

Validation Device for the Stiffness of Cylindrical Coiled Pressure Springs

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Abstract: This work presents a structural design as well as a created 3D model used for subsequent physical implementation of a validation device that allows for measuring the force as well as the shortening of a coiled pressure spring during laboratory experiments. The described device was created in order to verify and determine the stiffness of cylindrical coiled springs which are used, e.g., for tension equalizers in lift carrying ropes and handling unit fixation mechanisms. The device is located in the Laboratory of Research and Testing at the Institute of Transport, Faculty of Mechanical Engineering of VSB - Technical University of Ostrava, and is used for presentation events focusing on engineering intended for elementary and high school students as well as for teaching Bachelor and Master courses at the FME. This work presents (using tables) the pressure forces and shortening of two types of pressure cylindrical springs obtained experimentally using the validation device. The figures describe the lines obtained by purchased sensors, the sizes of immediate forces and immediate compression of the specific examined spring. These experimentally obtained values can be used to calculate the stiffness of the given spring (i.e., the actual stiffness of the spring) via the formulas specified herein, and to compare these to the stiffness values listed in the spring manufacturer's catalogue. Since there is no standard or general guideline, it may be possible to measure a stiffness value that is up to an order higher than the data listed on the product packaging for most spring manufacturers. This may logically lead to problems after the assembly of the intended machine, whereas its configuration may assume a certain stress that differs from the reality, leading to greater and unexpected stress on parts and possibly greater wear and tear.

Keywords: stiffness of spring

1. Introduction

Springs should exert a specific force at a specific length [9]. If they do not perform correctly, they can cause problems on production lines and even pose a risk to the safety of employees [17].

Standard testing systems [15, 16] are equipped with a six- or nine-component force measuring platform for this. This enables the specific determination of the spring intersection points and the resulting force from the force components when loading the spring under compressive force [13]. These characteristic values are important to evaluate the following quality attributes: friction, wear, and service life.

Springs may elastically deform in one or several directions and afterwards return to their original position. Thanks to this property, they have found a surprising number of applications in industry and are used in a range of different machines. Springs are used to speed up or accumulate forces, to flexibly connect various parts to each other, as well as to dampen shocks and oscillation.

In road vehicles, springs are used to cushion the chassis and engine or close the valves in the engine. For rail vehicles, springs (leaf springs, parabolic springs, torso rods,

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coiled springs, rubber-bonded metal elements, hydraulic membrane or bellows springs) are used mainly for primary (between the chassis frame and the wheels) or secondary (between the chassis frame and the vehicle's body) dampening, for the fenders and pulling equipment [18].

Springs are also used in machinery such as crushers, cutters, mills, and in transport and handling equipment such as vibration conveyors, lifts [1] or escalators, and last but not least lifting equipment [3, 4].

The stiffness (constant) of a spring k_p [$\text{N}\cdot\text{mm}^{-1}$] is generally defined as the force which will cause its unit compression. The device (see Figure 1) was created for the purpose of determining the k_p (in a laboratory) for coiled pressure springs [19] used for mechanical tensile equalizers for cables [2] or in mechanical locking brakes [6] of handling units.

2. Experimental Section

The laboratory device for determining the stiffness of cylindrical coiled pressure springs was designed (Figure 1 and Figure 2) and assembled (Figure 3) in order to experimentally determine the stiffness k_{pij} , validate the obtained stiffness value k_{pij} with respect to the stiffness value k_{pi} computed via the formula (1), and draw the graphical deformation curve (the change ΔL_i [m] to the original length L_0 [m]) based on a stressing static force F_{pij} [N] applied to cylindrical coiled pressure springs [6, 19].

The laboratory device consists of a steel rod with a diameter of U65 1 (length: 613 mm), see Figure 1, attached to a direct source of propulsion 2 [9]. The steel rod 1 is welded to the lower area of the

pedestal 3, which was created by bending from a 2 mm wide sheet metal.

The cylindrical part of the direct source of propulsion 2 is held between two parts via flanges 4. The flanges 4 are attached to the steel rod 1 via two screw connections 5 (M8 x 70). Direct propulsion 2 is mechanically connected to the steel rod 1 via screws 6 (M10 x 60).

The output shaft of the DC direct engine 2 is connected via the peg 7 (ϕ 10 mm) to the charge 8, whose end is equipped with an inlet with a M6 thread. The inner metric thread of the charge 7 contains a screw of the weight sensor 9 (pressure sensor LCM 202-5 kN) [12]. The opposite screw of the weight sensor 9 is connected to the flange via a screw 10.1. Both shafts of the screws of the weight sensor 9 are equipped with flexible pads 11, which are designed to prevent the sensor 9 to turn around the axis once the screws are tightened. The analysed coiled pressure spring 12 (with a max. outside diameter of 25 mm) is inserted between the flanges 10.1 and 10.2. The back side of flange 10.2 is connected to the horizontally moving board 14 via a threaded inlet and the appropriate screw 13, whereas the board allows springs 12 of distinct lengths to be held between the flanges 10.1 and 10.2 of the validation device (Figure 1) in order to ascertain the stiffness of the screw pressure springs.

In order to determine the deformation of a pressure springs 12 when compressed, the side inlet with a M6 thread on flange 10.1 is used to hold the threaded pole 16, which is secured against rotation via the nut 17. At the end of the threaded pole 16 there is a groove containing a flat pole 18 with

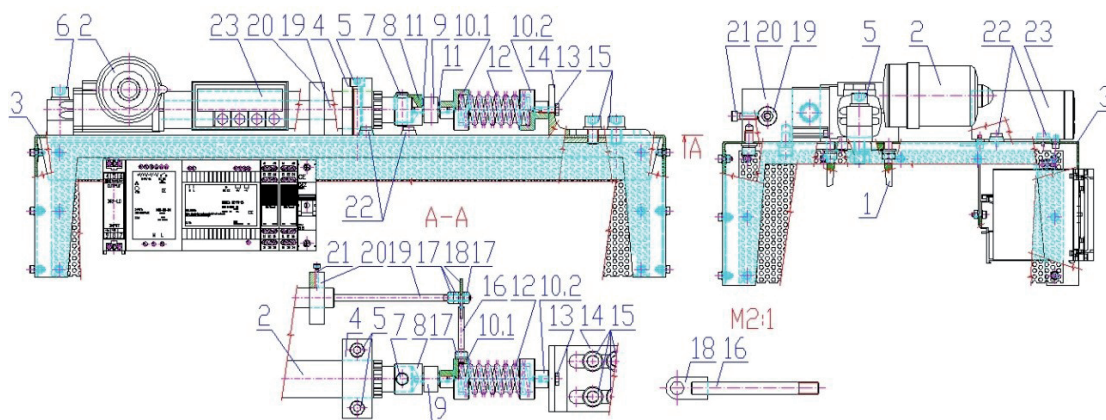


Figure 1: Validation device for determining the stiffness of cylindrical coiled pressure springs, design in AutoCAD 2010.

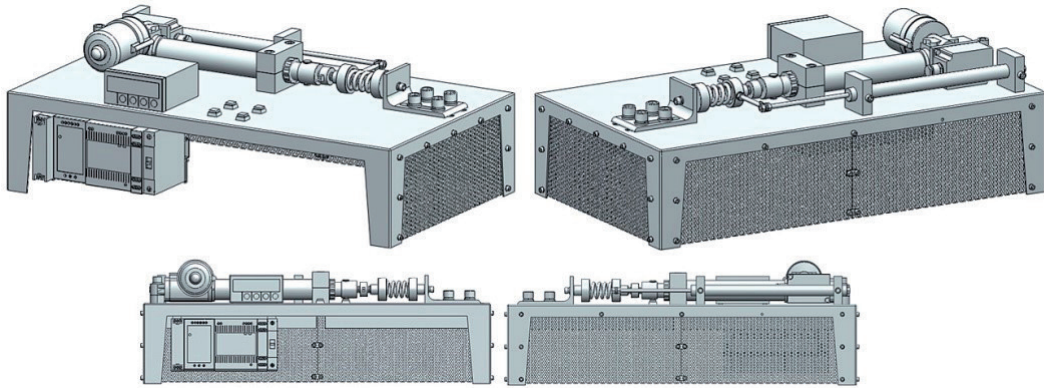


Figure 2: Validation device for determining the stiffness of cylindrical coiled pressure springs, 3D design in SolidWorks 2012x64 SP 5.01

an inlet containing the shaft of the displacement sensor 19.

The end part of the shaft of the displacement sensor 19 is equipped with a thread holding two security nuts 17 that anchor the flat rod 18 and delimit the alignment of the body of the displacement sensor 19 compared to the longitudinal axis of the direct engine 2.

The required deformation (compression) of the pressure spring 12 is calculated via the direct drive 2. The extension and retraction of the piston of the direct engine 2 is used controlled by buttons 22, whereas the electric contacts of the buttons 22 are actuated when they're pressed (and once the button is released, the electric contacts are disconnected).

The deformation (compression) of the coiled pressure spring 12 is detected by the longitudinal (extension) sensor 19 [11], which is supplied to the market under the commercial name of "displacement sensor for 0 to 150 mm, with an output of 4 to 20 mA" and ref. no. LD 630-150.

Once we know the deformation (compression or extension, depending on the type of spring) of the spring 12 as detected by the displacement sensor 19 and the pressure (tensile) axis force detected by the tensile stress sensor 9, it is possible to determine the (fixed) stiffness of the spring by using the appropriate formula.

The output electrical signals for both sensors 9 and 19 are displayed on the screen of the panel measuring device (which is equipped with a graphical screen) 23 [10], ref. no. DPI 1701-USB-AR/N.

In order to obtain and store the data values supplied by sensors 9 and 19 and visualized on the

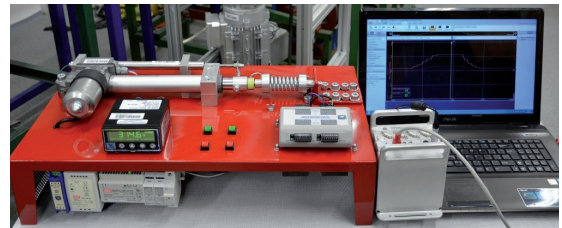


Figure 3: Laboratory device for determining the stiffness of cylindrical coiled pressure springs.

panel measuring device 23, the signals from the panel measuring device are transferred via a USB cable leading to a convertor for scale sensors, ref. no. DRF-LC-24VDC-20mA-0-10 [14].

3. Results and Discussion

The stiffness of the spring k_{pi} is defined by the relation (1), where F_i [N] is the force exerted on the spring and ΔL_i [mm] is the difference between the lengths of the spring before deformation (compression) L_0 [mm] and after deformation L_i [mm].

$$k_{pi} = \frac{F_i}{\Delta L_i} = \frac{F_i}{L_0 - L_i} \text{ [N}\cdot\text{mm}^{-1}] \quad (1)$$

Experimental testing was carried out using two pressure springs of ref. no. TL 0400 x 0240 x 0630 [19] and TL 0500 x 0250 x 0560 [19] $d \times D_i \times L_0 \times z \times n \times L_8 \times F_8 \times c \times i$, where d [mm] is the diameter of the wire, D_i [mm] is the outside diameter of the spring, L_0 [mm] is the length when not stressed, z [-] is the total number of coils, n [-] is the number of active coils, L_8 [mm] is the length of the spring when compressed, F_8 [N] is the force exerted by the spring when compressed, c [N.mm⁻¹] is the stiffness

of the spring (the force exerted by the spring when compressed by 1 mm) and i [-] is the ratio of the coiling, D/d , $4 \times 24 \times 63 \times 10.5 \times 8.5 \times 48.5 \times 549 \times 37.88 \times 5, 5 \times 25 \times 56 \times 8.5 \times 6.5 \times 47.9 \times 980 \times 120.95 \times 4$.

$$k_{pi} = \frac{E \cdot d^4}{16 \cdot (1 + \mu) \cdot D^3 \cdot n} = \frac{G \cdot d^4}{8 \cdot D^3 \cdot n} \quad (2)$$

When the dimensional parameters of the spring are known (d , D , n), it is also possible to express the stiffness of the spring using the formula (2), where E [Pa] is Young's module ($E = 2,1 \cdot 10^{11}$ Pa), μ [-] is the Poisson number (for steel $\mu = 0.27 \div 0.30$), $D = D_i - d$ [mm] is the diameter of a coil of the spring and G [Pa] is the shear modulus ($G = 8,1 \cdot 10^{10}$ Pa).

Table 1: Compressive force of the spring TL 0400 x 0240 x 0630 [19]

i [-]		1	2	3	4	5	6	7	8	9
L_i [mm]		63	62	61	60	59	58	57	56	55
ΔL_i [mm]		0	1	2	3	4	5	6	7	8
F_{Ti} [N]	j	0	37.88	75.76	113.64	151.52	189.40	227.28	265.16	303.04
i [-]		9	10	11	12	13	14	15		
ΔL_i [mm]		54	53	52	51	50	49	48		
F_{Ti} [N]		340.92	416.68	416.68	454.56	492.44	530.32	568.20		
ΔL_{ij} [mm]		0.4	0.9	1.3	2.2	3.1	4.0	5.0 ¹	6.0	6.9
F_{pij} [N]	1	16.8	32.9	52.6	84.1	118.5	152.0	190.5 ¹	227.6	263.9
ΔL_{ij} [mm]		7.9	8.9	9.7	10.2	10.8	11.3	11.8	12.3	12.6
F_{pij} [N]		300.8	337.1	367.9	387.8	408.7	426.4	445.2	464.5	475.6
ΔL_{ij} [mm]	2	0.2	0.6	1.2	1.8	2.7	3.6	4.5	5.4	6.4
F_{pij} [N]		11.7	26.9	47.2	71.7	103.5	137.8	171.0	206.6	241.7
ΔL_{ij} [mm]		7.4	8.4	9.4	10.4	11.4	12.6			
F_{pij} [N]	3	279.0	320.0	356.5	393.3	430.6	475.3			
ΔL_{ij} [mm]		0.5	1.0	1.7	2.8 ²	3.9	5.0	6.1	7.2	8.3
F_{pij} [N]		17.8	40.1	66.4	107.7 ²	148.1	190.6	232.1	274.5	317.0
ΔL_{ij} [mm]		9.4	10.5	11.2	12.0	12.2				
F_{pij} [N] ²		357.8	396.9	424.8	453.7	464.1				

¹ see Figure 5 records from laboratory measurements, ² see Figure 6 records from laboratory measurements

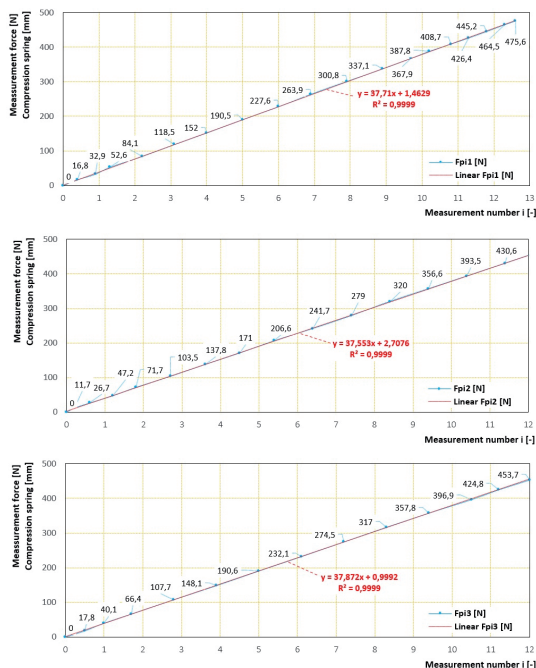


Figure 4: Measured values of the deformation force F_{pij} [N] for the appropriate shortening ΔL_{ij} [mm] of spring TL 0400 x 0240 x 0630, for measurement "j" as per Table 1.

The values of the measured deformation force F_{pij} for a gradually increasing shortening ΔL_{ij} of the spring TL 0400 x 0240 x 0630, for three measurements "j", see Table 1, as per Figure 4.

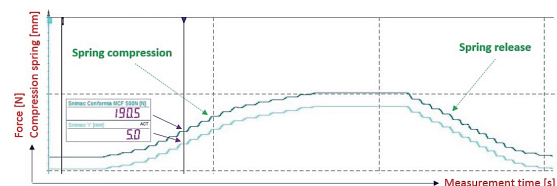


Figure 5: Graphical depiction of the compression and release ΔL_{ij} [mm] and the deformation force F_{pij} [N] of spring TL 0400 x 0240 x 0630.

Measured values of shortening ΔL_{ij} and the deformation force F_{pij} of spring TL 0500 x 0250 x 0560, for two measurements "j", see Table 2, as per Figure 7.

In order to determine the exact value of the real stiffness of springs, it is necessary to perform an operating calibration [8] of the weight sensor 9 and the displacement sensor 19 [11] before each measurement on the laboratory device (Figure 3).

Table 2: Compressing force of spring TL 0500 x 0250 x 0560 [19].

i		1	2	3	4	5	6	7	8	9
L_i [mm]	j	56	55	54	53	52	51	50	49	48
ΔL_i [mm]		0	1	2	3	4	5	6	7	8
F_{Ti} [N]		0	120.95	241.90	362.85	483.80	604.75	725.70	846.65	967.60
ΔL_i [mm]	1	0.2	0.6	1.2	2.0	3.1	4.2	4.5		
F_{pij} [N]		20.5	72.3	153.5	256.0	373.5	507.8	546.1		
ΔL_i [mm]	2	0.1	0.6	1.4	2.7	3.4	4.1	4.5		
F_{pij} [N]		19.3	89.8	182.1	327.0	414.1	489.2	545.7		

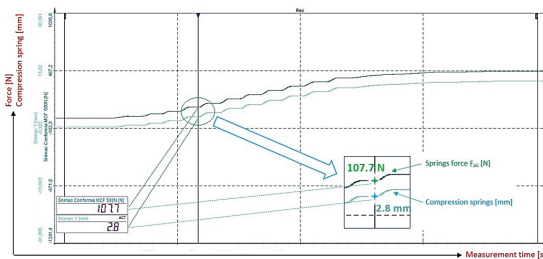


Figure 6: Development of the compression ΔL_{ij} [mm] and deformation force F_{pij} [N] of spring TL 0400 x 0240 x 0630.

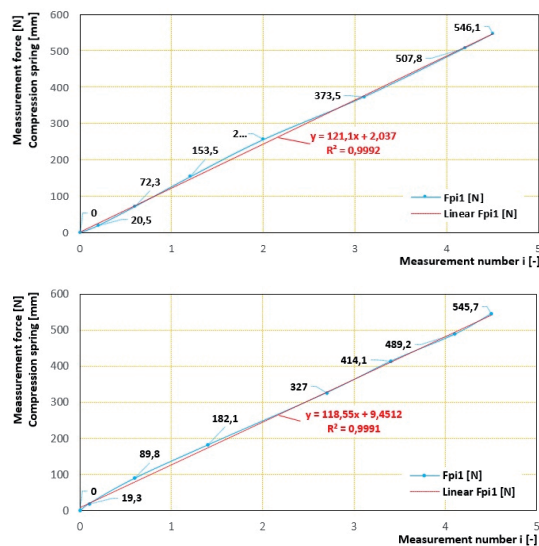


Figure 7: Values of the deformation force F_{pij} [N] for the listed shortening ΔL_{ij} [mm] of spring TL 0500 x 0250 x 0560, for measurement "j" as per Table 2.

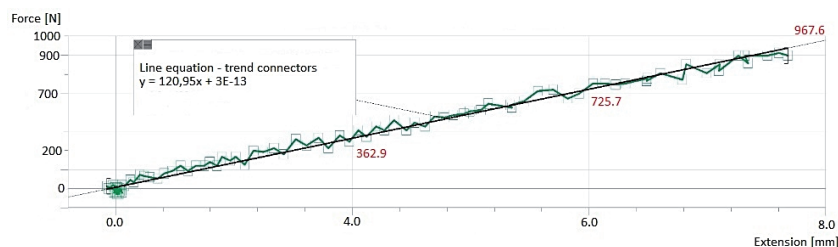


Figure 8: Graphical depiction of the shortening of the original length with respect to the outer force exerted on spring TL 0500 x 0250 x 0560.

The operating calibration is of great importance, since it will verify the whole measurement chain precisely in the state and link-up as will be used for the actual measurement. The significance of this calibration is based on the fact that the calibrated measurement standard is connected to a sensor and the standard's value is compared to the value indicated by the measurement chain. These measurements are used to calculate the final sensitivity of the sensor, deviation from the referential value, and the measurement uncertainty.

Gauges used for educational purposes whose use does not impact the quality and quantity of products, control of the technological or test processes, OHS or the environment, need not be kept in the calibration and tracking system and need not carry a calibration label; in many cases, they need not even have identification labels.

In order to determine the stiffness of a spring in a laboratory as part of training, sensors 9 and 19 are sealed before the beginning of the actual measurements as per the manufacturer's provided calibration curve, which describes the properties of the sensor in its operating range and its sensitivity. This production calibration however does not come with a fully-fledged calibration sheet and hence certainly does not represent an accredited calibration [7] of the sensors.

4. Conclusions

From a physical standpoint, a spring is an element whose deformation is ideally governed by

Hook's law. The characteristic property of a spring is its stiffness, whereas the inverse of the stiffness is called the flexibility.

This work showcases, on the two introductory figures, the structural 2D and 3D design of a validation device that can experimentally determine the values of the compressive force corresponding to the appropriate compression of a coiled spring. The individual parts and components of the machine are detailed in the work.

The first table listed in the work presents the values of three measured values (from repeated measurements, carried out under the same conditions): shortening and deformation forces of one out of two coiled pressure springs described herein (specifically, the one with lower stiffness). The second table lists the values from two measurements of the second spring (with higher stiffness). The accuracy of the values obtained via the sensors is closely tied to the accuracy of the calibration, which is a set of tasks used to specify the relationship between the parameter values under the specified conditions - specifically, the values indicated by the gauges or the measurement system or the values represented by an explicit gauge or referential material, and the corresponding values as realized by the measurement standard.

The figures show the obtained value of the deformation force F_{pij} obtained by the weight sensor 9 and the shortening ΔL_i obtained by the displacement sensor 19 for the spring depending on the measurement time Δt .

The last image presents a dependency of the measured force F_{pij} of the coiled pressure spring depending on the shortening ΔL_i of the spring. If the value of the force for the appropriate shortening of the spring were to be extracted from this image and these two values were inserted into formula (1), these values would allow the calculation of the stiffness on the validation device used to measure the spring.

The correct functionality of the constructed laboratory device (Figure 3) used to determine the stiffness of coiled pressure springs was verified and confirmed.

The ratio between the measured values, i.e., the deformation force and shortening of the spring, can be used to calculate the stiffness of the spring obtained by measurement for the specific deformation of that spring. For measurements

repeated n times, statistical methods (such as, e.g., Student's distribution) can be used to determine the average and deviation of the obtained stiffness of the spring and compare these with the stiffness values declared by the manufacturer.

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