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Experimental Verification of Device for Setting of Position Based on Induction Heating-Produced Thermoelastic Effect

***Abstract**. Experimental verification of thermoelastic effect is performed with the aim to calibrate the device for accurate setting of position built in our laboratory. The time evolution of temperature and dilatation of the action element was measured for a sufficient spectrum of field current parameters (amplitude and frequency). The resultant graphs were compared with results obtained by numerical simulation.*

***Streszczenie.** W pracy opisano eksperymentalną weryfikację modelu numerycznego nagrzewania indukcyjnego. Zmiana rozmiaru elementu wykonawczego została zmierzona dla szerokiego zakresu amplitudy i częstotliwości prądu wzbudzającego. Wyniki uzyskane z pomiarów zostały porównane z rezultatami symulacji numerycznych. (**Eksperymentalna weryfikacja urządzenia do precyzyjnego pozycjonowania zbudowanego w oparciu o efekt termoplastyczny z podgrzewaniem indukcyjnym**)*

Keywords: experimental verification, setting of position, thermoelastic effect, numerical analysis.
Słowa kluczowe: weryfikacja eksperymentalna, ustawianie pozycji, efekt termoplastyczny, analiza numeryczna.

Introduction

Accurate setting of position on the order of 10^{-5}–10^{-3} m may be realized by a number of techniques based on mechanical, hydraulic, pneumatic, electromagnetic and other principles. All these systems, however, contain movable parts, whose presence often makes complications. Qualitatively much better results can be achieved using the principle of thermoelasticity produced by induction heating. Our team proposed a device [1] that was modelled numerically, and that exhibits very prospective results. That is why we decided to build a real device and verify these results experimentally.

Description of the device

The arrangement of the device is depicted in Fig. 1. The dilatation element **2** made of a suitable metal is inserted into a harmonic current-carrying coil **3** fixed in frame **4**. The whole system is placed in a Teflon insulating shell **1**. The device is clamped by its bottom part **5** (Teflon front) in the basement **6** that is supposed to be perfectly stiff. The time-variable magnetic field generated by field coil **3** induces in the dilatation element **2** eddy currents that produce heat and consequent geometrical changes (mainly in its longitudinal direction z) of the thermoelastic origin.

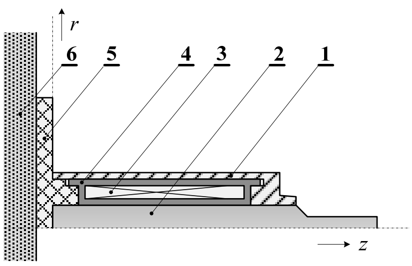

Fig. 1. The basic arrangement of the device **1** – Teflon shell, **2** – dilatation element, **3** – field coil, **4** – fixing frame, **5** – Teflon front, **6** – stiff wall

The device should reach a prescribed dilatation u_{d} of element **2** (see Fig. 2) in the shortest time possible, but under the condition that the highest temperature of the system does not exceed the given limits.

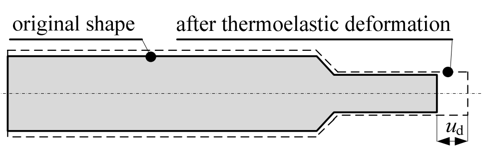

Fig. 2. Dilatation element **2** before and after deformation

The goal of the paper is to suggest and solve the mathematical model of the device and to experimentally verify the most important results.

Continuous mathematical model and its solution

From the physical viewpoint, the task represents a triply coupled problem. Its mathematical model consists of three partial differential equations describing the distribution of magnetic field, temperature field and field of thermoelastic dilatations.

The device does not contain any ferromagnetic part. If the field coil **3** (Fig. 1) carries harmonic current of density $\boldsymbol{J}_{\mathrm{ext}}$, the magnetic field in the system may advantageously be described by the Helmholtz partial differential equation for the phasor $\underline{\boldsymbol{A}}$ of the magnetic vector potential $\boldsymbol{A}$ in the form [2]

$$\text{(1)} \qquad \mathrm{curlcurl}\underline{\boldsymbol{A}} + \mathrm{j}\cdot\omega\gamma\mu_0\underline{\boldsymbol{A}} = \mu_0\underline{\boldsymbol{J}}_{\mathrm{ext}} .$$

Here, symbol μ_0 denotes the magnetic permeability, γ is the electric conductivity, ω stands for the angular frequency, and $\underline{\boldsymbol{J}}_{\mathrm{ext}}$ is the phasor of external harmonic current density in the field coil. The conditions along the axis of the device and artificial boundary placed at a sufficient distance from the system are of the Dirichlet type ($\underline{\boldsymbol{A}} = \underline{\boldsymbol{0}}$).

Heat power in the system is generated by external currents in the field coil and induced currents in the dilatation element. The distribution of the temperature in the system is then given by equation [3]

$$\text{(2)} \qquad \mathrm{div}\left(\lambda\cdot\mathrm{grad}T\right) = \rho c_{\mathrm{p}}\frac{\partial T}{\partial t} - p_{\mathrm{J}} ,$$

where λ denotes the thermal conductivity, ρ is the specific mass, and c_{p} stands for the specific heat at a constant pressure. Finally, the symbol p_{J} denotes the time average internal sources of heat represented by the volumetric Joule losses. These are given by the formula

$$\text{(3)} \qquad p_{\mathrm{J}} = \frac{\left|\underline{\boldsymbol{J}}\right|^2}{\gamma}, \quad \underline{\boldsymbol{J}} = \underline{\boldsymbol{J}}_{\mathrm{ext}} + \underline{\boldsymbol{J}}_{\mathrm{ind}}, \quad \underline{\boldsymbol{J}}_{\mathrm{ind}} = \mathrm{j}\cdot\omega\gamma\underline{\boldsymbol{A}} ,$$

where symbol $\underline{\boldsymbol{J}}_{\mathrm{ind}}$ denotes the induced current density.

The boundary conditions should take into account both convection and radiation. But since the dilatation element **2** and field coil **3** are placed in a Teflon insulating shell (characterized by a very poor thermal conductivity λ), radiation can be – with a practically negligible error – disregarded.

The distribution of displacements in the dilatation element **2** follows from the solution of the Lamé equation [4]

$$(\varphi+\psi)\cdot\operatorname{grad}(\operatorname{div}\boldsymbol{u})+\psi\cdot\Delta\boldsymbol{u}- \\ -(3\varphi+2\psi)\cdot\alpha_{\mathrm{T}}\cdot\operatorname{grad}T+\boldsymbol{f}=\boldsymbol{0}, \tag{4}$$

where $\varphi\geq 0,\ \psi>0$ are coefficients associated with material parameters by the relations

$$\varphi=\frac{\nu\cdot E}{(1+\nu)(1-2\nu)},\ \psi=\frac{E}{2\cdot(1+\nu)}. \tag{5}$$

Here E denotes the modulus of elasticity and ν is the Poisson coefficient of the contraction. Finally, symbol $\boldsymbol{u}=(u_r,u_\varphi,u_z)$ represents the vector of the displacement, α_{T} is the coefficient of the linear thermal dilatability of the material, and $\boldsymbol{f}$ stands for the vector of the internal volumetric forces. These consist (at least in the dilatation element **2**) of the gravitational and Lorentz volumetric forces. But in comparison with the thermoelastic strains and stresses they are very small and may be neglected.

The boundary conditions depend on the particular arrangement. In the solved case the displacements of the dilatation element **2** at the place of clamping are assumed to be equal to zero.

Numerical solution

The numerical solution was performed by a combination of professional codes COMSOL Multiphysics and Matlab that were supplemented with a lot of own procedures and scripts. Special attention was paid to the convergence of the results (dependence of the distribution of physical fields on the density of discretization meshes and in the case of electromagnetic field also on the position of the artificial boundary).

Experiments

Experiments were realized on a physical model depicted in Fig. 3.

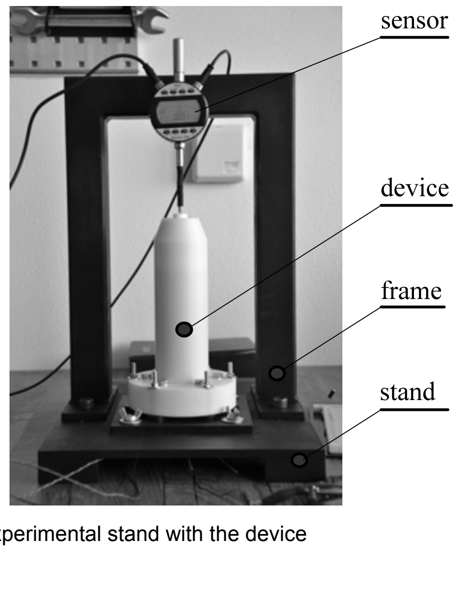

Fig. 3. Experimental stand with the device

The field coil **3** of the device was loaded by currents of varying amplitude and frequency. The principal dimensions of the device follow from Fig. 4.

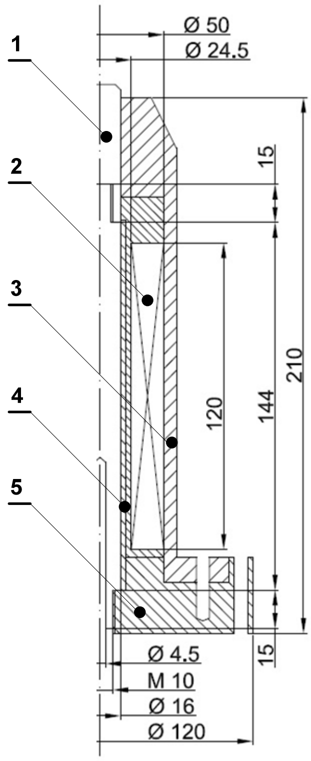

Fig. 4. Arrangement of the tested actuator (dimensions in mm) **1**–brass dilatation element, **2**–field coil, **3**–nylon shell, **4**–ceramic tube, **5**–nylon bottom

The measurements on the thermoelastic actuator were performed in several operation regimes for different parameters of the field current; namely for frequencies 519 Hz, 1005 Hz and 2210 Hz and effective values 0.5 A and 1 A. The sinusoidal signal from the frequency generator was amplified to the required value of current at the given frequency. In series with the actuator we also connected a small resistance on which we determined (by means of an oscilloscope) the value of the current from the measured voltage and resistance of the resistor. The thermoelastic actuator may be considered an RL circuit and for obtaining the maximum current this circuit must be set to resonance. For compensation we used roll capacitors proposed for the prescribed frequency. Realization of the compensation term requires taking into account available types of the capacitors, so that it is practically not possible to reach the accurate value of capacitance. Thus, the process must be finely tuned by frequency, which explains its values above. The displacement was measured by a digital meter in time interval $\langle 0-300\rangle$ s, the step being 30 s. The temperature was measured by means of thermocouples placed in small bores in the dilatation element and recorded in the same time intervals.

Results and their evaluation

For simulation, the first task was to find the physical parameters of individual parts of the model and their temperature dependences. This represents, however, a severe complication because there is a wide variety of brasses differing in their composition, and their parameters considerably differ one from another (and it was not known what kind of brass was used for manufacturing of the dilatation element).

Next paragraphs show the most important results obtained both by simulation and measurements. For computations we considered bras of type UNS C26000. Its physical paremeters and their temperature dependences were found in the database [5]. The other structural elements of the actuator are made of standard materials and finding their properties makes no problem. The initial temperature of the system (before heating) was 25 °C. The parameters of the field current were $I_{\mathrm{eff}} = 1$ A and $f = 2210$ Hz.

For illustration Fig. 5 shows the simulated distribution of temperature in the system after 300 s of heating. It is obvious that (due to the ceramic tube surrounding the dilatation element whose thermal conductivity is very poor) the process is almost adiabatic. Figure 6 depicts the distribution of axial displacements for the same time.

The time evolutions of the average temperature of the dilatation element and its dilatation obtained by simulation and experiment can be seen in Figs. 7 and 8. There are differences reaching up to 12 %, most probably caused by incorrect parameters of brass taken for numerical modeling.

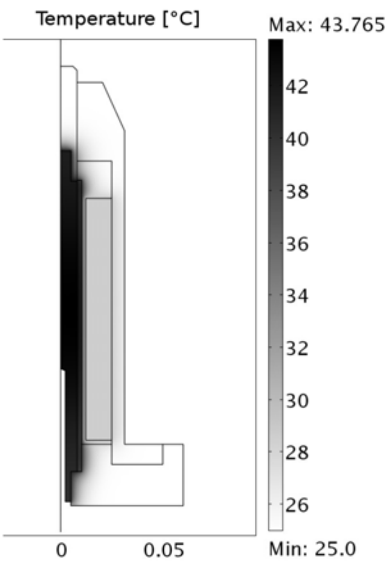

Fig. 5. Distribution of temperature in the system ($t = 300$ s, $I_{\mathrm{eff}} = 1$ A, $f = 2210$ Hz)

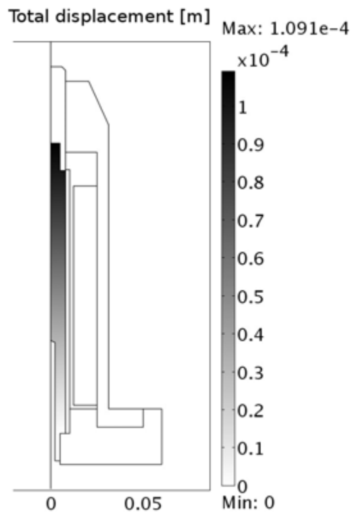

Fig. 6. Distribution of displacements in the dilatation element ($t = 300$ s, $I_{\mathrm{eff}} = 1$ A, $f = 2210$ Hz)

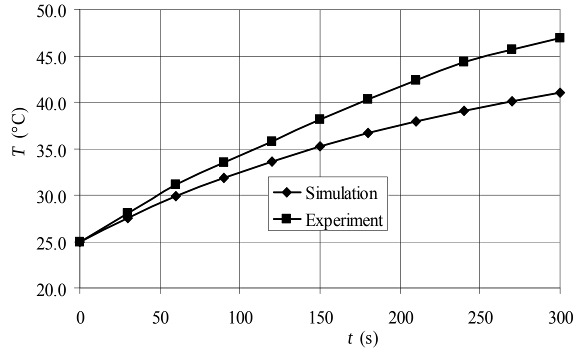

Fig. 7. Time evolution of the temperature ($I_{\mathrm{eff}} = 1$ A, $f = 2210$ Hz)

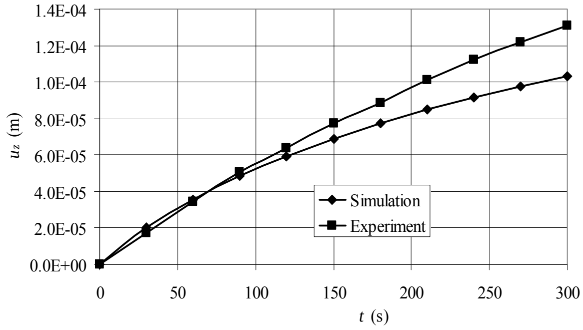

Fig. 8. Time evolution of the axial displacement ($I_{\mathrm{eff}} = 1$ A, $f = 2210$ Hz)

Conclusion

Thermoelasticity may prove to be a mighty tool in some applications where setting of accurate position is needed. The process of reaching the required dilatation is slow, but reliable.

Nevertheless, accuracy of the results strongly depends on correctness of the input data. Further research will be, therefore, aimed at possibilities of their improvement.

Another important aim is to accelerate the heating process. New possibilities are investigated in this direction, based on using variable amplitude of the field current, which can be realized, for example, by pulse-width modulation.

Acknowledgment

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