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AN INNOVATIVE NEW BASIC MODEL IN DESIGN METHODOLOGY FOR ANALYSIS AND SYNTHESIS OF TECHNICAL SYSTEMS

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Abstract

The correlation between layout and function of technical systems is an important clue for the comprehension and description of technical systems. A basic for a methodology that helps the designer to master the interface between the abstract description of the function and the real layout of a technical system must be clear enough to fulfil this transfer without problems. However it must be global enough to be able to describe the complexity of any technical system. The method ought to be applicable for the analysis of an existing machine system as well as for the synthesis of an new one. The paper introduces a new methodological model – the Element Model “Contact & Channel Model C&CM”, “Working Surface Pairs & Cannel and Support Structures” (Wirkflächenpaare & Leitstützstrukturen WFP & LSS) that has been developed at the Institute of Machine Design and Automotive Engineering of the University of Karlsruhe (TH), Germany (mkl). The fundamentals of this Element Model C&CM are presented in their most important definitions and based on simple technical systems. Further the application within the scope of actual research projects is presented in order to show the strengths of the model on analysis as well as on synthesis of technical systems.

Keywords: design methodology; Element Model; Contact & Channel Model, Working Surface Pairs, Channel and Support Structures, Analysis; Synthesis

1 Objectives

Product development is the entirety of all operations involved in the process of collecting, documenting and creating the information necessary for a product and it’s life cycle [1]. A product developer needs to set out the entire product development cycle in advance, in order to integrate the attributes desired by the customer into the product. Once developed, the product will be expected to fulfil its functions. If it does not, it will lose its entitlement for existence, will therefore become worthless, or possibly even cause considerable damage under certain circumstances. Therefore, the functions of a technological product are the basics for the product development process.

The search for solutions to the issue of fulfilment of product functions is supported by a variety of design methods. In order to ensure that the product can fulfil a function, the product design needs to comply with the product functions. The step from solution principle to constructional design of a product is often a major challenge for the product developer.

The design process of a product is a synthesis process that brings together a whole new entity. In order to support this process it is vital to consider also the analysis of technical systems, as the technical solution is developed in the discourse of the design process [9]. During the design process, the developer switches back and forth between creative notions regarding design development and analytical considerations reviewing the newly developed design. The analytical considerations are followed by another synthesis process for the creation of an optimised design, etc. If this basic interrelation is taken into account, a model supporting the creative phase of the product development, is applicable for analysis as well as for synthesis.

Since 1997 one of the main fields of research of mkl is the development of a new method that supports the designer more continuous than previous methods. It is important that such a method is able to describe all kinds of technical systems without being too far abstracted from real systems. The designer that uses such a method must be able to change easily from the real machine system to the abstracted form of it in every phase of the design process and to change as easy as this back to the real system. The newly developed method differs from previous methods by the connection of function and embodiment design and by the implementation of a new level of abstraction.

In order to extend the acceptance by the product developer, the model is transferable onto all technical systems consisting also of fluids and gases and on those that are based on any physical effects as e.g. field effects. Additionally it is obvious, pragmatical, easy to realise and fractal, i. e. adaptable to a variety of problems.

2 The Element Model C&CM

Extensive analysis of real constructional design processes and systematic abstraction were made. The result of these analysis and further activities of research caused in the perception that a general correlation between function and embodiment design of technical systems can only be found regarding the smallest elements of each technical system on the functional level. By dint of these elements a model was created that is flexible enough to describe technical systems in any level of abstraction. This allows a pragmatic problem-oriented use of the model, multi-scale on different levels of abstraction. The model has a fractal character.

First of all an abstract but still pragmatic view on technical systems was developed.

Based on this abstract view it became possible to develop a model that builds the basis for methodical acting at the analysis of existing as well as at the synthesis of new machine systems. The newly developed Element Model is able to support the product development process methodically and continuously. It is a method that can help to control the process of thinking and acting during the product development without constricting it. The change between different levels of abstraction is supported to be able to regard the system as a whole during each phase of product development. Coexistent it is possible to change rapidly to any detailed level of the technical system or one of its subsystems.

These considerations resulted in the Element Model C&CM (Contact and Channel Model) “Working Surface Pairs & Channel and Support Structures” (Wirkflächenpaare & Leitstützstrukturen WFP & LSS) – for the correlation between design and functionality of technical systems. [1;2] By ascribing any technical function to the interactions of the Working Surface Pair and the connected Channel and Support Structure, a definite and efficient concept for design definition develops under ancillary conditions including the system environment. According to this model, Working Surface Pairs and Channel and Support Structures are elements common to all technical systems. Thus, the designation “Element Model” was chosen for C&CM.

Actions and reactions in an technical system are realized by the design of basic elements according to certain rules. These rules are framed in the basic hypotheses of the model.

Existing methodical approaches are adopted for the description of the interrelation between functionality and design and then processed to a new, holistic approach. The idea of the Working Surface Pair which is already used by constructional methodology, is extended and transferred from solids to fluids and fields.

The Element Model C&CM is founded on the abstraction of a technical system to the smallest elements that aid to fulfil the function. This are the generalised surfaces of the system elements that generate the function by interaction with other system elements, the Working Surface Pairs and the volumes linking them, the Channel and Support Structures. For being able to describe technical systems and also physical effects like e.g. the forces of a field completely, WFP and LSS are not only defined at solid bodies but also in a general form at fluids, gases and fields. The function is fulfilled in the WFP and LSS by the exchange and storage of the system variables material, energy and information.

Within the scope of actual research at mkl already several acknowledgements and rules were developed that facilitate the application of the Element Model C&CM at technical systems. One of its basic propositions is e.g.:

To realise any function in technical systems at least <u>two</u> Working Surface Pairs and one Channel and Support Structure are essential.

Figure 1 shows a simple technical system: two gearwheels of a spur gear unit. Between the tooth flanks of the two gearwheels a WFP is formed, WFP_1. This WFP transmits force from gearwheel 1 to gearwheel 2. It is formed because of the functional contact of the Working Surfaces WF_1 and WF_2 of the both gearwheels. At the flank of the fitting key the force is transmitted into the key, here is the second WFP to fulfil the function of gearwheel 2. Both Working Surface Pairs are connected by the LSS of the body of the gearwheel.

If <u>one</u> of both WFP was removed, e.g. between the gearwheel and the flank of the fitting key, the function could no longer be realised. This basic proposition is valid for all technical systems.

The function of a technical system is always assigned to Working Surface <u>Pairs</u> and not – as postulated in other approaches – to Working Surfaces. So a technical function only exists as long as the associated Working Surface Pairs are existing. [1] and [2] the theory is described completely.

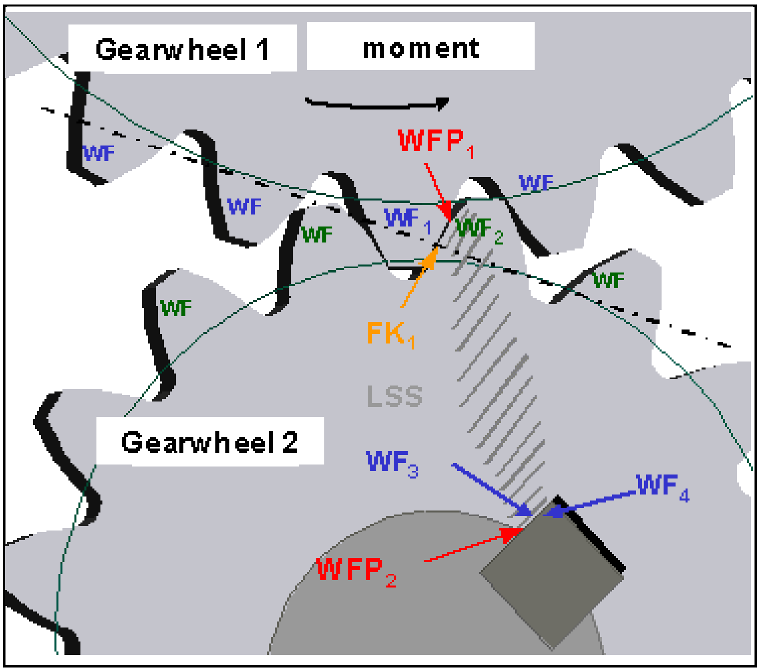

Figure. 1: WFP & LSS at the example of a gearing

Regarding more complex technical systems there will always be two Working Surface Pairs and one Channel and Support Structure to fulfil elementary functions like e.g. transmission of forces between the elements of a technical system. If one of the Working Surface Pairs was removed – e.g. WFP2 in figure 1 – the system could no longer fulfil its function.

The following examples show how the Element Model C&CM can deepen the comprehension of a machine system and how it has successfully aided solving several problems in an actual field of research of the mkl. Here it has allowed to find a solution at the synthesis of a complex technical system by solving contradictions.

3 Results - Application of the Element Model C&CM

3.1 Application of the Element Model exemplified on the derivation of a bolted connection

The simple task of linking two plates by form closure shows the advantages of the application of the Element model clearly: The plates are to overlap like shown in figure 2 and they are to be stressed each by the force F parallel to the plates. Between the plates a WFP is formed (in the figure WFP_1). This WFP fulfils the function „transmit the force F from plate 1 to plate 2“.

To transmit a force parallel to WFP1, a friction force, a normal force must be generated in this WFP according to Coulombs law:

$$F_R = \mu \bullet F_N \qquad (1)$$

The function „generation of a normal force“ can – as described above - exclusively be fulfilled by two WFP and one LSS linking them. So an additional WFP must be generated. Figure 3 shows an example realising this: The both plates are linked with a rivet.

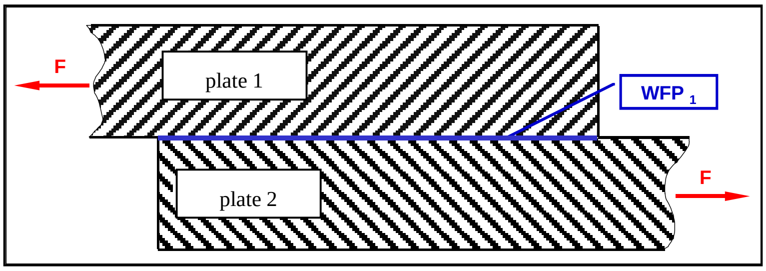

Figure 2: starting point: two plates

A part of the outer limiting surfaces become WF and form WFP with the surfaces of the rivet, WFP_2 at the upper side and WFP_3 at the lower side. The body of the rivet forms the LSS linking the both new WFP. The tension forces that are induced by the plastic deformation during the assembly are transmitted into the plates in WFP_2 and WFP_3 and generate the demanded normal force in WFP_1.

Further demands on the connection of the plates can be realised either by changing the arrangement or the properties of the WFP and LSS or by the introduction of further WFP and LSS.

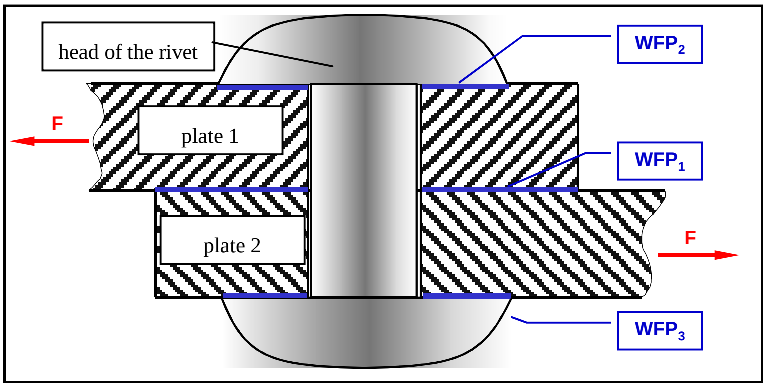

Figure 3: link of two plates with a rivet

If the connection has to fulfil the additional function „ensure the loosening of the connection“ this can be realised e.g. by the introduction of a new WFP. This WFP can e.g. divide the rivet. In this example the head of the rivet is to be linked with its shaft by the additional WFP. If the connection is to be realised by force closure, the principal arrangement of the WFP shown in figure 4 is one possible solution:

The newly introduced WFP_4 is arranged in a certain angle to the previous WFP. Moving the indicated $LSS_{3,4}$ to the right the necessary normal force can be formed and transmitted into the plates in the WFP_2 and WFP_3. Above that the normal force can be changed by moving $LSS_{3,4}$ and, as demanded, the connection can be solved.

Changing the geometrical arrangement of WFP by rolling it up around the axis of the rivet the transition to a bolted connection can be made.

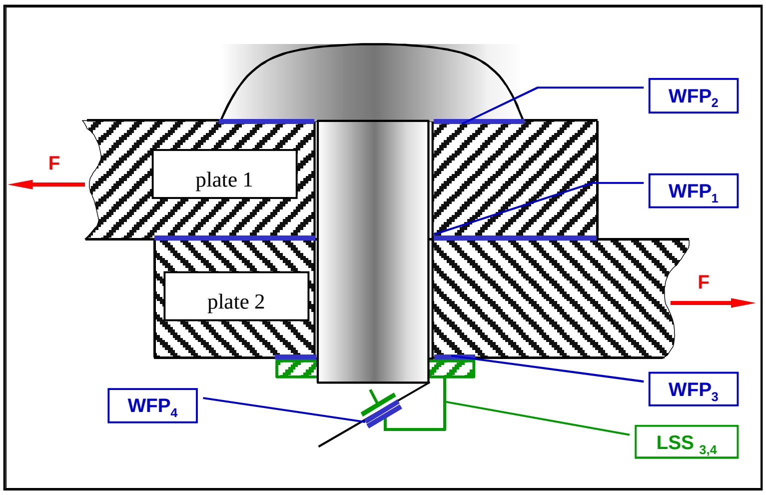

Figure 4: principle of a solvable connection with a rivet

Of course there are several other possibilities to fulfil the function of linking the plates. An other possibility could be this: Introduction of a new Working Surface Pair perpendicular to the forces. This new Working Surface Pair would fulfil the function in connection with the Working Surface Pairs that conduct the forces into the plates.

3.2 Application of the Element Model C&CM in synthesis exemplified on the friction contact between pin disc of a CVT

At the example of the friction contact between pin and disc of a CVT the application of C&CM as a method for finding solutions for unknown problems can be shown.

A CVT bases on the principle of a chain that runs between two conic discs with variable distance. The torque is transmitted by force closure between one pair of discs to another (Figure 5). Changing the distance between the discs the transmission can be varied. The contact between conic disc and pin is realised by pins that are linked by the mounting links of the chain. Here especially the WFP between one pin and one of the conic discs is to be considered (Fig. 6).

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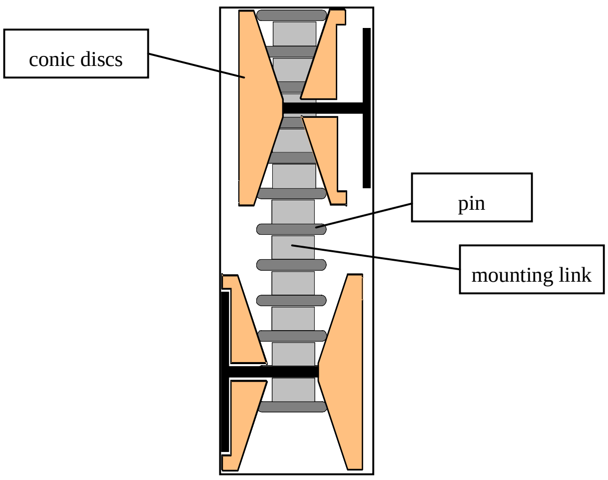

Figure 5: principle of a CVT

At current CVT's both pin and discs made of a metallic material are state of the art. The Centre of excellence in research 483 "High performance sliding and friction systems based on advanced ceramics" considers possibilities and risks of the use of advanced ceramics.

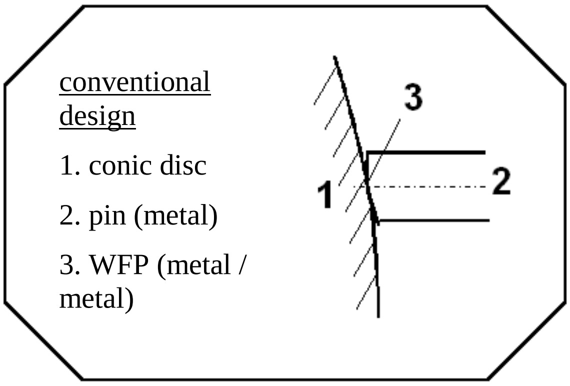

Figure 6: contact between pin and disc

Advanced ceramics allow a higher contact stress and higher friction coefficients so the power density can be higher. So advanced ceramics should be able used to improve the properties of a CVT. A first solution had been discs of ceramic material and pins of metal. This hybride solution indicated positive operating characteristics, but the wear resistance of the metallic pin was not good enough.

Due to the improvement of wear resistance in a WFP ceramic / ceramic between pin and disc the possibility of manufacturing the pin no more out of a metallic but out of a ceramic material is topic of research.

But regarding the complete subsystem pin with all its WFP that are necessary to fulfil its function it is obvious that a main stress for the pin is bending as the forces that are transmitted into the pin in the WFP between pin and disc are transmitted through the LSS „pin" to the mounting links of the chain.

Due to the fact that even advanced ceramics have a limited load capacity at bending load, the pin should better be made of metal.

Regarding the requirements on the pin a contradiction can be realised:

To fulfil the function in the WFP between pin and disc the pin should ideally be made of a ceramic material. But on the other side the LSS of the pin should be made of metal for being able to resist the stress that is transmitted into the LSS in the different WFP.

This conflict can be solved by a rule that was already used in a different form in the above described example. This rule is formulated on the higher abstracted level of the Element Model:

For solving a conflict that is due to different requirements in the used material, an additional WFP can be introduced.

By the introduction of a new WFP the functions of the pin can be divided: This new WFP is introduced between the outer (turned towards the disc) region of the pin that realises the force transmission between pin and disc and the inner region of the pin that is stressed by bend. The pin is divided, the outer region is made of a ceramic material, the inner region is made of a metal. Between these both regions the newly introduced WFP is formed.

The function of those new WFP is „link the both regions of the pin considering the stress safely“. This requirements are hints for the embodiment design of this newly introduced WFP.

Among others following prerequisites are to be proved: Is the force to be transmitted parallel to the WFP, i.e. by force closure or orthogonal to the WFP, i.e. by form closure? Is the connection to be loosened or not?

Using a connection which cannot be loosened it is possible to realise the transmission of the force with a adhesive binding. In this example this possibility is to be regarded more intensively.

Pasting the both regions of the pin not only one new WFP is formed but two like shown in figure 7: WFP_2 between the ceramic part of the pin and the adhesive and WFP_3 between the adhesive and the metallic part of the pin. Dimensioning this connection it has to be proved that both WFP and the additional LSS can sustain the stress. In the considered case this is for the most part shear strain. Selecting the adhesive both new WFP are important as both of them define the adhesion.

As a adhesive linking cannot stand the shear strain in the considered case safely, the above used rule can be used once again to realise a further function, namely building a forme-closure-connection in the direction of the main stress. This is also shown in figure 7: Inlays made of a ceramic material are put into a hollow at the end of the metallic part of the pin. The newly created WFP_4 parallel to the axis of the pin transmits the radial force by form closure, i.e. orthogonal to the new WFP. The original WFP orthogonal to the axis of the pin prevent the ceramic part of the pin from falling out of the metallic part by the adhesive link But it is no more stressed by the shearing strain.

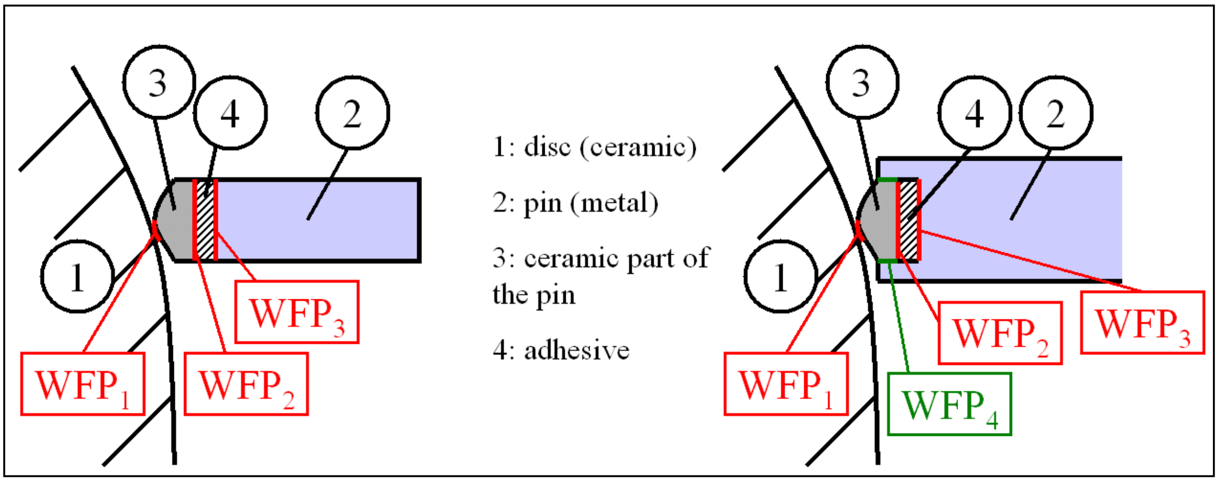

Figure 7: concept: metal pin with ceramic inlet (ratio of sizes for a better understanding scewed)

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4 Key Conclusions

Regarding the described examples the consequences of the introduced Element Model C&CM are obvious: It can be used both at the analysis of a existing machine system or effect and at the synthesis of a new machine system or subsystem. Caused by the clearness and the flexibility of use the Element Model C&CM it is easy to learn and use for new tasks.

Applicating rules like e.g. the described introduction of a new WFP for the fulfilment of additional functions for passing by a conflict problems can be solved on an abstract level without defining a concrete embodiment design.

This new methodical concept was successfully validated in a number of real product development projects in co-operation with the industry and in research and has proven its efficiency regarding the analysis of unexpected events of damage and especially regarding the creative design of new products. In practical application during development project in co-operation with the industry, it has already proven to be very efficient and has led to a number of patent applications and concrete new products.

One of the model's strengths is the continuous applicability for all levels of consideration. The model is fractal, i. e. it can be applied on different levels of consideration following the same modus operandi.

It also supports the design of technical systems, whose internal build-ups do not need to be known to the designer in detail (black box construction).

The element model C&CM was successfully implemented during innovative product development projects in co-operation with the industry and in research and has proven its practicability. It methodically brought about a number of innovative solutions and patents within the scope of these products.

The model is also the basis for the "Karlsruhe education model for industrial product design – KaLeP" [6;7;8], an education concept developed at the Institute for Mechanical Design and Automotive Engineering. Here it is also used in education in the Humboldt way of university education including actual results of research. The success of its introduction into the education is constantly supervised. So hints for its further development are created.

At the mkl there are several research project for the further development and optimisation of the Element Model C&CM.

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