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Thermodynamic optimization of mechanical systems with dissipative processes

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Abstract

A modelling of the mechanical systems with dissipative processes as thermodynamic systems has been performed in this article. On the basis of the Gouy–Stodola's theorem the entropy generation minimization method for thermodynamic optimization of these systems has been applied. The outcomes of a thermodynamic optimization of metal-forming processes and rotor brake systems have been shown. It has been proved that the generated entropy is a generalized optimization criterion for this kind of systems. The vector optimization criterion has been substituted by the generated entropy functional depending on the vector of controlling factors (process parameters). The generated entropy plays the role of a surrogate function of a feasible scalarized function, and therefore it is not necessary to scalarize the vector optimization criterion. The optimization is reduced to generated entropy minimization. The effectiveness of the latter approach has been proved.

Keywords: Entropy generation minimization; Thermodynamic optimization; Spherical mandrelling (SM); Cold hole expansion; Rotor brake systems

1. Introduction

Five basic forms of motion of matter exist—mechanical, physical, chemical, biological and social but in the practice of mechanical engineers the first three are important as behaviour of matter in various material systems as a result of exchange of energy and substance in them. Even in seemingly ‘‘sheer’’ mechanical systems whose deformations are elastic only, heat exchange which is a physical form of the matter motion occurs because of the hysteresis of the material. Therefore these material systems are essentially thermodynamic: the individual subsystems interact both with each other and with the environment.

Most of the material systems studied by mechanical engineers are mechanical systems with internal and surface heat sources. A mechanical system is a set of solids in which the position of each solid depends on the positions of the rest, respectively a mechanical interaction exists between the solids. The change in the system state expressed by a variation in at least one of its mechanical parameters is a mechanical process. During each real mechanical process, as a result of hysteresis and internal friction along the contact surfaces of the individual subsystems, there is dissipation of mechanical energy—heat is generated inside and along the boundaries of the subsystems. In some cases the dissipated part of the mechanical energy is insignificant and in other cases it can be too large. In the second case these mechanical systems constitute a large group of thermodynamic systems—mechanical systems with dissipative processes [1] (Fig. 1).

The processes in these systems are thermodynamic ones and they would proceed most smoothly if the mechanical, thermal, etc. resistances overcome were the lowest. In this aspect an optimization theory for mechanical systems with dissipative processes, following the entropy generation criterion considered as a quantitative indicator of the resistances overcome has not been developed yet. Entropy generation minimization in these systems is equivalent to its optimization.

Entropy generation minimization (EGM) is the method of modelling and optimization of real devices that owe

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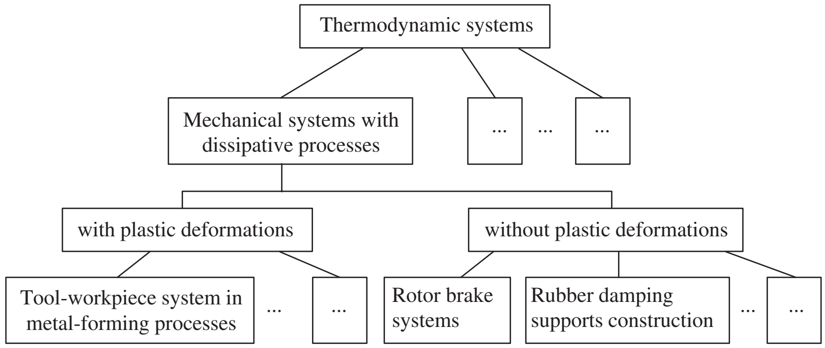

Fig. 1. Mechanical systems with dissipative processes as thermodynamic system.

their imperfection to heat transfer, mass transfer, and fluid flow and other transport processes [2]. Although isolated publications had appeared throughout the 1950s and 1960s, EGM emerged as a self-standing method and field in engineering in the 1970s. EGM method was first described as a modelling and optimization method in [3] by Bejan. EGM as a fundamental optimization approach has been implemented most complexly by Bejan to processes with heat and fluid flows [2–7]. For the same kind of processes using Bejan's approach, thermodynamic optimization is shown in Refs. [8–10]. In [11] the approach has been implemented to optimize power systems. The second law of thermodynamics is applied in [12,13] for forecasting the fatigue life of the rubber damping supports constructions. In [14] as criterion for reliability of mechanical constructions, the entropy generation rate has been used when the material yield. But no information is available on EGM method application to deformable solids and, in general, to mechanical system with dissipative processes.

Metal-forming process optimization is reduced to solving a multiobjective optimization task. One of the most powerful approaches to the solution of this task is the vector criterion scalarization approach which is realized by reference approach methods [15]. The synthesis of the scalarized function is performed on the basis of combination of the separate components of the vector optimization criterion. The introduction of weight factors [15] brings to a certain extent an element of subjectivity.

In this aspect the modelling of the metal-forming processes as thermodynamic ones predetermines a new (thermodynamic) approach to solving the multiobjective optimization task. The role of a scalarized function will be played by the generated entropy functional which replaces in thermodynamic aspect a feasible scalarized function synthesized according to some methods described in [15].

The main objective of this study is to obtain of a generalized model of the state of the mechanical systems with dissipative processes modeled as thermodynamic ones and also thermodynamic optimization by means of generated entropy functional minimization.

2. Modelling of the mechanical systems with dissipative processes as thermodynamic systems

2.1. Generalized model of the mechanical system state, modelled as thermodynamic system

A thermodynamic system, which consists of z in number subsystems (deformable solids) is considered. The following $z+1$ in number coordinate systems (CS) are introduced: Ox_i—static (absolute); $Ox_i^{(r)}$—immovably connected with the moving as a rigid body rth subsystem whose points perform displacements in $Ox_i^{(r)}$. The contact of each subsystem with the rest is a part of surface—contact point set (CPS).

2.1.1. Parameters of the thermodynamic system state

The basic parameters of the thermodynamic system state are [1]: strain tensor, stress tensor, temperature in the subsystems.

2.1.1.1. Kinematic equations.

- *Law of motion of z noninteracting subsystems* $(0<t<t^*)$ *in static CS* Ox_i:

$$x_i = x_i(\eta_i^{(r)}, t), \tag{1}$$

where $\eta_i^{(r)}$ and t are Lagrange variables.

- *Law of motion of z interacting subsystems* $(t^* \leqslant t)$ *in static CS* Ox_i:

$$x_i = \eta_i^{(r)} + u_i^{(r)}, \tag{2}$$

where $\vec{u}^{(r)} = [u_1^{(r)}\ u_2^{(r)}\ u_3^{(r)}]^{\mathrm{T}}$ is displacement vector of the subsystem (r) in $Ox_i^{(r)}$.

- *Strain tensors in subsystem* (r) *in generalized view*:

$$\varepsilon_{ij}^{(r)} = \frac{1}{2}\left(\frac{\partial u_i^{(r)}}{\partial x_j^{(r)}} + \frac{\partial u_j^{(r)}}{\partial x_i^{(r)}} - \gamma^{(r)}\frac{\partial u_k^{(r)}}{\partial x_i^{(r)}}\frac{\partial u_k^{(r)}}{\partial x_j^{(r)}}\right), \quad \gamma^{(r)} = \begin{cases} 0, \\ 1. \end{cases} \tag{3}$$

- *Strain velocity tensor and rotation tensor in subsystem* (r)

$$\xi_{ij}^{(r)} = \frac{1}{2}\left(\frac{\partial v_i^{(r)}}{\partial x_j^{(r)}} + \frac{\partial v_j^{(r)}}{\partial x_i^{(r)}}\right), \quad \Omega_{ij}^{(r)} = \frac{1}{2}\left(\frac{\partial v_i^{(r)}}{\partial x_j^{(r)}} - \frac{\partial v_j^{(r)}}{\partial x_i^{(r)}}\right), \tag{4}$$

where $\vec{v}^{(r)} = \vec{v}^{(r)}(x_i^{(r)}, t)$ is velocity field.