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The development of a Novel Hybrid Gas Turbine digital twin to predict performance deterioration

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Abstract

The potential of Digital Twins (DT) to forecast the behaviour of Gas Turbines (GT) and optimize their operations and useful components lives has become increasingly recognized. Cyber-Physical systems (CPS) and Big Data Analytics tools have enabled the Electric Power Research Institute's model to predict future performance trends and assist in power management decisions. This paper proposes a novel hybrid (physics-empirical) model to represent the thermodynamic and physical characteristics of gas turbines. The physics component replicates the geometrical designs of the compressor, combustor, and expander, while the empirical component contains GT historical degradation and operational data. The model utilizes thermodynamic relationships and correlations to accurately simulate the performance of the gas turbine and predict future deterioration effects. The proposed model is distinctive in its ability to accurately forecast the decrease in performance of the GT due to a particular degradation mechanism of a selected row (rotating or stationary), within a specified operating period. Our hybrid approach utilizes real-world data sets to provide accurate deterioration data, enabling better power planning and optimization of the gas turbine's useful life. Using this model, it is possible to perform cause-effect analysis, making it ideal for failure investigations and troubleshooting scenarios.

Keywords: Digital twins; Degradation; Deterioration Trends

1. Introduction

Gas Turbine (GT) based plants (mainly consisting in Gas Steam Combined Cycle plants, GSCC) are playing an important role in electric systems. Such plants are characterized by a quite good operational flexibility, a satisfactory maintainability, relatively low capital costs and really high efficiency, which altogether lead to a competitive electricity production cost (Cerri, Borghetti & Salvini, 2005).

Under the ongoing global energy transition, GT based plants are facing new modes of operation. In the recent past, it was common for operations to maintain a nearly constant high-level load for extended periods of time. The increasingly penetration of renewable energy sources (RES) contributes significantly to the reduction of CO2 emission and to the sustainability of the overall energy system (Bossman, Barberi & Fournié, 2018). Conversely, the intermittency and the uncertainty in predicting RES availability pose relevant issues in the management of electric grids. The production of RES (particularly wind and solar) is inherently independent from the electricity demand. As a result, in order to reliably meet the load requirements over time, the production from thermo-electric and hydro plants has to be scheduled accordingly. Therefore, reliable fossil fuelpowered generating plants, such as GT based ones, are required to quickly provide flexible back-up and/or reserve power. This new operation mode implies huge and fast load variations, more frequent peak and reduced load operations and a large number of start-up and shut down (Salvini, 2018; Farhat & Salvini 2022).

Such an operation modes lead to the accelerated progression of various deterioration phenomena which typically occur inside a GT (creep, fatigue, erosion, fouling and so on). These phenomena have a profound impact on both the lifespan of gas turbine components and their performance levels (output power and efficiency). In relation to the latter point, the mentioned phenomena result in the alteration of the shape and quality of surfaces in contact with the working fluid (i.e. the compressor and expander moving and stationary blades). Consequently, the performance of the gas turbine is adversely affected in terms of its ability to exchange work, process mass flow and extent of energy dissipation phenomena.

The application of Digital Twins (DT) to GTs has the potential to revolutionize how these systems are monitored and maintained. By applying DT, such as demonstrated in (Lim et al 2021), operators can continually assess the system's performance and address any potential issues before they arise (e.g. diagnosis and prognosis). Furthermore, DT can be used to accurately forecast the future degradation of GT components and performance.

The methodology proposed here has been developed by the Fluid Machinery and Conversion Energy Research Group of Roma Tre University (Cerri, Borghetti & Salvini, 2005, 2006a and 2006b; Cerri et al 2011; Cerri, Mazzoni & Salvini 2013; Giovannelli, Tamasi & Salvini, 2019). The GT model is based on a modular approach, each module representing a GT plant component. Each component module contains suitable deterioration coefficients which allow the component model to reproduce the actual component behavior in terms of work exchange, energy losses and effective flow functions.

The modular methodology makes use of demonstrated GT models and historical data. The latter are characterised and analysed for possible correlations between the deterioration coefficients and physical changes, and in terms of GT operating history (number of hours, starts, etc.).

The structure of this paper is as follows. Chapter 2 provides a comprehensive overview of the current state of the art regarding DTs, with specific emphasis on their applications in the industry and energy sectors. Chapter 3 (Material and Methods) elaborates on the detailed methodology proposed for developing DT models of gas turbines. In Chapter 4, several application cases are presented and discussed. Lastly, Chapter 5 summarizes the main conclusions drawn from the research work.

2. State of the art

The current state of literature on DTs has been thoroughly examined, with a focus on their integration in the energy sector and decision making processes. Notable works such as by (Yu et al 2022; Granacher et al 2022) have been reviewed to gain insights into the application and benefits of digital twins. (Yu et al 2022) provide a comprehensive description of digital twins, including a brief historical overview tracing their evolution since their inception in 1970. They specifically highlight the most prominent areas of digital twin research, prioritizing manufacturing processes, buildings and energy. The review emphasizes the urgent need for further research and practical applications of DTs, particularly within the manufacturing and energy industries. The aim is to optimize energy efficiency, facilitate decarbonization, and effectively address the challenges associated with scaling and covering the entire life cycle of assets.

(Granacher et al 2022) conducted research on the integration of digital twins in the superstructure optimization process. Their findings demonstrate that integrating digital twins significantly enhance the decision-making process. By considering the preferences and needs of decision makers throughout the solution synthesis and exploration, meaningful solutions can be generated for complex engineering applications. (Granacher et al 2022) introduce a digital twin framework specifically designed for process and energy system design. This framework translates the needs and preferences of decision makers into an optimization-based model, facilitating the generation of meaningful solutions. To demonstrate its effectiveness, the method is applied to integrate biorefinery concepts into a typical Kraft pulp mill. Multiple solutions are successfully derived, aligning with the decision maker's preferences and showcasing different system configurations. This showcases the capacity of digital twins to enable strategic solution generation and holistic exploration of complex optimization problems

(Hickey, Gachon & Cosgrove, 2022) researched the application of digital twins in process and project management. They highlight the potential benefits of utilizing digital twin technology in these domains, such as enhancing project management, improving communication, and optimizing processes. The authors provide an example of an ongoing plating line project that has shown promising initial progress.

(Cimino, Gnoni, Longo & La Rosa, 2022) propose a methodology based on digital twins to support effective design of industrial production lines. They emphasize guidelines that offer insights into how various design parameters impact production line performance. The authors provide recommendations for maximizing productivity and utilization while taking into account factors such as the number of operators and raw material metal sheets. Additionally, the authors propose classifying DT based on different integration levels. Four levels are identified in the smart energy application field: low carbon city, smart grid, electrified transportation, and advanced energy storage system. Each level is explained using literature examples to illustrate their practical implications.

GT performance assessment is of great importance to optimize operations and support decisions concerning maintenance interventions. The need of a reliable health assessment, for obvious reasons, was especially felt for GTs used for aircraft propulsion. Indeed, the first applications were oriented to the aero-engine field. (Urban, 1973) firstly proposed a method based on a linear Gas Path Analysis (GPA) for fault diagnosis purposes. Since that time, non-linear and adaptive GPA method have been proposed (Volponi 2014; Aretakis, Mathioudakis & Stamatis, 2003).

In the recent years, many concepts of DT have been introduced to assess GT performance and for fault detection (Xie et al 2021). (Kraft & Kuntzagk 2017) proposed a top-down approach to build a multilevel DT from component level to the entire GT system. A high-fidelity multi-physics DT model has been proposed by (Krishnababu, Valero & Wells, 2021). The model includes Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM) to evaluate in service performance deterioration and to estimate the impact of maintenance interventions. (Zaccaria, Stenfelt & Aslanidou, 2018) chose an adaptive physic-based model to establish the DT of aircraft engines. The abovementioned researches indicate that high-fidelity physical models are required to ensure adequate levels of precision, as highlighted by (Sun et al 2023).

In summary, researchers emphasize the definition and application of DTs in the energy field, with a specific emphasis on power-related systems. Despite the optimistic prospects and broad applicability of DT, several challenges persist that require comprehensive research for resolution. The primary challenges revolve around data collection and processing, real-time computing capabilities, storage capacity, and limitations in the existing DT models. Specifically, there is a lack of feedback and updates in the management of functional logical components, which inhibits the consideration of dynamic operational processes and product life prediction beyond the manufacturing & operational phases. Giving due attention to extending product life and managing product health is essential, but the current DT models primarily focus on the operational phase, leaving gaps in the production and reuse phases. Rectifying these challenges necessitates further investigation and development efforts.

The modified physics-empirical model discussed in this paper, provides the possibility to perform a differentiation analysis to isolate the single effect of a particular degradation mechanism. This is in addition to predicting the GT deterioration using health parameters and/or deterioration parameters, giving the possibility to model losses in the rotating and stationary stages separately. There are two main contributions of the proposed model with respect to the state of the art DT models in the respective research. First, it enables the simulation of the stage-by-stage (or row-by-row) degradation which could occur in the gas turbine. This capability provides critical information regarding the performance of the gas turbine and facilitates decision-making concerning maintenance topics. The second main contribution is the correlation of the physical changes such as tip clearances , airfoil geometry and effective flow area to performance. While researchers such as in (Kurz et al 2008; Burnes & Kurz 2018) detailed the implication of compression and expander degradation, their work revolved around analyzing the implication of the deterioration in the component efficiencies on the GT performance, rather than the individual degradation mechanism.

3. Materials and Methods

The proposed approach constitutes a systematic methodology for the development of digital twin models for GTs. It is adaptable to different gas turbine designs, provided that there is an underlying physical model or detailed geometrical information available.

The approach can be split in two parts:

- Physics-based modeling;
- Empirical-based modeling (Historical data).

3.1. Physics-based modeling

The structure of physics-based GT models is shown in Fig. 1. The model (coded in FORTRAN language) enables the part-load simulation of a GT in the deteriorated condition. The approach follows a framework, each module representing a GT component (compressor, combustor, expander, cooling system, etc.) Each module incorporates governing equations derived from the principles of conservation of mass, momentum, and energy. Auxiliary equations are introduced to evaluate quantities required to fully describe phenomena occurring inside each GT component. Such quantities are, for example, effective flow areas, effective flow angles, blade profiles, incidence losses in moving and stationary blades, cooling effectiveness, combustion efficiency, pressure loss in combustion chamber, and so on. A mean line row by row approach has been adopted to model both the compressor and expander. Such an approach has been favored over the one based on compressor and expander performance maps, usually adopted to assess the effect of degradation phenomena on GT performance such as performed by (Kurz, Brun & Wollie, 2008). The adopted approach requires a higher computational effort, but allows a more detailed insight into the compression and expansion processes, because the model provides values of pressure and temperature at the inlet and at the exit of each compressor/expander row.

The first step of the modeling process is the implementation of a model capable of reproducing the GT behavior in absence of deterioration phenomena, i.e. in New&Clean (N&C) condition.

If the geometrical details and empirical relations characterizing each component were known, the model would represent correctly all the thermo-fluid dynamic phenomena occurring in the real component. However, when building a model, usually only partial sizes, shapes and correlations are available and, necessarily, unknown quantities involved in the process (i.e. work and heat exchange, losses, velocity distributions, etc.) are evaluated by using empirical correlations based on similarity concepts or assumed on the basis of current GT design practice.

As a consequence, the model response does not fit perfectly the real N&C GT behavior. To fully establish the N&C GT simulator, suitable coefficients are introduced to modify the correlations adopted to model processes occurring inside each plant component (heat and work transfer, entropy production, flow functions, etc.) to align the model’s output to the real machine performance.

Such coefficients are evaluated by solving a minimization problem whose objective function is a Mean Square Error (MSE) function, errors being the differences between real and calculated quantities, i.e. measured pressures and temperatures along the gas path, output power, fuel mass flow, etc. The real N&C quantities can be provided by the manufacturer or, alternatively, collected at acceptance tests. After the evaluation of the abovementioned coefficients, the model is capable of replicating the GT N&C behavior. It is interesting to note that, as the manufacture and the commissioning of the machine end with the acceptance test, the implementation of its DT requires a calibration operation carried out by using acceptance test data.

As mentioned earlier, the performance of a gas turbine (GT) gradually declines over time due to degradation phenomena such as fouling, corrosion, erosion of parts, and more. Essentially, the GT consists of various components (machines and apparatuses), and their performance undergoes continuous changes as a consequence of the progression of deterioration processes. Consequently, it is necessary to periodically reassess the actual behavior of GT components and adapt the GT model accordingly. Therefore, a set of coefficients has been introduced to allow the GT model to reproduce the actual deteriorated behaviors of main plant components with reference to:

- work exchange and heat transfer;
- dissipative phenomena related to internal friction and coupling between working fluid and surfaces;
- effective flow function modifications.

For each component or a part of it (e.g. a single compressor/expander moving or stationary blade row), an array of coefficients can be introduced. Such coefficients are evaluated by minimizing the MSE between measured and calculated data. Therefore, the number of coefficients that can be introduced depends on the number of available monitored data.

The values assumed by such coefficients can be taken as a measure of how much deterioration phenomena affect the performance of the particular GT component. Hence, they can be considered as "health parameters" since they provide insight into the deviation of the component's actual behavior from its N&C performance.

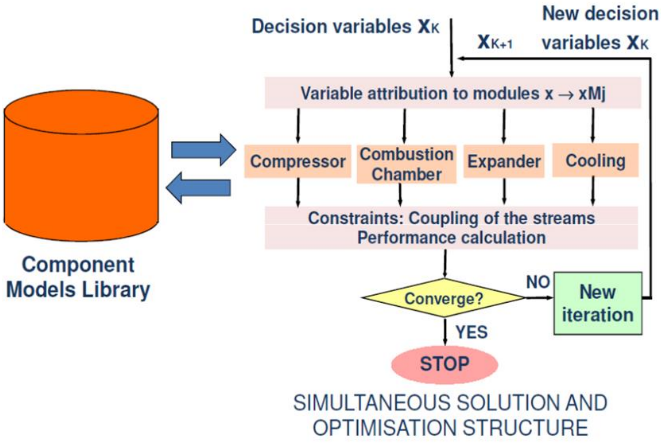

Figure 1. An Overview of the Roma TRE Modular approach. Taken from (Mazzoni, Chennaoui, & Giovannelli, 2014).

The validation of these physics-based codes has been extensively described in the works of (Cerri, Borghetti, & Salvini, 2005; Cerri, Chennaoui, Giovannelli & Salvini, 2011). Sensitivities studies have been demonstrated for the LM6000 and Ansaldo/Siemens 94.3 GTs, demonstrating capability of reproducing field data within 1% error.

3.2. Empirical-based modeling

The Empirical-based modeling comprises of a regression analysis, targeting the relationships within the degradation mechanisms and between them and the operational conditions/history (i.e. number of hours, starts, etc.). The use of correlations is not proposed as a substitute for the physics-based approach, it is intended to reinforce the quantitative predictions. Furthermore, the empirical approach allows for the normalization of the physical changes and GT health parameters, this is proposed to overcome one of the main challenges with the compatibility of existing systems and the need to have specific geometrical and operational data of each type of GT. The operational data limits, intervals and respective criteria have been detailed in (Farhat & Salvini, 2022a, 2022b). The authors detailed two popular methods used in the industry to calculate the inspection intervals and component lives including hour/starts based criterion and equivalent operating hours. The proposed approach contributes to the state-of-the-art prediction models in several ways:

- segregating hours vs. starts driven degradation mechanisms;
- performing a cause-effect analysis (degradation vs. performance);

- correlating changes in the physical features to health parameters.

The integration of historical data on gas turbine operations and degradation into the model plays a crucial role in capturing the behavior and performance of the gas turbine system. This historical data is collected from various sources, such as field measurements and observations, maintenance records, and operational information. To ensure consistency and comparability, the data is standardized to a common scale. This standardization process involves normalizing the data values to eliminate variations caused by different measurement units, ranges, or data formats.

Once the historical data is standardized, the regression analysis is performed to identify relationships between the operating variables (such as operating hours, load, type of fuel) and degradation effects (such as component deterioration and physical deviations). The regression analysis allows for the identification of patterns and correlations within the data, enabling the model to make precise predictions about the gas turbine's conditions and performance based on the given operating parameters.

By incorporating these techniques, the digital twin model can provide valuable insights into the current and future state of the gas turbine system. This information enables proactive maintenance strategies, allowing operators to identify potential issues or performance degradation in advance and take appropriate actions to mitigate them. It also facilitates optimization strategies by providing a means to evaluate and optimize the gas turbine's performance under different operating conditions or parameter settings.

Furthermore, the proposed DT model allows for the integration of empirical relationships concerning the GT performance. This means that not only the operational aspects but also the physical characteristics and behavior of the components are taken into account. This comprehensive representation of the gas turbine system allows for a more accurate simulation and prediction of its performance.

With sufficient computing capabilities, the digital twin model can be expanded into a real-time model. This means that the model can continuously update and adjust its predictions and recommendations based on the real-time data obtained from the operating gas turbine. This real-time capability enhances the model's responsiveness and its ability to support decision-making processes in dynamic operational environments.

In summary, by integrating historical data, applying regression analysis, and considering the modular components, the digital twin model of a gas turbine can accurately predict its conditions and performance. This capability enables proactive maintenance and optimization strategies, ultimately leading to improved operational efficiency and cost-effectiveness. The construction of the DT-GT model, as depicted in Figure 2, follows the main steps outlined in the methodology.

3.2.1. *Pre-processing and testing*

The data pre-processing and testing involves cleaning and preparing the measured data for use in the model. This includes characterizing and normalizing the data, eliminating outliers, data redundancy and transforming data into a format that is suitable for modelling. Testing is used to identify patterns in the data, in addition to addressing its accuracy and integrity. It involves running simulation tests and comparing the results to actual gas turbine performance. This provides important feedback and insight into the reliability of the data and trends.

3.2.2. *Normalization*

Normalization is performed to adjust the data values (from the prior step) to a common scale "physical change factor". This is done to make sure that data gathered from different types and classes of gas turbines is consistent and comparable. Nominalized predictive models, which gauge the relationship between deterioration factors (or actuality functions) and operational history, are developed as results. This allows for accurate predictions of components' conditions and gas turbine performance.

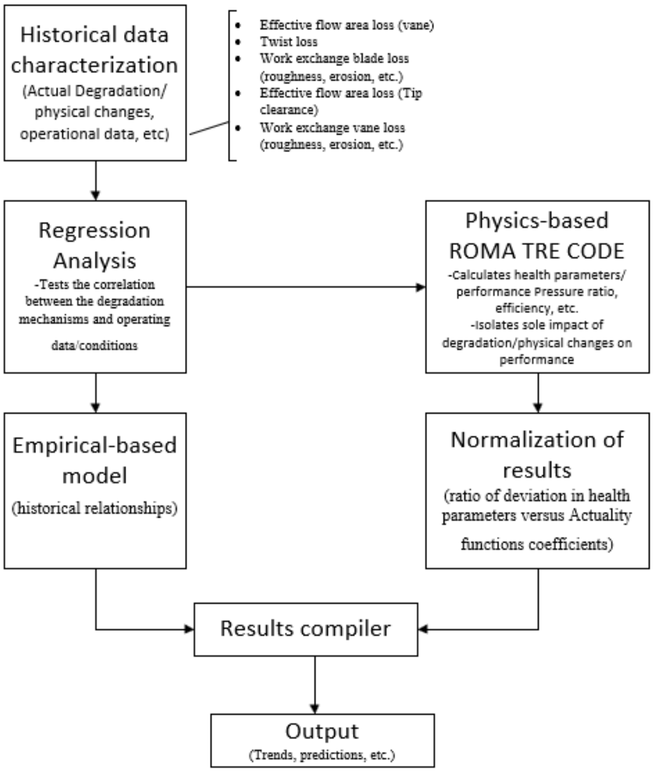

Figure 2. Digital model overview.

Finally, to take into account changes in characteristics such as filters efficiency, flow areas, twist angle, and blade losses, actuality functions must be calculated.

These functions represent the real condition of the various modules (i.e. compressor, expander, and so on). They quantify the degradation from a reference status (e.g. N&C status or after a major overhaul) by taking into consideration:

- frictional losses from roughness increase, cracking, coating surface deterioration, etc.;
- changes in the airfoil shapes such as deformation, erosion, twist, etc.;
- deviation in the effective flow areas caused by changes in the passages, tip clearances, concentricity, etc.

3.2.3. Regression Analysis

The regression analysis is performed using Minitab software. The ordinary least square regression method is applied to identify the relationship between the operating hours, starts, load, type of fuel, and deviations from the effective flow area, corrosion, erosion, and blade twist. By examining past observations, correlations between input variables (operating history) and output variables (degradation effects) can be determined and used to forecast trends in the effect of certain types of operations and/or aging components on the gas turbine's performance.

4. Results and Discussion

The results depicted in Figures 3 and 4 demonstrate the correlation weights between the historical data of different types of gas turbines and their respective operating regimes.

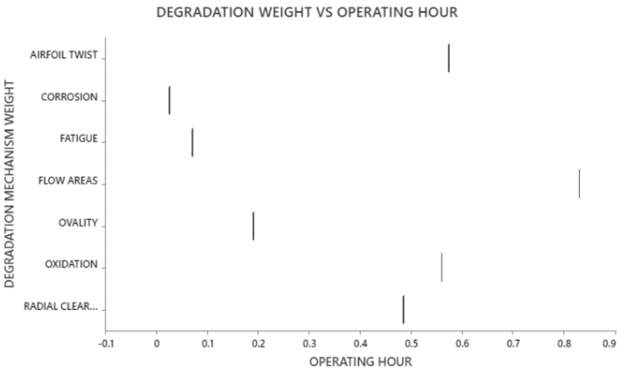

Figure 3. RA results- Degradation mechanisms weights by operating hours.

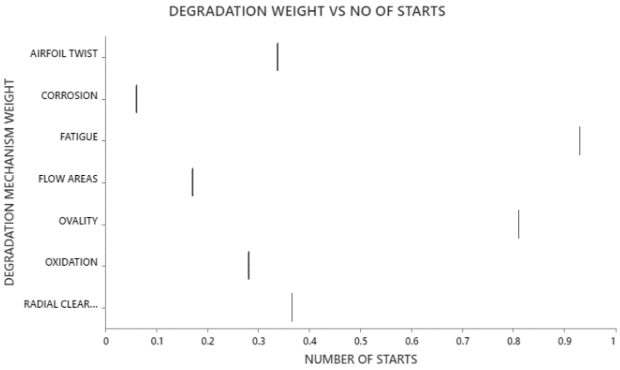

Figure 4. RA results- Degradation mechanisms weights by number of starts.

A regression analysis was conducted to examine the rate of deviation according to the number of hours (Figure 3) and/or starts (Figure 4). The airfoil twist, oxidation, radial clearances, and flow areas were the features/mechanisms most affected by the number of hours. However, ovality and fatigue were the components more significantly impacted by the number of starts. The correlation weights do not equal one because other factors, such as the type of protective coating and fuel type, can also influence the rate of degradation.

By leveraging prior results, it is possible to analyze the GT deterioration in terms of operating hours and number of starts. Figures 5 and 6 demonstrate the effects of three critical features (airfoil twist, vane effective flow areas, and blades' tip clearances) of the expander in terms of physical characteristics and corresponding performance change, respectively. As seen in Figure 5, the deviation in the effective flow areas over the operating intervals of 24K, 48K and 72K hours results in an inverse relationship with the pressure ratio, while increases in radial leakages and airfoil twist negatively affect the power output by circa 4%. This is due to reduction in flow areas (caused by accrued contaminants and corrosive elements) and rise in clearances and airfoil twist. To recover these losses, the turbine inlet temperature is increased by burning more fuel, leading to efficiency loss of circa 6.5%.

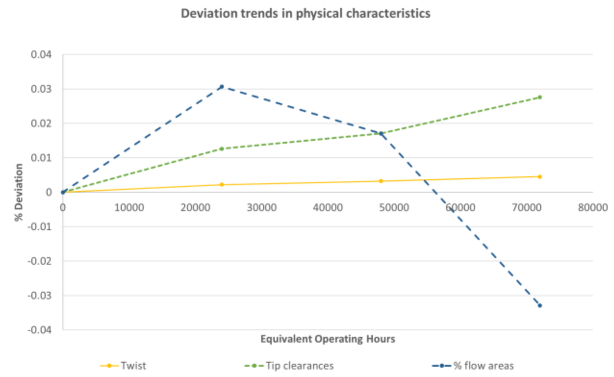

Figure 5. Deviation trends in physical characteristics.

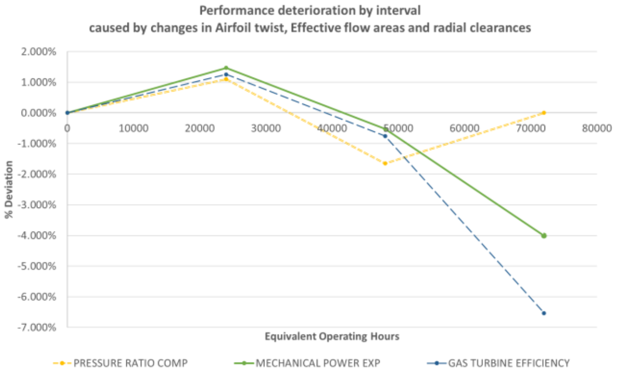

Figure 6. Deviation trends in GT performance.

The performance deterioration due to radial clearances, effective flow area, and airfoil twist is compared to the relevant literature of (Radtke & Dibelius 1980; Kurz et al 2008; Burnes & Kurz 2018). Radtke and Dibelius reported that a 0.5% and 0.4% reduction in blade height in the rotating and stationary rows, respectively, lead to a 0.6% drop in efficiency. Our model showed that a 0.5% decrease in blade height in the 1st stage rotating row causes a 0.5% decrease in efficiency. This difference can be attributed to the additional losses from the stationary clearances, which were not included in our case. (Kurz et al 2008) reported a 2.5% efficiency drop for a 1% overall component degradation. Finally, (Burnes & Kurz 2018) reported a power drop of around 9% and a heat rate increase of over 5% when using a more conservative approach. Their results compared the degradation at the 3rd interval to the clean condition.

5. Conclusions

This paper introduces a novel hybrid gas turbine model, combining physics-based and empirical approaches, to analyze the impact of degradation on GT performance across different operating intervals. This study presents the complete methodology in Section 3, marking its first application. The results demonstrate promising trends in GT deterioration over time, exhibiting strong alignment with pertinent literature in the field.

Research can be expanded to include other loss coefficients or degradation mechanisms such as surface roughness and oxidation. Additionally, the integration of emerging artificial intelligence (AI) tools presents an opportunity to reduce the reliance on the physics-based aspect of the model and expand its empirical components. This approach holds the potential to greatly enhance the model's versatility across various gas turbine designs and classes, improving its overall applicability.

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