SENSITIVITY OF COMPENSATING TUBULAR SPRING INSTRUMENTS

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Owing to their versatility, tubular spring instruments have found wide application in industry. The tubular spring as a measuring element is applied in various manometers, depth gauges and altimeters, teleinstruments, recording instruments, mercury contact and telethermometers, differential manometers.

In tubular spring instruments the sensing element is connected with the field of some medium under pressure through the connecting part. This medium fills the inside of the tube and pressure forces the tube to straighten to a certain extent. The deflection of the free end of the tubular spring is transmitted by a geared device consisting of a pull rod, toothed segment and toothed shaft to the indicating, signalling and recording part of the instrument.

If the cross section is of appropriate shape the deflection of the free end of the tubular spring is proportional to the internal overpressure. The tubular spring is bent to an encircling angle of $\frac{3\pi}{2}$, but in the case of high pressures an encircling angle of only $\frac{\pi}{2}$ is used (Fig. 1).

The shape of the cross section of the tubular spring is chosen to correspond to pressure ranges. For low pressures the shapes of the cross sections of the tubular spring are shown in Figs. 2a—d; the shape of the cross section used in the pressure range 100—300 atm can be seen in Fig. 2e. For higher pressures up to 5000 atm the so-called cross sections of uniform strength (Figs. f—g) are used, with very thick walls [5]. For the measurement of very high pressures the spring is made of a solid one-piece steel with an off-centre boring (see Fig. 2h).

These forms of the cross section have, since a long time, been elliptical but no satisfactory explanation was found for the fact why the tube tries to straighten under internal pressure. A possible explanation is *e. g.* that the surface area of the upper part of the bent tubular spring is larger than that of the lower part and, therefore, it is the effect of the difference between the forces acting on the surfaces that causes the deflection of the tubular spring. This viewpoint is wrong as it implies a similar behaviour of the tubular spring of circular cross section. According to experience, however, tubes of circular cross sections do not straighten when internal pressure is increased.

For tubular springs of low-arched cross sections calculations were first carried out by FEDOSJEV (1940), who attempted to prove theoretically that

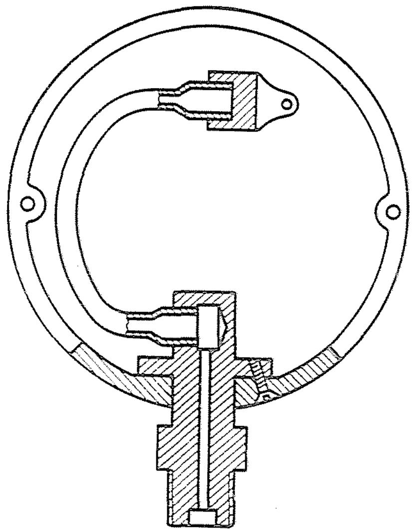

Fig. 1. Tubular spring instrument for measuring high pressures

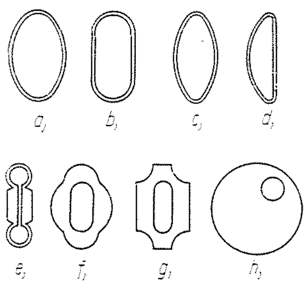

Fig. 2. Tubular spring cross sections

internal pressure makes the tubular spring of oval cross section swell *i. e.* the cross section tends to approach the circular shape, while the free end of the tubular spring, the other end of which is clamped, deflects. FEDOSJEV calculated this deflection for the angular change expressed as the fraction of the total encircling angle, giving

$$\omega = \frac{\Delta\psi}{\psi} = p \left\{ \frac{1}{E} (1-\mu^2) \frac{r^2}{bs} \left(1 - \frac{b^2}{a^2} \right) \frac{a}{\beta + \lambda^2} \right\}, \tag{1}$$

where ψ is the encircling angle of the tubular spring, $\Delta\psi$ is the change of the encircling angle, p is the pressure in the internal field (kg/cm²), E is the elastic modulus of the material of the spring (kg/cm²), μ is the Poisson factor of the material of the spring $\approx \frac{1}{3}$, r is the radius of curvature of the tubular spring (mm), s is its wall thickness (mm), a and b are the half major and minor axes of the ellipsis, respectively (mm), and $\lambda = \frac{rs}{a^2}$ is the characteristic of the tubular spring. The values of the factors α and β depend on the relation between the axes of the cross section of the tube [6].

For α and β in the range $0 < \frac{s}{b} < 0.6$ the values shown in Table 1 can be assumed.

Table 1

$\frac{a}{b}$	1	1,5	2	3	4	5	6	7	8	9	10
α	0,750	0,636	0,566	0,493	0,452	0,430	0,416	0,406	0,400	0,395	0,390
β	0,083	0,062	0,053	0,045	0,044	0,042	0,042	0,042	0,042	0,042	0,042

For the function of angular change W. WUEST has deducted a more general result

$$\omega = \frac{\Delta\psi}{\psi} = \left[- F_1(\alpha_1 \lambda) \left(\frac{a^3}{b}\right) \frac{a}{b} (1 - \mu^2) \frac{1}{E} \right] P . \tag{2}$$

The graphs for the function $F_1(\alpha, \lambda)$ are given in Figs. 3 and 4.

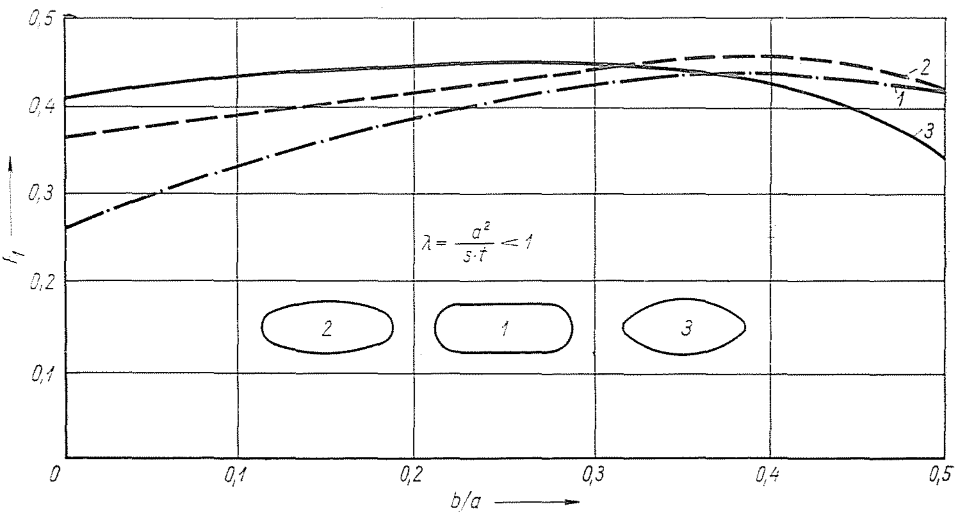

Fig. 3. Graph $F_1(\alpha, \lambda)$ of W. Wuest for various cross sections

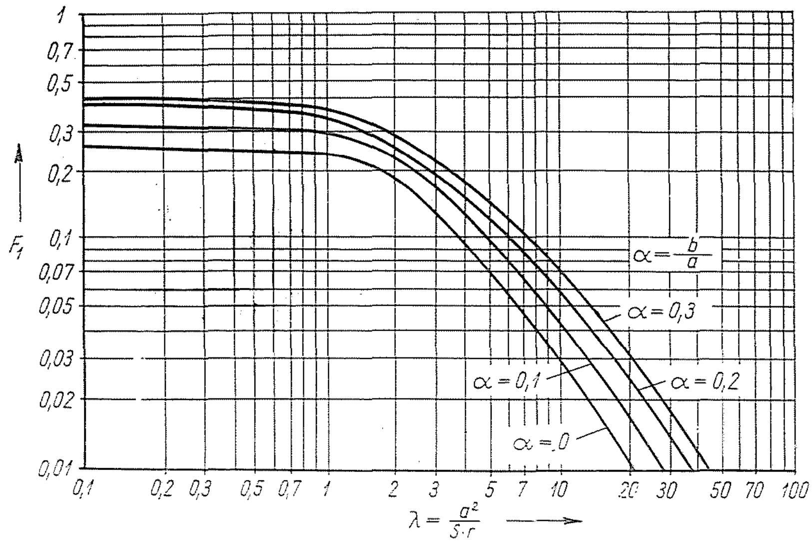

Fig. 4. Detailed graph $F_1(\alpha, \lambda)$ of W. Wuest for low-arched cross sections

The expression [2] can be applied to tubes of various cross sections (see cross sections in Fig. 4) with the restriction

$$\lambda = \frac{a^2}{rs} < 1 . \tag{3}$$

Namely, if $\lambda < 1$ the function $F_1(\alpha, \lambda)$ no longer depends on α.

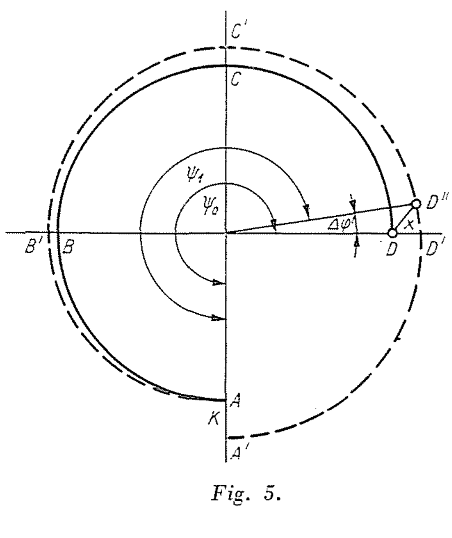

Fig. 5.

It is suitable to perform the calculations for the tubular spring in a polar coordinate system, the centre of which is the centre of the circular tube. In this case (Fig. 5) the change $\Delta\psi$ of the encircling angle is related to the encircling angle ψ in the following way

$$\omega = \frac{\Delta\psi}{\psi} = \Phi(c_p, p) = c_p p \tag{4}$$

where p is the pressure acting inside the tube and c_p is a constant depending on the dimensions of the tube.

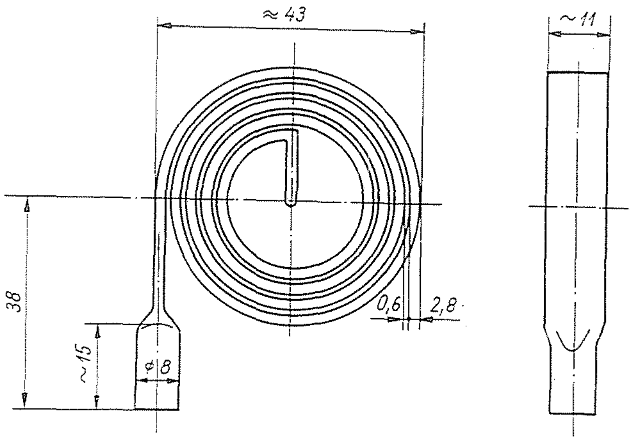

Fig. 6. Coil spring

By applying a practical rule and using the expression

$$\frac{D}{100}\Delta\psi = x, \tag{5}$$

with an encircling angle $\psi_0 = 270°$, E. HOFFMANN obtained for the deflection of the end of the tube an accuracy satisfactory for practice. In formula (5) D is the diameter of the curvature of the tube in mm.

In tubular spring instruments the coil spring shown in Fig. 6 has also been widely applied. The elastic properties of this measuring element are not so good as those of the tubular spring having an encircling angle of $\frac{3\pi}{2}$, but its application for pulsating stresses is much preferred.

Tubular spring mercury thermometers, in which mercury expanding under the effect of temperature exerts pressure on the measuring element of the instrument, the tubular spring, have found especially wide application.

In telethermometers mercury is led from the sensing element to the tubular spring normally by means of a flexible steel capillary (approx. 0.3 mm in diameter). Without compensation this steel capillary can be used up to distances not exceeding 9 m within the accuracy limits of the measurement. As in practice the indicating part of the instrument has to be separated from the sensing part at a greater distance, the effect of the temperature of the surroundings is eliminated by using a compensating lead [3].

The compensating solution compensates for the change of the volume of mercury in the capillary of the instrument and in the tubular spring, as this change would falsify the result of the measurement. At compensation the deflection of the measuring tubular spring falsifying the measurement,

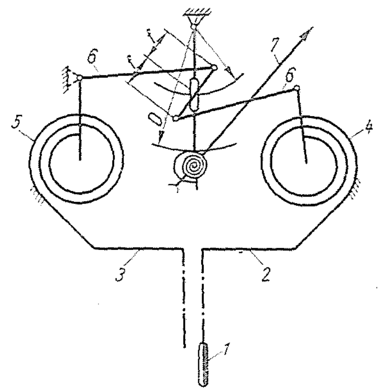

Fig. 7. Kinetic scheme of compensating tubular spring instrument

1 — mercury bag, sensing element
2 — measuring capillary
3 — compensating capillary
4 — measuring tubular spring
5 — compensating tubular spring
6 — pull rod
7 — pointer

which is transmitted by means of the geared device to the toothed segment, is mechanically deducted from the deflection of the toothed segment when adjusted in a direction opposite to the direction of operation, by means of the compensating tubular spring. The kinetic scheme of the compensation measuring device is shown in Fig. 7. In order to improve measuring accuracy the value of the measuring momentum can be increased by increasing the length of the pull rod to a permitted extent by the dimensions of the instrument's housing.

Investigating the precise operation of the instrument, the first basic point is that the stress on the tubular spring should always remain within the limits of elasticity. On the one hand, we know that the deflection of the free end of the tubular spring is proportional to overpressure only within certain limits, and this limit of proportionality must be taken into account in determining the dimensions [6] and on the other hand, if the tubular spring does not revert to its normal position, not even a few hours after having released the stress, the instrument is unusable, as the next measurement, if the pointer of the instrument does not revert to normal position, starting with this zero error [1]. It may occur in any tubular spring instrument that owing to the so-called elastic hysteresis of the tubular spring (Fig. 8) the pointer of the instrument

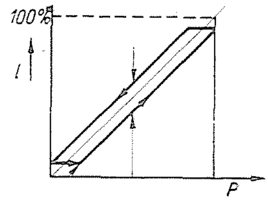

Fig. 8. Hysteresis of tubular spring instrument

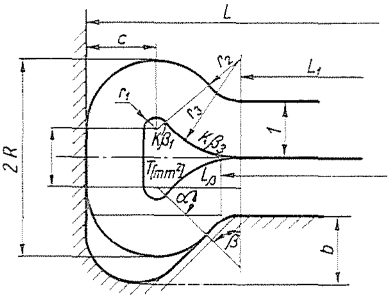

Fig. 9.

does not immediately revert to zero position, but only a few minutes later. The error of resetting, however, must not exceed 0.5% and in reference instruments 0.1% of the end value of the scale.

As for stresses of alternating direction the use of the scales is confined to a still smaller range, and the range of measurement is influenced by a number of other components (dimensions, shape of the housing, method of applying the stress, operating position, pressing medium, external mechanic effect, additional equipment, etc.) the accuracy of the instrument has still to be improved. As the requirements in regarding tubular springs so far used cannot be set higher, a new type of tubular spring had to be found. The investigation carried out at the National Office of Measures (Budapest) have resulted in the formation of new tubular spring cross section (Fig. 9) and in producing tubular springs and coil springs of new cross sections from steel tubes of Standard No. 35.29 FL MNOSZ 2899, 8×1. The starting parameters have been listed in Table 2.

Table 2

	r_1 (mm)	r_2 (mm)	r_3 (mm)	$2R$ (mm)	ε_5 (mm)	L_0 (mm)	T (mm)	L_{sz} (mm)	h (mm)
1	0,1	0,5	1,5	2,3	0,1	11,17	0,08025	11,0	2,74
2	0,1	1,0	2,0	2,3	0,1	11,184	0,0854	11,0	2,74
3	0,15	0,5	1,5	2,45	0,15	11,024	0,1668	10,8	3,09
4	0,15	1,0	2,0	2,45	0,15	11,035	0,1761	10,8	3,09
5	0,2	0,5	1,5	2,55	0,15	10,94	0,2401	11,7	3,30
6	0,2	1,0	2,0	2,55	0,15	10,955	0,2505	10,7	3,30
7	0,25	0,5	1,5	2,7	0,2	10,69	0,3763	10,5	3,64
8	0,25	1,0	2,0	2,7	0,2	10,854	0,3920	10,6	3,44
9	0,3	0,5	1,5	2,85	0,25	10,63	0,5403	10,4	3,80
10	0,3	1,0	2,0	2,85	0,25	10,64	0,5616	10,4	3,80

The tubular springs of new cross sections are flattened by cold rolling in four stages, then by cold tube bending and coil winding in one stage. The measuring elements are mounted after having completed the anticorrosive precedure Standard No. MMG Sz 2/10—55 and the second galvanization Standard No. MMG Sz 2/18—55.

Experiments show that the properties and the ranges of operation of the new measuring element exceed the efficiency of the tubular springs of cross sections formerly used and can be used in telethermometers, compensating thermometers well beyond the ranges of conventional sensitivity and measuring accuracy. The hysteresis of these measuring elements in compensation instruments manufactured for the particular ranges of measurement with prescribed accuracy requirements remains well within the permitted value. The minimal value makes possible to carry the measurement within the permitted error limits. The operation of measuring devices containing such measuring elements satisfies the accuracy requirements of metrology.

Summary

In this paper the sensitivity conditions of tubular spring instruments are treated. It is stated that the sensitivity of tubular springs of cross sections so far used cannot be increased any further. To increase sensitivity a tubular spring of new cross section is introduced.

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