Degradation Effects on Marine Gas Turbines

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Abstract. This paper provides a discussion on how degradation develops and affects the performance of marine gas turbines. As the operation of a gas turbine is the result of the aerothermodynamic matching of several components, especially in the case of marine gas turbines that are multi-shaft engines, the emphasis of this paper is on the interaction of the engine components and the effect of several degradation phenomena on both performance and operability parameters. The model of a typical twin-shaft marine engine is subjected to various types of degradation, and the effect on operating parameters is studied. The focus is on three areas: How does component degradation impact the operation of the engine compressor, especially with respect to the surge margin, how does component degradation impact full load and part load gas turbine performance and operation, and how does component degradation impact measurable engine operating parameters in order to provide fault signatures, thus providing guidance for the practice of condition monitoring.

Keywords: marine gas turbine, component degradation, fouling, erosion, fault signatures
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INTRODUCTION

Marine gas turbines have been in service for more than three decades and have proved to be reliable and offer significant advantages to the user. Despite the well-proven reliability of these machines, their operation in the hostile marine environment results in the degradation of their performance characteristics. Several mechanisms result in engine degradation, such as fouling, erosion and tip clearance increase causing a change of the rotating components' operation and consequently a change of the whole engine operation. From operational, economic, and safety considerations, gas turbine performance deterioration has emerged as a very important topic of research. For the marine gas turbine user it is crucial to have the ability to identify the fault type, if it is recoverable or not, if it affects the engine's life cycle and to have a clear idea of the effect of the fault on the engine performance, namely power output and fuel consumption.

It is the aim of this paper to provide a throughout discussion of the effect of faults on the engine operation and specifically on the match of the components. At the same time fault classification and identification are essential information for the user, thus it is of interest to examine the deviation of the engine monitoring parameters with respect to the degradation phenomena and to the operating point. For this reason typical fault signatures are presented for different engine control variables in order to identify the most suitable measurements for specific faults identification and to examine the effect of the engine control variable on the fault signatures.

ENGINE MODEL

In order to have the ability to examine the operation of gas turbines of different configuration, under various operating conditions and control variables, a generic 0-D non-linear adaptive performance model is used. The model was developed by the research group of the LTT/NTUA. The model is capable of simulating all existing gas turbine configurations from a single shaft engine, to a three spool engine with power turbine, reheating, recuperation and water injection at various positions along the engine. Also as the control variable of different engines may be different, or even change throughout their operation the model is capable to acknowledge several parameters as control variables like Turbine Inlet Temperature (TIT), Compressor Discharge Pressure (CDP), Shaft Speed, Power output, etc. depending on the engine configuration. The model layout and the system of equations to be solved are modified in accordance with the engine configuration under consideration.

A schematic representation of the generic model and its break down scheme to individual components is shown in FIGURE 1. The components' operation is modeled via maps (e.g. turbomachinery component maps), via analytical relationships (e.g water/steam injection [1]) or a combination of analytical relationships including empirical constants (e.g. duct pressure loss).

The model utilizes the adaptive modeling technique, as introduced by the research group of the LTT/NTUA [2], which will be used in order to model the engine faults. The basic idea behind the adaptive modeling is that component characteristics (e.g compressor map) are allowed to change through the introduction of appropriate modification factors. The values of these factors in the case of adaptive modeling are determined by requiring that the available engine performance data are matched by the engine model results. In the end of the adaptive procedure a unique set of components characteristics is produced. The engine model incorporating this set is capable of simulating the specific engine operation with great accuracy (Tsalavoutas et al. [3]).

When diagnostic applications on an actual engine are considered, the modification factors are used as engine health indices as, for example, presented in [4], in order to identify faulty engine components. The use of the model as a diagnostic tool requires the creation of an accurate model of the healthy engine by means of adaptive modeling. The adaptive (or modification) factor for each component parameter is defined via eq.(1).

$$f = \frac{X_{act}}{X_{ref}} \tag{1}$$

Specifically, if a particular component parameter has a value X_{ref} on the reference map and a value X_{act} on the actual "engine" map, then the relation between the two can be expressed by means of the modification factor f. The value of this factor shows how strong is the deviation of a particular performance parameter with respect to its reference/nominal value.

Each rotating component (compressors and turbines) employs two modification factors, one related to pumping (or swallowing) capacity and the other related to efficiency. The swallowing capacity factor is:

$$f_{SWi} = \frac{\left(W \cdot \sqrt{T} / p\right)_{act}}{\left(W \cdot \sqrt{T} / p\right)_{ref}} \tag{2}$$

The efficiency factor is:

$$f_{SEi} = \frac{\eta_{act}}{\eta_{ref}} \tag{3}$$

It should be noted that, as discussed by Li et al. [5], a component pressure ratio modification factor can be utilized as well.

In the case of the combustion chamber, the modification factors correspond to the pressure losses and the combustion efficiency (see for example [1]). Pertaining to all modification factors the term i corresponds to a specific component of the selected engine configuration. For example in the case of a twin shaft arrangement and for the rotating turbomachinery factors i=1 corresponds to the compressor, i=2 to the gas generator turbine and i=3 to the power turbine.

A schematic representation of the generic engine configuration and its subdivision to individual components is shown in FIGURE 1.

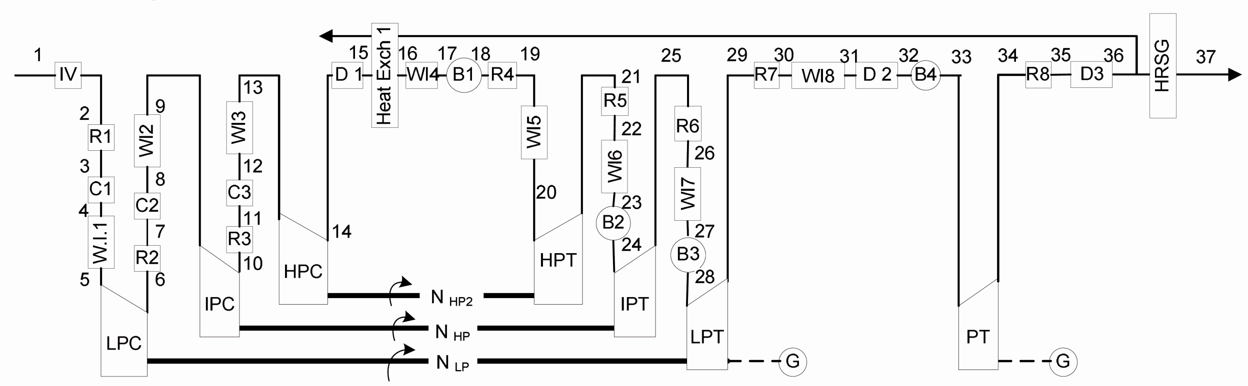


FIGURE 1. Schematic representation of a three spool gas turbine and its various components

The GE LM2500, an engine widely used for marine propulsion purpose, is selected as a test engine in order to simulate the degradation phenomena and their effect on engine performance and components operation. The engine model used is capable to reproduce the engine's operation with acceptable accuracy as discussed by Yfantis and Kapasakis [6]. The GE LM2500 is a twin shaft engine.

AIR FILTRATION SYSTEM

The filtration systems currently installed on the majority of the warships have the primary purpose of substantially reducing the levels of salt ingested in the Gas Turbine. The salt removal systems employed in the Navies today utilize either a two stage Coalescor/Vane removal philosophy, or a three stage approach which includes an additional vane separator/mist eliminator stage in front of the two stage system as discussed in [7]. Fouling of inlet filtration system occurs progressively over time, resulting to the increase of pressure drop in the inlet, thus deteriorating the engine performance. In FIGURE 2 the effect of inlet pressure loss on power and specific fuel consumption (sfc) is presented for the examined engine.

It is evident that the effect of inlet pressure drop can be rather significant, as for example an increase of inlet pressure depression from 10mbar to 30mbar will result to a power decrease of 3.2% and an increase of specific fuel consumption in the range of 1.23% for the case of the examined engine. According to these values it is evident that a strict schedule on filters cleaning/changing should be followed in order to achieve good operating conditions and fuel economy.

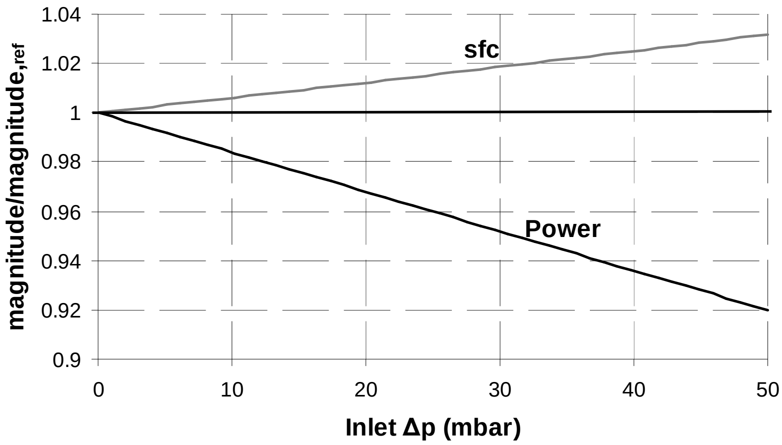


FIGURE 2. Impact of inlet pressure loss on engine power and specific fuel consumption (sfc)

DEGRADATION OF COMPONENTS

The faults are simulated by modifying the performance characteristics of the components from their “healthy” values, using the appropriate modification factors. The modified characteristics are used by the engine model and the deviations of the performance parameters are established. For example, setting the value of the swallowing capacity of the compressor 0.97 it represents a 3% reduction in compressor pumping capacity from the nominal (healthy) operation. To simulate the existence of a malfunction, modification factors with values different from unity will be used, based on experimental and numerical data from the literature.

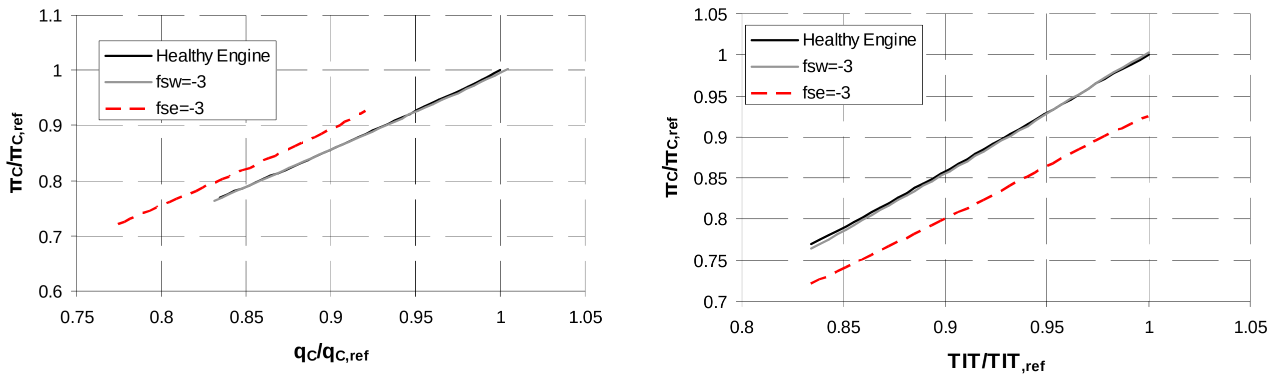
It must be noted that the impact of individual components degradation is influenced by the control system and the control modes of the engine. Specifically the effect of components degradations on a multi-shaft engine depends on the control mode they are in, namely if the shaft speed or the firing temperature is the limiting factor. Also in normal operation it is expected the limiting factor to change according to the operating envelope. For this reason the engine operation analysis will be done assuming the Turbine Inlet Temperature as the control parameter of the engine, while the shaft speed will be limited according to the value of the healthy engine case. It should be noted that in practice both the location of the measured control temperature and the measuring technique will influence the behavior of the engine in degraded conditions.

The degradation phenomena that will be examined concerns the rotating turbomachinery components, as the combustor efficiency is usually not significantly decreased during operation, except for severe cases of combustor distress. In the case of combustor faults usually scheduled boroscope inspections in combination with the monitoring of the exhaust gas temperature distribution allows the identification of a fault occurrence.

Compressor Degradation

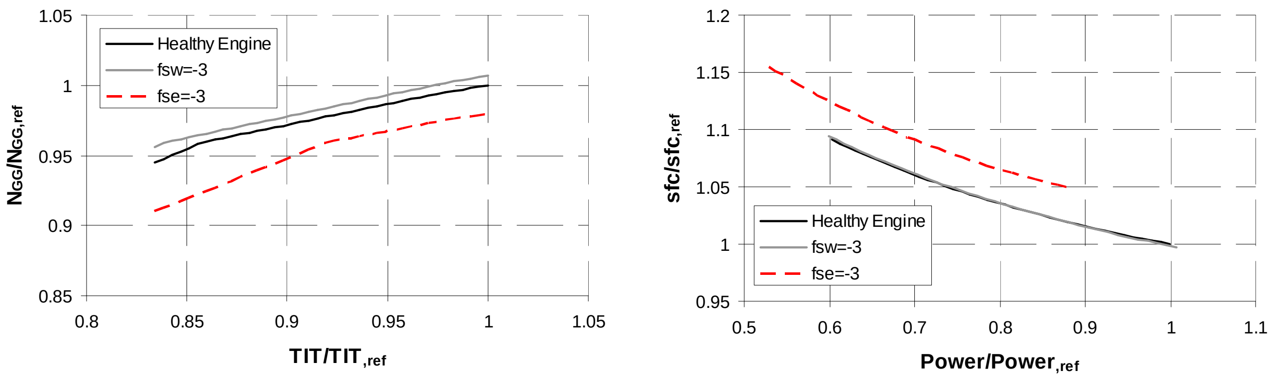
Compressor degradation is going to impact pressure ratio, efficiency and flow capacity, albeit the effect on these parameters is dependent of the degradation type as presented in [8]. Usually for the case of compressor the independent parameters that are used for diagnostic purposes or fault simulation are the compressor swallowing capacity and efficiency, assuming the shape of the compressor map unaltered. According to the recent work by Morini et al. [9], this assumption is valid for relative high rotational speeds. For this reason the analysis is limited to power setting down to 50% of the nominal one. In order to investigate the effect of compressor degradation on the engine and compressor operability the effect of these parameters are firstly investigated separately by imposing a 3% reduction on swallowing capacity and efficiency, independently. In this way general conclusions can be drawn in order to give general guidelines for condition monitoring practice. Then specific ratio between the swallowing capacity factor and efficiency factor are used in order to simulate specific compressor faults.

In FIGURE 3 the effect of reduced swallowing capacity and efficiency on the compressor operating line and engine pressure ratio is presented. It is evident that for the case of TIT as control parameter the effect of reduced swallowing capacity is rather small on the operating line. In reality as the downstream capacities remain unaltered the operating line remains the same and the compressor is working at higher rotational speeds, as seen in FIGURE 4 (a), in order to maintain the inlet mass flow and the pressure ratio. As a result the effect of decreased swallowing capacity on the engine performance is minimal as seen in FIGURE 4 (b) and depends on the compressor efficiency gradient across the map. For the case of efficiency reduction the operating line is shifting closer to surge line, while the net effect is a reduction in both pressure ratio and mass flow for the same firing temperature compared with the healthy engine, as seen in FIGURE 3. This behavior is the result of the increased power consumption by the compressor which leads to the decrease of the gas generator speed as seen in FIGURE 4 (a) and consequently of the mass flow. The efficiency reduction results in a significant degradation of the engine's performance as seen in FIGURE 4 (b), as the specific fuel consumption (sfc) is significantly increasing throughout the operation, while power output is diminishing.



(a) (b)

FIGURE 3. Impact of reduced swallowing capacity and efficiency on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter



(a) (b)

FIGURE 4. Impact of reduced swallowing capacity and efficiency on (a) the gas generator speed and (b) engine performance for TIT as the control parameter

In real operation overspeeding protection may occur, in order to maintain gas generator speed (N_{GG}) below a certain value. Assuming that the maximum gas generator speed of the healthy engine is the limiting control value, then for the case of swallowing capacity decrease the engine will have a limit at the maximum power output, as it is working in higher rotational speed. Consequently the user for the case of maximum continuous power setting will witness a decrease on the available power compared to the healthy engine as seen in FIGURE 5 (a). At the same time the maximum measured pressure at the compressor exit will be lower as the faulty engine at the maximum power output is working underfired (FIGURE 5 (b)). It should be noted that an operating point at part load can still be maintained with a degraded compressor, albeit at higher rotating speed for the case of decrease swallowing capacity and at higher TIT for the case of decreased efficiency as seen in FIGURE 5 (b). The need to operate at higher TIT for part load operation may result to increased maintenance needs for specific conditions.

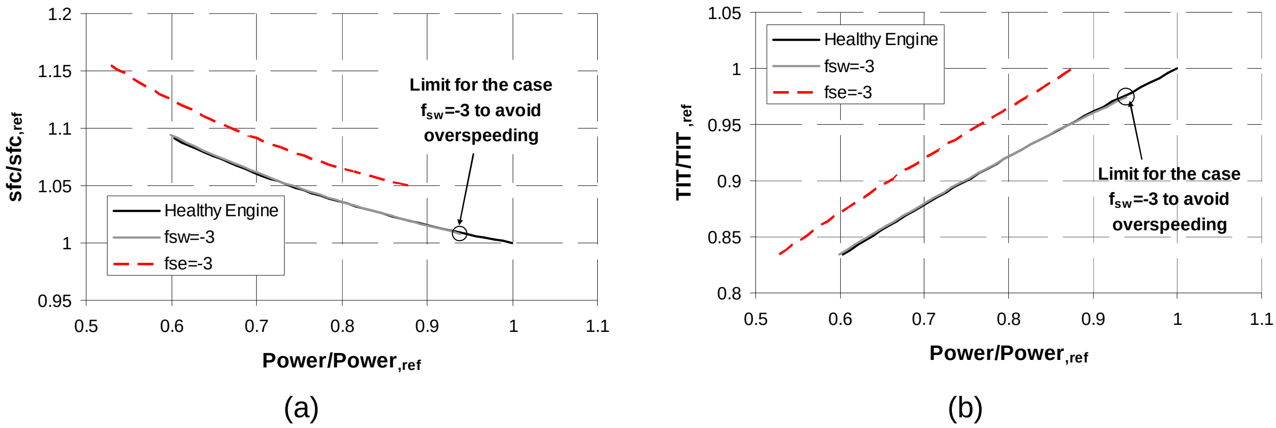
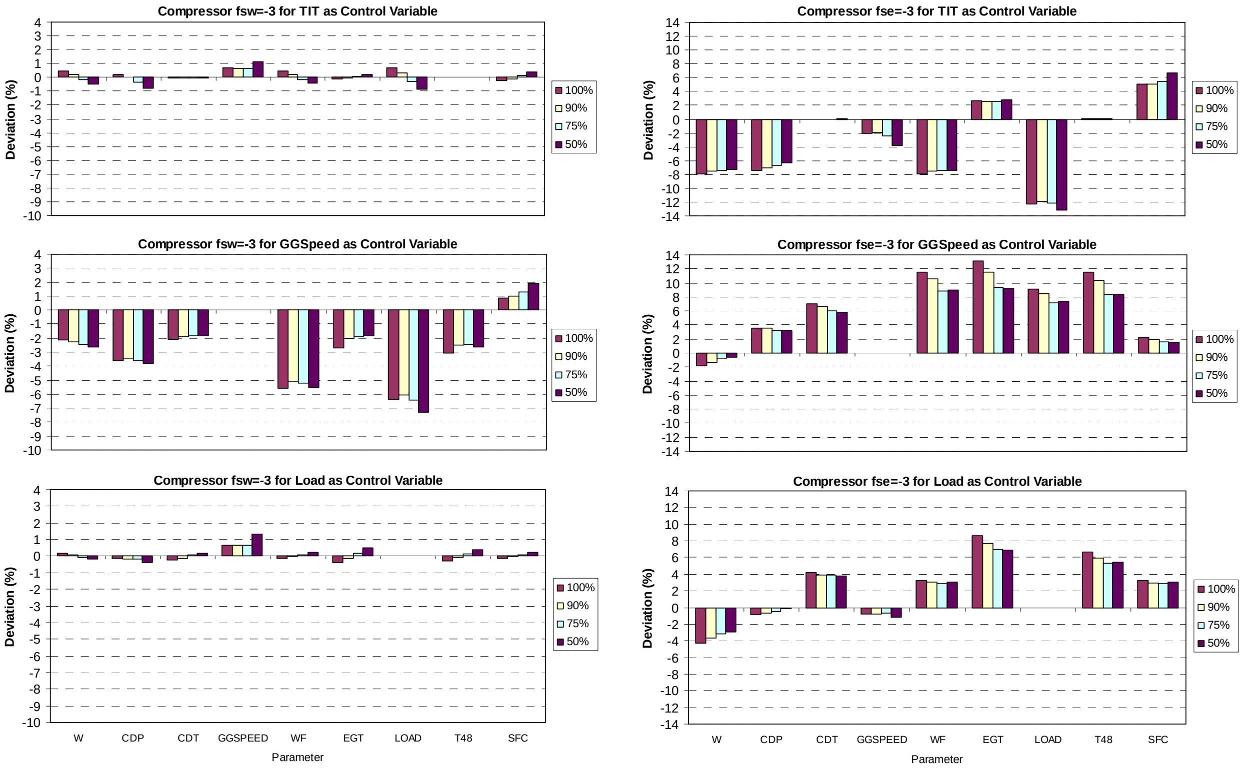


FIGURE 5. Impact of reduced swallowing capacity and efficiency on (a) engine performance and (b) turbine inlet temperature versus power setting for TIT as control variable and imposing an overspeeding limit

Analyzing the effect of the two different degradation modeling parameters on the engine operation and performance some interesting conclusions can be drawn with respect to condition monitoring. The reduction of the swallowing capacity results in the increase of the Gas Generator speed, while the effect on performance is rather minimal. This means that in the case of fault signatures that are usually used for condition monitoring the measurement that is expected to be more affected is the gas generator speed. At the same time it is expected to see the most visible measurements deviation, thus having a clearer fault signature, when measurements at the same rotating speeds are compared (Gas Generator speed as control variable). This is due to the fact that then the degraded engine is actually working on a different operating point compared with the healthy one. These observations are evident by examining FIGURE 6 (a). As seen in FIGURE 6 (a) when measurements for the same TIT and Load are compared the fault signatures do not give any clear information, while the signature using measurements taken for the same GG speed gives a clear indication of a deteriorated engine.

For the case of efficiency reduction the engine performance is significantly affected thus fault signatures under various control parameters will give a clear indication of engine deterioration. The engine under the same firing temperature is working at lower gas generator speeds, lower pressure ratios and mass flows (W), thus to lower Load. As seen in FIGURE 6 (b) these are the measurements that produce the most notable deviations from the healthy ones for operation under the same TIT. When the deteriorated engine is working at the same GG Speed or Load as the healthy one then it is working at higher firing temperature, thus the hot section temperatures are the measurements that give a clear indication of a degradation occurrence. Also in the case of operating at the same Load and GG Speed the engine is working at pressure ratios close to the ones of the healthy engine, thus as the efficiency is decreasing the Compressor Discharge Temperature (CDT) is increasing noticeably, also giving indication of a degraded engine. It is worth mentioning that for the case of efficiency reduction and for all three different control variable cases the inlet mass flow reduces, indicating the shift of the engine operation from the healthy one, but inlet mass flow measurement is not standard on operational engines.

It must be noted that when measurement deviations are considered the magnitudes used are the corrected ones in order to take into consideration the change of the engine operating point due to the ambient conditions. An in depth discussion of the corrected parameters can be found in [10].



(a) (b)

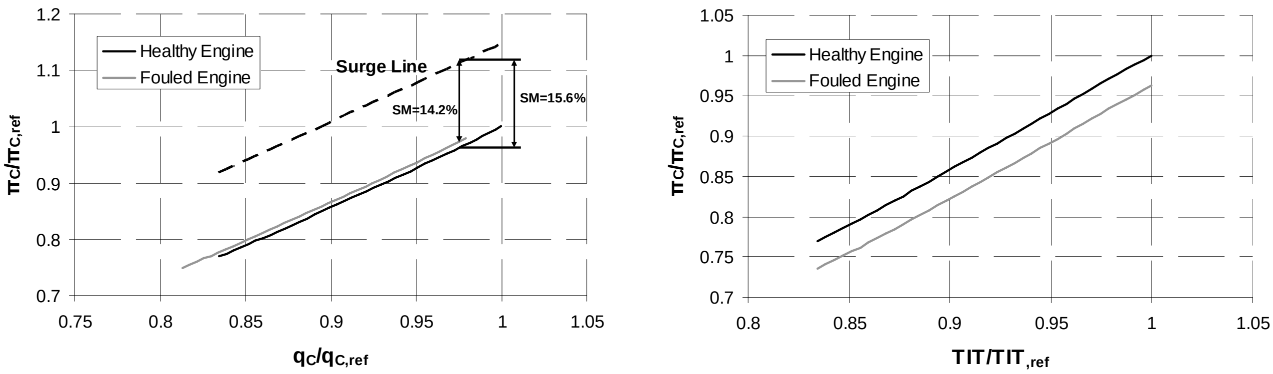
FIGURE 6. Fault signatures for the case (a) of decreased swallowing capacity and (b) of decreased compressor efficiency

Compressor Fouling

All compressors are susceptible to fouling as a result of the ingestion of air impurities that accumulate on and stick to gas path free surfaces, blades and shrouds, modifying the airfoil geometry [11]. In addition oil leaks from compressor seals and bearings mix with some of the ingested particles and deposit on the blade surfaces [12]. In the case of marine gas turbines salt ingestion and deposition is also a major contributor to compressor fouling. The result of fouling is the deterioration of airfoils aerodynamic behaviour and the reduction of flow area, meaning that fouling will result to a decrease on both the compressor swallowing capacity and efficiency. It should be noted that, according to the experimental results of Tarabrin et al. [13] and more recently of Syverud et al. [14], the distribution of contaminates on the blades is close to exponential with the first two stages significantly more prone to fouling than the subsequent ones. Fouling can be often reversed to some degree by washing of the compressor, mainly by off-line washes, while on-line washing is also very popular in order to extend the operating period between off-line washes. It should be noted that the on-line washing process may transport contaminants from the first stages of the compressor towards the rear stages or the turbine section, as discussed by Kurz et al. [15].

For the case of fouling the ratio of swallowing capacity reduction to the efficiency reduction is taken equal to 3.37 according to the findings of Aretakis et al. [8], which agrees well with available experimental data. The maximum swallowing capacity decrease selected is 3.1% and the corresponding efficiency decrease is 0.906. It must be noted that in actual engine operation the degradation can be even larger. For example Diakunchak [11] reported site test data obtained on a large industrial gas turbine indicating that compressor fouling resulted in a 5 percent reduction in inlet mass flow and 1.8 percent reduction in compressor efficiency.

As the reduction of the swallowing capacity has minimal effect on the operating line, it is the reduction of the efficiency that alters the operating line. Specifically the efficiency reduction results to a shift of the operating line towards the surge line, while at the same time the compressor operation is moving towards lower mass flow and pressure ratio compared to the healthy engine and for the same TIT, as seen in FIGURE 7. This behavior is in agreement with the experimental results presented by Syverud et al. [14] for the case of salt ingestion on a J-85 engine. The reduce of the Surge Margin is rather small, as for example for the maximum continuous load of the fouled engine the Surge Margin is 14.19%, while for the same mass flow the healthy engine has a Surge Margin of 15.57%, indicating that surge margin reduction is not of major concern in a fouled engine.

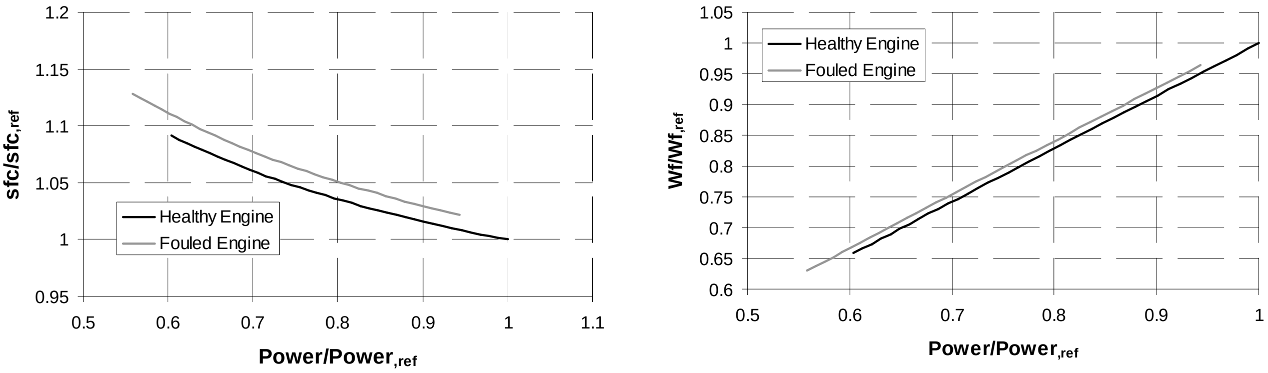


(a) (b)

FIGURE 7. Impact of fouling on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter

Apart from the small reduction in the surge margin; there is also a significant degradation of the engine performance, as seen in FIGURE 8. As an example a fouled engine working at the maximum allowable TIT (TIT max for the healthy engine) will witness a reduction of 5,7% in gas turbine power and an increase of 2,2% in sfc. This means that under maximum continuous operation a fouled engine will not give the expected power. For the case of part load operation the user will witness a net increase of the fuel consumption, for example at the 90% of nominal power the increase in fuel consumption is 1.26%.

In FIGURE 9, the fault signatures for different control parameters for the case of fouling are presented. As discussed compressor fouling produces an effect on engine operation that can be reproduced by a decrease on the compressor swallowing capacity and efficiency. Thus for the case of TIT and Load as control variables it is the efficiency reduction effect which is dominant, as the decreased swallowing capacity does not significantly affect the fault signatures. If measurements for equal gas generator speed are used to produce the fault signature it is the reduced swallowing capacity effect that is dominant. This behavior means that if the user is comparing measurements taken for the same N_{GG} or TIT then CDP, inlet mass flow and Load are the magnitudes that give the clearer indication of a fouled engine. In the case that the user is comparing measurements taken for the same Load, then as expected the temperatures are the measurements that give the higher deviation.



(a) (b)

FIGURE 8. Impact of fouling on (a) engine performance and (b) fuel consumption

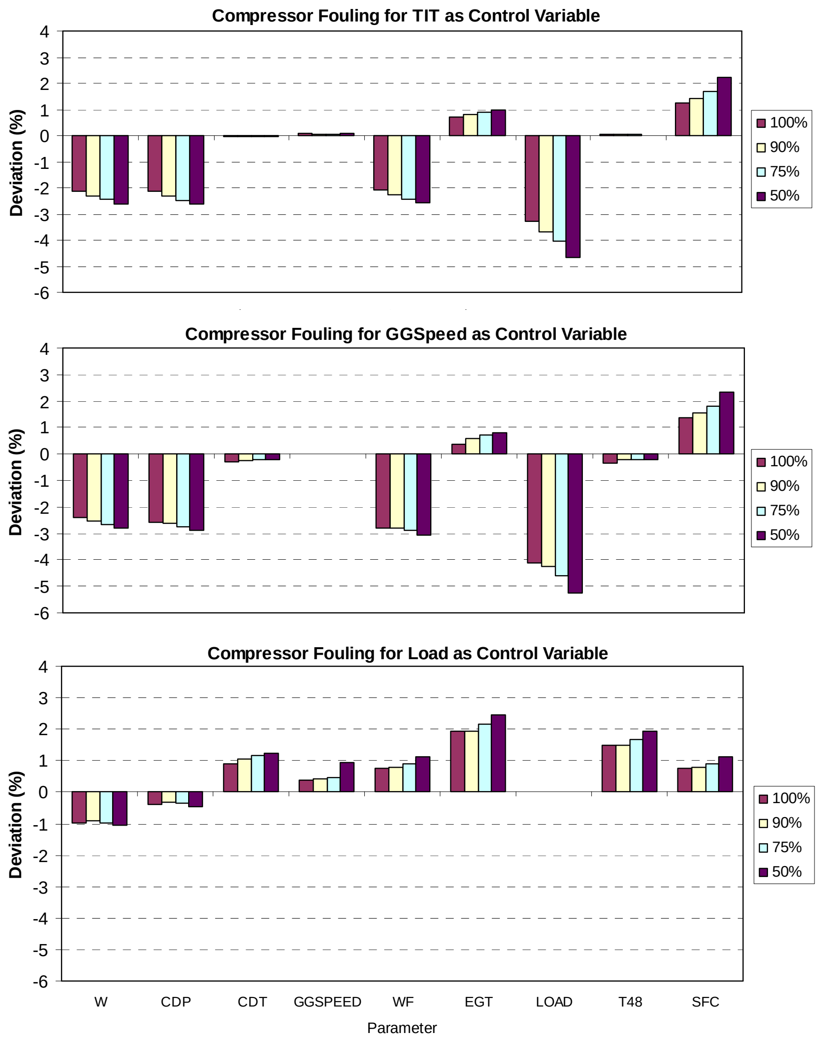


FIGURE 9. Fault signatures for the case of fouling and for different control parameter

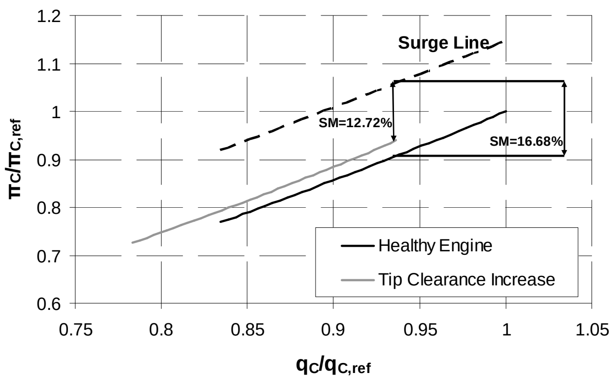
Compressor Tip Clearance Increase

Excessive compressor blade tip wear is a typical fault for in service engines, in case the compressor rotor becomes unbalanced or misaligned due to front or rear compressor bearing damage. Depending on the operation, it may be the result of differences in thermal growth of the rotors and casing during transient phenomena as discussed by Zaita et al. [16].

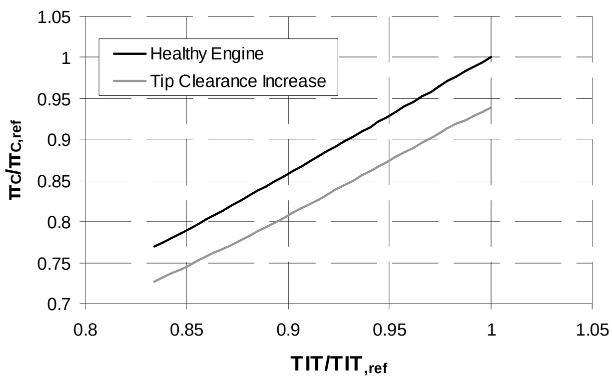
Also in the case that the blades are not in contact with the casing, the clearance may be increased by erosion as discussed by Schmücker and Schäffler [17]. In any case, compressor tip clearance increase results in a severe reduction of air mass flow rate and pressure ratio as reported by MacLeod et al. [18]. According to the experimental results given by Schmücker and Schäffler [17] compressor tip clearance increase should be represented by reduced swallowing capacity at the component inlet as well as by a reduction in the component efficiency, while from the mean loss for a 1% change in tip clearance, is 2% in both efficiency and mass flow rate, thus giving a ratio of change equal to 1. This value is in agreement with the results presented by Aretakis et al. [8] for the case of simulated faults, thus the ratio of 1 will be used herein. The maximum swallowing capacity decrease selected is 2.44%.

The effect of tip clearance increase is the movement of the operating line closer to surge line, as a result of the efficiency reduction. For the specified severity simulated herein this may give a reduction in surge margin from 16.68% for the case of a healthy engine to a value close to 13%, as seen in FIGURE 10 (a). Thus the surge margin decrease can be a problem only in the case of an engine that already has deteriorated surge margin due to other reasons. As expected tip clearance increase effect is more evident than in the case of fouling, as the efficiency reduction effect is dominant (FIGURE 10 (b)). This behavior results in a significant deterioration of engine performance as seen in FIGURE 11. Specifically the maximum continuous power output will decrease down to the 90% of the healthy one, while at the same time the used fuel will increase by 2.4%.

In FIGURE 12, the fault signatures for different control parameters for the case of tip clearance increase are presented. In the case of tip clearance increase the effect of the efficiency reduction is dominant when the fault signatures are considered. In the case of constant TIT the indicative measurements are inlet mass flow, CDP and Load, while the fuel flow is also decreasing as a result of the operating point moving to lower mass flows and pressure ratios. The CDT is not affected as although the compressor efficiency is decreasing, at the same time the CDP is also decreasing. The measurements deviation for the case of constant N_{GG} and Load indicates that the temperatures (CDT, EGT and T48) are the magnitudes that react strongly for the specific fault.



(a)



(b)

FIGURE 10. Impact of tip clearance increase on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter

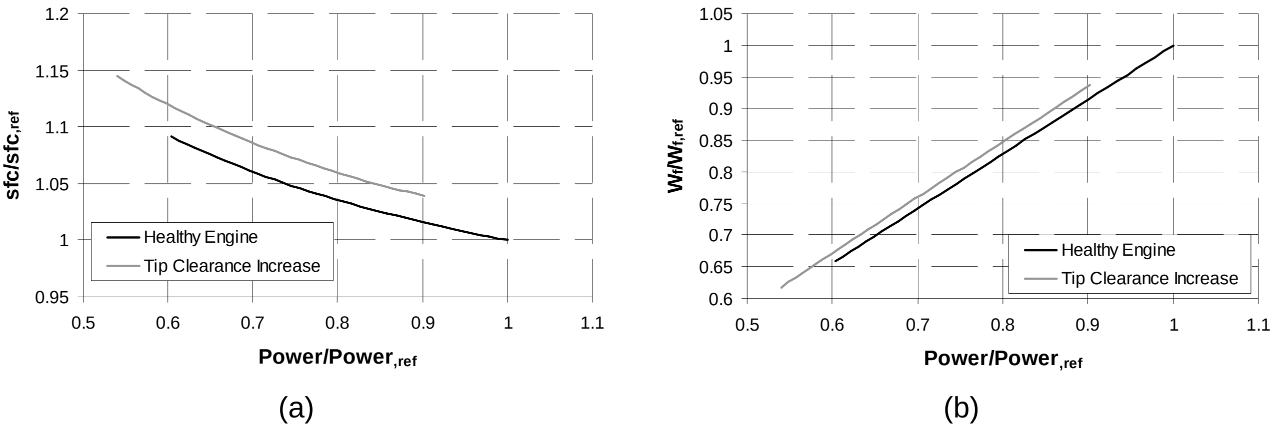


FIGURE 11. Impact of tip clearance increase on (a) engine performance and (b) fuel consumption

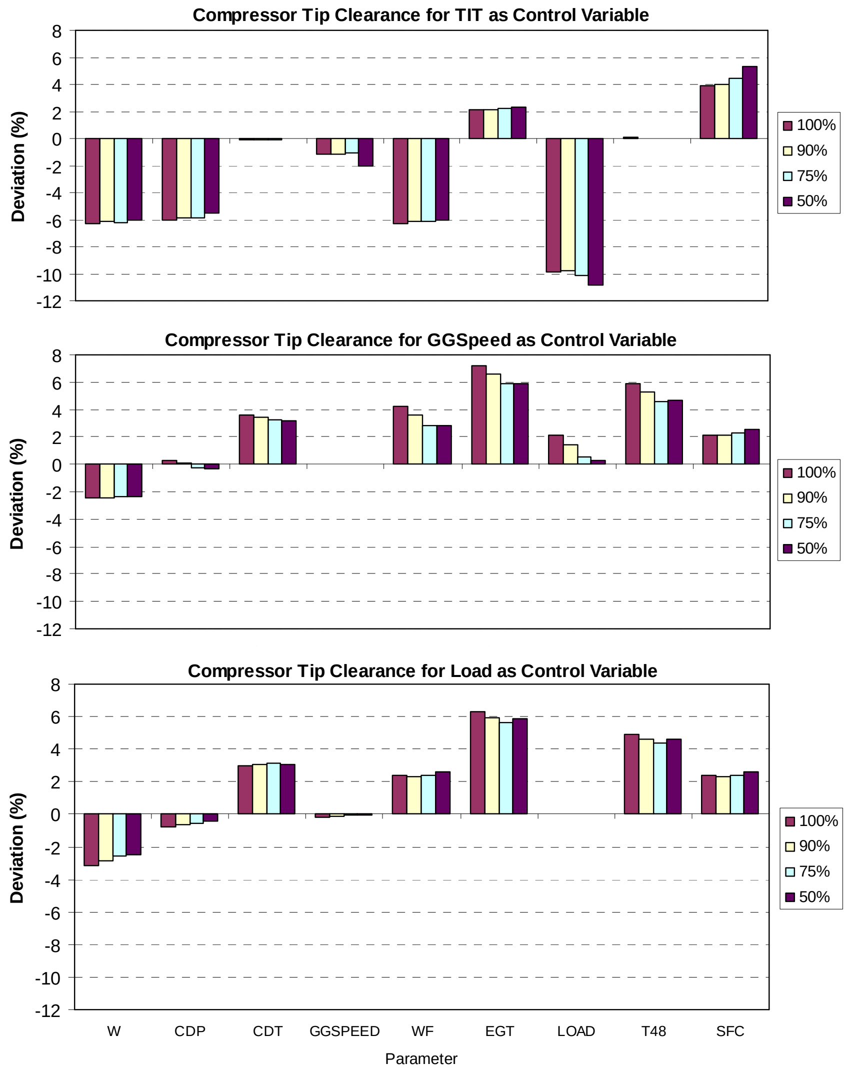


FIGURE 12. Fault signatures for the case of tip clearance increase and for different control parameter

Compressor Erosion

While in service, the engine will swallow dust and small sand particles resulting to the exfoliation of blade material. This material removal causes increased tip clearances and reduced chord lengths. The erosion of the blade, results in increased surface roughness, changes in the inlet metal angle (hence, a change in airfoil incidence), change in airfoil profile, change in airfoil throat opening, and an increase in blade tip and seal clearances. The results of these changes are increased losses and therefore a reduction in the compressor performance. Erosion has been manifested to be more severe in the tip region at the rear part of the compressor due to the existence of centrifugal forces which cause the migration of solid particles to the outer diameter, as discussed by Tabakoff [19] and adopted by Zaita et al. [16].

No experimental data concerning the alternation of the modification factors due to erosion is available in literature, thus the results derived by Aretakis et al. [8] through the modeling of erosion for a multistage compressor will be used herein. The results indicate that the blade erosion effect, not accounting for the tip clearance increase, will affect mainly the air mass flow and only slightly decrease the compressor efficiency, results that are in agreement with the findings reported by Kurz et al. [15] for engines that have been subject to regular condition based water washing. Thus for the compressor erosion simulation a ratio between swallowing capacity reduction and efficiency reduction equal to 8.5 will be used with the compressor swallowing capacity decreased by 2.6%.

In the case of erosion the dominant effect is the effect of the swallowing capacity, thus according to the analysis presented the effect on the engine performance is expected to be minimal, as the compressor is operating on the same operating line, albeit in higher rotational speeds. Thus the part load performance is only slightly deteriorated, due to the slight efficiency reduction as presented in FIGURE 13. At the same time the maximum load is bounded from overspeeding protection, meaning that the user will not have the capability to reach the maximum continuous power output with a eroded compressor. For example in this case, which is not severe, the maximum power output of the faulty engine is the 96% of the healthy engine.

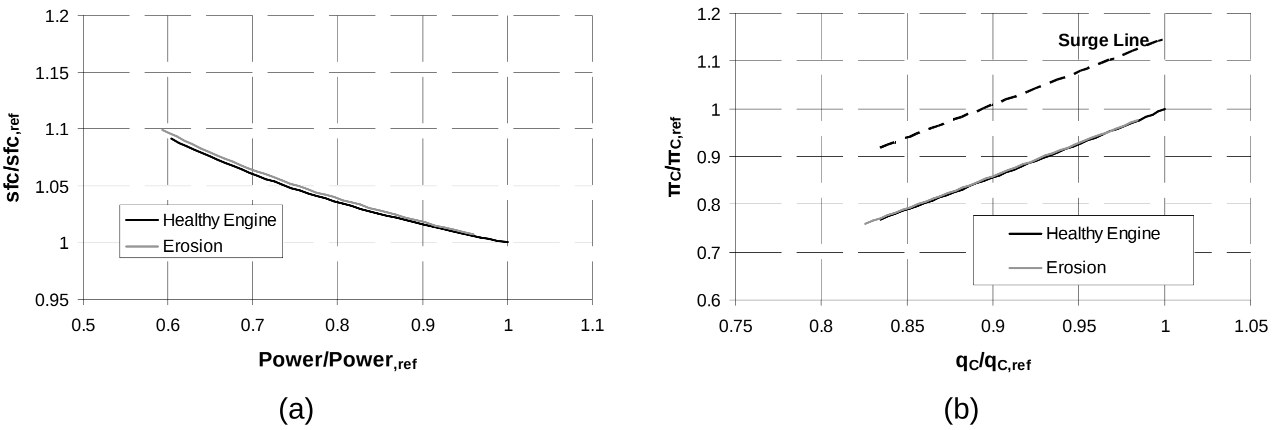


FIGURE 13. Impact of erosion on (a) engine performance and (b) compressor operating line

In FIGURE 14, the fault signatures for different control parameters for the case of erosion are presented. In this case the dominant effect on the fault signatures is the one of the reduced swallowing capacity. This means that the fault signatures for the case of TIT and Load as control variables do not give a strong indication of the fault. On the other hand the fault signature for the N_{GG} as the control variable gives a clear indication of a faulty engine. In the case that measurements from equal N_{GG} for healthy and faulty operation are used it is the compressor oriented measurements that can be used in order to recognize the fault, along with the engine Load.

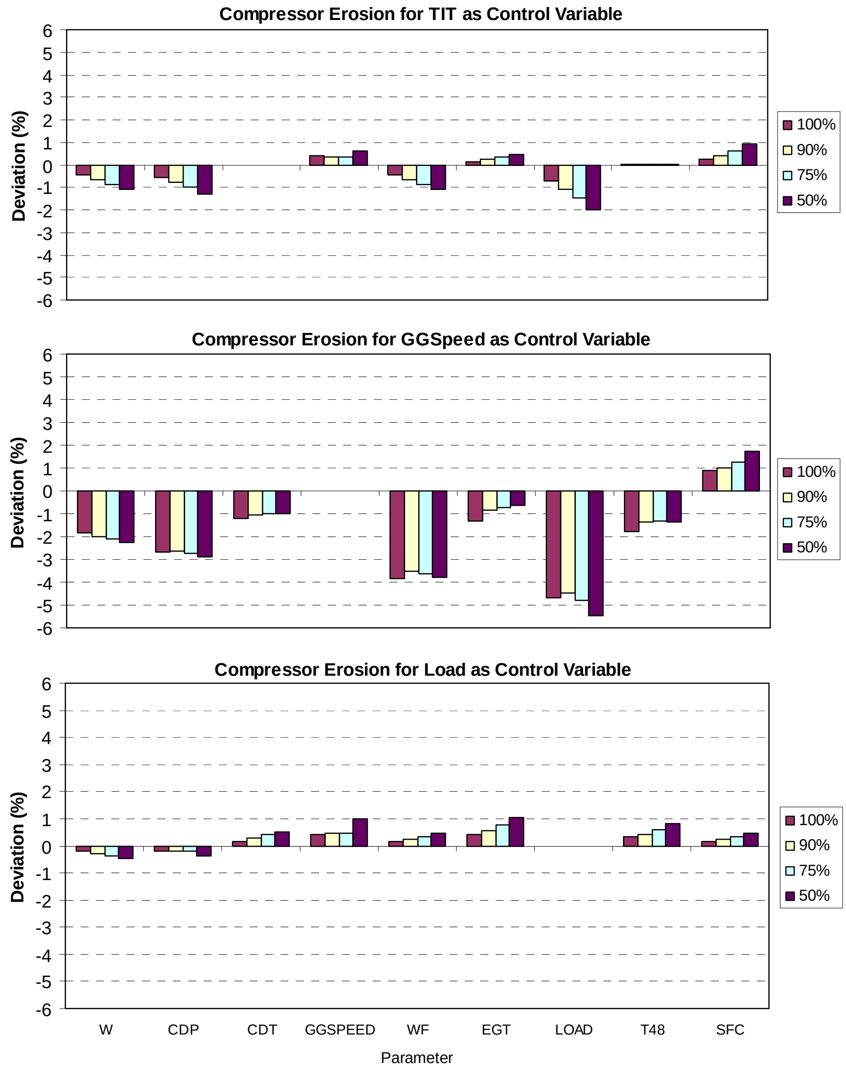


FIGURE 14. Fault signatures for the case of erosion and for different control parameter

Gas Generator Turbine Degradation

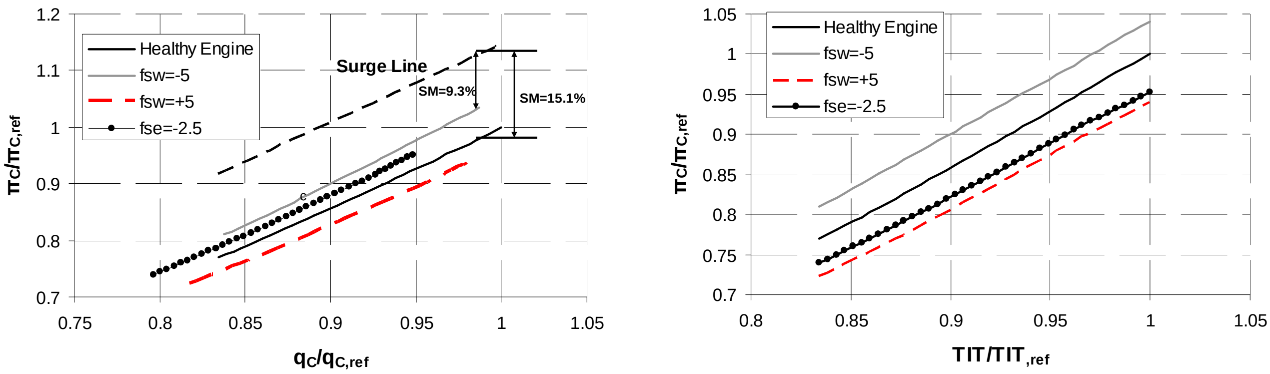
As for the compressor section the degradation is going to impact efficiency, pressure ratio and flow capacity for the case of the turbine as well. According to Morini et al. [9] the turbine swallowing flow capacity factor and efficiency factor are capable to simulate the fault occurrence. The analysis of the turbine degradation phenomena materialized herein is focused on the gas generator turbine, as it is the turbine that is working at the most aggressive environment, thus it is more prone to deterioration.

Degradation effects on the flow capacity of the turbine can either increase or decrease the flow capacity. Specifically the reduction of the flow path, as discussed by Kurz [23] is either due to added surface roughness or the result of eroded leading edges, which lead to thicker boundary layers and consequently to reduced effective throat area. On the other hand the throat area increases when the nozzle trailing edges erode as a result of the impingement of particles against the blades, or as a result of corrosion. Thus the analysis of the engine operation will be done by assuming both a decrease and an increase of 5% for the swallowing capacity of the examined turbine and a decrease of 2.5% of efficiency.

The decrease of the turbine swallowing capacity results in a pronounced change in the operating line of the compressor, shifting it to higher pressure ratios, as seen in FIGURE 15. This change results in a significantly reduction of the compressor surge margin. As an example a reduction in surge margin from 15.1% to 9.3% has been predicted for a 5% reduction in turbine swallowing capacity. The move of the operating line to higher pressure ratios results in the reduction of the engine specific fuel consumption, as seen in FIGURE 16 (b). At the same time and although the N_{GG} is increasing (FIGURE 16 (a)) the off-design operation results in lower power output. The reduction in the power output is a result of the decreased mass flow rate and of the compressor working off-design.

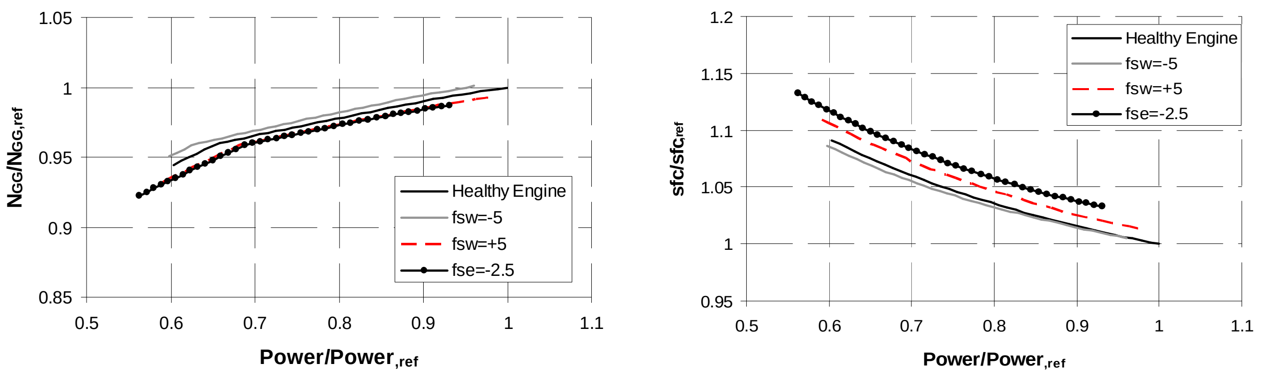
The increase of the turbine swallowing capacity results in a pronounced change in the operating line of the compressor as well, moving it towards chocking this time. The resulting reduction of the pressure ratio leads to an increase in the engine specific fuel consumption as seen in FIGURE 16 (b). At the same time the off-design operation of the compressor (lower efficiency) results in a reduction of the engine power output.

The decrease of the turbine efficiency has the most pronounce effect on the engine performance as seen in FIGURE 16 (b). This is a combination of reduced air mass flow, engine operating pressure ratio for specific TIT as seen in FIGURE 15 (b) and the reduction of the component efficiency. Also it must be noted that the decrease of pressure ratio and air mass flow is at different rates resulting to a mild shift of the compressor operation towards stall (FIGURE 15 (a)).



(a) (b)

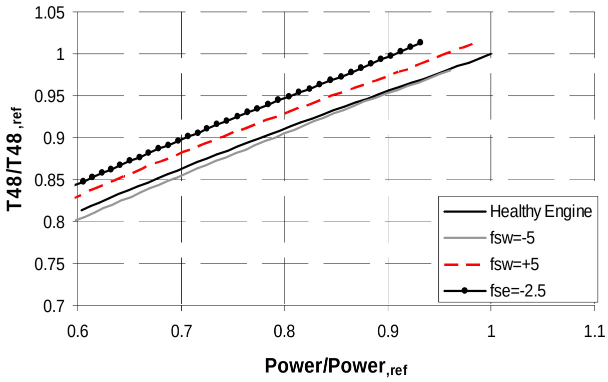
FIGURE 15. Impact of reduced GG turbine swallowing capacity and efficiency on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter



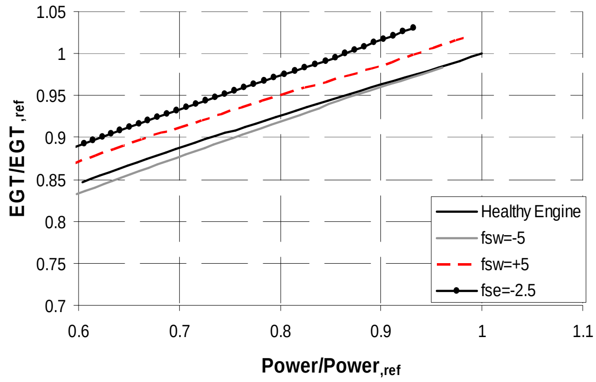
(a) (b)

FIGURE 16. Impact of reduced GG turbine swallowing capacity and efficiency on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter

An interesting observation underling the importance of the measurement that is used in order to limit the engine operation can be deducted from FIGURE 17. It is evident that if the firing temperature is indirectly controlled via the power turbine inlet temperature (T_{48}) or via the power turbine exhaust temperature (EGT) then the engine will work underfired in the case of increased swallowing capacity and decreased turbine efficiency. This means that in operation the engine continuous maximum power output will decrease as a result of both the engine deterioration and the effect of the control mode. In the case of reduced efficiency and for the EGT as the limiting measurement the maximum power output will be the 0.86 of the nominal one, while for the case of T_{48} the maximum power output will be the 0.9 of the nominal one.



(a)



(b)

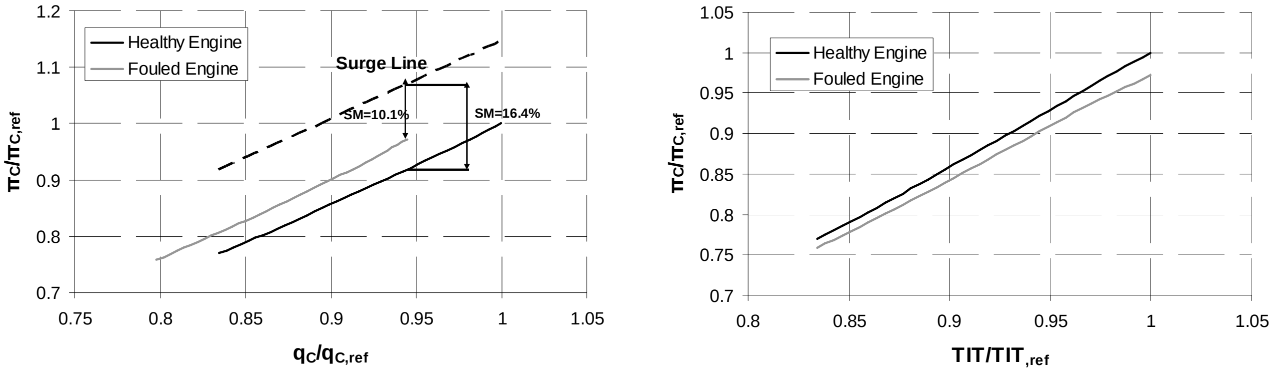
FIGURE 17. Impact of reduced GG turbine swallowing capacity and efficiency on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter

Gas Generator Turbine Fouling

Turbine fouling is mainly depending on type and quality of the operating fuel as discussed by Meher-Homji [20]. If the gas turbine is running on clean fuel such as natural gas, the turbine degradation will be much slower, while when heavy fuel oil or crude oil is used, the turbine degradation is likely to appear earlier. Low melting point ashes, metals and unburned hydrocarbons can be aggregated in the turbine in the form of scale. The contaminants deposition will have an impact over blade, by changing the airfoil shape, the inlet angle and increasing the surface roughness. These effects will result to the reducing of the airfoil throat area and apparently reducing the performance characteristics and the service life of the component. Also, especially in marine gas turbines, sulfidication may occur resulting in turbine corrosion. As a result, fouling rate will increase, as discussed by Basendwah et al. [21].

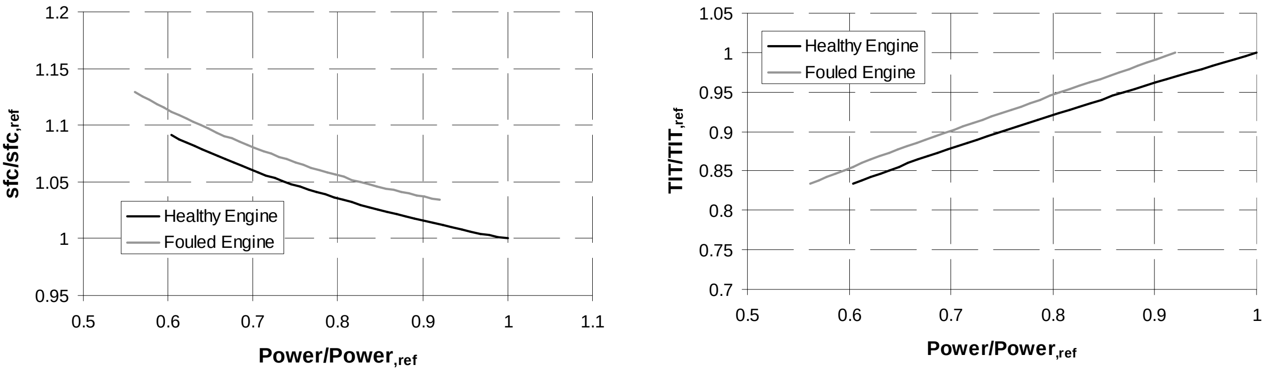
Turbine fouling is liable for the decrease of both turbine swallowing capacity and efficiency. According to the experimental results presented by Zaba [22] the ratio of the factors is expected to be in the range of 1. Thus, for the turbine fouling simulation, a ratio between turbine swallowing capacity reduction and efficiency reduction equal to 1 will be used. The value of the decrease used herein in order to examine the gas turbine behavior is equal to 2.5%, while in practice even larger values may appear, as for example presented by Zaba [22].

As seen in FIGURE 18 turbine fouling alters the compressor operation line significantly, moving it towards stalling. The loss of surge margin can be rather significant, as it reduces from 16.4% to 10.1%. Turbine fouling has a pronounced effect on the engine performance as both sfc and power output degrade compared to the healthy engine as seen in FIGURE 19 (a). This degradation is the result of the turbine efficiency reduction and the operation of the engine at lower pressure ratios. At the same time the engine is forced to work at higher TIT in order to maintain the load at part-load operation as seen in FIGURE 19 (b). It must be noted that if T_{48}, or EGT are used in order to control the engine firing temperature then the maximum power output will be bounded to even lower values that the ones due to the engine degradation as seen in FIGURE 20.



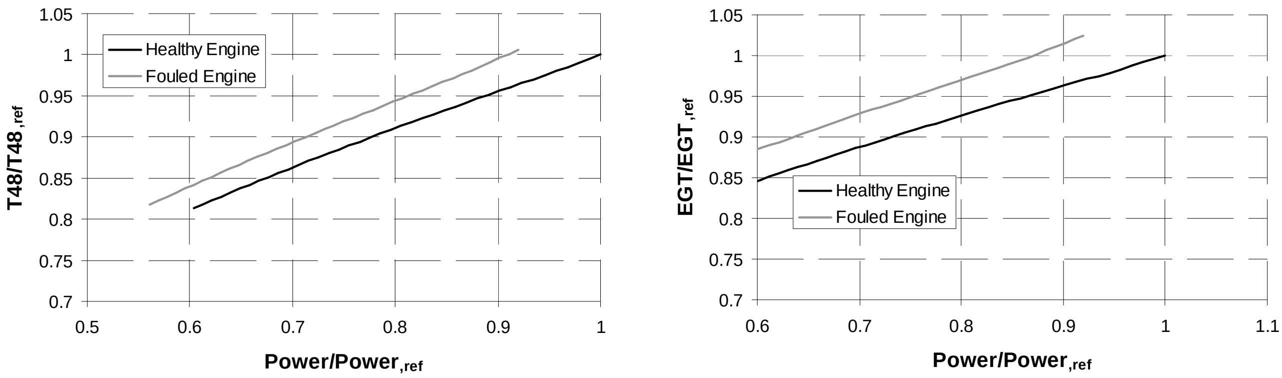
(a) (b)

FIGURE 18. Impact of GG turbine fouling on the compressor operating line versus (a) corrected mass flow and (b) operating TIT for TIT as the control parameter



(a) (b)

FIGURE 19. Impact of GG turbine fouling on (a) engine performance and (b) firing temperature for specific Power output



(a) (b)

FIGURE 20. Impact of GG turbine fouling on (a) power turbine inlet temperature (T_{48}) and (b) Exhaust Gas Temperature (EGT)

In FIGURE 21 the fault signature for different control modes and for a fouled turbine is presented. It is worth mentioning that for all three cases the inlet air mass flow indicate that the engine is faulty. For the case that N_{GG} and Load are the control variables the hot section temperatures are giving the clearer indication of a fault, while in the case that TIT is the control variable it is the inlet air mass flow and Load that are more sensitive to the specific fault.

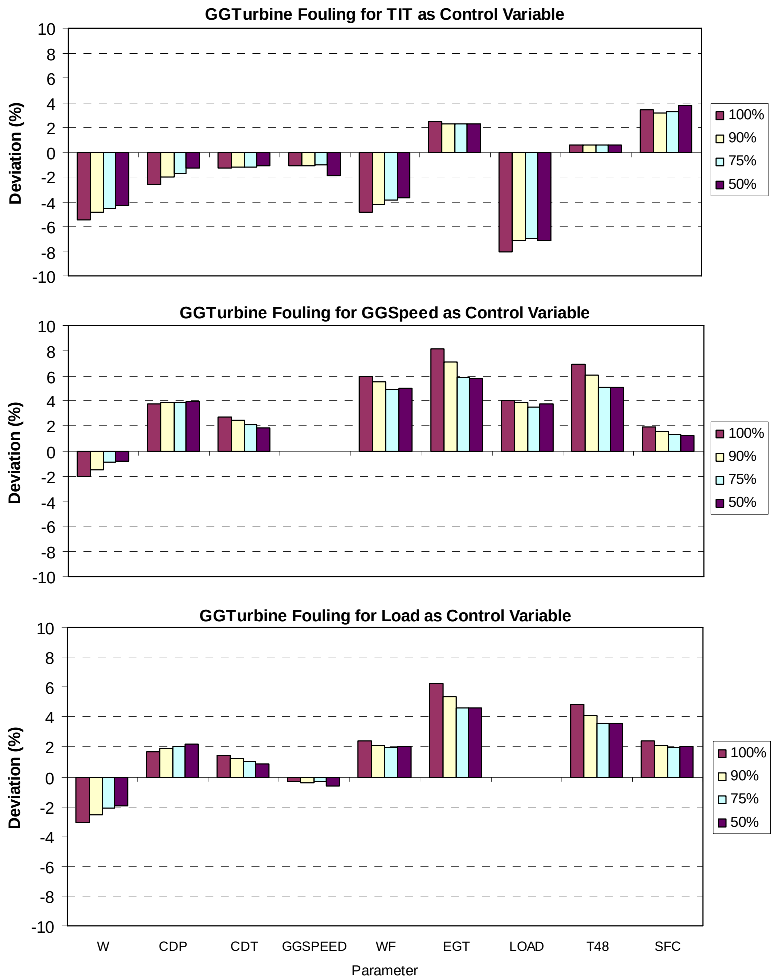


FIGURE 21. Fault signatures for the case of GG turbine fouling and for different control parameter

Gas Generator Turbine Erosion

Erosion is caused by the impingement attack of particles against the surface of the turbine blade. Due to the high speeds, at which the blades rotate, a collision with even a very small particle induces a significant damage effect on the turbine blade affecting the performance of the turbine. Erosion is generally attributed to the larger particle sizes in excess of approximately 20 μm in diameter. According to the 1-D analysis by Morini et al. [9], erosion causes a shift of the non-dimensional corrected mass flow rate curves towards higher values, while efficiency curves are in practice unaffected by this type of deterioration. The same effect of erosion was considered by Zhu and Saravanamuttoo [24] in their simulation, although they suggested that turbine erosion may cause efficiency degradation as well. No experimental data is available in the open literature thus, for the turbine erosion simulation, a ratio between swallowing capacity increase and efficiency reduction of (-) 8 will be used since the effect on swallowing capacity is predominant. The swallowing capacity increase used herein is 5%.

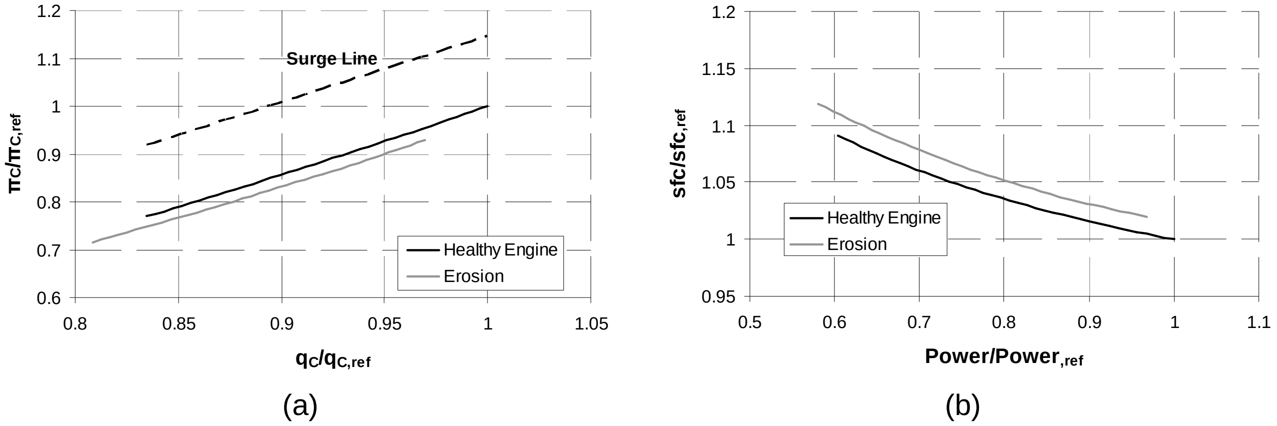


FIGURE 22. Impact of turbine erosion on (a) the compressor operating line and (b) engine performance for TIT as the control parameter

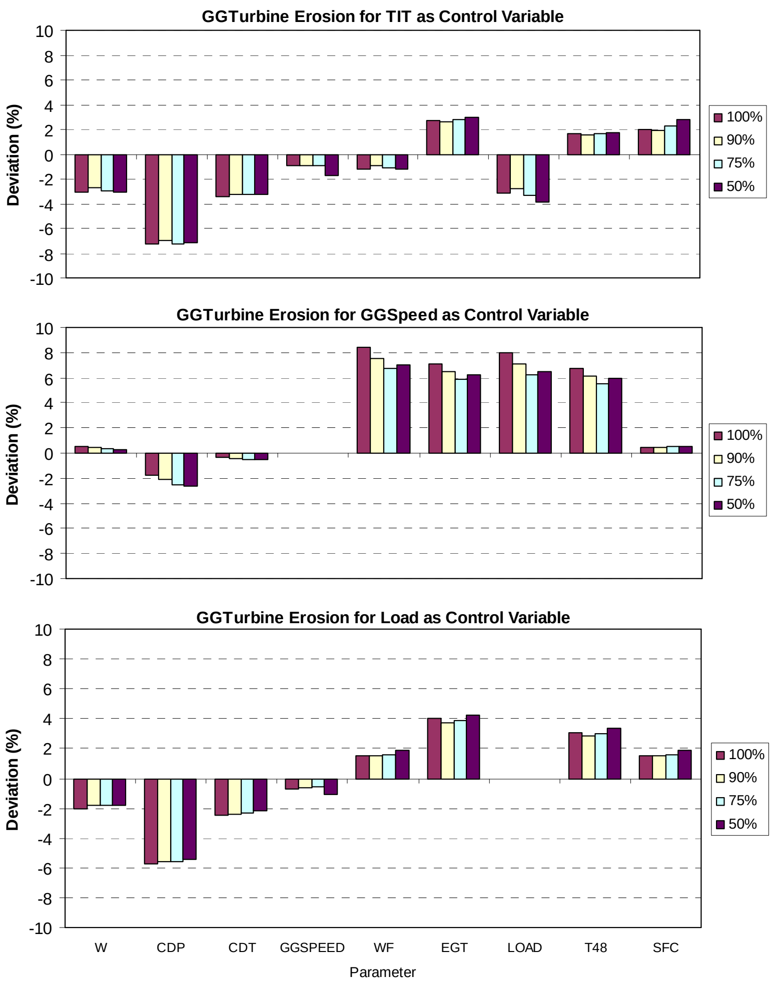


FIGURE 23. Fault signatures for the case of turbine erosion and for different control parameter

As seen in FIGURE 22 the operating line is moved towards the chocking region, thus the measured CDP of the faulty engine is expected to be lower than the healthy one. The engine performance is also deteriorated for the case of erosion, resulting to a significant increase on sfc and a noticeable decrease of the engine power output, as seen in FIGURE 22 (b).

In FIGURE 23 the fault signature for different control modes and for an eroded turbine is presented. For the case that TIT and Load are the control variables it is compressor oriented measurments that gives an indication for the fault, while if operating points for the same N_{GG} are compared the hot section temperatures and Load are giving the clearer indication of a fault.

CONCLUDING REMARKS

The paper covered in detailed degradation phenomena and the impact of component degradation on overall engine performance, result of both component degradation and component rematching. The effect of components fault on the engine performance has been discussed in detail in order to highlight the importance of a strict schedule on engine components maintenance, especially for recoverable faults as is the filter fouling and compressor fouling. It is clear from the results that a faulty engine will not be in a position to obtain the expected maximum continuous power output, thus the expected propulsive power can be significantly reduced, while at the same time the specific fuel consumption will increase. Fault signatures have been produced and the results indicate that different faults may be identified by using appropriate measurements and control variables.

For the case of compressor the analysis indicated that for a faulty engine the need to operate at higher TIT in order to maintain part load operation may increase maintenance needs during the engine operation. The most sever fault with respect to surge margin is the occurrence of tip clearance increase, although the surge margin reduce can be characterized as permissible if no other conditions that reduce surge margin occurs, like water injection.

Some interesting observations are deducted from the compressor fault signatures that may allow easier fault type identifications. If measurements from operating points at the same gas generator speed are used then fouling and tip clearance increase produce a significantly different fault signature, as in the first case the compressor oriented measurements present the most obvious deviation, while in the second case the hot section temperatures are more sensitive. The distinction is not as clear in the case that measurements for the same TIT or power output are used. In the case of compressor erosion the fault signature for the same GG speed is similar to the one of fouling, but the insensitivity of the measurements for the same Load and TIT can give an indication that the fault is erosion.

For the case of turbine the faulty engine needs to operate at higher TIT in order to maintain part load operation as well, while the effect of fouling on the surge margin can be rather significant and under specific conditions it may threaten the engine's stable operation. The importance of the measurement used in order to control TIT was discussed and the results indicate that in a faulty engine the maximum power output may be further decreased as although the engine can operate underfired the turbine exhaust temperatures may be greater than the ones of the healthy engine.

Concerning the fault signatures both examined turbine faults produce similar signatures with respect to the hot section temperatures, while the compressor oriented measurements (CDP and CDT) have different behavior when measurements for the same GG speed and Load are used, thus it can be said that the turbine faults can be clearly identified using measurements taken at the same GG speed or Load.

For the case of turbine and compressor faults it can be concluded that the turbine fouling can be identified versus all examined faults by using the fault signature for the Gas generator Speed as the control variable. In this case although the hot section measurements deviation is similar to some of the compressor fault signatures and to the turbine erosion signature, the CDP increase allows the identification of the specific fault. Turbine erosion on the other hand produces a distinct signature when the measurements from the same Load are used.

REFERENCES

1. Roumeliotis I., Mathioudakis K., Aretakis N., Performance analysis of twin-spool water injected gas turbines using adaptive modeling, ASME paper No. GT2003-38516.
2. Stamatis A., Mathioudakis K., Papailiou D.K., Adaptive Simulation of Gas Turbine Performance, ASME J Eng Gas Turbines Power 1990, 112(2): 168-175
3. Tsalavoutas A., S. Pothos, Mathioudakis K., Stamatis A., Monitoring the performance of a twin-shaft ship propulsion turbine by means of adaptive modeling, RTO Symposium on Gas Turbine Operation and Technology for Land, Sea and Air Propulsion and Power Systems, Ottawa, Canada, 18-21 October 1999
4. Stamatis, A., Mathioudakis, K., Smith, M., Papailiou, K.D., "Gas Turbine Component Fault Identification by Means of Adaptive Performance Modelling". ASME Paper 90-GT-376, 1990
5. Li Y.G, Abdul Ghafir M.F., Singh W.R., Huang K., Feng X, "Non–Linear Multipoints Gas Turbine Off-Design Performance Adaptation Using a Genetic Algorithm". ASME Paper GT2010-22285, 2010
6. Yfantis E. A., Kapasakis P., “Marine Gas Turbine Performance Diagnostics: A Case Study”, Diagnostyka Nr 3(47)/2008, September 2008, ISSN 1641-6414,pp. 61-64.
7. Oswald A.D. and Hiner S.D., “More Efficient Application for Naval Gas Turbines-Addressing the Mismatch between Available Technology and the Requiraments of Modern Naval gas Turbine Inlets”, ASME paper No. GT2006-90305
8. Aretakis N., Roumeliotis I., Mathioudakis K., ‘Perfromance Model Zooming for In-Depth Component Fault Diagnosis’, 2010, ASME paper GT2010-23262
9. Morini M., Pinelli M., Spina P. R., Venturini M., “Influence of Blade Deterioration on Compressor and Turbine Performance”, ASME paper No. GT2008-50043
10. Volponi A. J., “Gas Turbine Parameter Corrections”, ASME J. of Engineering for Gas Turbines and Power, Vol. 121, pp. 613 – 621
11. Diakunchak, I. S. , 1992, "Performance Deterioration in Industrial Gas Turbines» Asme J. of Engineering for Gas Turbines and Power, Vol. 114, pp. 161-168.
12. Lakshminarasimha, A. N., Boyce M. P., Meher-Homji C. B., 1994, "Modelling and Analysis of Gas Turbine Performance Detrerioration» ASME J. of Engineering for Gas Turbines and Power, Vol. 116, pp. 46-52.
13. Tarabrin, A. P., Schurovsky, V. A., Bodrov A. I., Stadler J-P, 1998, "Influence of Axial Compressor Fouling on Gas Turbine Unit Performance based on Different Schemes and with Different initial Parameters" ASME Paper No. 98-GT-416.
14.Syverud, E., Brekke, O., Bakken, L. E., 2005, "Axial Compressor Deterioration Caused by Saltwater ingestion" ASME Paper No. GT2005-68701
15. Kurz R., Brun K., Wollie M., 2008, "Degradation Effects on Industrial Gas turbines" ASME paper No. GT2008-50020
16. Zaita, A. K., Buley, G, Karslons, G., 1997 “Performance Deterioration Modeling in Aircraft Gas Turbine Engines” ASME paper No. 97-GT-278
17. Schmücker, J., Schäffler, A., 1994, “Performance Deterioration of Axial Compressors Due to Blade Defects” Paper presented at the Propulsion and Energetics Panel (PEP) Symposium held in Rotterdam, the Netherlands in April 1994
18. MacLeod, J. D., Taylor, V., Laflamme, J. C., 1992, “Implanted Component Faults and Their Effects on Gas Turbine Engine Performance” ASME J. of Engineering for Gas Turbines and Power, Vol. 114, pp. 174-179
19. Tabakoff, W., 1986, "Compressor Erosion and Performance Deterioration," ASME Publication FED-Vol. 37, presented at the AIAA/ASME 4th Joint Fluid Mechanics, Plasma Dynamics, and Lasers Conference, Atlanta, Georgia.
20. Meher-Homji. C. B, 1989, “Compressor and Hot Section Fouling in Gas Turbines – Causes and Effects”, Proceedings of the 9th Industrial Energy Technology Conference, Houston. September 16-18. 1987, Texas A&M University.
21. Basendwah A. A., Pilidis P., Li Y. G., “Turbine Off- Line Water Wash Optimization Approach for Power Generation”, ASME paper No. GT2006-90244

22. Zaba, T., 1980, “Losses in Gas Turbines Due to Deposits on the Blading,” Brown Boveri Review, Volume 67, Number 12, December 1980
23. Kurz R., 1995, “Effects of nonuniform Blade Pitch on the Flow through an Annular Turbine Nozzle”, Int. J. of rotating Machinery, Vol. 2, No.1, pp. 59-65
24.Zhu P., Saravanamuttoo H.I.H., 1994, “Simulation of an Advanced Twin – Spool Industrial Gas Turbine”, Asme J. of Engineering for Gas Turbines and Power, Vol. 114 , pp. 180-185