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Impact of Gas Turbine Cyclic Operation on Engine Aging – An Investigation of the GT24/GT26 Fleet

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ABSTRACT

The increasing share of intermittent renewable sources in the power generation market increases the need for balancing technologies to maintain overall electricity grid stability. Gas turbines can technically provide such capability through their ability for fast start-up, shut-down, load changes and frequency response. However, such cycling operation increases the thermo-mechanical stress on the engine components, which is generally associated with increasing wear and tear. The engines may thus undergo more pronounced component aging that potentially affects engine reliability and emission behavior and ultimately increases maintenance efforts and costs. As previously shown for the GT24/GT26 with sequential combustion, aging has a direct impact on NOx and CO emissions and combustor pulsation behavior, and can be physically explained by mechanical deterioration of combustor hardware. In order to estimate the impact of flexible operation on engine aging and to optimize operational planning, the relation between these underlying aging phenomena and the operation regime must be understood. Using extensive operation data from GE's GT24/GT26 fleet (i.e. 25 engines with a cumulative 70+ years of operation), this paper investigates and quantifies the impact of flexible operation on key aging indicators of the gas turbine combustors. The frequency of starts is demonstrated as a meaningful indicator that relates the operation regime to the main aging phenomena.

INTRODUCTION

The changing market position of European gas turbines manifests itself in a decreasing number of yearly operating hours and an ever rising number of engine starts (Figure 1), caused by the increasing share of volatile renewable power generation [1].

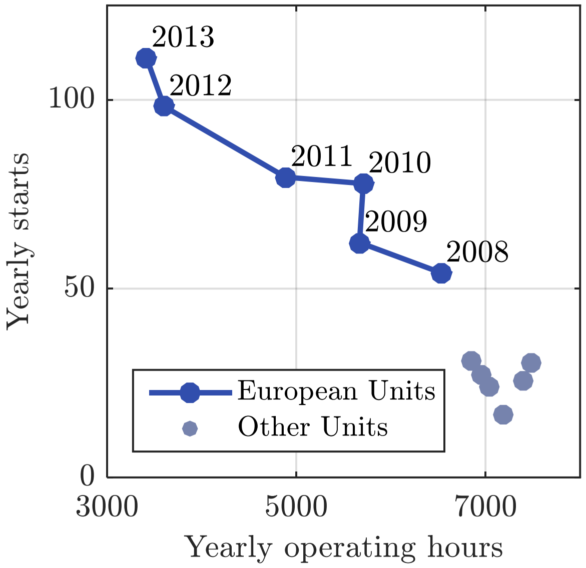

Figure 1: European and Non-European gas turbine units of the former Alstom GT24/GT26 fleet show different operation regime. Figure reproduced from [1].

Frequent engine starts in combination with a decreasing number of actual operating hours weaken the business case of gas turbine operators, as less electricity is produced during profitable operating hours. At the same time, the increasing number of engine starts leads to higher operational costs, because inspection intervals are shortened according to elapsed equivalent operating hours: Equivalent operating hours [2] typically do not only take into account actual operating hours of the engine but also account for the impact associated to, for example, load shedding, trips and start-ups,

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when lifetime consumption of noble parts is expected to be higher than during normal operation due to thermal stresses associated with these transient events. Once a threshold of equivalent operating hours (~ 30,000+ [3]) is reached, a complete inspection of the gas turbine and a replacement of highly loaded hot gas parts is performed. Responding to this increased market pressure on operation and maintenance costs, engine upgrades are often developed to enable an extension of this inspection cycle duration [4], which also underlines the economic importance of aging monitoring, diagnostics and, above all, its prevention. Relevant failure modes for the hot gas parts are for example High and Low Cycle Fatigue, creep, erosion and corrosion as reported by Immarigeon et al. [5] in aeroengines. Also for GT24/GT26 engines, analysis of field experience from inspections hints to increased wear phenomena and drift of operation points as a consequence of more cyclic operation [1].

According to Meher-Homji et al. [6] component degradation and their effect on gas turbine performance belong to unrecoverable degradation, which is one classification of degradation beside recoverable and permanent degradation. Unrecoverable degradation can only be repaired by a major overhaul, i.e. a costly replacement of the hot gas parts. Other non-recoverable degradation as stated in Meher-Homji et al. is for example flow path damage, surface erosion and corrosion leading to airfoil profile losses, tip and seal clearance increase and drift of control/calibration instrumentation.

The effect of bad instrumentation is also described by Gulen et al. [7], who highlights the impact of aging on the gas turbine control system by deviated turbine outlet temperature measurements. False turbine outlet temperature measurements are then identified as the root cause for unexpected power output changes. Beside power output, turbine outlet temperature measurement drift also results in undesired emission progression, which has been recently and thoroughly investigated by Lipperheide et al. for NOx [8] and CO [9] emissions of GT24/GT26 gas turbines with sequential combustion. Sequential combustion engines have a first combustor followed by a high pressure turbine (HPT) and a sequential second combustor with a low pressure turbine (LPT) downstream, thus multiple combinations of engine set parameters. For such engines, negative deviations in the high pressure turbine outlet temperature measurements have been found to lead to an increasing control bias of the firing temperature of the first combustor, eventually resulting in higher NOx emissions. Investigations on the CO emission have further substantiated this phenomenon by providing additional information about the increasing temperature measurement spread. Root causes of the measurement deviation were identified as actual cold gas break-ins lowering the mean temperature superimposed by marginal cold air streaks, which only influence the measurement itself. As a result, emission progression reduces the margin of a given combustor technology to strict emission limits and thus restricts maximum firing temperatures (NOx) and turndown capability (CO), which are a key factor for profitable gas turbine operation. The previous studies by Lipperheide et al. [8][9] on the aging phenomena and its impact on NOx and CO emission progression have been conducted for three GT24/GT26 engines only. The analyses of these selected engines featured enhanced data sets that have combined commissioning & long-term data with knowledge of operation concepts and service intervals, which made them suitable for the detailed investigations.

In order to expand the findings from the three engines to a larger fleet and to investigate the link between gas turbine operation and emission progression, the correlation between the previously established aging phenomena and the (cyclic) operation regime is evaluated in this study. This comprehensive investigation of an aging phenomenon and its occurrence throughout a larger fleet requires access to rarely available datasets for research including detailed engine information and fleet data. That also explains the lack of comparable studies in literature.

DATA

In total, 25 engines of GE’s GT24/GT26 fleet are examined in this study, yielding a data set of 70+ years of operation. This data set may thus serve to generalize the identified aging phenomena in the fleet.

METHODOLOGY

Since the limited number of three engines investigated in previous work was not sufficient to establish a distinct correlation between aging and operation regime (i.e. flexible vs. continuous operation), a broader statistical basis, i.e. a larger part of GE's GT24/GT26 fleet, is necessary. Within this fleet, different engines are operated in different markets, which results in significant variations of the operation regime. For example, base load engines run for a high number of operation hours but only a few starts per year, whereas cycling or peaking units feature daily start-stop cycles with a very limited amount of operation hours. The existence of different operation regimes within the fleet makes it possible to quantify the impact of flexible gas turbine operation on gas turbine aging: Starts are chosen as a measure for flexibility, as they increase thermo-mechanical stress in the engine and are already widely used in the calculation of equivalent operating hours in the industry. The drift of the high pressure turbine outlet temperature ($T_{\mathrm{HPT,out}}$) [8] is thereby considered a useful measure for gas turbine aging, as it directly results in undesired emission progression. This aging phenomenon is at least partially caused by increasing leakages and reliably detectable by the $T_{\mathrm{HPT,out}}$ - measurement drift (denoted ΔT_{HPT}).

Detection of temperature drift and inspection interval

Operation hours and starts are counted continually during the entire lifetime of the engine. Large inspections and maintenance after ~ 30,000 equivalent operation hours however re-establish the initial and unaged state of the engine. Since inspection intervals are not automatically recorded in the long-term operation data set, they yet must be identified from the data itself.

The according procedure is illustrated in Figure 2, which depicts the evolution of the investigated aging parameter, the turbine outlet temperature drift, over lifetime, and includes an inspection event in 2015 where the initial state is restored. The special architecture of the GT24/GT26 is used to evaluate that drift in turbine outlet temperature measurement in the presented research. Sequential turbine outlet temperature measurements allow for their quantitative comparison over lifetime during certain operation modes, neglecting aging effects for the low pressure turbine thermocouples, since they are not exposed to the same harsh environment as present at the high pressure turbine outlet. When the actually measured temperature difference $\Delta T_{HPT-LPT}$ is compared to its initial value $\Delta T_{t=0,HPT-LPT}$ the real high pressure turbine outlet temperature $T_{HPT,out,real}$ can periodically be recalculated during operation, as explained in [8], with;

$$T_{HPT,out,real} = T_{HPT,out} + \Delta T_{t=0,HPT-LPT} - \Delta T_{HPT-LPT} \quad [1]$$

The turbine outlet temperature measurement drift $\Delta T_{HPT,out}$ is then defined as:

$$\Delta T_{HPT} = T_{HPT,out,real} - T_{HPT,out} \quad [2]$$

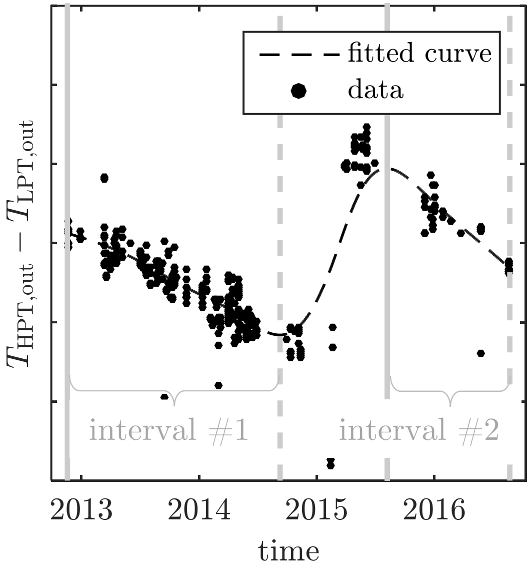

Figure 2: Detected temperature shift over service intervals

By means of a smoothed function (dashed line) of the (scattered) indicator for the measurement drift, peak values are identified and associated to the event of an inspection that re-establishes the initial state without aging. The entire data record time for each engine is thus divided into intervals from a maximum to a minimum, which correspond to one detected inspection interval each. For the entire interval, the $T_{HPT,out}$ measurement drift (ΔT_{HPT}) for this investigation can thus be calculated as the difference between the functional value of a maximum point to its corresponding value of the subsequent minimum point. This method however only provides one average value for the measurement drift over an entire inspection interval. Additional investigations show that some engines change their operation regime between seasons, so that intervals should be further subdivided. Though, available data quality and the temporal distribution of suitable sequential turbine outlet temperature measurements for drift detection did not allow for a more detailed resolution of such operational "subperiods" with sufficient precision.

Data set quality

Figure 3 depicts the distribution of the 25 engines according to their operation regime. Obviously, the fleet data set features independent variations of engine starts and operation time, which was explained to be necessary for this investigation. There are several engines with similar operation time between two inspections, but differing number of engine starts in that period. This distribution enables an isolated investigation of engine starts as a measure for the impact of flexible operation on aging. If starts and operation hours were strongly correlated, a clear identification of flexible operation on aging would not be possible, since aging could either be a function of operation hours or starts.

However, some of the investigated operation intervals lack of consistent and sufficiently frequent observations. The "density" of available data is quantified through a data record ratio, which is defined as ratio between the time span with an active data acquisition system and the total time period in the corresponding operation interval. Infrequent data logging makes the investigation less reliable, since parameters must be interpolated for the unrecorded time and the smoothing as shown in Figure 2 has to bridge large gaps. For very large gaps and insufficient data, the method might then even miss inspection intervals.

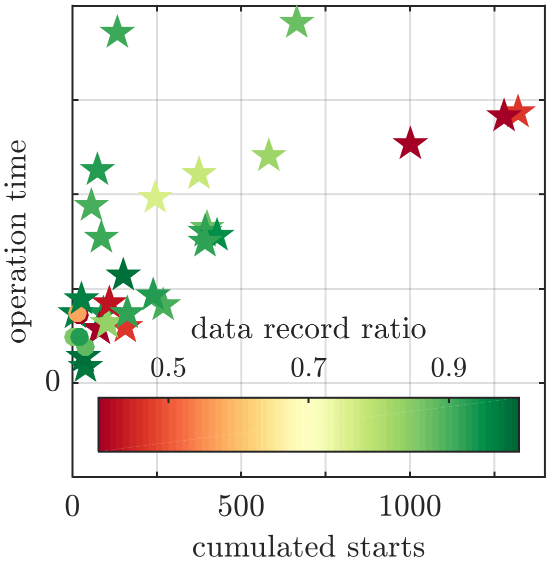

Figure 3: Fleet investigation on (partial) independence of starts and operating hours (Round points show insufficient total interval time or drift data points).

Thus, intervals with infrequent data records (data record ratio less than 50%), an unsatisfying amount of total temperature drift data, or a short total time period were discarded from the investigation. Additionally, intervals with a total detected temperature drift below a threshold, which is expected to be the accuracy of the detection method, are discarded from the investigation, so that 16 inspection intervals remained for further investigations (see Figure 4).

Although the cleaning of the data set removes some variance from the data set, the distribution of the remaining engines is still considered to be valid for the assessment (Figure 4).

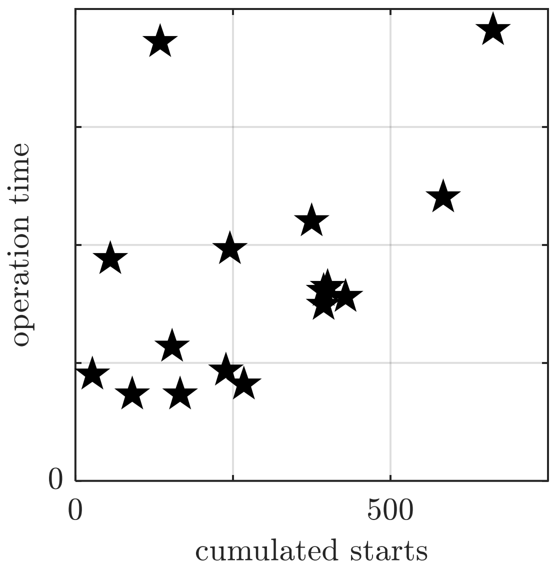

Figure 4: Remaining data points after filtering.

Indicator selection

In order to extract the desired information from the fleet data, the indicators used for evaluating flexible operation and aging (as displayed on the axis in the following figures) must be chosen wisely. Cumulated engine starts have been identified as an appropriate indicator for flexible operation, while aging is well represented by the $T_{\mathrm{HPT,out}}$-drift. Further, the indicator for lifetime, i.e. the operation hours as a third variable, must also be displayed to check for a spurious correlation. Since cumulated absolute starts and $T_{\mathrm{HPT,out}}$-drift are expected to increase with operation time, only an uncoupled variation of operation time and engine starts ensures an isolated identification of the aging impact by cyclic operation.

A normalization of aging phenomena to operation time would seem to be an obvious method to include lifetime as a third variable. Though, this normalization would unphysically overestimate the influence of inspection interval duration against the actual aging phenomenon by the reciprocal nature of the normalization.

RESULTS AND DISCUSSION

The aging parameter $T_{\mathrm{HPT,out}}$ -drift shows a clear correlation with the indicator for flexible operation (starts/day) for the investigated GT24/GT26 fleet data (see Figure 5). The remaining scattering as visible in Figure 5 was tested against other possible influence parameters as e.g. the average load level during operation, which showed no correlation. Also the operation time, indicated by the colorbar, is uncoupled from the correlation. As outlined above, this was intendend by the incorporation of elapsed operation time to the definition of the aging evalution parameter.

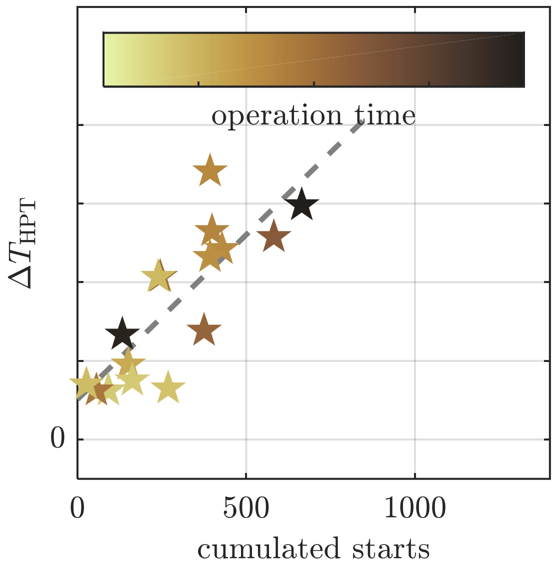

Figure 5: Operation time averaged HPT outlet measurement drift vs. engine starts per day of available data logging for selected data points.

As a comparsion, Figure 6 shows the exact same result for the entire available data set with results from insufficient data sets. Even though the scatter is increased and outliers are present, the general trend is kept with a notable uncertainty in the very cyclic operation region (starts per day >0.5). The spread of data points around zero, especially the negative temperature drift, is physically not meaningful but caused by the inaccuracy of the drift detection when data becomes scarce. The engines and their inspection periods with highly cyclic operation above 0.5 starts per day would definitely enrich the investigation as they provide more variance in the operation regime, but had to be handled as outliers due to their infrequent and thus unreliable data.

A similar study was also conducted with the second aging indicator for the EV combustor, which suffers from a decreasing combustor flow coefficient over lifetime. This combustor flow coefficient was extracted from fleet data for each inspection interval of the respective engine. After deleting irrelevant data and dismissing periods of infrequent data record, the data basis did however not allow for a further investigation, as operation hours and starts were correlated in the remaining data set.

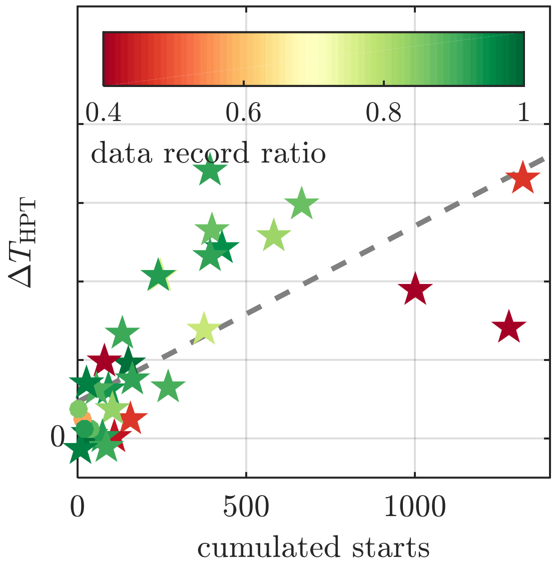

Figure 6: Operation time averaged HPT outlet measurement drift vs. engine starts per day of available data logging (Round points show insufficient total interval time or drift data points).

CONCLUSIONS

This paper has successfully linked an aging phenomenon that has been identified in earlier work [8] to the engines' operation regime by a systematic analysis of the GT24/GT26 gas turbine fleet. The fleet data set was shown to be suitable for the investigation since different engines feature various operation regimes, which decouple cumulated starts from elapsed operation hours. A drift in turbine outlet temperature measurement, which was previously shown to have sensible impact on emission progression, was used as an exemplary indicator for aging due to wear and tear. Its temporal evolution was determined from raw operational long-term data sets, which were subdivided into intervals by an automatic inspection detection algorithm. The detected aging progression was further referenced to operation time to account for the obvious effect of increasing aging with lifetime. The intensity of cyclic operation is meaningfully expressed by the cumulative number of starts. Results show a clear correlation between these two parameters with more pronounced aging when more starts occur. The so established link between a known aging mechanism [8] and the operation regime provides the possibility for a more accurate planning of future maintenance timing and scope, and thus for an improvement of asset reliability, availability and maintenance cost. At the same time, it can used to optimize the business case for plant operators by properly accounting for lifetime and maintenance cost impacts when defining the target operation profile.

NOMENCLATURE

$\Delta T_{\text{HPT-LPT}}$	Temperature difference between high pressure and low pressure turbine outlet
$\Delta T_{\text{t=0,HPT-LPT}}$	Initial temperature difference between high pressure and low pressure turbine outlet
ΔT_{HPT}	High pressure turbine outlet temperature drift
$T_{\text{HPT,out}}$	High pressure turbine outlet temperature (average of individual measurements)
$T_{\text{HPT,out,real}}$	Corrected high pressure turbine outlet temperature (considering detected error)
$T_{\text{LPT,out}}$	Low pressure turbine outlet temperature (average of individual measurements)

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REFERENCES

[1] P. Marx et al., "GT26 Operational experience under changing market condition V1.2," in Power-Gen Europe 2014.

[2] Gas turbines - procurement - Part 9: Reliability, availability, maintainability and safety, ISO 3977-9:1999(E), 1999.

[3] C. Lechner and J. Seume, Eds., Stationäre Gasturbinen, 2nd ed. Berlin: Springer, 2010.

[4] GE Power. [Online] Available: https://www.gepower.com/services/gas-turbines/upgrades/gt24-gt26-mxl2.

[5] J. P. Immarigeon, W. Beres, P. Au, A. Fahr, and W. Wallace, "Life cycle management strategies for aging engines," NATIONAL RESEARCH COUNCIL OF CANADA OTTAWA (ONTARIO) INST FOR AEROSPACE RESEARCH, 2003.

[6] C. B. Meher-Homji, M. Chaker, and H. Motiwalla, "Gas turbine performance deterioration," in Proceedings of the 30th Turbomachinery Symposium, 2001, pp. 17–20.

[7] S. C. Gulen, P. R. Griffin, and S. Paolucci, "Real-time on-line performance diagnostics of heavy-duty industrial gas turbines," in ASME Turbo Expo 2000: Power for Land, Sea, and Air, Munich, Germany, 2000.

[8] M. Lipperheide, F. Weidner, M. Gassner, S. Bernero, and M. Wirsum, "Long-term NOx behavior of heavy-duty gas turbines: An approach for model-based monitoring and diagnostics," in ASME Turbo Expo 2017.

[9] M. Lipperheide, F. Weidner, M. Wirsum, M. Gassner, and S. Bernero, "Alterungsinduzierte Emissionsprogression in Hochleistungsgasturbinen (Typ GT24/GT26)," in Kraftwerkstechnik 2017 : Strategien, Anlagentechnik und Betrieb / Technische Universität Dresden, Institut für Verfahrenstechnik und Umwelttechnik ; [Herausgeber:] Michael Beckmann, Antonio Hurtado, Freiberg: SAXONIA, 2017.