FUNCTION AND DESIGN OF MECHANICAL COMPONENTS IN MECHATRONIC SYSTEMS

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Abstract. *Mechatronic products, such as measuring and positioning systems, manipulators, assembly equipment, vehicles etc., are physically heterogeneous systems composed of physically separated mechanical, electrical, electromagnetic and electronic as well as sometimes hydraulic components, whose functions are linked with each other via an internal and dedicated data processing system.*
The growing complexity leads to new requirementsof the design process, not only on the system level, but also and particularly of the design of the mechanical components, the task of which is to provide mechanical integrity of the entire system (in all working conditions) and to realise the (mechanical) energy flow. Analysing mechatronic products, four typical functions are carried out by mechanical components:
1 They have to *guarantee relative positions of all components and their integrity* which are necessary to provide the secure functioning of all system elements. *Frames, fasteners and supporting elements realise this static function.*
2. Providing mechanical energy for movements and other operations.
3. Transferring and transforming mechanical energy.
4. Transferring forces with controlled stress and strain.
These basic functions provide a synthesis-oriented classification of mechanical elements supporting modular design as well as creating ideas by abstraction and systematisation.
For mechatronic purposes a new generation of mechanical components is required which is capable to be controlled and integrated into the control circuit. Such kind of smart mechanical elements are provided with a signal interface besides the mechanical interfaces for fastening and energy transmission. The paper gives a systematic approach and a new function-oriented classification of these elements.
The non-steady state ("dynamic") behaviour is a particularly important aspect in mechatronics. In this resepct, particularly the mechanical components of mechatronic systems are difficult to integrate into the mechantronic development process because their dynamic behaviour is by tradition only considered in much later stages and usually by means of physical/layout models opposed to abstract/ formal/behaviour-oriented models like in the other domains. Therefore, in the last section of this contribution an approach is presented which can help to establish appropriate simulation models of mechanical (and, in fact, also other) components which, in an ideal case, is integrated into the classification of the mechanical elements.

***Keywords**: Mechatronics, Mechanical Elements, Functional Classification, Modelling*

1. INTRODUCTION

Mechatronic products, such as measuring and positioning systems, electronically controlled manipulators, assembly equipment, vehicles etc., are compound systems which consist of physically separated mechanical, electrical, electromagnetic and electronic as well as sometimes hydraulic components, whose functions are linked with each other via an internal and dedicated data processing system. There are also many examples where optical principles are applied in the functioning.

The engineering tasks which are to be performed by any mechatronic system are in most cases basically energy or material flows, with the information flow additionally implied in order to control and optimise the system behaviour. "Optimising the system behaviour" can mean adaptations of the basic ("static") transfer characteristics, but more often addresses the non-steady state ("dynamic") behaviour of the system.

Therefore, enabling the energy or material flow in the best possible way, allowing for any external or internal disruptive factors or interferences, is the first concern when designing a mechatronic system. But additionally it is necessary to design and integrate actuator elements modifying the internal processes and sensor elements supplying information about the status and progress, both of the processes and the system elements (Isermann 1996, Parkin 2000, Janocha 2007).

The growing complexity of the products in question has consequences for the course to be taken in their design. This applies to the system level (see e.g. VDI 2206), but also to the component level where new requirements also on the design of the mechanical components are posed, the task of which is to provide mechanical integrity of the entire system (in all working conditions) and to realise the (mechanical) energy flow.

Another point is how to realise early modelling and simulation of the dynamic behaviour of mechanical components within the context of the mechatronic system in such a way that it is consistent with corresponding models used in other domains (e.g. electrical and control engineering); a part of the problem here lies with the fact that in the mechanical domain dynamic modelling/simulation is usually considered only in much later stages of the development process and performed rather by means of physical/layout models instead of abstract/ formal/behaviour-oriented models used in other domains.

2. STRUCTURE OF MECHATRONIC SYSTEMS

To illustrate the focus of this contribution, at first an existing mechatronic system is analysed. The equipment shown in Fig. 1 is a computer-controlled manipulating set-up used to centre a single lens or a combination of lenses with high accuracy.

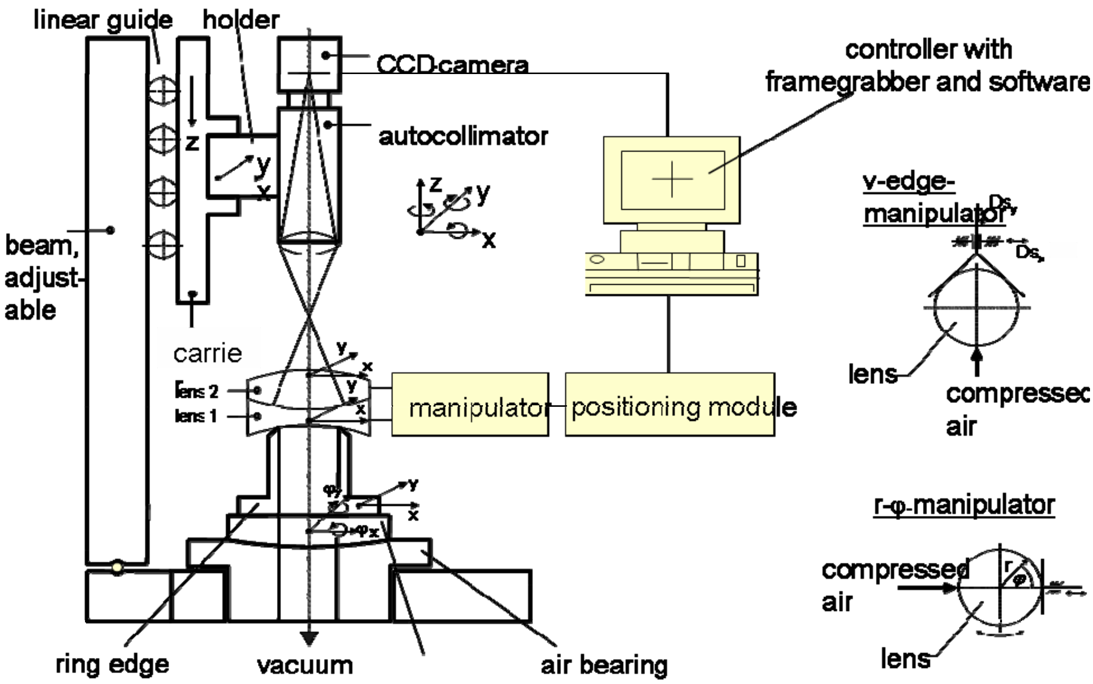

Figure 1. Adjustment system used for centring optical lenses

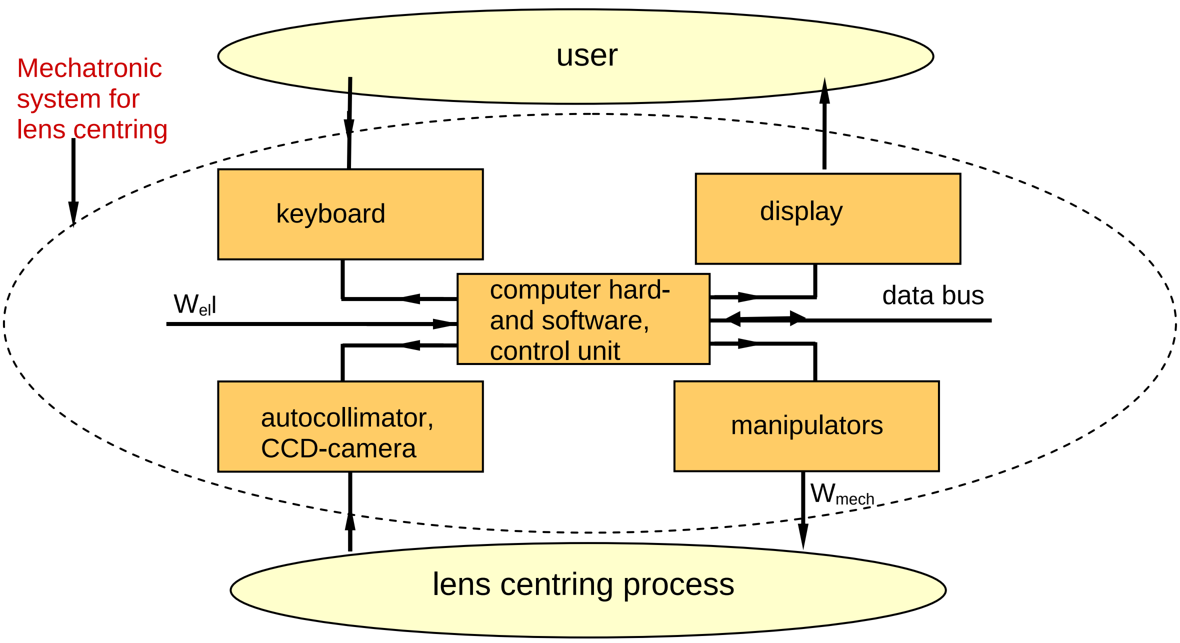

Figure 2: Function structure of the adjustment system in Fig.1.
W_{el} – electrical energy, W_{mech} – mechanical energy

The condition for centring is that the optical axis of the lense(s) is congruent with the axis of the rotating high quality air bearing. The centring state is detected by the autocollimator and the CCD camera, applying the high sensitivity of a reflected target by the lens surfaces. The necessary displacement of the lenses is generated by a positioning module and a manipulator. The figure shows two variants of the manipulator, both able to realise the centring process, however, each with their own adjustment algorithm: The v-edge-manipulator requires a positioning unit with two linear movements, while the r-φ-manipulator uses the rotation of the bearing and needs one radially acting linear drive.

Analysing and abstracting from the description of the equipment in Fig.1 leads to the block diagram of this mechatronic system (Fig. 2) which represents a general representation of the system's functional structure well-known in literature (Isermann 1996, Janocha 2007). On this abstraction level only the manipulators appear to carry out mechanical functions (realising the mechanical energy flow W_{mech}). However, in the real system we find a variety of components, belonging to the mechanical domain of the mechatronic system. For embodiment as well as for conceptual design it is important to know the sub-functions of those system elements.

3. FUNCTIONS OF MECHANICAL COMPONENTS IN MECHATRONIC SYSTEMS

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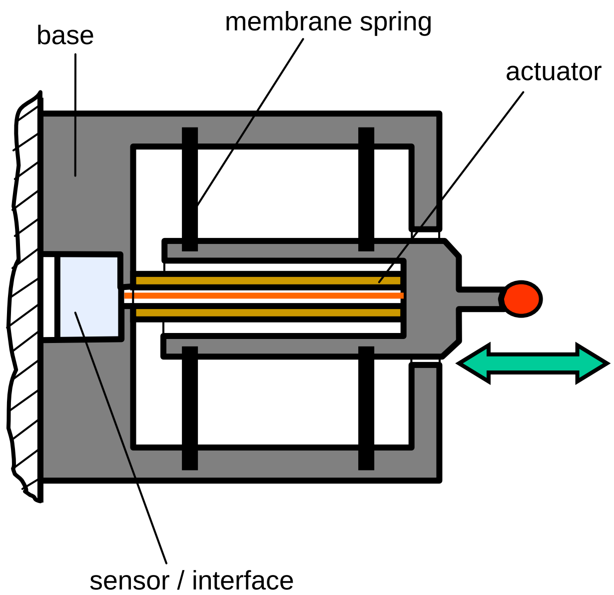
Analysing the adjustment system (Fig. 1), the parts of the functioning carried out by the mechanical elements can be categorised under four typical headings:

1. Firstly, mechanical elements are responsible for the correct positioning of all functional elements including sensors (autocollimator, CCD-camera) and manipulators, e.g. providing the base of the entire construction; examples are the adjustable beam, the carrier and the means of attaching the lenses and any other components. They have to ***guarantee relative positions of all components and their integrity*** which are necessary to provide the secure functioning of all system elements.
2. Actuators for the manipulators and the driving unit of the air bearing are of the second type, ***providing functions within the mechanical energy flow***, in this case for the centring process.
3. The positioning modules contain gearboxes (worm or screw gears etc.) which serve to ***transfer and/or transform the mechanical energy flow*** to the needs of the process operations. For instance, in the case of the v-edge manipulator the rotational motion of two stepping motors must be transformed into translational motion in x- and y-direction.
4. The roller guide, the air bearing and the adjustable joint carry the load of the moving components; all contribute to the ***transfer of forces*** to the base with controlled stress and strain.

Mechatronic systems generally reveal new requirements for mechanical components.

Most important, the machine elements must not be seen as "passive" components (as is the case in conventional concepts), but have to become part of an "active" control system and have to be "sensitised" by the integration of one or more sensor functions. So, in our example, position and orientation of the adjustable components in the lens centring set-up must be detected, in case of a misalignment must be corrected and finally the correct state has to be securely locked.

For these purposes it is necessary to integrate sensor and/or actuator functions into mechanical components. In this way machine elements are enhanced to "smart" components suitable to be linked into the control loop of mechatronic systems. This is accomplished by introducing adequate interface concepts as shown in Fig.3.



- **Mechanical interface**
  (forces, torques, degree of freedom, friction)
- **Non-mechanical energy interface**
  (electrical, hydraulic/pneumatic, thermal)
- **Information/signal interface**
  (electrical, optical, acoustic, …)

Figure 3. Three interfaces of mechatronic elements

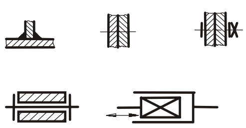
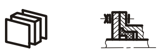
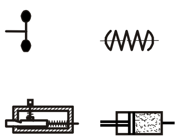
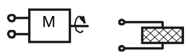
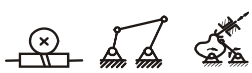
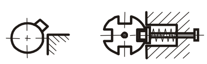
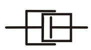
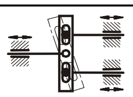
Smart engineering components created in this manner will require three interfaces for their effective use:

1. Firstly, mechanical connections, allowing for
   – external forces and torques to be applied and transferred,
   – the provision of the required degrees of freedom between the pairs of elements, also their safety,
   – disassembly or replacement of components where necessary.
2. Secondly, an interface to permit the actuators to function with the aid of
   – electrical energy,
   – hydraulic or pneumatic energy,
   – thermal energy.
3. Thirdly, a bus interface to permit information/signal transfer by means of
   – the physical carrier, whether electrical, optical, thermal or mechanical, and
   – the type of signal, whether analogue or digital.

Within the structure of the whole product there will be an even more complex function network as a result of these interfaces. When technical products are being designed, this situation must be taken into account. Thus, the design process – overall as well as its mechanical side – is far more complex than it used to be.

4. FUNCTION ORIENTED CLASSIFICATION OF MECHANICAL ELEMENTS

Table 1. Classification of mechanical elements as components of mechatronic systems

Function class	Function	Mechanical elements	Sketch of examples	Mechatronic elements
1. Arranging components	to support	Rod, bar, base, stand, frame, rack		Piezo stacks
	to join	*Fixed in all directions:* by material, by force, by form *Movable in selected dir.:* bearing, guide		Memory joint, "sensitive screw", magnetic bearing, field guidance
	to protect	Housing, box, container, cover, seal		Controlled sealing
2. Supplying mechanical energy	to store	Mass, flywheel, pendulum, spring, air spring, start mechanism		Quartz-oscillator, quartz-controlled step mechan-ism
	to transform	Electromotor, electromag-net, bimetal, piezo-element		Magneto-/electrostrict-ive, piezo, ultrasonic act-uators, etc.
3. Adapting mechanical energy	to convert to amplify/ reduce	Gear, linkage, screw, belt, worm, lever, spring, cam mechanism, break, damper,		Eoupled electric motors, electr. controlled gears, break, damper, eddy cur-rent brake,
	to lock to interrupt	Stop, blocker, impeder		Electromagnet, piezo-, memory-clamp, electro-stat., magnet-blocker
	to switch	Clutch		Electromagn., electrost., magnet powder coupling
4. Transmitting mechanical energy	to couple	Rigid or flexible coupling		Coupling with piezos, abrasion detection
	to conduct	Axle, shaft, tube, gear i=1, string, bowden cable		"Electrical" or "magnet-ic" shaft
	to distribute	Difference und sum mech-anism, gearbox		Coupled actuators, coupled drives

In table 1 the four row headings are assigned to the various types of known mechanical elements contributing either to the functions or to the construction of a mechatronic system (Krause 2004). In the right column, additional to conventional approaches, mechatronic elements of the mechanical domain are listed which can realise the respective functions. The number and variety of such elements is constantly increasing and more and more of them are available on the market (Naumann 2005, da Silva 2005, SKF 2006).

This classification can support the modular design and create ideas by abstraction and systematization.

5. MODELLING OF MECHANICAL ELEMENTS AS COMPONENTS OF MECHATRONIC SYSTEMS

5.1 Requirements

As was mentioned in the introduction, one important aspect in mechatronics is the system behaviour in non-steady states ("dynamic behaviour"). Because of its importance this has to be taken into account quite early in the design process by means of simulation. For the mechatronic system as a whole, the simulation has to be based on models that span all different domains, has to be applicable already in early stages of product and system development and, ideally, has to accompany the entire development process with the models / model complexity increasing along the process. As was already stated that it is the mechanical components ("machine elements") that are difficult to integrate in this respect.

In an ideal case the function-oriented classification of mechanical elements as components of mechatronic systems shown in section 4 is accompanied by appropriate simulation models of the respective elements. These models have to fulfil the following requirements:

- Should be based on a unified modelling approach ("theory") that is able to connect different domains.
- Should be a formalised approach, e.g. easy to transfer to existing simulation software, but
- at the same time should be compatible with existing "conventional" approaches in the mechanical domain.
- Should be applicable already in early phases of product and system development, but
- at the same time, with regard to their complexity, the models should be easily "expandable" throughout the entire development process.

5.2 Multi-port theory as a common base, some basic considerations

As was explained in [Weber 2005 a/b] in more detail, the so-called multi-port theory is an approach that meets these requirements and has the additional advantage that its concept is quite close to the way of reasoning in the mechanical domain. In this section a brief introduction of the basic concept and some results is given.

As explained in the preceding sections of this contribution, mechanical components of mechatronic systems ("machine elements") can be understood as solution elements that transmit mechanical energy flows, i.e. that transmit forces and motions. It is important that the term "mechanical energy flow" is further decomposed into its two basic values: force and velocity (**F**, **v**) in the translational case and torque and angular velocity (**M**, **ω**) in the rotational case, respectively. Only on the level of these basic values the functions especially of machine elements can be properly described.

The two physical values assigned to each one of the two external ports are, in more general terms, called "effort value" or "effort variable" and the "flow value/variable". Thus, a system having two ports has in total four external inputs and outputs or "poles", which gives the four-pole its name.

In the most simple case of a mechanical energy flow there is just one input and one output, leading to the block diagram according to Fig. 4 (here shown for transmitting rotational mechanical power).

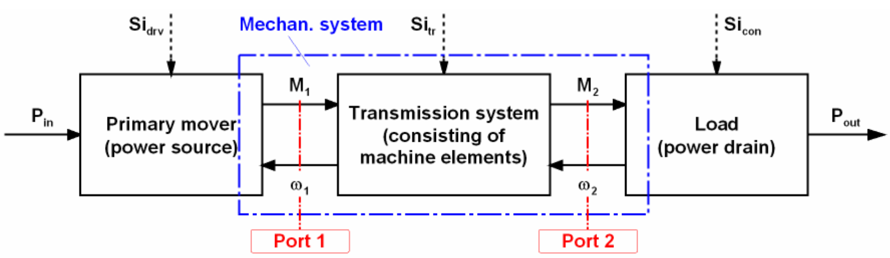


Figure 4. Machine elements as constituents of systems transmitting mechanical power (here: rotational); most simple case illustrated: two external connections ("ports", "shafts"); one static and one kinematic degree of freedom

Based on Fig. 4, some significant aspects can be explained:

- When looking at the block diagram, bearing in mind the context of the entire system, at every external port of a mechanical system ("shaft" or other "interface" to transmit mechanical power into or out of the system) only one of the two constitutive values of the mechanical energy flow – force/torque ***or*** motion – can be assigned, i.e. can be independent input in a logical/functional sense. The other value – again in logical/functional sense – is fed back as a result of the behaviour of the neighbouring system(s) connected to that port, i.e. is output value.
- The same statement is vaild for all internal flows: At any potition outside and within the structure the logical/functional directions of the two corresponding flow and effort vaulues are opposite.
- These findings are not at all new, they rather correspond to rules known in mechanism and transmission technology, but expressed in different terms: A mechanism has as many degrees of freedom as it has external ports (shafts or other interfaces), at every external port exactly one degree of freedom is assigned [Müller 1998]. Depending on whether force/torque or motion is assigned, it is differentiated between a "static" or "kinematic" degree of freedom.
- How many of the total number of degrees of freedom of a system are static and how many kinematic, depends on the structure of the system itself.
- Finally, at any position outside and within the structure the multiplication of the corresponding effort and flow variables gives the power that is transmitted at the respective port or at the respective "channel" of the system.

The case shown in Fig. 4 occurs very often: Here the transmission system (with two external ports in total) has one static and one kinematic degree of freedom, so it can be any kind of (gear) wheel transmission or belt drive without slip.

In the field of machine elements forces and motions are not always considered at the same time: Mechanism technology (part of function class 3 in table 1) often concentrates mainly on motions (purely kinematic view); in other cases (e.g. fixed joining elements, see function class 1 in table 1), motions are usually not considered. These are two special cases which are part of the general model according to Fig. 4:

The mechanical system shown in Fig. 4 is now a "two-port" element (i.e. having two interfaces to transmit mechanical power into or out of the system), at the same time a "four-pole" (i.e. having four external input and output values). Four-poles (sometimes called "quadrupoles") and, more general, multi-poles are modelling concepts that are well-known in electrical and control engineering, but also in acoustics (looked upon as a coupled electro-mechanical domain). They help to describe the dynamic behaviour of systems that transmit power [Oppelt 1972].

If we assume linear behaviour, i.e. only linear equations that connect the system's external and internal values (as is common practice in the field of electrical, control and acoustic engineering) the (linear) four-pole has the generic structure illustrated in Fig. 5 – here again shown for the case of transmitting (rotational) mechanical power and for one static and one kinematic degree of freedom (as in Fig. 4).

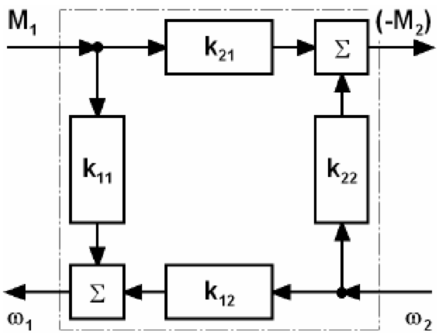


Figure 5. Generic structure of a linear four-pole (here: transmission of rotational mechanical power)

It is worth mentioning that the structure shown in Fig. 5 as well as in all other block diagrams discussed in this paper differ from figures normally used in control engineering in one point: The summation/superposition of values is indicated by a rectangular box with the symbol "Σ" in it and not – as in the field of control engineering – by means of a small circle and a "plus" sign ("⊕"). This is done to avoid some potential confusion later (see below).

The system behaviour (transfer of input to output values) of the mechanical linear four-pole according to Fig. 5 can be described as:

$$\omega_1 = k_{11} \cdot M_1 + k_{12} \cdot \omega_2 \quad (1)$$

$$(-M_2) = k_{21} \cdot M_1 + k_{22} \cdot \omega_2 \quad (2)$$

Hence as a matrix:

$$\begin{bmatrix} \omega_1 \\ (-M_2) \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \cdot \begin{bmatrix} M_1 \\ \omega_2 \end{bmatrix} = \underline{\underline{K}} \cdot \begin{bmatrix} M_1 \\ \omega_2 \end{bmatrix} \quad (3)$$

In this case, as in all other, even very complex cases the overall transfer functions are derived by "calculating backwards": Start from the output values (that are connected to different ports!), follow them up across all the different inner elements of the structure, until the input values (that are also connected to different ports!) are reached.

The assumption of linearity is no strict necessity, it is just common practice in other domains in which the four-pole approach is widely used. When considering non-linear cases, in equations (1) and (2) the linear mathematical functions with their constants k_{ij} have to be replaced by general functions of the form $f_{ij}(X_j)$ – principally any function appropriate to describe the respective physical effect is possible: polynomials, trigonometric functions, …. However, in this case a matrix form according to equation (3) is not applicable anymore, since matrices can only capture linear relations.

In the field of mechanical systems non-linear relations are needed quite often. Therefore, the matrix representation as shown in equation (3) is not used any longer.

By using four-pole models like the ones shown in Fig. 5, some general questions with regard to the behaviour of the described systems can be discussed on a quite formal level, i.e. without having to go into physical or even layout details.

One of the most interesting questions is: Which are conditions where the system has a behaviour free of power losses? This shall be investigated for all operating conditions, i.e. for all possible input values (**M₁**, **ω₂**).

In the mechanical case powers $\mathbf{P_1}$ and $\mathbf{P_2}$ can be calculated as follows:

$$\mathbf{P_1 = M_1 \cdot \omega_1 = M_1 \cdot (k_{11} \cdot M_1 + k_{12} \cdot \omega_2)} \tag{4}$$
$$\mathbf{P_2 = M_2 \cdot \omega_2 = -(k_{21} \cdot M_1 + k_{22} \cdot \omega_2) \cdot \omega_2} \tag{5}$$

No power losses / no dissipation means:

$$\mathbf{P_1 + P_2 = k_{11} \cdot M_1^2 + (k_{12} - k_{21}) \cdot M_1 \cdot \omega_2 - k_{22} \cdot \omega_2^2 = 0} \tag{6}$$

If equation (6) is to be valid for all possible input values ($\mathbf{M_1}$, $\boldsymbol{\omega_2}$), then the following conditions must be fulfilled:

$$\mathbf{k_{11} = k_{22} = 0} \tag{7}$$
$$\mathbf{(k_{12} - k_{21}) = 0} \tag{8}$$

Interestingly enough, the two conditions (7) and (8) immediately lead to conclusions about the "allowed" inner structure of (linear) four-poles and, subsequently, about the necessary structure of corresponding real systems: As a general rule, dissipation-free power transmitting systems have to have two separate structural transfer branches between input and output values. Fig. 6 illustrates this finding for the mechanical four-pole according to Fig. 5:

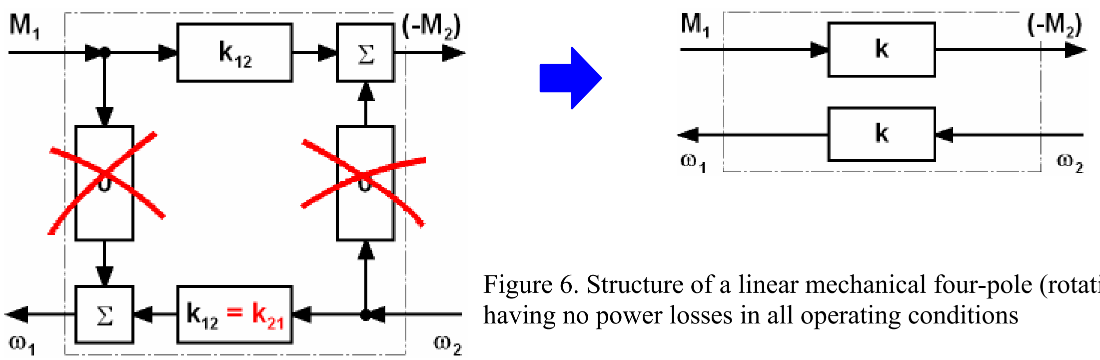


Figure 6. Structure of a linear mechanical four-pole (rotational case), having no power losses in all operating conditions

Some interesting conclusions can be drawn from the discussion about non-dissipative power transmissions:

- Power transmission with good efficiency ratio throughout the whole operating range is not a quality influenced primarily by physics, but rather by the inner structure of the system.
- Many machine elements are, in fact, constructed in a way that follows the ideal structure illustrated in Fig. 6: All positive locking gear trains and clutches transmit forces/torques decoupled from motions, consequently the "static" and "kinematic" aspects can be considered separately.
- The same is true vice versa: In all cases in which power losses occur (or are even part of the required system behaviour), the static values are ***not*** decoupled from the kinematic values.

"Two-ports" or rather "four-poles", which describe systems with two external power ports, can be extended to so-called "multi-ports" (sometimes called "n-poles") by adding further external ports ("shafts", "terminals", …), e.g. gearboxes with three external shafts being a "three-port" / a "six-pole". This will not be discussed here in further detail.

5.3 Element types

In multi-pole models (as in all other similar models, see [Wellstead 1979, Karnopp et al 2000]) there can only occur three basic types of elements. They are introduced and explained in detail by [Weber 2005 a/b], in this paper Fig. 7 only gives a summary. All these element types are quite well known in systems theory and have distinctive names which in Fig. 7 are stated in brackets. In all cases the mutual dependence of the outputs on the inputs can be expressed by formulae which will not be discussed here. In Fig. 7, for reasons of simplicity, only linear(ised) equations are indicated. Especially in mechanical engineering non-linear cases have to be considered (e.g. even in the most simple Coulomb / "dry" friction case) which is again not discussed any further in this paper.

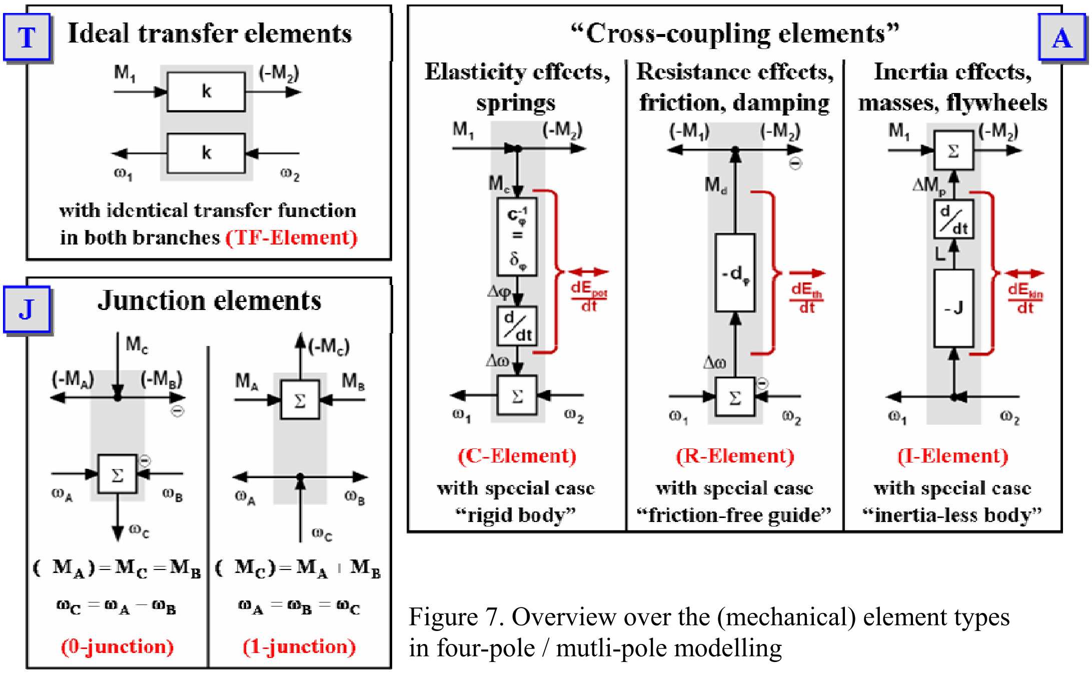


Figure 7. Overview over the (mechanical) element types in four-pole / mutli-pole modelling

T: Ideal transfer elements have the structure of a non-dissipative four-pole, i.e. a four-pole made up of two separate branches (Fig. 7, right). Examples in the mechanical domain are all non-dissipative translators of forces (e.g. levers) which at the same time are always motion translators, as well as all positive gear trains which also transmit forces/ torques and (angular) motions simultaneously, but separately. Beyond mechanics, hydrostatic pumps and motors are examples for this element type, again if assumed free of power losses.

J: Junction elements are used to model connections of more than two ports (e.g. connecting more than two "shafts"). In the elementary case shown in Fig. 7, J-section, exactly three ports are coupled without additional changes of the transmitted values. For this kind of elementary "three-ports" / "six-poles" there are exactly two alternative concepts:

a. Summation/superposition of flow variables, accompanied by identical effort variables

b. Summation/superposition of effort variables, accompanied by identical flow variables

The summation/superposition of values in one branch of the structure (illustrated by a rectangular box with the symbol "Σ") is connected inseparably to the coupling of three identical values in the other branch of the structure; this is displayed in the block diagrams by a "branching-off point" in form of a filled node. It is very important to avoid confusion here, and that is the reason why the notations displayed in Fig. 7, J-section, and all subsequent figures differ slightly from the usual notation in control engineering.

The summation/superposition of the three values in one branch of both types of junction elements requires that two of them have to be logical/functional inputs (i.e. are determined by neighbouring elements or systems); otherwise, the sum can not be evaluated. Accordingly, the coupling of three identical values in the other branch of the respective junction element requires only one of them to be input (to be defined from outside the element).

Examples for junction elements according to concept a (Fig. 7, J-section, left) from the mechanical domain are the relative movement of two bodies with (identical) contact force, in electronics and hydraulics it is the parallel connection of three electrical/hydraulic units. A mechanical example for junction elements according to concept b (Fig. 7, J-section, right) is the sum of all forces/ torques acting on a moving (rigid) body. In electronics and hydraulics it is the series connection of three electrical/ hydraulic units.

A: In this contribution the term "cross-coupling elements" denotes structural elements in four-pole/multi-pole models which directly connect interrelated effort and flow values (in the mechanical case: force/torque directly coupled to motion). As already discussed in section 5.2 these elements have a special significance as they are the structural cause of (at least temporary) power losses.

There are three different types of "cross-coupling elements" which differ from each other as they connect effort values with flow values of different temporal derivations. In the mechanical case these are:

a. Coupling acceleration/angular acceleration (the derivation of velocity/angular velocity with respect to time) to force/torque: inertia-induced force/torque ("masses and flywheels").

b. Coupling velocity/angular velocity directly to force/torque: resistance-induced force/torque ("friction and damping elements").

c. Coupling displacement/angular displacement (the integration of velocity/angular velocity with respect to time) to force/torque: elasticity-induced force/torque ("springs").

These three types of "cross-coupling elements" are shown in Fig. 7, A-section, graphically, each of them in its base version. It should be noted that two of these three elements contain derivation elements in time (**d/dt**), according to the derivatives of the velocity/angular velocity value that determines the behaviour of the respective element. In these cases the resulting transfer equation is a differential equation.

In all cases the logical/functional directions of the external as well as internal values could be reversed, with the consequence that the derivation elements would have to be replaced by integration elements (**∫…dt**) and that the resulting transfer equation will be an integral instead of a differential equation.

Without going into details, it should be noted that the equations describing the transfer behaviour of the "cross-coupling elements" are often ***assumed*** linear (as indicated in Fig.7, A-section). Especially in the case of mechanical engineering, however, non-linear cases appear quite frequently. An example is already the most simple Coulomb ("dry") friction, very widely used as approach to describe mechanical resistances, which is non-linear and has to be described by a signum function).

5.4 Modelling systems

Based on the considerations explained in the previous sub-sections, it is now possible to build up multi-pole models of machine elements (and other components and systems, not necessarily confined to mechanical ones). For this purpose the basic element types will be coupled to one another according to the structure of the real system to be modelled.

In doing so, only the element types introduced can occur. However, especially in the field of mechanical elements and systems in very many cases non-linear equations will have to be used instead of the linear ones which prevail in other domains. The equations which have to be used in a particular case result from the particular physical principle implied and from parameters which are defined by designing the system.

The equations to describe the (dynamic) system behaviour then result from "calculating backwards" through the whole system model, starting from the output values, following them up across all the different inner elements of the structure, until the input values are reached (as already shown schematically in sub-section 5.1).

Provided that elements of differentiation and/or integration occur in the "cross-couplings" we will end up with differential equations or integral equations, respectively, as descriptions of the transfer characteristics of the whole system.

In [Weber 2005 a/b] several examples are presented to demonstrate how multi-pole block diagrams are set up and how the resulting (differential) equations describing the (dynamic) system behaviour (transfer of input to output values) are deduced for mechanical as well as other applications. It is also shown that system modelling according to the principles and rules presented in this contribution can vary in level of details, i.e. the approach is "expandable" throughout the development process by leaving out effects and elements in the early phases which can afterwards be added step by step along with the increasing level of details in the later phases of the development process.

The authors' conclusion is that these models could be a possible unified basis for the modelling (and subsequent simulation) of mechatronic systems. When asking for alternatives, on one hand control block diagrams [Isermann 1999, Nordmann & Birkhofer 2003], and on the other hand so-called Bond Graphs [Wellstead 1979, Karnopp et al 2000] are named and sometimes clearly favoured. Therefore, in [Weber-05] advantages and disadvantages of these alternatives are briefly discussed and reasons are given for the authors' preference of the multi-pole models presented here. The main reasons are:

- Multi-pole models have a clear set of rules which, if followed thoroughly, guarantee complete structures of the system to be modelled; in this respect they are similar to the Bond Graph approach and more secure than the block diagram method.
- Additionally, multi-pole models show forces and motions ***explicitly*** – and these values are the biggest concern in mechanical engineering; in the authors' view this makes them better suited to the way of reasoning in the mechanical domain than Bond Graphs where forces and motions are "only" attributes of energy flows.

The introduction of multi-pole block diagrams for mechanical (and other) components as well as the subsequent derivation of the transfer (differential) equations are not an end in itself, but precondition and basis for computer-supported system simulation. For that purpose, the equations/equation systems have to be transferred into corresponding programmes (like MatLab Simulink), here they have often to be re-formulated and can then be (numerically) solved.

Finally, introducing multi-pole modeling into the domain of machine elements not only makes these "mechatronics-compatible", but also provides benefits for the subject "machine elements" itself: The logical/functional way of reasoning opens new options to explain the functioning and the physics of machine elements much more systematically and sometimes even more accurately (i.e. with less simplifying assumptions and with more overview) than is possible with traditional approaches and methods.

6. CONCLUSIONS

Mechatronic products require a new generation of mechanical components with extended functionality, capable of regulation and detection of important parameters. Such intelligent mechanical elements will require three interfaces to transmit mechanical parameters, other energy and information/signals.

The main functions of mechanical components in technical products, arrange components, supply, adapt and transmit mechanical energy provide a function-oriented classification of the mechanical domain in the context of mechatronic systems. This systematic approach shall support the conceptual and embodiment design of sophisticated products and give an orientation for the further development of machine elements.

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