Efficiency Increase and Start-Up Strategy of an Axial Turbine Stage Under Periodic Inflow Conditions Using Extremum Seeking Control

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Abstract. Since the efficiency increase of state-of-the-art gas turbines has become incrementally smaller, a significant improvement seems unlikely using the established concepts. Replacing the underlying constant pressure combustion with a constant volume combustion may change this and may yield significant efficiency increases. A possible realization of such a machine can be accomplished using firing tubes that utilize pulsed detonation combustion. This results in unsteady, periodic boundary conditions, generating challenges to the operation of the machine. A possible solution to operational difficulties is presented here using extremum seeking control (ESC). This model-free, easy to parameterize control approach is tested using a mock-up test rig designed specifically to mimic the pulsed flow conditions in front of an axial turbine. The ESC is defined in such a way that it maximizes either the calculated turbine efficiency or the specific work that is converted by the turbine by changing the synchronization between firing tubes only, leaving the parameter space of single firing events unaffected. Further, a concept for the start-up of such a gas turbine using ESC is introduced.

Keywords: Extremum seeking control · Pulsed detonation combustion · Axial turbine · Efficiency increase · Closed-loop control

1 Introduction

The accomplished efficiency gains of state-of-the-art gas turbines have been decreasing over time [1] due to the fact that the efficiency increase was mainly driven by the evolutionary improvements of single turbine components. Therefore, it seems unlikely that such an approach will yield significant efficiency improvements in the future.

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One possible option to push beyond the estimated limits of state-of-the-art gas turbines is through a change of the underlying thermodynamic cycle. Current gas turbines utilize the Brayton cycle. It has been theoretically shown that if this cycle were replaced by the Humphrey cycle, an additional increase in thermal efficiency would be attainable [2], possibly allowing an expansion of current efficiency limits of gas turbines. The necessary Humphrey cycle must be realized by a change from the currently used isobaric combustion process to an isochoric one.

Different technical approximation approaches to an isochoric combustion process have been published, e.g., rotating detonation combustion (RDC) [3], shockless explosion combustion (SEC) [4], and pulsed detonation combustion (PDC) [5]. SEC and PDC applications are considered here. However, for reasons of space, explanations are only given in reference to the PDC case.

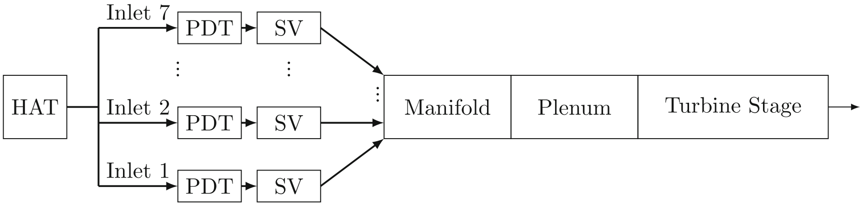
A PDC-based gas turbine features several detonation tubes. These are driven in a cyclic manner, where each cycle is divided into three stages: actual combustion of a combustible mixture, purging of the detonation tube, and refilling of the tube for the next cycle. Due to the pulsating nature of detonation tubes, it can be expected that other machine components will experience non-constant boundary conditions. A turbine positioned downstream will therefore experience not only an inhomogeneous periodic inflow over time, but also strong pressure and velocity fluctuations. The non-constant inflow to the turbine might decrease the overall efficiency of the machine. This should be mitigated for obvious reasons, passively by the coupling of machine components, e.g., the detonation tubes and the turbine, using buffering elements such as plena, or actively, e.g., through control.

A possible reduction of pressure fluctuations in front of a turbine stage under pulsating inflow conditions has been investigated in [6], using a mock-up turbine test rig for the analysis of the turbine behavior under pulsating inflow conditions [7]. In [6], a suitable operation mode minimizing the pressure fluctuations in front of a turbine stage using only the synchronization of firing tubes has been shown, based on a combination of an optimal open-loop control and a closed-loop control using extremum seeking. The applied ESC was chosen as a closed-loop control approach because it is model free, is easy to parameterize, and allows for the compensation of model uncertainties. Furthermore, disturbances are rejected that are not addressed by open-loop control alone. While a successful operation regarding the minimization of pressure fluctuations was already shown, the versatility of ESC regarding possible different operational objectives was not investigated. In this contribution, it is shown how such an ESC approach can be used to maximize not only the specific work, but also the efficiency of a turbine stage using only the synchronization between the firing events. Further, a possible start-up concept for a multi-tube PDC gas turbine is introduced and applied using the so-called TU Pulse test rig.

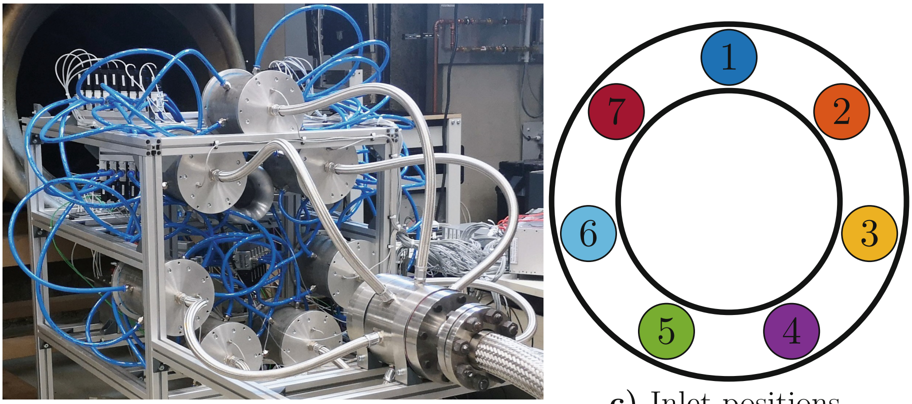
The remainder of this contribution is organized as follows. Section 2 describes the turbine test rig to which the proposed concepts were experimentally applied. In Sect. 3, the basic concept of ESC and the implemented algorithm are presented. Section 4 defines the different applications of ESC-supported operation that were addressed, and results are shown and discussed in Sect. 5. A conclusion is drawn in Sect. 6.

2 Experimental Setup

The TU Pulse test rig was designed for preliminary studies of the behavior of a PDC-based gas turbine. It represents the link between combustion tubes and the first stage of the actual turbine. The setup was specifically designed for research focusing on the turbine behavior under pulsating inflow conditions. Therefore, no actual combustion was needed in this test rig, but mock-up tubes mimicked the impulse-like character from fluid discharge of an actual unsteady combustion system. Detailed information characterizing the rig can be found in [7]. Here, a short overview defines the main characteristics. The most important elements that affect the flow of the test rig are exemplified by the block diagram in Fig. 1a), and an additional impression of the realization is given in Fig. 1b).



a) Block diagram of components affecting flow.



b) Actual test rig.

c) Inlet positions.

Fig. 1. TU pulse.

The setup was operated with air from the so-called Hot-Acoustic-Test-Rig (HAT), a joint facility of German Aerospace Center (DLR) and Technische Universität Berlin [8], which supplied it with an air mass flow of up to $0.78\,\mathrm{kg\,s^{-1}}$, with a maximum flow temperature of 823 K. The supplied air mass flow was distributed into seven inlets, where each represents a PDC combustion chamber. Figure 1c) exemplifies the inlet positions. In each inlet, a pressure damping tank (PDT) serves as a hot air reservoir. It decouples upstream effects of the different inlets. Additionally, a battery of six parallel connected solenoid valves (SVs) was installed at the end of each inlet.

The SVs were packed to a battery of five synchronously controlled valves and a single permanently opened one. From this point, each battery is referred to as one SV. The permanently opened SV in each inlet was used to create a steady base mass flow to the components downstream to reduce the strain on the turbine stage. The ends of the inlets were linked to a manifold, which was connected to a turbine stage via a small plenum. The turbine stage was mechanically coupled to a compressor to allow for load adjustment. For the experiments published here, only a subset of available sensors of the TU Pulse were used. Temperature measurements were done with type-K thermocouples. The sensor measuring the upstream turbine temperature, T_4, was mounted into the 12 o'clock position (first inlet) in the manifold, while the sensor measuring the downstream temperature, T_5, was mounted into the 3 o'clock position behind the turbine. The total pressure upstream of the turbine, p_{T4}, was obtained using a pitot tube, which was mounted in the line of sight of the fourth inlet position in the plenum in front of the turbine. The total pressure, p_{T5}, was determined using a five-hole probe downstream of the turbine. The corresponding pressure and temperature values were time-averaged over two actuation periods. Further, six pressure sensors with a high bandwidth (Kulite XTEH-10L-190) were flush-mounted in the circumference of the plenum. These sensors were used to characterize the pressure fluctuations in front of the turbine stage. In all performed experiments, the supplied air mass flow was $0.27\,\mathrm{kg\,s^{-1}}$, resulting in an operation point of 50% of the calculated design rotation speed of the turbine.

The rotation speed was measured using a laser and a photodiode, which generated a TTL-signal that was evaluated by an integrated counter. In all performed experiments, an inflow temperature of around 293 K was used. For the actuation of the test rig, impulse-like flows coming from the inlets, so-called firing events, were defined and realized through the application of control signals to the battery of SVs in each inlet. A firing event was defined by periodically opening and afterwards closing an SV with a defined firing frequency f and duration, given as duty cycle. During the experiments, the duty cycle was set to 50%, which described the part of an actuation period during which a valve was opened. The associated firing frequency was fixed at 20 Hz in all experiments. The beginning of a firing event within a period was defined as the firing instant or trigger. The synchronization between the firing instants in a common period defined the firing pattern, which was later changed by the controller. The upper part of Fig. 2 shows, for example, a generic firing pattern, which was used as a starting point for each experiment. The peaks indicate the firing instants of this pattern. In the lower part of Fig. 2, the resulting control signals of the corresponding SVs can be seen, where 1 indicates an open SV and 0 a closed one.

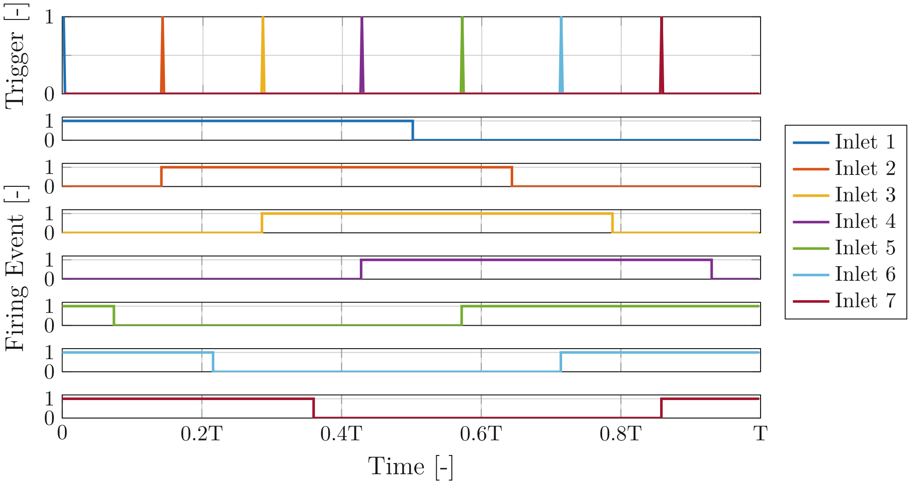


Fig. 2. Reference firing pattern defined by triggers and corresponding firing events over a period with $T = 1/f$.

2.1 Characterization of the Turbine Behavior

For the application of an ESC, an objective function must be defined that describes the system behavior in such a way that the control can either maximize or minimize this objective function to achieve a desired effect. Here, three figures of merit based on the sensor values of the TU Pulse were used as objective functions: specific work, turbine efficiency, and variance of the pressure sensor signals in front of the turbine. The specific work $\tilde{w}$ can be characterized by Eq. (1) [9]

$$\tilde{w} = c_p(T_5 - T_4) \quad , \tag{1}$$

with c_p representing the specific heat capacity in kJ/(kgK), which is assumed to be constant here. The temperatures T_4 and T_5 are given in K. While T_4 and T_5 can be measured directly in the setup, such a direct calculation should be treated carefully because of measurement noise and sensor dynamics. The first can be compensated for online through filtering, but this induces additional delays that must be accounted for in further examination. In the evaluations performed here, we have used a moving average filter of the obtained signals over two full actuation periods to compensate for measurement noise. The dynamic of the sensors and the influence of the filters are addressed by a delayed analysis within the ESC. While the specific work can be a useful characterization of the turbine behavior, one of the main parameters to describe the performance of a turbine is the isentropic efficiency η, which is described by [9]

$$\eta = \frac{1 - \frac{T_4}{T_5}}{1 - (\frac{p_{T5}}{p_{T4}})^{(\frac{\kappa - 1}{\kappa})}} \quad , \tag{2}$$

where κ represents the heat capacity ratio, which is assumed to be constant here. Similar to the specific work, a direct calculation of the efficiency is omitted and the signals that are used in this calculation are filtered by a moving average over two actuation periods. Notice that this averaging approach will result in a higher boundary estimation of the real efficiency, as is discussed in [10]. Since a high resolution in time of the efficiency would require temperature sensors with a very high bandwidth, which were not used in the setup, this estimation had to be used.

As discussed in [6], a possible operation strategy for a turbine under pulsating inflow conditions could be defined by a homogenization of the pressure field in front of the turbine. The homogeneity of the flow can be characterized by the variance σ^2 of all $n_y = 6$ pressure sensors y_i, based on two full actuation periods in the circumference of the plenum upstream of the turbine. With $2n_p$ discrete measurement points,

$$\sigma^2 = \frac{1}{2n_p n_y} \sum_{k=0}^{2n_p-1} (\sum_{i=1}^{ny} y_i^2(k)) - (\frac{1}{2n_p n_y} \sum_{k=0}^{2n_p-1} (\sum_{i=1}^{ny} y_i(k)))^2 \tag{3}$$

follows.

3 Extremum Seeking Control

ESC is a model-free control approach that can be applied if the control target is defined as a maximization or minimization of a static objective function. The basic idea behind ESC is an online, gradient-based optimization. To that end, the gradient of the objective function with respect to the control inputs is estimated. Depending on the system and the problem formulation, the gradient can be estimated in a continuous or discrete fashion. More specifically, a gradient approximation is obtained by applying perturbations to the control input. As a model is not required in ESC, it can be used as well in systems too complex or too uncertain to be modeled. However, this advantage comes at the cost of time-consuming gradient estimations, which additionally scale with the number of control variables. As a result, a rather slow convergence toward an extremum occurs. Moreover, a gradient-based search does not guarantee finding the global optimum. Because ESC does not stop the perturbations of the control input, even when the desired extremum or its neighborhood is reached, the value of the objective function is not held constant using ESC, but oscillates near the extremum.

The control input that is investigated in this contribution is the firing pattern, which consists of seven firing instants in total. Since all firing tubes use the same frequency, the number of required control inputs to define a firing pattern can be reduced to six by relating them to a fixed firing instant of a first tube.

As objective functions, the efficiency, the specific work of the turbine, and the pressure variance in the plenum are examined here.

Since the consequences of a change of the firing pattern appear only when a full firing period has passed, no continuous actuation of the system is possible. Therefore, no standard ESC approach as described in the literature can be used here. Instead, an approach called 'iterative learning control based on extremum seeking' [11] will be exploited. This was already applied for the minimization of the pressure variance in front of a turbine stage under pulsating inflow conditions in [6]. The basic idea behind this ESC approach is that a discrete optimization of the objective function performed subsequently over several iterations. Given an iteration step, an open-loop control is applied to the system. The system response at each time step in the iteration is recorded and evaluated in the cost function at the end of this iteration step. Using this value of the objective function, a new control trajectory for the next iteration is calculated and applied to the system, resulting in a closed-loop control over the iterations. As an easy to parameterize approach for the minimization of the objective functions, a gradient descent approach with a simple finite difference gradient estimation was used. The applied algorithm can be summarized as follows [6]:

Adapted Gradient Descent ESC Algorithm:

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1. Define iteration counter as $j = 0$ and perturbation counter as $n = 0$.
2. An initial open-loop control $\underline{u}_{j,n}$ is applied to the system.
3. After a fixed amount of time is passed and a steady state of the
   system has been attained, the cost $Q(\underline{u}_{j,n})$ is evaluated.
4. The perturbation counter is increased to $n = n + 1$ and the $(n + 1)$st
   entry in the open-loop control $\underline{u}_{j,n}$ is perturbed with a small, fixed
   value $d$.
5. The previous two steps are repeated until all possible perturbations
   with a perturbation size of $\pm d$ were realized.
6. The attained objective function values are used to estimate the
   gradient $\underline{g}$.
7. $n = 0$ and $j = j + 1$ are set, and $\underline{u}_{j,0} = \underline{u}_{j-1,0} + \lambda \underline{g}$ is calculated.
   Afterwards, the algorithm starts with step 2 again.
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The parameter λ represents a step-size and d the perturbation amplitude. Both represent the only tuning parameters in this approach and were chosen through manual tuning in this contribution, starting with low values respectively. $d = 0.01$ was applied in all experiments; the varying values of λ are given below. The first initial open-loop control was defined in all experiments as the reference firing pattern, which was shown in Fig. 2. The fixed amount of time that is defined in the algorithm before a steady state is reached and evaluated was defined very conservatively with a length of 40 times the actuation period. This was done to eliminate the delaying influence of the used filtering of the objective functions and to guarantee that no transient behavior was falsely accounted for in the evaluation. For simplicity reasons, the ESC was always performed as a minimization. Therefore, in the experiments maximizing the efficiency, the actual objective function was defined as the efficiency times -1, but for a more intuitive understanding, the efficiency will be shown in the results. Further, in the performed experiments, the applied firing instances were normalized over the period length T using $\underline{u}^*_{j,n} = \underline{u}_{j,n}/T$ to represent the firing pattern in an interval between 0 and 1.

4 Applications Using ESC

In this contribution, multiple possible ways for the operation of a PDC-based gas turbine using ESC are presented. While simple maximization or minimization of system states, e.g., the specific work and the efficiency of the turbine, can be done using ESC, an ESC-supported start-up strategy for a PDC-based gas turbine is also introduced.

4.1 Maximization of Efficiency and Specific Work

The simplest operational goal can be defined as a maximization or minimization of possible objective functions characterizing the machine. Here, two possible targets are considered: the absolute value of the specific work and the efficiency of the turbine. As will be shown in the results, these characteristics depend on the applied firing patterns used in the actuation of the test rig. Hence, the introduced ESC approach can be applied directly to the test rig. Note that the specific work of the turbine has a negative magnitude due to its definition and is therefore minimized.

4.2 Start-Up Strategy of a PDC-Based Gas Turbine

A starting process of a multitube PDC-based gas turbine may be challenging due to the intrinsic nature of such a machine. One possible starting strategy can be defined by beginning to fire with the PDC tubes with no evaluation of feedback and readjustments. After a start-up is completed successfully, the parameters defining the firing events, e.g., fuel mass per firing event, firing pattern, and firing frequency, could be modified steadily until a desired operation point is reached. While such a start-up approach would be easy to define, possible drawbacks may occur in actual operation. For instance, the interaction of multiple tubes within the starting process may affect the start-up. Since all firing tubes are connected via a plenum with the turbine and each firing event excites the pressure field in front of the turbine, induced pressure fluctuations resulting from one firing event may affect other firing tubes. This could result, e.g., in a suboptimal purging and/or refilling of firing tubes that would therefore affect new firing events, thus possibly cascading in an unstable operation mode.

As a possible alternative start-up strategy, an ESC-supported starting process is introduced here that considers the possible interactions of multiple firing tubes. This approach can be subdivided into two phases, i.e., continuous operation of all tubes as in a conventional gas turbine to start the rotation and then changing of the firing mode of individual tubes to an unsteady operation. The instant at which each combustion tube starts to fire in the PDC mode can then be defined manually, e.g., by an operator, or by a pre-defined function.

To determine when an additional firing tube should be added to the unsteady operating tubes, the output signals coming from the machine could be used. One possible signal to determine whether the unsteady operation should start in the next combustion tube could be the variance of the pressure sensor signals in the plenum that characterizes the corresponding pressure fluctuation. In the approach described here, the pressure variance is minimized through a firing pattern altering ESC, ensuring that a desired state is reached. Further, after each added combustion tube, the power of the conventionally working tubes is reduced to reach the desired operation point of the complete system. This procedure is repeated until all combustion tubes fire in PDC mode.

In the experiments performed in the cold test rig, we used an operator-based determination to decide when an additional firing tube should be added. This decision was made using the variance of the pressure sensor signals, as defined in Eq. (3), that was minimized through the ESC over the start-up process. Additionally, a cold bypass stream was used to start the turbine rotating. Further, since no extra inlets exist at the test rig, which allowed for the supply of a bypass mass flow, the mass flow was channeled through the firing inlets that were not yet added to the operation by keeping all the corresponding SVs open. In the first phase of the start-up and after each added firing inlet, the supply mass flow through the HAT was manually adapted by the operator in such a way that a mass flow of $0.27\,\mathrm{kg\,s^{-1}}$ was maintained.

5 Results

5.1 Efficiency and Specific Work Increase

An experiment to maximize the turbine efficiency, as calculated in Eq. (2), was performed using an ESC that adapts the firing pattern, named η-ESC. In Fig. 3, the applied firing pattern and the corresponding online calculated efficiency are shown. The latter is represented as a percentage of the efficiency that was measured in an experiment using the same inflow conditions, e.g., mass flow and design rotation speed, but no pulsation (relative efficiency).

Starting from a relative base efficiency slightly above 85% compared to the steady flow case, using the reference pattern, the conservatively parameterized ESC with $\lambda = 0.05$ adapted the firing pattern in such a way that a relative turbine efficiency of around 105% was reached at the end of the experiment. This resulted in a significant increase of 20% points in relative efficiency compared to the reference case with no changes to the inflow conditions other than the firing pattern. A convergence into three clusters of the firing instants that define the pattern can be seen in subfigure b), where the firing instants are shown as normalized to an interval of $[0, 1]$. This interval represents the length of an actuation period of 0.05 s.

Note that the upper limit of 1 indicates the end of an actuation period, which is followed by the starting instant of the next period, which is represented by the lower limit of 0. Therefore, both limits represent the same instant in time, and inlets 1 and 7 belong to the same cluster. Further, no change of the firing instant of the first inlet can be seen, since it has been fixed at 0 s in each period to decrease the amount of control inputs for the ESC.

Since the maximum efficiency of the turbine stage under pulsating operation was not known beforehand, the experiment was performed using the fixed inflow parameters and the variable firing pattern until no further increase of efficiency was realized by the ESC. This experiment indicates a strong sensitivity of the turbine behavior and efficiency under pulsating inflow conditions regarding the firing pattern, similar to the sensitivity of the pressure fluctuation in front of the turbine, as shown in [6]. Further, it consolidates the assumption that the firing pattern should not be chosen arbitrarily for the operation of a turbine under pulsating inflow conditions. The obtained pattern of clustering was not predictable beforehand and could be replicated in repeated experiments, always resulting in a cluster of the first and seventh inlets, the second and third inlets into another cluster, and the remaining inlets into a third cluster. However, the positive effect of clustering with respect to the turbine is less favorable for the last compressor stage, see [12].

In a second experiment, the cost function for the so-called $\tilde{w}$-ESC was changed to the specific work that the turbine extracts from the flow. Because the magnitude of the objective function had changed compared to the efficiency values[1], a value of $\lambda = 0.01$ was used. As can be seen in Fig. 4 a), the absolute value of the specific work could be maximized, starting from approximately $-3.05\,\mathrm{kJ\,kg^{-1}}$ to almost $-3.6\,\mathrm{kJ\,kg^{-1}}$, resulting in an increase of about 15%. A similar clustering of firing instants, as in the previous experiment, can be seen in Fig. 4c). This can be explained because the numerator in Eq. (2) is linearly correlated to the specific work, as calculated in Eq. (1), and the change is mainly driven by the development of T_5, as can be seen in Fig. 4d). The denominator in Eq. (2) saw an almost negligible change throughout this experiment, as can be seen from the corresponding signals in Fig. 4b), resulting in a similar dependency of the objective function to the control input, as in the previously shown experiment.

5.2 Start-Up Process

Finally, an experiment using the proposed start-up strategy for PDC-based gas turbines was performed. The pressure variance in the plenum in front of the turbine stage was used as the characteristic state of the system that should be optimized through a start-up-σ-ESC. As in the previous experiments, the ESC

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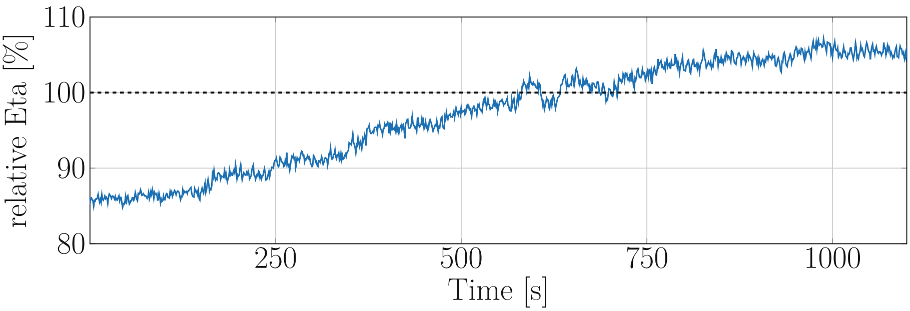
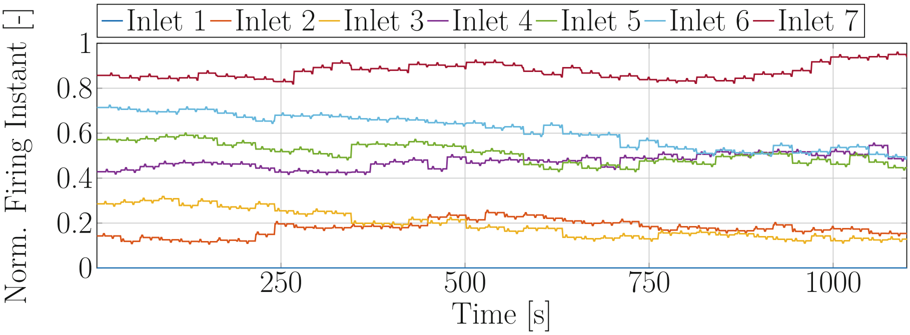
[1] The range of the calculated efficiency was $[0, 1]$.



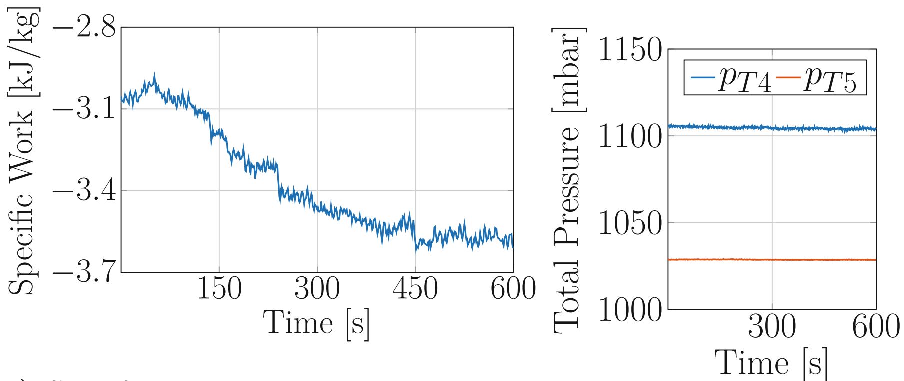
a) Efficiency development using η-ESC.



b) Firing pattern using η-ESC.

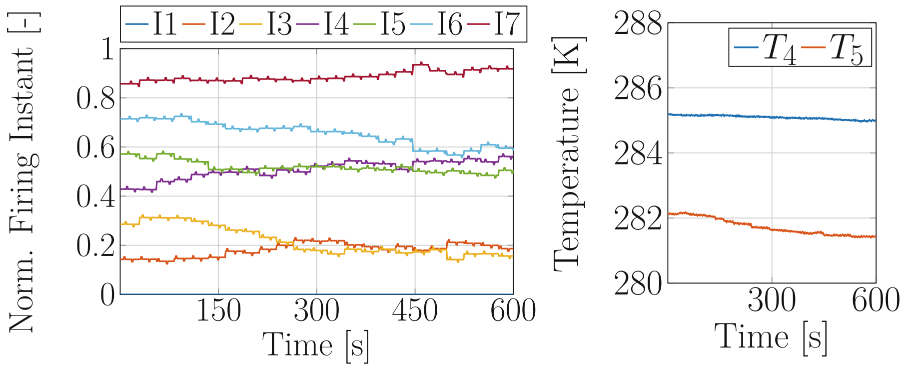
Fig. 3. Development of efficiency and corresponding firing pattern over time in an experiment using η-ESC.

could only change the firing pattern, but the firing tubes were added sequentially to the operation. Unlike in the previously shown experiments, the air supply through the HAT had to be changed manually during the experiment to ensure a desired flow of $0.27\,\mathrm{kg\,s^{-1}}$ to the turbine. A less aggressive parameterization of λ was used in the ESC, compared to the one chosen in [6], which was based on the same objective function. This was done to ensure a smooth evolution even under pronounced varying inflow conditions through the changed mass flow. Here, $\lambda = 0.5$ was set. The first phase of the start-up was realized through a gradual increase in the supply mass flow by the HAT with all SVs opened and is not shown here. Therefore, the experiment starts with the second phase of the start-up. Figure 5 shows the variance as calculated by Eq. (3), which was minimized by the start-up-σ-ESC, as defined in Sect. 4.2. The black dashed line indicates when a firing tube was added to the operation, while the colored dashed lines indicate the starting pattern for the non-pulsating tubes until they are added to the unsteady type of operation. The experiment began bypass mass flow only. After each added firing inlet, the inflow mass flow was manually



a) Specific work developement using $\tilde{w}$-ESC.

b) Pressure using $\tilde{w}$-ESC.



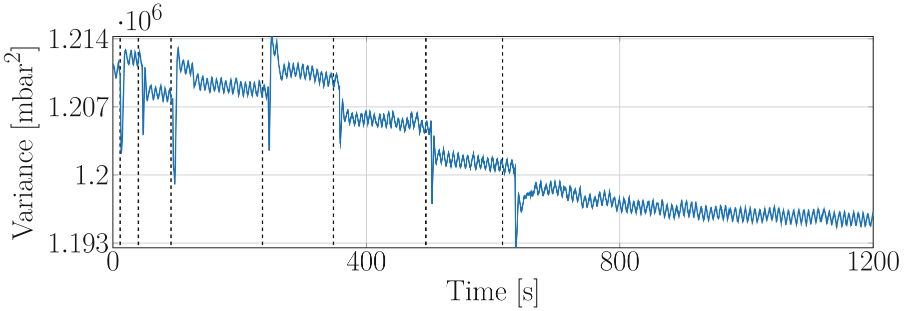
c) Firing pattern using $\tilde{w}$-ESC.

d) Temperature using $\tilde{w}$-ESC.

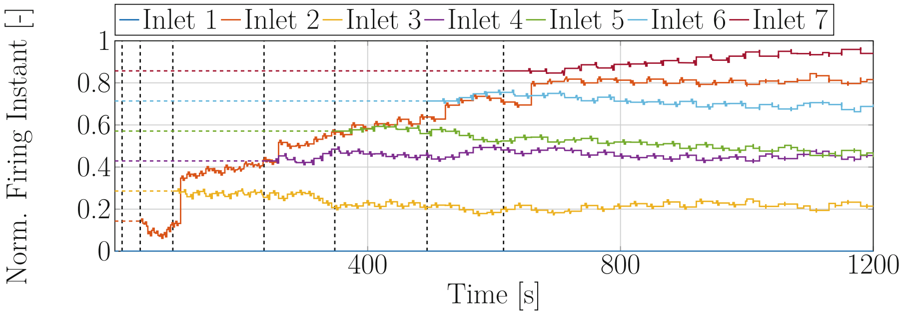
Fig. 4. Development of specific work and corresponding firing pattern, temperature, and pressure over time in an experiment using $\tilde{w}$-ESC.

adjusted by the machine operator in such a way that the supplied mass flow to the turbine was brought back to $0.27\,\mathrm{kg\,s^{-1}}$, as noted above. The instants at which an additional tube should be added were also chosen manually. This was done when a minimization of the variance through the ESC given the current number of firing tubes was regarded as mostly completed. In future work, this step could be automated as well.

The first inlet was added to the operation at 11 s. The drop in variance that can be seen thereafter arose because of change in the flow resistance. The rise in variance afterwards is caused by the manual change of the mass flow. Since the first inlet's firing instant is fixed in the actuation period, this ESC does not yet interfere. Starting at 40 s, the second inlet is added to the firing pattern and the mass flow is adjusted. The ESC immediately tries to adapt the firing instant



a) Pressure variance development using start-up-σ^2-ESC.



b) Firing pattern development using start-up-σ^2-ESC.

Fig. 5. Development of pressure variance in front of the turbine and corresponding firing pattern in an experiment using start-up-σ^2-ESC.

of this tube, but since no significant improvement is seen, the next firing tube is added to the operation at 91 s. The bypass mass flow had to be readjusted twice afterwards because of overshoots in the supplied mass flow, which explains the hard drop in variance shortly after the rise at around 100 s. The ESC then minimized the variance until the next tube was added at 235 s. Here, two mass flow adjustments had also to be done to ensure the desired flow. The next firing tubes were added to the operation at 347 s, 494 s, and, finally, at 615 s, with just one adaptation of the mass flow after the addition of each firing inlet.

The ESC successfully minimized the variance of pressure sensor signals in front of the turbine stage between each added firing event. This is especially true after all firing tubes had been added at the end of the experiment.

Looking at the firing pattern, it can be seen that the firing instant of the second firing inlet changed significantly over time. This is assumed to be due to the effect of the manually adapted mass flow that was not considered in the evaluation of this ESC and because an adaptation of the supply mass flow was always performed while the firing instant of the second inlet was perturbed.

Hence, this affected the gradient estimation of the second inlet. Further, an increase can be seen in the time interval between perturbations. This is due to the fact that each added firing tube increased the number of parameters that had to be changed for the gradient estimation of the ESC. After the start-up, the η- or $\tilde{w}$-ESC could be activated to reach another goal.

6 Conclusion

In this contribution, different applications of ESC to the operation of a PDC-based gas turbine were introduced and applied to a cold mock-up test rig. It was designed specifically for the analysis of turbine behavior under pulsating inflow conditions. Using an ESC, which can only adapt the synchronization times between different firing tubes, an efficiency increase of the turbine of about 20% points was reached within the experiment and compared to a non-pulsating operation using the same inflow characteristics an efficiency increase of 5% points was obtained. Further, a maximization of the specific turbine work in operation was presented using the same control approach, resulting in a similar synchronization at the end. Additionally, a possible ESC-supported, sequential start-up strategy for PDC-based gas turbines was introduced. This also was applied to the test rig, where it could successfully minimize the variance of pressure fluctuation in front of the turbine to protect the turbine from too-harsh changes in its inflow conditions.

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