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Towards Improved Prediction of Compressor Flow by Uncertainty Quantification of Spalart-Allmaras Turbulence Model

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Motivation

Reynolds-Averaged Navier-Stokes (RANS) simulation with the Spalart-Allmaras (SA) turbulence model is a conventional approach to analyze compressor stall. However, it falls short of predicting the compressor stall boundary especially at off-design speeds.

This research explores the uncertainty and the sensitivity of SA model coefficients on predicting compressor flow features. It aims to guide future modifications of the SA model for improved compressor stall prediction.

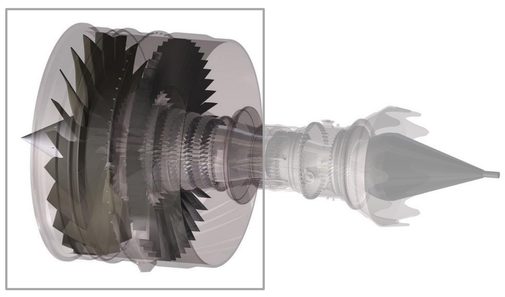
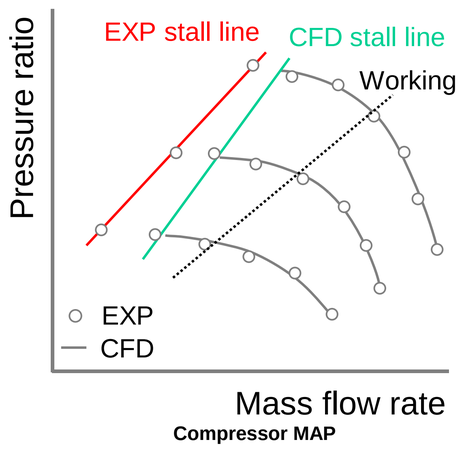


Illustration of compressor

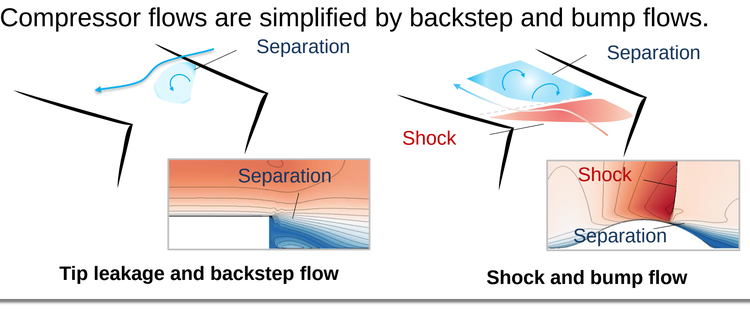


Compressor MAP

Methodology

Feature Extraction

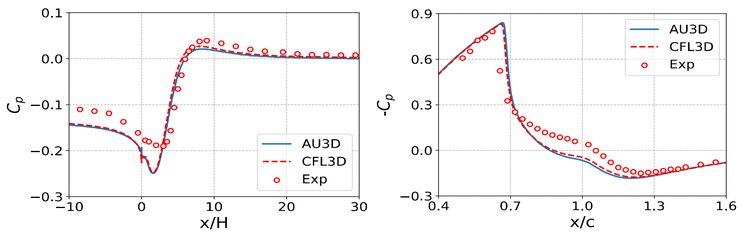
Compressor flows are simplified by backstep and bump flows.



Tip leakage and backstep flow — Shock and bump flow

Validation and Verification

The in-house solver AU3D is then verified in both backstep and bump flows against NASA's simulation and experiment results.



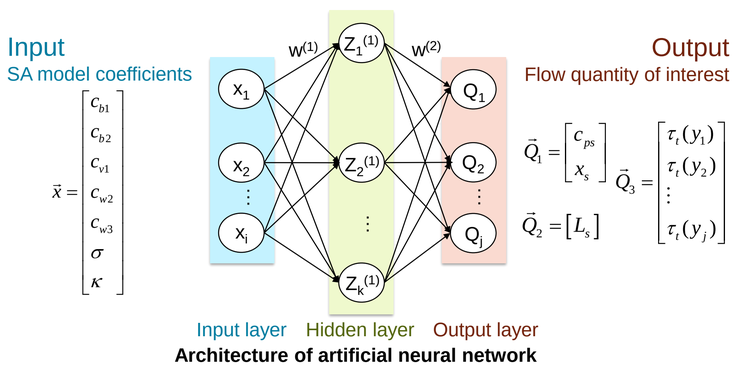
Surface pressure distribution: backstep (left) and bump (right)

Design of Experiment

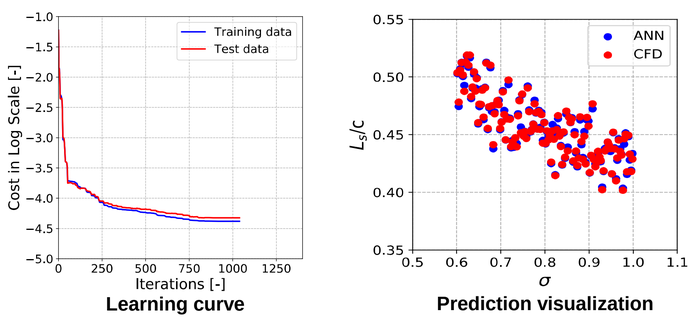
496 sets of SA coefficients are generated within physical bounds by Latin hypercube sampling, then simulated by AU3D.

Artificial Neural Network (ANN)

An artificial neural network is built and trained based on the database, serving as a surrogated model of the AU3D solver.
(i.e., $\vec{Q} = N(\vec{x})$)



Architecture of artificial neural network



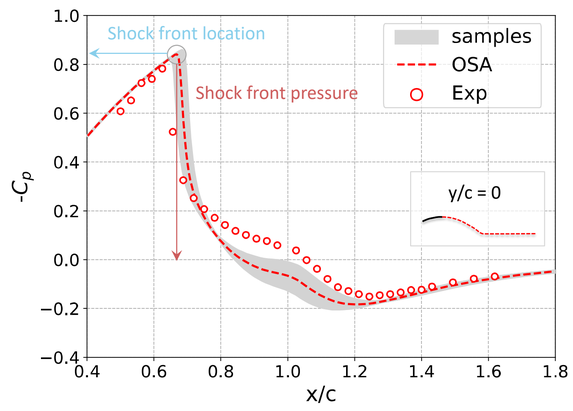
Learning curve — Prediction visualization

Uncertainty Quantification

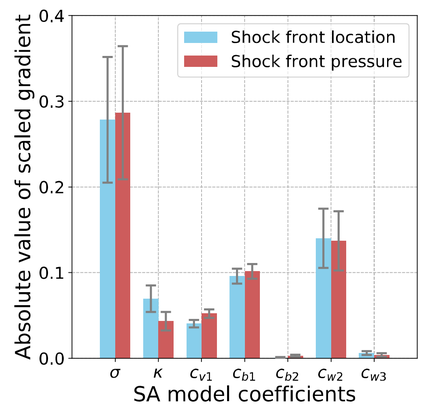
Finally, uncertainty and sensitivity of each coefficient can be quantified by its gradients based on the ANN.
(i.e., $\partial\vec{Q}/\partial x_i$)

Results

Shock. SA models predict a delayed shock front with a smaller pressure. Coefficients σ, κ, c_{v1}, c_{b1} and c_{w2} are found important to shock prediction.



Surface pressure distribution



Sensitivity on shock prediction

Separation. SA models predict a smaller size of separation. Coefficients σ, κ, c_{b1}, c_{w2} and c_{w3} are found important to separation prediction.

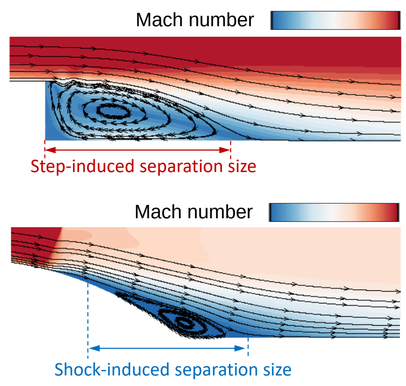
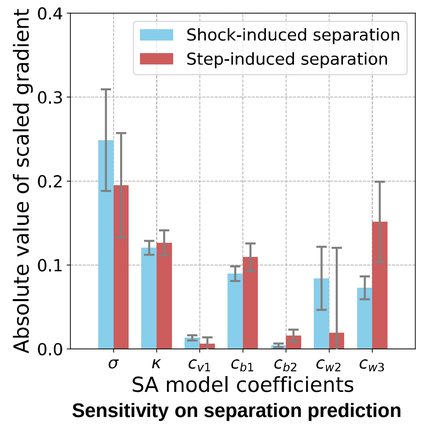
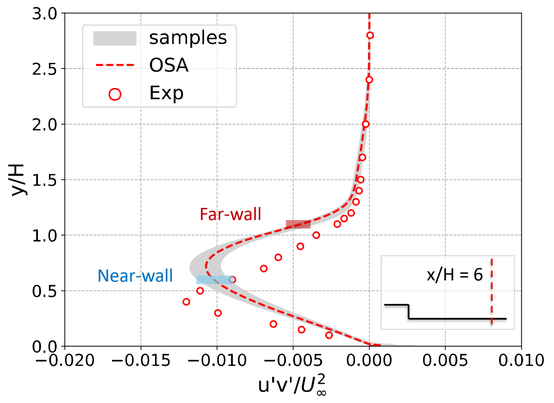


Illustration of separation size

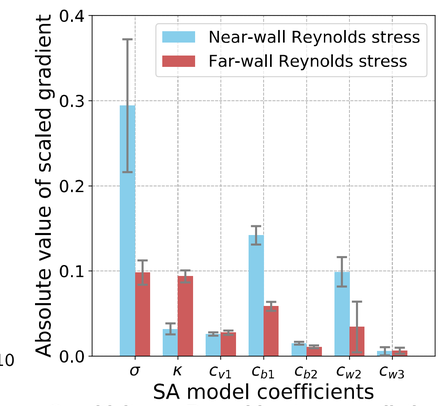


Sensitivity on separation prediction

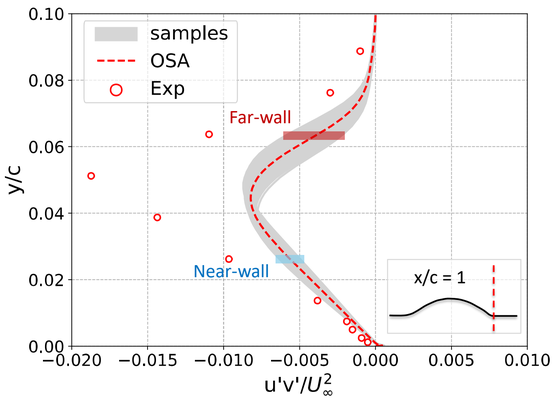
Reynolds Stress. SA models fail to reproduce the Reynolds stress in separated region. Coefficients σ, κ, c_{v1}, c_{b1} and c_{w2} are important to Reynolds stress prediction.



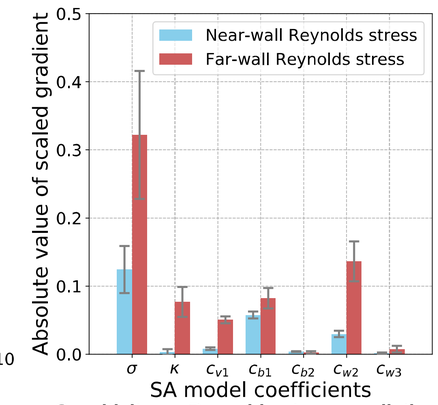
Reynolds stress distribution (backstep)



Sensitivity on Reynolds stress prediction (backstep)



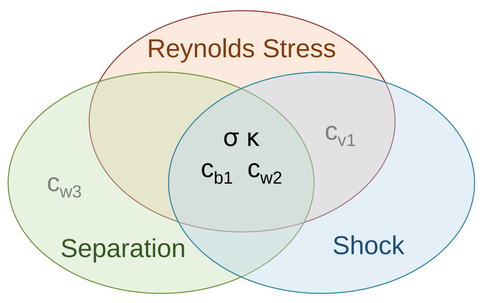
Reynolds stress distribution (bump)



Sensitivity on Reynolds stress prediction (bump)

Conclusion

- The SA model fails to reproduce shock, separation and Reynolds stress, thus inducing uncertainties on compressor stall prediction.
- σ, κ, c_{b1} and c_{w2} are most influential on compressor flow features. Physics-informed modifications on these terms are recommended in future research.



Summary of sensitive coefficients

Acknowledgement

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