Andrzej FRĄCZYK, Jacek KUCHARSKI

Lodz University of Technology, Institute of Applied Computer Science

doi:10.15199/48.2018.04.17

Compensation of heat power generation delays in the induction heating system of a rotating steel cylinder

***Abstract**. In this paper the problem of delayed heating power generation in the induction heating system applied for a rotating steel cylinder has been presented. The source of the delay along with the method of its identification based on analysis of the infrared image of cylinder surface temperature have been discussed. As a consequence, a simple compensation method of the delay has been proposed and experimentally verified.*

***Streszczenie.** W artykule przedstawiono zagadnienie opóźnień generowania mocy grzejnej w układzie indukcyjnie nagrzewanego wirującego walca stalowego. Omówiono źródła tych opóźnień oraz metodę ich identyfikacji na podstawie analizy obrazów termograficznych pola temperatury powierzchni walca. Następnie zaproponowano oraz doświadczalnie zweryfikowano prostą metodę kompensacji zidentyfikowanych opóźnień. (**Kompensacja opóźnień generowania mocy grzejnej w układzie indukcyjnego nagrzewania wirującego walca stalowego**).*

Keywords: induction heating, rotating cylinder, control of temperature field.
Słowa kluczowe: nagrzewanie indukcyjne, wirujący walec, sterowanie polem temperatury.

Introduction

For last several years research on the development of a semi-industrial system for induction heating of steel cylinders has been conducted at the Institute of Applied Computer Science of the Lodz University of Technology [1, 2]. Such a heating system can be used in various branches of industry such as paper or textile appliances, being an alternative or supplementary solution for traditional vapour or oil heating systems. Its unique feature is the possibility of obtaining almost any temperature distribution at the cylinder surface both along its generatrix and circumference. In the proposed setup this is achievable by the use of a set of moving inductors (enabling temperature profile shaping along the generatrix) and by synchronization of required heating patterns with the rotational position of the cylinder (enabling temperature profile shaping along the circumference). The research carried out in this field so far covers the development of signal and image processing procedures for generation of control signals [3], as well as designing and analysis of appropriate control algorithms [4, 5]. These efforts enabled to build an effective heating and control system, assuring high quality control of temperature distribution on cylinder surface, but a considerable destructive influence of cylinder rotational speed on temperature distribution along its circumference has been observed. Since it concerns particularly the location of the beginning of the heated area the authors realized that there are some delays in the heating power generation system that should be compensated. The main aim of this article is to prove this hypothesis and to elaborate a compensation method of identified delays.

Description of semi-industrial laboratory setup

Figure 1 provides a schematic diagram of a semi-industrial laboratory set up. A 120 cm long rotating steel cylinder of a diameter around 40 cm is heated by six mobile inductors supplied by dedicated high-frequency (HF) generators. In the multi-loop computer-based measurement and control system, four main functional channels can be distinguished as follows:

- cylinder surface temperature measurement and control channel, which is the main loop in the entire system;
- stabilized power generation channel;
- cylinder rotation speed measurement and control channel;
- inductor position control channel.

The main control element in this set up is a PC computer, which (on the basis of information obtained from the infrared camera manager and rotation speed control system) determines setpoint values for heating power, rotation speed and inductor positions. It also decides which zones along the cylinder circumference are to be heated.

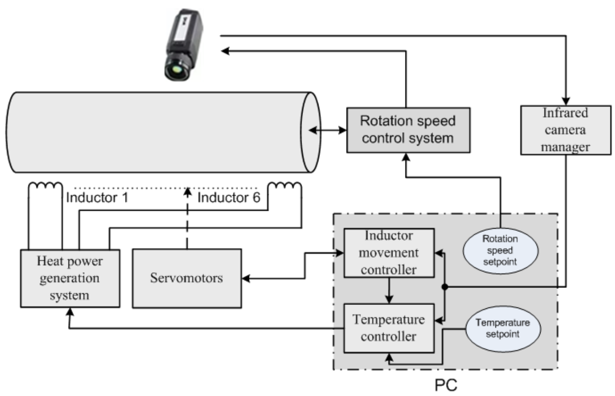

Fig.1. Structure of the experimental setup

Required heating power becomes the setpoint for another control loop – the power generation loop. The main components of the heating power generation system are: a three-phase transformer, high frequency generators, an ENIKA ENI-ZL250/40 AC voltage stabilizer, system-blocking high frequency generators with dependence on angular cylinder position, and characteristics linearization systems for inductors and heating power.

An A615 FLIR infrared camera is used for surface temperature measurements. It is supported by a dedicated controller, the main task of which is to reconstruct a full map of the cylinder surface temperature. The reconstructed 2D image of the surface temperature is sent (via Ethernet interface) to the temperature controller and the inductor movement controller.

An MOK40-5000-5-BZ-N encoder, supported by a specially designed driver, is used to measure rotation speed. The rotation speed setpoint is transferred from the temperature controller to a Hitachi SJ200 inverter via RS 485 interface. On the basis of the signals obtained, a PID controller (implemented in the inverter) determines the frequency and voltage supply to an asynchronous motor, which rotates the cylinder.

All six inductors are placed at the required positions by SMBW 240 MINI 4/8 AMP servomotors. The inductors are mounted on the trolleys of an HGH15CA-Z0-H linear guideway and moved by six KGSR 2525-2000mm FSC ball screws. Each of these ball screws is rotated by a dedicated AC60 SQA 13030 engine (controlled by a single servomotor). The trolleys are moved along two rails, with three trolleys on each rail. Each of the servo drives is equipped with a mechanical limiting sensor and a mechanical position encoder. Motion parameters, such as target position and speed of movement, are transmitted from the PC to the servomotors via Ethernet.

For the purpose of the study reported in this paper only part of the system comprising elements that directly affect the temperature distribution along the perimeter of the cylinder is of paramount importance. The block diagram of the system viewed from this perspective is shown in Figure 2.

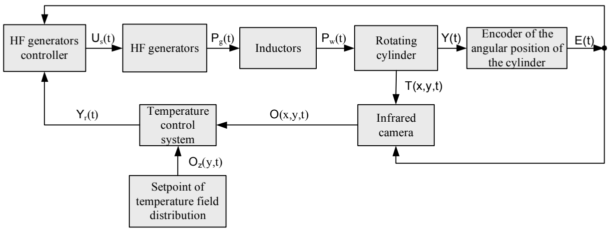

Fig.2. Block diagram of analysed part of the system

The temperature control system sends $Y_r(t)$ signal to the HF generator within the main control loop basing on the required temperature distribution along a circumference of the cylinder, $O_Z(y, t)$, and the current surface temperature distribution, O(x, y, t), acquired by the infrared camera. The $Y_r(t)$ signal contains a set of values of cylinder angular positions at which the heating power is to be switched on or off. The generator controller uses both $Y_r(t)$ signal and the encoder output signal, E(t), to control the heating power during normal cylinder operation [6].

Influence of a power generation delay on temperature field of the cylinder surface

In order to illustrate the influence of the cylinder rotational speed on the temperature distribution along its circumference Figure 3 shows the image of the distribution obtained during static heating of the cylinder at two values of cylinder speed: 25 rpm (Fig. 3a) and 125 rpm (Fig. 3b). Dotted lines in both figures indicate the area along the perimeter of the cylinder, which - according to the control target - was supposed to be heated. Clearly to see that the areas heated in both cases differ in size, even though the HF generator (Fig. 2) controls the inductors in the same manner, i.e. the start and end of heating in being ordered for the same angular position of the cylinder. In the case of a higher rotational speed of the cylinder the heated area is significantly smaller, with visible offset of the start of heating. In either case the heated area ends almost at the same place.

The structure of the system (Fig. 2) indicates that the possible source of the observed phenomenon could be a delay occurring in the heating output channel. Therefore, the control voltage signal of the HF generator along with inductor's current were recorded for both analyzed rotational speeds of the cylinder. The obtained results are shown in Figure 4.

The waveforms shown in Figure 4 exhibit a delay in switching on of the heating power, while switching off phase is practically performed without any delay. Unfortunately, the shape of the inductor current signal does not correspond to the shape of the control signal of the generator (in the analyzed example it is not a rectangular signal), so it is difficult to directly and unambiguously determine the value of the delay.

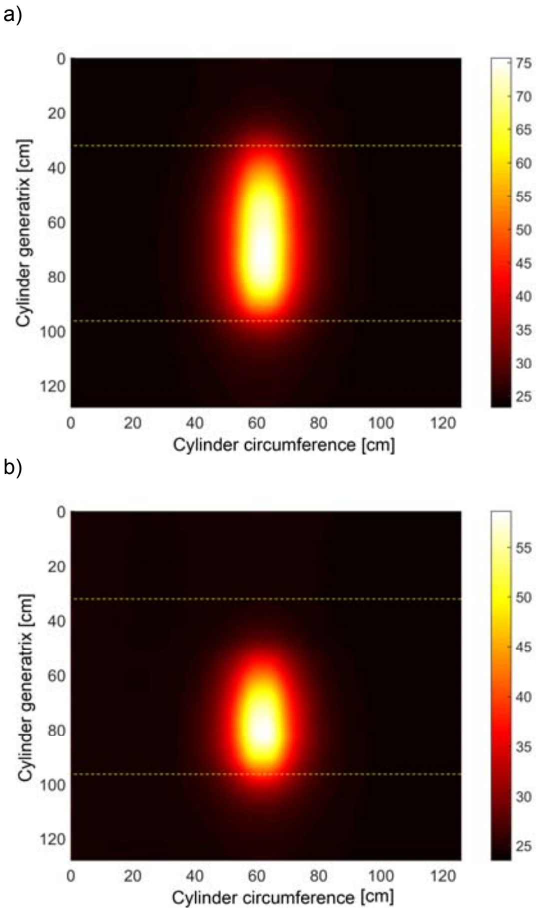

Fig.3. Temperature distribution at the cylinder surface for two values of rotation speed: 25 rpm (a) and 125 rpm (b)

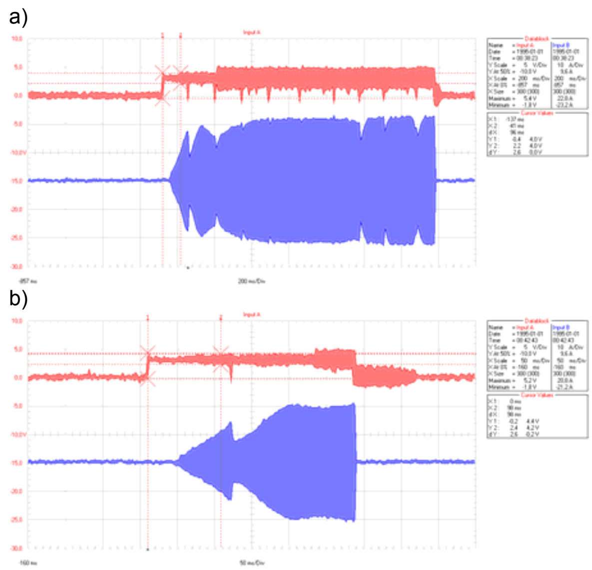

Fig.4. Control voltage signal of the HF generator (upper graphs) and the inductor current (lower graphs) for two cylinder speeds: 25 rpm (a) and 125 rpm (b)

Only equivalent delay, covering a clear signal delay (visible in Figure 4 in the initial phase) and a period of time reflecting the gradual build-up of the current in the inductor, can be considered. Moreover, the dynamics of the inductor-cylinder system also influences the inductor current. In view of the above, it seems reasonable to assume that the effective delay of the analyzed signals could be identified experimentally by comparison of the images of cylinder surface temperature distribution.

Equivalent delay identification of the power generation channel

The proposed delay identification method consists in replacement of the actual temperature profile along the circumference of the cylinder by a rectangular waveform so that the mutual offset of the corresponding areas in the thermographic images of the cylinder can be clearly defined. The idea of the method is illustrated in Figure 5.

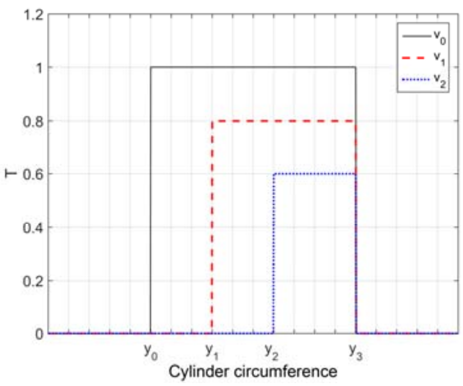

Fig.5. Simplified rectangular temperature profiles along a circumference of the cylinder (y coordinate) under different heating conditions

The temperature distribution during static cylinder heating (v_0 = 0) performed by the static inductor (whose dimension along the cylinder perimeter equals to y_3-y_0), is portrayed by continuous line in Fig. 5. When heating the cylinder that moves with linear velocities of v_1 and v_2 along its circumference (where v_1<v_2) and assuming a constant delay in the heating channel, it would result in the temperature distributions indicated in Figure 5 by dashed and dotted lines respectively. Given the coordinates y_1 and y_2 (the starting points of the heated areas) and the linear velocities of cylinder movement, the equivalent delay, L, of power generation channel can be calculated as:

(1) $$L = \frac{y_2 - y_1}{v_2 - v_1}$$

In practice, surface temperature distributions of the heated cylinder do not have sharp boundaries (Figure 5), due to natural physical phenomena (mostly heat conduction in the cylinder mantel), thus the temperature profile along the circumference of the cylinder never reaches a rectangular shape. In order to apply the above described method of equivalent delay determination the normalized temperature distributions for both analyzed speeds of the cylinder were used as shown in Figure 6, assuming T = 0.5.

By putting into equation (1) the coordinates y_1, y_2 of the starting points of heated areas and the linear velocity of the cylinder in both cases, the equivalent delay of the heating channel was calculated as L = 98.4 ms.

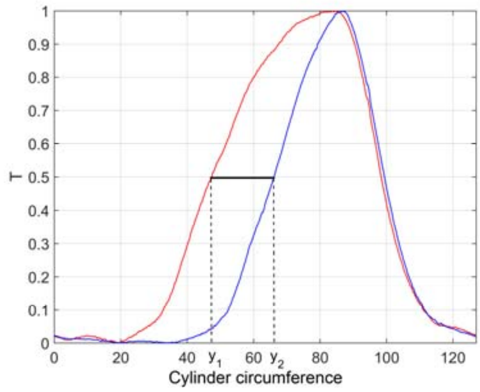

Fig.6. Determination of the equivalent delay of the heating channel

Compensation of a heating channel delay

Compensation of the identified delay of the heating channel needs readjusting $Y_r(t)$ signal so that the coordinates along the circumference of the cylinder, for which the heating process should start, become respectively smaller (this means the apparent acceleration of the heating power switching on time).

a)

b)

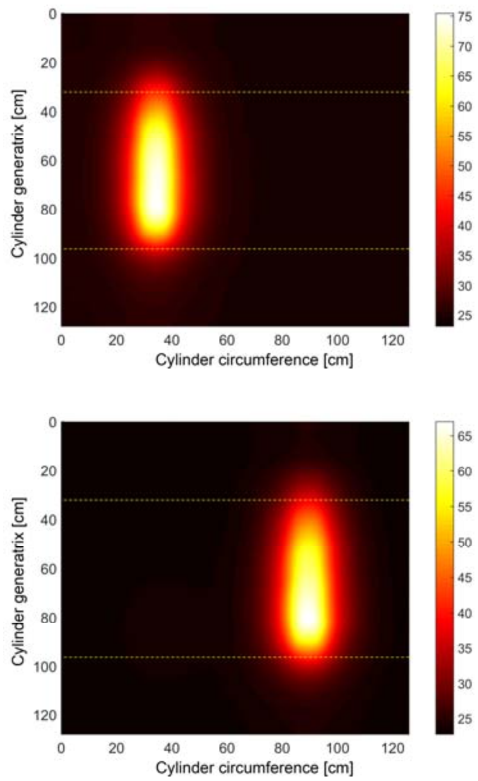

Fig.7. Temperature distribution at cylinder surface for two rotation speeds: 25 rpm (a) and 125 rpm (b), after correction of the heating circuit delay

Corrected y-coordinate value as a function of delay, L, and cylinder speed, v_w , can be determined from:

(2) $$y_k = y_z - L \cdot v_w$$

where: y_k- corrected coordinate of switching on point, y_z- original coordinate of switching on point for the system without delays, v_w - linear velocity of the cylinder surface, L - equivalent delay of the heating channel.

The procedure described above has been verified experimentally by applying the corrected values of y_k for two analysed cylinder speeds with delay compensation activated. The obtained surface temperature distributions are shown in Figure 7.

Comparing Figure 7 and Figure 3 presenting infrared images of temperature distributions on cylinder surface for two rotational speeds it can be seen that application of the proposed correction procedure has significantly improved the location and size of the heated area, particularly at speed of 125 rpm.

Comments and conclusions

The problem of delayed power generation in an induction heating system of rotating steel cylinder presented in this paper arises as an important problem in surface temperature control, especially when precise temperature distribution along cylinder circumference is required. Performed experiments have shown that the delay is particularly evident in a power switching on phase while its influence is most significant at higher rotational speed of the cylinder. Under such conditions, adequate compensation of this delay can be realized by adjusting of switching on time of heating power. The identification method of the equivalent delay of power generation channel has been proposed and adequate compensation procedure has been elaborated. Despite its simplicity the method makes it possible to significantly improve the temperature distribution along the surface. However, the obtained results indicate the need for developing a method of compensation of full dynamic properties of HF generator as well as the inductor-cylinder system, which will be a subject of further work.

***Authors**: dr inż. Andrzej Frączyk, Politechnika Łódzka, Instytut Informatyki Stosowanej, ul. Stefanowskiego 18/22, 90-924 Łódź, E-mail: andrzej.fraczyk@p.lodz.pl; dr hab. inż. Jacek Kucharski, Politechnika Łódzka, Instytut Informatyki Stosowanej, ul. Stefanowskiego 18/22, 90-924 Łódź, E-mail: jacek.kucharski@p.lodz.pl.*

REFERENCES

[1] Urbanek P., Kucharski J., Frączyk A., Methods of determination of dynamic properties of induction heated multi input – multi output systems, *Przegląd Elektrotechniczny*, nr 11, 2008, 180-183

[2] Zgraja J., Simplified model for simulation the heat transfer between induction heated calender rolls and wet paper, *Przeglad Elektrotechniczny,* no. 11, 2011, 85-88

[3] Urbanek P., Frączyk A., Kucharski J.: Algorytmy eliminacji wpływu zmian emisyjności powierzchni w bezstykowych pomiarach temperatury wirującego walca stalowego, *Automatyka*, tom 12/3, 2008, 841-851

[4] Frączyk, A., Urbanek, P., Kucharski, J., Modelling and optimal temperature control of in-duction heated rotating steel cylinder, *13th IEEE IFAC International Conference on Methods and Models in Automation and Robotics*, Szczecin, 2007, 351-355

[5] Urbanek P., Kucharski J., The induction heated rotating steel cylinder as a control plant, *51st Internationales Wissenschaftliches Kolloquium, Technische Universität Ilmenau*, 2006

[6] Jaworski T., Wykorzystanie informacji wizyjnej w cieplnych procesach przemysłowych poprzez rozmyte przetwarzanie obrazów termowizyjnych. Praca doktorska, Politechnika Łódzka, 2015