ADAPTIVE OBSERVERS FOR MONITORING SOILING RATES IN THERMAL SOLAR COLLECTORS

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Abstract—Soiling represents one of the most important factors influencing the operation of solar concentrator fields. The cleaning cost represents an important percentage of the total maintenance cost for this type of installations. The estimation of soiling rates can be used to improve significantly the performance of the system by devising cost effective cleaning schedules. In this work, two adaptive observers are proposed to estimate soiling rates using available information in solar collector fields. Simulation results illustrate the main characteristic of each algorithms and their good performance under different operating conditions. Comments on how these encouraging results can be extended to deal with more complex scenarios are also provided.

Keywords—Observers, solar concentrators, hyperbolic systems.

1 Introduction

The maintenance costs associated to soiling represent one of the most important cost factors to be taken into account during the normal operation of a thermal solar collectors. (Sarver et al., 2013) provide a comprehensive overview of soiling problems, primarily those associated with dust (sand) and combined dust–moisture conditions that are inherent to many of the most solar-rich geographic locations worldwide.

The effect of soiling in solar concentrators influences the output of solar thermal power plants significantly, see (Wolfertstetter et al., 2012). It has been estimated that the loss in specular reflectivity due to dust on the mirrors could be as high as 14% or even 26% after a few months. As it has been pointed out by (Sarver et al., 2013), these figures varies significantly with location since also depend on moisture conditions. The loss of thermal output of the solar field assuming a constant direct normal irradiance (DNI) as input to the power plant correlates linearly with the loss in reflectivity or transmittance.

The losses due to soiling in power plant components can be reduced by cleaning. However, cleaning increases maintenance costs and water use even if sophisticated technologies such as cleaning robots are used. Therefore, researchers and maintenance teams of power plants are aiming at cost optimization for cleaning measures. At least two input values are needed for this optimization: the cleaning cost for a unit mirror surface and the actual optical efficiency reduction. The cleaning costs can be estimated pretty well for each plant site after some time of operation. However, the efficiency reduction due to reflectivity losses is not known in a continuous manner. In the market can be found sensors; such as, TraCS (Tracking Cleanliness Sensor), for measuring soiling level of solar mirror. The wide area covered by the collector field and the harsh atmospheric conditions make the use of optical instruments too expensive and impractical. In the photograph of Figure 1, can be seen the effect of soiling in a Chilean solar collector field.

Current procedures rely on reactive strategies based on the plant operator’s experience with the local weather. For instance, if some extreme event, such as sandstorm, soils the collectors, then a team of workers can clean the collectors during several nights. The increase in efficiency usually upset the cost of cleaning. A more cost effective strategy is to consider the calculation of a reflectivity threshold value at which such a cleaning effort makes sense. Thus, the power plant’s efficiency could be increased even if the mirrors lose their reflectivity due to more subtle effects, less obvious than an extreme event.

In order assist power plant operators and maintenance teams to optimize their cleaning cycles based on a real time measurement, this work proposes the use of adaptive observers for esti-
mating the soiling rate based on measurements of radiation and temperatures at the boundaries of the collector. The design of observers based on boundary injections have been reported for different applications. For instance, in (Aamo et al., 2006) a boundary observer for pipeline monitoring is presented. (Mechhoud and Laleg-Kirati, 2015) describe a boundary observer with fixed gain for estimating the temperature profiles of thermal collectors. An adaptive boundary observer has been proposed by (Mechhoud and Laleg-Kirati, 2016) for estimation the source term. On the other hand, Luenberger observers are presented in (Elmetennani and Laleg-Kirati, 2016) for estimating the temperature profile and in (Igreja et al., 2007) an adaptive version for the estimation the uncertain heat transfer coefficients. The asymptotic convergence of these estimation methods is established using Lyapunov theory.

In (Zhang, 2001), (Zhang, 2002), (Xu and Zhang, 2004) a more complex adaptive strategy for time-varying linear system has been proposed. This strategy is based on a coordinate transformation; which under suitable assumptions may lead to establish exponential converges of the estimates. An extension to deal with distributed parameter systems is proposed and analyzed in this paper.

This work is organized as follows. Section 2 describes the model of a solar collector. In section 3 two adaptive observers are presented along an analysis of their convergence. Some simulation results, in section 4, provide some highlights about their performance under different conditions. Finally section 5 summarizes the conclusions of this work and provides some hints about future work.

2 Dynamic modelling

The solar collectors can be modeled by using energy balance of the heat transport of the circulating fluid. If the losses are neglected, then the following Hyperbolic partial differential equation can describe the variation of the fluid temperature inside the collector. For modeling purposes a normalized length; i.e. \( l = 1 \), is considered

\[
\frac{\partial T}{\partial t} + q(t) \frac{\partial T}{\partial x} = \theta(t) I(t)
\]

(1)

where \( x \) and \( t \) are the coordinate and time variables, \( T(x, t) \) is the fluid temperature, \( q(t) \) is the fluid volumetric flow-rate and \( I(t) \) is the solar radiation. The time-varying parameter \( \theta(t) \) is defined as:

\[
\theta(t) = \frac{G}{\rho c_f A v_0(t)}
\]

(2)

where \( \rho \) is the fluid density \((kgm^{-3})\), \( c_f \) the fluid specific heat capacity \((JC^{-1}kg^{-1})\), \( A \) the tube cross-sectional area \((m^2)\), \( G \) mirrors optical aperture \((m)\) and \( v_0(t) \) is a time variant optical efficiency of the mirrors. The boundary conditions are defined as follows:

\[
T(0, t) = T_{in} \quad T(x, 0) = T_0 \quad x \in [0, 1]
\]

(3)

The available measurements are the solar radiation and temperatures at the boundaries; i.e. \( T_{in} \) and \( T(1, t) \). The solar radiation term and the flow rate also satisfy the following assumptions:

Assumption 1: There exist positive constants \( \delta, \beta_1, \beta_2 \) such that \( \forall t \) the source term \( I(t) \) satisfies the following

\[
\beta_1 \leq \int_t^{t+\delta} I^2(\tau)d\tau \leq \beta_2
\]

(4)

Assumption 2: There exist positive constants \( \beta_3 \) and \( \beta_4 \) so that \( \forall t \) the volumetric flow rate \( q(t) \) satisfies the following:

\[
\beta_3 \leq q(t) \leq \beta_4
\]

(5)

Under normal operation of the solar collector both assumptions are verified in practice. Since the dynamic of soiling is much slower than the dynamic of the temperature, the soiling effect can be modeled as:

\[
\dot{\theta} = 0
\]

(6)

3 Adaptive observers for soiling rates estimation

The adaptive observers consider a boundary observer plus an adaptive law for estimating the soiling effect.

3.1 Fixed gain observer

This adaptive observer considers a boundary observer defined by the following equation

\[
\frac{\partial \hat{T}}{\partial t} + q(t) \frac{\partial \hat{T}}{\partial x} = \dot{\theta}(t) I(t)
\]

(7)

with boundary conditions

\[
\hat{T}(0, t) = T_{in} + k_0(T(1, t) - \hat{T}(1, t)) \quad \hat{T}(x, 0) = T_0 \quad x \in [0, 1]
\]

(8)

and an adaption law for \( \dot{\theta} \)

\[
\dot{\theta} = \eta I(t)(T(1, t) - \hat{T}(1, t))
\]

(9)

where \( k_0 \) and \( \eta \) are positive constants.

Theorem 1 If \( I(t) \) satisfies Assumption 1 and \( q(t) \) Assumption 2, then the adaptive state observer defined by (7), (8) and (9) with positive constants \( \mu, k_0 \leq e^{-\mu t}, \) and \( \eta \), is an asymptotic adaptive observer for system (2); i.e. the errors \( T - \hat{T} \) and \( \theta - \dot{\theta} \) tend to zero when \( t \rightarrow \infty \).
Proof: Let the estimation errors for the temperature and the parameter be \( \hat{T} = \hat{T} - T \) and \( \hat{\theta} = \hat{\theta} - \theta \) respectively. Subtracting (7) and (2), the dynamic of the estimation error is given by

\[
\frac{\partial \hat{T}}{\partial t} + q(t) \frac{\partial \hat{T}}{\partial x} = \dot{\hat{\theta}}(t) I(t)
\]

with the following boundary conditions:

\[
\begin{align*}
\hat{T}(0, t) &= -k_o \hat{T}(1, t) \\
\hat{T}(x, 0) &= \hat{T}_0 \\
&\quad x \in [0, l]
\end{align*}
\]

For establishing the convergence of the observer we consider the following Lyapunov function candidate

\[
V(t) = \hat{\theta}(t)^2 + \int_0^1 e^{-\mu x} \hat{T}(x, t)^2 dx
\]

Taking the time derivative and replacing the error dynamic (10)

\[
\begin{align*}
\dot{V}(t) &= 2\hat{\theta}(t) \dot{\hat{\theta}} + 2\hat{\theta}(t) I(t) \int_0^1 e^{-\mu x} \hat{T}(x, t) dx \\
&\quad -2q(t) \int_0^1 e^{-\mu x} \hat{T}(x, t) \frac{\partial \hat{T}}{\partial x} dx
\end{align*}
\]

The integral of the second term can be upper bounded by the outlet error temperature, (Mechhoud and Laleg-Kirati, 2016),

\[
\int_0^1 e^{-\mu x} \hat{T}(x, t) dx \leq \frac{1}{\mu} \hat{T}(1, t)
\]

Using the upper bound (14) and integrating by part the third term it follows

\[
\begin{align*}
\dot{V}(t) &\leq 2\hat{\theta}(t) \dot{\hat{\theta}} + \frac{4}{\mu} \hat{T}(1, t) I(t) \\
&\quad -q(t)(e^{-\mu \hat{T}(1, t)^2} - \hat{T}(0, t)^2) \\
&\quad -q(t)\mu \int_0^1 e^{-\mu x} \hat{T}(x, t)^2 dx
\end{align*}
\]

Replacing the boundary condition (8) and the adaption law (9) with \( \eta = \mu^{-1} \)

\[
\begin{align*}
\dot{V}(t) &\leq -2q(t)\mu \int_0^1 e^{-\mu x} \hat{T}(x, t)^2 dx \\
&\quad -q(t)(e^{-\mu} - k_o^2) \hat{T}(1, t)^2
\end{align*}
\]

\[
\dot{V}(t) \leq -\beta_5 \mu V
\]

Thus \( V(t) \leq V(0) \) and therefore \( \hat{T} \) and \( \hat{\theta} \) are bounded. In addition, \( \hat{T} \) and \( \hat{\theta} \) are also bounded and by the Barbalat’s lemma

\[
\lim_{t \to \infty} \hat{T}(x, t) = 0
\]

In addition, since \( \dot{\hat{\theta}} = -\eta I(t) \hat{T}(1, t) \) it follows that \( \dot{\hat{\theta}} \) tends to a constant value. Thus, by (10) and for a positive constant \( \delta \) when \( t \to \infty \)

\[
\int_0^{t+\delta} I^2(\tau)d\tau \to 0
\]

By Assumption 1, the integral is bounded from below and therefore it follows that \( \dot{\hat{\theta}} \to 0. \quad \Box \)

Remark 1: The upper bound (14) is a key result for establishing the convergence of the estimates.

3.2 Variable gain observer

The variable gain observer presented in this work is an extension of the ideas proposed by (Zhang, 2001) for fault detection in linear time-varying systems. The adaptive observer has the following structure:

\[
\frac{\partial \hat{T}}{\partial t} + q(t) \frac{\partial \hat{T}}{\partial x} = \hat{\theta}(t) I(t) + \gamma(x, t) \hat{\theta}
\]

with boundary conditions defined as follows:

\[
\begin{align*}
\hat{T}(0, t) &= T_{in} + k_o(T(1, t) - \hat{T}(1, t)) \\
\hat{T}(x, 0) &= \hat{T}_0 \\
&\quad x \in [0, 1]
\end{align*}
\]

The proposed adaption law is given in terms of the boundary information

\[
\dot{\hat{\theta}} = \eta \gamma(1, t)(T(1, t) - \hat{T}(1, t))
\]

where the dynamic gain \( \gamma \) is obtained as the solution of the following Partial Differential Equation

\[
\frac{\partial \gamma}{\partial t} + q(t) \frac{\partial \gamma}{\partial x} = I(t)
\]

with boundary conditions

\[
\begin{align*}
\gamma(0, t) &= -k_o \eta \gamma(1, t) \\
\gamma(x, 0) &= \gamma_0 \\
&\quad x \in [0, 1]
\end{align*}
\]

Assumption 3: The gain \( \gamma(1, t) \) is persistently excited; i.e. there exist positive constants \( \delta_1, \beta_5 \beta_6 \) such that \( \forall t \)

\[
\beta_5 \leq \int_t^{t+\delta_1} \gamma(1, \tau)^2 d\tau \leq \beta_6
\]

Theorem 2 Under Assumptions 1, 2 and 3, the adaptive state observer defined by (19), (21), (20), (22), (23), with positive constants \( \mu, \beta_0 \leq e^{-\mu} \), and \( \eta \), is an exponential observer of system (2); i.e. the estimation error \( T - \hat{T} \) and the parameter error \( \theta - \hat{\theta} \) tend to zero exponentially.

Proof: Let the auxiliary variable \( \tilde{z} \) defined as

\[
\tilde{z}(x, t) = \hat{T}(x, t) - \gamma(x, t) \hat{\theta}
\]

The dynamic of \( \tilde{z} \) is

\[
\frac{\partial \tilde{z}}{\partial t} + q(t) \frac{\partial \tilde{z}}{\partial x} = \hat{\theta}(t) \left( \frac{\partial \gamma}{\partial t} + q(t) \frac{\partial \gamma}{\partial x} - I(t) \right)
\]

Letting \( \gamma \) be the solution of the following partial differential equation

\[
\frac{\partial \gamma}{\partial t} + q(t) \frac{\partial \gamma}{\partial x} - I(t) = 0
\]

with boundary conditions (23), the dynamic of \( \tilde{z} \) is just given by the following equation

\[
\frac{\partial \tilde{z}}{\partial t} + q(t) \frac{\partial \tilde{z}}{\partial x} = 0
\]
with boundary conditions
\[ \tilde{z}(0, t) = -k_0 \tilde{z}(1, t) \]
\[ \tilde{z}(x, 0) = \tilde{z}_0 \quad x \in [0, 1] \] (29)

Let
\[ V(t) = \int_0^1 e^{-\mu x} \tilde{z}(x, t)^2 dx \] (30)

be a Lyapunov function candidate for (28) and taking its time derivative an integrating by parts, it is possible to write
\[ \dot{V}(t) \leq -q(t) \mu V(t) \] (31)

Using the relationship between the norm \( \| \cdot \|_2 \) and \( \| \cdot \|_2 \), it follows
\[ \| \tilde{z}(:, t) \|_2 \leq \| \tilde{z}(:, 0) \|_2 e^{-\beta_4 \mu t} \] (32)

Thus, \( \tilde{z} \to 0 \) exponentially.

Using (25) the dynamic of the parameter error can be expressed in terms of \( \tilde{z} \) as
\[ \dot{\tilde{\theta}} = -\eta \gamma(1, t) \left( \tilde{z}(l, t) + \gamma(1, t) \tilde{\theta} \right) \] (33)

and re-organizing terms
\[ \dot{\tilde{\theta}} = -\eta \gamma(1, t)^2 \tilde{\theta} - \alpha \gamma(1, t) \tilde{z}(1, t) \] (34)

By Assumption 1, \( I(t) \) is bounded and \( \gamma(1, t) \) is also bounded since (22) with boundary conditions (20) represents an exponentially stable system driven by a bounded input. Furthermore by Assumption 3 the homogenous part of (34) is exponentially stable. Thus, \( \tilde{\theta} \) is exponentially vanishing because the homogenous part of (34) is exponentially stable and its non homogeneous term is exponentially vanishing. \( \Box \)

Remark 2: This observer is more complex than the fixed gain one, but it ensures exponential convergence.

Remark 3: The use of a change of coordinate provides the necessary degrees of freedom for decoupling the dynamic of the transformed variable with respect to the parameter error dynamics. This key step in turn enable the design of the observer.

4 Simulation Results

The first example considers the simulation of a thermal collector subject to a constant radiation with unknown parameter representing the effect of soiling rate. In all the examples a constant fluid flow rate is considered. Both algorithms use the same tuning parameters; i.e. \( k_0 = 0.05 \) and \( \eta = 0.4 \). For the fixed gain observer, Figure 1 shows the time evolution of the temperature estimates and Figure 2 shows the convergence of the soiling rate.

For the variable gain observer the initial condition for calculating the dynamic gain was \( \gamma_0 = \)

Figure 1: Estimated temperatures. Fixed gain observer

10. Figure 3 shows the time evolution of the temperature estimates and Figure 4 shows the convergence of the soiling rate. Under these simulation conditions both observers have similar behavior.

The second example considers the simulation of a thermal collector field designed to heat electrolyte for a copper electro-refinery. The thermal collectors are plate collectors and the radiation profile is depicted in 5. The simulation considers a step change in the soiling rate, even though this is unrealistic condition, it represents a challenging condition for the observers. Figure 6 depicts the convergence of the parameters and the estimated temperature at the output. It can be seen that for the fixed gain observer the convergence of the soiling rate strongly depends on the solar radiations. However, for the variable gain observer, as seen in Figure 7, the estimates converge faster since they depend on a filtered version of the solar radiations.
5 Conclusion

Two simple adaptive observers with fixed and variable gains were proposed for estimating the soiling rate in thermal concentrators. The simulation results for real solar radiation profiles show that the adaptive algorithm with variable gain has a better performance in terms of parameter convergence. These simulation results are encouraging and further work is under way. Experimental trials, more complex dynamic models for soiling, and the use of multiple temperature measurements in several thermal collectors connected in series, are being considered.

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References


