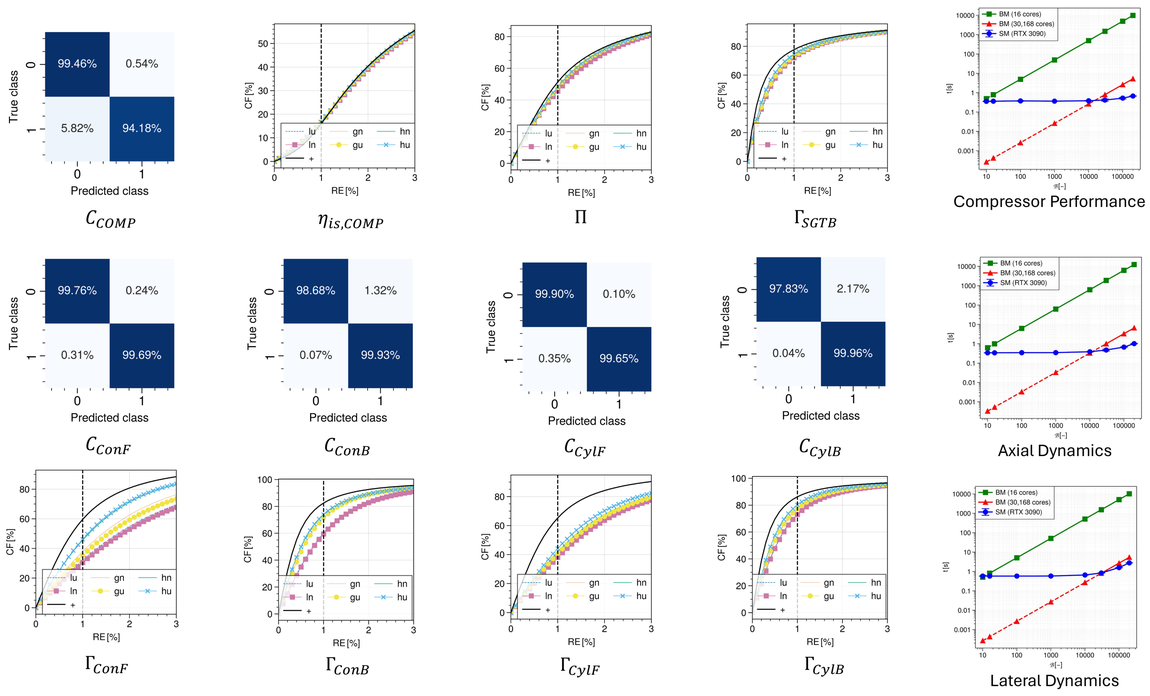
Multi-Objective-Optimization Setup

- NSGA-III [9,10,11] targets four key areas—bearings robustness $\overline{HV}$, mass flow range between surge and choke $\Delta\dot{m}^*_{\Pi=\Pi_{target}}$, signal-to-noise ratio $\overline{S/N}$, and overall efficiency η_{tot} in turbocompressor designs
- Balances 42 constraints with 45 variables to refine compressor geometry and materials, prioritizing operational reliability and manufacturing tolerance
- Scales across compressor designs for mass flows of 25 to 200 g/s, streamlining efficiencies for power ranges between 1 kW and 8 kW

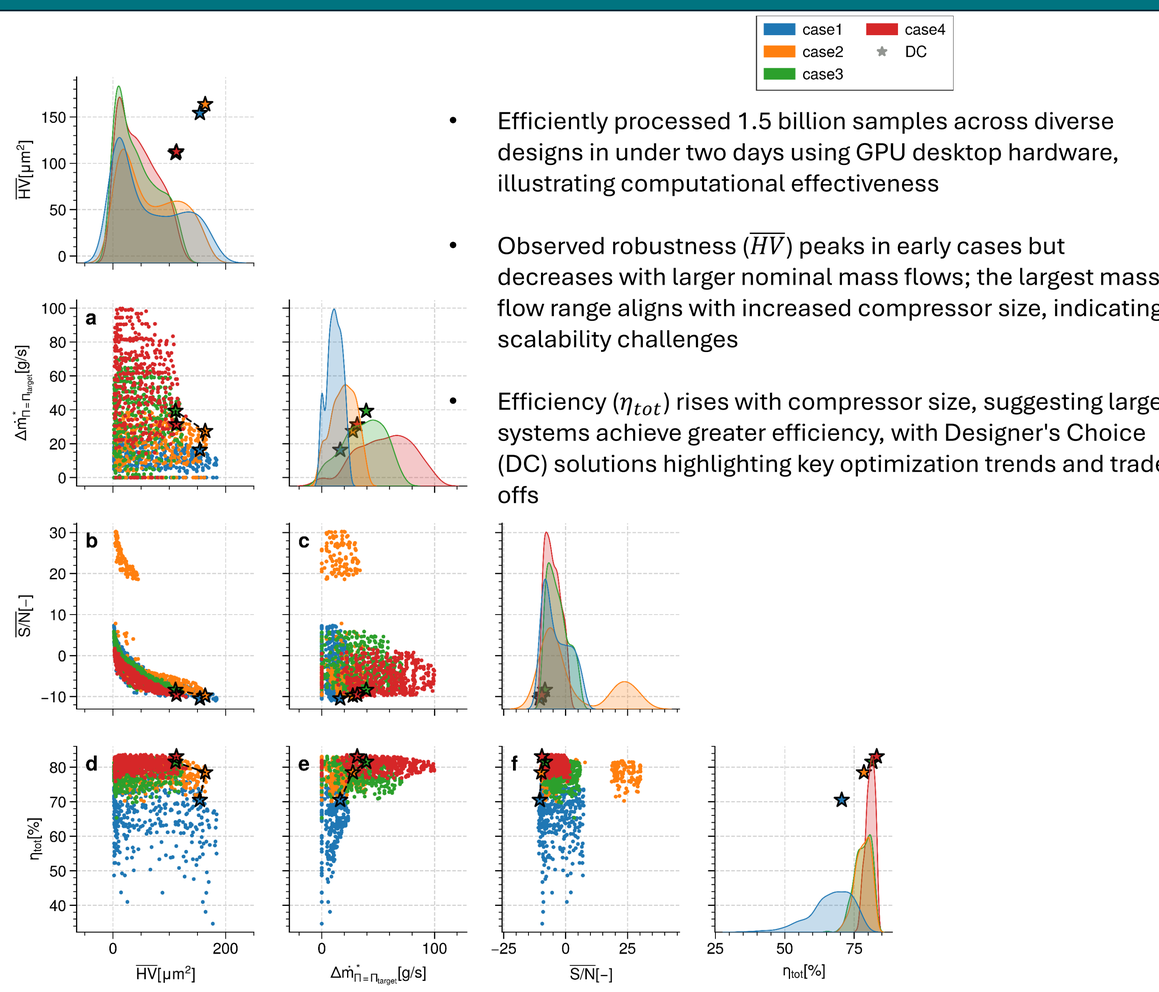


Surrogate Model Performance

- Validated across 500,000+ test samples, ensuring reliable predictions for compressor performance, axial dynamics and lateral dynamics
- Ensemble ANNs achieve high classification precision and recall as seen on confusion matrices. Cumulative frequency plots show a reduction of the relative error for the ensemble regressors
- GPU-accelerated computations of the surrogate model (SM) outperform traditional methods, optimizing speed and scalability for extensive datasets



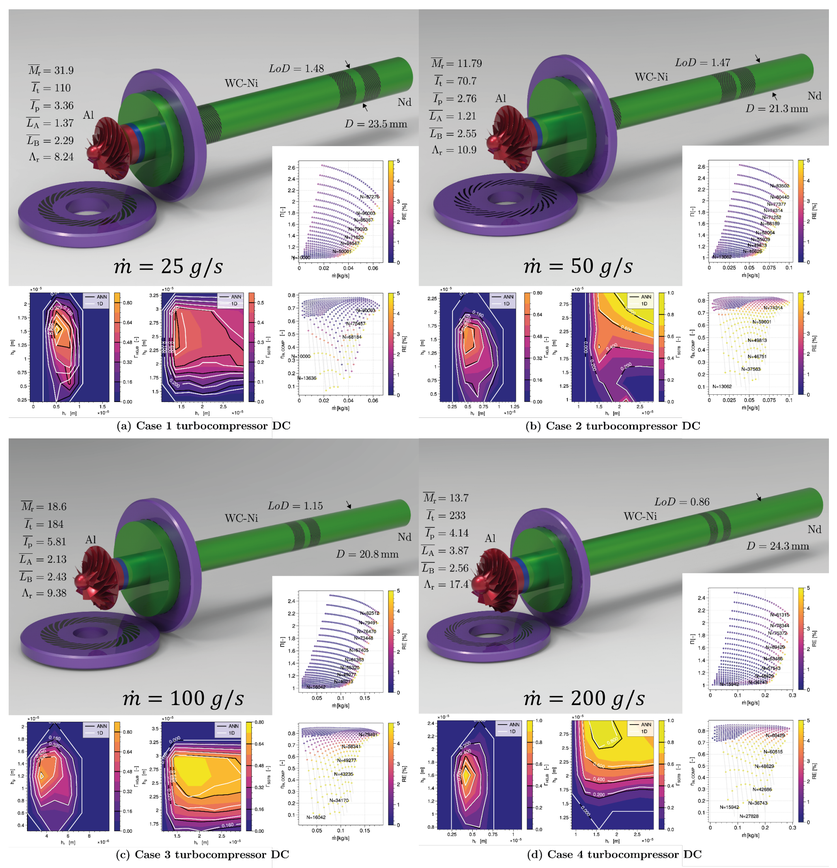
Pareto Fronts



- Efficiently processed 1.5 billion samples across diverse designs in under two days using GPU desktop hardware, illustrating computational effectiveness
- Observed robustness ($\overline{HV}$) peaks in early cases but decreases with larger nominal mass flows; the largest mass-flow range aligns with increased compressor size, indicating scalability challenges
- Efficiency (η_{tot}) rises with compressor size, suggesting larger systems achieve greater efficiency, with Designer's Choice (DC) solutions highlighting key optimization trends and trade-offs

Selected Designs

- Robustness and efficiency findings reveal that early DC cases handle larger deviations in radial bearing clearances better than later cases, indicating nuanced design adaptability and varying tolerance grades based on compressor size
- Surrogate model precision in predicting rotordynamics robustness across all DC cases, highlighting the model's accuracy in forecasting system behaviors under varied operational conditions
- All DC cases demonstrate high efficiency levels, with efficiency exceeding 0.8 in larger compressors, and relative errors for critical performance metrics generally staying below 3%, showcasing the surrogate model's predictive effectiveness



(a) Case 1 turbocompressor DC

(b) Case 2 turbocompressor DC

(c) Case 3 turbocompressor DC

(d) Case 4 turbocompressor DC

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