Identification of a Furnace From Quasi-Periodic Measurements

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***Abstract*—Controllers of industrial furnaces operate differently in different temperature ranges. The controller has different parameter sets for each of these ranges. The operation of controllers is switched according to the temperature. It is desirable to change the parameters continuously following the temperature. The continuous change of parameters instead of mode switching may decrease the switching transients and lead to more accurate temperature control.**

A furnace identification scheme is investigated in this paper. Measurement problems and possible corrections that result in more accurate models after processing the collected data are shown. A possible "interpolation" technique of frequency-domain models is also shown here.

***Index Terms*—Frequency domain, furnace, identification, nonperiodic excitation, nonstationary experiment.**

I. Introduction

Temperature controllers must set the temperature very accurately in order to meet the needs of technological processes. So, when we design a controller for an electric furnace, precision is extremely important. To provide an exact model of the furnace for this purpose, we identify the system from measured data. Using the identified models, the controller parameters can be determined. Since the system models differ slightly for different temperatures, the objective of this research is to develop z-domain models for different temperatures and to find a way to "interpolate" between these models according to the temperature.

II. Preliminaries

Experimental results are obtained from a small, laboratory heat-treating furnace (volume of 1.4 L). The furnace is embedded in a control loop as shown in Fig. 1. The input to the furnace is an on–off signal that switches the heating element to the main supply. The output is the temperature fed back into the on–off controller.

The conditions of accurate frequency-domain system identification are met when the *excitation is periodic* and the measured variances can be reduced by averaging. Unfortunately, as will be seen in the next section, this basic condition cannot be fulfilled in a closed-loop measurement setup.

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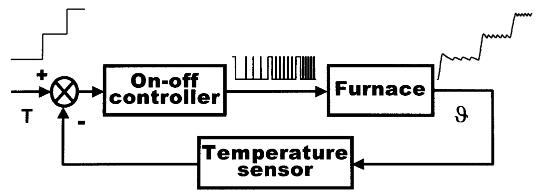

Fig. 1. Control loop of the furnace.

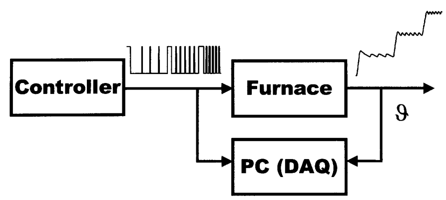

Fig. 2. Open-loop measurement setup.

The bandwidth of the transfer function of the furnace is very low (∼10 mHz). One period of an excitation signal, which excites the system from 1 to 10 Hz (the crossover frequency), will last about 17 min. To precisely identify the transfer function, several consecutive periods should be collected, which will take about 1.5–2 h.

III. Measurement Enhancement

The identification of a furnace cannot be achieved in a straightforward manner. This is due to the following technical problems.

- The *controller* influences the measurements. It suppresses the effects of environment by varying the filling factor of the input signal; however, by doing this, it distorts the measurements. As a remedy, the closed loop needs to be interrupted, so that the controller simply directs the furnace.
- The model of the furnace can be regarded as linear only at certain *temperature setpoints*. This indicates that individual experiments should be done around each setpoint, and it is not possible to measure the furnace in one step.
- The timing of observations is imprecise due to the method of the present implementation, originally designed for digital control only. As a consequence, it is difficult to execute *periodic measurements*.
- The *disturbing effects* of the environment are unknown. Since their effect was suppressed by the controller, the perturbation sources of the environment were not taken into consideration during control. However, to precisely identify the system, these disturbance signals should also be measured and modeled.

After considering all of the possible difficulties that may arise during identification, we have tried to eliminate them. While

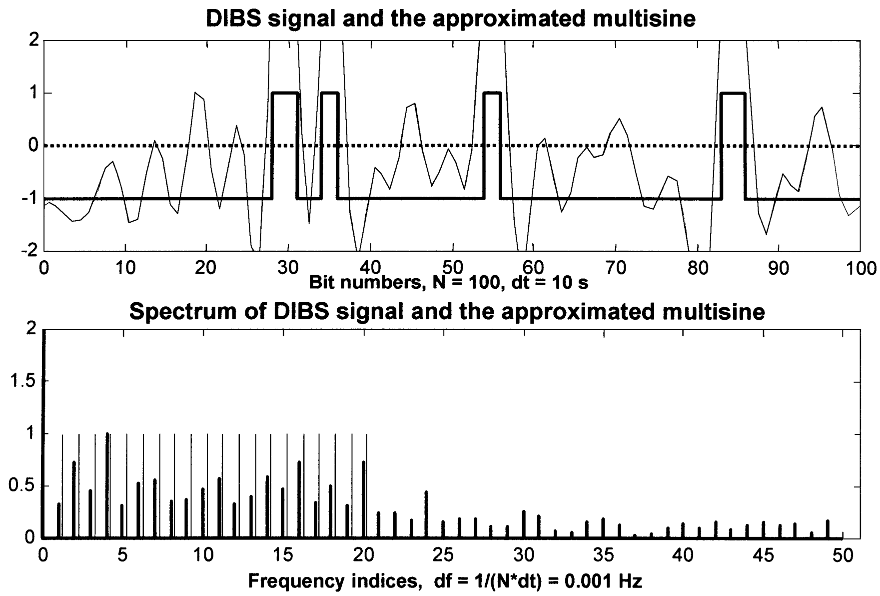

Fig. 3. DIBS signal with a 10% filling factor (thick) and the approximated spectrum (thin).

some of the above-mentioned problems can be eliminated with simple measures, others cause major challenges in identification.

The closed loop may be interrupted, if it is ensured that the temperature does not rise over a certain limit. As the input injects energy into the system, and the temperature depends on the energy injected, the filling factor[1] of the input signal must be properly set.

From earlier closed-loop experiments, the necessary filling factor can be estimated to heat the system to a given temperature, and keep the temperature around this operating point. The measurement setup after eliminating the closed loop is shown in Fig. 2.

The temperature dependency of the system can be analyzed by applying excitations with different filling factors. These measurements will provide information about the system at different operating points.

A simple square wave, however, is not an optimal excitation, since there is no choice on the spectrum. Instead, a discrete interval binary sequence excitation (DIBS) can be used. The advantage of DIBS is that the given amplitude distribution of the signal can be approximated with a square wave [4]. The design algorithm of DIBS signals is well known and implemented in MATLAB [3]. The designed DIBS sequence is applied to the system as direct input. Thereby it is possible to excite the furnace according to a given spectrum by simply switching the main supply of the furnace on and off. Such a signal can be seen with its spectrum in Fig. 3. The figure also shows the ideal, flat spectrum, which is approximated by the DIBS signal. The ideal flat spectrum and its corresponding time-domain representation are shown with thin lines in the figure.

Open-loop experiments have shown that the timing of observations is sometimes wrong. The observed input signal was, unfortunately, not the same as had been designed with DIBS. The lengths of the on and off sections of the measured signal vary from period to period, and the length of a single period is also changing. The timing error has two components.

[1]The filling factor is the fraction of time of a period in which the square-wave is in its high state. Some authors use the expressions fill-in coefficient or duty factor.

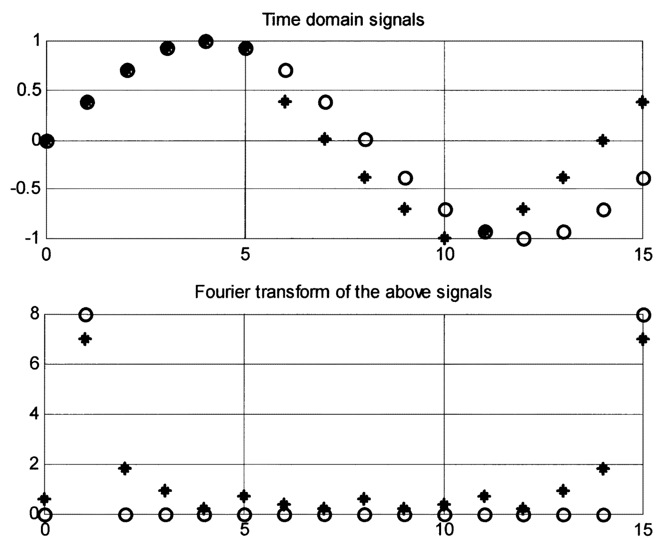

Fig. 4. Effect of missing data. o: single period of a sine wave (above) and its spectrum (below); *: single period of an incorrectly measured sine wave with two lost data points in the sequence (above) and its spectrum (below).

- There is a cumulative error (∼0.04%) due to the difference between the frequencies of the two real-time clocks used in the measurement setup. There is one on the controller panel and another one on the mainboard of the PC, which collects and stores the measured data.
- The communication between the controller and the PC introduces a changing delay to the measurements, and even some data can be lost during transmission without any warning generated. The problem arises from the nonperfect communication of the controller with the data acquisition PC. Because there is no communication when the controller operates, this caused no problem earlier. Fig. 4

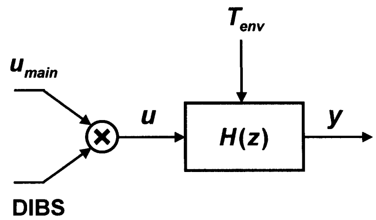

Fig. 5. Refined black-box model of the furnace.

shows the spreading effect of missing data on the spectrum. A period of a sine wave and its spectrum are plotted with circles. The stars mark the time-domain representation and spectrum of a sine wave with two data points missing in the period. As the figure shows, missing data distorts the spectrum considerably, so the enhanced measurement setup should ensure that data losses are avoided.

The timing errors can be avoided in the following ways.

- The synchronization of the two real-time clocks with each other is not a real option. Now, we are in the course of implementing a new measurement setup which depends only on one real-time clock.
- A timestamp on the collected data could be used on the PC side.
- Downsampling can decrease the effect of the changing delay due to the communication, but it does not effect the jitter. Hence, long-time measurements will always be distorted.

Because of these problems, the closed loop has been opened according to Fig. 2, and a new measurement program has been implemented. The program handles data losses by applying a timestamp to each collected data sample. With the help of timestamps, the place of lost data is exactly known in the time series, and lost data can be estimated and taken into consideration during the DFT. Estimation is performed with an interpolation using the neighbors of lost data.

IV. Effects of Environment

Because the records of the temperature measurements are long, the slowly changing effects of the environment must be taken into consideration. One of these effects is the changing of weather (i.e., the movement of air changes the rate of thermal losses, or the sun shines stronger, etc.).

Another significant distortion effect arises from slow changes in the main supply (line power). This change consists of daily fluctuations in the power supply and the burst-like load of heavy current customers. From experience, these changes in the line power can reach up to 10% at the measurement site. In order to obtain a reasonable model, the *temperature of the environment* and the *applied input power* must also be measured. At present, these parameters are not measured, since the PID controller suppresses their effect at the cost of varying the filling factor, as well as distorting the measurements. The enhanced black-box model of the furnace can be seen in Fig. 5.

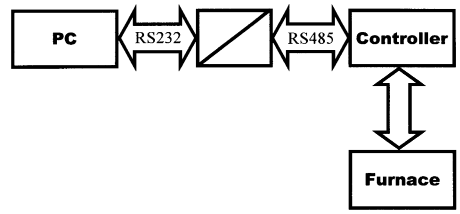

Fig. 6. Measurement setup.

V. Measurement Implementation

To eliminate the timing uncertainty from temperature measurements, a new data acquisition program has been implemented, specific for the furnace. The program running on the PC communicates with the controller as shown in Fig. 6. The control program is entered into the controller before the measurement starts. During measurement, the DAQ program polls the controller for the measured temperature and the current input signal. The control loop is not closed in the measurement setup. The controller simply directs the process and does not control it. The main supply of the furnace is switched on and off according to the DIBS sequence previously designed. The DIBS sequence is periodically repeated. With this method, the measurements can be averaged over several periods, so the variances of frequency response functions (FRFs) of individual periods can be decreased.

VI. Interpolation of Models or Controllers

The interpolation of models is not the only possibility to follow the continuous change of temperature. The controller parameters themselves could also be interpolated. So far, the parameter interpolation method is not investigated; hence it is uncertain whether or not it would result in a better (more accurate, robust) controller. We have made an assumption that the models can be adjusted to the temperature change by a linear interpolation of models at different setpoints. After having the interpolated model set, the PID algorithm can be run to determine the controller parameters. To find the best solution possible, the result of model interpolation should be compared with the result of parameter interpolation in the future. The measurements, however, have verified our assumption and showed that the FRF models of the furnace do not change drastically with the temperature, so there is a chance to develop a model which includes temperature as a parameter and is valid in a wide temperature range.

Measurements have been executed at different setpoints. In the first measurement, an input signal with a 10% filling factor was applied, which caused the temperature to settle at 320 °C. The measured data can be seen in Fig. 7. The second measurement was carried out using an input signal with a 15% filling factor, which caused the temperature to settle near 410 °C. The measured data can be seen in Fig. 8.

As the data show, the second measurement had a significant trend, which caused the temperature to change slowly. Avoiding the processing of transient data, we worked only with the last eight periods of data from the second measurement, and during identification we used the transient elimination method as described in [6]. It is important to note that the preliminary es-

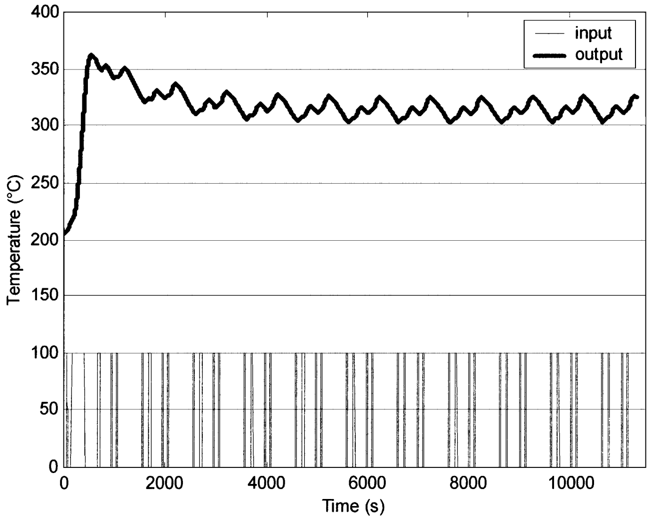

Fig. 7. Measured data (input signal with 10% filling factor).

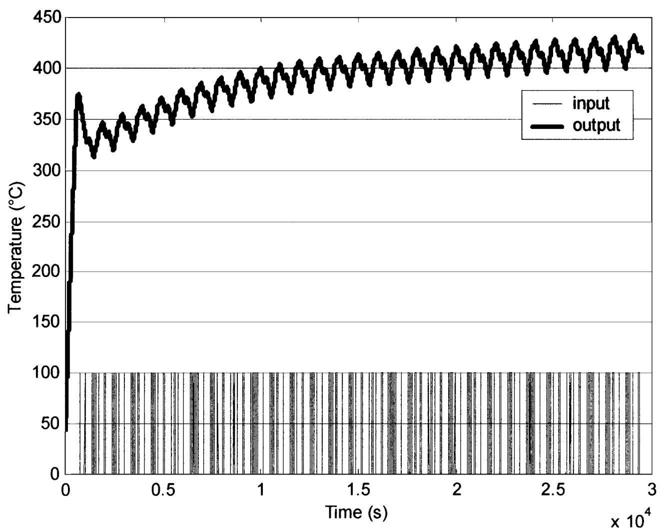

Fig. 8. Measured data (input signal with 15% filling factor).

timation of the steady-state temperature of a given signal with a fixed filling factor is crucial. After executing measurements at two different setpoints, with DIBS signals of 10% and 15% filling factor, we have identified the furnace and determined a linear system model at both setpoints. The best model fit could be achieved with 2/3-type rational z-domain models (e.g., exciting the system with a signal with 10% filling factor, the identified model has the following coefficients in descending power of $z^\wedge - 1$: $b0 = -0.002\,834$, $b1 = +0.005\,74$, $b2 = -0.002\,406$, $a0 = +0.2633$, $a1 = -0.7063$, $a2 = +0.6299$, $a3 = -0.187$). Using the identified models, we could start to interpolate between these models and try to give some estimations on the behavior of the system at 11%, 12%, 13%, and 14% filling factor. The following expression was used to interpolate between two setpoint-models (H_A and H_B). The interpolated model, H_x depends on the setpoint-models and on the filling factors, used to determine the setpoint—models $(d_A, \, d_B)$

$$H_x(z) = \frac{d_B - d_x}{d_B - d_A} \, H_A(z) + \frac{d_x - d_A}{d_B - d_A} \, H_B(z). \qquad (1)$$

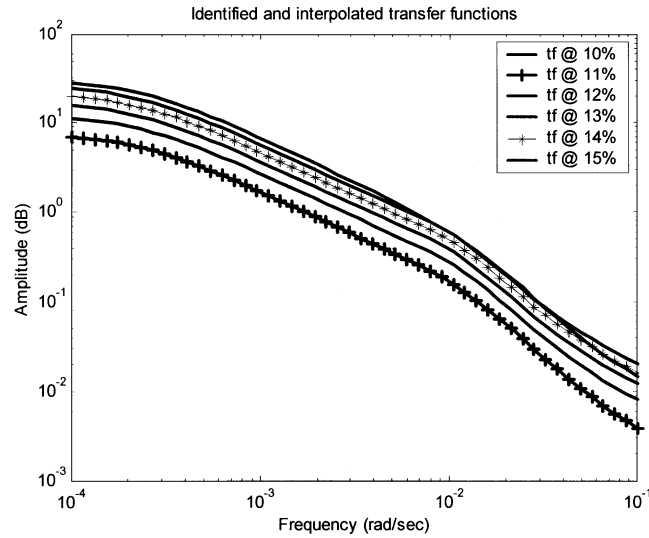

Fig. 9. Bode diagram of the measured (identified) and interpolated models

The result of interpolation is shown in Fig. 9, where the amplitude diagram of measured and interpolated models is shown. As Fig. 9 shows, the measured models are close to each other; however, interpolated models introduce some change (even at dc), which is a result of the model addition used, which may be subject to some improvements in the future.

VII. Conclusion

We have determined that the low quality of the preliminary measurements arises from the measurement setup and from applying blindly the equipment designed for closed-loop operation. The closed loop and the disturbing effects of the environment together make it impossible to excite the furnace periodically.

The closed loop rejects the effects of disturbing noises on the system plant, but at the same time distorts the input signal in an unacceptable measure. Hence, environmental noise is transformed to the input of the system. To execute good quality measurements and to set up an exact model, the closed loop should be eliminated; however, in this case, the possible disturbances must also be measured and processed when setting up the model. We recognized that the application of the controller for identification must be taken into consideration even at the design of the controller, in the future.

The elimination of the closed loop can be executed in two phases. In the first (control) phase, we observe the furnace in the closed loop. Using this observation the filling factor can be estimated. In the second (identification) phase, the DIBS signal with the estimated filling factor can excite the furnace in an open loop. Based on the considerations listed in this paper, we have executed DIBS measurements. We are in the course of processing and evaluating observations at different setpoints. Thereafter we plan to investigate other possible interpolation techniques (e.g., parameter interpolation) to compare the resulting models.

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