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HEALTH MONITORING IN AN INDUSTRIAL GAS TURBINE APPLICATION BY USING MODEL BASED DIAGNOSIS TECHNIQUES

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ABSTRACT

Monitoring of an industrial gas turbine is important since it gives valuable information for the customer about maintenance, performance and process health. The objective of the paper is to develop a monitoring system for an industrial gas turbine application with a model based diagnosis approach. A constant gain extended Kalman observer is developed. The observer compensates for different ambient conditions such as pressure, temperature and relative humidity, due to the amount of water in the atmosphere. The developed observer, extended with seven health parameters, is automatically constructed from the diagnosis model. These health parameters shall capture deviations in some of the gas path performance parameters such as efficiency, mass flow, turbine inlet area and head loss. The constructed observer is evaluated through a simulation study where the ambient conditions are changed. The considered observer capture the change in different ambient conditions nearly perfect. An observer that does not compensate for different ambient conditions gives an error for about $1-2\,\%$ *for the considered health parameters for the given test case. The constructed observer is also evaluated on measurement data from a mechanical drive site. A degradation in efficiency and mass flow for the compressor due to fouling can be seen in the estimations. After the compressor wash is performed, the degradations for the compressor are partially restored by about* $2\,\%$ *which can be seen in the considered health parameters.*

1 INTRODUCTION

In industrial gas turbine applications, deterioration of components in the gas path is common and contribute to the overall performance degradation of the gas turbine. Therefore, it is of great importance to supervise the deterioration of these components to efficiently plan service and maintenance. Monitoring of gas turbines is a widely studied topic in the gas turbine diagnosis literature, see for example Ref. [1, 2] where the performance parameters are estimated. It is desirable, by the service engineers, that it should be easy to construct and evaluate different kinds of test quantities. One idea is to construct tests directly from the gas turbine performance model.

In papers Ref. [3, 4], several mechanisms that cause degradation in gas turbines are presented. The major contribution for degradation in industrial gas turbines is fouling, caused by small particles and contaminants in the air. These particles increase the roughness of the rotor and stator surface. Another degradation effect is tip clearances which is a common diagnosis for older gas turbines. Tip clearances denotes an increasing gap between the rotating blades and the stationary casing. Fouling due to increased roughness can partially be restored by washing the compressor, while a component replacement is often needed for tip clearances. In Ref. [5], an offshore gas turbine application study is presented where different deterioration effects leads to compressor fouling.

A common solution, in the gas turbine diagnosis literature, about how to estimate deviation in performance from a nominal baseline is to introduce health parameters see e.g. Ref. [6–8]. In the two first papers, Kalman filters are used to estimate the consid-

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ered health parameters. The degradation in performance is natural, so if the model does not compensate for this degradation it can be hard to avoid sensor false alarms in the considered diagnosis model. In Ref. [9], it is demonstrated that a non-linear constant gain extended Kalman observer can be used in a wide operating range for an in-flight aircraft engine diagnosis application. These studies indicate that it is not necessary to evaluate a new Kalman gain for different operational points, such as health and power. Instead, it is more important that the gas turbine model, used to construct observers, has high accuracy.

To achieve high model accuracy, one factor that can affect the performance estimations is the humidity in the ambient air. This phenomenon is often neglected since the change in absolute humidity does not vary significantly in an industrial gas turbine application. A study performed with an investigation of humidity effects in the health parameters estimation procedure is presented in paper Ref. [10]. There it is shown that a compensation for the ambient conditions reduce the undesirable daily variations in the health parameters.

In this paper, a thermodynamic package that compensates for different ambient conditions is presented. The humidity compensation in the package was introduced because experimental evaluations indicate that the ambient temperature varies with the estimated efficiency degradation in the gas generator and power turbine. Since the gas turbine application considered in the present paper is a mechanical drive site, it is of great importance to investigate how different operating points affect the estimation of performance degradation.

The objective of the paper is to present a thermodynamic package that compensates for different amount of water in the atmospheric air due to the ambient conditions such as temperature, pressure and humidity. With this package a constant gain extended Kalman observer, with introduced health parameters, can be constructed in an automatic manner. This observer is evaluated on simulated and experimental data.

Finally, the contribution of this work is a systematic method that can be used to construct an observer for performance deviation estimations when the ambient conditions are varied. Experimental data shows that the constructed observer can be useful in the decision when a compressor wash is necessary due to fouling.

2 GAS TURBINE SIMULATION ENVIRONMENT

For this work, a twin shaft gas turbine with a specific power of 29 MW is considered. The gas turbine, SGT-700, is developed and produced by Siemens Industrial Turbomachinery in Finspång, Sweden. Since the gas turbine is twin shafted, there is no mechanical connection between the gas generator and the power turbine so it is possible to adjust the turbine speeds independently of each other. Typical applications for this kind of gas turbines are mechanical drive sites. In these applications, the gas turbine is connected to a driven component such as a pump or an external compressor and in this paper, the emphasis is on mechanical drive.

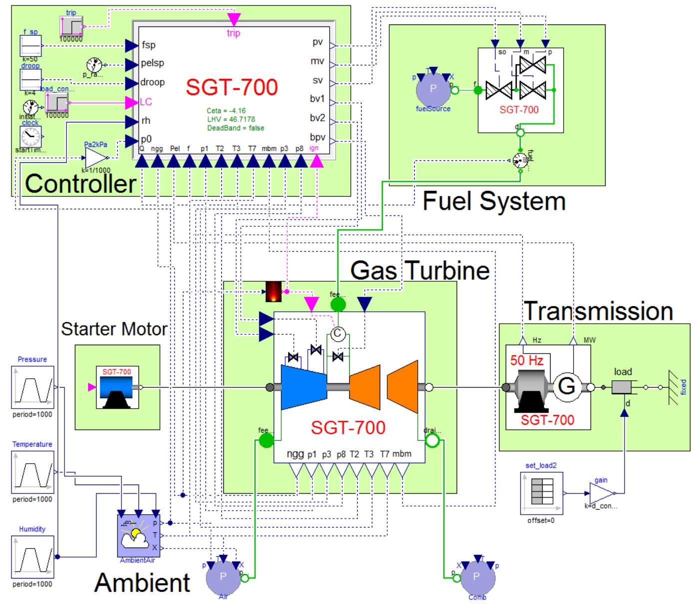

FIGURE 1. SIMULATION PLATFORM.

A simulation platform, see Fig 1, is available for the work in this paper. The simulation platform is developed and used for performance calculations by the industry partner. As can be seen in the figure, the simulation platform consists of a controller, a starter motor, an ambient air component, a fuel system, a transmission and a gas turbine. The simulation platform and its components are developed in the Modelica environment. Modelica is a modeling language that is based on differential algebraic equation (DAE), and can handle different physical domains. Here, it is a connection between the thermodynamic, mechanical and electrical domains. The gas turbine sub-model is considered large since it consists of about 2500 equations, and about 60 of these equations are state equations.

All components, except characteristics, are written in the Modelica language and are evaluated through the tool Dymola 7.2. In the characteristic calculations, corrected parameters according to Ref. [11] are utilized. These corrected parameters are for the compressor and turbine:

$$m^*_{flow} = m_{flow}\frac{p_{ref}}{p}\sqrt{\frac{T}{T_{ref}}\frac{R}{R_{ref}}\frac{\gamma}{\gamma_{ref}}} \quad (1a)$$

$$C^* = C\sqrt{\frac{R}{R_{ref}}\frac{\gamma_{ref}}{\gamma}} \quad (1b)$$

$$n^* = n\sqrt{\frac{T_{ref}}{T}\frac{R_{ref}}{R}\frac{\gamma_{ref}}{\gamma}} \quad (1c)$$

where $(*)$ and (ref) denote the corrected parameter and refer-

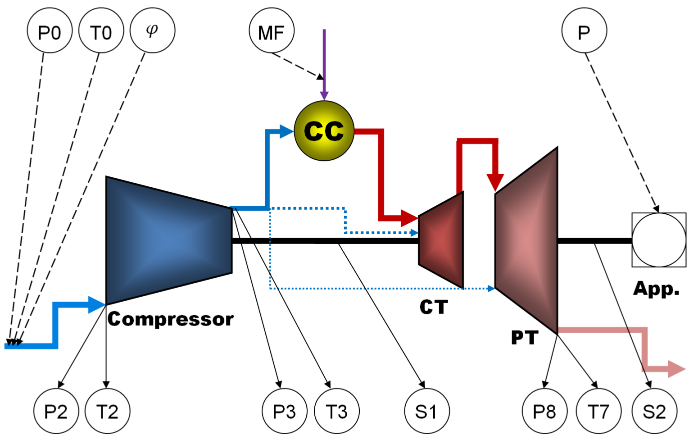

FIGURE 2. GAS PATH INPUT AND OUTPUT SIGNALS.

ence value at datum state. m_{flow}, C and n are mass flow, turbine flow number and shaft speed respectively. From these corrected parameters is n^* used, together with pressure ratio, in respective characteristic function to calculate the corrected parameters m^*_{flow} and C^*. The corrected parameter for the isentropic efficiency is also calculated for the both components.

Input and Output Signals

To get redundancy, which is necessary for diagnosis purposes, a number of measurement signals are needed. In this case, redundancy is achieved with measurements of temperatures, pressures and shaft speeds in the gas path. The total number of measured quantities are eight, and can be seen in Fig 2. These signals are temperature and pressure before and after the compressor, temperature and pressure after the power turbine and speed of the gas generator and power turbine.

To avoid a diagnosis model that also contains the fuel system, the mass flow of fuel is considered as an input signal to the model. A more appropriate solution is to include also the fuel system in the diagnosis model, and then use the signals from the controller as inputs. In that case the, the mass flow of fuel can be seen as an output signal. In the real application, the controller does not utilize the mass flow signal. Therefore the signal can be unreliable if the sensor is not calibrated. Other input signals are generated power by the application and ambient signals such as pressure, temperature and relative humidity.

3 GTLib – A THERMODYNAMIC PACKAGE

In the previous work, described in Ref. [12], a thermodynamic library suitable for performance calculation and diagnosis purpose is developed in the Modelica language. The thermodynamic properties in the library are described by the Modelica media package, which consists of gas data. These gas data are based on the well known NASA Glenn Coefficients [13]. The disadvantage of using Modelica media package, without any modification, is that the number of equations and states increase with the number of species in the gas. In GTLib, the number of equations are independent of the number of species for a given mixture. The necessary assumption is that the combustion is lean and a stoichiometric matrix is specified. In practice, gas properties in GTLib package is a wrapper between the gas state and the NASA Glenn Coefficients.

The GTLib package also consists of a number of components such as volumes, pipes, turbines, etc. For more information of these components see Ref. [12].

Diagnosis Model

The diagnosis model is a reduced and simplified version of the reference gas turbine model that is presented in Fig. 1 and is constructed with the GTLib package. Here, reduced means that the number of equation and states have decreased and simplified means that some model simplifications have been done. The diagnosis model is valid only during operational condition, i.e., not valid during stop and start phases. Input and output signals to the diagnosis model are the same as presented in Fig. 2. The output signals are used for feedback in the constructed observer.

Health parameters In the diagnosis model, health parameters can be injected in the equations that describe the performance of a certain component. The primary goal with the introduced health parameters is the ability to capture degradation in performance parameters. These performance parameters are isentropic efficiency, mass flow, turbine flow number and pressure drop. In this paper the health parameters have been added additive to the performance equation, but other constellations are possible. Health parameters are well discussed in the gas turbine diagnosis literature, see e.g., Ref. [7, 8]. Another advantage with the health parameters is the ability to avoid false alarms for sensor faults, since a natural degradation occurs in the gas turbine.

In the diagnosis model, 7 health parameters are considered. These health parameters shall capture deviations for efficiency and mass flows through compressor, efficiency and mass flows through compressor turbine, efficiency for power turbine and pressure drop in the inlet (air filter) and outlet duct. The introduced health parameters can be seen in Fig. 3.

After the health parameters are added to the diagnosis model, the mathematical form of the system is:

$$F(\dot{x}, x, \dot{h}, h, y, u) = 0 \tag{2}$$

where x is unknown variables, h is health parameters, y is measurement signals and u is input signals. Both function F and its arguments are vectors with appropriate dimensions. This is a general mathematical description, where both algebraic and dynamic

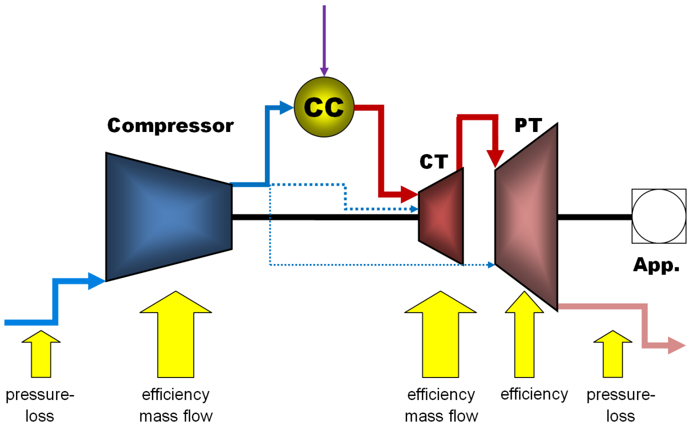

FIGURE 3. HEALTH PARAMETERS.

constraints are mixed. For a comprehensive study of DAE system see for example Ref. [14]. In the present case, the diagnosis DAE model in Eq. (2) can be written in the form according to Eq. (3), where the health parameters h capture slow deviation in performance parameters and can not be measured explicitly.

$$F_1(\dot{x}, x, h, u) = 0 \tag{3a}$$

$$\dot{h} = 0 \tag{3b}$$

$$y = g_1(\dot{x}, x) \tag{3c}$$

Gas State in a Control Volume

In GTLib, the gas in a control volume is specified through the three states temperature T, pressure p and air/fuel ratio λ. The air/fuel ratio is defined, according to [15], as

$$\lambda = \frac{m_a/m_f}{(A/F)_s} \tag{4}$$

where m_a and m_f are masses of air and fuel fluids. $(A/F)_s$is the stoichiometric air/fuel ratio and depends on the actual fluids.

Combustion stoichiometry In this case, the fluids of air and fuel consist of the species Ar, CO_2, H_2O, N_2 and O_2 respective $C_2H_6, C_3H_8, CH_4, N_2$ and CO_2. In the combustion process these fluids are considered to react according to the chemical formula:

$$\begin{aligned}
(C_2H_6 + 3.5O_2)\tilde{x}_{f,C_2H_6} &\rightarrow (2CO_2 + 3H_2O)\tilde{x}_{f,C_2H_6} \\
(C_3H_8 + 5O_2)\tilde{x}_{f,C_3H_8} &\rightarrow (3CO_2 + 4H_2O)\tilde{x}_{f,C_3H_8} \\
(CH_4 + 2O_2)\tilde{x}_{f,CH_4} &\rightarrow (CO_2 + 2H_2O)\tilde{x}_{f,CH_4} \\
N_2\tilde{x}_{f,N_2} &\rightarrow N_2\tilde{x}_{f,N_2} \\
CO_2\tilde{x}_{f,CO_2} &\rightarrow CO_2\tilde{x}_{f,CO_2}
\end{aligned}$$

where $\tilde{x}_{f,i}$ is mole concentration of substance i in the fuel. This reaction together with the incoming air gives the amount of species in the combustion gas. The substances are the same both in combustion and incoming air. The amount of argon and nitrogen are not affected by the combustion which means that, for example, no NOx is produced independently of the combustion temperature. To calculate the stoichiometric air/fuel ratio techniques from [12] can be used.

State equations Since the concentration of species through the gas path is changed, according to the combustion and the injection of cooling air in the both turbines, the classical control volume equations need an extension. In paper [12], the total energy and ideal gas law equations are extended with an equation that also handle concentration of species. In the paper it is assumed that the species in the ambient air are not changed during an evaluation, which in practice means that that absolute humidity has to be constant. For higher simulation efficiency, state equations in [12] can be expressed in states pressure p, temperature T and air/fuel ratio λ (instead of mass m, total energy and air/fuel ratio) according to:

$$mc_v\frac{dT}{dt} = H_{flow} - m_{flow}u - m\frac{d\lambda}{dt}\left(\frac{\partial h}{\partial \lambda} - T\frac{\partial R}{\partial \lambda}\right) \tag{5a}$$

$$V\frac{dp}{dt} = m_{flow}RT + m\left(R\frac{dT}{dt} + T\frac{\partial R}{\partial \lambda}\frac{d\lambda}{dt}\right) \tag{5b}$$

$$m\frac{d\lambda}{dt} = \sum_i m_{flow,in,i}\frac{(A/F)_s\lambda + 1}{(A/F)_s\lambda_{in,i} + 1}\left(\lambda_{in,i} - \lambda\right) \tag{5c}$$

where the partial derivatives of air/fuel ratio appear explicitly since the enthalpy h and the gas constant R both depend on the species fraction. m_{flow} and H_{flow} are total mass and energy flow into the control volume and u is the internal energy. To derive Eq. (5a)-(5b) the relationship of total energy $E = mu$, enthalpy definition $h = u + RT$ and the ideal gas law $pV = mRT$ are considered. The small indices *in* mean that the state is only affected by the incoming variable.

The partial derivatives, according to the air/fuel ratio are calculated as:

$$\frac{\partial R}{\partial \lambda} = \frac{(A/F)_s}{(A/F)_s\lambda+1}(R_{air}-R) \quad (6a)$$

$$\frac{\partial h}{\partial \lambda} = \frac{(A/F)_s}{(A/F)_s\lambda+1}(h_{air}-h) \quad (6b)$$

where R_{air} and h_{air} are the gas constant and enthalpy of the ambient air. These parameters can be calculated with a large λ in the function call. For simplicity, the variable dependencies are omitted in Eq. (5)-(6). In fact, heat capacity $c_v(T,\lambda)$ and enthalpy $h(T,\lambda)$ are both dependent on T and λ. The gas constant $R(\lambda)$ only depends on λ. In the GTLib package, these parameters are implemented as functions of the dependent variables.

In Eq. (5)-(6), the product $(A/F)_s\lambda$ remains constant independently of the stoichiometric air/fuel ratio. This means that the product is unchanged even when the ambient conditions are modified. This is obvious, since mass flow ratio in Eq. (4) is unchanged independently of the ambient air. The density of the gas depends on ambient condition, but here, the mass flow is proportional to the pressure drop, so the mass flow ratio is not affected by the ambient humidity. So the conclusion is, if it is not desirable to have an explicit value of the air/fuel ratio it is not necessary to calculate a value for the stoichiometric ratio.

In this paper, the objective is to handle different ambient conditions. This extension procedure can be done in the following steps:

1. Calculate concentration of species in the ambient air, i.e., use a moist air model.
2. All thermodynamic function, such as $h(T,\lambda)$, $c_v(T,\lambda)$, $R(\lambda)$, etc,. are now dependent on the ambient air and need to be updated.
3. When the thermodynamic functions are updated, the air/fuel ratio gives the concentration in the exhaust gas when the stoichiometric matrix and mass flow of fuel are utilized.

These steps are instantaneous updated in all control volumes in the gas turbine model, which results in an error during dynamic changes of the fluid due to different ambient conditions. Simulation experiences have shown that this is not a problem since the high throughput speed in the gas turbine.

Ambient Condition

To imitate more realistic environment conditions, a moist air model is introduced in the GTLib package. Here, a gas model for the saturation pressure of water described by Buck in Ref. [16] is utilized. This expression is well used in the meteorological context and has high accuracy in the region of -80 to 50^oC. The saturation pressure of water is described by:

$$p_{(H_2O)_s} = 6.1121 \cdot \left(1.0007 + 3.46 \cdot 10^{-3} p\right) \cdot \exp\left(\frac{17.502T}{240.97+T}\right) \quad (7)$$

where the ambient temperature T is expressed in Celsius and the absolute pressure p is expressed in bar. The saturation pressure of water $p_{(H_2O)_s}$ is expressed in hectopascal.

The relative humidity, see for example Ref. [15], is defined according to:

$$\varphi = 100 \cdot \frac{p_{H_2O}}{p_{(H_2O)_s}} \quad (8)$$

so it is possible to calculate the partial pressure of water vapor. Here it is assumed that the moist air consists of dry air and water steam, so the partial pressure of dry air is simply equal to the difference in atmospheric pressure and the partial pressure of water vapor, i.e., $p = p_{H_2O} + p_{air}$. This, together with ideal gas law, gives an expression for the mass fraction of water according to:

$$x_{H_2O} = \frac{p_{H_2O}R_{air}}{p_{H_2O}R_{air} + p_{air}R_{H_2O}} \quad (9)$$

Since the mass fraction of species in the dry air is known, the mass fraction of the moist air is also determined. When the moist air medium is known, it is possible to calculate thermal properties such as enthalpy and heat capacities as a function of temperature and air/fuel ratio in the gas path. It can be noted that a change in the absolute humidity in the ambient air affect the stoichiometric air/fuel ratio for a given hydrocarbon fuel. How the amount of water depends on the ambient condition such as relative humidity and temperature can be seen in Tab 1.

TABLE 1. MASS OF WATER, IN GRAM, FOR 1 KG MOIST AIR AT DATUM PRESSURE 1.013 BAR.

T (C^o)	$\varphi = 40$ %	$\varphi = 60\%$	$\varphi = 80\%$
15	4.21	6.33	8.45
20	5.78	8.69	11.61
25	7.85	11.80	15.78
30	10.53	15.85	21.20
35	13.99	21.08	28.22

It can be seen in the table that the amount of water in the air increases drastically with temperature and humidity. On the other hand, the stoichiometric air/fuel ratio is changed only about 2.5% from the datum state for the considered fuel.

4 OBSERVER DESIGN

To estimate change in health parameters, the concept of Kalman filters are utilized in the present paper. Here, a variant of a constant gain extended Kalman observer (CGEKF) is automatically generated. In Ref. [9], a CGEKF for an in-flight engine performance estimation procedure is utilized. In the present paper, the CGEKF switches between two constant feedback gains. If two gains are utilized, it is possible to switch between an observer with fast and slow dynamic. In the start and after a compressor wash it is desirable to have an observer with fast dynamic to avoid to specify appropriate initial conditions of the observer.

The starting position for the observer construction algorithm is the diagnosis DAE model defined in Eq. (3). This design procedure contains a number of important steps. An overview of these steps can be seen here, but for a more comprehensive study see the previous paper in Ref. [12]. The design procedure is:

1. If y in Eq. (3) is considered as a known signal vector, the system in Eq. (3) gets overdetermined. If the measurement equation $y = g_1(\dot{x}, x)$ in Eq. (3) is removed, then the system gets exactly determined which is required in the next step.
2. Acquire the structural model of the system.
3. Check and reduce the DAE index of the system (if necessary). For this step, Pantelides algorithm [17] is utilized and the input to the algorithm is the structural model.
4. Add the removed sensor measurement equations from step 1.
5. Update the structural model.
6. Find an overdetermined part of the structural model, i.e., remove all exactly determined parts. For this step a Dulmage-Mendelsohn decomposition is made [18] and the whole overdetermined part is picked out.
7. An ordinary state space form is now obtained.
8. Construct an observer for the state space equations.

The structural model is a coarse model description where only the variable dependencies in each equation are considered, see e.g., Ref. [19]. The structural model is suitable for large systems where relevant part of the model, for diagnosis, can easily be extracted, see Ref. [20]. The constructed observer from step 8 has the form:

$$\dot{\hat{z}} = f(\hat{z}, u) + K(y - h(\hat{z})) \tag{10a}$$

$$\hat{y} = h(\hat{z}) \tag{10b}$$

where $\hat{z}$ is the estimated state vector. Note that $\hat{z}$ is not an estimation of the unknown variable in Eq. (3). The system in Eq. (3) contains parts that is not relevant in the estimation procedure and are therfore removed. Here, the health parameters are included in the state variable $\hat{x}$. For a complete description of the observer design procedure, see the previous paper in Ref. [12].

The Kalman gain K in Eq. (10) is calculated for the linearized system achieved in step 7 above. The linearization is made for an operation with a generator with frequency 50 Hz and generated power 21 MW. The ambient conditions are at datum state, i.e., $p_0 = 1.013\,\text{bar}, T_0 = 15\,\text{C}^o$ and $\varphi = 60\,\%$. Generated power of 21 MW was chosen because measurement data is available around this stationary operation point.

The design parameters for the observer are the noise covariance matrices Q and R. These matrices are used for tuning the estimation, i.e., the ratio between *fast and noisy* or *slow and filtered* estimations. In this case, except for start up, the health parameters have slow dynamic. To do relevant comparisons in different cases the covariance matrices are determined once, and after that they are not changed.

Ambient Compensation in the Observer

In previous paper, the constructed observers did not compensate for different ambient conditions. This means that the gas properties, such as enthalpy, entropy, etc., are the same even if the concentration of species in the air are different. As discussed earlier, these thermodynamic parameters need to be updated and this is done automatically in the GTLib package. An example what happens if no update is done, is that the gas constant R in the corrected parameter in Eq. (1a) is constant, or equal to R_{ref}, for the corrected mass flow through the compressor. So different ambient inlet conditions are not captured by the characteristics. Another example is that the combustion temperature is decreased if the fluid consists of more water. Note that the change in ambient temperature is captured by the thermodynamic properties although in the case of an observer that not compensate for different ambient conditions.

In the next section, two observers is compared where the absolute humidity in the air is changed.

5 OBSERVER EVALUATION

In this section two test cases are demonstrated. In the first case, two observers, one that compensate and one that does not compensate for humidity in the ambient air, are compared. In the second test case, measurement data from a gas turbine site is evaluated. In both cases, in addition to the deterioration estimation parameters, also friction losses, pressures and temperatures in the gas path can be estimated. For example, the inlet compressor turbine mixed temperature can be relevant to supervise.

Different Ambient Condition

In the first test case, two observers one that compensate and one that does not compensate for humidity in the ambient air are constructed. The observer that does not compensate for humidity in the air is developed for the fixed ambient conditions $p_0 = 1.013\,\text{bar}$, $T_0 = 25\,\text{C}^o$ and $\varphi = 60\,\%$. Input data to the two observers is collected from the simulation platform viewed in Fig. 1. In this test case, ambient temperature is varied according to $15 - 35\,\text{C}^o$ and relative humidity is varied according to $40 - 80\,\%$. At the same time, power generated by the electric motor, is varied in the interval $16-26$ MW. Because of the varied power, the gas generator speed is also varied. The goal is to estimate performance deterioration, therefore is a deviation, in percent from respective baseline reference value, injected in the performance parameters according to the tabular below:

1. Compressor efficiency deviation δ_{C1} is -3.4 % from nominal ref. value.
2. Compressor mass flow deviation δ_{C1F} is -2.5 % from nominal ref. value.
3. Compressor turbine efficiency deviation δ_{T1} is $+2.4$ % from nominal ref. value.
4. Compressor turbine area deviation δ_{T1A} is $+4.6$ % from nominal ref. value.
5. Power turbine efficiency deviation δ_{T0} is -1.2 % from nominal ref. value.
6. Inlet duct deviation δ_{IN} is 0 % from nominal.
7. Outlet duct deviation δ_{OUT} is 0 % from nominal.

The results from the estimation procedure are presented in Fig. 4. The five first sub-figures show the estimated degradation in the gas path for previous defined components. The two last sub-figures show the generated power and the amount of water in 1 kg in the atmosphere. The highest and lowest value denote the two extreme cases from Tab. 1. For this two extreme, the deviation estimation for the observer that does not compensate for the amount of water is between $1-2$ % for all cases except the efficiency for the compressor turbine. The observer that compensates for different amount of water follows the injected deterioration perfectly, except during transients. One explanation is that gas properties, according to the change in ambient air, is updated simultaneously in the whole observer. It can also be seen in the figure that different operating points does not affect the estimations, but here, a generator is connected to the power turbine so the speed of the turbine is constant. At a mechanical drive application, the power turbine speed can also be changed.

Mechanical Drive Site Data

In the second test case, measurement data from a mechanical drive site, located in the middle east, is evaluated. The ambient air at this site is dry and the environment consists of a high grade of air pollutions, such as sand, salt and oil. This results in frequently compressor fouling, so the customer need to shut down the gas turbine for maintenance and clean the compressor quite often. As can be seen in Fig. 5, a sequence of 20 days is studied. The parameters that are viewed in the figure are exactly the same, except the two last sub-figures, as in the previous test case. In the two last sub-figures speeds of gas generator and power turbine are showed in thousand rpm. The amount of water in the surrounding air is calculated according to Eq. (9), and the absolute level is pretty low and does not vary to much. So in this test case, an observer that is calculated for the datum ambient point is sufficient

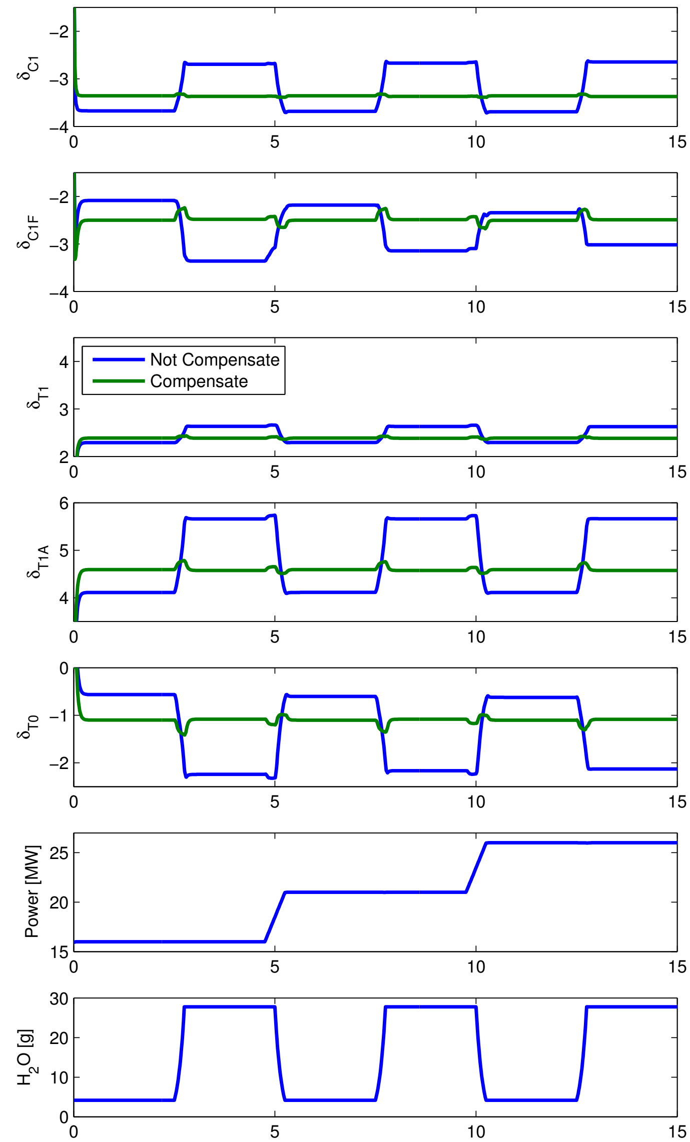

FIGURE 4. PERFORMANCE DETERIORATION ESTIMATION.

to consider. Simulations also indicate that this is true, but are omitted here for simplicity.

mechanical The estimations of the degradation in the both turbine are quite volatile. One idea for this phenomenon is the lack of a temperature sensor between the both turbine. A incorrect estimation of this temperature signal, gives unreliable values of the degradation estimations. It can be seen in the figure that it is an inverse correlation between the efficiency in power and compressor turbine, i.e., when efficiency of the power turbine goes up efficiency of the compressor turbine goes down. The inlet area deviation for the turbine is quite large, i.e., more than 10 % from the reference value. The large deviation can be interpreted

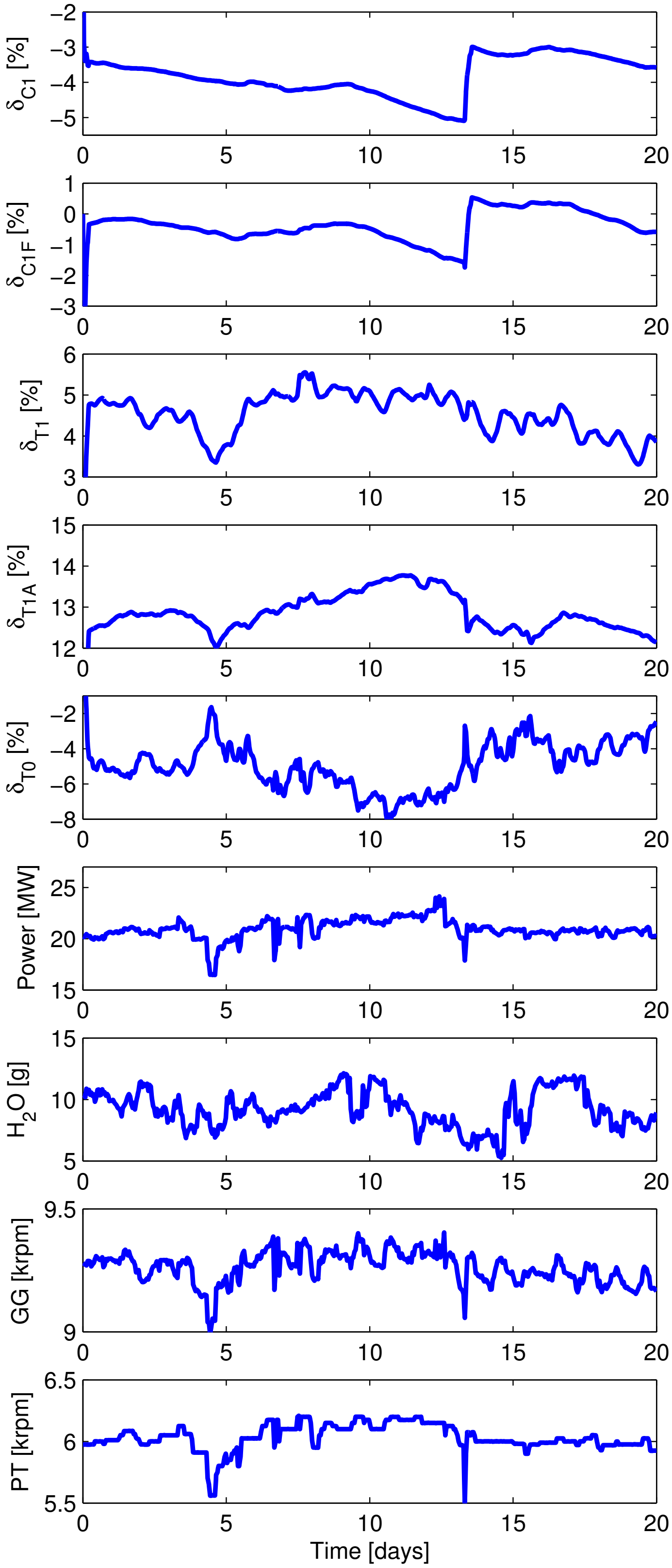

FIGURE 5. ESTIMATED HEALTH PARAMETERS FOR A MECHANICAL DRIVE SITE.

as a leakage in the turbine, or an increased clearances between the rotor and stator. If the pressure ratio over the compressor is studied, it can be noted that the ratio is much less than for the nominal model.

The two first sub-figures in Fig. 5 describe the performance deviation for efficiency and mass flow in the compressor. These parameters capture the degradation due to fouling well. After the compressor wash at day 13, the performance is partially restored about 2 %, as the figure indicates. After the wash, the performance starts to degrade once again. The observer with fast dynamic is used just after the compressor wash for a short time period.

6 CONCLUSIONS

In this paper, a thermodynamic package, written in the modeling language Modelica and suitable for gas turbine performance modeling, is presented. In the package, different amount of water steam in the incoming air can be considered, according to the ambient conditions such as pressure, temperature and relative humidity, during a simulation. An advantage, with models constructed in the GTLib package, is that nearly the same model can be used both for performance and diagnosis purposes. Here, the diagnosis model is augmented with seven health parameters that shall capture deviation in the performance through the gas path. After the diagnosis model is augmented with relevant parameters, a constant gain extended Kalman observer can be extracted in a systematic manner. In this paper, two test cases are studied in this paper where the observer is evaluated on data collected from the simulation platform and measurement data collected from a mechanical drive site.

The constructed observer, that handle different amount of water steam in the incoming air is compared with an observer that is constructed for the ambient datum state. Data for the evaluation is gathered from the simulation platform, where certain component deteriorations are introduced. The observers try to estimate the injected degradation and simulation results show that the observer that compensates for the different ambient conditions capture the degradation nearly perfect. The estimation difference between max and min for the observer that does not compensates for ambient conditions is about $1-2\,\%$.

The constructed observer is evaluated on measurement data from a mechanical drive site. It is possible to see a 2 % degradation, in efficiency and mass flow for the compressor, due to fouling. After the compressor wash, the degradation is partially restored. For this test case, the amount of the water in the incoming air is not varied significantly according to the location of the site.

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NOMENCLATURE

CGEKF	Constant Gain Extended Kalman Filter
DAE	Differential Algebraic Equation
T	Temperature
p	Pressure
m	Mass
R	Gas constant
h	Enthalpy
u	Internal energy
c_v	Heat capacity
E	Total energy
H	Enthalpy flow
V	Volume
γ	Isentropic exponent (specific heat ratio)
C	Turbine inlet area
n	Shaft speed
φ	Relative humidity
m_{flow}	Mass flow
λ	Air/fuel ratio
λ_{in}	In-flowing air/fuel ratio
$(A/F)_s$	Stoichiometric air/fuel ratio
δ	Health parameter
x	Mass fraction
$\tilde{x}$	Mole fraction
(ref)	Reference value
$(*)$	Corrected parameter

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