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DESIGN MODIFICATION OF AN INNOVATIVE SPLIT-SINGLE TWO-STROKE ENGINE

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Abstract

A prototype of an innovative split-single two stroke engine is presented. With the aim of increasing the power-to-weight ratio for later mobile use, the individual engine components have to be revised. The focus is on the development process for the redesign of the crankcase. Through a preliminary examination of the necessary CAx systems, an iterative process chain that combines suitable synthesis and analysis tools is derived. This includes the design of the machine elements, a numerical strength verification using FEM and preparing the model for machining.

Keywords: design tools, computer-aided design (CAD), prototyping, finite element method (FEM)

1. Introduction

Internal combustion engines can also make a major contribution to electrified mobility in the future. Their use as mobile power generators or in vehicles, also known as range extenders, is changing the requirements towards small volume, light, rolling bearing mounted engines with a power output of 30 - 50 kW (Tschöke, 2015). According to Schaumann and Schmitz (2010), engines that operate according to the four-stroke principle are the favourable choice. Compared to conventional two-stroke engines, these engines are characterized by lower specific fuel consumption and lower pollutant emissions (Schaumann and Schmitz, 2010). In contrast, two-stroke engines represent an attractive engine concept for the above-mentioned application (Ferrari et al., 2012) and offer enormous advantages in terms of their simple design, weight and space savings, higher performance (Pischinger and Seiffert, 2016) and, for the same design, a production cost that is two times lower than that of a four-stroke-engine (Winkler, 2009).

A two-stroke engine in which the high fuel consumption caused by scavenging and the resulting carbon-hydrogen emissions are minimized is essential for a successful establishment on the market. The basis for this is the split-single engine according to an engine design of DKW (Dampf-Kraft-Wagen) (Zima and Ficht, 2010). The resulting concept has been manufactured as a prototype and has been successfully validated on the test bench. (Diwisch, 2019)

During the development of the prototype, practical aspects such as strength and durability were prioritized and considerations of lightweight construction, which is very important for the mobile application, were left out of the equation. The aim of the project is to prepare the concept for future mobile use e.g. as a range extender. Therefore the next step is to increase the power-to-weight ratio of the engine. The crankcase, which is currently designed as a welded steel construction, offers an enormous potential for weight reduction. A compromise between weight reduction and structural strength is to be

achieved utilizing the design and layout criteria of modern engines, while maintaining compatibility with all other engine components.
In order to achieve the mentioned goal as economically as possible, a process chain for the virtual prototype development of the new housing has to be determined. In addition to tools for the realization of lightweight design, a material selection will be integrated into the process. Numerous CAx systems are available for the individual steps of reworking the design. This includes the adaptation of the CAD design, the dimensioning and design of the required machine elements, a numerical strength and stiffness verification of the housing using FEM (finite element method) and a final production simulation. To minimize the necessary iterations between the individual software tools and thus accelerate the product development process, an intelligent link is required. ICROS (**i**ntelligent **cro**ss-linked **s**imulation) offers a method for creating a suitable process chain. This has already been successfully applied to various problems in the field of prototype development (Alber, 2008; Diwisch, 2019). On this basis, a process chain meeting the requirements is developed and its applicability to the problem is examined.

2. Preliminaries

This section explains the theoretical foundations for the upcoming development. First, the current prototype of the split-single two-stroke engine is described. Then the ICROS method for creating process chains in product development is presented.

2.1. Design of the split-single two stroke engine

Figure 1 shows the sectional view of the double piston engine in use at 120°, 240° and 360° crank angle. If the pistons move, as shown at 120° crank angle, from top to bottom dead centre, the outlet slot is opened first while the inlet slot remains closed. The exhaust gases thus escape into the exhaust system. The charge cycle takes place with open slots between 135° and 225° crank angle. The outlet slot is then closed, which causes charging to take place via the inlet slot, which is still open. From 260° crank angle the compression of the fuel-air mixture takes place.

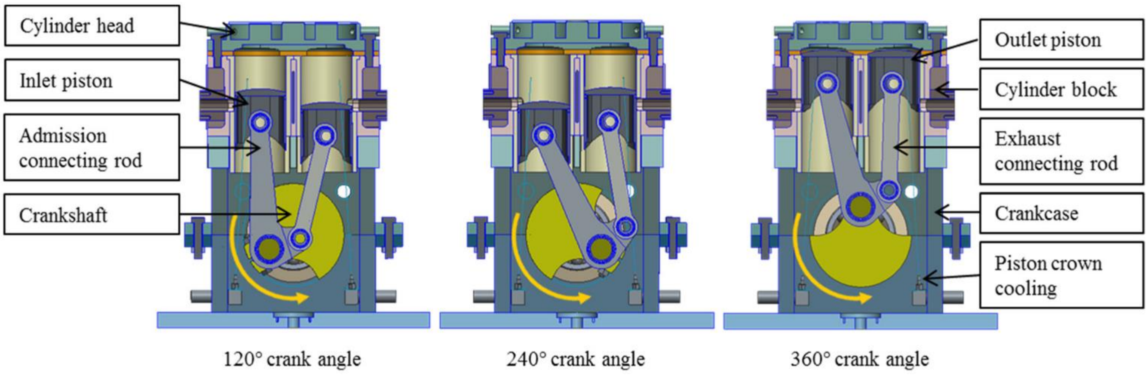

Figure 1. Sectional view of the prototype (Diwisch et al., 2016)

The motor shown has three horizontal separation points and is thus made up of the following four main components:

- Lower crankcase
- Upper crankcase
- cylinder block
- cylinder head

Stud bolts are used for the force-locking connection from cylinder head to crankcase. The crank drive with the Zoller connecting rod is positioned between the two halves of the housing via roller bearings (Zoller, 1935). The aluminium pistons run in the cast iron liners used in the cylinder block. The two-piece crankcase is maintained as welded construction made of S355 steel plates, most of which are CNC (computerized numerical control) machined. The two halves are connected by bolt connections

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distributed around the edge, which absorb the bearing forces of the crank drive and must also ensure the sealing of the system against the environment.

2.2. Creation of process chains with ICROS

The use of CAx systems in product development has established itself across all industries. With their help, the time from the product idea to its creation can be significantly reduced. Virtual prototypes form the basis for this, whereby the costly and time-consuming production of real prototypes for system tests can be reduced to a minimum.

For the application of CAx systems, users can rely on a broad knowledge base. Their usage has long since become part of everyday life and generally no longer requires expert knowledge (Vajna et al., 2018). An overview of selected tools is shown in Figure 2. These can be categorized as synthesis or analysis tools according to Vajna et al. (2018). A synthesis is used to specify product characteristics such as dimensions or material parameters. An analysis serves to record the product properties, which are determined by the defined characteristics. For example, the deformation behaviour or the carbon dioxide balance of the product can be determined using appropriate tools. However, it is not always possible to distinguish clearly between analysis and synthesis tool as the optimization with CAO-Tools uses the finite element method to create design proposals (Frisch, 2015).

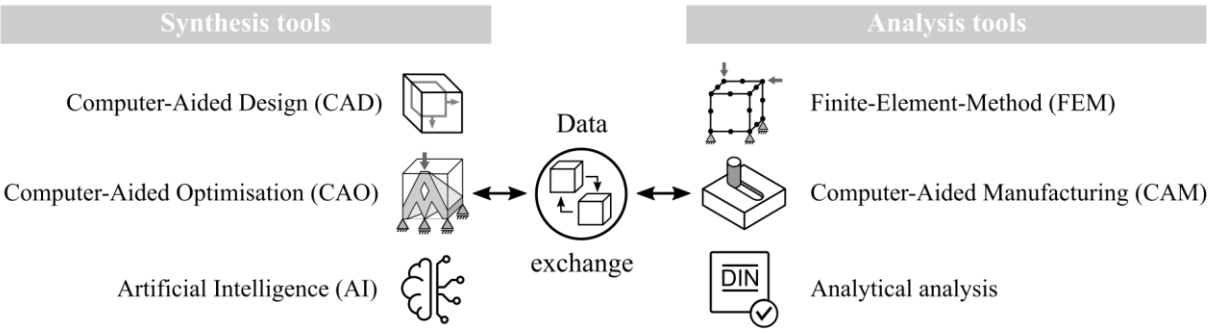

Figure 2. Selection and categorization of CAx systems

Modern products are characterized by increasing complexity. The development of the individual subsystems requires the application and coupling of a multitude of CAx systems. Customer requirements and safety regulations can lead to further demands on the process chain. In structural mechanics, for example, analytical verification calculations of individual machine elements are common in addition to finite element calculations of the overall system.

The development of strategies for an efficient coupling of the individual systems to a process chain is therefore decisive for a competitive product. These should help to make a selection from the available programs and to arrange them in a suitable chronological order. ICROS (**i**ntelligent **cro**ss linked **s**imulation) offers a method for creating such process chains (Alber et al., 2006). The focus here is on the application-oriented creation of a process sequence for the CAx systems to be used, see Figure 3. The arrangement of the individual process steps depends on their mutual dependency (Zapf et al., 2010). If there is a strong dependency, for example between the CAD design and the testing of the component deformation using the finite element method, early coupling of the systems is to be favoured. In this way, necessary changes to the product can be detected and corrected at an early stage.

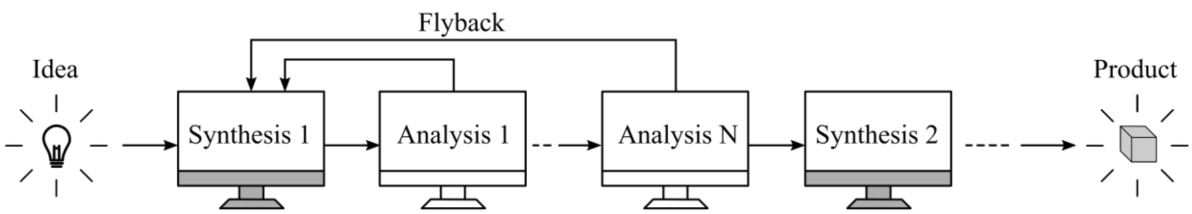

Figure 3. Creation of process chains by suitable combination of synthesis and analysis tools

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The strength of the dependencies between the CAx systems used is always problem-specific and therefore cannot be generally specified. Nevertheless, process chains created once can be transferred to similar problem cases and help to standardize development processes.

3. Definition of aim and method for realization

The redesign of the crankcase of the single-split engine aims to increase the power-to-weight ratio by using a lightweight construction. Compatibility with the existing engine concept is to be maintained. This includes the main engine components such as the crankshaft drive, cylinder block and cylinder head as well as the current system for crankcase ventilation. The design of the crankcase is therefore already largely determined by the installation space requirements of the attachments. Furthermore, the loads occurring during operation at the bearing points of the crankshaft drive can be adopted for the redesign. For the implementation of lightweight construction, a process chain is necessary which, on the one hand, links suitable tools for the synthesis and analysis steps and, on the other hand, keeps the iterations between the development steps to a minimum. As basic method the previously described ICROS is used to create a CAx process chain.

In previous publications, the process chain consisted of CAD, FEM, CAM tools and test bench trials. The process was then extended by a moulding simulation tool to develop a flexible polymer clutch (Alber, 2008). The application on the engine was first introduced with the optimization of the cylinder head cooling. This required the extension of the process with a computer fluid dynamics software (Diwisch et al., 2016). Test bench trials have shown that the previously neglected consideration of the connection between cylinder head and block requires a more detailed examination of the contact conditions. As a result, the components lifted off, which meant that the sealing of the system was no longer guaranteed. For the now planned application of the method, the bolted joints required for the connection should therefore also be considered. In addition to design aspects, the lightweight construction goal can also be achieved by suitable material substitution. Therefore, the choice of material and the resulting interfaces to the synthesis and analysis tools in the process must also be determined and taken into account.

The starting point for the process chain in Figure 4 is the functional prototype and the test bench trials carried out. In these tests the boundary conditions for the following analysis steps could be determined.

The CAD system serves to create the design proposals which is followed up by a finite element analysis to calculate the cutting loads for the joint between the housing parts.

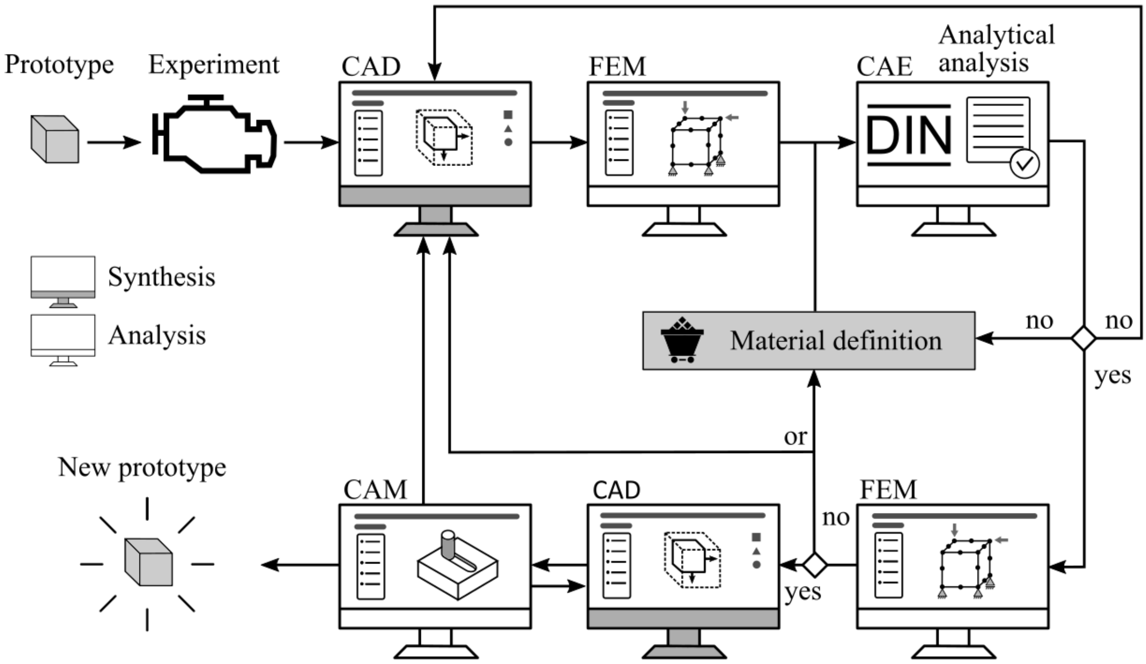

Figure 4. Creation of a process chain with ICROS

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Both the cutting loads and the material definition are necessary for the analytical analysis of the bolted joints. Here, standardized methods exist, which have been continuously developed and can be used via CAE (computer aided engineering) tools. These allow the automatic calculation of different parameter sets of bolted joints. If no suitable connection can be determined, either the design must be adapted or the material definition must be changed. Otherwise the process chain is continued and the design is subjected to a finite element analysis. The evaluation criteria are the stiffness and stress of the housing as well as the contact state in the joint. In case the required stiffness is too low, the maximum bearable stress is exceeded or the housing halves are lifting off of each other, changes must be made. To shorten the product development process, a material with suitable strength properties can be selected if possible. Otherwise the design must be revised and the process chain must be run through again. For preparing a model that is suitable for production, the CAD design must be modified, e.g. in case of casting appropriate allowances for shrinkage and the modelling of draft angles are required. This is checked at the end of the process by a CAM manufacturing simulation to ensure the manufacturability. Small details can be changed directly in the previous CAD design step. Major changes require a renewed analytical and numerical proof. Ultimately, a compromise between the weight reduction and the structural strength and stiffness has to be achieved.

4. Modification of the crankcase design

The previously derived process chain in Figure 5 is now to be used for the adaptation design of the crankcase.

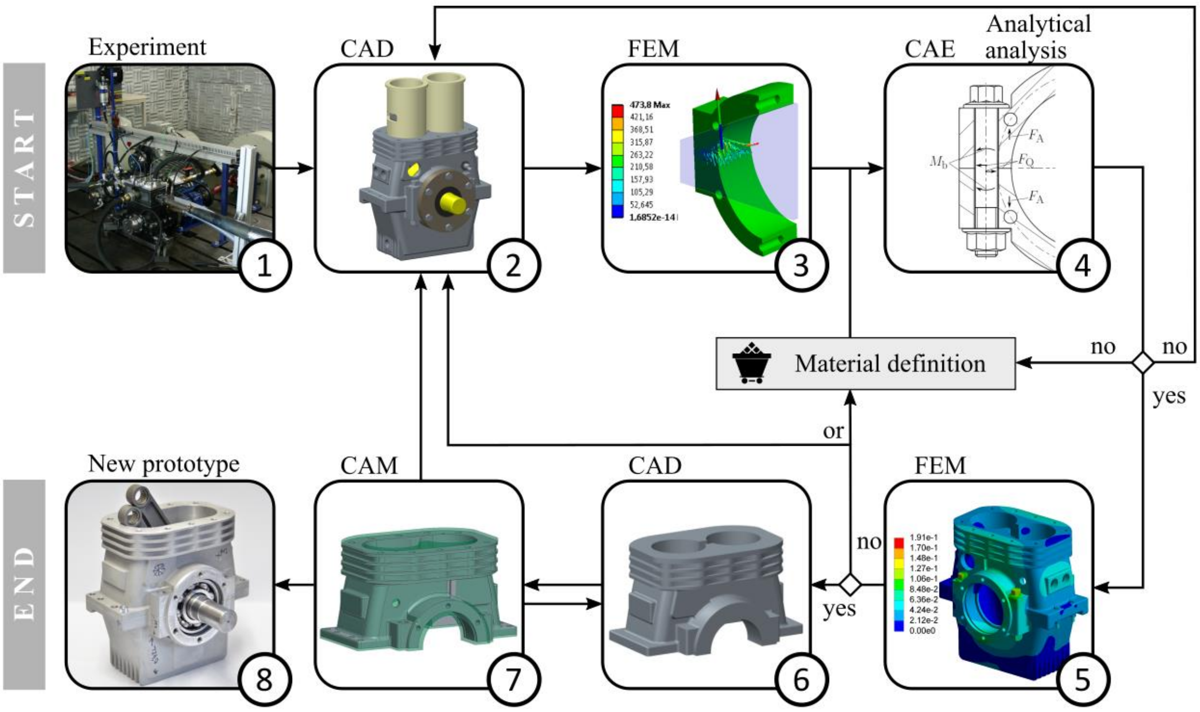

Figure 5. Applying ICROS for the modification of the crank case design

The originally used welded steel construction of the crankcase allowed the design and testing of the crankshaft drive (step one in Figure 5). The loads acting on the bearing points can be determined from the calculations and measurements carried out within the framework of mass balancing. The minimum required installation space, which is needed for the redesign in CAD (step two), is determined by the clearance zone of the Zoller connecting rod geometry. This is described by the envelope curve of the movement during one complete revolution, which has the characteristic form of a fiddle, see Figure 6 (van Basshuysen and Schäfer, 2017). Further requirements result e.g. from the position of the connections for the crankcase ventilation and the injection nozzles for the top of the piston cooling.

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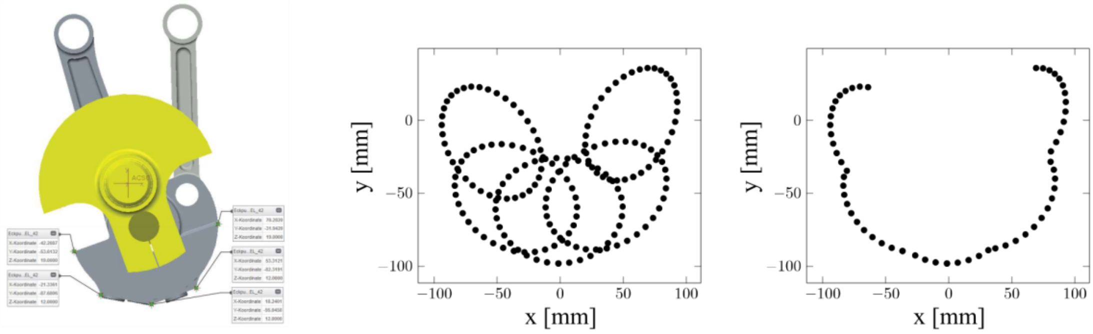

(a) Measure points (b) Line of movement (c) Envelope curve

Figure 6. Determination of the envelope curve for the crank shaft drive

In the first iteration loop (steps two to four in Figure 5), the bolted joints are designed. These must absorb the forces generated at the crank drive during operation and prevent the housing halves from lifting off. The VDI 2230 Part 1 (2014) guideline, which is used via a commercial CAE application, is applied for the design of the highly stressed bolt connections. In (VDI 2230 Part 2, 2014) procedures to isolate the individual connection from the multi-bolt connection are outlined.

Using the model symmetry, a simplified FEM model of the bearing location is created (step three). With this model, the operating forces and moments at the joint of the connection can be determined and used as input variables for the analytical verification calculation (step four) (Rieg et al., 2019). Due to the simplified model, different designs can be quickly created and calculated. For the calculation of the bolt connection the specification of a suitable material for the housing halves is necessary. In order to achieve the goal of lightweight construction and low-cost production in small series, aluminium casting alloys are the favourable choice.

In the fifth step, the overall system is verified using a FEM contact model. The bolts are taken into account as fasteners and loaded with the analytically calculated prestressing forces. A dynamic safety factor is considered for the resulting loads at the bearing points. The displacements and stresses occurring in the system are evaluated. Critical stresses occur particularly in the bearing seat area and are compared with the permissible strength values of the aluminium alloy. In addition, the durability of the bolted joints is checked again.

Of particular interest here is the contact condition in the parting line between the upper and lower halves of the housing in Figure 7. The aim is to prevent the lift off over the entire joint. The evaluation in the FE model helps to identify the lifting contact points (contact state close) and thus shows undersized or unfavourably positioned bolt connections.

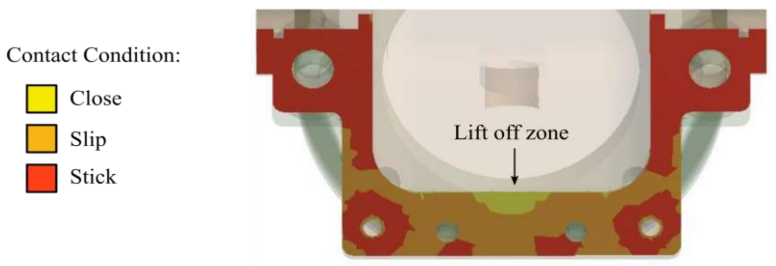

Figure 7. Contact condition between the upper and lower crank case

Finally, the CAD design is prepared for production. The housing is manufactured from AlSi10Mg by gravity die casting. For this purpose, a PMMA model of the lost mould is additively printed from the CAD data provided (Roller and Buck, 2016). To ensure the manufacturability, a model is created which takes the given shrinkage dimension into account (step six). Furthermore additional material is applied to the bearing seats and the joints between the housing halves and the cylinder block. A production simulation is used to generate the NC code for the post-processing of the housing (step seven).

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Figure 8 shows a comparison of the old and new crankcases. By adapting the design with an aluminium alloy, the component weight could be reduced from approx. 38.0 kg to 4.4 kg. A large part of the reduction can be achieved due to the elimination of the massive base plate, which was intended for clamping on the machine bed. For the new crankcase, a frame construction for a four-point bearing is being planned instead.

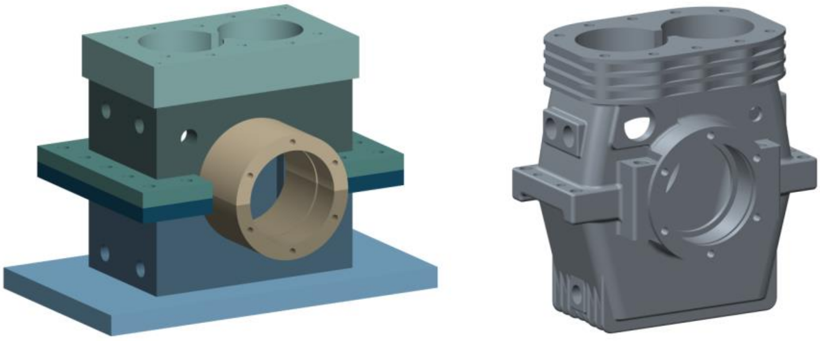

Figure 8. Comparison of the old crankcase (left) with the modified design (right)

5. Conclusion

A two-stroke engine concept in which the high fuel consumption caused by the scavenging and the resulting carbon-hydrogen exhaust emissions can be minimized is provided by the split-single engine according to DKW (Dampf-Kraft-Wagen). The resulting concept has been manufactured as a prototype and was successfully validated on the test bench.

With the aim of increasing the power-to-weight ratio for later mobile use, the individual engine components have to be revised. This paper describes the development process for the redesign of the crankcase. With the focus on cost-effective production a compromise between the achieved weight reduction and the structural strength as well as the stiffness is aimed at.

In order to achieve this goal as economically as possible, a process chain for the virtual prototype development of the new housing is necessary. A suitable framework for this task offers ICROS (**i**ntelligent **cro**ss-**l**inked **s**imulation).

The method was used to derive an iterative process chain. To minimize unnecessary iterations in product development the individual program systems are linked according to their mutual dependence. For synthesis steps a CAD system is used to create the design. The bolt joints connecting the housing parts are designed using a CAE system, which offers the relevant calculation standards. The required housing stiffness and strength is verified using the finite element method (FEM). A manufacturing simulation (CAM) also ensures manufacturability. The method was further extended by a material selection, which influences the design process in different steps. The process chain created was successfully used for the redesign of the crankcase.

For the procedure described above, the additional inclusion of vibration simulations to check the NVH (noise vibration harshness) properties of the engine will be an option for future work. This could be used to derive further requirements for the stiffening of the housing in order to dampen the noise and vibrations that occur during operation.

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