JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
3, 38, 2000

INTELLIGENT STRUCTURES OF SPRINGS

BOGDAN BRANOWSKI

Faculty of Working Machines and Vehicles, Poznań University of Technology
e-mail: bbra@stanton.bmd.put.poznan.pl

The work is concerned with principles of design of "intelligent" sets of springs with *a priori* determined structure (the so called differential set of springs). Certain interesting properties can be obtained in such sets considering the thermal influence of the environment. These properties enable realisation of the selfcompensation function or even amplification of loading applied to the set in higher and varying temperatures, and to create the drive function of the linear motor while producing pulsatory temperature changes. The problem of loading selfcompensation has been solved considering the temperature changes of the shear modulus or the stress relaxation. The drive function enables one to apply the differential set of springs together with the spring made of shape memory alloy (SMA) to create a unique linear pulse micromotor. The SMA spring, activated thermally, operates as an actuator assuring pulse changes of the deflection in the differential set. These changes together with the unidirectional mechanism constitute the principle of operation of the micromotor robot that moves inside a tube).

Key words: intelligent constructions of springs, mobile robots, SMA actuator

Notations

D	–	mean diameter of coil
E	–	modulus of elasticity
G	–	shear modulus
L_{bl}	–	calculated length of spring with totally compressed coils
L_0	–	free length of spring
N	–	number of cycles of loading changes
P	–	spring force (spring load)
P_{1i}, P_{2i}	–	initial and final work of the loading in the ith spring
P_z	–	loading of the set of springs

R_m – tensile strength
c – spring rate
d – diameter of wire
f – deflection of spring at force P
k – stress correction factor
w – spring index
z_c – number of active coils
τ – shear stress

1. Introduction to selfcompensation of thermal changes in differential set of springs

Under frequently changing temperature conditions an intensification of many physical phenomena that have a significant influence on decreasing of the spring loading (for the assumed deflection) can be observed. Such a decreasing of the loading is caused by stress relaxation, changes in modulus of elasticity and by thermal expansion. The aim of this work is to find the proper construction of the differential set of springs that can be applied to varying temperature conditions. The mechanical properties of such a set are to be kept fixed by means of selfcompensation or by means of varying characteristic in a given range of the loading.

There are also other possibilities of creating the temperature independent characteristics, e.g. by applying wire materials with moduli of elasticity poorly sensitive to changes of working temperatures (e.g. Nispan-C, Isoelastic, Nivarox, Safeni) or by applying special technological treatment (e.g. heat treatment of springs). Unfortunately, such solutions are rather limited concerning the compensation changes of spring characteristics.

A spring composed of differential set of springs made of particular material and having proper geometric shape assures a constant characteristic in a wide temperature range. In the differential set of springs the force transmission system can be obtained in a single or a double way. In the single transmission system one spring is compressed and the other one is stretched, whereas in the double transmission system both springs are compressed. The easiest way to obtain such a spring function is to apply coil springs (see Fig.1). In the double transmission system it is also possible to apply other types of springs (e.g. two sets of disc springs or a combination of coil spring with coil torsion one). In the assembled state each spring of the set is loaded with the initial force.

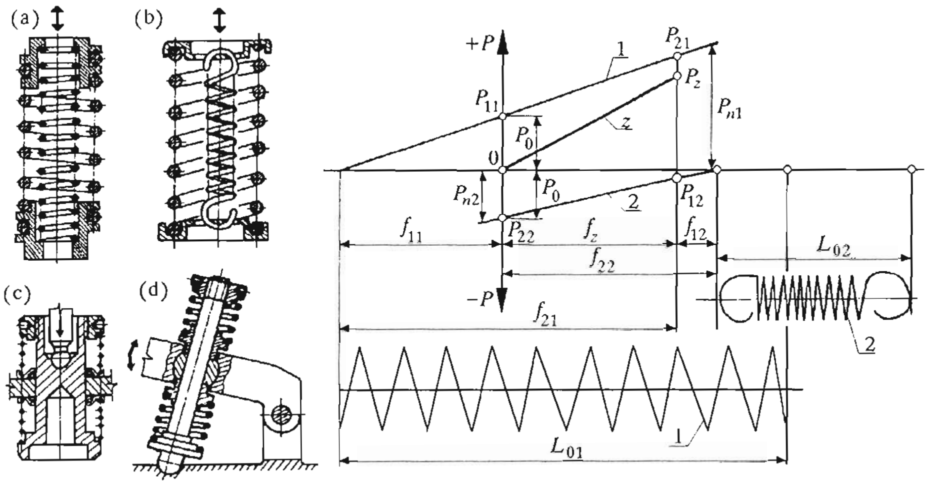

Fig. 1. Differential sets of springs for single (a and b) and double (c and d) force transmission system and a chosen force-deflection characteristic (for set b)

When the loading is applied the force in one spring increases while in the other one decreases in such a way that the total loading is equal to the difference of these forces.

Basic computational relationships for differential sets of springs in the initial state of temperature T_p are as follows

$$P_z = P_{21} - P_{12} = c_z f_z \tag{1.1}$$

where

$$c_z = c_1 + c_2 \qquad c_1 = \frac{P_{21} - P_{11}}{f_z} \qquad c_2 = \frac{P_{22} - P_{12}}{f_z} \qquad P_{11} = P_{12} \tag{1.2}$$

As the temperature raises up to T_k in a sufficiently long period of time t, the following changes of loading in each spring and the whole set can occur due to the above-mentioned phenomena

$$\Delta P_{zT} = P_z - P_{zT} \qquad \Delta P_{21T} = P_{21} - P_{21T} \qquad \Delta P_{12T} = P_{12} - P_{12T} \tag{1.3}$$

Describing the relative changes of the loading as

$$R = \frac{\Delta P_{zT}}{P_z} \qquad R_1 = \frac{\Delta P_{21T}}{P_{21}} \qquad R_2 = \frac{\Delta P_{12T}}{P_{12}} \tag{1.4}$$

one finally obtains

$$R = \frac{P_{21}R_1 - P_{12}R_2}{P_z} \tag{1.5}$$

Taking into consideration the relative change R of the set of springs the three following scenarios can be obtained:

- when $R = 0$, which is equivalent to $\Delta P_{zT} = 0$, the system is selfcompensated in terms of the loading with temperature growth and for $P_{21} = P_{12}(R_2/R_1)$
- when $R > 0$, which is equivalent to $\Delta P_{zT} > 0$, the system exhibits weakening characteristics with temperature growth and for $P_{21} > P_{12}(R_2/R_1)$
- when $R < 0$, which is equivalent to $\Delta P_{zT} < 0$, the system characteristic is increasing with temperature growth and for $P_{21} < P_{12}(R_2/R_1)$.

The relative changes of loading R_1 and R_2 are presented as functions of the material, loading and geometric features concerning the spring construction and the environmental conditions

$$R_i = F_i(T, t, \tau, \delta, M) \qquad i = 1, 2$$

where
T – temperature
t – time
τ – initial stress
δ – factor related to overall dimensions, mostly commonly wire diameter
M – function of chosen material properties such as:
  m – coefficient of temperature changes in the modulus of elasticity
  α – coefficient of thermal expansion.

2. Selfcompensation of themally induced load changes

The problem of selfcompensation in differential sets of springs, in particular for the relative loading changes $R_i = F_i(T, M)$, $i = 1, 2$, has been analysed in the paper. A change in the shear modulus G caused by temperature as well as thermal expansion has an influence upon the spring characteristic. As it has been already stated by the author (Branowski, 1990), in such conditions it is necessary to take into consideration the loading changes caused by a drop in the elasticity brought about by temperature changes of the shear modulus G. The influence of thermal expansion on the spring characteristic is very small. Therefore a linear change of relationship between the shear modulus G and the temperature T has been assumed

$$G_T = G(1 - mT) \tag{2.1}$$

Spring rate c_T of the coil cylindrical spring at the temperature T is defined as

$$c_T = c\frac{G_T}{G} = c(1 - mT) \tag{2.2}$$

where

c – spring rate at temperature 20°C; $c = Gd^4/(8D^3 z_c)$

m – temperature change coefficient of the shear modulus G.

Considering the characteristic shown in Fig.1e one writes down

$$R_1 = m_1 T \qquad R_2 = m_2 T \qquad R = 0 \tag{2.3}$$

In the increased temperature T, the forces developed in springs 1 and 2 after application of hte loading are

$$\begin{aligned} P_{21T} &= P_{21}(1 - m_1 T) \qquad P_{12T} = P_{12}(1 - m_2 T) \\ P_{zT} &= (P_{21} - P_{12})(1 - R) = P_{21}(1 - m_1 T) - P_{12}(1 - m_2 T) \end{aligned} \tag{2.4}$$

and then for $R = 0$

$$P_{12} = P_{21}\frac{R - R_1}{R - R_2} = P_{21}\frac{m_1}{m_2} \tag{2.5}$$

Finally, for the given force P_z and the deflection f_z (for the whole set) it is possible to find the design parameters for particular springs 1 and 2

$$P_{21} = P_z\frac{1 - m_1}{m_2} \qquad P_{12} = -P_z\frac{m_1}{m_2} \tag{2.6}$$

The initial assembly force $P_0 = P_{11} = P_{22}$ for springs 1 and 2 can vary in a wider range but it decreases as the elasticity of the compressed spring alows. The following condition is then fulfilled

$$\frac{c_1}{c_2} = \frac{P_{21} - P_0}{P_0 - P_{12}} \tag{2.7}$$

The algorithm for design of springs in the given selfcompensation system was discussed by the author in his work (Branowski, 1990). The effectiveness of the method can be evaluated basing on Olesin's work (1969) as it has been done by the author. Calculation results and experimental data for the given set have been presented in Fig.2. The design features of the set have been fixed as:

(1) – comparisson spring: $d = 5\,\mathrm{mm}$; $D = 50\,\mathrm{mm}$; $L_0 = 79\,\mathrm{mm}$; $z_c = 4$; $z = 6$; $c = 11.58\,\mathrm{N/mm}$; $\tau_{dop} = 471\,\mathrm{MPa}$; material EI 128 with nonlinear variability of the shear modulus $G(T)$:

T [°C]	20	100	200	300	400
G [$10^3\,\mathrm{N/mm^2}$]	75.5	74.6	73.2	71.6	69.7

(2) – tension spring; $d = 3\,\mathrm{mm}$; $D = 16.5\,\mathrm{mm}$; $z_c = 13.5$; $z = 16.5$; $\tau_{dop} = 559\,\mathrm{MPa}$ material EI 696M with varying $G(T)$:

T [°C]	20	100	200	300	400
G [$10^3\,\mathrm{N/mm^2}$]	69.7	67.7	65.7	62.8	59.8

The set has been loaded for varying temperatures from 0°C up to 500°C by $P_0 = P_{11} = P_{22} = 196\,\mathrm{N}$ at $f_z = 8.5\,\mathrm{mm}$ (Fig.2.bI).

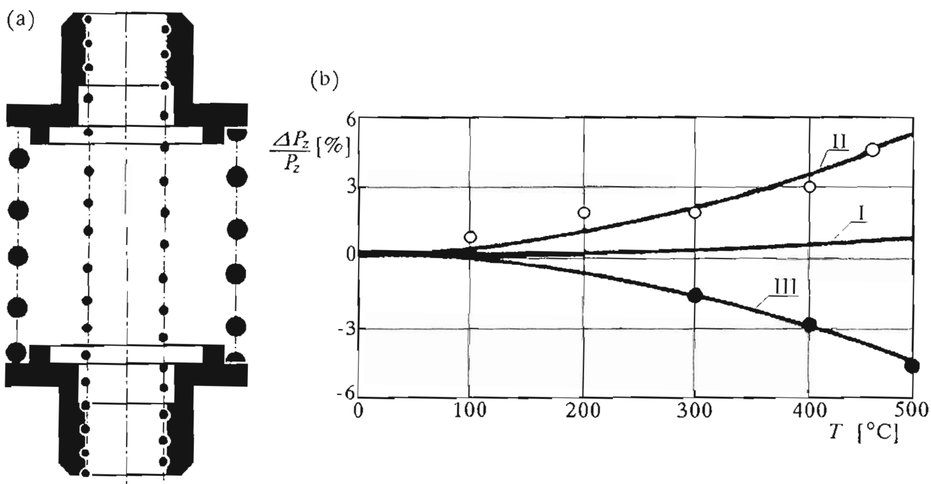

Fig. 2. Compensation of changes of spring characteristic in high temperatures (Olesin, 1964); (a) differential set composed of compression and tension spring; (b) change of loading for the temperature growth at $P_z = 196\,\mathrm{N}$ (I); $P_z = 245\,\mathrm{N}$ (II); $P_z = 147\,\mathrm{N}$ (III)

3. Selfcompensation in terms of stress relaxation in springs

Another problem of selfcompensation in differential set of springs for a particular case of the relative loading changes $R_i = F_i(T,\tau,d,M)$, $i = 1,2$, has been analysed in the paper. The problem is concerned with temperature relaxation changes that can affect spring characteristic. It has been assumed that the relaxation changes in the range of $< T_{\min}, T_{\max} >$ may cause a slight increase in the relative loading within the range of $\Delta P_z/P_z \in < 0;\ 0.02 >$. The following experimental model of the relaxation $R = \Delta\tau/\tau$ in springs, see Schüle (1968) has been applied

$$\Delta\tau = A\Delta f = ab\, 3.0^{\frac{T-110}{100}} 1.85^{\frac{t-25}{17}} (\ln t + 5.5) \tag{3.1}$$

where: $A\,[\mathrm{kG/mm^3}]$ – constant value related to spring design $(A = Gd/(\pi z_c D^2)$; $\Delta f\,[\mathrm{mm}]$ – spring deflection loss during creeping; a – material constant related to manufacturing of spring wires ($a = 0.29$ – oil hardened non-alloyed valve wire VD according to DIN 17223 T.2; $a = 0.19$ – oil hardened alloyed valve wire CrV according to DIN 17223 T.2); b – dimensional coefficient ($b = \sqrt{d}$, $d\,[\mathrm{mm}]$); $\tau\,[\mathrm{kG/mm^2}]$ – initial stress taken from the range $< 40, 80 >$ regardless of correction coefficient k; $T\,[^\circ\mathrm{C}]$ – temperature taken from the range $< 100, 240 >$; $t\,[\mathrm{h}]$ – time.

In the algorithm of relaxation calculations, following the experimental confirmation of the Schüle suggestion, the τ stress has been assumed as the mean of the τ_{psr} stress found from the initial τ_p and the terminal τ_k stress of the relaxation process. The above equation describes the process of creeping in valve springs.

Applying the following data: material, design constant a, spring dimensions, stresses $\tau = \tau_p$ at the initial loading P, time t ($t = 48$ hours as the period of the fixed relaxation in springs according to DIN 2089), wire diameter d; one can formulate the calculation algorithm at any temperature as in the following

(1) $b(d) = \{\ \}$

(2) $\Delta\tau(b,T,\tau_p,t) = \{\ \}$

(3) $\tau_k = \tau_p - \Delta\tau$

(4) $\Delta\tau_{sr} = ab\, 3.0^{\frac{T-110}{100}} (\ln 48 + 5.5)\Big(\dfrac{1}{\tau_k - \tau_p} \displaystyle\int_{\tau_p}^{\tau_k} 1.85^{\frac{\tau-25}{17}}\, d\tau\Big)$

(5) $\tau p_{sr} = \tau p - \Delta\tau_{sr}$

(6) $\Delta\tau_{sr}(b,T,\tau_{psr},t) = \{\ \}$

$$(7)\quad \mathrm{Re}(P) = \frac{\Delta\tau_{sr}}{\tau_p} = \{\,\}$$
$$(8)\quad \Delta P = P\mathrm{Re}(P)$$

For the given set it is necessary to describe

$$(1)\quad \Delta P_z = \Delta P_{12} - \Delta P_{21}$$
$$(2)\quad P_z = P_{21} - P_{12}$$
$$(3)\quad \mathrm{Re}(P_z) = \frac{\Delta P_z}{P_z}$$

The calculations have been carried out for a differential set of springs defined by the following data:

- External spring 1: $d = 3.5\,\mathrm{mm}$; $D = 24\,\mathrm{mm}$; $z_c = 6$; $z_n = 6$; $l_0 = 42\,\mathrm{mm}$; $c = 18.35\,\mathrm{N/mm}$; material Si-Cr with $R_m = 1618\,\mathrm{N/mm^2}$
- Internal spring 2: $d = 2\,\mathrm{mm}$; $D = 12\,\mathrm{mm}$; $z_c = 5.5$; $z_n = 2$; $l_0 = 27$; $c = 17.13\,\mathrm{N/mm}$; material VD with $R_m = 1648\,\mathrm{N/mm^2}$.

The set has been loaded with $P_z = 148\,\mathrm{N}$ at $f_z = 3.75\,\mathrm{mm}$ ($P_{21} = 274\,\mathrm{N}$; $P_{11} = P_0 = P_{22} = 239\,\mathrm{N}$; $P_{12} = 141\,\mathrm{N}$; $f_{12} = 8.23\,\mathrm{mm}$; $f_{11} = 13\,\mathrm{mm}$).

For temperatures varying within the allowable range for the spring material $T \in (20, 160°\mathrm{C})$ the following results have been obtained.

Table 1. Changes of the relaxation loading in for the spring set

T [°C]	20	40	60	80	100	120	140	160
Relaxation $\Delta P_z/P_z$ [%] of the differential set according to calculations	+0.97	+1.10	+1.33	+1.51	+1.69	+1.82	+1.87	+1.88
Relaxation $\Delta P_z/P_z$ [%] of spring 1 at τ_{21} according to DIN 2089	+0.40			+1.00		+1.50		+2.20
Relaxation $\Delta P_z/P_z$ [%] of spring 2 at τ_{22} according to DIN 2089				+4.70				+6.00

Basing on these results, one can state that the given differential set of springs satisfies the selfcompensation requirements concerning the relaxation changes of the loading for a wide range of temperatures. The changes of loading of the entire set have been found significantly lower than corresponding changes in each single spring.

4. Application of the concept of the differential set to design of the linear pulsatory motor

4.1. General idea of motor design

In a mechanism composed of the differential set with two initially loaded springs (one exibiting the bidirectional shape memory effect) it is possible to generate pulsatory translations of the elements while periodically heating and cooling the spring with shape memory effect. General idea of the linear motor is based on this principle with additional design restriction assuring transformation of the translatory motion in one direction.

A shape memory alloy (SMA) van be employed as carrying element, temperature sensor and regulator. All these functions made the SMA materials able to realize the so called mechatronic functions of the actuator (see Fig.3).

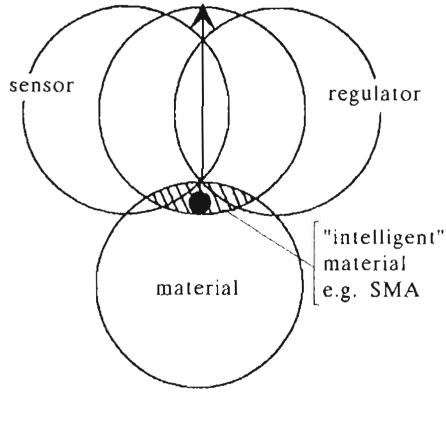

Fig. 3. Mechatronic functions of the intelligent material with shape memory effect

The principle of operating the linear pulsatory motor has been presented in Fig.4. The motor moves inside the elastic tube. The motor consists of a mechanism with differential set of springs, tension spring (1) and compression spring (2). The compression spring is made of the shape memory alloy. On the top of it there is the elastic self-locking mechanism (3) assuring unidirectional movement and protecting from the movement in the direction opposite to the velocity vector. In Fig.4 the three stages of the motor have been presented:

- Initial stage 0 at the initial temperature T_P of the SMA spring
- Working stage I during the temperature increase up to T_k
- Final stage II at the temperature T_P.

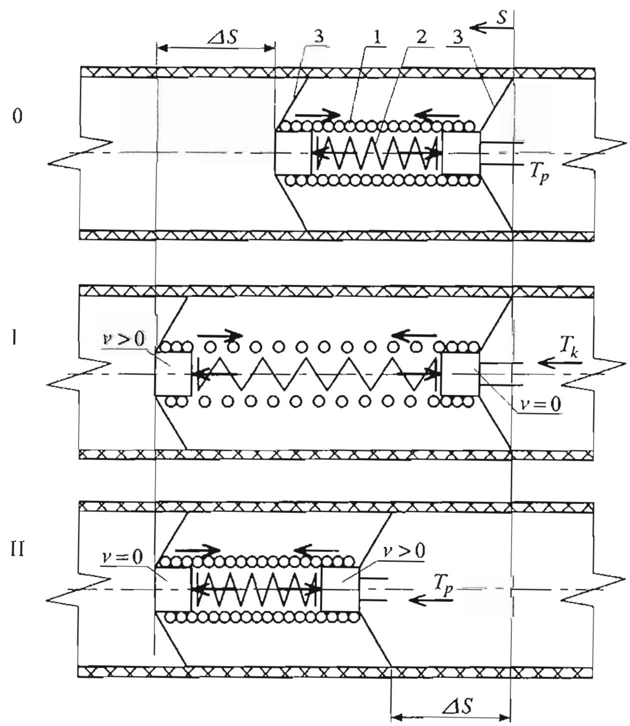

Fig. 4. Principle of operating of the linear motor – three stages of the cycle 0, I, II; 1 – tension steel spring, 2 – compression spring with shape memory effect, 3 – self-locking mechanism

The driving force results from the reversible martensitic transformation in the SMA element. While heating (stage I) up to temperature T_k, the force developed in this element increases and causes movement Δs of the front element of the motor (the rear element of the motor is stopped). After cooling (stage II) down to temperature T_P the rear element of the motor moves forward (the front element of the motor is stopped). As a result of N such martensitic transformations the motor reaches the total movement of $N\Delta s$.

The principle of operating is based on the differential action of the spring set. The relationships between force P, deflection f and temperature T have been presented in Fig.5. The actuator force is produced by the compression spring (2) with shape memory effect. The reverse force is comes from the steel spring (1). The spring rate of the SMA spring in the austenitic state (Fig.5a) at the temperature $T = 80°C$ (for SMA alloys of NiTi) is much higher than the spring rate of the same spring in the martensitic state at the temperature of 20°C. The spring rate for the steel spring remains constant. The whole system moves $\Delta f = \Delta s$, due to acting force that is equal to the difference ΔP of forces in both springs.

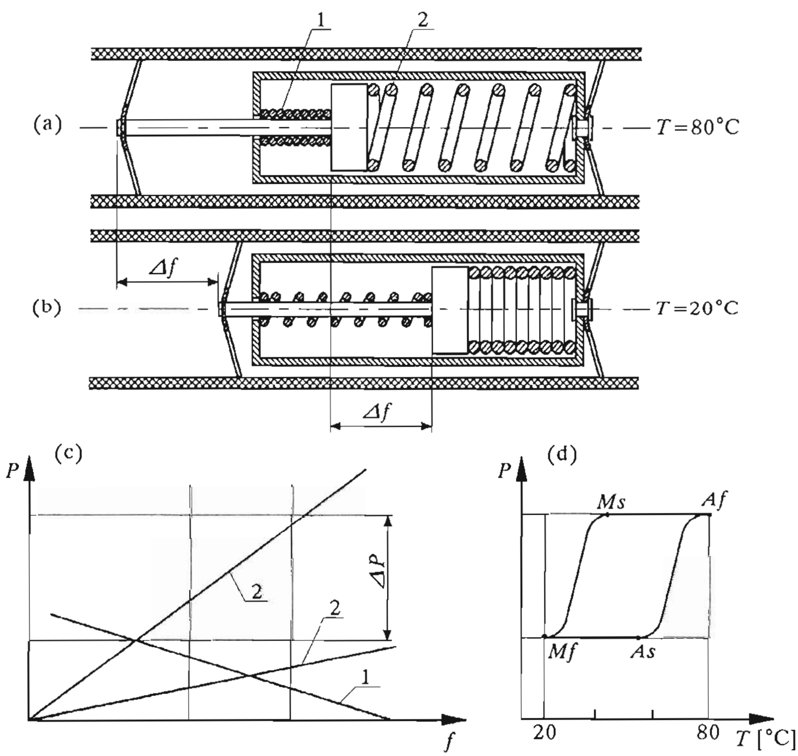

Fig. 5. Temperature changes of the force-deflection function in the differential set of springs; (a) system in the state of austenitic transformation, (b) system in the state of martensitic transformation, (c) force-deflection characteristics for 1 – steel spring, 2 – spring with shape memoryeffect, (d) force-temperature characteristic for the SMA spring

Elements with shape memory effect can be activated in three following ways:

- thermally
- electrically
- mechanically

as it has been shown in Table 2.

When activated thermally the element with shape memory effect acts due to the surrounding heat as sensor and actuator. While electrical activating electrically, one can obtain a uniform control because of the action of the current.

In drive mechanisms the effect of shape memory is applied directly to thermal activation: coil springs or disk springs, and to electrical activation: coil springs, bent bands or wires. In the control strategy with indirect application of the shape memory effect the thermal (e.g. coil spring) or electrical activation (e.g. bent band) is incorporated.

Table 2. Activation of the adjusting elements with shape memory effect

Activation	Adjusting element	Principle of work	Construction shape
Thermal	adjusting element with shape memory (SMA)	thermal shape memory	spring, wire, bent band
Electrical	adjusting element (SMA)	thermal shape memory	spring, wire, bent band
Mechanical	adjusting element (SMA)	mechanical shape memory	wire

Obtaining the repeatability of transformations is influenced by the time of heating and cooling. For an electrically activated system the Peltier effect can be applied. In that case the Peltier module, that is connected to a DC source, is in the form of a heat pump and can be used for heating and cooling. In the case of thermal activation (Fig.6.) it is possible to apply a two-way flow of the heating (e.g. water) and the cooling medium (e.g. CO_2, N_2, freon).

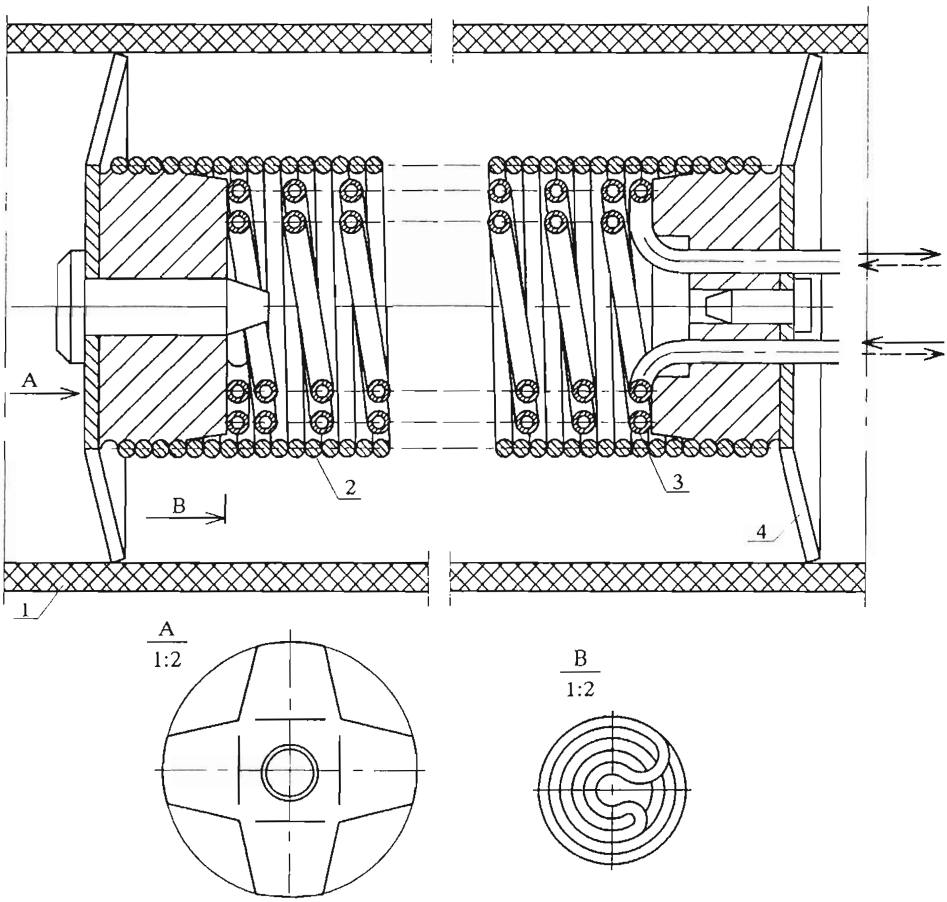

Fig. 6. Linear pulsatory motor thermally activated by flow of heating and cooling medium through the tube spring with shape memory effect: 1 – flexible leading tube, 2 – tension steel spring, 3 – double compression spring made of SMA, 4 – elastic skids of the self-locking mechanism

4.2. Required design properties of the material with shape memory effect

A proper choice of the material with shape memory effect should consider the following characteristic aspects:temperature of transformation (Af, Mf, hysteresis width), force in the austenitic state of the structure, limitting number of cycles during transformation; stability of the transformation effect (transformation temperature, hysteresis of forces) for the given number of cycles. Changes of the transformation temperature, width of the hysteresis and number of the transformation cycles for the abovementioned three groups of alloys, has been presented in Fig.7.

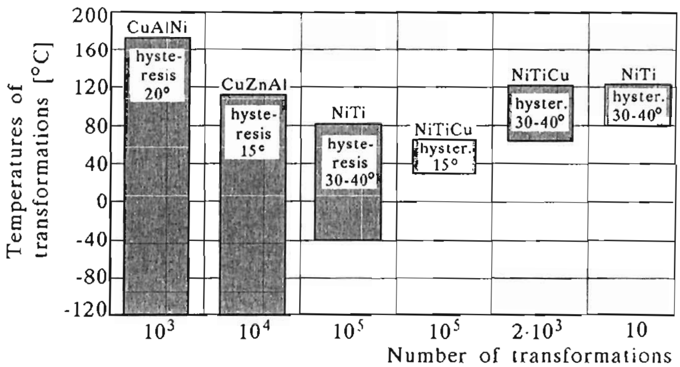

Fig. 7. Values describing choice of material with shape memory effect

These values, during the design process are compared with the following data: (1) number of transformations, (2) range of operating temperatures, (3) values of forces, (4) allowable costs, (5) infrastructure and assembly conditions.

The set of the chosen physical and mechanical properties of the applied alloys has been presented in Table 3. Additionally, the data for Nitinol have been presented.

Basing on the analysed material data a technical project of the miniature mobile robot moves inside the tube according to the general idea shown in Fig.5 has been worked out. It is predicted to construct such a robot in its real shape.

Table 3. Properties of the alloys with shape memory effect (Romankiewicz et al., 1996; Nitinol materials, 1999)

Property	NiTi (generally)	Nitinol	CuZnAl	CuAlNi
Transformation temperature [°C]	200+100	−100 up to +100	200+120	150+200
Hysteresis range [K]	$10 \div 30$	$30 \div 40$	$10 \div 20$	$20 \div 30$
Overheating temp. [°C] at which the shape memory effect disappears	250	240	$160 \div 200$	300
Maximal deformation [%] – one-way effect – two-way effect – superelasticity	 8 5 8	 5 	 5 1 2	 6 1.2 2
Density [g/cm^3]	6.45	6.45	$7.8 \div 8.0$	$7.1 \div 7.2$
Melting temperature [°C]	$1240 \div 1310$	$1240 \div 1310$	$950 \div 1020$	$1000 \div 1050$
Coeff. of thermal expansion [10^{-6}/K]	Martensite 6.6 Austenite 11		$16 \div 18$	$16 \div 18$
Hardness [HV]	$180 \div 350$		$140 \div 190$	$190 \div 220$
Modulus of elasticity E [GPa]	$70 \div 100$	high temp. 75 low temp. 28	$70 \div 100$	$80 \div 100$
Specific electric resistance [$\mu\Omega$mm]	$0.5 \div 1$	high temp. 0.82 low temp. 0.76	$0.07 \div 0.12$	$0.10 \div 0.14$
Strength R_m [MPa]	$800 \div 1000$	$754 \div 960$	$400 \div 700$	$600 \div 900$

5. Conclusions

The differential sets of springs presented in this paper are of very interesting design properties and they are characterized by, so the called "recognising" of the preceding physical state they are in, and ability to find the proper response. That is the reason they can be called "intelligent" systems. Variable heat conditions in the surrounding can be applied to implement new useful functions of such system. The work has presented some design fundamentals concerning the differential systems composed of elastic elements.

These systems are able to realize the principle of selfcompensation of the loading during a heat processes in the springs. Possibility of obtaining a linear pulsatory motor by making use of the differential system of springs with one of them having the shape memory effect has also been mentioned in the paper.

The idea of the motor that can move due to heat changes of the surrounding has to be further developed in order to presenting final design of the springs with the shape memory effect with respect to all the technological and material problems.

References

1. BRANOWSKI B., 1977, *Metallic Springs* (in Polish), Wydawnictwo Naukowe PWN, Warszawa
2. BRANOWSKI B., 1990, Synthesis Methods and Design Research Methods of Spring Construction (in Polish), *Rozprawy*, **237**, Politechnika Poznańska, Poznań
3. CISZEWSKI B., PRZETAKIEWICZ W., 1993, *Nowoczesne materiały w technice*, Wyd. Bellona, Warszawa
4. GAŁKOWSKI Z., 1996, Analiza drgań swobodnych układu mechanicznego zawierającego sprężynę z pamięcią kształtu, *Prace Instytutu Podstaw Budowy Maszyn Politechniki Warszawskiej*, **17**, 5-18
5. GMITERKO A., KELEMEN M., DOVICA M., CAPAK M., 1999, Miniature Mobile Robot for Moving in a Tube with Small Diameter, *Proc. Internat. Conf. "Mechatronics and Robotics'99"*, Brno, 67-70
6. HORNBORN E., 1987, Legierungen mit Formgedächtnis – Neue Werkstoffe für die Technik der Zukunft?, *Metall*, **5**, 488-493
7. MEISSNER M., SCHORT H-J., 1997, *Metallfedern (Grundlagen, Werkstoffe, Berechnung und Gestaltung)*, Springer, Berlin
8. OLESIN J.W., 1969, Konstrukciya i rashchyot pruzin s postoyannymi i izmienyayushchimsya w zadanykh peredelakh silovymi kharakteristikami pri peremennykh temperaturakh, *Viestnik mashinostroeniya*, **49**, 4

9. ROMANKIEWICZ F., SKOCOVSKY P., GOROCKIEWICZ R., 1996, *Niekonwencjonalne materiały konstrukcyjne*, Politechnika Zielonogórska, Zielona Góra

10. SCHÜLE W., 1968, Das Setzverhalten von Schraubenfedern aus ölschlussvergüteten Drähten in der Wärme, *Draht*, **19**, 4, 5, 9

11. SCHLEGL M., 1995, Ni-Ti – Formgedächtnislegierungen unter zyklischer Beanspruchung im pseudoelastischen Zustand (Anwendungen aus dem Automobilbau), Dissertation zur Erlangung des Grades Doktor-Ingenieur, Fakultät für Maschinenbau, Ruhr-Universität Bochum

12. STÖCKEL D., 1993, Superelastische Nickel-Titan-Legierungen. Eigenschaften und Anwendung, *Metall*, **8**, 728-733

13. Publications TiNi Alloy Company and Nitinol Development Corporation, California, USA, in Internet, 1999, (www.sma-mems.com)

"Inteligentne konstrukcje" sprężyn

Streszczenie

Przedmiotem pracy są podstawy projektowania "inteligentnej konstrukcji" zespołu sprężyn o określonej *a priori* strukturze tzw. różnicowego układu sprężyn. W tych zespołach można ukształtować interesujące właściwości przy cieplnym oddziaływaniu środowiska. Umożliwiają one realizację funkcji samokompensacji, a nawet wzmocnienia, obciążenia zespołu w podwyższonych i zmiennych temperaturach oraz funkcję napędu silnika liniowego przy wywołaniu pulsacyjnych zmian temperatury. Rozwiązano zadania samokompensacji obciążenia przy oddziaływaniu na sprężyny zespołu zjawiska zmian temperaturowych modułu sprężystości lub zjawiska relaksacji naprężeń. Funkcja napędowa pozwala zastosować analizowany zespół różnicowy ze sprężyną z pamięcią kształtu SMA do budowy oryginalnego pulsacyjnego mikrosilnika liniowego. Aktywowana termicznie lub elektrycznie sprężyna SMA jest aktuatorem, zapewniającym pulsacyjne zmiany ugięcia w zespole różnicowym, które wraz z mechanizmem jednokierunkowym tworzą zasadę działania mikrosilnika (robota poruszającego się we wnętrzu rury).

Manuscript received February 24, 2000; accepted for print May 8, 2000