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The First Jet Pilots

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Many in the turbojet community are probably not familiar with the names of two individuals who were key to the very first jet engine powered flights. They were the test pilots: Germany's Erich Karl Warsitz (1906-1983) and England's Phillip Edward Gerald (Gerry) Sayer (1905-1942)

In the December 2023/January 2024 issue of this column [1], I briefly reviewed these two historic flights: On Sunday morning, August 27, 1939, test pilot Erich Warsitz took off in the single jet-engine Heinkel He 178 from the Heinkel Airfield in Rostock-Marieneke, Germany on its maiden flight over shores of the Baltic Sea. It was powered by Hans von Ohain's aviation 1,000-pound thrust (lbt) gas turbine, He S 3B, the very first flying turbojet. Twenty months later, on May 15, 1941, at RAF Cranwell, England, Frank Whittle's W. 1, 900 lbt jet engine powered the maiden flight of the first British turbojet aircraft, a Gloster E.28/39. Test pilot Gerry Sayer flew it for 17 minutes, at over 500 mph (800 km/h) in level flight, greatly exceeding then current propellor driven fight speeds.

This duality of independent turbojet inventions has been recognized as a rather unique technological happening. Both Whittle (1907-1996) and von Ohain (1911-1998) had independently conceived the idea of the jet engine, as university graduate students in the early 1930s, Whittle (as an RAF officer on-leave) at England's Cambridge and von Ohain at Germany's Göttingen.

In response to this earlier column [1], Frank Whittle's son, Ian Whittle, now a retired commercial pilot in the UK, emailed me (subsequently now published as a letter-to-the-editor [2]) to add new facts and observations to what I had reported on these dual maiden jet engine flights.

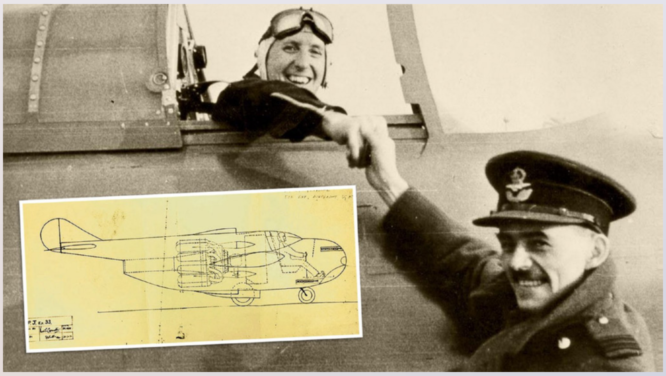

Figure 1. "Frank Whittle and the test pilot Gerry Sayer and, inset, Whittle's 1938 design."

As a pilot himself (of Boeing 747s and other aircraft), what his email mentioned about test pilots Warsitz and Sayer and their first jet flights was fascinating and new to me. For instance, from [2]: "The first flight of the Gloster E28/39, powered by the Whittle engine, was accomplished nearly 20 months after Erich Warsitz's adventures flying the He 178. However, the difference between the two achievements was considerable.

The E28 was powered by a pilot-friendly engine that had undergone 25 hours of stringent testing before installation into the airframe. It was then cleared for no less than 10 hours of flight-tests before an inspection was deemed advisable. Powered by the Ohain engine, the He 178 was good for {only} six minutes at flight-thrust."

TEST PILOT GERRY SAYER

Gerry Sayer, born in Colchester, England in 1905 as the only son of RAF Wing Commander E.J. Sayer, joined the Royal Air Force in 1924. After demonstrating great skills in handling a variety of aircraft, he became a test pilot in 1929. In 1934 Sayer was appointed chief test pilot for the Gloster Aircraft Company. Gloster, acquired by Hawker Aircraft in 1934, subsequently produced many of the British Hurricanes and Typhoons for WWII operations.

Through mutual RAF connections, Sayer had known Whittle for many years. During Sayer's Gloster E.28 May 15, 1941, first jet engine take-off, one observer commented to Whittle, "Frank, it flies!". In the heat of the moment, Whittle's curt response was: "Well, that was what it was bloody-well designed to do, wasn't it?" [3]. Some days later in May 21, Sayer piloted the E.28 on a demonstration flight for RAF officials, pulling up into a steep climbing turn, shooting skyward...with what was for them, producing the new strange whistling roar of Whittle's propellerless jet engine.

Less than 17 months later, Gerry Sayer's test pilot career ended. On October 21, 1942, Sayer departed the RAF Acklington Station in a Typhoon to carry out tests on a gunsight involving gun firing into Druridge Bay Ranges, in the North Sea. He was accompanied by another Typhoon. Neither aircraft returned, and it was assumed that they collided over the bay. Sayer, England's first jet pilot, was then 37 years old.

TEST PILOT ERICH WARSITZ

Erich Warsitz, born in Hattingen in the Ruhr, Germany in 1906, was the son of Robert Warsitz, an engineer in industrial furnace design and who later formed a family-owned manufacturing facility in Berlin. During Germany's interwar period, the Treaty of Versailles banned it from having an air force. Warsitz developed an early passion for flying[4] and thus trained to become a pilot in civil aviation schools. In due course he advanced to become a flight instructor, a training leader and then a company test pilot.

By 1936, at age 30, Warsitz was recognized as one of the most experienced German test pilots of the time and was known to have an extraordinary level of aircraft and flight knowledge [5]. With the Nazi Third Reich in power since 1933, Warsitz was selected in late 1936 by the Air Ministry (Reichsluftfahrtministerium—RLM) to work with rocket expert Wernher von Braun (1912-1977) and pioneer aircraft designer and manufacturer, Ernst Heinkel (1888-1958). The RLM had awarded Heinkel a contract to build the world's first pure rocket aircraft, the Heinkel He 176.

The maiden flight of the He 176 took place at Peenemünde, Germany's rocket and missile center on June 30, 1939. Warsitz, now with the RLM rank of flight captain (Flugkapitän), piloted the He 176 with flight speeds up to 600 kmph (497 mph), powered by its 600 kgt (1323 lbt) rocket engine. The He 176 had a narrow cockpit fitted around Warsitz, who sat on a parachute in probably the first aircraft ejection seat. (A few days later, on July 3, he tempted rocket engine explosion fate again, by piloting a short demonstration flight, arranged for Führer Adolf Hitler.)

As I noted at the beginning of this article, Warsitz piloted the maiden flight of Heinkel's He 178, powered by Han von Ohain's jet engine at the Heinkel Airfield on August 27, 1939, just a month after his He 176 rocket engine flights. As I reported in [1], at a 1990 IGTI conference Dr. von Ohain related to me some details of this very first jet engine flight. He recalled that Erich Warsitz arrived in flight gear, carrying a hammer. He 178 did not have an ejection seat (as did He 176). Warsitz informed von Ohain he would use the hammer as an escape tool, in the event he needed to get out of the He 178 cockpit in a hurry! As detailed in [4], the He 178 maiden flight (and others to follow) was a success, so Warsitz had no need to use his hammer!

On September 1, 1939, some five days after the historic He 178 jet flight, Germany invaded Poland, starting WWII. As the war commenced, Warsitz continued as chief test pilot at Peenemünde, and instructed bomber squadrons in the use of rocket boosters, that had been developed by Wernher von Braun. During a test flight on a Messerschmitt 109 in 1942, he had an accident that ended his career as a test pilot (by coincidence, the same year that Gerry Sayer had his ended).

Figure 2. Jacket cover [4] of son Lutz Warsitz's account of his father's test pilot life.

Warsitz then took over managing the family business in Berlin. After the end of the war, he was living in an apartment in the Berlin's American Sector. On December 5/6, 1945, he was abducted by four Soviet officers. After refusing to cooperate with the Russians on technology issues, he was transported to Siberia to a penal colony. Finally, five years later in 1960, the West German Government was able to arrange for his return to Germany. Erich Warsitz subsequently moved to Lugano, Switzerland. There, on July 12, 1983, he died at age 76, ending a remarkable career as a test pilot and as Germany's first jet pilot. ◆

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Performance Improvement of Micro Turbine Engine with Additive Manufacturing Technology

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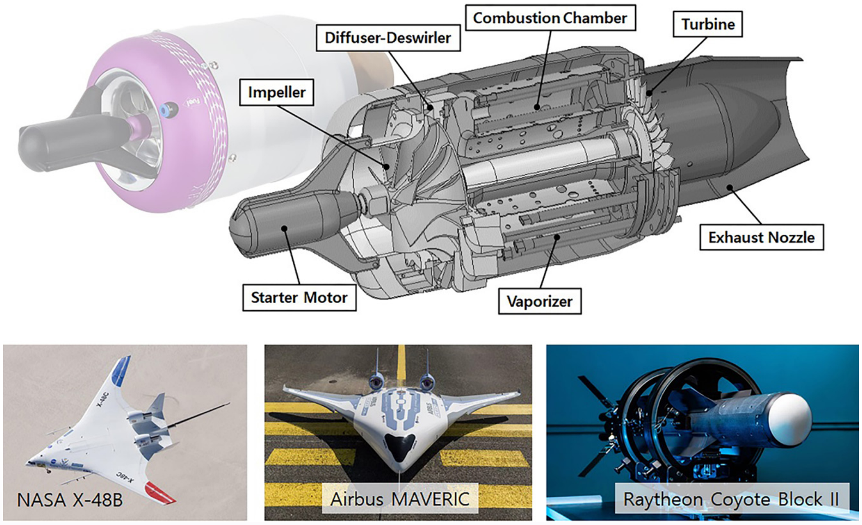

Figure 1. Micro gas turbine engine structure [1] and various types of unmanned aerial systems with micro turbines (turbojet engines) [2-4].

Micro gas turbine engines, characterized by their structurally simple design [1] (as shown in Figure 1) and relatively low cost, have been widely used for the propulsion system of unmanned aerial systems (UAS). Recently, there has been a significant increase in demand for various civil and military applications such as unmanned leisure radio-controlled planes, subscale flight test vehicles [2,3], target drones, surveillance drones, counter UAS [4], manned flying vehicles, and more.

However, it also faces several technical issues such as high fuel consumption and limited operating time due to the low performance of its components. Therefore, several practical research studies have been conducted on the development and performance improvement of micro gas turbine engines. Fuchs et al. [5] conducted a study on combustion efficiency improvement and suggested a novel design for the injection system. Buerger [6] studied compressor performance improvement for micro gas turbine applications and presented a 'crossover' diffuser, which enables significant performance improvement not only in the compressor but also in the entire engine system. Bohan and Polanka [7] conducted an experimental analysis of an ultra-compact combustor (UCC) for a micro turbojet engine, Jetcat P90-RXi and achieved 33% reduction in length while maintaining comparable engine performance. Cosentino and Murray [8] presented their miniature turbofan engine research using an off-the-shelf turboshaft engine for their Blended Wing-Body demonstrator application and obtained a 44% reduction in specific fuel consumption.

Design revision and modification have very huge impact on performance improvement of micro gas turbines due to their simple structural configuration and 'low level' performance, which makes the micro turbine very suitable system for performance improvement research with novel technologies including 'Additive Manufacturing Technology'.

Since 2016, Korea Aerospace Research Institute (KARI) has been conducting studies on micro turbine performance improvement using additive manufacturing technology. The micro gas turbine engine used in this research was the JetCat P300-RX, which has a maximum thrust of 300 N. All the metal components were additively manufactured and inspected as presented in Fig. 2, to explore the potential and limitations of AM parts. Since the dimensional tolerance of additive manufacturing is not as good as subtractive manufacturing, key parts, including impeller, diffuser-deswirler and turbine rotor, should initially be additively manufactured as 'near-net shape' and subsequently must undergo precision machining to meet the stringent tolerance requirements.

Then a set of performance tests and evaluations of micro turbine engine was conducted at KARI Altitude Engine Test Facility (AETF). For the engine with AM components, approximately 45% of the components were replaced with AM components. As shown in Fig. 2, the performance of the engine with AM components is quite comparable to the baseline engine.

Following the validation of the AM components' functionality, the component performance improvement research was conducted. The primary focus of this research was on improving combustion efficiency in the micro turbine. Generally, combustion efficiency in micro turbine ranges from 90 to 93%, which is a very low value compared to the conventional gas turbine engines. In addition, the combustion chamber has a dozen vaporizer tubes, which can increase manufacturing time and cost. Through the application of additive manufacturing technology, part consolidation and performance improvement were achieved at the same time. A vaporizer, originally consisting of more than 12 parts, can be manufactured as a single-piece component, and combustion efficiency of 99% or higher was achieved after adopting the advanced vaporizer design as presented in Fig. 3. The advanced model has vaporizer tubes with an angled elliptical exit, which can promote turbulence and swirl flow inside the combustion chamber. It features micro grooves inside the tube to increase the wetted area and enhance fuel evaporation. Those design features are difficult to realize using conventional manufacturing techniques. Additionally, research on weight reduction and performance enhancement of micro turbine engine components has been conducted based on additive

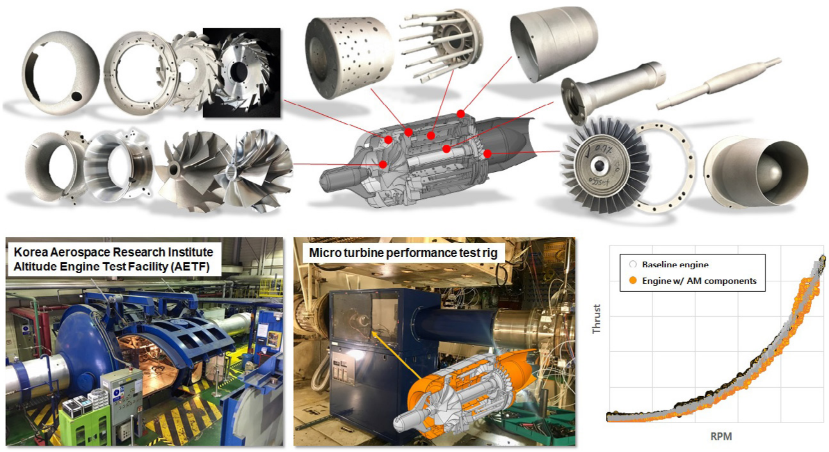

Figure 2. Additively manufactured components in micro gas turbine engine and performance test with AM components at KARI Altitude Engine Test Facility.

manufacturing technology. Using the topology optimization method, the weight of the impeller was reduced by up to 28.9%, while the stress level remains almost unchanged and the pressure loss of the exhaust nozzle is decreased by 4% with the design optimization method.

Recently, KARI has been focusing on various types of propulsion systems of UASs using micro turbines: turbofan engine based on micro turboprop (turboshaft) engine and sub-scale hybrid electric propulsion system using hydrogen fuel. In these studies, additive manufacturing technology has also been employed to realize the complex designs for performance improvement, including the design optimization of fan outlet guide vane (OGV) and combustor fuel flexibility. For example, implementing fan module with 3D shaped OGV onto the engine improves the thrust and specific fuel consumption (SFC) of the engine by 50% when compared with the turbojet engine.

As introduced above, additive manufacturing technology is a powerful tool for achieving performance improvement designs for micro turbine engines. However, there are also several challenging issues to be solved in AM technology. For example, reliability on mechanical property, manufacturing tolerance depending on component geometry, repeatability and so on. KARI conducted a parametric study on the manufacturing process of the Power Bed Fusion (PBF) method, examining variables such as laser power, scan speed, hatching distance, and layer thickness. In this study, mechanical properties such as tensile strength, low cycle fatigue (LCF), and creep were measured and compared across various parameters. The mechanical properties were improved, with significantly reduced standard deviation using optimized processing parameters. This indicates that, ironically, the processing parameters must be carefully selected and applied to AM components to ensure reliable properties. Paul et al. [9] summarized various factors to consider when adopting AM technology to the propulsion system. Therefore, as Thole and Fishbone mentioned in Ref [10], designers should move away from traditional design and manufacturing perspectives and pursue new design approaches and at the same time, they need to address and strive to improve the limitations of additive manufacturing technology. ◆

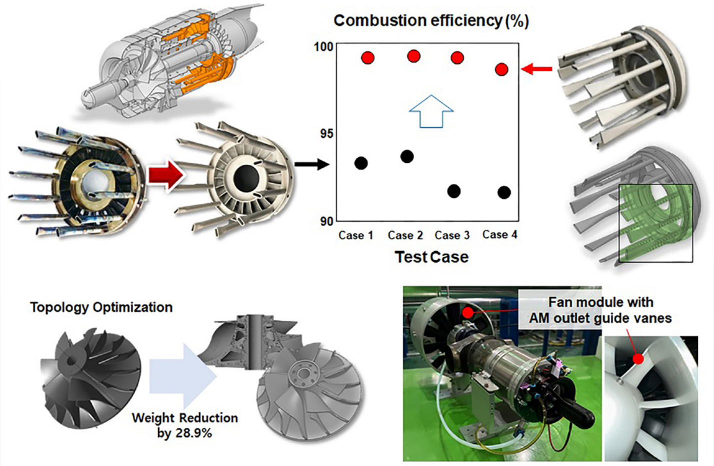

Figure 3. Examples of part consolidation and performance improvements for micro turbine engine using AM technology.

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Machine Learning in Computational Fluid Dynamics and its Implication on Turbomachinery

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INTRODUCTION

With the growing emphasis on energy efficiency and emission reductions, the turbomachinery industry faces the dual objective of improving performance and integrating renewable energy technologies. Computational Fluid Dynamics (CFD) remains a pivotal tool in the design and optimization processes of turbomachines, providing crucial insights into fluid flow dynamics essential for enhancing turbine efficiency and reliability.

While traditional CFD methods are powerful, they often face limitations in accurately simulating turbulent flows, particularly under real-world operating conditions. The advent of Machine Learning (ML) has emerged as a transformative force in this arena, offering innovative approaches to enhance turbulence modeling and expedite simulations. ML techniques, particularly those incorporating data-driven models, have begun to refine the predictive capabilities of CFD by harnessing datasets from both experimental rig tests and high-fidelity numerical simulations, leading to the development of cost-effective ML-augmented Reynolds-averaged Navier-Stokes (RANS) models [1, 2].

The subsequent integration of ML-augmented RANS models holds the potential to revolutionize turbine design processes by enabling more precise predictions of turbulent flows within and around the turbomachinery [3]. For example, in aircraft engine design, accurate turbulence modeling facilitates the optimization of blade shapes for maximum thrust and minimal fuel consumption. Similarly, in power generation, enhanced models contribute to the development of turbines capable of operating efficiently across various conditions, thereby supporting fluctuations in power demand and the integration of renewable energy sources.

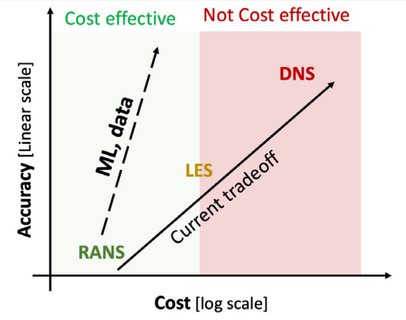

Figure 1. The graph illustrates the prevalent trade-off between accuracy and cost in computational fluid dynamics, as characterized by the use of DNS, LES, and RANS methods. Wall-modeled LES and hybrid RANS/LES currently offer feasible solutions for certain turbomachinery flows, with RANS typically serving as the foundational approach. The potential of ML lies in its ability to disrupt this established trade-off, aiming to deliver significantly enhanced accuracy for a slight increase in cost.

RECENT ADVANCEMENTS AND APPLICATIONS

A notable advancement in ML-augmented RANS modeling is the Field Inversion and Machine Learning (FIML) approach [4]. This method involves initially correcting turbulence models by aligning CFD simulation outputs with experimental data or high-fidelity simulations through methods like adjoint and Kalman filter. Subsequently, machine learning algorithms learn a correction formula applicable across different flow conditions.

Another critical development is the use of physics-informed neural networks (PINNs) [5], which help with RANS closure by incorporating data from high-fidelity simulations or other sources through data assimilation. Symbolic regression, particularly through gene expression programming (GEP), has also emerged as a powerful method for RANS modeling [6]. The method evolves analytical expressions that can effectively correct the Reynolds stress discrepancies in RANS models. Furthermore, the Sparse Regression of Reynolds Stress Anisotropy (SpaRTA) technique represents a significant leap forward [8]. It involves sparse regression to identify essential features that contribute to turbulence anisotropies.

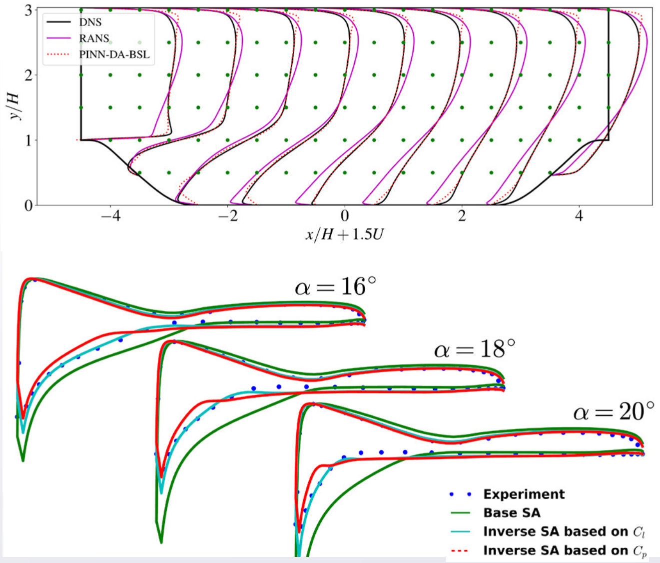

Figure 2a, 2b. Examples of ML-augmentations to conventional CFD. Top Panel: Mean streamwise velocity in periodic hill flow for DNS, RANS-SA, Var-DA-SA, and PINN-DA-SA. Here, SA stands for Spalart-Allmaras, and DA stands for data assimilation. The Var-DA-SA and PINN-DA-SA results are results of machine learned models. Figure adopted from figure 5 in Ref. [5]. Bottom panel: Surface pressure coefficient for S809 airfoil at various angles of attack. The inverse SA based on Cl and inverse SA based on Cp results are due to machine learned models. Figure adopted from figure 15 in Ref. [12].

CHALLENGES AND POTENTIAL SOLUTIONS

Despite the promise of ML-augmented RANS models, significant technical challenges persist in their practical application [8, 9].

A primary concern is the susceptibility of ML models, especially complex ones like deep neural networks, to overfitting. This characteristic is problematic in turbulence modeling, where operational conditions can vary extensively, necessitating models capable of generalizing effectively from limited training data to diverse and

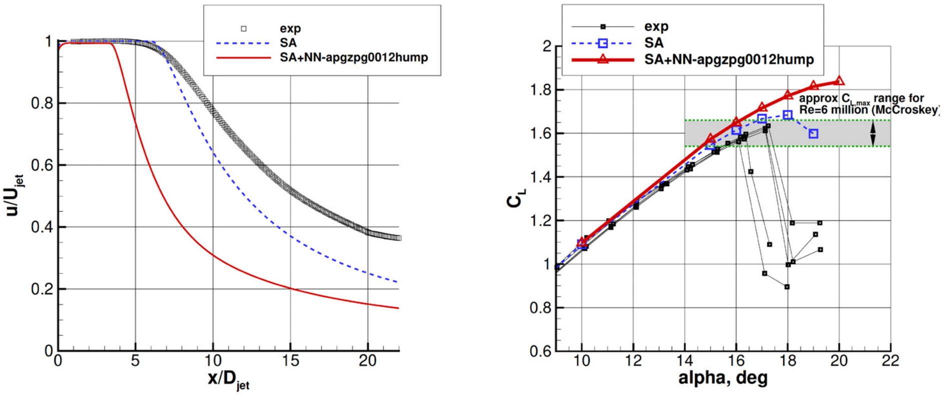

Figure 3a, 3b. Applying trained ML model outside the training dataset. Left panel: centerline velocity along the axis of a jet flow. Right panel: lift coefficient as a function of attack angle. Here, exp stands for experiment. SA is result due to the off-the-shelf Spalart-Allmaras model, SA+NN-apgzpg0012hump is result due to a machine learned model. Figure adopted from figure 16(c, e) in Ref. [8].

novel scenarios without extensive retraining. Further complicating matters is the integration of empirical knowledge: traditional turbulence models are crafted with a deep understanding of empirical insights, which are not automatically transferable to ML algorithms.

The “black box” nature of many ML models also poses challenges, particularly in fields like CFD where understanding underlying physics and causal relationships is crucial for trust and further development. High accuracy without interpretability can hinder the acceptance and utility of ML models, making it difficult to diagnose errors, understand model behavior, or derive insightful conclusions about the fluid dynamics involved.

A potential solution to the outlined challenges is the progressive modeling approach, also referred to as the “rubber-band” approach [10, 11]. This method complements the aforementioned ML methodologies that concentrate on how to apply ML augmentations and emphasize where ML augmentations are introduced. By employing a progressive ML strategy, a baseline RANS model is systematically calibrated against increasingly complex flows. This ensures each calibration builds upon the previous, preserving all prior adjustments and maintaining the model’s integrity across various flow conditions. Additionally, this approach allows for the utilization of any dataset introducing new flow physics, simplifying the interpretation of recalibrated models and making them more transparent and understandable for developers and users alike.

CONCLUSIONS

The integration of machine learning with computational fluid dynamics represents an emerging frontier in turbomachinery design, offering significant potential for advancements in efficiency and performance. However, despite promising developments in ML-augmented CFD models, fully realizing their potential, such as using ML-augmented tools for design optimization, remains on the horizon. Challenges such as data dependency, model generalization, and the need for transparent, interpretable results that align with empirical knowledge persist in current applications within the industry. Thus, while ML techniques hold the promise to revolutionize turbomachinery design by enhancing simulation accuracy and efficiency, practical implementation and acceptance in industry settings are still evolving. The journey towards fully leveraging ML in turbomachinery CFD is ongoing, requiring further research, development, and gradual adoption of these advanced technologies in everyday engineering practices. ◆

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