MACHINE ELEMENTS – INTEGRATION OF SOME PROPOSALS

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1. Introduction – General Context

Machine elements has long been a staple subject for mechanical engineering education, and an extensive literature exists, e.g. [Doughtie 1964, Faires 1965, Spotts 1985, Juvinall 1991]. Nevertheless, there is a general lack of a systematic classification, the literature presents partly-ordered listings, examples of existing machine elements, and extensive engineering science analysis, with little attempt at revealing the underlying principles. As the subject 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.

Technical Systems are products of an enterprise that have a substantial engineering content, and that are intended to be used (as operators of a transformation process, figure 1 [Hubka 1996]) to perform a given task, a purpose function [Hubka 2001]. Four degrees of complexity have been defined [Hubka 1996], compare figure 2:

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 (a lathe);

Complexity level II – sub-system: sub-assemblies of the parts, as intermediate stages of assembly (shafts with gear wheels, keys, bearings, etc. mounted); assembly groups of different complexity (the saddle, tailstock or headstock of a lathe), composite machine elements (rolling contact bearing, coupling, etc.);

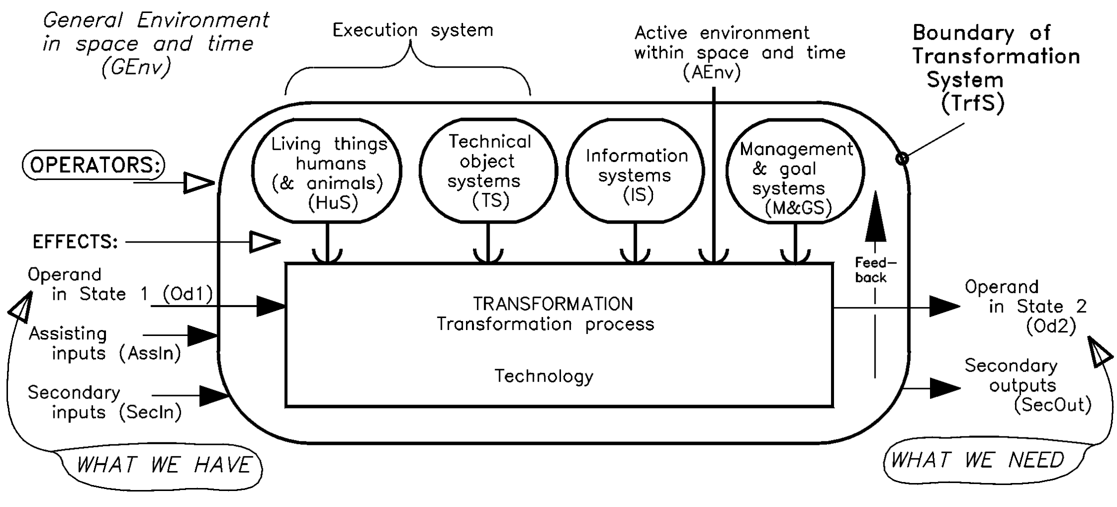

Figure 1. General Model of a Transformation System

Level of Complexity	Technical System	Characteristic	Examples
I (simplest)	Constructional part, component	Elementary 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 elements that can fulfill some higher functions	Gear box, hydraulic drive, spindle head, brake unit, clutch, shaft coupling
III	Machine, apparatus, device	System that consists of sub–assemblies and constructional elements (components, parts) 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 elements (components, parts), and that constitute a spatial and functional unity	Hardening plant, machine transfer line, factory equipment, refinery, underground transportation system

Each lower class is a constructional part for higher systems –– by creating (connective) relationships among them.

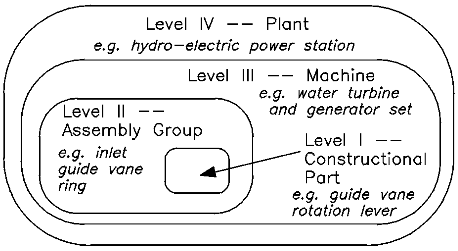

Figure 2. Technical Systems Classified by Complexity

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 sub-divided by destroying the part (screws, nuts, wedges, shafts, washers, electrical condensers, resistances), simple machine elements.

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. The literature usually presents machine elements in a loosely classified listing, with examples of construction, and details of analysis according to the engineering sciences. Such items 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.

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. A wider definition to include these parts is needed.

2. 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 3 [Weber 1997]. 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)	
Mechanical translational	force	F	velocity	$v = ds/dt$
Mechanical rotational	torque	$M = F.r$	angular velocity	$\omega = d\alpha/dt$
Fluid	pressure	$p = F/A$	volume flow rate	$\dot{V} = dV/dt$
			mass flow rate	$\dot{m} = dm/dt$
Electrical	voltage	U	electric current	$I = dQ/dt$
Thermal	temperature	T	entropy	$\dot{S} = dS/dt$

Figure 3. Forms of Energy and Quantities

Machine elements, redefined as *design elements* [Weber 1997], 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.* 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, etc.

Engineering Design Science [Hubka 1996] recognizes four transformation processes: (A) processing to change structure, (B) manufacturing to change form, (C) transporting to change location, and (D) storing to change the time coordinate; and these can be applied to four kinds of operands: (a) materials, (b) energy, (c) information / signals, and (d) humans and other living things, giving 16 'pure' transformations – and many more combinations.

The verbs of function can be characterized in this sense as: (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 also be accomplished by serial application of two 'transform' operations, e.g. mechanical rotation to hydrodynamic flow to mechanical rotation, as in fluid couplings and torque converters. A systematic classification of design elements (in general) according to functions (augmented from [Weber 1997]) is shown in figures 4 and 5.

More extensive classifications may become too complex for human searching (compare design catalogs [Roth 1995, Koller 1985, Ehrlenspiel 1995]), and may be better implemented in computer-resident form, e.g. using hypermedia [Birkhofer 1997]. Such a structure of information, adapted to mechanical couplings, may show many dimensions, see figure 6 (adapted from [Birkhofer 1997]). Energy transfer (in such couplings, and elsewhere) mainly takes place at action location pairings (organs) by different manifestations of closure as shown in figure 7 [Birkhofer 1997], 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 8 [Birkhofer 1997]. A search for existing coupling principles according to various criteria is thus possible. This procedure shows some similarity to a morphological matrix.

3. Machine Elements – Synthesis Considerations

It is also possible (and was demonstrated [Ehrlenspiel 1987]) to search out new principles, and to use systematic variation, especially of active organs and constructional details. According to check lists [Ehrlenspiel 1995, Koller 1985], 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 figures 9, 10, 11 and 12 [Ehrlenspiel 1987]. Many patents have been issued on this basis.

Forms of Energy	'Function' Verbs			
	transmit	reduce/increase	connect/ disconnect	store
Mechanical translational	rods, links, cables, belts, chains, ...	levers, wedges, pistons, ...	ratchet mechanisms, traction couplings, ...	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, chains, friction drives, ...	clutches, brakes, ...	springs, flywheels, ...
Hydrostatic	pipes, tubes, fittings, ...	diffusers, ...		pressure vessels, hydraulic accum– ulators, ...
Hydrodynamic	vanes, guides, wings, ...		valves, ...	
Electrical	wires, fuses, ...		insulation, switches, ...	capacitors, inductors, accumulators, ...
Electronic (analog, digital)	conductors, ...	amplifiers, attenuators, chokes, inductors, ...	transistors, diodes, ...	magnetic memory, ...
Thermostatic	heat pipes, cooling fins, ...	heat exchangers, ...	thermal insulation, ...	
Thermodynamic	combustors, spray nozzles, ...	heat pumps, ...	diverter channels, ...	
NOTE:	special case of 'reduce/increase'	special case of 'transform' (see figure Sp7–12)	addition to 'transmit'	

Figure 4. Classification of Design Elements for Some 'Function' Verbs

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.

4. 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.

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Forms of Energy — Transform from: / Transform to:	Mechanical translational	Mechanical rotational	Hydrostatic	Hydrodynamic	Electrical	Electronic	Thermostatic	Thermodynamic
Mechanical translational	(see 'reduce/ increase' in figure Sp7–11)	wheels, rack and pinion, slider–crank,	cylinder/ piston		linear generators	linear transducers (piezo, lvdt, strain gage	linear brakes	reciprocating gas compressors
Mechanical rotational	wheels, rack and pinion, slider–crank, motion screws	(see 'reduce/ increase' in figure Sp7–11)	hydrostatic pumps	turbo–pumps	rotary generators	rotary transducers	rotary brakes	rotary gas compressors
Hydrostatic	cylinder/ piston	hydrostatic motors	(see 'reduce/ increase' in figure Sp7–11)			pressure sensors, specific gravity sensors		
Hydrodynamic	water jet	turbines	pitot–static tubes, fluidic control units	(see 'reduce/ increase' in figure Sp7–11)	magneto–hydro–dynamic generators		throttles	
Electrical	linear motor, actuator, solenoid	rotary motor, rotary actuator	magneto–hydro–dynamic pumps		(see 'reduce/ increase' in figure Sp7–11)		electrical resistances	
Electronic	mechatronics	mechatronics				(see 'reduce/ increase' in figure Sp7–11)		
Thermostatic	linear heat engines, combustion engines	rotary heat engines, combustion engines				heat sensors, temperature sensors	(see 'reduce/ increase' in figure Sp7–11)	
Thermo–dynamic	turbojet engines, turboprop engines	gas turbine engines						(see 'reduce/ increase' in figure Sp7–11)

Figure 5. Classification of Design Elements for 'Function' Verb 'Transform'

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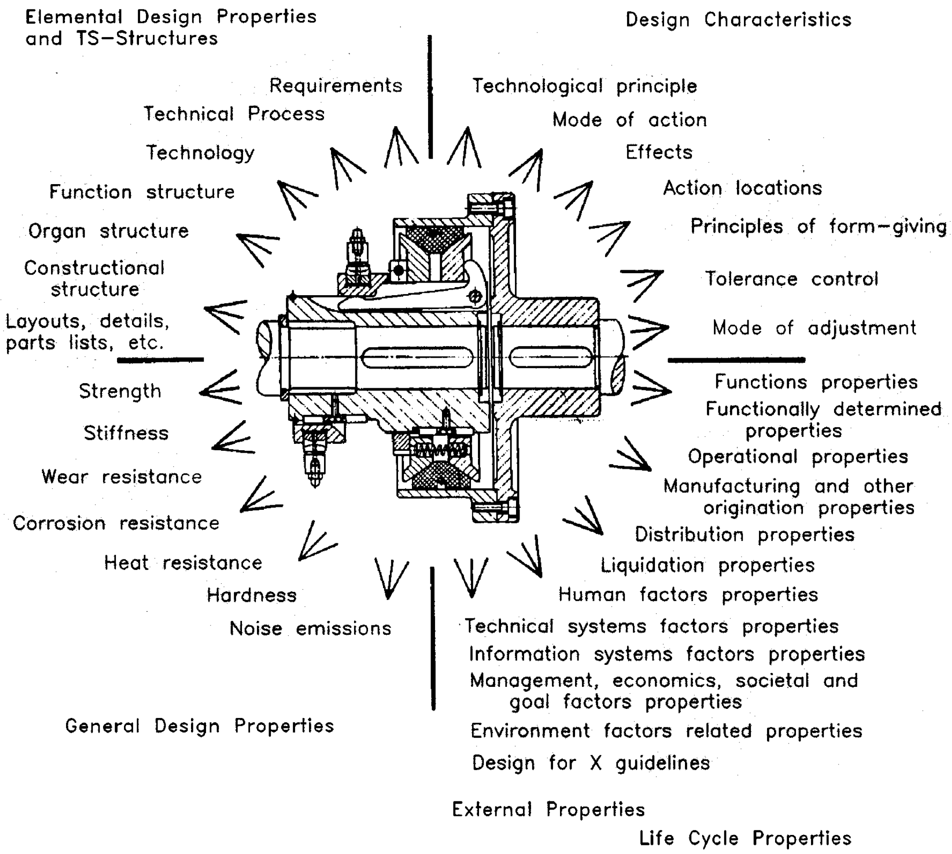


Figure 6. Machine Elements and Related Information

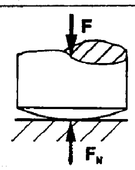
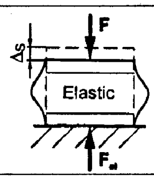
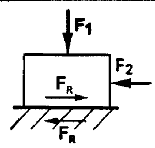
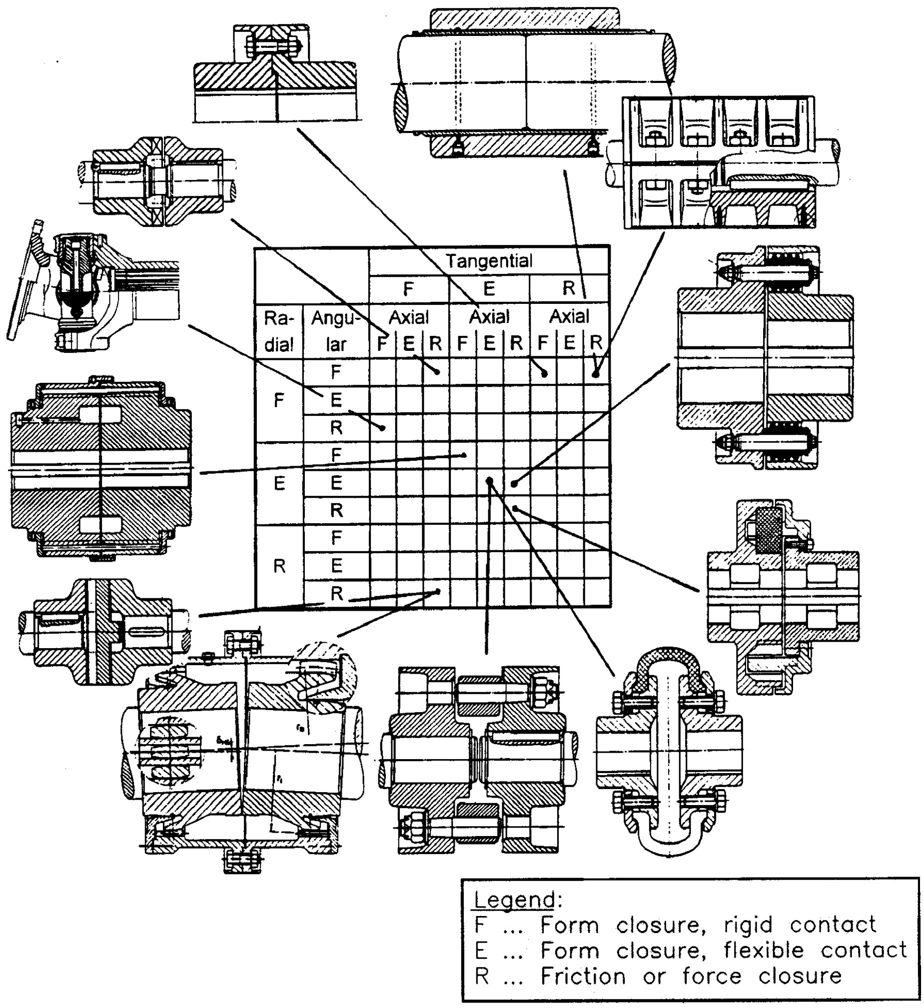
	Type of Closure Principle		
	Form Closure		Friction or Force Closure R
	Rigid Contacts F	Flexible Contact E	
Iconic Representation			
Equation	$F_N = F$	$F_{el} = c \cdot \Delta_s$	$F_R = \mu_H \cdot F_2$
Types of Stress on Materials and Surfaces	Surface pressure, Hertz contact stresses, Sub–surface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

Figure 7. Closure Principles as Classification Criteria for Machine Elements

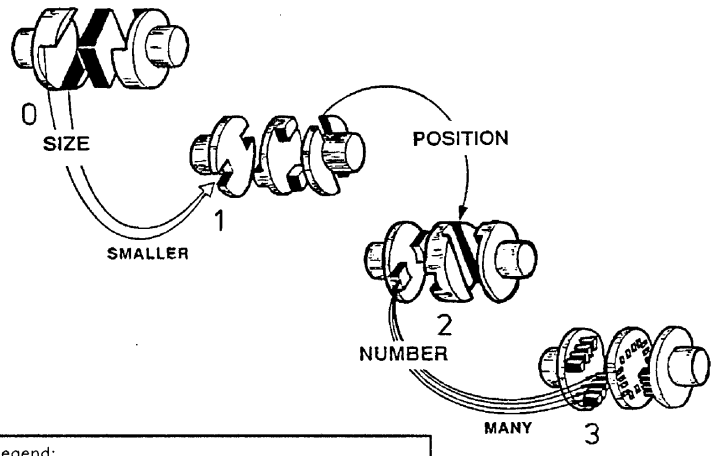


Types of Mis–Alignment:

Angular, intersecting axes
Parallel axes
Skew, non–intersecting angular axes
Axial displacement

Static, no substantial change during operation
Dynamic, substantial change of offset and/or angle during operation

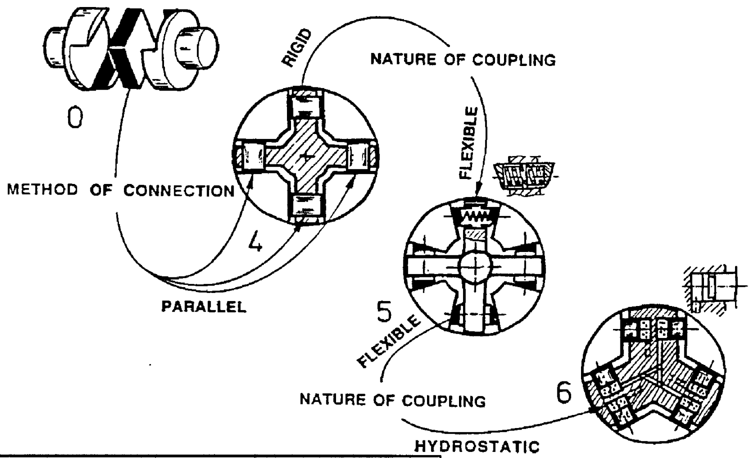
Figure 8. Classification of Couplings



Legend:
0 ... original Oldham coupling, action surfaces of two organs (left hub to slider, and slider to right hub) shown in black
1 ... change of size of transmission organs
2 ... change in position of slots and sliders
3 ... change in numbers of slots and sliders

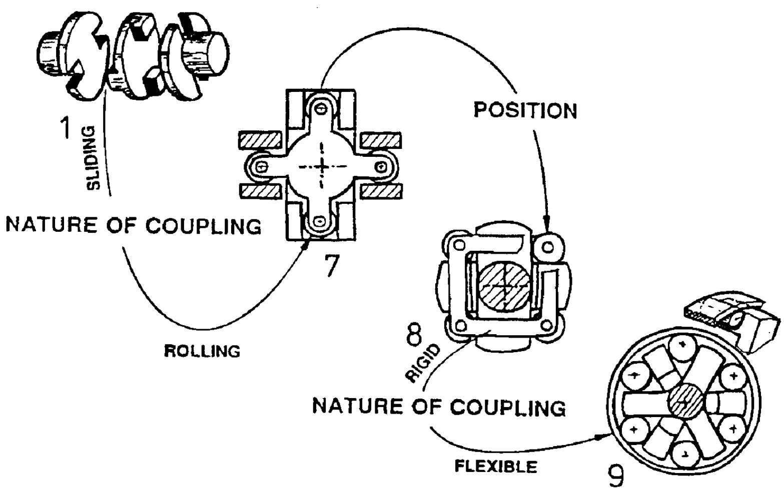
NOTE: Oldham couplings provide a rotational connection between two shafts and allow small angular mis-alignment.

Figure 9. Variations on an Oldham Coupling



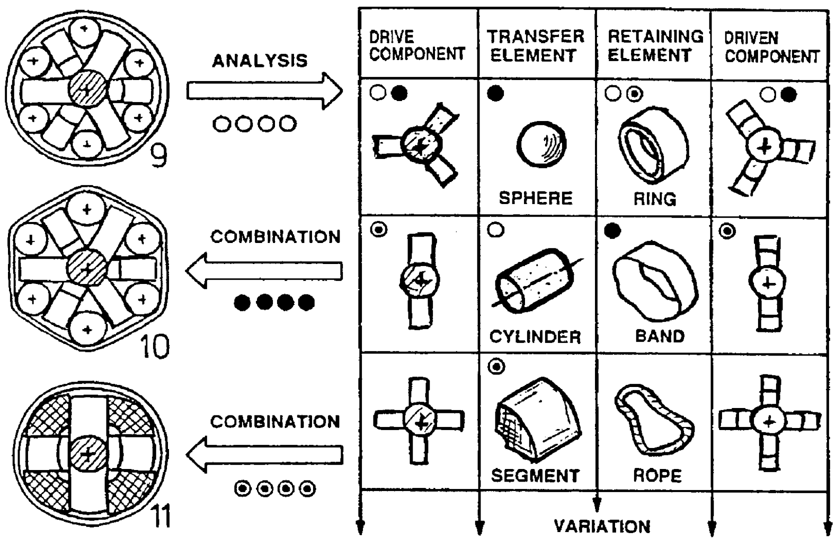
Legend:
0 ... original Oldham coupling, action surfaces of two organs (left hub to slider, and slider to right hub) shown in black
4 ... change in principle of connection – rigid 4-point star and slots
5 ... change in principle of connection – flexible 4-point star and slots
6 ... change in principle of connection – hydrostatic 3-point star and slots

Figure 10. Variations on an Oldham Coupling



Legend:
1 ... Oldham coupling, variant 1 from figure Sp7–16
7 ... change in principle of connection – rolling 4–point star and slots
8 ... change in principle of connection – rolling 4–point frame and sliders
9 ... change in principle of connection – flexible roller containment and 3–point star sliders

Figure 11. Variations on an Oldham Coupling



Legend:
9 ... Oldham coupling, variant 9 from figure Sp7–18
10 ... analysis of variant 10, new combination
11 ... analysis of variant 10, new combination

Figure 12. Variations on an Oldham Coupling

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