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Criteria for Choosing the Elastic Elements of Force Transducers

Dan Mihai Stefanescu*, Alexandru Stefanescu**
* *National Institute for Aerospace Research, Bucharest, Romania*
** *"Politehnica" University of Bucharest, Romania*

A thoroughgoing study idea of the sensitivity increasing methods for strain gauged force transducers sprang up many years ago in Romania. It's a theme that requires the knowledge of different fields: Applied Metrology, Deforming Solid Mechanics, Strength of Materials and Elasticity, Experimental Stress Analysis, Force & Torque Measurements, Electronic Instrumentation, Numerical Methods, Structural Optimization. The measurement and analysis of the forces and moments require special transducers with utmost precision and remaining robust in severe experimental conditions. Their design is based on the use of strain gauges which offer many advantages: small bulk, ease of use, remote electrical measurements, reliability and so on.

In a previous stage it could be noticed that the mechanical sensitivity of the force transducer is especially ensured by means of a correct application of formulas for the size determination for its elastic element. These formulas can be found in the engineer's memo books (along with the geometrical and strength properties of the sections) as well as in different technical works. The considered relations are often rough and must be verified also by other means (analogies, comparisons, reciprocity, and superposition) [1].

To compare the mechanical sensitivity of different elastic element types a unified notation is required, like in Table 1. So, to compare the sensitivity of some elements (column, yoke) at different loading modes (elongation, bending) such as model 1 (extended column) compared with 2 (bending beam) and 3 (clamp) compared with 5 (yoke), the choice of a unique dimensional parameter, **a**, as comparison criterion, becomes necessary. The five elastic elements, that can be made of the same material (the elasticity modulus E, the volume weight γ, and the maximum normal tension σ_{max}, being identical) can be compared according to five basic metrological and functional characteristics [2]:

- the apparent maximum volume, V (an overall size);
- mass: $m = \gamma \cdot V$;
- the relative maximum load: P/σ_{max};
- the sensitivity ξ defined as a ratio between the specific deformation

under a single active strain gauge and the applied load;

- the elastic constant: K (the classical force/displacement ratio in mechanics).

The hierarchy from the tensometrical sensitivity point of view is the expected one: cantilever beam (2), clamp (3), yoke (5), ring (4), extended column (1). The elastic constant has great variations (from 1 to 1500); it shall have the smallest value for the displacement transducers and the greatest value for the force ones. The choice of an ideal shape for the transducer elastic element needs a complex multicriterial analysis based on a "decision matrix"; the relative variations of the characteristics considered as compared to the initially established reference version shall be introduced in this matrix [3].

The present stage of strain gauged force transducers analyses comparatively a dozen of typical **e**lastic **e**lements (EE) for the **s**train **g**auged **f**orce **t**ransducers (SGFT) and shows synthetically their basic characteristics: load range and mechanical and electrical sensitivity (Table 2). A simplified model - a leading illustration of the present stage - as well as a personal improved variant, conceived and/or made by the author, are presented for each type of SGFT elastic element: stretched/compressed column, stretched /compressed tube, bending beam, bending and/or torsion shaft, middle bent bar with fixed ends, shear beam, bending ring, bending yoke, bending diaphragm, axial-stressed torus, axisymmetrical EE, and voluminous EE.

For example, the IXth above-mentioned type (bending diaphragm) [4] is presented in Figure 1. Shape optimization of such circular membranes in order to increase their tensometrical sensitivity is possible using FEM (the **f**inite **e**lement **m**ethod) as method of research. Starting from a chosen shape and preliminary dimensions established by analytical computation on simple models, a first discretization for the elastic element and FEM analysis are made. The results are examined and, if necessary, the initial dimensions are modified and FEM computation is made again. After several statical analysis the transducer elastic element reaches its optimum shape - a good example of novelty. All these elastic elements for strain gauged force transducers will be presented in Poster Session within the 17th International Conference on Force, Mass and Torque Measurements, Istanbul - Turkey, 17-21 September 2001.

The study of increasing SGFT sensitivity emphasizes the connection of different factors, which can interfere, the problem demanding a general vision. The author's main original contributions, included in his doctor's degree thesis [5], can be summed as follows:

1. including of the thesis subject in the mechatronics field, with explanations of the strain gauges application in the structure of modern force transducers and an opening to virtual instrumentation;

2. definition of the tensometric sensitivity of force transducers elastic elements and their classification according to loading types;

3. hierarchization of elastic elements according to strain gauge sensitivity in connection with the adopted Wheatstone bridge scheme;

4. establishing of 12 basic structures of elastic elements where the present status is rigorously analyzed by also indicating the improving methods and by showing their main characteristics and pointing out the measuring sensitivity;

5. presentation of the basic characteristics of the elastic materials and the use of compared methods for experimental stress analysis and analytic and/or digital calculation for the increase of mechanical sensibility of tensometric force transducers;

6. the detailed analysis of the electrical methods for increasing the sensitivity of SGFT: the enlarging of strain gauges number, selected by specific criteria in compliance with a certain geometric progression, then the increase of the Wheatstone bridge number, the raising of supply voltage and/or incorporation of electronic circuits;

7. definition of new terms/notions in the strain gauge field: deformability, quality factor, multiple strain gauges and strain gauging;

8. drawing up of the calculation SV-01 program for the specific deformations of elastic elements of SGFT, a program correlated with various evolution stages in hardware and software, and adopted by the international technical literature;

9. the application of the elastic elements structural optimization instead of the numerical analysis by finite elements tested in tens of cases, some of which already implemented;

10. the drawing up of a synoptic table (like a universal poster) for the strain gauged force transducers sensibility factors;

The specific measuring software for the strain gauge instrumentation shall be adapted to the force transducers. In order to choose a certain elastic element several criteria shall be considered, even if contradictory, that can make the option difficult:

- the elastic properties of material;
- processing and treatment facilities;
- available space limitations;
- getting a high global (mechanical and electrical) sensitivity under linearity and immunity at parasitic or environmental factors;

- achieving a mechanical and electronic symmetry of the force transducer;
- other specific characteristics of force measurement in Robotics.

Such a multicriterial analysis requires the modern technique of computation. Even databases for the SGFT elastic elements have been conceived, but the force transducer specific field is not to be found in the available databases yet. In the near future this idea concerns the author who intends to initiate activities in the view of creating the database for force transducers, along with an expert program to be used in the design and optimization of the transducers elastic elements.

References

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[2]. Constantinescu I.N., Stefanescu D.M. and Danet G., *Le choix de la configuration optime pour les elements elastiques des capteurs, Al IV-lea Simpozion National de Tensometrie, Brasov, Romania, 24-27 sept. 1986, vol. 1, pp. 73-78.*

[3]. Stefanescu D.M., Sandu Adriana, Sandu M.Al. and Sorohan St., *Computation particularities for the elastic elements of strain gauge transducers*, Proceedings of the 10th International Conference on Experimental Mechanics, Lisbon, Portugal, 18-22 July 1994, vol. 2, pp. 983-986.

[4]. Stefanescu D.M., *Comparative study of some force gauges with membrane–type flexible element utilized for measurements in civil engineering,* International Symposium on Geomechanics, Bridges and Structures, Lanzhou, China, pp. 253-259, 1-5 September 1987.

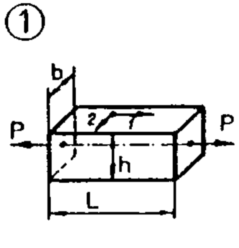
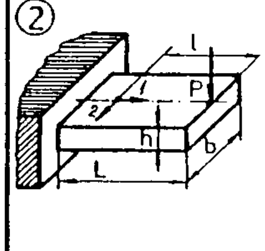
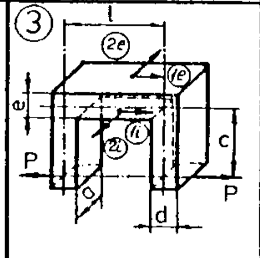
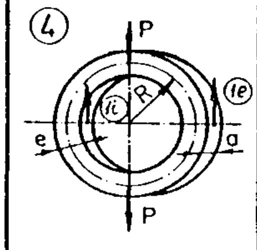
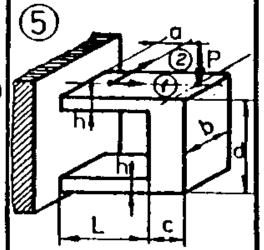
[5]. Stefanescu D.M. *Metode de crestere a sensibilitatii traductoarelor tensometrice de forta*. Teza de doctorat magna cum laude (160 pagini, 26 tabele, 86 figuri, 336 referinte bibliografice), Universitatea "Politehnica" Bucuresti, 10 septembrie 1999.

Contact Person for Paper:

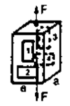
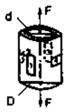
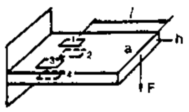
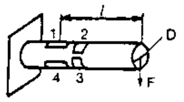
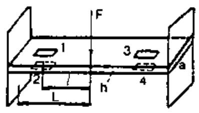
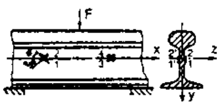
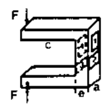
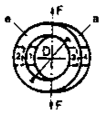
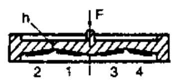
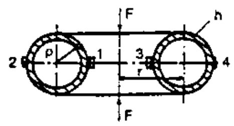
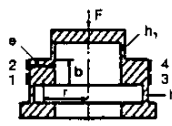
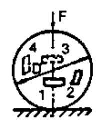
Dr. Dan-Mihai Stefanescu

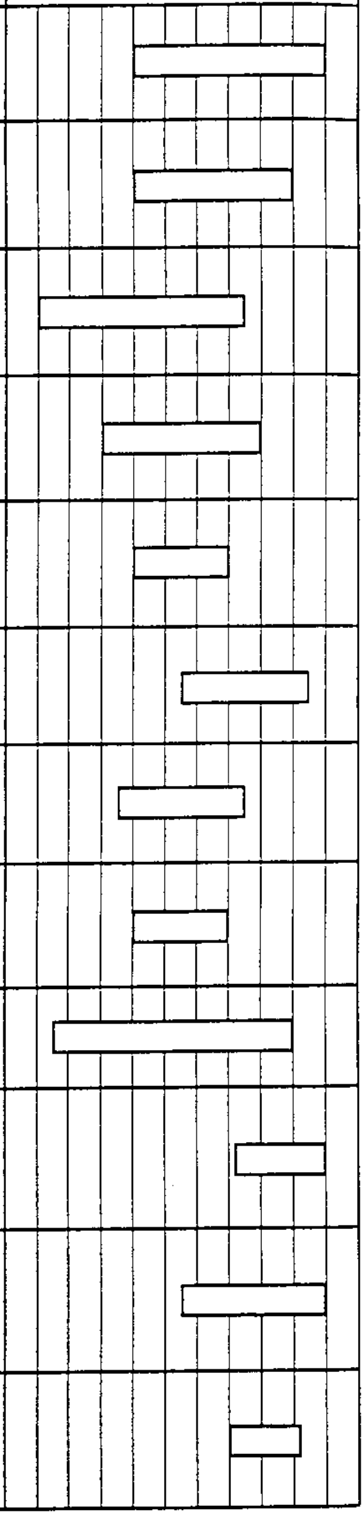
Address: The National Institute for Aerospace Research “Elie Carafoli” Bd. Iuliu Maniu 220
Bucharest - 77538, ROMANIA
Fax: + 401 413 06 90
Tel: + 401 413 50 02

TABLE 1.

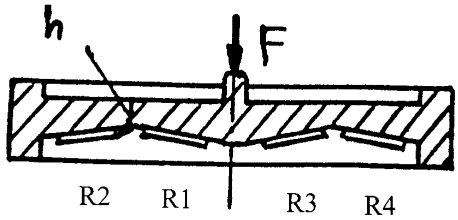
		Barre droite soumise à traction	Barre droite encastrée soumise à flexion	Étrier rectangulaire	Anneau circulaire	Portique rectangulaire
Schéma d'élément élastique et notations						
Forme définie par les relations:		$b = h = a$ $L = 3a$	$h = a$; $b = 3h = 3a$ $L = 5b = 15a$ $l = 12a$	$d = e = a$ $c = 3a$ $l = 5a$	$e = a$ $R = 5a$	$h = a$; $b = 3a$ $c = 5a$; $d = 9a$ $L = 15a$
Relations de calcul	Deformation ε_l	$\varepsilon_l = \frac{P}{Eb h}$	$\varepsilon_l = \frac{6Pl}{Eb \cdot h^2}$	$\varepsilon_{li} = \frac{P}{Eae}\left(\frac{6c}{e}+1\right)$	$\varepsilon_{li} = \frac{P}{2Eae}\left[1+\frac{3R}{e}\left(1-\frac{2}{\pi}\right)\right]$	$\varepsilon_l = \frac{3P(L-2a)}{2Eb \cdot h^2}$
	Constante élastique k	$k = \frac{Eb \cdot h}{L}$	$k = \frac{Eb \cdot h^3}{4L^3}$	$k = \frac{Ea}{4c^2\left(\frac{2c}{d^3}+\frac{3l}{e^3}\right)}$	$k = \frac{Eae^3}{12\left(\frac{\pi}{4}-\frac{2}{\pi}\right)R^3}$	$k = \frac{2Eb \cdot h^3}{L^3}$
Caractéristiques de base	Volume maximum V	$V = 3a^3$	$V = 45a^3$	$V = 21a^3$	$V = 121a^3$	$V = 540a^3$
	Poids G	$G = 3a^3\gamma$	$G = 45a^3 \cdot \gamma$	$G = 11a^3\gamma$	$G = 31{,}4a^3\gamma$	$G = 225a^3\gamma$
	Charge maximum P/σ_{max}	$\frac{P}{\sigma_{max}} = a^2$	$\frac{P}{\sigma_{max}} = \frac{a^2}{30}$	$\frac{P}{\sigma_{max}} = \frac{a^2}{19}$	$\frac{P}{\sigma_{max}} = \frac{a^2}{3{,}225}$	$\frac{P}{\sigma_{max}} = \frac{a^2}{7{,}5}$
	Sensibilité $\mathfrak{J} = \varepsilon_l/P$	$\mathfrak{J} = \frac{1}{a^2E}$	$\mathfrak{J} = \frac{24}{Ea^2}$	$\mathfrak{J} = \frac{19}{Ea^2}$	$\mathfrak{J} = \frac{3{,}225}{Ea^2}$	$\mathfrak{J} = \frac{6{,}5}{Ea^2}$
	Constante élastique k	$k = \frac{Ea}{3}$	$k = \frac{Ea}{4500}$	$k = \frac{Ea}{756}$	$k = \frac{Ea}{223{,}17}$	$k = \frac{Ea}{562{,}5}$

Tabelul 2. Elementele elastice pentru traductoare de forțe

Tip	Denumire	Schiță element elastic	Sensibilitate		Game de forțe [N]
			mecanică [μm/m]	electrică [ε]	10^{-2} 10^{1} 10^{4} 10^{7}
I	Coloană		$\frac{F}{E\,a\,e}$	2,6	
II	Tub		$\frac{4F}{\pi E(D^2 - d^2)}$	2,6	
III	Lamelă		$\frac{6Fl}{E\,a\,h^2}$	4	
IV	Arbore		$\frac{32Fl}{\pi E D^3}$	2,6	
V	Bară încastrată		$\frac{1{,}5F(2l - L)}{E\,a\,h^2}$	4	
VI	Forfecare		Funcție de: F, E și dimensiunile profilului	4	
VII	Jug		$\frac{F\left(6\frac{c}{e} - 1\right)}{E\,a\,e}$	2,6	
VIII	Inel		$\frac{3FD}{\pi E\,a\,e^2}$	3,7	
IX	Membrană		$\frac{1{,}24F}{\pi E h_{med}^2}$	4	
X	Tor		$\frac{2(1-\nu^2)\left(1-\frac{\rho}{r}\right)F}{\pi^2 E h \rho\left(1+\frac{3}{2}\frac{h^2 r^2}{\rho^4}\right)}$	3,7	
XI	Axial - simetric		Funcție de: F, E, b, c, h_1, h_2, r	4	
XII	Sferă		Funcție de: F, E, D	2,6	



IX - MEMBRANĂ ÎNCOVOIATĂ



Variantă proprie

Game de sarcini [N]: 5 x 10^{-2}. . . 10^{6}

Sensibilitate mecanică [μm/m]: $\frac{1{,}24\,F}{\pi\, E\, h^2_{med}}$

Sensibilitate electrică [ε]: 4

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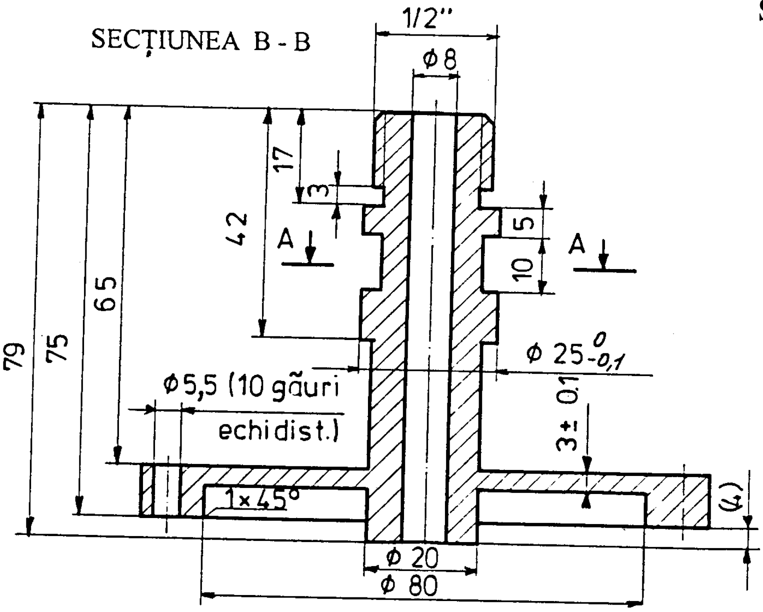

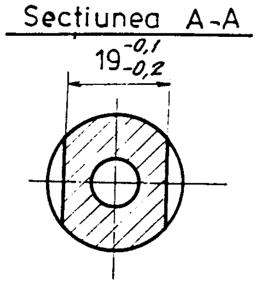

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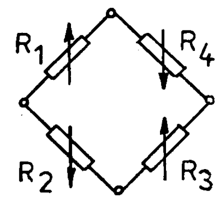

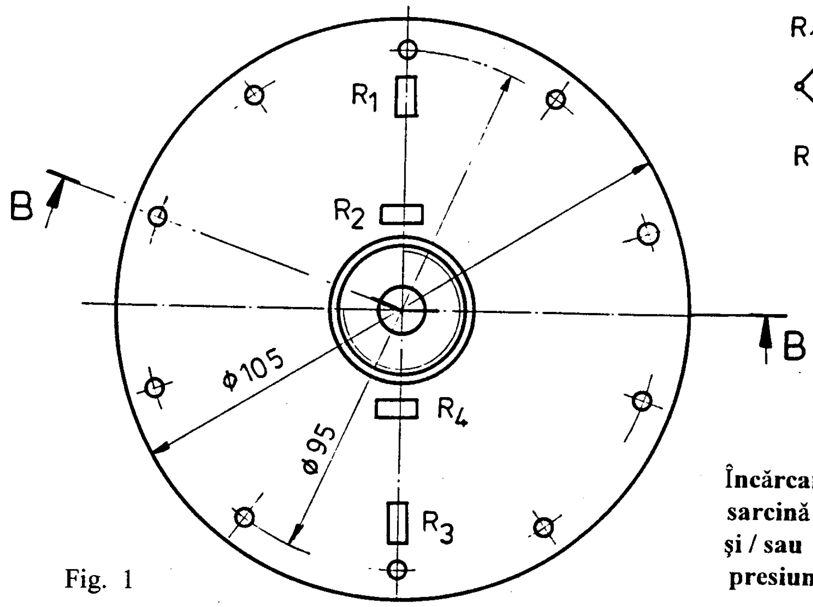

Fig. 1

Încărcare cu sarcină concentrată și / sau presiune distribuită