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TESTING OF A SPRING WITH CONTROLLABLE STIFFNESS

SUMMARY

The paper shows the structure of a mechanical spring with controllable stiffness and outlines the temperature control systems solutions. This spring was developed in the Department of Process Control, AGH University of Science and Technology (AGH-UST). Its main components are bars made from shape memory alloy (SMA). The unique properties of SMA are outlined. Of particular importance are parameters that affect the spring special behaviour. The spring was tested in an experimental set-up and the compiled test results are provided. Chosen results was shown for different excitations and working temperatures. Obtained results show that the spring built using SMA has many interesting features. It is clear that the spring changes its stiffness during changing working temperature. Unfortunately spring stiffness has nonlinear behaviour so that in the paper was proposed a nonlinear mathematical model of the spring. Model was developed having in mind its usage. It was built for designing a controller spring stiffness.

***Keywords**: shape memory alloy, spring*

BADANIA LABORATORYJNE SPRĘŻYNY O STEROWANEJ SZTYWNOŚCI

W artykule przedstawiono konstrukcję mechaniczną sprężyny o sterowanej sztywności, jak również układy sterujące jej temperaturą. Sprężynę tę opracowano w Katedrze Automatyzacji Procesów Akademii Górniczo-Hutniczej w Krakowie. Głównym elementem sprężyny są pręty wykonane z metalu z pamięcią kształtu SMA (Shape Memory Alloy). W artykule skrótowo przedstawiono podstawowe właściwości SMA, przy czym zwrócono szczególną uwagę na parametry istotne dla własności sprężyny. Sprężynę przebadano na stanowisku laboratoryjnym. Wybrane wyniki przedstawiono w niniejszym artykule. Badania przeprowadzono dla różnych wymuszeń i temperatur. Otrzymane wyniki pokazują, że sprężyna zbudowana z SMA ma wiele interesujących właściwości m.in. to, że sztywność sprężyny zmienia się wraz ze zmianą jej temperatury pracy. Niestety charakterystyki sprężyny są nieliniowe, dlatego zaproponowano nieliniowy model matematyczny. Model został zbudowany na potrzeby syntezy regulatora sztywności sprężyny.

***Słowa kluczowe**: metal z pamięcią kształtu, sprężyna*

1. INTRODUCTION

Springs are mechanical elements often employed in machines as structural components, energy-accumulating devices or the elements controlling the dynamic characteristics of the system. There are linear progressive springs (also referred to as “hard”) and constant force degressive springs (“soft”) [6, 3]. Springs are key components of vibrating systems. Generally, spring stiffness together with the mass of an object, which usually remains beyond our on-line control, determine the natural frequency of vibrations of mechanical systems. In vibrations isolation systems springs are utilised to shape the frequency characteristics; that is why most diverse spring embodiments are available to make use of different spring properties. Since it is sometimes necessary to change the characteristics of the whole plant or its selected sub-system, the stiffness coefficient has to be precisely controlled. Such springs enable us to design vibration isolation systems that afford controlled variations of plant characteristics. The control of the stiffness coefficient is achieved through the incorporation of an additional unit comprising elastic elements or pneumatic springs and springs made from materials with controllable properties, such as shape memory alloys (SMA). When ordinary (e.g. steel) springs are added, the changes in the stiffness coefficient are discrete whilst the addition of pneumatic or SMA springs leads to smooth, continuous variations of this parameter.

This paper shows the structure and the control strategy for a spring with controllable stiffness, supported by the test results. Such spring allows the design of vibrating systems¹⁾ with controllable dynamic characteristics. This group includes vibration-reduction and vibration-generation systems. Variation of the stiffness coefficient allows for modification of natural frequencies which extends the applicability range of such systems and in some cases enables the implementation of solutions which so far have remained impracticable for technical reasons. The only parameter of the vibrating systems that could be modified so far was the damping ratio. When springs with controllable stiffness are employed, another key parameter can be varied easily: stiffness coefficient.

Stiffness of a metal spring depends on its shape, dimensions, and metal properties, particularly the Young modulus of the spring material. While a designed spring is being fabricated, it is given a proper shape and dimensions. In practical applications geometric parameters of springs are not modified while they remain in service. Though one can

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1) The term “vibrating systems” refers to vibrating mechanical systems, i.e. those comprising mass, elastic and damping elements.

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imagine a spring whose shape or dimensions would be varied smoothly and continuously, the spring structure would have to be very complex. Modification of spring shape and diameter is not viewed as an effective stiffness control strategy. However, application of SMA springs affords us the means to modify the spring stiffness via the control of the Young modulus. The Young modulus of SMA spring materials varies with the change in the temperature of an alloy [2, 4]. There are some materials which change their properties under the action of other physical phenomena, for example magnetic fields.

SMA springs were investigated by Wang Z. G. (several publications: [9, 10]) and [1] who concentrated on manufacturing techniques, spring properties and control strategies. Toi *et al.* [8] did the FEM modelling of helical springs. All these papers concerned helical springs, widely applied as drive elements in motor industry, household appliances and in various control valves. Vibration reduction by the use of SMA composites has been explored extensively. SMA strips or plates might be glued to structural elements to change their properties and behaviour. The applications of SMAs to vibration reduction were explored by Williams [12, 13], who studied one degree of freedom (1-DOF) and 2-DOF systems and patented a SMA string to be applied in vibration control systems [2, 11].

This study focuses on the structure of controllable-stiffness springs which might be utilised in vibration reduction systems, for example in the driver seats. It is a flat spring, designed to shape the dynamic characteristics of the systems. The spring is made from nickel–titanium alloy (Ni 48%, Ti 46%, Cu 6% and C 0.05%). The symbol % means WT%. The characteristic transformation temperatures for this alloy are: Mf = 30^{o}C, Ms = 45^{o}C, As = 50^{o}C, Af = 70^{o}C. Mechanical properties of this alloy are summarised in Table 1.

The properties of spring steel are given for comparison. If the Young modulus for austenite is twice the value for martensite, the stiffness coefficient of a SMA spring can be modified through the control of temperature of the spring material, affording us the means to change the stiffness coefficient even by 100%. For the considered alloy NTC01 the spring stiffness for the SMA austenite (high-temperature) phase should be no less than 200% of the value at the martensite (low-temperature) phase.

2. SPRING CONSTRUCTION

Springs are widely applied constructional elements and hence various types are available, including helical, ring, disk, diaphragm, flat springs. Several spring embodiments were analysed, taking into account the manufacturing costs, repair procedures, replacement of elastic elements, the presence of elastic elements after thermal treatment or untreated, modifications of alloy composition. Of particular importance were: complexity of the manufacturing process, heating potentials, maximum deflection ±30 mm, the range of stiffness controllability and applicability range of composite materials.

For the purpose of comparison, calculations are performed for several types of Nitonol (NTC01) springs and for springs made of steel 65G. The bars considered all had the circular cross-section and identical geometric parameters: length $l = 180$ mm, diameter $d = 4.6$ mm. Several spring types were considered: a cylindrical helical spring (a single coil 57.3 mm in diameter), a spring in the shape of a cantilever rod, a spring in the shape of a supported beam, a spring in the form of a tensile bar. The calculations were performed for the spring steel 65G for comparison, and for two phases of Nitinol (austenite, martensite). In order that the results be comparable, the equivalent state of stress is always taken, no matter what the type of stress.

Results are compiled in Table 2.

Table 1
Mechanical and Physical Properties of NTC01 [1] and steel 65G

Parameter name	Martensite	Austenite	65G
Young modulus	15 GPa	30 GPa	211 GPa
Ultimate Tensile Stress	1000 MPa	650 MPa	800 MPa

Table 2
Compilation of results

Spring type	Spring material	Young modulus [GPa]	Equivalent stress [MPa]	Maximal load [N]	Maximal displacement [mm]	Stiffness [N/m]
Cylindrical helical	NTC01 austenite	30	340	227	$s = 63.7$	3571
	NTC01 martensite	15	340	227	$s = 127$	1785
	Steel 65G	211	419	279,8	$s = 11$	2529
Cantilever bar	NTC01 austenite	30	650	34,5	$f = 101.7$	339
	NTC01 martensite	15	650	34,5	$f = 203.5$	170
	Steel 65G	211	800	42,5	$f = 17.8$	2386
Supported beam	NTC01 austenite	30	650	138	$f = 25.4$	5427
	NTC01 martensite	15	650	138	$f = 50.9$	2713,5
	Steel 65G	211	800	170	$f = 4.46$	38169
Tensile bar	NTC01 austenite	30	650	10802	$y = 3.9$	2769800
	NTC01 martensite	15	650	10802	$y = 7.8$	1384900
	Steel 65G	211	800	13295	$y = 0.68$	19481000

It is readily apparent that the spring in the shape of a cantilever rod is the softest whilst that in the shape of a tensile bar seems the hardest. It has been found out that spring stiffness depends on its shape and material properties. The comparison of springs made from NTC01 and from steel 65G suggests that the stiffness of NTC01 springs is by one order of magnitude smaller, though the major advantage of NTC01 is that the stiffness of springs made from this material may changed even by 100% during an austenite-martensite phase transition. A spring in the shape of a supported beam is selected from among spring embodiments shown in Table 2 (see Fig. 1). The fabricated spring prototype (Fig. 2) consists of 6 SMA bars.

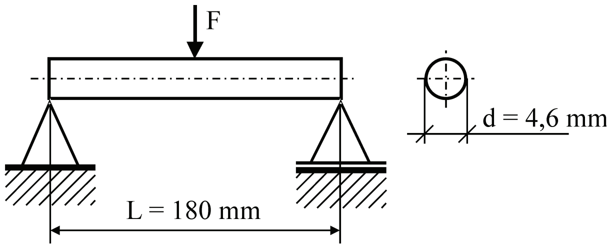

Fig. 1. Schematic diagram of a SMA spring (one SMA bar)

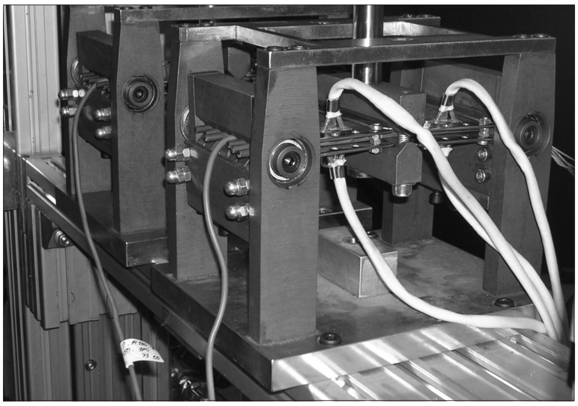

Fig. 2. Springs with controlled stiffness – general view

The spring shown in Figure 2 is designed such that its basic stiffness can be easily modified through changing the number of bars (rods) or through the replacing its bars for those made from different alloys. Springs can operate in sets, connected in series or in parallel. Table 3 provides the stiffness values for SMA springs made from SMA materials wholly composed from the austenite or martensite phase.

Table 3 compiles the ultimate stiffness values, stiffness parameters for a spring comprising one SMA bar and for a set of two springs connected in parallel, each having six bars and the set of two parallel SMA springs, with seven bars each. Test results for the latter case are elaborated in the further sections. It is readily apparent that the stiffness coefficient of such set can be varied over a very wide range. Even for one configuration of bars the stiffness coefficient changes by 100% during the martensite-to-austenite phase transition. This modification is smooth and each intermediate value of the stiffness parameter can be achieved.

3. ACTUATING SYSTEMS

Since the stiffness of a SMA spring changes as the result of the change of temperature of a spring material, the following heating strategies were considered:

a) Heating by flowing liquid. The spring must be made from a closed profile through which a liquid with a predetermined temperature is flowing, alternatively a spring might be immersed in a liquid tank. This method might be well applied in vehicles with heat engines as there is heat redundancy to be transferred to the coolers. The cooling liquid has sufficiently high temperature for SMAs.

b) Heating by hot air stream. In this case the hot air stream from a (direct resistance) heater is targeted at the spring to be heated. This solution does not share the drawbacks of the option a): leakage flows, the presence of a tank and cooler. However in this case very low specific heat of air and its low thermal conductance give rise to very large time constants and might lead to major heat losses in the open flow circuit.

c) Indirect resistance heating using thermal (resistance) elements. Indirect heating involves heat generation in the heating element and heat transfer to the spring by one of the three methods:
   1) radiation,
   2) convection,
   3) conductance.

   In the indirect resistance method the thermal elements might be in shape of grains, rings, plates, sleeves, pipes or heating conduits.

d) Direct resistance heating method whereby heat is generated directly in the spring bars under the action of the flowing current. This approach seems most promising as the whole spring volume can be heated, the heating rate is fast whilst the thermal inertia remains rather low. However, on account of low resistance of spring bars, the current intensity will reach even several hundred amperes, which is a major problem for designers. In the case of high levels of current utmost care must be taken to provide sufficiently thick supplying cables and high-quality connections.

Table 3

Examples of SMA spring stiffness

Number of bars	Stiffness *k* for martensite [N/m]	Stiffness *k* for austenite [N/m]
1	2713,5	5427
12	32561	65122
14	37988	75976

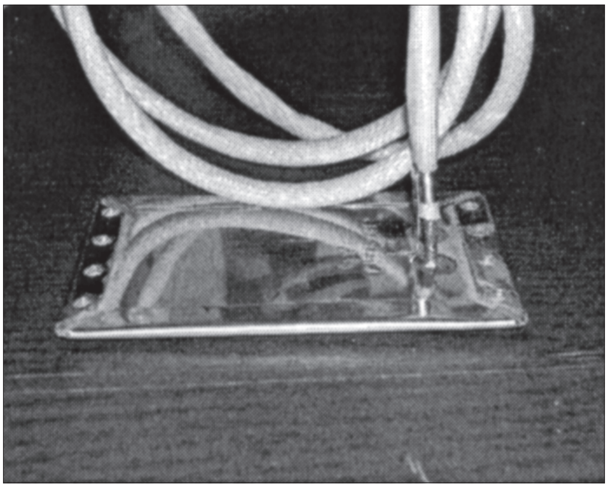

Fig. 3. Heating element – general view

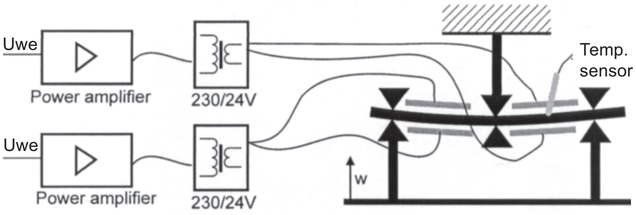

Fig. 4. Block scheme of the actuator system for spring temperature control

Heating methods utilising microwave and induction are rejected due to large costs of heating equipment. The indirect resistance method was chosen here because of low costs and simplicity of its implementation. The heating elements are in the shape of plates (Fig. 3), with the power rating 150 W for the supplying voltage 24 V. Figure 4 shows the block diagram of an actuating system for spring temperature control. The system comprises two voltage-controlled power regulators and four transformers supplying the heating plates so the temperature of SMA bars can be controlled from any device generating voltage signals in the range 0÷10V: a PC with a measurement and control card, a generator or a potentiometer voltage divider.

4. SPRING TESTING

Springs were tested in the experimental set-up shown in Figure 5, in the Laboratory of Dynamic Systems and Structures [5] of the Department of Process Control AGH-UST. It consists of an electrohydraulic pulsator used to generate various types of exciting signals (sine, square and random excitations). The pulsator is controlled from a microprocessor equipped with a DSP processor. This set-up allows for static and dynamic testing of 1-DOF and several DOFs structures. The spring considered in this study was tested accordingly.

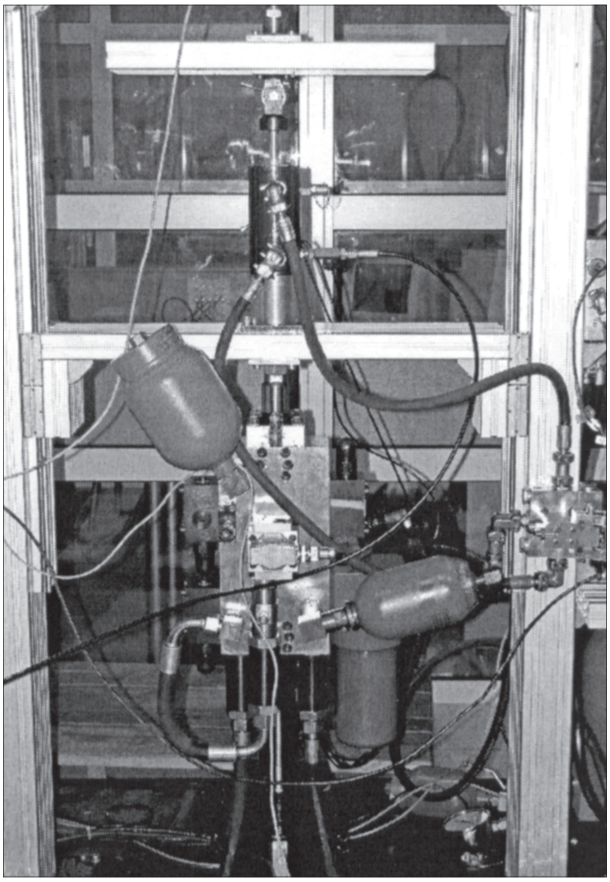

Fig. 5. Testing stand – general view

The main purpose of the testing programme was to establish the static and quasi-static characteristics of the spring. The spring, or rather two springs connected in parallel, were tested as shown schematically in Figure 6.

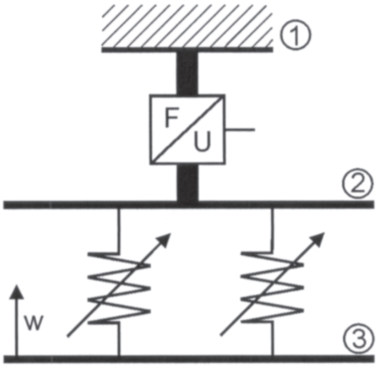

Fig. 6. Schematic of the mechanical system structure. 1 – upper platform, 2 – platform, 3 – lower platform

Figure 7 shows the springs (4) ready for tests and the force sensor (5). The blocked upper platform (1) is connected mechanically with one end of springs via the force sensor (5) and the platform (2) whilst the motion of the springs bodies is induced by an electro-hydraulic pulsator via the lower platform (3).

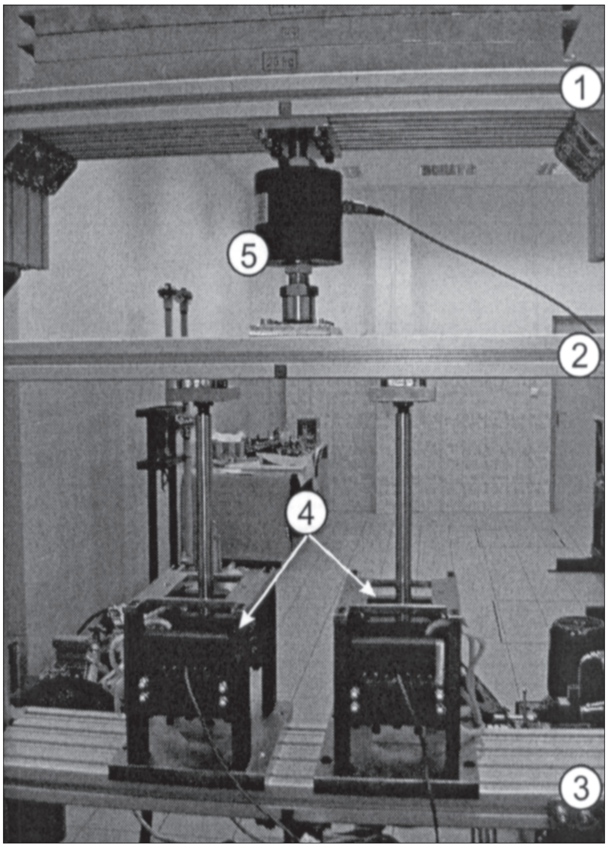

Fig. 7. Spring with controllable stiffness ready for tests
See text

This configuration enables us to implement nearly all spring deflection patterns. Measurements of relative displacement of springs, displacement of platform (3) with respect to platform (1) corresponding to spring deflection, force generated by the spring and temperature of SMA bars yield the static and dynamic characteristics of the spring. Force measurements were taken with an force transducer (5), displacements were measured with a Micropulse Linear Transducer. Bar temperature measurements were taken with a thermocouple mounted at the bar midspan, that is at the point where maximal deflections would occur.

The main aim of the tests was to find a functional relationship between the force generated by a spring and its deflection or temperature.

Two groups of characteristics were acquired:

1) force vs. temperature for constant deflection,
2) force vs. spring deflection at constant temperature.

4.1. Force vs. temperature for constant deflection

These characteristics were obtained for spring deflection being constant. The deflection was preset by a cylinder in a hydraulic pulsator and remained constant throughout this stage of testing: 5, 10 or 15 mm. Temperature of SMA bars was varied in the range 20÷150^{o}C (Fig. 8).

Thus obtained characteristics are shown in Figures 8 and 9.

A temperature – force relation is shown in Figure 8. The sampling frequency was 100 samples/s, measured quantities were archived with the use of a PC. Figure 9 shows the force – temperature relationship for the deflection value 5, 10, 15 mm. It was assumed that at 20^{o}C the force generated by the spring should be 0 N, hence we get the force variation due to the temperature change.

It appears (see Fig. 9) that force generated by a spring (when deflection remains constant) is strongly affected by temperature. This dependency is nonlinear, involving a hysteresis. Spring deflection remains constant, hence the force generated by the spring results from the change of its stiffness coefficient.

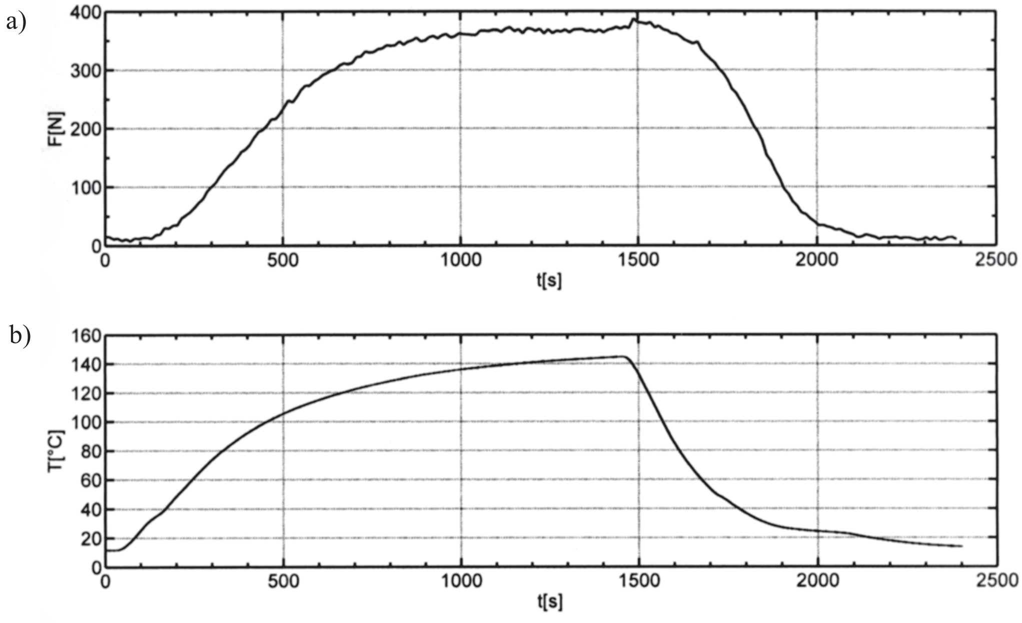

Fig. 8. Force *F* generated by the spring (a) and temperature (b) in the function of time, for spring deflection 15 mm

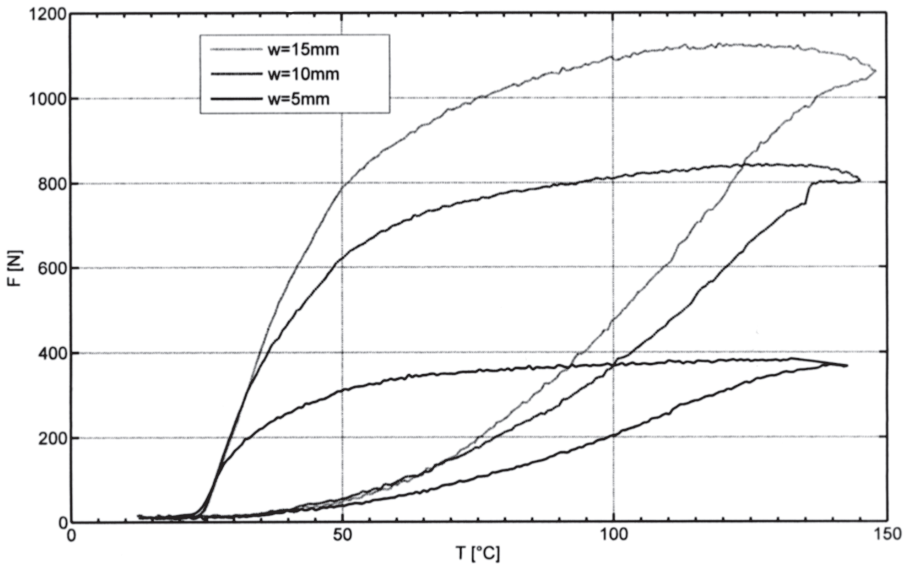

Fig. 9. Spring force in the function of temperature, for spring bending 5, 10, 15 mm

4.2. Force vs. spring deflection at constant temperature

These characteristics were obtained for temperatures that remained constant throughout the whole test procedure. The temperature levels were: 22, 70, 80, 85, 90, 95, 100°C. Slow-changing low-frequency sine excitations were applied, with the amplitude 5, 15, 25, 30 mm. Measurements of temperature, displacement and force were taken in the same manner as in the test a). Figures 10 and 11 show the force vs. spring deflection relationship for various levels of ultimate deflection (amplitude of the exciting signal) and for selected spring temperatures.

The force – deflection curves shown in Figure 12 suggest that spring stiffness strongly depends on the temperature of SMA bars. By changing this temperature, we are able to modify the stiffness of the spring set (two springs each having 6 SMA bars) in the range 26 000÷54 000 N/m.

The range of the stiffness coefficient achieved through temperature changes was determined experimentally. Thus obtained ultimate stiffness values were compared with predicted (computed) ones, provided in Table 3.

It seems that experimental values are lower than those found analytically ones by nearly 20%. A through scrutiny of characteristics in Figures 10 and 11 leads us to the conclusion that spring stiffness depends on the deflection w and the direction of its action.

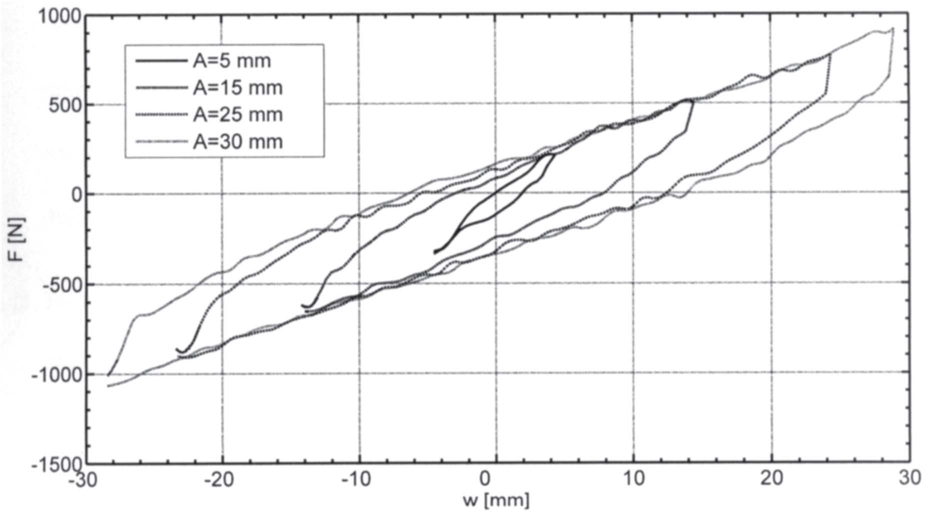

Fig. 10. Family of characteristics of the spring $F = h(w)$
for displacement 5, 15, 15, 30 mm and temp. 22°C

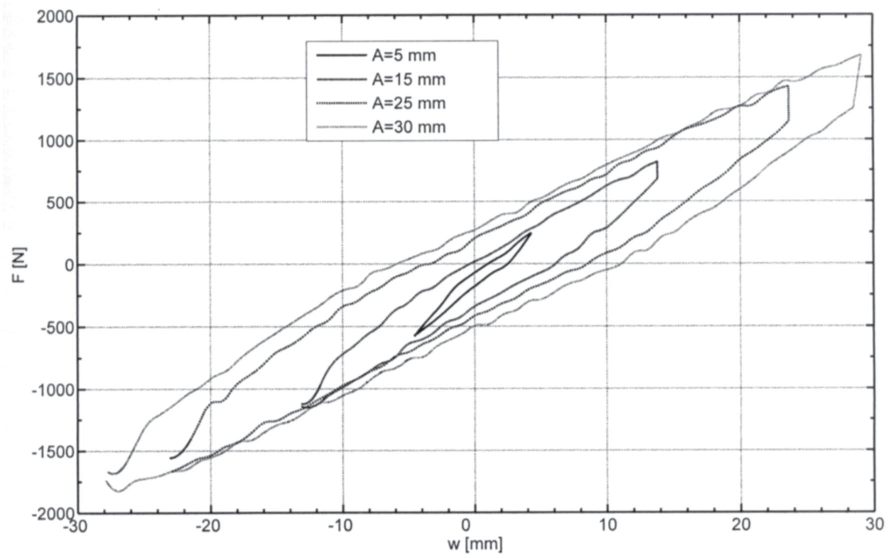

Fig. 11. Family of characteristics $F = h(w)$ for excitation amplitudes 5, 15, 15, 30 mm and temperature 100°C

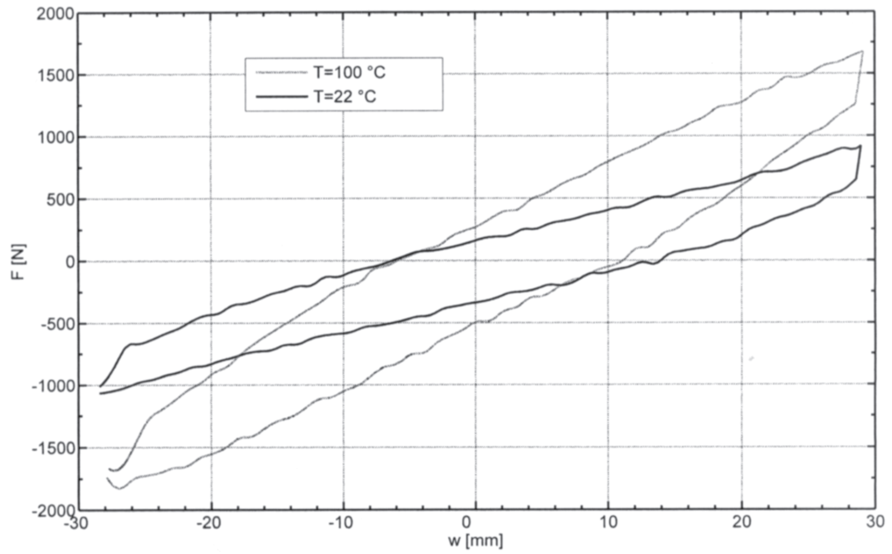

Fig. 12. Characteristics of the spring $F = h(w)$, temp. 22°C, 100°C

5. MODEL OF SMA

Spring force in the function of temperature, for spring deflection is hysteretic (Fig. 9). Therefore hysteretic model of the spring based on hyperbolic tangent was proposed in the form shown below.

Hyperbolic operator on T function at t was defined as:

$$F(T)(t) = y_a \int_0^t h(t) \cdot \dot{u}(t)\,dt + y_b \tag{1}$$

$$\begin{aligned} h(t) = 0.5 \cdot \left(1 + sign\left(\dot{T}(t)\right)\right) \cdot \tanh'\left(k \cdot \left(T(t) - x_a\right) - k \cdot a/2\right) + \\ +0.5 \cdot \left(1 - sign\left(\dot{T}(t)\right)\right) \cdot \tanh'\left(k \cdot \left(T(t) - x_a\right) + k \cdot a/2\right) \end{aligned} \tag{2}$$

where:

a, k, x_a, y_a, y_b – parameters of hysteresis,
T – temperature.

6. CONCLUSIONS

It is readily apparent that the stiffness coefficient of SMA springs can be controlled. The properties of a spring considered in this paper can be controlled by electric methods. The variability range of controlled stiffness is really wide, amounting to even 100%. Tests revealed that spring characteristics are nonlinear. Ultimate spring behaviours depend on the SMA composition and spring construction. Springs with controllable stiffness might be employed in vibration isolation systems, e.g. in Frahm absorbers [7].

The main shortcoming is that the stiffness values of SMA springs are by an order of magnitude lower than for steel. Besides, NTC01 have poorer fatigue endurance than spring steel 65G. These features have to be considered while exploring potential applications of SMA springs. On the other, smooth and easy change of the SMA spring stiffness remains its chief benefit.

This unique property makes controllable springs appropriate for many diverse fields of applications, including vibration reduction systems where they can be easily tuned to variable operating conditions.

At the present stage the research on SMA spring stiffness seems a relatively easy task. Novel, improved SMA materials displaying new properties facilitate the design process, manufacturing, operation and maintenance of controllable-stiffness springs.

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References

[1] Aslanidis D., Roebben G.: *Shape Memory Nitinol Wire. PowerWire (NTC01). Product specification.* AMT, 2002

[2] Bojarski Z., Morawiec H.: *Metale z pamięcią kształtu.* Warszawa, PWN 1989, ISBN 83-01-09346-3

[3] Branowski B.: *Sprężyny metalowe.* Warszawa, PWN 1997, ISBN 83-01-12378-8

[4] Hodgson D.E., Wu M.H., Biermann R.J.: *Shape Memory Alloys.* www.sma-inc.com, 2002

[5] Konieczny J., Ornacki R., Pluta J.: *Stanowisko do badań sterowanych układów redukcji drgań.* IV Szkoła „Metody Aktywne Redukcji Drgań i Hałasu", Kraków-Krynica kwiecień 1999, s. 103–112

[6] Kowal J.: *Sterowanie drganiami.* Krakow, Gutenberg 1996, ISBN 83-86310-06-5

[7] Rączka W.: *Controlled SMA Spring in Frahm's Vibration Absorber.* Półrocznik AGH Mechanika, t. 22, z. 3, 2003, pp. 389–394

[8] Toi Y., Lee J.B., Taya M.: *Finite Element Analysis of Superelastic, Large Deformation Behavior of Shape Memory Alloy Helical Springs.* Computers and Structures, vol. 82, Issue: 20–21, 2004, pp. 1685–1693

[9] Wang Z.G., Zu X. T., Feng X.D., Lin L.B., Zhu S., Sou L.P., Wang L.M.: *Design of TiNi Alloy Two-way Shape Memory Coil Extension Spring.* Mater. Sci. Eng., A345, 2003, pp. 249–254

[10] Wang Z.G., Zu X.T., Fu Y.Q., Wang L.M.: *Temperature Memory Effect in TiNi-based Shape Memory Alloys.* Thermochimica Acta, 2005, pp. 199–205

[11] Williams K.A., Chiu G.T., Bernhard R.J.: *Vibration Absorber Using SMA.* Patent number: US 6290037, Publication d&e, 18 September 2001

[12] Williams K., Chiu G., Bernhard R.: *Adaptive-Passive Absorbers Using Shape-Memory Alloys.* Journal of Sound and Vibration, 249(5), 2002, pp. 835–848

[13] Williams K.A., Chiu G.C.-T., Bernhard R.: *Dynamic modelling of a shape memory alloy adaptive tuned vibration absorber.* Journal of Sound and Vibration, 280, 2005, pp. 211–234