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DEVELOPEMENT OF NEW TECHNICAL SOLUTION FOR STARTER MOTORS FOR PASSENGER CARS

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This paper discusses an industrial project which can be solved by “classical” design methods. Many theories and methods were and have been developed during the last few decades. Methods to support product development cover well-known paradigmatic approaches and models. They are partly built upon experiences from practice, and a lot of them haven't changed much during the last 20 to 30 years. In a product development process or design process, conceptual design is one of the most important phases in which customer needs and technical requirements are translated into design solutions. Conceptual design is a component part of a design process during which designers first create new ideas and then translate them into a design structure by synthesis [15]. First of all we defined the formulation of the task and determined the basic functions. After we are looked for solution variants and used to explore the theoretically possible solutions at principle impact level. It was found that the solution field obtained could be divided into three large groups, such as starters controlled by hydraulic, pneumatic, and electric energy sources. We also determined the development direction and finally designed a new possible solutions.

Keywords: design methodology, starter motors, pinion-engaging mechanism

Introduction

Today international competition in the market, accelerating engineering technological development and increasing purchaser requirements have made it crucial for companies to develop competitive products. Steadily increasing demands have led to the emergence of the science of methodical design, which encompasses a great number of established and proven principles and methods widely applied in industrial practice as well. So this design theories and methodologies such as systematic design methodology so-called „Classical” design theories [1, 2, 3, 10, 11]. Theory of Inventive Problem-Solving [12], Autogenetic Design Theory, [5], Axiomatic Design Theory [4], General Design Theory [Yoshikawa], etc. have been developed for the last fifty years.

„Classical” development and design methods are based on the paradigm that a complete description of requirements and boundary conditions will lead (at the very end) to exactly one solution (the so-called funnel approach) [5]. The German VDI guidelines 2221, 2222 and 2225 describe an integrated model of product development. There are based on the respective design theories developed mainly by Pahl, Beitz, Hubka, Koller, Franke, and Roth. All these design processes have in common that they arrive at the solution in every case by dividing a complex task or problem into sub-tasks and sub-problems and elaborating those separately. They also have in common that they divide the individual processes into three stages which cannot separated from each other markedly and which are the stages of formulating the task, the functional and the construction (design) stage.

The objective of this paper is to present the solution of a particular industrial task by means of ‘classical’ design methodology. The project was born in 2006 from an industrial commission, with the objective of developing and constructing a new, state-of-the-art starter for passenger cars. The contents of the paper are related to this objective. The foundation of the task was provided by these classical design methods.

Here the process plan elaborated in [3, 14, 15] and the Franke search matrix [14] were taken as the starting point for solving the problem at hand.

In order to obtain a transparent view of starters, it is expedient to do a comprehensive literature and patent research as a first step. The various papers on vehicular electricity [17, 18] discuss the structural analysis and operation of starters for passenger cars, heavy duty and two-stage starters for trucks. The Internet search engines of the Hungarian, US and European patent offices were used to find several hundred patents in this field. In the course of the research no new development based on scientific foundations was found, therefore the patent specifications found were analysed and catalogued according to the solution applied.

Towards solving the problem

Internal combustion engines emerged at the end of the 19th century and were used for driving vehicles. The vehicles ran on petrol and were started using an external, mechanical source of energy (pushing, acceleration on an incline, use of a manual starting handle). The 'tradition' of manual starting was to be found in vehicles for nearly a century to a decreasing extent, until the 1980s. Later, with the use of electrical energy supply units, electrical starter units, called starters *(Fig. 1),* came to the foreground. The task of a starter is to accelerate the main axle of an internal combustion engine from its stationary state to the ignition revolution number n_c. The operation of the internal combustion engine becomes self-propelled when the revolution number of its main axle is greater than the ignition revolution number, [17, 18].

The first step of the design is an abstraction of the task. It is expedient to formulate the task so that it will include only the objective to be performed by the technical device created in the design process.

Accordingly, the task was defined as followed: "Designing a device of a new technical principle suitable for starting the internal combustion engines of passenger cars".

It is of utmost importance that the fundamental requirements *(Table 1)*, providing the starting point for the further unfolding of the task set, are formulated in this stage. The requirements can be divided into four large groups on the basis of [16].

Table 1: Requirement list

Requirements set for the task	
Functional requirements	starting an internal combustion engine
	new technical solution
General requirements	a great number of connections, short connection time
	building block principle, modular design
	low level of noise
Priority requirements	rapid repair, service or replacement in case of faults
	easy fit in many different engines
	operability also in extreme weather conditions
	Reliability
Requirements typical of all machines	compactness and small weight
	long life
	manufacturing requirements
	industrial law requirements
	other (e.g. servicing) requirements

On the basis of the research of the literature and the patents, starting an internal combustion engine requires the generation of an impact that can be brought about via the main axle. After the internal combustion engine gets started, it may force the device generating the impact to perform such a great revolution number that exceeds the speed limit and the may endanger the integrity of the construction.

Therefore the objective is to design a device that drives the main axle of the internal combustion engine with the necessary revolution number and moment, and then the starter returns to normal after the fuel has been ignited in order to prevent possible damage.

In the next stage of the design process, it is possible to determine the fundamental theoretical solutions by setting up the structure of functions, finding and combining solution principles. [14, 16] The task formulated is called the overall task, which it is expedient to reduce to simple sub-tasks for which there already exist well-established solutions, and to so many parts that their number can still be followed. These sub-tasks may appear as well-established solutions in a great number of other technical devices. Next the sub-tasks are to be divided into sub-functions and the sub-functions into the impacts and impact carriers embodying them.

The collection of verbs containing 220 words and expressing actions in engineering practice provides considerable help for the accurate description of function definitions [7]. These can be used to give simple definitions for the particular sub-tasks and sub-functions. *Fig. 8* shows the sub-tasks and sub-functions performing the task total and the impacts achieving them. In the individual blocks of the structure of functions underlining highlights the verbs expressing the actions. In the following the individual sub-tasks and sub-functions are written in **bold.** In the blocks where there are four dashed lines, they represent connections to mechanical, hydraulic, pneumatic and electric blocks.

Account must be taken of what sources of energy are there, and which of them are suitable for solving the overall task. On the basis of Fig. 8, the sub-task **Use energy source** in vehicles is a supply unit housed in vehicles, which is necessary not only for starting the internal combustion engine, but also performs other functions not belonging to the task.

Each impact carrier, creating sub-tasks and sub-functions, can be grouped by the energy sources, e.g. mechanical (rigid and flexible bodies), hydraulic (fluids), pneumatic (air) and electric (electrons) supply units can be distinguished. Flywheel energy sources are most often used as mechanical energy sources. In the present state of technology, there also exist supra-conducting flywheel energy sources, with an efficiency of 96%. Mechanical, hydraulic and pneumatic supply units have to provide the appropriate primary energy source, which are usually electric supply units. Starters applied today receive the necessary energy from batteries.

Sub-task **Connect device to the crankshaft** includes two sub-functions. Sub-function **Create a connection** refers to the type of connection (e.g. flywheel gear rim gearwheel connection), which may be direct and indirect transfer of energy. Sub-function **Operate connection** refers to the method of creating the connection (e.g. operation in the axial direction).

Sub-task **Drive crankshaft** includes as its sub-function the bringing about of rotary motion. For devices suitable for generating rotary motions there exist well-established design catalogues [12]. These catalogues have the advantage that they include existing part solutions and one only has to select the one best suited for the task.

There exist solutions in practice, which, in addition to the existing main-axle-device connection, also include a separate moment-strengthening unit (e.g. epicyclic gear, or counterdrive). Therefore the sub-task **Change moment** – which is a sub-function at the same time – has the objective to impart the greatest possible moment to the main axle, and to reduce the dimensions of the device.

After starting the internal combustion engine, the **device** is to be **controlled** (set in the starting position) in some way. On the one hand that the process can be repeated at the next starting, and, on the other, in order to prevent damage. A device is set in the starting position when it is in some positive connection with another component (the main axle in this case).

The sub-function **Change function** can be closely linked to direct drive. In this case the device cannot be stopped.

On the basis of function analysis, it is possible to build a graph hierarchy (structure of functions) between the sub-functions implementing the individual sub-tasks. In order to obtain a solution meeting the requirements of the task set, it is practical to place the individual impacts into a morphology box (matrix) *(Table 2)*. In the matrix the fields belonging to the individual rows are connected with the elements of the next row. Assigning the individual energy carriers to each sub-function and connecting them gives the possible combinations of the chain of impacts.

Table 2: Morphology matrix

S_{FA}		A1	A2	A3	A4
S_{FB}	S_{FB11}	B11.1	B11.2	B11.3	B11.4
	S_{FB12}	B12.1	B12.2	B12.3	B12.4
	S_{FB21}	B21.1	B21.2	B21.3	B21.4
	S_{FB22}	B22.1	B22.2	B22.3	B22.4
S_{FC}		C1	C2	C3	C4
S_{FD}		D1	D2	D3	D4
S_{FE}	S_{FE11}	E11.1	E11.2	E11.3	E11.4
	S_{FE12}	E12.1	E12.2	E12.3	E12.4

Notations S_{FA}, …, S_{FE} are interpreted by *Fig. 3* and the list of notations. The last figures in the notations – from 1 to 4 – refer to the mechanical, hydraulic, pneumatic and electric energy carriers, respectively. In this way e.g. $S_{FB21.1}$ means: **Ensure axial connection by mechanical energy transfer.**

The number of possible theoretical solutions is given according to the following relation:

$$T_S = S_{FA} \cdot S_{FB11} \cdot S_{FB12} \cdot S_{FB21} \cdot S_{FB22} \cdot S_{FC} \cdot S_{FD} \cdot S_{FE11} \cdot S_{FE12} = 4^9 = 262144$$

It is easy to see that between the sub-functions S_{FB11} and S_{FB12}, S_{FB21} and $S_{FB22,}$ and S_{FE11} and S_{FE12} there exists an or connection, therefore the number of theoretical solutions according to (2) is

$$T_S = \frac{(S_{FA} \cdot S_{FB11} \cdot S_{FB12} \cdot S_{FB21} \cdot S_{FB22} \cdot S_{FC} \cdot S_{FD} \cdot S_{FE11} \cdot S_{FE12})}{8} = 32768$$

In the functional design stage the characteristics of the solution principles at a low level of concretisation in general are not known to the extent that combination and optimisation can be performed by mathematical methods. In order to develop the solution concepts, it is often not sufficient to have the physical relations, for geometrical (production engineering, assembly, incompatibility, etc.) relations may also set limits and exclude compatibility in a particular case. In more complex systems, the designers have to decide between the variants in this stage of the design process by means of the reduction selection process, which can be described by the activities of selection and prioritising.

The impact carrying part solution of the mechanical energy source A1 may be a spring, a flywheel or human force. This solution can be immediately discarded, for it does not meet the requirements of the age or technology.

Accordingly, the sub-functions S_{FB21} and S_{FB22}, i.e. the method of bringing about the device – internal combustion engine connection is omitted in this stage, the impacts not achieving particular sub-functions (B12.4, C1, D4, E1.1) are removed from the morphology matrix in Table 2.

Thus the number of theoretical solutions is:

$$T_{SM} = (S_{FA} \cdot S_{FC} \cdot S_{FD} \cdot S_{FB12} \cdot S_{FE2}) \cdot 2 = (3 \cdot 3 \cdot 3 \cdot 4 \cdot 4) \cdot 2 = 864$$

It is purpose to limit the theoretically possible solution field to the feasible solutions. Placing the solution possibilities of two compatible impact carriers in the head column and head row of a matrix, and filling the description of the combination (impossible or unfeasible, possible combination) in the field, compatibility can be easily checked in sequence.

	A2	A3	A4	B1.1	B1.2	B1.3	B1.4	C2	C3	C4	D1	D2	D3	E1.2	E1.3	E1.4	E2.1	E2.2	E2.3
A2						●	●		●	●	●		●		●	●			●
A3					●			●		●	●	●		●		●		●	
A4								●	●			●	●	●	●			●	●
B1.1																			
B1.2									●				●		●				●
B1.3								●				●		●				●	
B1.4																			
C2													●		●				●
C3												●		●				●	
C4																			
D1														●	●			●	●
D2															●	●			●
D3																		●	
E1.2																			
E1.3																			
E1.4																			
E2.1																			
E2.2																			
E2.3																			

Figure 1: Compatibility matrix

On the basis of the compatibility matrix (Fig. 1), the possible theoretical solutions of the task total can be arranged in a tree diagram Sub-functions S_{FB21} and S_{FB22} were removed in working with the solution principles, however, they are necessary in the analysis, therefore the number of possible theoretical solutions is

$$T_{SM} = 2 \cdot 4 \cdot 28 = 224 \, ,$$

which can be divided into three different groups:

- Device controlled from a hydraulic supply unit (A2 branch):
$$T_{SMA2} = 2 \cdot 4 \cdot 12 = 96$$
theoretical solutions.
- Device controlled from a pneumatic electric supply unit (A3 branch):
$$T_{SMA3} = 2 \cdot 4 \cdot 12 = 96$$
theoretical solutions.
- Device controlled from an electric supply unit (A4 branch):
$$T_{SMA4} = 2 \cdot 4 \cdot 4 = 32$$
theoretical solutions.

In hydraulic and pneumatic supply units the appropriate primary energy source, usually an electric supply unit, is to be provided. Starters used today obtain the necessary energy from batteries. Since this is a well-established solution, it is not worthwhile deviating from this sub-function. The idea, however, is not discarded immediately, we may return to it later on. Since internal combustion engines cannot be altered, i.e. neither the flywheel, nor the crankshaft can be modified, the number of theoretical solutions of branch A4 is consequently reduced from 64 to 2.

The methods applied for selecting the appropriate solution variants were the Use Value Analysis (UVA) of system technology and the evaluation according to the guidelines VDI 2225 [8]. It follows from the analyses that the most sensitive point of the device is the mechanism ensuring the axial connection, i.e. pinion-engaging mechanism (PEM).

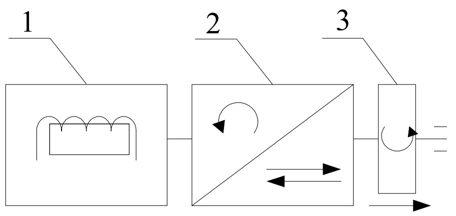

Figure 2: Block scheme of the PEM

Modelling and simulation of the PEM

The basis of developing variants is how the PEM can be replaced by other solutions, since the solenoid switch is one of the most sensitive parts of the starter. The length of the path covered by the iron core is an important characteristic, for this determines the axial displacement of the engaging gearwheel. If the path of the displacement is shorter than necessary, the gearwheel connection is not appropriate, and if it is longer, the gearwheel will butt on. Moreover, the closing contact of the main circuit must make contact in the appropriate displacement position. The contacts must have burning-up spare, for in operation, when the circuit is closed, and particularly when it is broken, there is intense sparking due to the high amperages, which leads to a reduction of the contacts. To sum up, new structural solutions have to perform with reliability the two main functions of the magnetic switch, which are:

- **Establishing the engagement of the gearwheel** and its disconnection, by means of an intermediary device
- **Closing the main circuit** and its disconnection as fast as possible.

The two functions are in close connection with each other, therefore variants meeting these requirements were developed. The switch mechanism has to be placed on the starter with the shortest possible leads to be used. The mechanism used so far (Figure 2) consists of an iron core coil (1) (electro-magnet), a translation to translation motion transducer (lever) (2) and the driving gear (3). The driving gear performs both linear and rotary movements, through a helical involute profile spline shaft – boss connection.

Fig. 3 shows that the solenoid switch has 3 pre-tensioned springs. The armature return spring (10) ensures that the switch opens again when the solenoid is switched off and the armature returns to its resting position. When the solenoid armature hits the armature shaft (9), the movable switch contact (8) moves against the force of the armature shaft spring (it is not numbered in Fig. 3). When the switch contacts (6, 8) are closed, the main circuit (the hold-in winding activated at this time) is also closed and the contact spring (5) ensures the best possible surface contact. [18]

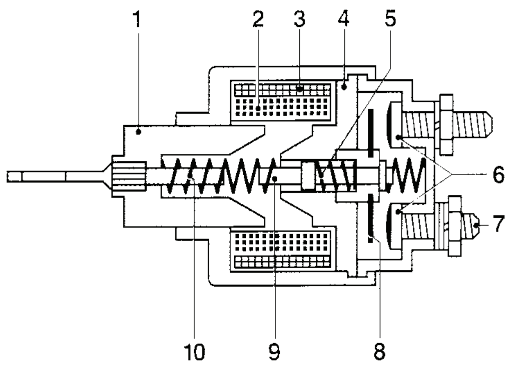

Figure 3: Solenoid switch

The function of the PEM can be divided into five phases. The electromagnetic force has to overcome the force of the pre-tensioned return spring in the first phase. Phase 2 is what is called the free travel phase when the solenoid retracts, but does not operate the pinion-engaging lever. This is significant when the power supply to the solenoid is switched off, because there must be sufficient free travel to allow opening the primary circuit switch. If this were not the case, the pinion-engaging lever would hold the armature in place. The other three phases cover the operation of the three springs *(Fig. 4)*.

The simulation of PEM was performed by Matlab. The simulation investigations resulted in obtaining time curves of the PEM current *(Fig. 5)*, the solenoid armature and the pinion displacement *(Fig. 6)* and velocity, the force of the pinion engaging mechanism. The individual curves represent the individual phases, and the resultant curve shows the joint conditions. The simulation results are compared with the measurement results (dot line in Fig 5 and solid line in Fig 6).

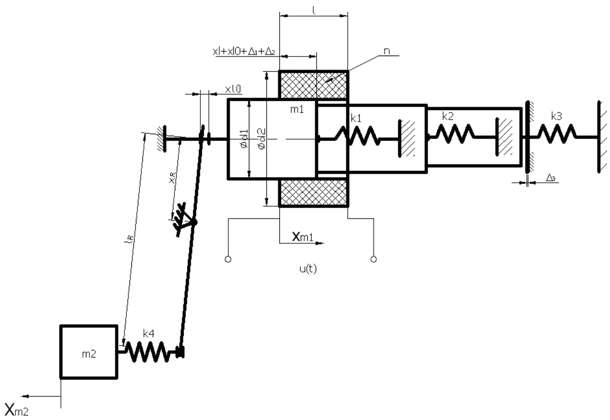

Figure 4: Mechanical model of the PEM

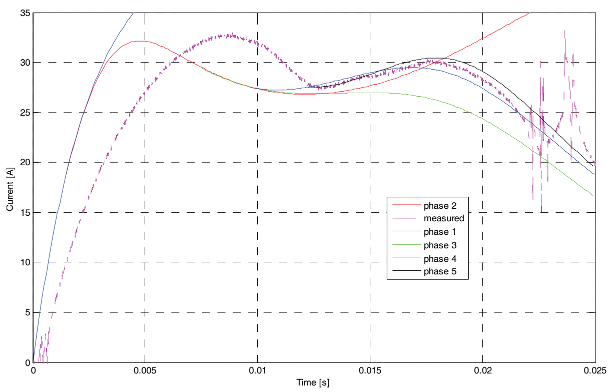

Figure 5: Simulation and measurement results of the PEM current

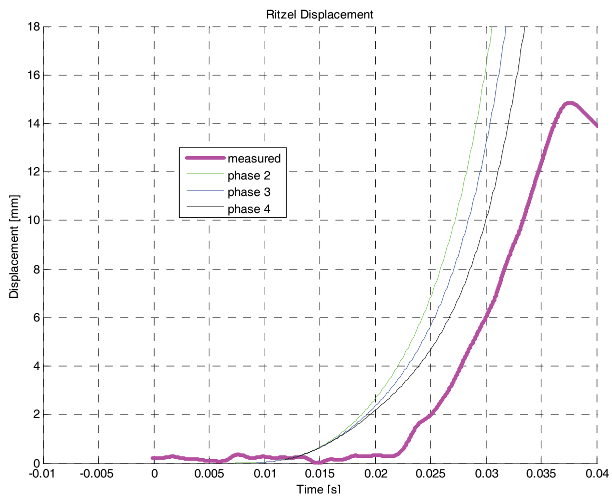

Figure 6: The pinion displacement

Each curve seems to be the same. Naturally, the values of the each curve show some difference. The reason for this difference is that the battery can be modelled by a constant, and we neglect the mass of the spring, the pinion- engaging lever, the armature shaft and the switch contacts, and the form of the solenoid armature, the frictional losses, the electric losses (eddy current losses, switch contact losses, air gap losses, etc.), and the magnetic losses.

Validation of the new solution proposal

The aim was set that the new switch mechanism should be coaxially placed with the axle of the electric motor so that the axial increase in dimension should be as small as possible. The operation of the switch mechanism *(Fig. 7)* is performed by an electric motor (4) and a rotary-linear motion transformer drive (2). In the course of the fatigue testing of the experimental device more than 300,000 switchings were simulated.

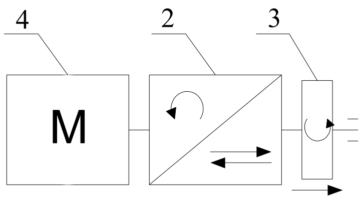

Figure 7: Block scheme of the new PEM

Summary

The primary objective in the development project was to design and construct a state-of-the-art device. Classical design methodology was used to explore the theoretically possible solutions at the principle impact level. It was found that the solution field obtained could be divided into three large groups, such as starters controlled by hydraulic, pneumatic, and electric energy sources. Our findings were proved by the registration of the patent claim no. 2,845,916 by L. J. Pihel on 5 August 1958 called Hydraulic starting system for internal combustion engine, and the publication of the patent by Massami Tanaka of a Starting device with air motor for internal combustion engine (Patent No.: 4,694,791) on 22 September 1987. Various decision preparation methods were used to select and determine the viable solutions. Determination of the development direction – the decision – was always prepared in cooperation with the engineers of the project partner. Design catalogues were prepared and used for each sub-function of the theoretical solutions. These were used to establish that design and development did not each cases mean the conception of something new, but it is much more logical to select the most suitable one of the already existing similar products, and to improve its weak points to fit the modified requirements and boundary conditions.

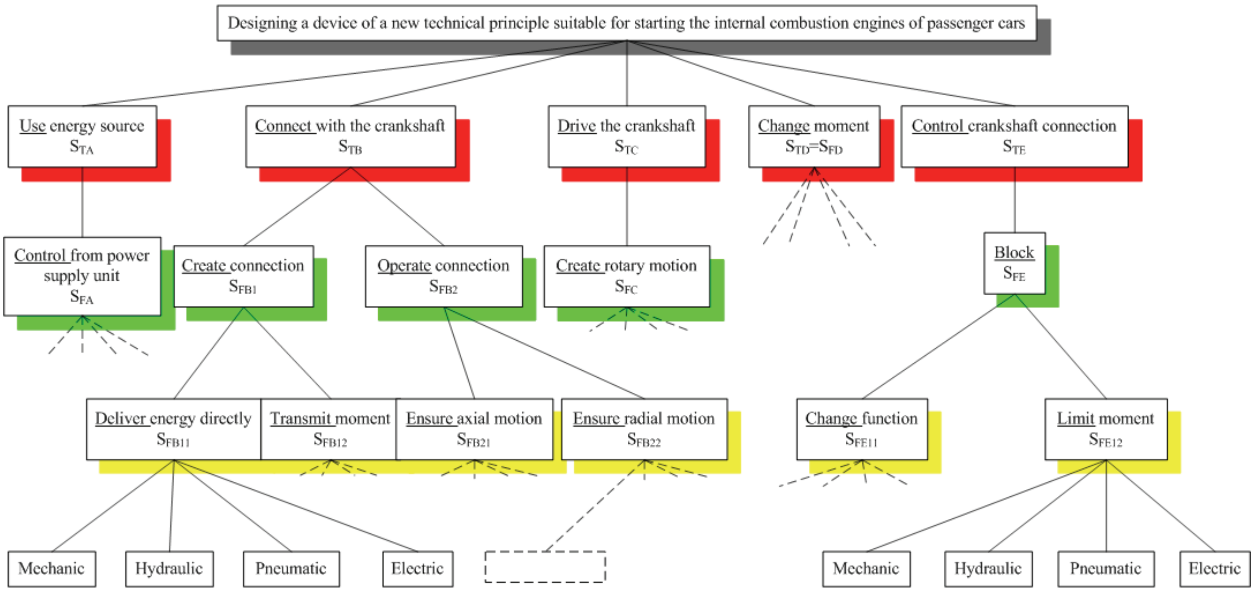

Figure 8: Structure of functions

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