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CPR for the hydraulic industry: The new design of the Innas Free Piston Engine

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Summary

In this paper the Dutch company's NOAX and Innas present the CENTAUR, a new Innas Free Piston Engine (IFPE). In previous models the IFPE could operate in a wide pressure range between 5 and 30 MPa. Contrary to this, the CENTAUR is designed for a rather narrow band width between 26 and 32 MPa. Combined with a reduction of the piston stroke and some other design changes, the limitation of the pump pressure has resulted in a free piston engine which is much more cost effective than the previous model of the IFPE. The engine weight and volume (per unit of hydraulic output power) have been reduced by a factor of three and the number of components has been reduced with more than 60%. Furthermore the CENTAUR is expected to improve the average cycle efficiency and emissions of the free piston engine.

The CENTAUR is specifically designed for application in hydraulic systems with a common pressure rail (CPR). This CPR, with hydropneumatic accumulators connected to it, separates the pump unit from the cylinders and hydraulic motors. The hydraulic transformer (IHT) which has been developed three years ago by Innas acts as an interface between the hydraulic cylinders and constant displacement motors on the one side and the common pressure rail on the other side. This paper will emphasise on the advantages of CPR-systems in combination with the new CENTAUR.

1 Introduction

Imagine a system with many load points. A complex application, to be manufactured for a customer that sets high demands for ease of control and operation. Of course the system needs to be stable, reliable and durable and needs to fulfil all regulations and demands with respect to safety, energy efficiency, emissions and noise. Last but not least the system has to be sold, not only to one customer but if possible to many customers, thereby fulfilling the different demands of the different customers as much as possible. This means the system has to be based on a simple concept built upon modules that can be chosen according to client specifications.

Many electric systems fulfil these demands. Most hydraulic systems don't. The reason behind this is the fundamental difference in system approach:

- Electric systems are based on a common (voltage) rail. This rail separates the two essential functions of the system: energy generation on the one side and load control on the other side. Designers can build their system around the backbone of this 'grid', designing their motors as separate modules. They can arrange their systems on the basis of these building blocks as easy as choosing electric devices to be connected to the electricity grid.
- Hydraulic systems are flow ("current") controlled. Since flow always follows the path of least resistance, the flow must be controlled from the source (the pump) to the various load points (the hydraulic motors and cylinders). This leads to complex star-shaped networks which look like the monstrous serpent Hydra from the Greek Mythology (see figure 1). Especially when complex control strategies are applied the design of these systems is elaborate and can only be handled by specialists.

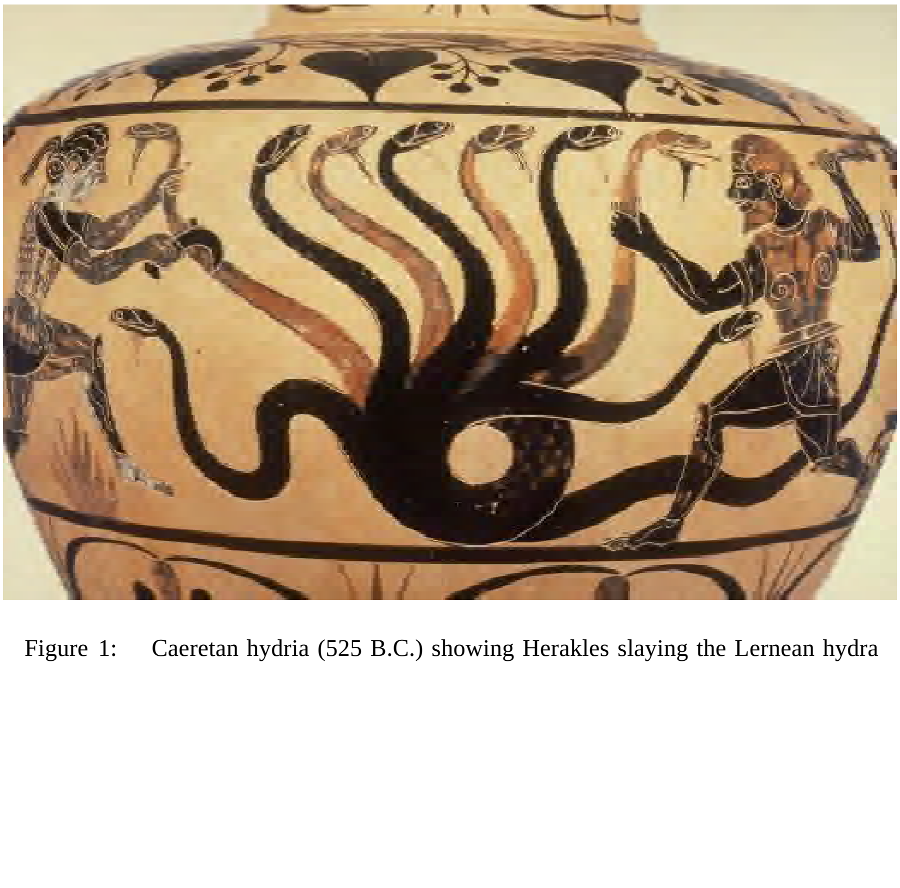

Figure 1: Caeretan hydria (525 B.C.) showing Herakles slaying the Lernean hydra

The flow control approach forces the hydraulic industry in a defence position, thereby loosing terrain to other means of energy conversion and transport that are more flexible and better qualified for the demands of today’s customers and markets. As an answer the hydraulic industry has to pick up the course towards secondary control systems that Nikolaus, Kordak and others have plotted many years before [1…8]. A course that is based on a common pressure rail (CPR) with an imposed pressure as the basis of control in stead of an imposed flow.

2 New CPR components

New components will be necessary to realise this CPR-approach, two of which have been designed by the Dutch engineering company Innas:

- Innas Free Piston Engine (IFPE [9…16])
- Innas Hydraulic Transformer (IHT [15…18])

This article will describe the CENTAUR, a new free piston engine Innas has developed especially for CPR-systems. Whereas a centaur is a combination of a man and a horse, the free piston engine is an integrated combination of an internal combustion engine and a hydraulic pump. The core of this engine is the piston which is a combustion piston on one end and a hydraulic plunger on the other end (see figure 2). The piston is not connected to any mechanism but is free to move within the limitations of the cylinders.

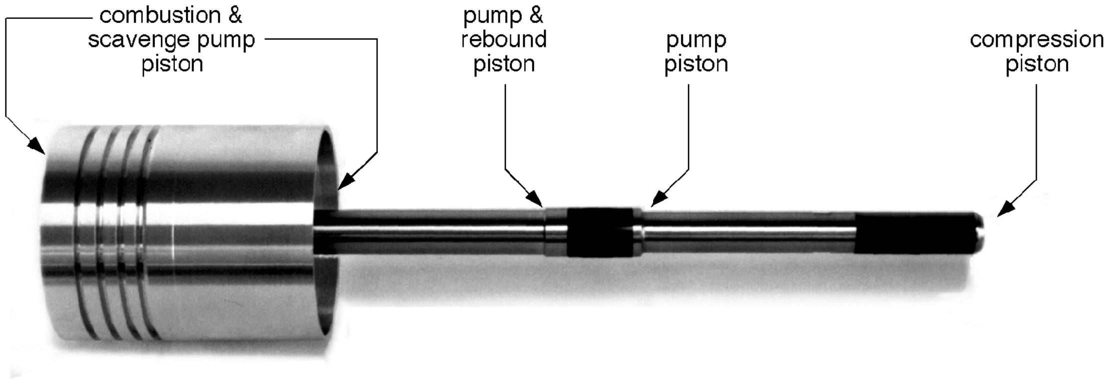

Figure 2: Piston of the CENTAUR

The direct combination of the combustion piston and the hydraulic pump plunger avoids the elaborate mechanisms which are needed in current motors and pumps (see figure 3). Furthermore the IFPE is a two-stroke engine with a simple port controlled scavenge process. The backside of the combustion piston is used as the scavenge pump. This results in a compact and cost-effective construction.

The integrated design of a internal combustion engine and a pump looks so obvious that it raises the question why it has not been developed before. There are several answers to this question.

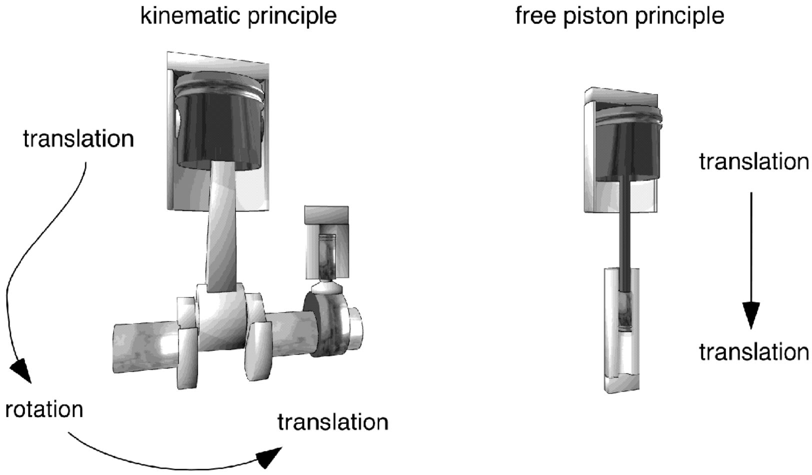

Figure 3: conventional 'kinematic' principle versus free piston principle

The first answer concerns the control of the free piston engine. For internal combustion engines the control of the compression ratio i.e. of the piston movement is very critical. In current engines, the mechanism of the piston rod and crank shaft defines the geometrical end positions of the piston trajectory i.e. of the compression ratio. Without a mechanism attached to the piston, the control of the free piston has to be realised by means of sensors, actuators and electronics. Also the synchronisation of the piston movement with the fuel injection can only be realised by means of electronic control. Today the electronic industry produces these components in a large variety at low cost and with a high reliability. But until a few years ago, these components were not available and the control problems of the free piston engine could not be solved at acceptable costs and performance.

Another reason why free piston engines have not been developed successfully in the past is the need of accumulators. The free piston engine delivers its hydraulic energy in pulses. In order to avoid cavitation at the suction side and pressure pulsation's in the rest of the system, hydropneumatic accumulators must be used. Although very effective for pulsation damping, the accumulators act as an integrator in the hydraulic system thereby slowing down the dynamic response in the pressure domain to unacceptably low levels.

The slow dynamic response in the pressure domain is however only a problem for flow controlled systems. In CPR-systems the load control is realised at the motor side of the system and the accumulators of the common pressure rail have no effects on the load response of the system. Accumulators are even welcome in these systems since they provide the possibility to recuperate energy and perform power management.

Yet, CPR- or secondary controlled systems have not been a success so far. Although secondary controlled motors have been developed in the past, the difficulty of controlling these motors resulted in expensive solutions. Moreover there was not an acceptable solution for controlling hydraulic cylinders which have a fixed piston area and cannot be made variable. The design of the Innas Hydraulic Transformer (figure 4) seems to have resolved this issue.

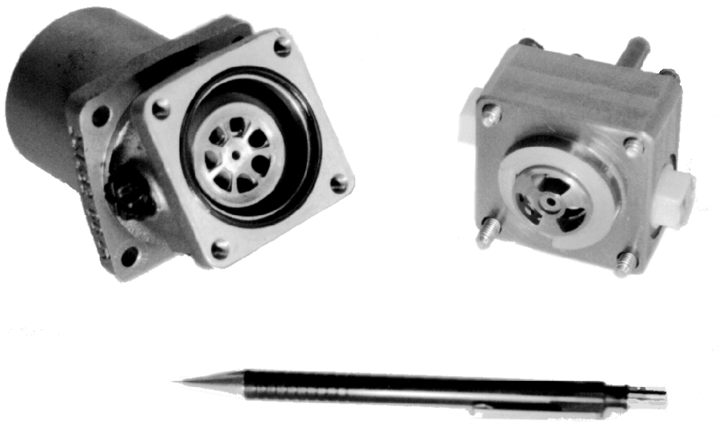

Figure 4: Opened prototype of the Innas Hydraulic Transformer (IHT). On the right side the valve plate with three ports can be seen. This valve plate can be rotated over an angle of about 70° to control the output pressure and flow of the IHT.

The Innas Hydraulic Transformer or IHT is a compact hydraulic version of a continuously variable transmission. It converts a given input flow at a certain pressure to an output flow at any other pressure level. The conversion is in principle reversible i.e. the product of pressure and flow at the input is (in principle) equal to the product of pressure of flow at the output (similar to an electric transformer where the product of voltage and current in principle remains constant). This indicates that the IHT has a high efficiency. Furthermore the IHT can also act as a pressure amplifier and transform hydraulic energy to a higher pressure than the input level. The transformation ratio between input and output can be varied manually or by means of a direct electric control. Of great importance for secondary control is the high dynamic response of the IHT.

The hydraulic transformer Innas has developed is the missing link in connecting hydraulic cylinders to a common pressure rail, thereby combining a high efficiency with good controllability. But also in combination with constant displacement hydraulic motors the IHT has proven to be an efficient and cost effective solution. A comprehensive description of the IHT can be found in the literature [15-18]. This paper will emphasise on the effects the IHT or the CPR-approach had on the design of the CENTAUR.

3 Innas Free Piston Engine in CPR-systems

Typical for a common pressure rail with accumulators is the relatively constant pressure level at which the hydraulic energy is transported and distributed. Given this ‘constant’ pressure, changes in the power need of the total system will always be seen predominantly in the form of flow variations (See figure 5). This means that all transients at the load side, whether these are in the speed or the force domain, are reflected at the common pressure rail in the form of flow variations. This can be clearly seen in figure 5 where points 2 and 3 require the same flow (but a different pressure level) at the load points, whereas the required corresponding flows at the common pressure rail are quite different for the two points. Secondary controlled units and transformers take care of this transformation to the common pressure rail.

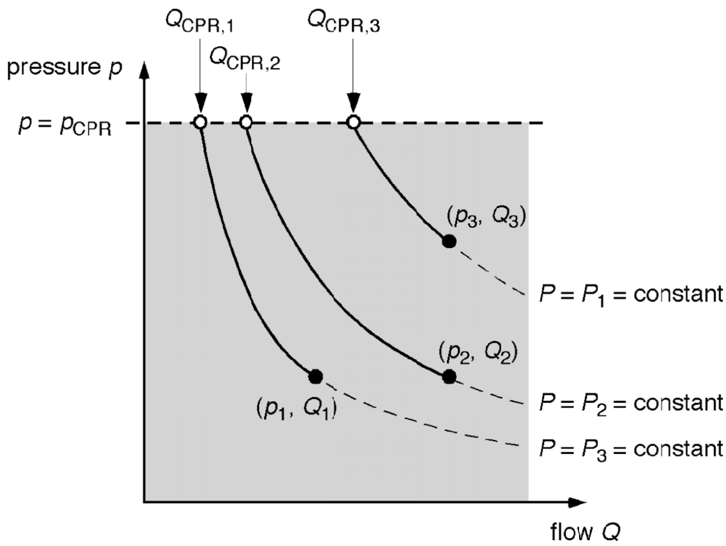

Figure 5: Pressure and flow conversion for three load points in a CPR-system

The accumulators of the common pressure rail can accommodate a part of these flow transients. But due to the limited capacity of these accumulators, the pump will have to supply the rest. The Innas Free Piston Engine is especially fitted for this task. It has an extremely high dynamic response in the flow domain. Unlike conventional engines, the IFPE can operate between 0 Hz and the maximum piston frequency, making it possible to supply any kind of desired flow. Furthermore the frequency i.e. the rate of output flow of the IFPE can change instantaneously. In a conventional engine the rate of speed change is limited by the inertia of the engine-pump-combination.

The other advantage of the Innas Free Piston Engine relates to the efficiency and the exhaust emissions. Current engine-pump-combinations are characterised by having a near maximum efficiency in a limited area. In most applications, the system is never operated in this best point. As a result the average cycle efficiency is often much lower than the best point. A similar situation can be seen with respect to particulates, NO_x or other emissions.

In the IFPE the emissions and efficiency can be optimised for the specific movement of the free piston. Unlike current crankshaft engines the piston movement itself is not influenced by the engine speed. Therefore the optimised values for emissions and efficiency are in principle valid for the complete frequency, flow and power domain. In other words, the IFPE will have a better cycle efficiency and lower average emissions than the equivalent conventional engine will have.

Finally, like all hydraulic free piston engines, the IFPE directly produces hydraulic energy. This gives a clear advantage over current combinations of internal combustion engines and pumps in terms of costs, performance, efficiency and emissions.

4 Critical design parameters of free piston engines

The principle of the free piston engine is as old as the internal combustion engine. In the 17th century the first experiments with internal combustion were performed on a free piston engine. Since then, many engineers have been appealed by the simplicity of the principle. Within the group of hydraulic free piston engines the Innas Free Piston Engine represents only one of the many different design concepts. Table 1 shows the general design characteristics of the Innas Free Piston Engine.

Table 1: Main design characteristics of the Innas Free Piston Engine

- single piston (not an opposed piston or dual piston)
- stepped hydraulic piston with three piston area's:
  - the compression piston for supplying the compression energy to the piston
  - the pump piston which delivers part of the effective hydraulic power
  - the pump and rebound piston which delivers the other part of the hydraulic power and limits the bouncing movement of the piston in the bottom dead centre due to the compressibility of the oil
- control of the compression ratio by means of controlling the pressure in the separate compression accumulator
- flow control by means of pulse pause modulation (PPM) of the piston frequency
- closed loop electronic control of the fuel injection system
- HEUI fuel injection system

The first rule in designing a free piston engine is that it is not only a pump or (only) a motor. It is a direct combination of a combustion cycle and a pump cycle, governed by means of a control system. Whatever happens in the combustion cycle will have an effect on the pump cycle and vice versa. The most critical part in the sequence of these energy conversion processes is the combustion cycle. The efficiency, the emissions, the noise, the durability, the cold start behaviour and many other characteristics are all in the first place determined by the combustion process. The quality of this process is subsequently foremost determined by the compression ratio i.e. by the quality of the control of the amount of energy that is supplied to the piston by the hydraulic system during the compression stroke.

To our believe the only way to realise the accurate control of the compression ratio is the single piston principle [10, 12]. This principle also allows to control the frequency of the engine by means of pulse-pause-modulation [11, 12] resulting in a flow that can be fully varied between zero and maximum. This is contrary to free piston engines build on the basis of the dual-piston principle that can only run at a maximum (natural) frequency. For opposed piston engines the control of the piston frequency is not a problem. The Achilles heel of this principle is however the synchronisation of the two free moving pistons.

Often the unbalanced movement of the piston is seen as the key obstacle of the single piston principle since this unbalance is believed to result in an unacceptable vibration of the engine block. The solution for this vibration issue is found in choosing a correct mounting of the engine. The movement of the engine block is a reaction to the movement of the piston. In a free piston engine the piston movement is more or less fixed and not dependent of the piston frequency. As a result the corresponding movement of the engine block also has a typical set of harmonic frequency's that, aside from the engine frequency itself, is independent of the flow and the hydraulic output power. This is different from current engines were the full harmonic spectrum is directly related to the engine speed. The typical behaviour of the free piston engine permits to choose engine mountings that avoid vibration transfer to the chassis, thereby avoiding the transfer of most vibrations. If necessary the piston frequency can be controlled in a way to avoid certain unwanted points of resonance. This strategy couldeventually also be applied for avoiding possible area's in the piston frequency domain where the scavenge efficiency is poor.

The principal advantage of the crankshaft mechanism in current engines is the build-in guaranty that the piston always will follow a certain trajectory, independent of the many variations in engine operation:

- engine and intake air temperature,
- air pressure,
- fuel quality,
- variations of the injection system,
- engine efficiency,
- load,
- speed.

In free piston engines these often unpredictable variations will lead to a change of the energy balance over the piston. This can lead to deviations of the piston movement i.e. in the end positions. These deviations are cumulative: although maybe small between successive strokes, the stroke to stroke variations can build up to rather large changes in engine behaviour and characteristics, even resulting in frequent miss firings. For the IFPE with its pulse-pause-modulation there are even two extra variations:

- rebound of the piston at the end of the expansion stroke due to the expansion of the oil volumes in the hydraulic cylinders
- creep of the piston while waiting for a new stroke.

The control of these variations in an inexpensive but effective way has been the most difficult task in designing the IFPE in the past years. Without the developments in the field of electronics, sensors and actuators this would not have been possible. Especially the injection of the diesel fuel has been difficult to realise in the free piston engine because of the lack of a mechanism connected to the piston to synchronise the injection events to the piston movement. The hydraulic electronic unit injector (HEUI) developed by Caterpillar, the availability of low-cost but reliable position sensors and the electronic control have solved this issue [14].

5. Influence of CPR on the design of the CENTAUR

It is evident that the Innas Free Piston Engine is very suited for CPR systems and will improve the efficiency and exhaust emissions of these systems. It is also clear that the integrated design of the IFPE could substantially reduce the costs of these systems. The opposite however is also true: the choice to focus the design of the CENTAUR on CPR-systems has had a very positive effect on the characteristics and costs of the engine. Whereas earlier the IFPE had to be designed for a wide pressure range, now the pressure range would be set by the almost constant pressure of the common pressure rail. Although it might seem insignificant, this change had a dramatic impact on the design resulting in a reduction of complexity and costs on the one hand and an improvement of the performance and characteristics on the other hand:

- The pump pressure could be chosen as such that it is always higher than the pressure level of the compression accumulator. This allows a simple strategy to control the pressure level of the compression accumulator as well as charging the injection system at the necessary pressure level.
- The rebound piston (see figure 2), which is necessary to restrict the bouncing movement of the piston at the end of the expansion stroke, can now be charged with the pump pressure. This results in a simpler bearing and sealing of the hydraulic part of the piston.
- The small pressure range results in small accumulators. Aside from the direct positive effects this has on engine size, weight and costs, the large and heavy construction needed to mount the accumulators on the engine could be avoided.
- The pump action can be split between the compression and expansion stroke. This results in smaller pressure pulsation's.
- In case of a misfire, the piston needs to be returned to its starting position in the bottom dead centre. This is realised by means of an internal hydraulic circuit which is integrated in the design of the IFPE. Given the high pump pressures in the case of the CPR-concept, this system could become much more simple than in the previous model of the IFPE. Figure 6 shows the hydraulic diagram of the previous IFPE,

highlighting the components that were needed for the return procedure. Due to the large pump pressure range a miss firing might also occur at a low level of the pump pressure. For that reason a pump and a special, ring shaped piston was was needed to bring the piston back to the starting position. In the new CENTAUR these components were not needed anymore (see figure 9).

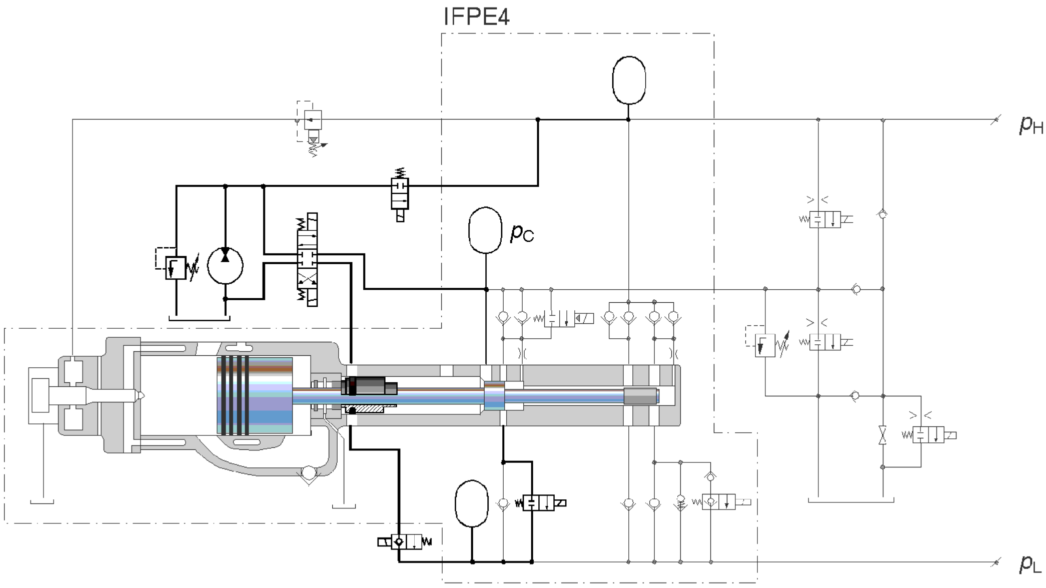

Figure 6: Hydraulic diagram of the previous IFPE model (IFPE4) highlighting the components needed to bring the piston to the starting position after a miss fire.

- The smaller range of the pump pressures implicates that the indicated work of the combustion cycle is also more or less constant. As a consequence the combustion process can be better optimised with respect to efficiency and emissions.
- Since the efficiency of the free piston engine is higher at high loads i.e. high pump pressures, the average cycle efficiency will be higher than before when the engine had to work in a wide pressure range.
- The narrow pressure band width of the CPR-system also allows a better optimisation of the drive of the cooling water pump, the generator the fuel pump and other auxiliaries, resulting in a reduced fuel consumption.

It is not yet clear what the effects of the limited pressure range will be on the noise level of the engine. It is well known that high engine loads result in an increase of the noise level with a few decibel. On the other hand the application of transformers could well lower the peak pressure levels using the amplifier capabilities of the IHT to create the necessary peak pressures whereas the rail pressure can be kept at a medium pressure level. Of a larger influence on the noise level will be the improvement of the stiffness and the reduced resonance area of the new design of the free piston engine. This is for a large part due to the CPR-concept since this concept allows to reduce the size of the accumulators on the engine itself.

6 Reduction of the piston stroke

The stroke and the bore size of an internal combustion engine have an important effect on the power density. A reduction of the cylinder dimensions results in a decrease of the indicated work and thus of the maximum load. The maximum power of an engine is however not only determined by the maximum load but also by the maximum speed. In free piston engines the speed is –amongst others– determined by the piston mass. The shorter stroke leads to a reduction of the piston length and therefore to a reduced piston mass. If, on the other hand, the forces on the piston remain constant, the mass reduction results in an increase of the piston acceleration and thus in a higher piston frequency. Moreover, the piston can travel a shorter stroke in less time. This will also increase the maximum piston frequency. These effects indicate that a decrease of the stroke length has two opposite effects on the power output of a free piston engine:

- on the one hand it will decrease the power output since a shorter stroke will result in a smaller combustion cylinder volume;
- on the other hand a shorter stroke results in a higher piston frequency and, with that, in a higher power output.

At a first glance it looks like the increase of the piston frequency would compensate completely the decrease of the indicated power due to the reduced cylinder volume. A reduction of the stroke length would then be very favourable since the engine size would be reduced whereas (again in theory) the maximum output power would remain constant.

There is however a number of restrictions that will limit the reduction of the piston stroke. Some effects we do not know yet, especially on the combustion side. Since there is not a complete analytical understanding of the ignition and combustion processes in internal combustion engines, predictions can often only be made with a large margin of uncertainty. For certain, the shorter stroke and reduced piston mass will increase the piston acceleration around the top dead centre (TDC) i.e. during the combustion process (see figure 7). Theoretical research at the University of Wisconsin [19] has shown that an increase of the piston speed results in a faster combustion, lower emissions (both NO_x and soot) and an improved efficiency. It is nevertheless yet to be seen to what extent the experiments will validate these calculations, especially in the case of the free piston engine, but at least the trend is positive.

Restrictions concerning the stroke to bore ratio are the in-cylinder scavenge processes and the heat load of the combustion piston. The heat load of the piston crown can be reduced by introducing extra means for cooling. The scavenge process can be optimised also for the higher frequency's by tuning the exhaust and intake systems especially for the higher frequency domain, whereas for the lower frequency's the longer waiting period of the piston in the bottom dead centre can be used for improving the scavenge process.

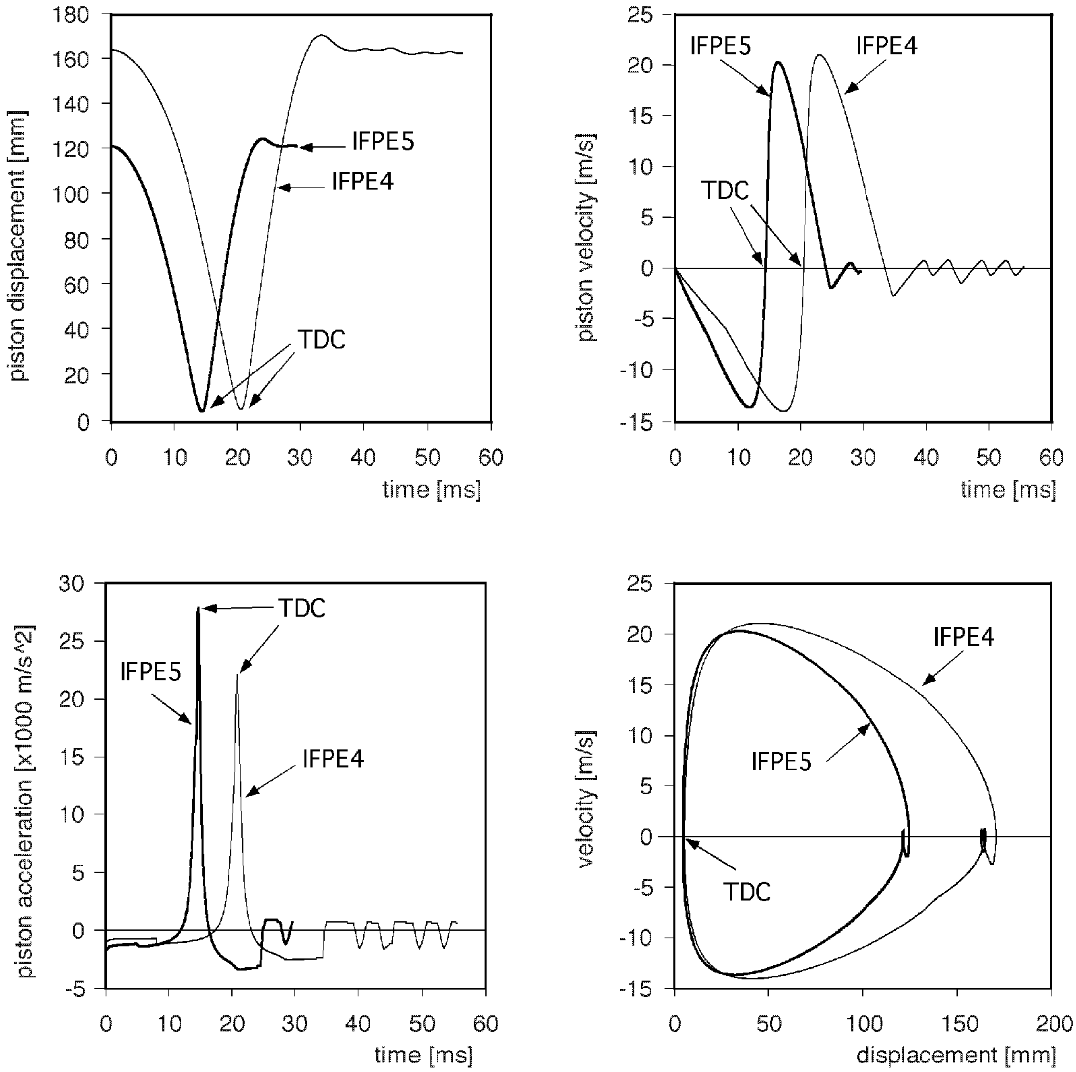

Figure 7: Comparison of the piston dynamics between the CENTAUR (IFPE5) and the previous IFPE4-model (TDC = Top Dead Centre point at the end of the compression stroke)

On the hydraulic side the switching of the check valves on the pump side of the free piston engine and the increased acceleration of the oil columns sets some limits to the increase of the piston frequency. Also here the situation can be improved by for instance changing the design of the check valves. Last but not least it has to be conside-red that the valves in the hydraulic block need space, as well as the internal connecting lines. Eventually the length of the hydraulic block will get too short to give room to all the components and there will be no more advantage in terms of size or weight.

7 Description of the new IFPE

For the new CENTAUR we have chosen a bore of 110 mm and a stroke of 120 mm. Combined with a piston mass of around 2,6 kg this results in a maximum frequency of 42 Hz. This is 50% higher than the previous IFPE.

The shorter stroke and the limited pressure range of the common pressure rail have resulted in a free piston engine that is much smaller than its predecessor. Figure 8 shows the differences in dimensions, weight, power and power density. As can be seen the power density has been increased by a factor of three. The comparison is based on the engine block itself, excluding the intake, exhaust and auxiliary equipment. But also these components will be reduced in size and weight.

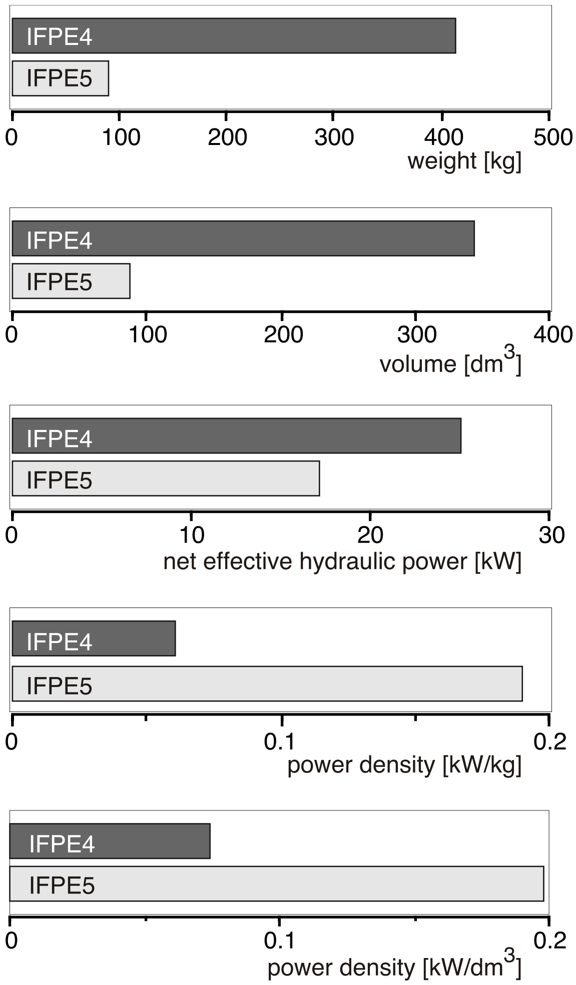

Figure 8: Power density of the new CENTAUR (IFPE5) compared to the old IFPE4

As can be seen in figure 8 the net effective power of the new engine has been reduced to about 17 kW. The new power level has been chosen on the basis of a market research, showing the largest grow possibilities in the smaller engine sector. In this respect it is important to realise that the power level of the free piston engine cannot be compared directly to the power level of the internal combustion engine it replaces. First of all the free piston engine directly produces hydraulic power, whereas the power of the original engine still has to be converted into hydraulic power by means of one or more pumps. The energy losses of this conversion will also reduce the maximum hydraulic output power.

Furthermore the energy efficiency of CPR-systems will in many cases be higher than of comparable flow controlled systems. This could for instance be the case if the open centre steering systems are replaced by closed centre steering systems. Finally the accumulators in the CPR-system can also be used as power sources. Although the energy capacity of these accumulators is limited, in many applications the peak power is only required for short intervals. In those applications the accumulators can be used as peak shavers, thereby limiting the maximum power need of the engine.

Aside from the weight and dimensions, also the complexity of the hydraulic system is reduced to a large extend (see paragraph 5 of this paper). In the predecessor of the CENTAUR, the number of valves to control the engine was that high and the hydraulic circuitry was so much complicated, that a separate valve block was necessary. This manifold had to be connected to the free piston engine with a relatively large number of hoses. In the CENTAUR the number of directional valves could be reduced by more than a factor of two. What was left could be integrated in the hydraulic part of the CENTAUR, thereby avoiding the valve block completely (see figure 9).

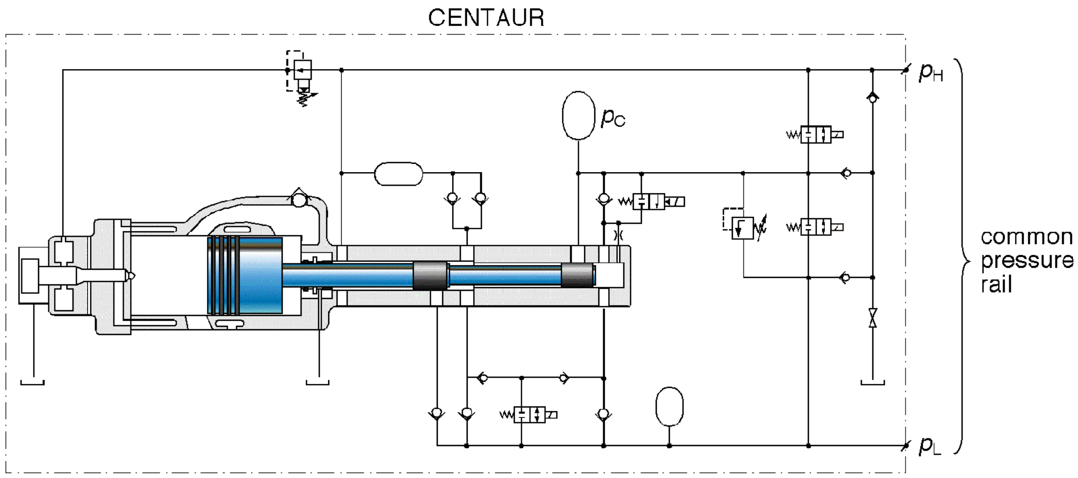

Figure 9: Hydraulic diagram of the CENTAUR

Figure 10 shows two drawings of the new free piston engine: as an assembly and in an exploded view, illustrating some of the main components of the new engine. Not shown are the intake and exhaust. Also the auxiliary components, with the cooler as the largest component is not shown.The total length of the CENTAUR is about 0.82 m. The CENTAUR has a height of 0.35 m and a width of 0.32 m. The weight of the engine (as shown in figure 10) is about 90 kg. The engine is designed to operate in a pressure range p_H from 26 to 32 MPa. The pressure p_C of the compression accumulator can be controlled between 16 and 26 MPa. The high pressure level is needed during cold start to overcome the higher friction losses, but also to create a higher compression ratio during cold start in order to improve the ignition process in the combustion cylinder.

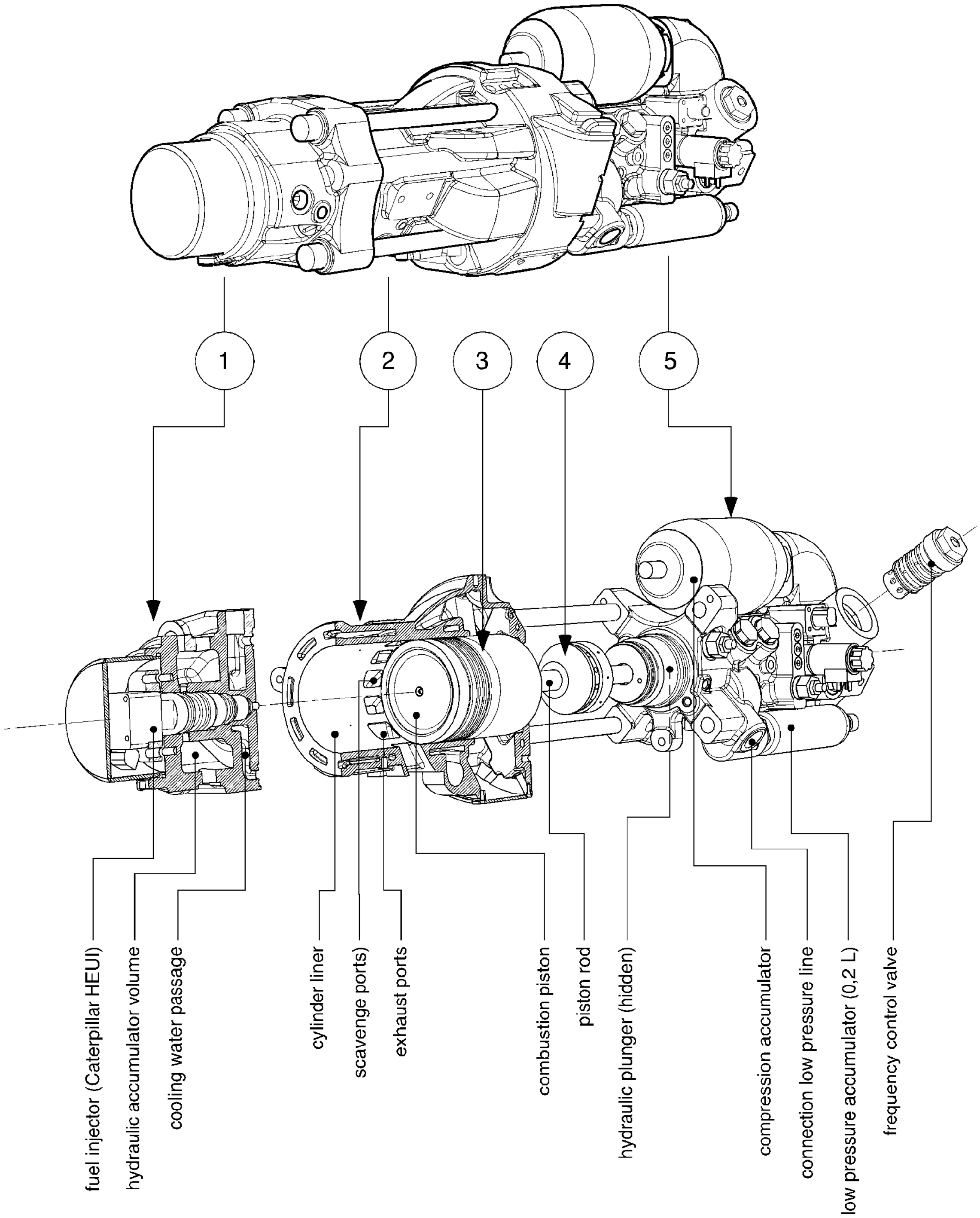

Figure 10: Drawing of the new CENTAUR.
The length of the engine is 0.82m, the width 0.3 m and the height 0.35 m.

1. Cylinder head
2. Combustion cylinder & scavenge pump
3. Piston
4. Sealing ring between hydraulic and combustion part
5. Hydraulic part

8 CPR for the hydraulic industry

The strategy of Innas in the design of the free piston engine was from the beginning to replace mechanical complexity (crankshaft, piston rods, valve trains, etc.) by modern electronic ways of control. It was known already that the elaborate mechanism of the crank shaft, piston rods, valve train and swash plate can be avoided almost completely by combining directly the combustion piston with the hydraulic plunger. Yet the question was whether the sensors, actuators and electronic control modules to control this free piston principle would not introduce more complexity and costs than had been taken away. Furthermore it was not known how the free piston principle would affect the combustion process and its efficiency, emissions and cold start behaviour.

Measurements at Innas and other company's have already proven that the combustion in the Innas Free Piston Engine has better characteristics than in comparable crankshaft engines, provided a good control of the compression ratio and the injection timing could be realised. It was also shown that the time was ready for production of the free piston engine since all components and techniques to control the engine had become available on the market, including a hydraulically operated and electronically controlled fuel injection system.

In the past year Innas has decided to develop its free piston engine solely for application in pressure imposed hydraulic systems with a common pressure rail or CPR. The development has resulted in a new Innas Free Piston Engine (IFPE) called the CENTAUR. Compared to the previous IFPE-model, the CENTAUR has a power density which is three times as high. The number of components is reduced with more than 60%. The focus on CPR-systems has become possible because of the new hydraulic transformer Innas has developed. This IHT overcomes the problems of the slow dynamic response of the free piston engine in the pressure domain which is caused by the hydropneumatic accumulators it needs.

Studies, which have been performed in close co-operation with the industry, have shown that CPR systems on the basis of the free piston engine and the hydraulic transformer from Innas, reduce the costs and the fuel consumption of hydraulic systems. The motors and cylinders can now be designed together with the transformer as separate modules. The common pressure rail will act as a common energy and pressure source from which hydraulic energy can be taken or to which energy can be supplied. Contrary to current flow control systems, the control of these units is not anymore realised at the pump unit but is realised within these modules.

It is the opinion of the authors of this paper that the hydraulic industry needs a CPR in order to face the competition from other drive technology's. For this common pressure rail the new CENTAUR is the most efficient and cost effective pump unit available on the market for mobile applications.

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