An innovative prediction strategy for the compressor fouling effects during an airline mission

Riccardo Friso
University of Ferrara
riccardo.friso@unife.it
Ferrara, Italy

Alessio Suman
University of Ferrara
alessio.suman@unife.it
Ferrara, Italy

Nicola Zanini
University of Ferrara
nicola.zanini@unife.it
Ferrara, Italy

Michele Pinelli
University of Ferrara
michele.pinelli@unife.it
Ferrara, Italy

ABSTRACT

Solid particles ingestion is one of the main causes of performance degradation in gas turbine engine compressors. Particles that enter the engine can stick to the internal surfaces and then form deposits. These, in turn, involve a variation of blade surface roughness and geometry and then performance deterioration. In this work, a strategy for predicting the effects of compressor fouling on the engine performance during a complete airline mission is proposed. The mission analysis has been conducted by discretizing the altitude profile, then locally performing a force balance on a reference aircraft. Particles deposition is accounted for by modifying the compressor maps by means of appropriate degradation coefficients. Finally, engine performance has been computed by using an in-house 0D gas-path code. A predicted fuel consumption profile along the mission has been proposed to evaluate the effects of compressor fouling. In particular, a rise in this quantity in time has been encountered. The presented approach enables the prediction of the fouling effects on gas turbine engines, and then optimize their maintenance scheduling.

INTRODUCTION

One of the major problems in aero engines is their deterioration due to contaminant ingestion (Friso et al., 2020). This is aggravated by the absence of inlet filters, which are not installed in these types of engines given the nature of the operations (Suman et al., 2017). The contaminant in the form of particulate that enters the engine can deposit on the internal surfaces, modifying their roughness and geometry (Friso et al., 2019, 2021). This, in turn, affects the engine performance and contributes to increase the fuel necessary for the operation.

The first parts of the gas turbine are the most influenced by this detrimental issue (Shi et al., 2016). Specifically, the fan and the axial flow compressor are considered the most at-risk components (Igie et al., 2016). The only strategy to face this problem is to wash the entire engine, with online or offline washing procedures (Casari et al., 2020). This maintenance process has a strong impact on the mission costs, and its accurate prediction is of main interest for aviation companies.

In this respect, a few studies are conducted in the literature in order to find the best strategy for the prediction of the effects of gas turbine degradation due to fouling on the entire mission (Ellis et al., 2021; Igie et al., 2016). Many of them are completely data-driven-based, such as the work of Allen et al. (Allen et al., 2018), where optimization of washing scheduling is carried out by modeling engine degradation effects with data-driven techniques, thus considering only on-field measurements. Other works, on the other hand, tried to predict engine degradation effects by using both data-driven and physics-based models. An example is the work of Hanachi et al. (Hanachi et al., 2016), where the on-field measurements are used to feed a 0D gas path model, that in turn estimates the engine reactions due to fouling.

In this work, a strategy for the prediction of compressor fouling effects on the whole aircraft mission is proposed. Specifically, both the aircraft and the engines are physics-based modeled. In this respect, since the study is mainly focused on the methodology, ad-hoc parameters for describing the aircraft and the engines were selected from the literature. Fouling effects on the axial compressor are accounted for in terms of maps variations, that are obtained by experimental results acquired by an ad-hoc test rig. This represents the main novelty of the present work since it differs from the a priori parameters variation approaches commonly used in the literature Igie et al. (2016). Fuel consumption and SFC (Specific Fuel Consumption) profiles variation are monitored to evaluate the gas turbine performance degradation due to fouling.
METHODOLOGY

The model here proposed aims to replicate the engine behavior along with a complete airline mission. Since the study is focused on the assessment of the methodology, no specific aircraft and engines were selected. In particular, general geometric parameters found in the literature were considered to describe the airframe (Howe, 2000), whereas the performance maps available in the commercial software GasTurb9 were used to represent the engines. Furthermore, a short-haul mission was considered to evaluate the approach. Among the different outputs that can be extracted from the model, fuel consumption is the one that is of interest in this specific study. The algorithm developed is sketched in Fig. 1. The information required as input for running the model are:

- Mission information in terms of altitude profile;
- Aircraft geometry details necessary to estimate the weight and the aerodynamic forces;
- Performance maps of each engine component in order to model their behaviour.

The first step of the method consists of the discretization of the mission profile. Here, the whole mission is discretized into a user-specified number of segments, each delimited by two altitude values. Steady-state conditions were assumed in every segment for both aircraft and engines. After that, an iteration process along with the mission starts. For each segment, a force balance is performed on the aircraft, that is considered frozen in a specific position (Aircraft Module). This allows the estimation of the thrust needed for the aircraft for being at the specified altitude in the predefined position. The value of the thrust thus found is used as a constraint to compute the engine operating point, then the corresponding fuel mass flow rate (Engine Module). Before engine performance evaluation, the update of the components maps in consideration of the particle ingestion phenomenon is done. In this respect, the maps are modified to take into consideration the effects of fouling. Each module is detailed described in the following paragraphs.

Aircraft module

The first module composing the methodology is the aircraft module. Here, the required net thrust $F_T$ is determined for each discrete point, by solving the aircraft equations of motion (Eqs. 1 and 2) (Brandes et al., 2021). The equations can be easily derived by performing a force balance on the stability axes of the aircraft (see Fig. 2 on the left).

\[
F_t - F_D - m_A g \sin(\alpha) = m_A a
\]

\[
F_n + F_L - m_A g \cos(\alpha) = 0
\]

The quantities that enter the equations are the normal and the tangential components of the thrust ($F_n$ and $F_t$), the drag and the lift forces ($F_D$ and $F_L$), the aircraft mass ($m_A$), and the flow angle of attack ($\alpha$). Among them, the most important ones are the drag and the lift actions, which require knowledge of the aircraft geometry, its airspeed, and the air angle of attack. For the last two, the trend along the mission reported in Fig. 2 on the right is assumed, where $h/H_{\text{max}}$ represents the fraction of the altitude at which the aircraft is located. The reported profiles represent only half the mission, that is the ascending period since a mirrored behaviour is assumed for the descending one. As it can be noted, the airspeed is computed by assuming a Mach number ($Ma$) spanning from 0.3 (at the take-off and landing) to 0.8 (cruise). The angle of attack is calculated by assuming a maximum value of 11° at almost the mid of the ascending/descending period (Filippone, 2012).

![Figure 1 Outline of the mode algorithm.](image-url)
In order to estimate both the lift and the drag forces, Prandtl’s lifting line theory is used. Specifically, to compute the lift coefficient \( C_L \) the methodology used by Brandes et al. (Brandes et al., 2021) is adopted (Filippone, 2012). This formulation allows the calculation of \( C_L \) as a function of the angle of attack, the zero-lift angle \( (\alpha_0) \), the wing aspect ratio \( (\Lambda = b^2/A) \), the wing sweep angle at the half-chord line \( (\theta_{sw}) \), and the flight Mach number as shown in Eq. 3.

\[
C_L = \frac{2 \pi \Lambda (\alpha - \alpha_0)}{2 + \sqrt{(\Lambda / \cos(\theta_{sw}))^2 + 4 - (\Lambda Ma)^2}}
\]  

The wing aspect ratio is in turn computed as a function of the wingspan \( (b) \) and the wing area \( (A) \). All these parameters are indicated in Fig. 2 bottom-left side. The drag coefficient is determined by the summation of three components (Eq. 4), which expressed in coefficient form are: Zero lift drag coefficient \( (C_{D_0}) \), Vortex drag or lift induced drag \( (C_{D_L}) \), Wave drag \( (C_{D_W}) \).

\[
C_D = C_{D_0} + C_{D_L} + C_{D_W}
\]  

The first and the second drag coefficients are calculated according to Howe (Howe, 2000) (Eq. 5 and 7), while the third is calculated according to Torenbeek (Torenbeek, 1982) (Eq. 6). Other drag contributions, such as the spillage drag, were not considered here, but they can be taken into account by adding drag terms to Eq. 4 (Coats, 1986).

\[
C_{D_0} = 0.005 \left( 1 - \frac{2C_L}{R_w} \right) \left[ 1 - 0.2 Ma + 0.12 \left( \frac{Ma \cos(\theta_{sw})}{0.8 - t/c} \right)^{20} \right] 0.84 R_w
\]

\[
C_{D_L} = \frac{C_L^2}{\pi \Lambda e}
\]

\[
C_{D_W} = 0.026 \Lambda^{0.33}
\]

Table 1 Airframe parameters needed as inputs for the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_w )</td>
<td>5</td>
<td>-</td>
<td>(Howe, 2000)</td>
</tr>
<tr>
<td>( t/c )</td>
<td>0.1</td>
<td>-</td>
<td>(Howe, 2000)</td>
</tr>
<tr>
<td>( \theta_{sw} )</td>
<td>32</td>
<td>°</td>
<td>(Howe, 2000)</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>10</td>
<td>-</td>
<td>(Igie et al., 2016)</td>
</tr>
<tr>
<td>( e )</td>
<td>0.95</td>
<td>-</td>
<td>(Howe, 2000)</td>
</tr>
<tr>
<td>( m_A )</td>
<td>220000 kg</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
In the equations above, the following parameters are introduced: the Oswald factor \((e)\), the ratio of overall wetted area to the reference \((R_W)\), the pitch to chord ratio \((t/c)\), and the correction factor for wing thickness \((\tau)\). All these quantities are determined according to Howe (Howe, 2000). Particularly, for the last one, Eq. 8 is used.

\[
\tau = \left[ \frac{R_W - 2}{R_W} + \frac{1.9}{R_W} \left(1 + 0.526 \left(\frac{t/c}{0.25}\right)^3\right) \right]^{0.9}
\] (8)

To ease the reader, since no specific aircraft type was chosen, the summary of the aircraft geometric parameters needed for the model is reported in Tab. 1 with the respective references. With the configuration chosen, the thrust needed for the take-off is roughly 200 kN.

Degradation Module

The output of the Aircraft module is the net Thrust that the engine has to develop to contrast the aerodynamic actions and the weight. Before entering the Engine module, the preparation of the components maps is required, that is what the Deterioration module does. In this specific case, the performance maps available in the commercial software GasTurb9 are used (Aldi et al., 2021). In particular, these were adapted in order to achieve a net thrust of approximately 177 kN. This is because, since two engines were considered, the total net thrust of 200 kN meets the need of the aircraft configuration chosen.

The main purpose of the Degradation module is to parameterize the maps in order to allow their modification subsequently to compressor fouling. This is done by scaling them to obtain the generalized maps in terms of \(\psi\) and \(\phi\), defined as follows

\[
\psi = \frac{\Delta h_T}{U^2}
\] (9)

\[
\phi = V_a \frac{U}{\psi}
\] (10)

where \(h_T\) is the total enthalpy, \(U\) is the blade velocity at the mean radius, and \(V_a\) the mean axial flow velocity. The curve thus obtained is then interpolated by using the formulation proposed by Spina (Spina, 2002) and modified by Melino et al. (Melino et al., 2010) and expressed in Eq. 11.

\[
\psi = \psi_{\text{max}} - \left(\psi_{\text{max}} - \gamma \psi_D\right) \frac{\left[\phi_{\psi_{\text{max}}} + SF \left(\phi_{\psi_{\text{max}}} - \psi_D\right) - \phi\right]^2}{\left(\phi_{\psi_{\text{max}}} + SF \left(\phi_{\psi_{\text{max}}} - \psi_D\right) - \psi_D\right)^2}
\] (11)

where the best fitting has to be obtained only by varying SF (Shape Factor). In the case considered in this study, the value of SF that guarantees the best fit is 0.5. The generalized map obtained can be then reconverted in the compressor performance map by only applying the reverse scaling process.

As can be noted, a parameter \(\gamma\) is present in the formulation. This is a degradation coefficient that corrects the maps in response to compressor fouling. A clean engine corresponds to gamma equals 1, while a value of gamma less than one

Figure 3 High-pressure compressor maps in clean (solid) and fouled (dashed) conditions.
Engine Module

The engine is modeled with a 0D gas path code developed by the authors (Aldi et al., 2021). The engine architecture modeled is an unmixed-flow two-shafts turbofan. The modeling is based on a decomposition of the engine in its main components, which in this case are the fan, the high-pressure compressor, the high-pressure turbine, and the low-pressure turbine. Each one requires as input the corresponding performance maps, which are the only input needed by the model for the engine characterization. The reliability of the in-house code has been tested by comparing its results with the ones obtained with the commercial software GasTurb9. The results of the test in terms of temperature distribution along the engine are reported in Fig. 4. For a deeper analysis of the gas path code, the reader is referred to (Aldi et al., 2021). As done for the airframe geometry, since no specific gas turbine was chosen, also for the engine a summary of the design parameters is reported (Tab. 2). These values represent the default engine in the software GasTurb9, where only the mass flow rate and the TIT were varied to meet the aircraft thrust needed.

COMPRESSOR FOULING CASES AND EFFECTS

The algorithm results are obviously dependent on the choice of the degradation coefficients, which describe the effects of fouling on the high-pressure compressor. These coefficients are a function of several parameters, such as the type of contaminant ingested, the ambient conditions during the ingestion (relative humidity), the mass of contaminants ingested, etc. (Suman et al., 2017). In this work, the degradation coefficients are set by using the experimental results reported in

<table>
<thead>
<tr>
<th>Table 2 Design engine parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>By-pass ratio</td>
</tr>
<tr>
<td>TIT</td>
</tr>
<tr>
<td>Core nozzle angle</td>
</tr>
<tr>
<td>By-pass nozzle angle</td>
</tr>
<tr>
<td>HP spool speed</td>
</tr>
<tr>
<td>LP spool speed</td>
</tr>
<tr>
<td>Thrust</td>
</tr>
</tbody>
</table>
Table 3 High-pressure compressor degradation cases

<table>
<thead>
<tr>
<th>Mission</th>
<th>Cases</th>
<th>Degradation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>Clean</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mild fouled</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Severe fouled</td>
<td>0.85</td>
</tr>
<tr>
<td>3 Repeted</td>
<td>C-C-C</td>
<td>1-1-1</td>
</tr>
<tr>
<td></td>
<td>C-MF-MF</td>
<td>1-0.9-0.9</td>
</tr>
<tr>
<td></td>
<td>C-MF-SF</td>
<td>1-0.9-0.85</td>
</tr>
</tbody>
</table>

(Casari et al., 2021). In their study, they built the test rig reported in Fig. 5 with the purpose of conducting fouling tests on real turbomachinery. Specifically, in the cited work, they investigated the fouling effects on the multistage compressor unit aboard the Allison 250 C18 (see Fig. 5, bottom left). The tests were conducted in different engine operating conditions, and by using the Arizona road dust nominal $(0 – 3) \mu m$ as a contaminant. Uncertainty bars cannot be visualized since they are contained inside each marker. For a more detailed description of the test rig, the reader is referred to (Casari et al., 2021). The Authors are aware that the compressor taken as reference is scaled with respect to an actual compressor unit of a turbofan engine. The bases of our investigation are listed as follows:

- The reference compressor (Allison 250 C18) has characteristic curves in line with an actual unit (Aldi et al., 2014). Therefore, the shape of the performance curve (and its modification due to the degradation) could be assumed to be representative of a real unit;
- The coefficients of the degraded unit come from an experimental campaign conducted under controlled conditions.

Figure 5 Schematic layout of the test rig (Casari et al., 2021), and fitting model results for degrading compressor maps.
Figure 6 Change in TIT due to fouling during a mission.

This allows the accurate determination of the deposit effects by monitoring the contaminant concentration, type, and operating conditions (temperature and humidity).

- The modification (shape and magnitude) of the performance curves depends on the engine sensibility and susceptibility to compressor fouling (Meher-Homji et al., 2009). Therefore, each engine experiences different behaviour when it operates under contaminated conditions. The results reported in this paper must be intended relative to the clean conditions. The modifications of the curves have to be believed as an example to show the potential application of the methodology. Each engine (or compressor) shows a specific modification according to the experienced contamination.

It is obvious that to obtain more realistic results, experimental deposition studies have to be conducted with the same engine modeled here. Nonetheless, since the present work is mainly focused on the methodology proposed, only the physical soundness of the results was assessed rather than their absolute values.

The result of the fitting is reported in Fig. 5, bottom right. Specifically, the performance after 2 (mild fouling) and 4 (severe fouling) hours of contaminant exposition are considered, corresponding to the degradation coefficients equals 0.9 and 0.85 respectively.

In this work, the effects of compressor fouling in a single and in three repeated airline missions are analyzed. For this purpose, the cases reported in Tab. 3 are considered. For the single mission, the fuel consumption is computed in the case of a clean (C), mild fouled (MF), and severe fouled engine (SF). For the three repeated missions, the fuel consumption is estimated considering three different engine conditions:

- clean in all the three missions;
- clean in the first mission and mild fouled in the other twos;
- clean in the first mission, mild fouled in the second mission, and severe fouled in the third mission.

The results in terms of TIT (Turbine Inlet Temperature), SFC and fuel consumption during the single mission are presented in Fig. 6, Fig. 7 and 8 respectively, where also the altitude is reported (red solid line). A change in both TIT and SFC is observed throughout the mission with the increase in the fouling level, which results in higher fuel consumption. This can be better appreciated by focusing on Fig. 8. With the increase in the compressor fouling level (decrease of the degradation coefficient), the fuel consumption found after completing the mission increases by 4.6% in mild fouling conditions, and by 5.1% in severe fouling conditions. These values are in line with the ones found in the work of Igie et al. (Igie et al., 2016), where a priori mass flow rate reduction has been imposed at the engine inlet to account for fouling effects.

For what concerns the repeated missions, the results are presented only in terms of fuel consumption in Fig. 9. The study is carried out by considering three equal missions, that are a repetition of the single one previously analyzed. As it can be noted, as the fouling level increase, the fuel consumed after a set of missions grows. Specifically, extra consumption of 4.67% is found with the C-MF-MF case, and of 10.00% in the C-MF-SF case. A summary of the results found is reported in Tab. 4.
Figure 7 Change in SFC due to fouling during a mission.

Figure 8 Change in cumulative fuel consumption due to fouling during a mission.

Figure 9 Change in cumulative fuel consumption due to fouling during three repeated mission.
CONCLUSIONS

In this work, an innovative strategy to predict the fuel consumption change due to compressor fouling is proposed. Specifically, the effects after a complete aircraft mission are evaluated in order to test the methodology. The cases of a single mission and a sequence of three repeated missions are analyzed. Both the aircraft and the gas turbine are modeled with physics-based algorithms. To estimate as real as possible the engine behavior after fouling, the components maps are used to replicate the gas turbine performance. Fouling effects are accounted for by means of compressor map variations, which are obtained by experimental results acquired by an ad-hoc test rig. In this regard, three levels of degradation were replicated: clean, mild fouled, and severe fouled.

For what concerns the single mission, the fuel consumption with the three fouling levels was computed. The main result found is the increase in the fuel burn with the increase in the fouling level. A rise of 4.6% for a mild fouled engine and 5.10% for a severe fouled engine was found. Also for the three repeated missions, three degradation levels were considered. As for the single mission, also in this case the fuel consumption rise with the increase in the fouling level. Since these results are in agreement with those from the literature, the physical soundness of the outcomes can be considered achieved with the strategy proposed.

With the proposed strategy, the authors want to suggest a different approach to consider fouling in predictive maintenance, based on components map modification by using ad-hoc fouling coefficients. These last can be estimated either by experiments or numerical simulations.

NOMENCLATURE

- $a$: Aircraft acceleration
- $A$: Wing area
- $b$: Wingspan
- $C_L$: Lift coefficient
- $C_D$: Drag coefficient
- $C_{D_0}$: Zero lift drag coefficient
- $C_{D_L}$: Vortex drag coefficient
- $C_{D_W}$: Wave drag coefficient
- $e$: Oswald factor
- $F_L$: Lift force
- $F_D$: Drag force
- $F_T$: Net thrust
- $h$: Altitude
- $h_T$: Total enthalpy
- $H_{max}$: Maximum altitude
- $m_A$: Aircraft mass
- $m_{fuel}$: Mass of fuel burn
- $M_a$: Mach number
- $R_W$: Ratio of overall wetted area to the reference
- $SF$: Shape factor
- $SFC$: Specific fuel consumption
- $t/c$: Pitch to chord ratio
- $T$: Temperature
- $V_a$: Axial flow velocity
- $U$: Blade velocity at mean radius

Table 4 High-pressure compressor degradation cases

<table>
<thead>
<tr>
<th>Mission</th>
<th>Cases</th>
<th>Degradation Factor</th>
<th>$\Delta m_{fuel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>Clean</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Mild fouled</td>
<td>0.9</td>
<td>+4.60%</td>
</tr>
<tr>
<td></td>
<td>Severe fouled</td>
<td>0.85</td>
<td>+5.10%</td>
</tr>
<tr>
<td>3 Repeated</td>
<td>C-C-C</td>
<td>1-1-1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>C-MF-MF</td>
<td>1-0.9-0.9</td>
<td>+4.67%</td>
</tr>
<tr>
<td></td>
<td>C-MF-SF</td>
<td>1-0.9-0.85</td>
<td>+10.00%</td>
</tr>
</tbody>
</table>
Greek symbols
\( \alpha \) Aircraft angle of attack
\( \alpha_0 \) Zero-lift angle
\( \gamma \) Degradation coefficient
\( \Gamma \) Corrected mass flow rate
\( \theta_{sw} \) Sweep angle at the half-chord line
\( \Lambda \) Wing aspect ratio
\( \Pi \) Pressure ratio
\( \tau \) Correction factor for wing thickness
\( \phi \) Flow coefficient
\( \psi \) Pressure coefficient

References


