МЕТОДИ МОДЕЛЮВАННЯ ОБ'ЄКТІВ ПРОЕКТУВАННЯ

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B. Branowski, S. Głowala
Poznan University of Technology (Poland)

SYNTHESIS ATTEMPT AND APPLICATIONS OF THE UNIVERSAL PRINCIPLES IN DESIGN OF SPRINGS

Принципи проектування пружин – головне в цій роботі. Такі правила мають важливе значення в методології створення структури: одинарних пружин, матриці пружин, простих еластичних механізмів. Декілька варіацій правил було наведено в роботі. Проаналізовано багато застосувань для кожного з вказаних правил.
Ключові слова – проектування пружин, еластична конструкція

Principles of spring design are the main object of the work. These principles are of cognitive meaning in methodology of creation the structure of: single springs, set springs, simple elastic mechanisms. Several variations of principles have been presented in the work. The analysis of many applications for each of given sub principles, has been carried on.
Keywords – spring design, elastic construction

Construction principles in design, their meaning, kinds and position

Any designer mainly applies the knowledge he/she collected and processed himself/herself. Expert's knowledge in the range of designing or the knowledge of the experienced designer is based (acc. To V. Hubka [8]) on so called "feel for design" that means is based on the perception assimilation of the correct models due to the experience. The source of the knowledge is not only the experience but also the reflection obtained from the other persons' experience processing or theoretical scientific knowledge.

Theory of design, also called philosophy or technical design science is the practical science based on the scientific reflection that comes from the systematically carried on investigations concerning the designing. Designing as the rational, cognitive and divisible into phases process is possible to be taught with the condition that theory and teaching methods exist. The standard knowledge concerning principles and designing procedures as well as the designing evaluation methods are particularly important in designing methodology. "The designer, demonstrating creative abilities should have perfectly mastered the craft that is based on the knowledge of practical application of principles and rules connected with the correct designing" (L. T. Wrotny [16]). Application of principles is restricted because of the advisability and constructional demands and because of principle compromise necessity and set of criteria or constructional constrains (e.g. application the principle of the uniform strength causes the increase of the production costs).

The principle of designing or construction is the standard sentence with the fixed cognitive information content "how it should be". The function of such sentence is to control designing process assuring its using effectiveness [6]. Designing principles according to J. Dietrych [7] are the means of construction objectiveness as the final products properties. These means create the methods of the optimum achievement and they are the base for the creation of the designing methods. The principles and occurring out of them secondary principles (sub principles) are in the form of systematic set obtained by means of systematic relation.

Design principles are used to form properties of the analyzed system according to bilateral interaction of the technical process on the human being and/or machine as well as bilateral functional relevant interaction of the over system (environment) on the human being – machine system.

Designing principles can be divided into three separate types:

Specialised principles that are characteristic for design offices. Such offices are in the possession of particular and specific data and method resources, that means specific designing secrets (know – how);

General principles that are obtained as the result of theoretical research. They are not connected with only one type of technical objects, but they can be widely applied and not always universally. The example of the general designing principles can be presented as principles of structural element arrangement in the field of art. In artistic design there are distinguished principles of symmetrical, formal and approximate balance, principles of static and dynamic proportions, principles of rhythm, contrast, harmony and domination. Kesselring's formula concerning five general principles of product creation can be shown as another example: minimal production cost, minimal space, minimal mass (light construction), minimal losses, advantageous operational use.

Universal designing principles may be treated as improper ones due to the academic character of the designing art [13]. As the example it is possible to consider basic designing principles of A. Slocum [14], that are based on the application of the physic philosophy in examples of machine design (Newton's laws, law of conservation of energy, Saint – Venant's principles, golden section principle, Abbe's principle) as well as typical for construction principles such as: stability, symmetry, precise and repeatability, structural loops of force flow, initial tension and, so called self principles: self balancing, self reinforcing, self protecting, self limiting, self damaging, self braking.

Principles occur in many design fields such as: artistic, industrial, technical or construction.

The principles of the technical design as well as the construction principles in the field of the spring designing are the object of this work. The necessary limitation of the considering object is caused not only because of large subject matter "Principles of Design" but also because of , so called, methodological capacity of "the principle" meaning in various domains [6]. Ontological basics of the integral forming of the technical function and a general constructive shape of the designing object will be mentioned in principles of the technical design. Construction principles are the basic source to determine the set of the product properties.

Construction principles are of the main meaning in technical object structure setting. Its structure parts (question how to apply? in Fig.1) enable to preserve internal connections and to aid proper realisation of the demanded functions. But creation of principles (question why? in Fig.1) is treated as the heuristic method of searching in the given set, the best solutions regarding functions/phenomena as well as to find out the reason of such state in the principle description.

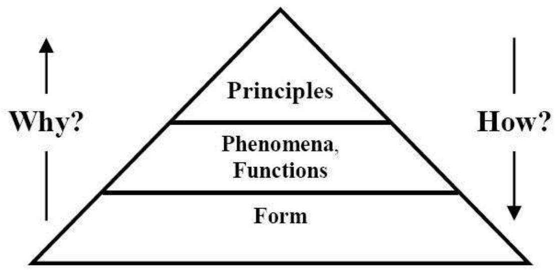

Fig.1 Abstractions of the hierarchy description

Construction principles have been assumed (Table 1) according to the proposal of the well known European monographs such as J. Dietrych [7] and G. Pahl and W. Beitz [11]. The author of the work has already been interested earlier in construction principles [3–6] and formulated principles basing on biological phenomena, functions and form occurring in bionics and proved that bionic principles are the archetype of construction principles. Bionic principles can be also treated as the base of engineer's concept based on biological analogies and anomalies, simple implementation or biological transfer. Possibilities of construction principle development based on structure and function of the biological system laws are going to be determined in order to assure in the mechanical systems the following features: (1) kinematic intelligence and memory" for mechatronic self adaptation on the way of learning during utilization, (2) dissipative kinematic diagrams forcing the minimum energy consumption, (3) redundancy of structure elements and their functions in order to improve the safety and reliability of the system, (4) uniform mechanical strength which is realised not only by the change of shape with the constant structure and density but also by the change of density and/or structure with the constant shape [3]. The other B. Branowski's construction principles [4–6] concern: the evaluation and function choose, conceptual solutions, solutions and forming of the construction features of the equipment with the destination for disabled and old people (Table 1).

Table 1

Construction principles

CONSTRUCTION PRINCIPLES IN:			BIONIC PRINCIPLES
MECHANICAL ENGINEERING		REHABILITATION ENGINEERING	
J. DIETRYCH [7]	G.PAHL, W. BEITZ [11]	B.BRANOWSKI [4,5,6]	B.BRANOWSKI [3]
optimum state of loading	transmission of forces	optimum loading optimum distribution of function between a man and technical mean	optimum form shaping
optimum construction material	partition of the problem	self aided technical mean arrangement and structure fitting	optimum energy utilization
optimum relations of bounded values	self aided (self adaptation)	antinomy overcoming optimum energy utilization	functionality
optimum of construction stability	stability	user – friendly	optimum material

In German methodological school construction principles are derived from the basic aims of the product development. These principles are given in the form of rules: unambiguously (function), simply (realisation) and safety (man and environment) reacting on the full cycle of the product life in their interaction results (Table 2). In German methodological school the construction rules "simply–unambiguously–safety" [9] are reduced to the principles of proper designing due to: (1) function, (2) material, (3) manufacturing, (4) beauty of form and colour ness (5) economy for the full life cycle of product. In more up–to–date subject literature (W. Steinhilper, R. Roeper [15]) there are generalised proper because of function and economy constructions, that fulfil the principles of load, material and form selection in construction.

Table 2

Three basic construction rules [9]

RULES →	SIMPLY	UNAMBIGUOUSLY	SAFETY
ENVIRONMENT	various setting–ups of relations to people (service, maintenance, control, repair) and to environment	error–free assembly, service, connection and maintenance and unambiguous production documentation and utilization	safety by means of protecting the system against environmental influence or protecting the environment against system influence
FUNCTION	possibly the smallest amount of the partial functions, connected in the way of logic and reviewing	defining and arrangement of partial functions and flows of mass energy and information	Avoiding of damaging partial interactions of functions, assuring the small complication and complex state
STRUCTURE	Possibly the smallest amount of elements, simple, easy to make geometrical forms, easy to calculate forms	avoiding of ambiguous places of element couplings that are undefined according to the value, direction and kind of loading, resistance to disturbances (temperature, wear, tolerances)	safety assuring by means of safety principles

Spring construction principles

Construction principles of the single and combination springs as well as the simple elastic mechanisms are the main aim of this work. The principles have been given in the form of arranged set concerning the shaping of the structure form as the function carrier of the flexible elements (Table 3). Then the various sets of cases of principle applications have been presented and characterised.

Table 3

Spring construction principles

PRINCIPLE OF THE OPTIMAL LOADING STATE Principle of the long transmission way and closing the force stream by the metal springs and short direct way by the elastomer springs Principle of the equal shape strength of the springs Principle of equalization effort in the part of spring construction Principle of equalization effort in the part of spring construction
PRINCIPLE OF OPTIMAL RELATIONS OF THE BOUNDED VALUES IN SPRING
PRINCIPLE OF THE OPTIMAL UTILIZATION OF THE HUMAN`S ENERGY WITH MAXIMAL MACHINE EFFICIENCY
PRINCIPLE OF INTEGRATION THE FUNCTION OR/AND STRUCTURE Principle of function integration Principle of structure integration
PRINCIPLE OF SELF ADAPTATION Principle of self protection Principle of self safety (intrinsic safety) Principle of self reinforcement (or self weakening)
PRINCIPLE OF THE CONSTRUCTION STABILITY Principle of resistance to buckling, torsion buckling, twisting, local instability of the shell Principle of the static and dynamic bistability

Spring construction principles Spring construction principles–application examples

Principle of the optimal loading state in springs can be defined by some sub principles such as: transmission of forces, given deflections, stream of forces and equal shape strength.

In metal springs forces should be transmitted on the long way of closing the stream of forces (Fig.2) while in elastomer springs the mentioned above way should be the short one. Long way of transmission and closing the stream of forces is obligatory only for metal springs with given characteristics: force – F, deflection – s. For metal springs deformability is connected with the creation of the geometrical construction form, so called action body (wire, rod, washer) in the form of the long (Hook's law) element. In case of elastomer springs where deformability is obtained by application of materials with small elasticity modulus E, G, the short and direct way of the closing the stream forces is obligatory.

The mentioned above construction principle of metal springs is not compatible with universal Pahl's and Beitz's principle that demands the force transmission by the direct and short way of closing the stream of forces in machine design. Authors of the principle of the optimal loading state justified its necessity by means of fulfilling the following functional demanding: vibrations, rigidity and damping, decreasing of material outlays with minimal deformations and maximal construction stability (e.g. buckling stability).

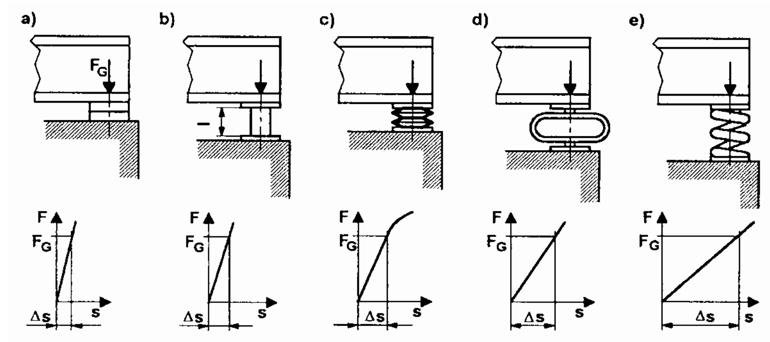

Fig.2. The principle of the long transmission way and closing the stream of forces by the metal springs that is shown as the example of machine vibroinsulation against the foundation or vehicle suspension. Increasing the force transmission way by: a) extremely rigid force transmission by means of supporting washers; b) rigid force transmission by means of compressed rod springs; c) less rigid force transmission by means of disk spring system with possible varying of the spring rigidity; d) flexible force transmission by means of bent bow spring with possible force measuring; e) extremely flexible force transmission by means of helical spring.

The bent flat springs with various constructional shape (Fig.3) are the best example of the principle of the equal shape strength application.

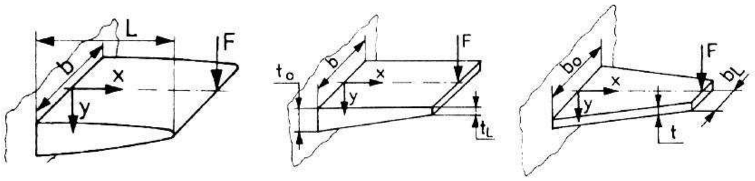

Fig.3. Principle of the equal shape strength obtained due to the arranged form of the construction element and fitted to the loading distribution in the bent flat springs [2].

The helical pull spring crack usually occurs in the spring loop, where bending or torsion stresses achieve their maximal values. Due to the spring dimensioning according to torsion stresses in coils of the cylindrical body with decreased allowable stresses comparing with push springs – it is obvious that better solution is application of the principle of equalization the construction stress effort by means of decreasing the bending arm or applying the springs with separate spring loops (Fig.4).

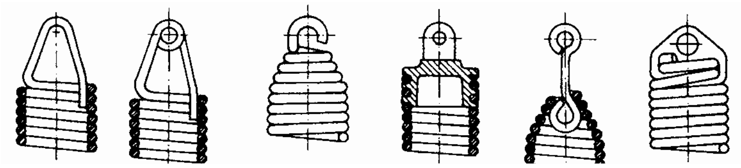

Fig.4. Principle of effort equalization in helical pull spring by means of the preliminary coil stress, with decreasing the bending arm of the spring loop or construction with separate spring loops.

In case of occurring the axial load of shaft bearings (Fig. 5a) or complex deformable body (Fig. 5b) with closed force circuit on the short way (Fig.5b), the more advantageous constructional structure can be assured by increasing the loading transmission ways in symmetrical load – carrying system of the conical friction clutch (Fig.5c).

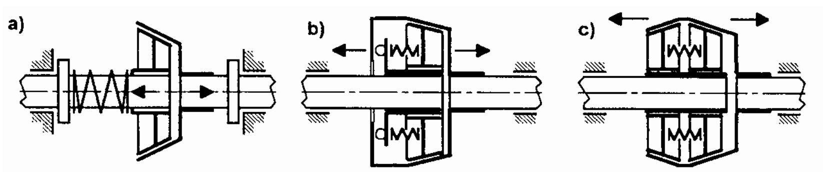

Fig.5. Principle of loading equalization on the short way of force stream closing in conical friction clutches: a) for small forces – acting force distribution without equalization on the shaft; b) for medium forces – acting force distribution by the equalized element; c) for great forces – acting force distribution by symmetrical arrangement [11].

Elastic support of "hanging" nut obtained by means of various elastic elements improves significantly the uniformity of load distribution on the thread coils. Such support protects the nut in the elastic way against loosening (Fig.6).

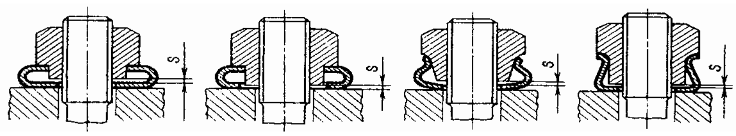

Fig.6. Principle of optimal loading distribution by means of applying elastic washers improving the uniformity of loading distribution on coils of the "hanging" nut and protecting the nut in elastic way against loosening.

The principle of optimal relations of the bounded values is often used in spring construction. Typical relations of the bounded values are functional relations of the relevant geometrical features in spring construction: e.g. in helical springs the relation of the mean diameter of the unloaded spring to the diameter of the wire $w= D/d$, in disk springs the relation of the external spring diameter to the internal spring diameter $\delta=D_e/D_i$. Small values of the w coefficient in spring ($w= 4 – 5$) assure the minimal assembly volume, that means the maximal relation of the work W to the spring volume V, small dimensional deviations and the great stress concentration in the wire. Basing on parametrical optimization in combination springs it is possible to assume that relation $(W/V)_{max}$ is equal to $w_{opt}= 4 – 5$ for single springs, or to $w_{opt} = 5 – 7$ for the set of two springs and to $w_{opt} = 7 – 8$ for the set of three springs. The criterion of the relation the work to the volume $(W/V)_{max}$ regarding the disc springs, usually occurs in widely applied standard diameter relation equal to $\delta=D_e/D_i = 2$. By comparing the various springs according to the W/V criterion, it has been stated that frictional ring springs can accumulate 1,5 time greater energy than disk springs or helical push springs or torsion rods [2].

The bounded relations are also the dimensional relations of the spring with elements of its constructional environment that are treated in the full “life cycle” of the “spring” object; e.g. relevant functional radial clearances between the guide and spring compensating the change of the external dimensions in axially pushed helical or disk springs, forming the nest of the spring guide for the assembly simplification (Fig.7a), forming the space between the spring coils that makes impossible the spring tangling after its automatic production (Fig 7b), forming of the lever that simplifies introduction of the spring loop (Fig. 7c).

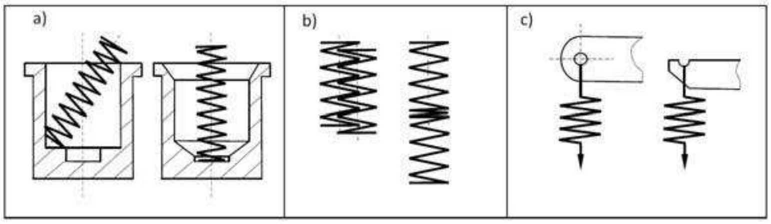

Fig.7. Improving possibilities of the relations of the spring bounded values and the spring environment considering the spring production (b) or the spring assembly (a, c).

The principle of the optimal efficiency while energy conversion into the machine effective work results from the economical matters concerning the minimization of the used energy as well as from technical matters concerning the optimal utilization of the limited energy in order to realise functions in man – machine systems. The equipment that is presented in Fig.8 is characterised by the high efficiency of transmission energy into mechanical work.

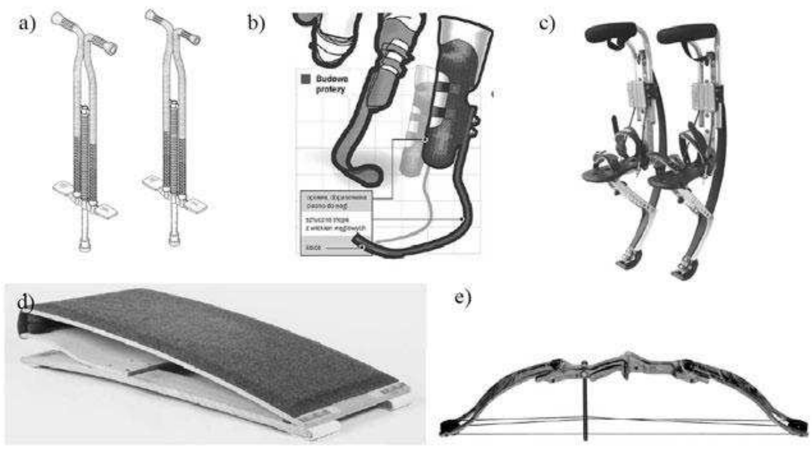

Fig.8. Principle of the optimal use of the man’s energy with maximal efficiency of energy transmission obtained by the aided equipment: a) jumping toy “Pogo stick” with helical springs, b) artificial limb made of carbon fibre “Gepard” made by Ossur company from Island, and applied by African sprinter Oscar Pistorius, c) jumping toy – Powerizer (other names: Upwing, Skyrunner, Flyjumper) with flat springs, d) gymnastic springboard with the flat spring system made of wood similar material, e) sport bow

The principle of the optimal function distribution is usually realised by connection – integration of the construction element function. The "nut – spring" that has been based on the original author's idea, with application of the multifunctional effects, has been shown in Fig. 9.

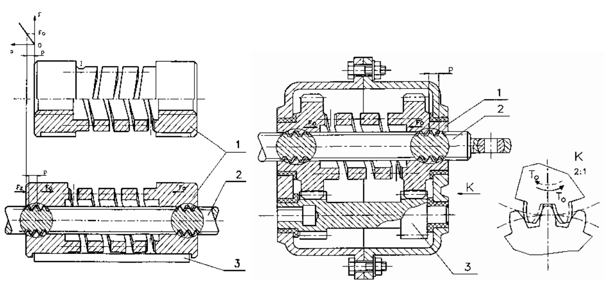

Fig. 9. The principle of the function integration has been shown on the example of the nut – spring as the constructional element. In this case the preliminary loading F0 that is equivalent to spring deformation by the one or multiple thread pitch and/or torsion with moment T0, causes clearance elimination in the kinematic pairs such as screw–nut and pinion–wheel. Moreover, it is possible to assure the condition of the thread self – locking with the safety redundancy in sequence cooperation of the left and right elements of the thread pair with changeable direction of the work loading F

Multifunction is also assured by other examples of the integral elastic constructions: locks, clips, double coiled helical – conical springs punched out of the one steel–sheet element and then tensed and heat – treated, or constructional elements of the one – way clutches (Fig. 10).

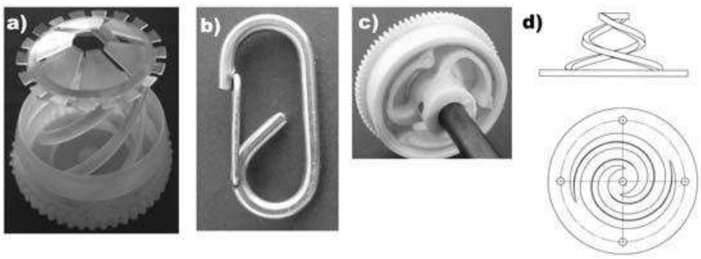

Fig.10 Principle of function integration in one element has been shown on the examples:
a) lock of the pill container (function of container closing and function of the preliminary pill pressure in order to avoid in transport the dynamic and striking loadings in case of loosing pills).
b) double element clip, c) body of the toothed wheel with the one – way pawl clutch, cooperating with the single element hub with the elastically tightened pawls.
d) single element double coiled helical – conical spring

While realisation of the single function the principle of structure integration is applied. The integration possibility by means of decreasing the number of elements in clip construction.

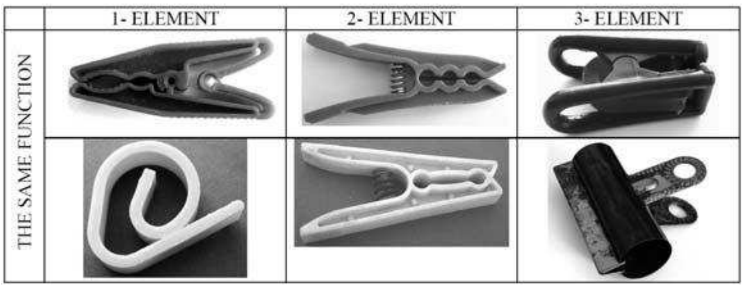

Fig.11 While realisation of the single function the principle of structure integration is applied. The integration possibility by means of decreasing the number of elements in clip construction

Connections of the function and structure are of the specific character for the springs due to the fact that single spring (elementary structure) can be treated as the element of many functions and that many various springs (elements and relations creating complex structures) can realise the same function. While changing the relation in the set of springs new structures occur. Such flexibility enables to realise the principle of structure and function integration (Fig.12).

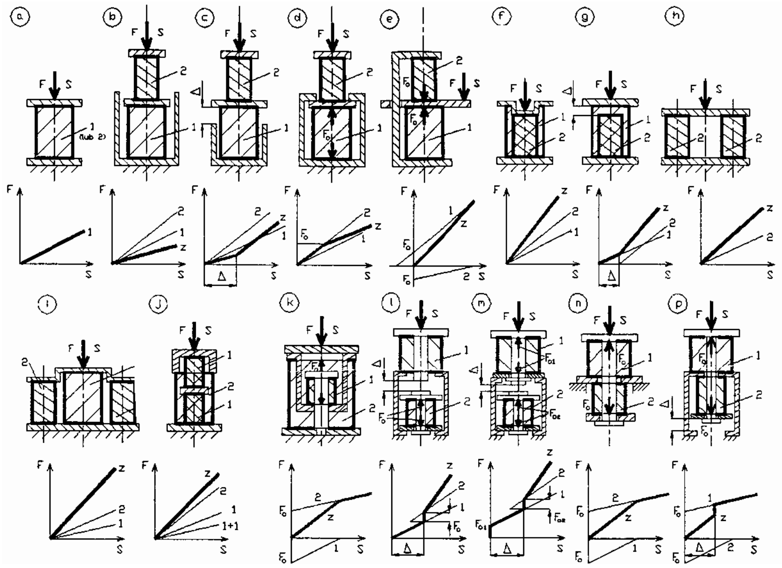

Fig.12. Principle of structure and function integration

Construction possibilities of creating 15 structures of combination springs basing on two standard or normal springs have been presented in Fig.12: a) connections in series, parallel, combined or differential; b) while immediate or sequenced spring engaging into loading or sequenced disengaging from the further loading; c) with and without the preload load.

Characteristics of these systems are linear or broken linear with progressive or non progressive course, with or without jump of the force. The number of the possible functions (e.g. force elastic transmission, accumulation of the potential energy or conversion of the kinetic energy) is not known and significantly exceeds the number of 15 systems of the structure and characteristic connections because of the fact that each characteristic may be proper to realise one or more functions. In problems of the system analysis it is necessary to start with the set of {E} elements, then to determine relations R in the set, and then to find structures S and equivalent characteristics CH which realise function set for the spring {F} and the aim verification C. In problems of the system synthesis, that means designing, the sequence of action is reversed:

Analysis →

{E} ⇄ R ⇄ S ⇄ CH ⇄ {F} ⇄ C

← **Synthesis**

Using of the ***self protection principle,*** it is possible to apply pre loaded disk springs with cuttings in order to fix other elements on the shaft or in the body (Fig. 13). In this case following physical effects are applied: lever effect, radial dimension change effect while loading the spring, Coulomb’s friction effect.

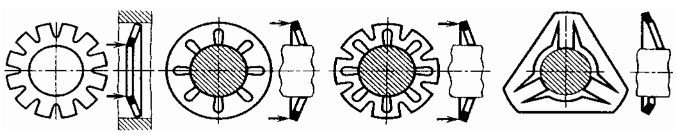

Fig.13. Principle of the self protection as the frictional – shaping form while fixing construction elements: a) in precise smooth holes, b) c) and d) on smooth shafts, by means of preloaded self – locking elastic toothed stopper rings – washers in the form of conical cut springs a) cut externally (disk star springs) b) cut internally (disk cut springs or membrane springs) c) cut bilaterally (Ringspann disk springs) d) cut internally (washers with flat elements and with extended height in order to decrease production quality demanding).

The self protection principle of the thread coupling against the self loosening by means of slotted conical disc springs and disc springs has been presented in Fig. 14 and Fig.15. This type of the frictional – shaping couplings (screw, nut, body)(Fig.15) is not recommended for bodies made of soft alloys (Al or Mg) or too hard materials (hardened) because of the possible damage of the body surface or because of decreasing the washer resistance to turn.

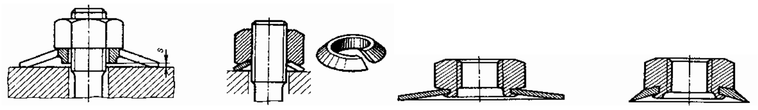

Fig. 14. Self protection principle of the thread coupling against the self loosening while vibrations and pulsations of forces and with the small friction moment on the face of the nut by means of separable (slightly decreased preloaded force) or non separable (assembly simplification) elastic disk washers.

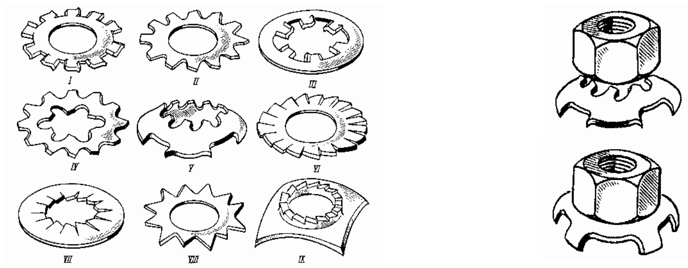

Fig. 15. Self protection principle of the thread coupling against the self loosening while vibrations and pulsations of forces by means of hard toothed washers with given elasticity obtained due to flat, cylindrical, conical or spherical of the washer shape with various configuration of supporting elements according to the shape and location in respect to washer's body (the effect of elasticity and effect of frictional – shaping fixing has been applied)

Self safety principle in springs is realised due to possible blocking of coils, disks or rings of the spring on each other or on the supporting plane (Fig. 16 a – e). For metal flexible clutches with damping, the functionality and safety of construction is assured by progressive characteristic of deformation (Fig 16 f) or by the strictly limited deformation (Fig.16 g).

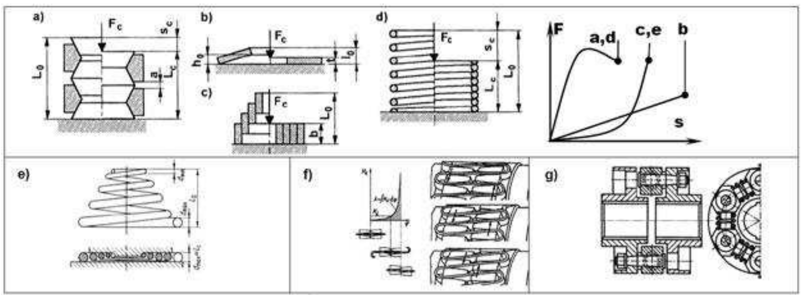

Fig.16. Self safety principle (adaptation against destruction) by means of excluding the flexible transmission of the loading stream as the result of: a) settlement on each other the internal rings of the disc spring; b) settlement of the single disc from the disc spring on the supporting plane; c)settlement of coils of the conical band in pressure telescope spring on the supporting plane; d) blocking of the wire coils of the cylindrical helical pressure spring as the result of static loading action or pulse dynamic loading (vibrating phenomenon of the spring waving occurring due to the transmission of the several compressed coils from one to the other end of the spring) f), g) metal springs of the flexible clutches with the advantageous characteristic obtained as the result of shortening the bending arms or implementation the rigid loading limitations [12].

In dischargeable friction disc clutches applied in vehicles, wear compensation of lining (self adaptation principle) [12] is assured by the cut "force–constant" disk springs. In frictional safety clutches the elastic switch of the limiting moment is applied. This switch is based on the wedge effect in order to obtain the self adaptation to loading (Fig. 17 a – c). Self adaptation principle can be presented as the example of the progressive springs in truck suspension with constant, independently on loading mass and vibrations frequency of the springing truck body (Fig. 17 d).

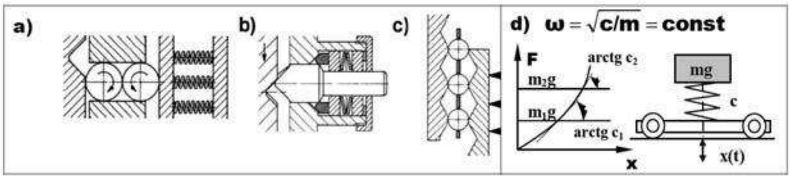

Fig. 17. Self adaptation principle for external loading in frictional overload clutch with switches: a) in the form of rolls; b) in the form of pin; c) in the form of ball; supported by springs and in the truck, with the constant vibration frequency of the truck body, independently of load mass (d)

Principle of the self reinforcement in turning moment has been applied in the frictional self locking system of axial forces and turning moments in worm wheel (Fig.18 a). In this case the pre loaded star disc springs pressured to the shaft and hub surface, have been applied. The reinforcement of the turning moment in variable – speed transmission unit is another example of this principle. In this case the spring clamp is realised by balls cooperating with the wedge groove of the unit hub [11]. In the changeable gear ratio unit (Fig. 18b) "***The self weakening principle"*** is realised by the change of the loading moment M_b. Another example of the self weakening principle is applied in the frictional overload clutch with the central pressure spring, where overloading moment makes disconnection of the clutch disks. This disconnection is caused as the result of balls' rotation in circumferential grooves located in disc.

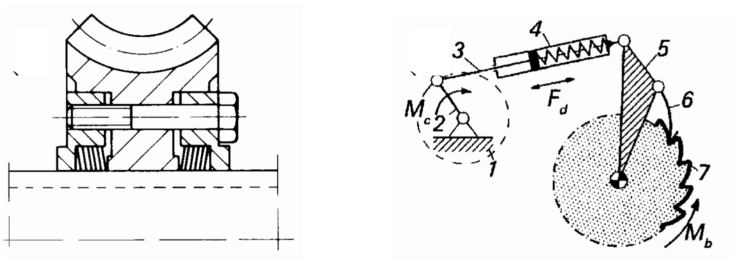

Fig. 18. The principle of the self reinforcement of the turning moment in worm wheel (a), and the principle of self weakening in the changeable gear ratio unit by means of automatic change of the link length (b).

The principle of the construction stability can be presented in buckling of the pressure helical springs (Fig.19). In this case the following principles are to be realised: – convex shaping of the coil envelope, assuring the step changeable of the coil lead in the medium zone; – application of the spring leading classic methods (in sleeve or on arbor); – division of the long spring into several shorter ones.

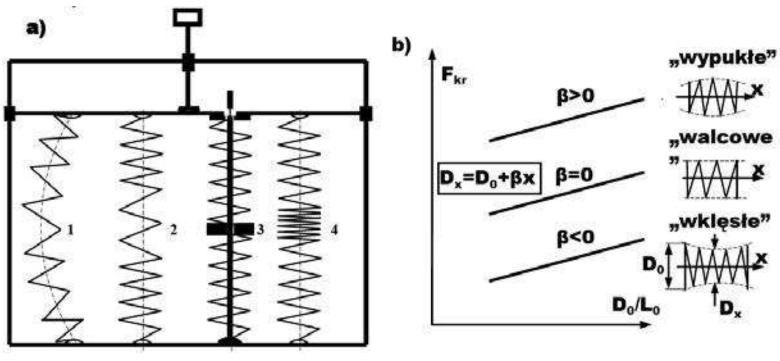

Fig. 19. Principle of the construction stability of pressure helical springs in buckling: a) increasing of resistance to buckling in cylindrical springs by: 2) step changeable inclination angle of coils in the medium zone; 3) division of the long spring into several shorter ones or special leading of the springs; 4) increasing the number of coils in the medium zone; b) increasing the resistance to buckling in special shape springs by means of convex shaping of the coil envelope

Principle of the dynamic bistability is applied in latches of high – speed machines (Fig. 20 a, b) and in frictional centrifugal clutches that are controlled by rotational speed: starting clutches and in clutches protecting the machine against overspeeding (Fig. 20 c, d).

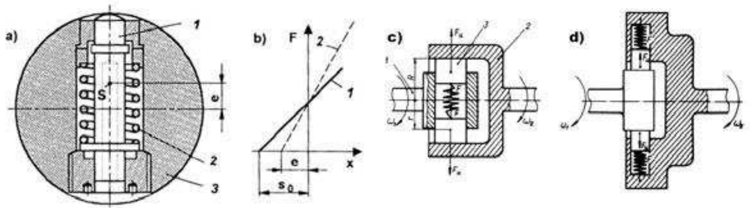

Fig. 20. Principle of the dynamic bistability by means of centrifugal latch link on the shaft of the turbine, the latch is predicted for the limit angular speed: a) construction of the latch (1 – connecting link, 2 – spring, 3 – shaft of the turbine, S – centre of gravity, e – distance between the centre of gravity and shaft axis); b) characteristics of: 1 – spring F = R(so + x); 2 – centrifugal force F0 = mω2(e + x); c) frictional centrifugal starting clutch; d) frictional centrifugal clutch protecting against machine overspeeding

Principle of the static bistability is applied in many mechanisms with elastic couplings such as: control mechanism of the frictional clutch, mechanism of the furniture door hinge, elastic lock of file box, elastic lock can cover (Fig. 21).

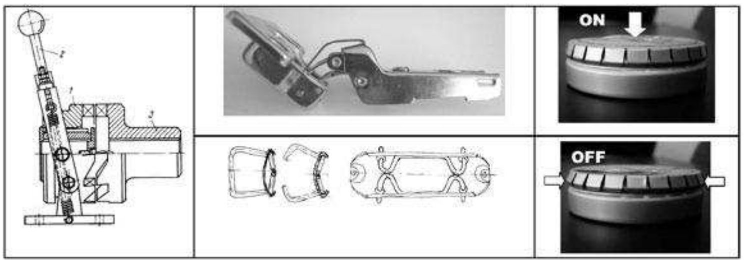

Fig. 21. Principle of the planned bistability with examples of the two position mechanisms: control of the clutch, furniture door hinge, lock of the file box, lock of the can cover.

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