System of Conceptual Design Based on Energy-Informational Model

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1 Introduction

As part of the science of engineering design a large number of design methods have been developed. Many methodologies have similar objectives, structure and inherit each other's design theory principles. Last research review is presented in [1]. Important conclusions that have been made in this work identified the following trends in engineering design:

1) the development of decision making intelligent systems of engineering design, based on a vast and complex knowledge bases
2) the development of ontology and semantic interoperability as the tool for engineers co-working.

In [2] there is a graph showing the value of design decisions at various stages of the product realization cycle and the availability of tools of human-computer interaction for designers (Figure 1).

As follows from this figure, only few tools are available to help designers make best decisions early in the product realization cycle, where they provide the greatest benefit.

In [1] 324 sources have been analyzed, and in [2] 80 journals and conference proceedings as well as about 20 R&D projects have been examined. This allows arguments to the following conclusions:

1) the creation of intelligent tools to support human-designer in the early stages of design is still relevant and useful task;
2) the creation of such tools need in creation and using of vast knowledge bases and ontological methods for fast and relevant search. It will provide engineers to work together in real or virtual space.

In [3] the classification of AI-based models of innovative design is discussed. It is shown that the methods using a systematic approach and knowledge base of the physical effects of different nature are the most effective ones. Additionally, this article lists several scientific schools involved in research related to the systematization and modeling of knowledge in natural sciences in order to develop intelligent systems for engineering design. The scientific school of Prof. Zaripov (Russia) is also mentioned there [4, 5, 6].

Therefore, in this paper we present A System for Conceptual Design Based on Energy-Informational Model (elaborated on base of Prof. Zaripov scientific school), consider the design of a knowledge base on the physical effects, which was elaborated on base of the domain ontology.

2 Theoretical Bases of Energy-Information Method of Analysis and Synthesis of Technical Solutions

2.1 Provisions of Non-Equilibrium Thermodynamics as the Theoretical Basis of Energy-Information Model of Chains of Different Physical Nature

Analysis of different systematic approaches to developing of knowledge bases for conceptual design [3], [12] showed that to systematize the knowledge we need in a method that combines:

- mathematical modeling of processes in the technical device (invariant to the physical nature of these processes)
- the possibility of operating with the physical effects and phenomena that are beyond the strict framework of the model,
- the possibility of structural description of the physical principle of the device operation.

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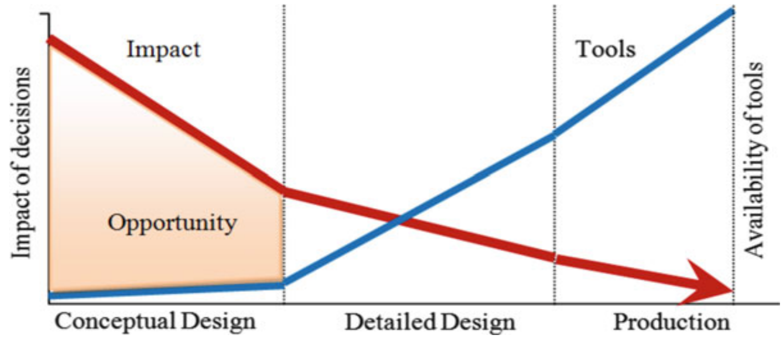


Fig. 1 Few tools are available to help designers make best decisions early in the product realization cycle, where they provide the greatest benefit.

Therefore, the basis of non-equilibrium thermodynamics was chosen for developing a conceptual model for systematization of knowledge on physical phenomena and effects for the synthesis of new technical devices (L. Onsager, S.R. de Groot and P. Mazur, I. Prigogine) [7, 8], as they allow you to obtain a complete system of transport equations and other laws, without opening their molecular mechanism. Additionally, you must expand the system of physical quantities and parameters used in the non-equilibrium thermodynamics like to the theory of electrical circuits, in order to use its methods of analysis and synthesis.

There are a number of phenomenological laws describing the irreversible processes in the form of direct proportional relationships. For example, Fourier's law of proportionality of the heat flux to the temperature gradient, or Fick's law which relates the diffusive flux to the concentration, Ohm's law of proportionality of electric current to the potential gradient, Newton's law of proportionality of the force of internal friction to the velocity gradient, the law of proportionality of the chemical reaction rate of the chemical potential gradient.

When two or more of these phenomena occur simultaneously, they are superposed on each other and cause the appearance of a new effect. For example, thermoelectricity occurs after imposing of thermal and electrical conductivity, thermal diffusion (Soret effect) - occurs after imposing of diffusion and heat conduction.

Thus, irreversible phenomena can be attributed to the following factors: temperature gradient, concentration gradient, the gradient of the electric potential, chemical potential, etc. In thermodynamics of non-equilibrium processes all of these factors are called thermodynamic forces and denoted by $(i = 1,\ 2,\ 3\ \ldots\ n)$. These forces cause the known irreversible phenomena: heat flux, diffusion current, chemical reactions, etc. All these are called fluxes and denoted by Ji $(i = 1, 2, 3 \ldots n)$.

In the most general case any force can cause any flux. For example, the diffusive flux can be caused by the presence of a concentration gradient or temperature gradient or electrical potential gradient. Therefore, any irreversible phenomenon can be written as a phenomenological relation:

$$J_i = \sum_{k=1}^{n} L_{ik} \cdot \chi_k \ (i = 1, 2, 3 \ldots, n), \tag{1}$$

Odds L_{ik} $(i = 1,\ 2,\ 3,\ \ldots\ n)$ are called phenomenological coefficients or transfer coefficients.

According to the expression (1) each flux is a linear function of all system thermodynamic forces. L_{ii} describe simple processes (electrical conductivity, thermal conductivity, diffusion, etc.). L_{ik} coefficients associated with superimposed phenomena (thermal diffusion, electrodiffusion, etc.) when $i \neq k$.

Fundamental Onsager reciprocal relation was derived for the phenomenological coefficients in the thermodynamics of nonequilibrium processes. It argues that the L_{ik} coefficient matrix is symmetric, i.e. cross ratios are equal:

$$L_{ik} = L_{ki}, \tag{2}$$

if the generalized fluxes J_i and forces χ_i appropriately selected.

Choosing of fluxes and forces is made by using the entropy balance equation:

$$dS = d_e S + d_i S, \tag{3}$$

where $d_e S$ - the entropy change due to its entering to the system from the environment $\left(d_e S = \frac{dQ}{dT}\right)$, dQ – is a heat, send to the system from the environment);

$d_i S$ - entropy change that occurs in the system (for reversible processes $d_i S = 0$ for irreversible - $d_i S > 0$).

Common forces, flows and coefficients for the physical effects of different physical nature can be defined via equations (1-3).

2.2 Energy-information model of circuits (EIMC) of various physical nature

Within EIMC the analysis and synthesis of the technical device expose therein the physical phenomenon of the particular nature (mechanical, thermal, electric, etc.) and the corresponding constructive elements of these phenomena. To describe these phenomena EIMC introduces the following concepts:

Axiom 1 *Circuit* of certain physical nature is the idealized material medium having certain geometrical dimensions and characterized by its physical constants inherent only to phenomena of given physical nature.

Axiom 2 *Values of circuit* of same physical nature vary in a wide range and is characterized an external influence on a circuit of a given physical nature and its corresponding reaction

Axiom 3 *Circuit parameters* characterize the relative unchangeability of a material medium in which physical processes occurs. Parameters are defined by their geometrical dimensions, physical and chemical properties of materials.

The most simple energy-information model uses the following values: P - action momentum; Q - reaction charge; U - action force; I - reaction rate; as well as parameters: R - resistance; $G = 1/R$ - conductance; C - capacitance; $W = 1/C$ - rigidity; L - inductance; $D = 1/L$ - deductance.

Axiom 4 *EIMC criteria* - a system of equations that reflect the links between values and parameters, and used to identify specific values and parameters in the circuits of different physical nature.

The quantities and parameters of EIMC are interrelated by six criteria (the most simple case):

- first criterion(energy) : $U \cdot I = N$ (N − power), (4)
- second criterion (invariable) : $I \cdot L = P$ or the derivative criterion : $P \cdot D = I$; (5)
- third criterion (invariable) : $U \cdot C = Q$ or the derivative criterion : $Q \cdot W = U$; (6)
- forth criterion (invariable) : $I \cdot R = U$ or the derivative criterion : $U \cdot G = I$; (7)
- fifth criterion (variable) : $U = dP/dt$ or the derivative criterion : $\int U dt = P$; (8)
- sixth criterion (variable) : $I = dQ/dt$ or the derivative criterion : $\int I dt = Q$; (9)

The authors identified the system of values (analogs of physical ones) and parameters (analogs of physical ones) to describe processes in circuits of different physical nature.

Axiom 5 Communication between circuits of different physical nature is going by means of physical and technical effects. *Physical&technical effect (PTE)* is the objectively existing causal link, reflecting the dependence between physical quantities, which could not be described through the only EIMC criteria.

Analytical expressions for the physical and technical effects (PTE) coefficients and the numerical values of these coefficients, as well as performance of technical constructions on base of these PTE determined from the results of theoretical and experimental researches in the field of physics and technology and available in various sources of scientific - technical information.

One should note the following features. One physical phenomenon could be provided as several PTE depending on what and in what proportion quantities and parameters of different physical nature are involved in the description of a physical phenomenon. For each effect input and output values should be clearly indicated.

3 Ontology for Modeling Design Knowledge on base of EIMC

All the variety of interactions between quantities and parameters can be described as a complex graph via energy-information models for describing of chains of different physical nature and parametric structural diagrams (Fig. 2). The figure shows the graph of physical and technical effects and intracircuit dependencies on n chains: mechanical, magnetic, electrical circuit and the i-th physical nature.

Ontology is often represented in the form of a semantic network graph with nodes reflecting concepts or individual objects, and the arcs reflecting the relationships or associations of these concepts [9].

From the viewpoint of ontological approach any physical effect (PTE), connecting two chains of i-th and j-th physical nature or parameter of the chain of i-th physical nature may be represented by tuples of type:

$$PTE = \left\{ H_{PTE}, B_{iin}, B_{j_{out}}, K, K_0, KM_{PTE}, D_{i_{in}}, D_{i_{out}}, EX_{n|1}^{N} \right\} \quad (10)$$

$$\Pi_i = \left\{ H_{\Pi}, B_{iin}, B_{j_{out}}, \Pi, \Pi_0, \Pi M_{\Pi}, D_{i_{in}}, D_{i_{out}}, EX_{n|1}^{N} \right\} \quad (11)$$

Tuples can be divided into 2 groups, where the first group is the description of the physical and technical effect:

H_{PTE}, H_{Π} - PTE or parameter name, text value,

$B_{i_{in}}$ - the i-th physical quantity,

$B_{i_{out}}$ - the j-th physical quantity,

K - PTE coefficient, reflects the dependence of the input and output value (the simplest case - a linear one $B_{j_{out}} = K_{ij} \cdot B_{i_{in}}$),

Π – parameter of the chain of i-th physical nature ($B_{i_{out}} = \Pi_i \cdot B_{i_{in}}$),

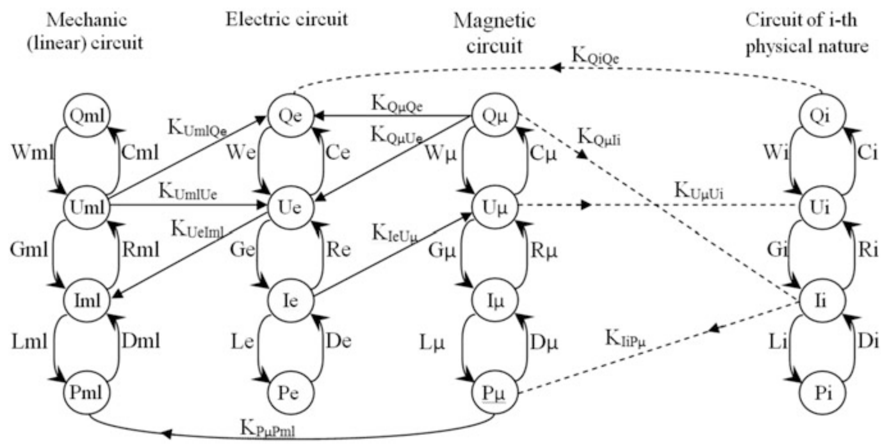


Fig. 2 Complex graph for n circuits of different physical nature.

K_0 or Π_0 - text variables, description of the K_{ij} coefficient or parameter and its physical formula through known physical constants, material parameters and its geometric dimension,

KM_{PTE} - mathematical model of PTE, which specifies the factors that influence the functional link of the physical input and output quantities, such as the influence of the fields (the value 1 or 0),

ΠM_{Π} - mathematical model of parameter (the value 1 or 0),

$D_{i_{in}}, D_{j_{out}}$ - variation range of input and output values. In order to ensure efficiency of the circuit it is necessary to observe the rules of crossing the ranges of output values for each of the previous effect and the input ones of each subsequent effect in the circuit: $D^n_{i_{in}} \cap D^{n-1}_{i_{out}}$ и $D^n_{j_{out}} \cap D^{n+1}_{j_{in}}$.

The second group - is a set of performance characteristics (with values from 0 to 10). The set is determined and filled by the group of subject area experts:

$EX^N_{n|1}$ - variables to calculate the performance of new synthesized physical operation principle. If we know values of operational characteristics of at least one type for all known PTEs in the synthesized circuit it is possible to calculate this operational characteristic for the entire device (entire circuit).

A complete correlation of output and input quantities of each in-circuit pair of PTEs is necessary and sufficient condition for the synthesis of the operation principle of technical device:

$$TD = \left(PTE_{i_1 j_1}, PTE_{i_2 j_2}, \ldots, PTE_{i_\Pi j_\Pi} \middle| PTE_{i_K j_K} \in DB \wedge j_k = i_{k+1} \wedge Q_{j_{k\ out}} = Q_{j_{k\ in}} \Big|_{k=1}^{\Pi}\right) \quad (12)$$

Thus technical device will be workable only if the corresponding quantities ranges overlap each other $D^n_{i\ in} \cap D^{n-1}_{i\ out}$

Operational characteristics of a technical device are computable only if each PTE in the circuit has calculated performance for the characteristic:

$$H_{nTD} = f(H_{nTD}, (\forall PTE \in TD)(\exists H_{nTD})) \quad (13)$$

The minimum set of values necessary for the successful synthesis procedure could be determined based on the PTE logical model and the above expressions

$$PTE = \{H_{PTE}, \mathrm{B_i}\, in, \mathrm{B_j}\, out, 1, 0, 0, (-\infty, +\infty), (-\infty, +\infty), \{0\}, 0, 0, 0, 0, 0\}$$

The sample PTE passport is shown in the Table 1.

4 Morphological synthesis of technical devices

Once the variety of operation principles is generated, an assessment of their performance is made and the best solutions are selected, engineer could assess the previous experience in designing of such devices and make some improvements. In order to do this he uses morphological approach.

Morphological investigation of the structure includes stage of analysis of array of known technical realizations of this structure as well as creation of structure's morphological matrix; and then goes the stage of new solutions

Table 1 The PTE sample passport

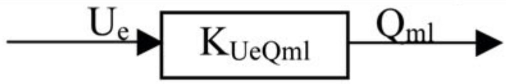
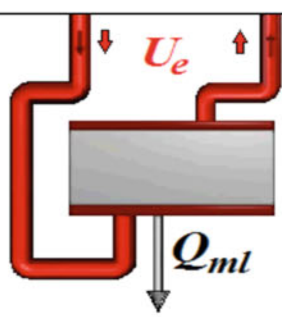
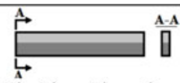
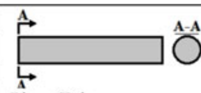
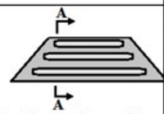
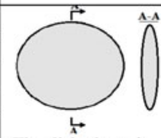
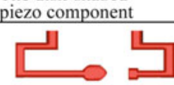
The reverse (converse) piezoelectric effect *(Name of the PTE)*	
 *(Parametric block diagram of the PTE)*	$Q_{ml} = K_{U_eQ_{ml}} \cdot U_e$ *(The PTE's formula, according to EIMC)*
$\frac{\Delta l}{L} = \varepsilon = d \cdot \mathrm{E}_e$ $\quad \varepsilon = \frac{Q_{ml}}{L};$ $\quad \mathrm{E}_e = \frac{U_e}{L};$ $\quad Q_{ml} = d \cdot U_e$ *(Phisical formulas of PTE description)*	
$K_{UeQ_{ml}} = d$ [m/V] *(PTE coefficient, reflects the dependence of the input and output value)*	
E_e - electric field strength [V/m] $\varepsilon = \Delta l / L$ - strain (relative length change), L - the thickness of the quartz plate [m] U_e – the electric potential difference [V] $Q_{ml} = \Delta l$ – the displacement of the faces quartz plate [m] d - the piezoelectric coefficient [C/N]=[m/V] *(Description of simbol in the formulas)*	$K_{U_eQ_{ml}} = d_{11} = 2{,}31 \cdot 10^{-12}$ [m/V] (quartz) $d_{33} = 16 \cdot 10^{-12}$ [m/V] $(LiNbO_3)$ $d_{33} = 100 \cdot 10^{-12}$ [m/V] $(BaTiO_3)$ *(Numerical values of physical constants and properties of materials)*
Sensitivity: $4 \cdot 10^{-10}$ [м/В] Price: 5 Reliability: $1 \cdot 10^{-5}$ [1/час] Error: 5 % Nonlineriaty: 3 %	Range: 0 ÷100 [В] Speed: $1 \cdot 10^{-6}$ [с] Losses: 0 Ecology: $1 \cdot 10^{-6}$ [Кг/час] Weight: 0,01 [Кг]
(PTE technical characteristics)	
S. Garcia, E. Kunitz, K. Sampson Piezoelectric effect and its applications // Retrieved 2013-01-24 from http://www.utwente.nl/ewi/tst/education/el-bach/mandt/extra/background/piezo01.pdf Jan Tichý et al. Fundamentals of Piezoelectric Sensorics // DOI 10.1007/978-3-540-68427-5 // Springer-Verlag Berlin Heidelberg 2010 Gautschi, G. (2002). Piezoelectric sensorics. Springer Berlin, Heidelberg, New York. *(Bibliografy of PTE)*	
 *(Figure of PTE technical realization)*	The reverse piezoelectric effect: the internal generation of a mechanical strain resulting from an applied electrical field The amount of deformation of the crystal varies linearly with changes in the field value. Inverse piezoelectric effect is used to measure large or rapidly changing pressures, particularly for the study of ultrasonic vibrations; voltage that appears on the faces of the deformed crystal is amplified and then supplied to the measuring instruments. *(Description of PTE features)*

Table 2 The fragment of the morphological matrix of a physico-technical effect

Feature (sign)	Values of features					
Shapes of the Piezo compo-nents	 The Piezo Rectangle Plate	2 3 2 2 2 2	 The Piezo Bimorph Rectangle Plate	5 1 5 3 3 3	 Piezo Tube	1 4 3 5 5 5
	 The Piezo Plate with variable section on height	4 2 4 4 4 4	 The disk-shaped piezo component	3 5 1 1 1 1	Sensitivity Price Liability Accuracy Non-linearity Range	
Conduc-ting electrode s	 Thick-film elec-trodes are applied to the piezo ceramic by screen printing technology.	2 1 1 1 1 2	 Thin-film electrodes are applied to the ceramic using modern PVD processes (sput-tering).	1 2 2 2 2 1	Sensitivity Price Liability Accuracy Non-linearity Range	
Piezo-electric materials	Natural monocrys-talline materials: Quartz, Tourmaline and Rochelle salt	1 3 3 1 1 1	Monolithic piezoelec-tric ceramics: $BaTiO_3$, Zirconate titanate (PZT),	3 1 1 3 3 3	Sensitivity Price Liability Accuracy Non-linearity Range	

Choice of one or several optimal technical solutions according to totality of their performance data.

synthesis according to morphological matrix and choice of optimal solutions according to field-performance data [10]. The authors have suggested to elaborate morphological matrixes not for a device in whole but for specific parameters or physico-technical effects, which make up the principle of operation.

The totality of existing and imaginary constructive realizations of each parameter or PTE make a morphological set. Finiteness of the set is stipulated by finiteness of human knowledge and by restrictions made by input circuit. Morphological set of each circuit parameter or PTE is being in evolution state. Any new constructive realization, new technology or new materials replenish this set. Advantage of using such matrix is that it enables to formalize the process of searching the best constructive realization of PTE on morphological set. An example of morphological matrix of a physico-technical effect is given in Table 2.

Stage of selecting of constructive realizations from morphological matrix is called a morphological synthesis, it includes the following actions:

Evaluation of all variants available in morphological matrix according to totality of performance data.

Choice of one or several optimal technical solutions according to totality of their performance data.

5 Comparing TIPS, SAPB and EIMC

In this article, we have discussed only the basic principles of the conceptual design based on energy-information model. Architecture of automated system for synthesis of new technical solutions is given in [5, 6, 11].

This section presents results of the systematic comparative analysis of the proposed conceptual design methodology with the one discussed in [12], presenting comparative analysis of the theory of Inventive Problem Solving and the systematic approach of Pahl and Beitz. Results are shown in Table 3. The aspects for the comparison have been selected to cover the task clarification and conceptual design stages of the design process.

Table 3 TIPS vs SAPB vs EIMC.

Aspect	TIPS	SAPB	EIMC
Scope	Emphasis on Inventive tasks and challenges of components design	Entire design process. Simple and difficult problems of systems design	Emphasis on Inventive tasks and challenges of components design
Task clarification	Laws of engineering systems evolution	General procedures	Laws of nonequilibrium thermodynamics, Onsager's theory.
Problem formulation	Identification of physical contradiction	Abstraction of essential problem	Setting of input and output values, performance coefficients
Systematic methods for solutions generating	Functions coupled to physical effects and examples of Standards Principles	Functions coupled to physical effects. Design catalogues	1) PTE catalogues are added with a set of performance characteristics, that allows you to organize the choice of solutions to aggregate performance 2) Each PTE has morphological matrix of variety of its technical implementations. It allows you to consistently improve the founded solution
Solution space	Focused - only "promising" directions are followed Minimal change of system	Large - "all" possible solutions considered	Solutions are ranked according to the aggregate performance, it allows you to select the best solutions
Product models	S-Field model	Design specification Function structure Concept (organ structure) Component structure	EIMC - energy-informational model of chains of different physical nature
Knowledge bases	Effects Patents Principles Laws of engineering systems evolution	Effects Design catalogues Engineering knowledge	PTE and morphological matrices for each PTE. Patents are grouped in a narrow class of technical devices and after grouped by the identified methods to improve performance
Learning time	Long time to learn	Short time to learn	Average time to learn
Computer support	Commercial	Research prototypes	Software Intellect-Pro - research prototypes

6 Conclusion

Analysis of the table shows that there are several differences of EIMC from other theories:

1) A description of each physical effect is formalized into a passport and morpho-logical matrix of possible technical implementations of this effect. It increases the number of synthesized technical solutions in several times.
2) The synthesis results can be ranged further due to preliminary expert assessment of performance characteristics. Thus each result can be assessed on the whole vector of performance characteristics, which is impossible in TIPS and SAPB.
3) Unlike TIPS EIMC has rigorous physical principles of nonequilibrium thermo-dynamics as the basis.

Thus, we can assume that these three methodologies can complement each other and lead to better solutions.

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