Machine Elements – Revision and Outlook for Design Education

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Abstract

Technical Systems (TS) are products intended to perform a task. Machine elements (ME) are technical systems of the two (of four) lower complexity levels, mostly mechanical engineering items. The literature presents loosely classified listings, but hydraulic, thermal or control elements usually do not appear.

The dominating TS-internal process concerns energy, characterized by a static and a dynamic property. ME carry functions, and have active connections to other constructional parts. A systematic classification of ME according to functions is presented. Systematic classification and variation assists creativity, and can produce many hundreds of alternatives, but increases demands for suitable selection and evaluation.

1. Introduction – General Context

Machine Elements has long been a staple subject for mechanical engineering education, and an extensive literature exists, e.g. [1,2,3,4]. Nevertheless, there is a general lack of a systematic classification. The literature presents partly-ordered listings, often with examples of existing machine elements (ME), and extensive engineering science analysis, with little attempt at revealing the underlying principles of action, i.e. understanding how they work and what properties they possess. After the Grinter Report [5], and with the development of digital computers, the tendency has been to neglect the examples, and to emphasize the analytical methods.

For many years it has been recognized that the curriculum changes introduced in the 1960's, as a result of the Grinter Report [5], were in some ways counter-productive. Quoting from Grinter (Appendix): 'The Committee considers that scientifically oriented engineering curricula are essential to achieve these ends and recommends the following means of implementation.' This major report then recommended ten 'means of implementation' (something helpful in achieving a desired end, Merriam-Webster Dictionary) of which the third is interesting in the context of this paper, it reads:

'3. *An integrated study of engineering analysis, design, and engineering systems for professional background, planned and carried out to stimulate creative and imaginative thinking, and making full use of the basic and engineering sciences.*' [5]

Scientists can usefully specialize in a small region

of the forefront of knowledge [6]. Engineers need a wide range of existing recorded information and knowledge [7], and need to know (as tacit, internalized knowledge [7a]) the contexts and relationships (a) among the items of knowledge, and (b) the relevance to society, culture, economics, politics, the quality of life, etc. Engineering is not just 'applied science', it has many other tasks and responsibilities, including societal, economic, law-related, innovative, management and coordinating functions [7]. Even in its technical aspects, engineering needs information that is not available or is even incapable of formulation in scientific terms [8,9]. Among other attributes, engineering is a reflective activity [10,10a]. A task for engineers is to provide the basis for making useful products, i.e. goods and services – summarized as designing. Problem solving alone is not enough. Designing has its own procedures, of which problem solving (see figure 1) is a sub-set. Problem solving includes analysing (at a verbal conceptual level in operations Op-H3.1 and Op-H3.3, and also using engineering sciences in operation Op-H3.3), synthesizing (in operation Op-H3.2), judging (Op-H3.3), representing and communicating (in words, diagrams, pictures, symbols, mathematics, gestures, etc., Op-H3.4), verifying and checking (Op-H3.6), and handling information (Op-H3.5).

Designing is not fully predictable. Nevertheless, procedures and methods for design engineering can be proposed, and related to ways of modeling systems. The needs to learn such design procedures in a more formalized way, especially to enhance creativity, have been discussed, e.g. [10,11].

Technical Systems (the subjects of design engineering) are tangible products of an enterprise that have a substantial engineering content, and that are intended to be used (as operators of a transformation process, figure 2) to perform a given task, a purpose function [12]. Four degrees of complexity have been defined [13], compare figure 3:

- *Complexity level IV – plant:* composed of technical systems of lower complexity;
- *Complexity level III – self-contained functioning system (machine):* complete assemblies (TS) that can perform a task (TP), e.g. a lathe that can be used to cut rotational workpieces;
- *Complexity level II – sub-system:* sub-assemblies of the parts, as intermediate stages of assembly (shafts with gear wheels, keys, bearings, etc.);

Figure 1 Problem Solving (Adapted from [15])

Figure 2 General Model of a Transformation System [15]

assembly groups of different complexity (the saddle, tailstock or headstock of a lathe); composite machine elements (rolling contact bearing, coupling, etc.); modules to be assembled in various configurations on a platform to supply functioning systems of different functionality;

- *Complexity level I – constructional part*: represent the lowest degree of complexity, mainly simple parts that are not normally capable of further disassembly, but that can usually only be subdivided by destroying the part (screws, nuts, wedges, shafts, washers, filters, electrical condensers, resistors, operational amplifiers), simple machine elements.

2. Machine Elements – General

As the subject of Machine Elements has grown into the curriculum by long tradition, it is mainly the purely mechanical elements that have been adopted, and they have been retained in the canon even if they have become somewhat obsolete.

Machine elements are conventionally defined as technical systems of lower complexity (levels I and II) that are frequently used as known and proven solutions for functions in technical systems. They are mostly regarded as mechanical engineering items [1,2,3,4] such

Level of Complexity	Technical System	Characteristic	Examples
I (simplest)	Constructional part	Elemental system, usually produced without assembly operations -- appears in parts list	Bolt, shaft, bearing sleeve, spring, washer
II	Group, mechanism, sub-assembly	Simple system consisting of constructional parts that can fulfill some higher functions	Gear box, hydraulic drive, spindle head, brake unit, clutch, shaft coupling
III	Machine, apparatus, device, equipment	System that consists of sub-assemblies and constructional elements (components) that together perform a closed function	Lathe, motor vehicle, electric motor, crane, kitchen machine
IV	Plant, equipment, complex machine unit	Complicated system that fulfills a number of functions, that consists of machines, sub-assemblies, groups and constructional parts, and that constitute a spatial and functional unity	Hardening plant, machine transfer line, factory equipment, refinery, underground transportation system

Figure 3 Technical Systems Classified by Complexity [15]

as individual constructional parts (e.g. shafts – level I), or assembly groups, sub-assemblies or mechanisms (e.g. rolling contact bearings, couplings, brakes, power transmission units – level II). The literature usually presents machine elements in a loosely classified listing, with examples of construction, and details of analysis according to the engineering sciences.

In the conventional literature, such mechanical principles as (static or dynamic) hydraulic, thermal or control elements usually do not appear. Nevertheless, similarly recurring parts exist in other engineering disciplines, e.g. steel-reinforced concrete columns (civil engineering), distillation columns (chemical engineering), diodes (electronic engineering), etc. Proven elements are also used in naval architecture, aeronautical engineering, and other related fields. Most current ‘machines’ are not exclusively mechanical, they are hybrids reaching across the conventional boundaries

of engineering disciplines – especially embracing control sub-systems using electronics, e.g. mechatronics. A wider definition to include these parts is needed, e.g. as *design elements* [14]. And knowing about a wide range of such constructional parts is essential to designing engineers.

3. Machine Elements – Conceptual Analysis and Classification

The dominating TS-internal process concerns energy. Materials and information need energy for their processing. Each type of energy is characterized by (a) a static, ‘across’, tension property – a ‘state variable’, and (b) a dynamic, ‘through’, rate property – a ‘flow variable’, see figure 4. Power is the vector product of a state variable with a flow variable.

Forms of Energy	Typical Physical Quantities			
	State Variable (static, 'across' variable)	Flow Variable (dynamic, 'through' variable)	Power (= state x flow variables) $P = dW/dt$	Work $W = \int P \cdot dt$
Mechanical translational	force F	velocity $v = ds/dt$	$P = F \cdot ds/dt = F \cdot v$	$W = \int F \cdot v \cdot dt = \int F \cdot ds$
Mechanical rotational	torque $M = F \cdot r$	angular velocity $\omega = d\alpha/dt$	$P = M \cdot \omega = F \cdot d\alpha/dt$	$W = \int M \cdot \omega \cdot dt = \int M \cdot d\alpha$
Fluid	pressure $p = F/A$	volume flow rate $\dot{V} = dV/dt$ mass flow rate $\dot{m} = dm/dt$	$P = \Delta p \cdot dV/dt$ $P = \Delta p \cdot \dot{m} / \rho$	$W = \int \Delta p \cdot dV$ $W = \int \Delta p \cdot m \cdot dt / \rho = \int \Delta p \cdot dm / \rho$
Electrical	voltage U	electric current $I = dQ/dt$	$P = U \cdot I = U \cdot dQ/dt$	$W = \int U \cdot I \cdot dt = \int U \cdot dQ$
Thermal	temperature T	entropy $\dot{S} = dS/dt$	$P = \Delta T \cdot \dot{S} = \Delta T \cdot dS/dt$	$W = \int \Delta T \cdot S \cdot dt = \int \Delta T \cdot ds$

Figure 4 Forms of Energy and Quantities [16]

Machine elements, redefined as *design elements* [14], are carriers of a (simple or more complex) function, have active connections (action locations) to other constructional parts of a working technical system, and provide connections among the action locations on each constructional part. An elemental organ consists of a pairing of action locations on two interacting constructional parts. Design elements are *organisms*. According to Weber [14], the verbs of their function (i.e. as flows) are mainly (1) transmit, (2) reduce/increase, (3) connect/disconnect, (4) store, (5) divide/unite, (6) transform, (7) distribute/combine, (8) distribute/collect, (9) separate/mix, and many others.

Engineering Design Science [13] recognizes four

kinds of transformation processes that change the properties of an operand: (A) processing to change structure, (B) manufacturing to change form, (C) transporting to change location, and (D) storing to change the time coordinate. These can be applied to four kinds of operands: (a) materials, (b) energy, (c) information/signals, and (d) humans and other living things (a special kind of material), giving 16 ‘pure’ transformations – and many more combinations. Operand (d), consisting of humans and other living things, is only applicable to the purpose of technical systems of complexity levels III and IV. Figure 5 shows how some of the verbs used by Weber relate to transformations of various kinds of operands.

TRANSFORMATION PROCESS (TrfP)		TRANSFORMATION			
		of structure	of form	of space coordinate	of time coordinate
		PROCESSING	MANUFACTURING	TRANSPORTING	STORING
OPERAND	Material M	M convert (process)	M transform (form, shape)	M transport	M store
	e.g.	iron ore --> steel	scantling --> workpiece	workpiece in storage bin -- wp on assembly line	workpiece in storage bin
	Energy E	E convert	E transform	E transport	E store
	e.g.	hydraulic --> electrical	50 000 V --> 220 V	power station --> consumer	in accumulator (battery, spring)
	Information I	I convert	I transform (translate)	I transport	I store
	e.g.	graphical --> digital	German text --> English	news sender --> receiver	speech on magnetic tape
	Human (animal) Hu (L)	Hu convert	Hu transform	Hu transport	Hu store
	e.g.	sick --> healthy	natural hand --> prosthesis	in London --> in Toronto	at home (in bed)
Typical verbs of operand transformation or of TS-internal function		convert, rectify, oscillate, process	enlarge increase, reduce connect, separate join, divide collect, diffuse combine, dissipate connect, interrupt couple, disconnect emit, absorb manufacture produce	conduct, isolate guide, release	store, retrieve hold, release keep, reject

Figure 5 Basic Classification of Transformation Processes and Technical Processes [15]

Comparing [14] with [13]: (4) ‘store’ is a transformation in *time*; (1) ‘transmit’ is a transformation in *location*, and is often a special case of ‘reduce/increase’; (3) ‘connect/disconnect’ is a special case of ‘transmit’; (2) ‘reduce/increase’ is a special case of ‘transform’, from one form to the same form; (6) ‘transform’ is a transformation of *form*; (5) ‘divide/unite’ is a transformation of *structure*. (2) ‘reduce/increase’ can be accomplished by serial application of two ‘transform’ operations, e.g. mechanical rotation to hydrodynamic

flow to mechanical rotation, as in fluid couplings.

A systematic classification of design elements (in general) according to functions (augmented from [14]) is shown in figures 6 and 7. More extensive classifications may become too complex for human searching (compare design catalogs [15,16,17]), and may be better implemented in computer-resident form, e.g. using hypermedia [18]. Such a structure of information, adapted to mechanical couplings, may show many dimensions, see figure 8. Energy transfer (in such coup-

Forms of Energy	'Function' Verbs <i>Verbs of TP operand transformation, or of TS-internal function</i>			
	transmit	reduce/increase	connect/disconnect	store
Mechanical translational	rods, links, cables, belts, chains, connection elements (e.g. connecting rod), guidances, ...	levers, wedges, pistons, ...	ratchet mechanisms, traction couplings, mechanical flip-flops, ...	springs ('static' strain energy), counter-weights ('static' potential energy), inertia masses ('dynamic' kinetic energy), ...
Mechanical rotational	shafts, keys, splines, serrations, cotters, clamp connections, force and shrink fits, couplings, bearings (sliding, rolling), guides, ...	gears, belts, timing belts, chains, friction drives, flat and vee belts, ...	clutches, brakes, ...	torsion springs ('static'), flywheels ('dynamic'), ...
Hydrostatic Pneumatic	pipes, tubes, fittings, ...		valves, ...	pressure vessels, hydraulic accumulators, ...
Hydrodynamic Aerodynamic	vanes, guides, wings, ...	diffusers, ...	valves, ...	
Electrical	wires, fuses, ...	transformers	insulation, switches, ...	capacitors ('static'), accumulators, inductors ('dynamic'), ...
Electronic (analog, digital)	conductors, ...	amplifiers, attenuators, chokes, inductors, ...	transistors, diodes, ...	magnetic memory, ...
Thermostatic	heat pipes, cooling fins, ...	heat exchangers, ...	thermal insulation, ...	heat storage units (fire-brick)
Thermodynamic	combustors, spray nozzles, ...	heat pumps, ...	diverter channels, ...	
NOTE:	special case of 'reduce/increase' if value and form of output = input	special case of 'transform' if form of output = input	addition to 'transmit'	

Figure 6 Classification of Design Elements for some 'Function' Verbs [16]

lings, and elsewhere) mainly takes place at action location pairings (organs) by different manifestations of closure as shown in figure 9, and these form an *information unit* in the hypermedia classification system. Consequently, various existing couplings can be classified in a matrix as shown in figure 10. A search for existing coupling principles according to various criteria is thus possible.

4. Machine Elements – Synthesis Considerations

It is also possible (and was demonstrated [19]) to search out new principles, and to use systematic variation, especially of active organs and constructional details. According to check lists [15,16], variations can be: (a) of form, (b) of position or orientation, (c) of number, (d) of size/dimension, (e) of sequence or arrangement, (f) of connecting structure, (g) of connection type, (h) of contact type, (i) of mobility, or (j) of constraint. Examples of these variations are shown in figure 11. Many patents have been issued on this basis.

Such systematic classification and variation obviously assists (personal, individual and group)

creativity, they can produce many hundreds to thousands of possible alternatives. These methods obviously also increase demands for suitable selection and evaluation of alternatives to find those combinations that show technical and economic merit. Capability of a designer to use such systematic variation is probably also essential for the New Century.

Engineering education should obviously include education about machine (design) elements. Ideally, this should involve a survey of possible manifestations of all kinds of design elements, a consideration of design processes for such elements, and indications about analytical investigations of their properties. Too much emphasis has been placed on mathematical modeling and analysis, the needs for design are urgent.

When designing a new technical system (i.e. not just minor modifications to an existing device), the first priority for the engineering designer should usually be to establish the purpose of the device, what it should be used for [15]. The second step should be to establish (with possible alternatives) what outputs are needed from the technical system. The third step should then be to establish (with alternatives) what the technical system should be capable of doing to produce the outputs [14],

Forms of Energy	Transform to:	Mechanical translational	Mechanical rotational	Hydrostatic Pneumatic	Hydrodynamic Aerodynamic	Electrical	Electronic	Thermostatic	Thermodynamic
Transform from:									
Mechanical translational		(see 'reduce/increase')	wheels, rack and pinion, slider-crank, motion screws	cylinder/piston		linear generators	linear transducers piezo, lvd, strain gage	linear brakes	reciprocating gas compressors
Mechanical rotational		wheels, rack and pinion, slider-crank, motion screws, cams	(see 'reduce/increase')	hydrostatic pumps	turbo-pumps	rotary generators	rotary transducers	rotary brakes	rotary gas compressors
Hydrostatic Pneumatic		cylinder/piston	hydrostatic motors	(see 'reduce/increase')			pressure sensors, specific gravity sensors		
Hydrodynamic Aerodynamic		water jet	turbines	pitot-static tubes, fluidic control units	(see 'reduce/increase')	magneto-hydrodynamic generator		throttles	
Electrical		linear motor, actuator, solenoid	rotary motor, rotary actuator	magneto-hydrodynamic pumps		(see 'reduce/increase')		electrical resistances	
Electronic		mecha-tronics	mecha-tronics				(see 'reduce/increase')		
Thermostatic		linear heat engines, combustion engines	rotary heat engines, combustion engines				heat sensors, temperature sensors	(see 'reduce/increase')	
Thermodynamic		turbojet engines, turboprop engines, ramjets	gas turbine engines						(see 'reduce/increase')

Figure 7 Classification of Design Elements for 'Function' Verb 'Transform' [16]

Figure 8 Machine Elements and Related Information [20]

	Type of Closure Principle		
	Form Closure		Friction or Force Closure R
	Rigid Contacts F	Flexible Contact E	
Iconic Representation			
Equation	$F_N = F$	$F_{el} = c \cdot \Delta_S$	$F_R = \mu_H \cdot F_2$
Types of Stress on Materials and Surfaces	Surface pressure, Hertz contact stresses, Sub-surface shear stresses	Surface pressure, Elastic/plastic deformation	Surface pressure, Surface shear stresses, Static friction (limited), Wear
Properties and Design Characteristics	With clearance: shock, plastic deformation. Without clearance: pre-load stresses, high precision of force transmission	Relative motion, Rebound (elastic strain energy), Vibrations, Damping, Compensates peaks of force application	Limited force transmission parallel to contact surface, Micro-movement at edge of contact (danger of fretting) Sliding when force exceeds static limit

Figure 9 Closure Principles as Classification Criteria for Machine Elements [20]

Figure 10 Classification of Couplings [20]

Variation of Form (Shape)

Variation of Position (Orientation)

-- in space

-- relative to other features

Variation of Number

Variation of Size (Dimension)

Variation of Sequence (Arrangement)

Variation of Connecting Structure

Variation of Connecting Type

rigid, articulated, elastic, plastic
fixed, releasable
re-usable, one-time use
material connection (e.g. welding, adhesive bonding)
form closure (e.g. interlocking)
force closure (e.g. magnetic, friction)

Variation of Contact Type

point (1, 2, 3, ...)
line (straight, curved)
area (flat, cylindrical, annular, conical, spherical)

Variation of Mobility

Variation of Constraint

Figure 11 Possibilities for Variation [17,18]]

how it should work, its mode of internal action. Some simulation may be applicable at this point. From this information, the engineering designer can establish with what (in principle, and with alternatives) the internal actions can be made to happen. This is where the principles of operation of typical machine elements is useful, and classes of machine elements can be chosen to make the device work. As a consequence, typical sizes can be established, usually by order-of-magnitude

estimations. Only when a sufficiently good layout (as general arrangement) has been developed in this way can better analytical tools be employed to verify the anticipated performance of the proposed technical system.

It follows that an encyclopedic knowledge of machine elements is useful in an early stage of design engineering, the full analysis only comes later. Should not the engineering curriculum, especially for machine elements, reflect this pattern of procedure in designing

[11,12,13]? And should not the engineering sciences (in their analytical emphasis) also take into account the need for an understanding of and 'feel' for the phenomena, with 'quick and dirty' estimations, developing assumptions for an improved analysis, as well as the full analytical treatment?

5. Closure

The subject of Machine Elements needs urgent revision to reach across the conventional boundaries among engineering disciplines, and to include the more recent elemental systems. A wide survey of design elements will enable our students to function by giving them the knowledge about designing using machine elements, combined with the tools to analyze problems as concepts. There is still a need to use mathematical analysis, mainly as a tool to estimate required dimensions, and as an evaluation tool. In this way we can bring engineering education into a state where the requirements for the new century can be met.

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