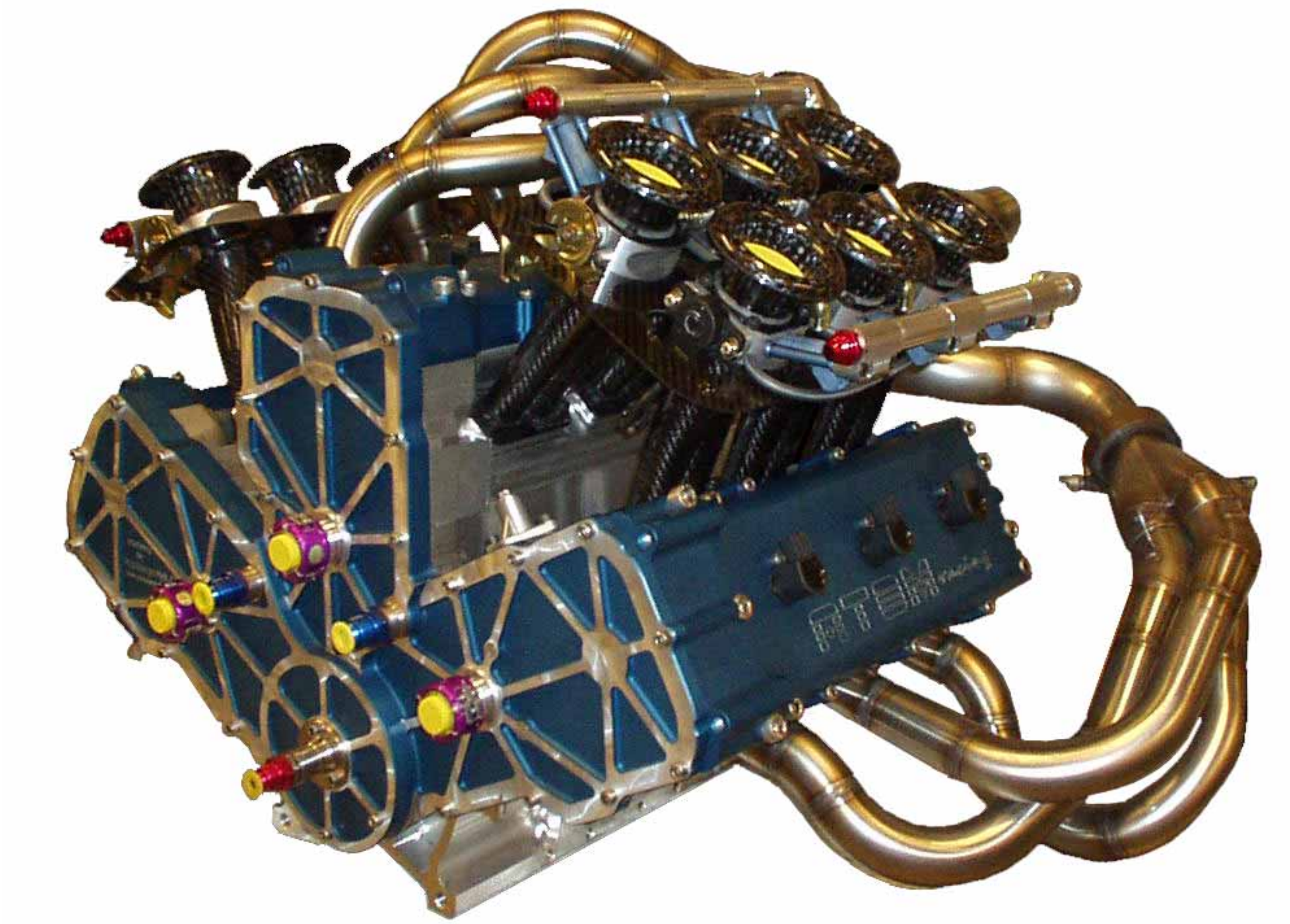
2006:099 CIV

MASTER'S THESIS

W-9 Engine Design



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Preface

It is rare to have the opportunity to spend a whole year, doing what you always have been dreaming about. In this thesis work, I saw the opportunity to combine earlier experiences in building and modifying race engines, with the knowledge and the powerful computer aid that I came in contact with, during my studies at the university.
As an engine tuner, it was instructive to analyze the fundamental dynamics in all areas of engine design and implement this knowledge in component production.
As always one fouls oneself about the time required, the whole project needed a couple of month's longer time than I expected. There is a phrase that says, that the last 10% of the work takes 90% of the time, I totally agree with that statement.

I could never have done this project, without the help of Tobias Mossberg at Mossbergs Mekaniska AB. His enormous skill and accuracy was vital in machining the engine. Knowledge, help and support from my brother Anders Johansson has also been invaluable.

I also want to thank my sponsors: APC Composite, Itek, Metallcenter, Momentum, MotoSpeed, NLR Systems and Uddeholm. Their contribution helped to reduce the cost involved.

Finally, I would like to thank my family, especially Lisa for coping with my unorthodox working hours and her support during the whole project. I also thank my lovely 1½ year old daughter Maja, for giving me energy with her joy and laughter.

Luleå, February 2006

Thomas Johansson

Abstract

In this thesis, the design of an internal combustion four-stroke engine is analyzed in the following areas; lubrication system, cooling system, crank train, valve train, induction system and exhaust system.
It was concluded that a unique engine configuration could be made i.e. a W-9 engine (a nine cylinder engine with three cylinder rows). This W-9 engine includes many attractive properties, such as: high efficiency, a compact and stiff engine block as well as a rigid crankshaft.
The whole engine was modelled in computer aided design (CAD) software and a finite element analysis (FEA) was made on vital parts. The dynamics of the engine were simulated in a multi-body simulation (MBS) software. The engine machining was performed with the latest computer aided manufacturing (CAM) software.
By scientifically combine different areas and use advanced computer aid, it was possible to construct and build an automotive engine from scratch, in a comparable short timeframe. Fittings of parts were excellent. The measured weight of 105 kg together with an estimated power above 500 hp, gives a superior power to weight ratio.

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1 Introduction

Internal combustion engines are without comparison, the most widespread transformer of chemical to mechanical energy. They were conceived and developed in the late 19^{th} century and have had a significant impact on mankind and society since then. Although the understanding of engine processes has increased and new inventions as well as better materials have improved the design, the basic engine principle is still the same. Internal combustion engines can deliver power from 0,01 kW to 20 MW depending on engine size. The advantages with internal combustion engines are their low weight and small bulk compared to the output.

1.1 Background

Engines have fascinated and inspired mankind through all times. They have found their way in all kind of vehicles and different applications. In the vehicle sector there is a limited range of engine configurations for cars available, there are for instance; inline four-cylinder, V-six and V-eight cylinder engines. It is hard to find a suitable engine for a high performing and lightweight sports car and one has to do with engines that are bulky and underpowered. By designing and building a lightweight and efficient engine, the foundation for a high performing sports car is made.

1.2 Purpose

The purpose of the assignment is to scientifically combine different areas where advanced computer aid is used to design an internal combustion engine from scratch.

1.3 Aim

The aim is to verify and develop accepted theories from different areas and then design and build an automotive internal combustion engine with high power to weight ratio.

2 Engine fundamentals

There are two common combustion cycles used in internal combustion engines, the Clerk two-stroke cycle and the Otto four-stroke cycle, named after their inventors. The four-stroke cycle is most common in automobiles, trucks and stationary gasoline engines. The two-stroke cycle is used in motorcycles, outboard motors, chain-saws, and other applications where its better power to weight ratio outweighs its drawbacks regarding higher pollution levels and poor fuel economy compared to the four-stroke.

2.1 Basic principle, four-stroke engine

The four-stroke engine has as the name implies four distinctive cycles, and it takes two crankshaft revolutions to complete one four-stroke cycle. The cycles are: Intake stroke; a combustible mixture of air and fuel is drawn past the open inlet valve as the piston descends to bottom dead center, increasing the volume and creating negative pressure. Compression stroke; all valves are closed and the piston moves towards top dead center, compressing the charge before ignition takes place. Power stroke; as a result from the combustion of air-fuel mixture, the pressure pushes the piston towards bottom dead center. Exhaust stroke; the burned gases are released by the open exhaust valve. Figure 1 shows the four-stroke principle.

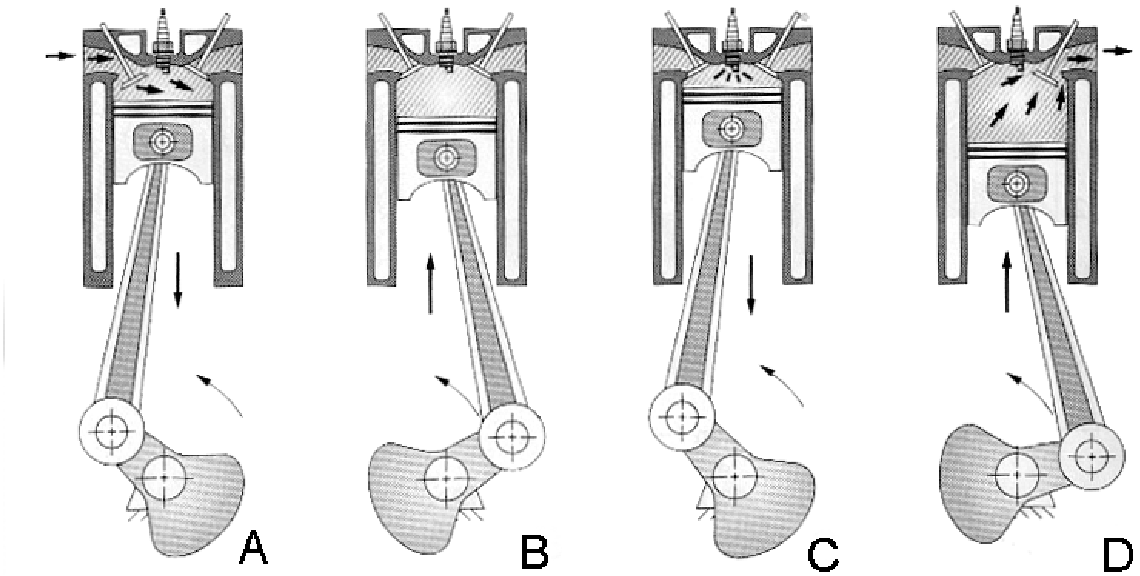

Figure 1: (A) Intake stroke, (B) Compression stroke, (C) Power Stroke, (D) Exhaust stroke

2.2 Lubrication system

The purpose of the lubrication system is to reduce friction, avoid contact between surfaces, take away heat and protect materials from oxidizing. In engines different kinds of oil can be used to fulfil that task.
The oil film is usually very thin and the thickness of these films range from 1- 100 μm [1]. The most significant property of a lubricant is the viscosity and it is strongly dependent on the temperature, the shear rate and the pressure. Different fluids will have different dynamic viscosity and the relationship can be written as in equation 2.1.

$$F = \eta \times A \times u/h \tag{2.1}$$

Where F is the force needed to move one surface, η is the dynamic viscosity, u is the speed of separation between the surfaces, and h is the distance between the surfaces.
With increasing temperature the viscosity falls rapidly and from an engineering viewpoint it is important to know the viscosity value at operating temperature, since it determines the film thickness separating the two surfaces.

The lubricants are dilute polymer solutions, consisting of approximately 80% base oil and 20% additives [2]. The additives can be wear and friction improvers, anti-oxidants, corrosion control additives and viscosity improvers.
In the journal bearing the mechanisms of hydrodynamic film generation is known and was first presented by Osbourne Reynolds in 1886. Today, loads of several thousands of tons are carried at sliding speeds of 10 m/s to 50 m/s [1]. The sliding surfaces are fully separated by a thin lubrication film and the friction coefficient is very low that is between 0,001 and 0,0005. In engine design the journal bearing in the crankshaft and the camshaft itself has to be examined to minimize friction and fulfil safe operating conditions. In the piston assembly and cam/ tappet the elastohydrodynamic lubrication have to be examined and appropriate materials and surface finishes and coatings must be chosen to minimize wear and friction [3]. In most automotive engines the lubrication system consists of a pressure pump to feed the engine with sufficient oil during all running conditions. Some type of oil cooler to take away heat and keep the properties of the oil consistent is also needed, as well as an oil filter to protect bearings and surfaces from contamination and minimize wear.

2.3 Cooling system

Due to the nature of internal combustion engines a vast part of the fuel energy is transformed to heat [4]. Coolant flow absorbs heat generated from engine combustion and engine friction. It is crucial to have continuous heat transfer to provide maximum efficiency and durability during all running conditions. The heat needs to be removed from the engine, and in vehicles that is done with air, water or oil. Air cooling is a simple and cheap way to cool the engine but it has some shortcomings regarding efficiency and running tolerances, and has therefore found application in less powerful engines. Water-cooling is the most common way of take away heat and is often mixed with some type of anti-freeze and/or anti-oxidation components. To further increase the heat transfer some type of additives can be added, for instance nanoparticles [5]. Oil cooling is often used in engines to cool the pistons but it can also be used to cool the cylinder head as well [6].
In most engines the cooling system consists of a water pump, a radiator, a thermostat and a reserve tank.

2.4 Crank train

To transform the power from the gas pressure in the cylinder to a rotating motion, some type of mechanical device is used. In internal combustion engines the most common way is by using a crank train consisting of the crankshaft, the connecting rod, and a piston assembly. In this way the motion and acceleration of the piston gives rise to forces and torques that are transmitted to the engine block.

To minimize these, appropriate counterweights are often used. The layout of the engine, regarding the number of cylinders and angle between the cylinders has a big influence on the engine balance. To calculate the engine balance a separation between reciprocating and rotating masses is done.

The reaction force (F_a) acting along the cylinder axis is dependent on the reciprocating masses (M_P), consisting of piston assembly, piston pin and equivalent mass of the upper end of the connecting rod, the crankshafts angular velocity (Ω), the engine stroke (2R) and connecting rod length (L). The equation 2.2 gives a good approximation [7].

$$F_a = Z (\cos \Theta + R/L \cos 2\Theta) \qquad (2.2)$$

$$Z = -M_P \Omega^2 R$$

In multi-cylinder engines, summation of forces is done. The cylinder spacing and the engine configuration decide the engine balance. Sometimes a balance shaft can be used, if appropriate crankshaft counter weighing can't be done based on engine configuration. The balance factor is depending on how big part of the reciprocating masses is compensated for in counter weighting.

The engine torque around the crankshaft axis is a result of the gas pressure on the piston. This torque varies, because both the cylinder pressure and connecting rod angle vary with crank angle. To lessen the effect of the varying torque, more cylinders or heavier flywheel can be deployed to store the kinetic energy. The result will then be a smoother running engine.

Engine vibration is divided in internal and external vibrations. In internal vibration the forces created by the inertia of moving parts and varying gas pressure results in vibrations of varying frequencies and amplitudes in the engine structure. The crankshaft is subjected to both torsional and bending vibrations, the critical speed depends on crankshaft stiffness, presence of a mass or inertial imbalance, geometrical eccentricity, lubricant friction in journal bearings, hysteresis effects in shafts, existence of gyroscopic inertial forces and asymmetrical support stiffness [8].

The engine vibration can also be altered by changing the firing order. Torsional oscillations can significantly affect the valve timing as well [9].

2.5 Valve train

The breathing capacity of the four-stroke engine is controlled by opening and closing areas into the cylinder where the poppet valve is now the universally used device. Sleeve and piston valves, rotary valves, slide valves etc. has so far never proved commercially successful [5]. The poppet valve is usually controlled by a camshaft, but there are other solutions like electro hydraulic, electromechanical or pneumatic hybridisation etc. that gives great freedom to control the valve events [10].
The valve motion with its high acceleration, raise the need for some type of valve return system, usually it is done with a steel spring but pneumatic or desmodromic devices have been used successfully. The camshaft can be located either below the valves or above the valves. Intake and exhaust valve lift profiles and timings can be defined in order to take full advantage of pressure waves and dynamic pressure effects, while providing large gas exchange areas to improve the efficiency.

2.6 Induction system

The gas flow into the engine is unsteady and when controlled by a valve whose area changes with time, the intake pipe pressure alters because the cylinder pressure is affected by the piston motion causing volumetric change within space. Since the speed of the air molecules is around 500 m/s at room temperature [11], the engine speed is always relatively much slower. This makes the filling of the cylinder very fast, and explains why even high rpm engines keep their efficiency.
Because the performance characteristics of an engine are controlled by this unsteady gas motion, it is important to understand this flow mechanism thoroughly to improve efficiency [12]. The pressure wave in the intake is caused by the intake stroke of the piston and the rapid closure of the valve that gives a sudden stop to the gas column [13]. The resulting pressure is reflected and will be reflected again, when it comes to a sudden area change like the bell mouth, but this time with opposite sign, there is now both expansion and compression waves in the inlet during the time the valve is closed.
The pressure wave strength is depending on how many times it has travelled up and down the intake, as well as the design of the intake path. When the intake valve is open, the wave is still present and there will be some superposition of waves. If the design of the intake is made to benefit from these waves a volumetric efficiency over 100 % will be the result [14]. To take full advantage of these waves, the inlet length should be fully variable to suit different engine speed [15].
The cross sectional area in the intake is responsible for the kinetic energy and pressure amplitude that takes place when the inlet valve closes. The common way to quantify the port quality is to test the intake port on a steady state flow rig. Higher flow is not always better since it can prevent the incoming air from creating a tumble motion, less charge motion and lower kinetic energy inside the cylinder affects the air/ fuel mixture and combustion efficiency [16].
Part of the induction system is the air-box and since it also has an unsteady flow, it will have some influence on the efficiency. The resonance inside the air-box is depending on engine configuration, volume and inlet design. It is essential with an even flow distribution between the cylinders.

2.7 Exhaust system

The purpose of the exhaust system is to minimize the required work to push out the residual gases and scavenging the cylinder from burned gases.

By designing the exhaust valve, exhaust port and pipe in order to get low backpressure and create an expansion wave that can be used at valve overlap, efficiency is improved.
At the exhaust valve opening, burnt gases exit the cylinder, and a compression wave starts to move to the open end where it will be reflected back as an expansion wave. With a tuned length of the exhaust pipe, there will be an expansion wave arriving at valve overlap that remove burnt gases and introduce fresh gases through the inlet valves, even if the piston motion is very low [16].

The time needed for the wave to travel downstream and backwards depends on pipe lengths, the speed of sound (at that temperature) and the actual flow velocity. When the exhaust valve opens, the in-cylinder pressure is relatively high and sonic speed occurs inside the seat gap for a while and then become sub-sonic [13].

By introducing some stepping or tapering in the exhaust pipe, modulation of the wave will take place. In multi-cylinder arrangements it is common to have a branched collector with a secondary pipe that can further improve the scavenging of burnt gases to have an expansion wave arriving back at the collector junction just in time to meet the next exhaust pulse from another cylinder arriving down its primary exhaust pipe [12].

The secondary pipe length and diameter together with branch angle in the collector have some influence on the efficiency [12].

3 The W-9 engine design

Designs of common automotive engines and a particular SAE paper [17] were analyzed. In this paper, a comparison between a V12 and a W12 Formula 1 engine is done. In the paper it was concluded that a W12 engine had improved efficiency due to fewer journal bearings. It had lower centre of gravity and a shorter and stiffer crankshaft than an ordinary V12.

These conclusions gave me the idea for a W-engine. By limiting the cylinders to nine, the cost is cut. To maximize power a large bore is used [18] and cylinder volume is restricted to three litres to control the inherent forces.
One problem with a W-engine is that the exhaust ports from the middle cylinder row, will point towards the intake on adjacent cylinder row. The engine design must have this drawback in consideration for a satisfactory function.
One reason that W-engines are rare is probably the increased cost to manufacture an engine with an extra cylinder row.

Historically engines have been in-line, V or radial engines. W engines are rare, but can be found. The Napier Lion aero engine was a W12, it had a high power to weight ratio and excellent specific fuel consumption [19]. Isotta Fraschini made a W18 engine with 1500 hp that was used in boats. Jim Fueling made a W3 motorcycle engine based on engine parts from Harley Davidson. The Rumpler tropfenwagen had a W6 engine, but the remarkable about that car was the C_d factor of 0,28 in year 1921. Volkswagen makes engines that are marketed as W engines, but they are more like inline V in V, which is missing in the normal engine nomenclature.
Bugatti made a W18 engine for their super car, but the engine never reached production. The W18 engine is shown in figure 2, note that the exhaust system has an extremely tight fit on the middle cylinder row.

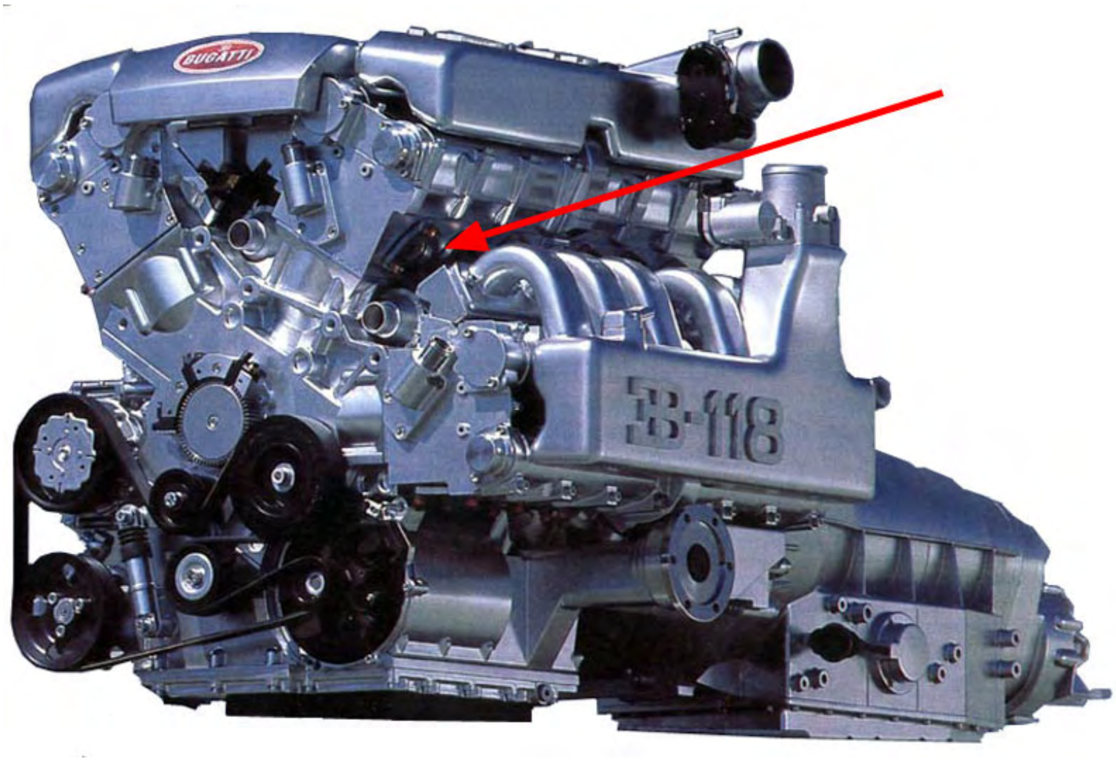

Figure 2: The Bugatti W18 engine, note the minimal clearance between exhaust and intake.

After initial sketches and evaluation of engine balance, it was clear that a W-9 engine with high power to weight ratio and good engine balance could be made. The technical data for the engine was set as following:

Nine-cylinder W-engine	
Cylinder volume	2977 cc
Bore	90mm
Stroke	52mm
W-angle:	60°-0°-60°
Compression	12.7:1
Fuel	Ethanol, E85
Weight	110 kg
Power	more than 500 hp
Cylinder spacing	104 mm
Head layout	4- valve, spark ignited

3.1 W-9 lubrication system

Since the W-engine share three connecting rods on the same crank pin, there has to be a compromise between bearing width, counterweight width and bore size to keep the cylinder spacing tight for a compact engine.
By choosing a high bore to stroke ratio there is enough space to design bearings and counterweights with sufficient width. One option is to design the counterweights with some heavy metal inserts to get decreased width, but the increased cost made it unfeasible.

The main journal bearings have to deal with more loading than a conventional V-engine, and to counteract this, the crankshaft is nose-feed and that gives plain main bearings, this solution is mostly used in racing engines. In normal production of engines there is some groove in the main bearing to feed the crankpin. The groove makes the bearing to two narrow bearings in reality with less load capacity [20].
A wider bearing gives squeeze film that better cope with transient loads and gives vibrational stability in bearings [1]. The nose-feed crankshaft needs to have increased oil feed at higher engine revs [21], but it requires less oil pressure since the oil supply to the crankpin does not have to overcome the centrifugal force as in main-feed bearings.

The camshafts are supported by journal bearings that are machined directly in the cylinder head. To minimize oil-gallery machining the bearings are feed by a hollow camshaft with supply holes at each bearing, feeded from the grooved end bearing. The cam/ valve tappets are lubricated by the leaking oil from the camshaft journal bearing. The valve tappet is kept in an oil bath by some pockets. The camshafts are driven by chains and sufficient lubrication is made by draining surplus oil from the cylinder head to the cam-chain area.
The principle oil system chart is shown in figure 3.

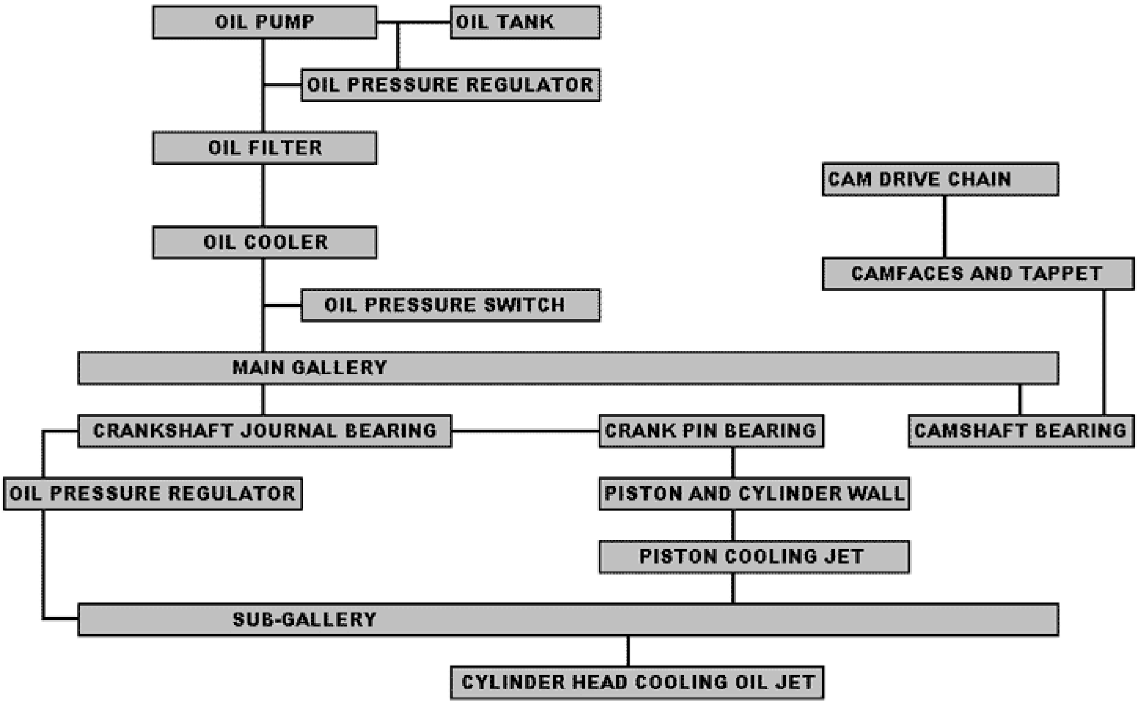

Figure 3: Oil system chart.

3.2 W-9 cooling system

To cool the engine a combination of water and oil cooling is used. In normal engine production, the engine block and cylinder head is casted, but when building this prototype engine, it was not an option, due to the time constraints and cost, instead the whole engine is machined from billet aluminium. By making the cylinder block with inserted wet cylinder sleeves, there is no problem to achieve the desired cooling capacity, but the cylinder head imposed some problems.

The cast cylinder head has water surrounding the combustion chamber and exhaust ports to take away sufficient heat. To achieve similar cooling capacity in a fully machined cylinder head, the water is routed outside the combustion chamber, beneath the exhaust and intake channels. Inside the cylinder head there are some large pockets machined between the combustion chambers, they are cooled by continuous oil supply from the oil system. The oil flow is controlled by some oil jets. These can be altered to suit different cooling needs. In this way the combustion is surrounded by water and oil and the good heat conductivity in aluminium gives an even temperature distribution in the cylinder head, that can be fully machined.
Figure 4 shows the W-9 engine cooling chart, note that a thermostat is not needed when an electrical water pump is used.

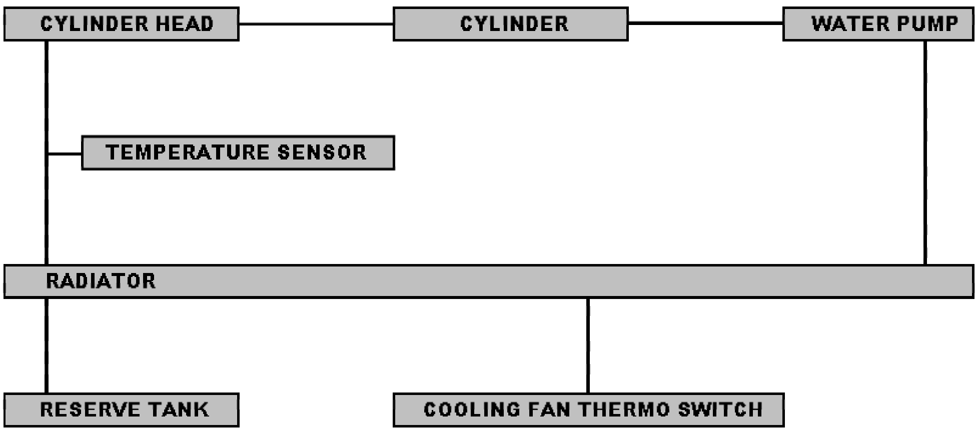

Figure 4: W-9 cooling chart.

3.3 W-9 Crank train

A refined engine ought to be well balanced and have a minimum of vibrations in order to minimize material stress and improve efficiency. Engine smoothness depends on the engine configuration as well.
To evaluate the engine balance in a W-9 engine, a multi body dynamics simulation software was used i.e. ADAMS/ Engine powered by FEV [22]. Adams is a motion simulation solution for analyzing the complex behaviour of mechanical assemblies. It allows to test virtual prototypes and optimize designs without having to build and test numerous physical prototypes. In this software, the main engine parameters are included such as; material stiffness, inertia properties, combustion pressure and bearing properties.

The balance in the W-9 engine was modelled and compared to known engine configurations with encouraging results. Numerous counterweights were tested in the software to find the optimum setup.

Here the properties of the piston assembly and connecting rod had to be established. The crankshaft, connecting rod and piston assembly were then modelled in the CAD software I-deas [23], where finite element analysis was made to check that the stress levels were acceptable for the materials that would be used. Figure 5 shows the crank train assembly in ADAMS/Engine.

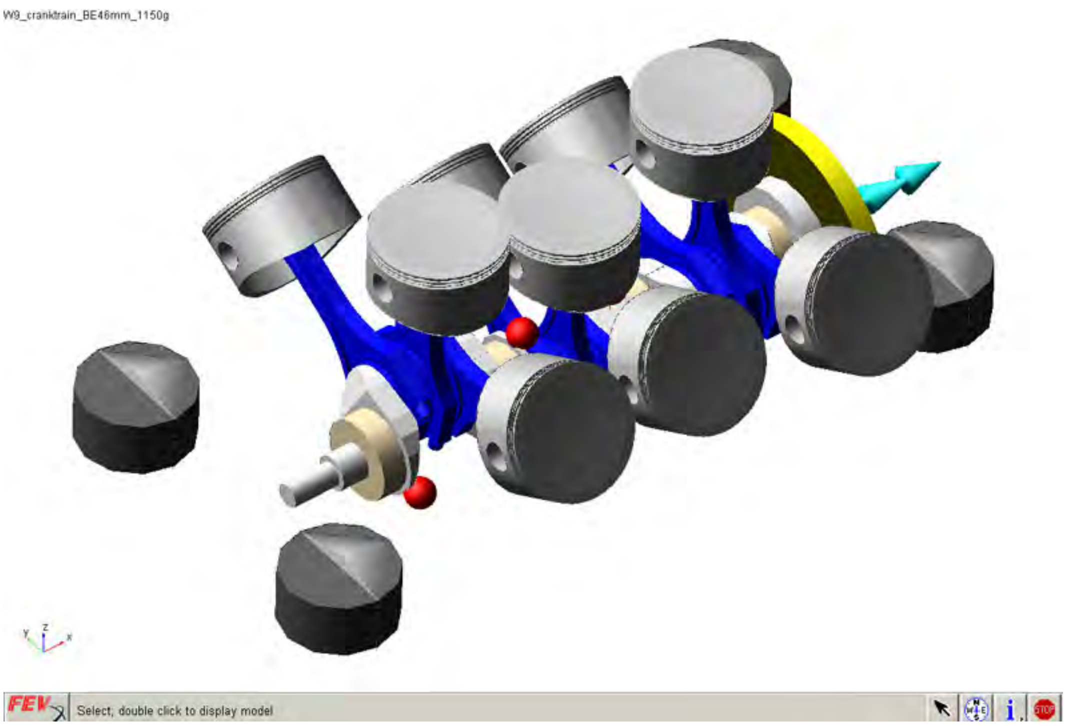

Figure 5: W-9 crank train assembly from ADAMS/Engine.

3.4 Valve train

When designing a valve train there is a general conflict between the demands for fast opening and closing of the valve at specific points that gives large valve accelerations. It is also important not to exceed the load limits.

To optimize the design within these constraints, consideration has to be made regarding not only the weight of the components but also the kinematics and dynamic characteristics of the components involved.
The valve spring is usually the softest component with the lowest frequency in the valve train. The contact between the windings gives a non-linearity of the spring, another phenomena is coil-clash, which has negative durability on the spring. By combining two or more springs there are more parameters available to satisfy the overall design requirements.

The valve train for the W-9 engine were evaluated in ADAMS/ Engine powered by FEV. The cam profile was designed with full acceleration and jerk control together with the lift/area factor to improve durability and lessen vibrations and Hertz stresses.

From the calculated valve lift data, ADAMS/ Engine powered by FEV converted these to a cam profile that was used to machine a cam master for the cam grinder. Figure 6 shows the W-9 valve train layout from ADAMS/Engine.

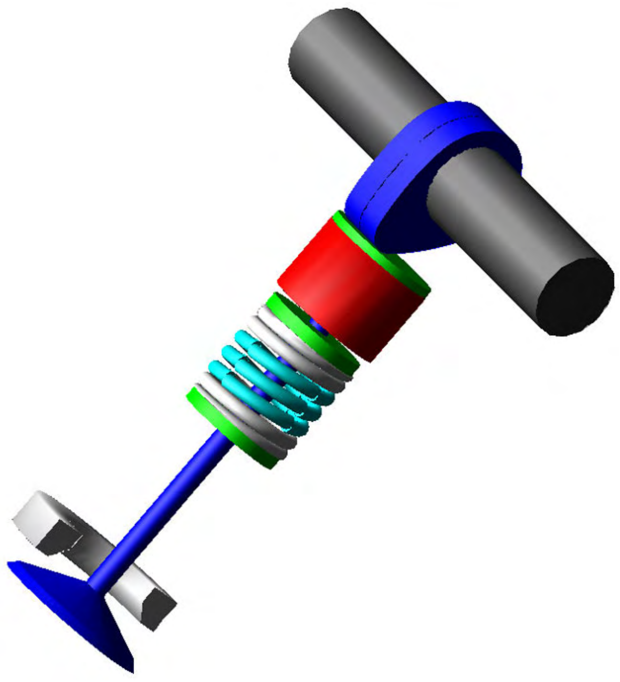

Figure 6: W-9 valve train rendering from ADAMS/Engine.

3.5 Induction system

The induction ought to be free flowing and be able to maintain high kinetic energy to improve efficiency; it also has to mix the fuel to a homogenous gas before combustion takes place. With a large bore to stroke factor there is plenty of room for big inlet valves that leads to improved breathing capacity at high engine speed [18].
The intake channel is convergent/ divergent to increase the kinetic energy and lessen the flow loss at the valve, tuning of the intake waves is also done by the design of the intake.

By making the intake downdraft, flowing is increased and a tumble motion of the incoming charge can take place inside the cylinder. A downdraft intake is also the choice in a W-engine, to clear the exhaust system from adjacent exhaust pipe.

The optimum intake length from the valve to the bell-mouth can be calculated, and Blair [12] has proposed equation 3.1.

$$L_{it} = a_0 \text{ x } C_{rp1} / N_p \tag{3.1}$$

Where L_{it} is intake duct length where intake ramming peak, a_0 is the local reference speed of sound in the intake duct, C_{rp1} is intake ramming factor, and N_p is engine speed where intake ramming takes place.
This formula was used to calculate the intake length for the W-9 engine. The dimension and design of the intake channel was based on earlier empirical experiences. To promote good vaporisation of the fuel at high engine revs the fuel injector should be placed high up in the intake duct. The design of the W-9 intake is according to figure 7.

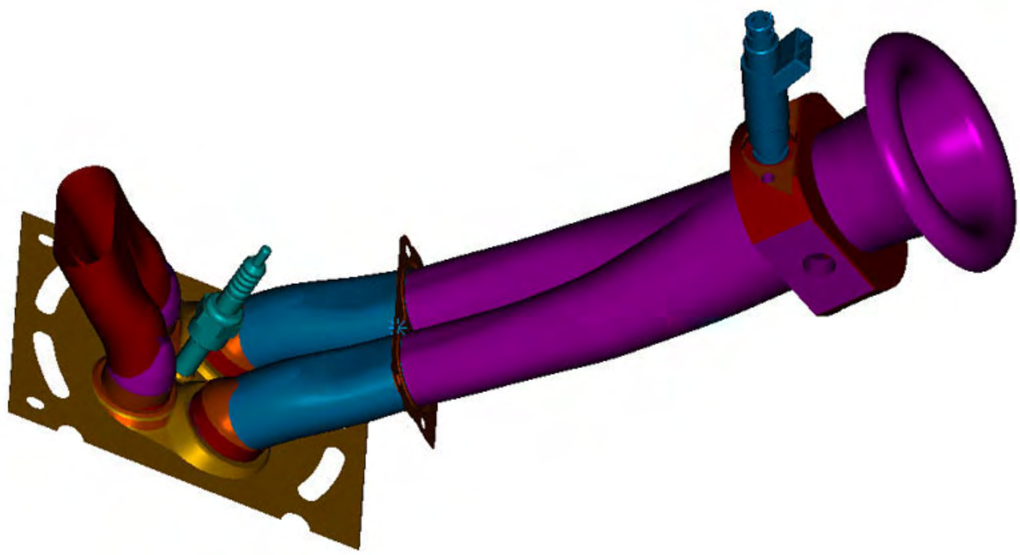

Figure 7: CAD image of the downdraft intake duct for the W-9 engine.

3.6 Exhaust system

The relatively large bore of the W-engine gives scope of large exhaust valves, which improve efficiency at high engine revs. The tuned length from the exhaust valve to major expansion area such as the atmosphere, a plenum, a branch or a branched collector can be calculated [12] by equation (3.2)

$$L_{et} = C_{et}\ T_{ex}^{-1} / N \tag{3.2}$$

L_{et} is the tuned length from exhaust valve to primary pipe end, C_{et} is the exhaust tuning factor, T_{ex} is the local speed of sound inside the exhaust pipe, and N is the tuned engine speed. The tuned exhaust length is preferably set to interact with the tuned length of the intake by having the exhaust tuned between two ramming peaks in the intake.
By routing the secondary pipes to a collector there is a third pipe to dimension, with this unique feature there has to be some trial and error testing to find optimum setup since empirical data can not be found.
To keep the strength of the sonic waves inside the exhaust system, it is preferable to make the pipes in a material that has low heat conductivity or use some type of insulating.
The exhaust system is visualized in I-deas to make sure that there is sufficient space to nearby intake duct, and that equal length pipes can be manufactured, se figure 8.

Figure 8: CAD image of W-9 exhaust system.

4 Results

By using computer aided design software together with multi-body dynamic software during the design process, the engine could be modelled in a relatively short timeframe.

4.1 Lubrication system

Since the engine oil is used both for lubrication and cooling, there has to be some control to make sure there is sufficient flow and pressure to the lubrication side.
The lubrication system supplies the main bearings and camshaft bearings with pressurized oil. There are five main bearings, nine connecting rod bearings and twenty-four camshaft bearings. The theoretical oil flow to these bearings was found to be around 6 litres per minute at half maximum engine speed.
The cooling system has twenty-one oil jets, which cools the cylinder heads and the piston underside. The theoretical flow is calculated by simplified [24] Bernoulli equation 4.1.

$$Q = \alpha A_0 \left(2 \Delta p / \rho \right)^{-1} \tag{4.1}$$

Where Q is flow, α is the flow coefficient A_0 is real flow area, Δp is pressure drop and ρ is the density of flowing media. The calculated flow for the oil jets is 15 litre per minute at 0,1 MPa pressure drop, and 31 litre per minute at 0,4 MPa pressure drop. If the oil pump capacity was based on these oil flows, it has to have a capacity around 16 l/min at engine idle. This gives a theoretical oil pump flow at 207 l/min at maximum engine speed that corresponds to five times the required amount. To better size the oil pump, the cooling side of the oil system is pressure regulated and expected to fully open at half maximum engine speed. That gives an oil pump theoretical minimum capacity of 84 l/min at maximum engine speed. By pressure regulating the cooling side of the oil system there is always enough pressurized oil for the lubrication system.
The pressure section of the oil pump is gear-type and the theoretical flow is 120 l/min, the main advantage with a gear pump is a simple trouble-free design and low cost [25].
In figure 9, the combined oil pump and scavenging pump is shown.

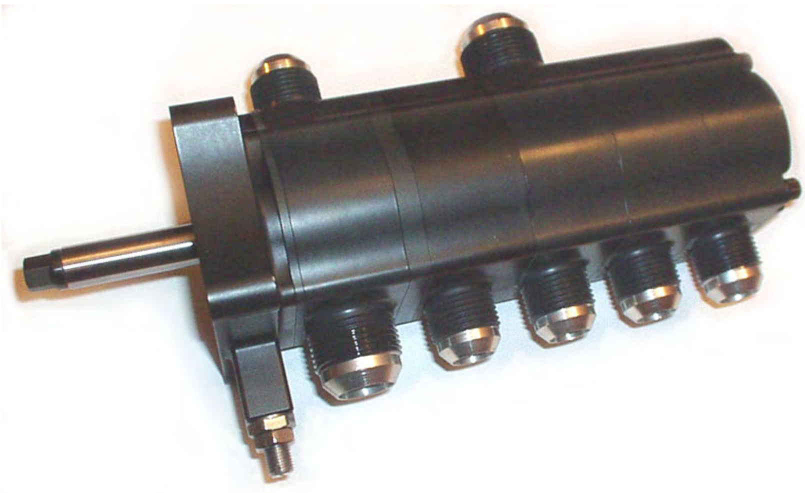

Figure 9: The oil pump, note the integrated adapters.

The rotating load in the engine is used to calculate the load capacity in the engine bearings. It can be seen that when the angular velocity of the rotating load is half the angular velocity of the rotating shaft, the surface velocity differences is zero and should be avoided.

The relative eccentricity in the journal bearings is set above 0,8 to prevent unstable vibration in the engine bearings [21]. The oil supply to the bearings is positioned in a low pressure zone [26] according to the results from ADAMS/ Engine, se figure 10.

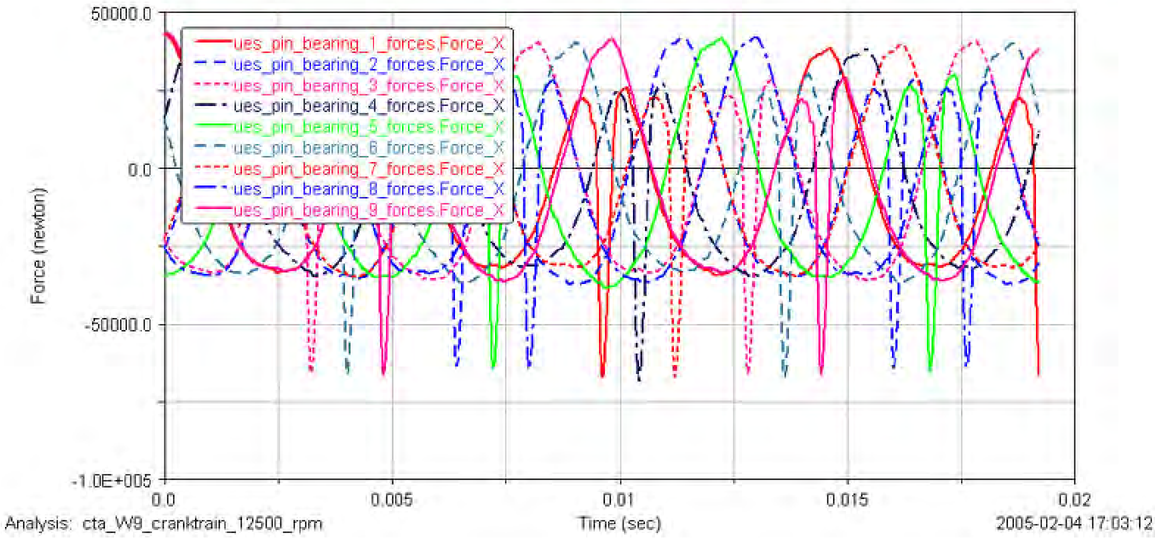

Figure 10: Crank pin forces at 12500 rpm.

The scavenging of oil from the engine is done with Roots-type pumps. Besides scavenging the oil, the pumps remove the blow-by gases and lower the crankcase pressure to improve efficiency [27]. The crankcase is sealed between every cylinder row to further improve the pressure drop. The blow-by from pistons is estimated from [28] and [29] to 85 l/min per engine compartment at maximum engine speed.

4.2 Cooling system

The engine cooling is done with oil and water. The water pump is electric driven, which gives freedom to suit the flow to the cooling requirement and not to the engine speed, which is the normal solution.
The wet cylinder liners are made of high strength steel with a yield strength at around 900 Mpa. Since the liner can be relatively thin, the heat release is increased.
The heat conductivity for steel is less than for aluminium and a coated aluminium-based cylinder liner is an option, but the higher cost involved makes it infeasible for the W-9 engine. The cylinder liner is plateau honed [30] in cross hatch pattern, se figure 11.

Figure 11: Cylinder liners

Each cylinder head is cooled by four 1,5 mm oil-jets that direct the oil to pockets between the combustion chambers. The oil-return channels, drains the oil to the cam chain area, where it is scavenged by the oil pump. To keep piston temperature down every piston is cooled on the underside by an oil jet, se figure 12, this gives the opportunity to make the piston lighter with increased fatigue properties.

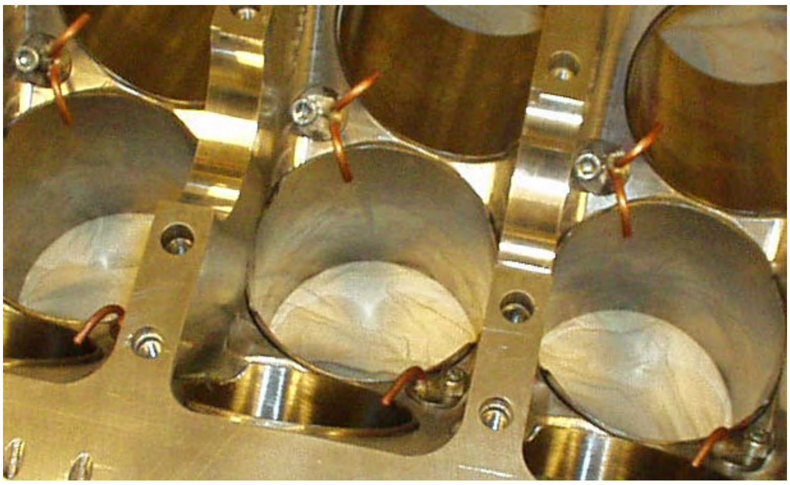

Figure 12: Oil cooling jets for piston underside.

4.3 Crank train

The required crankshaft counterweights were optimized in ADAMS/Engine. The best engine balance was found for counterweight 1,15 kg at half-stroke distance. To see which balance-factor ADAMS/Engine calculated for, a single cylinder crank-train was simulated and counterweights were changed to find the turning point of the engine block forces. The best balance was achieved with a balance-factor at 50%, which is inline with common use [31]. Figure 13 illustrates the difference between two different counterweights, by changing only 50 g, the imbalance forces is almost doubled.

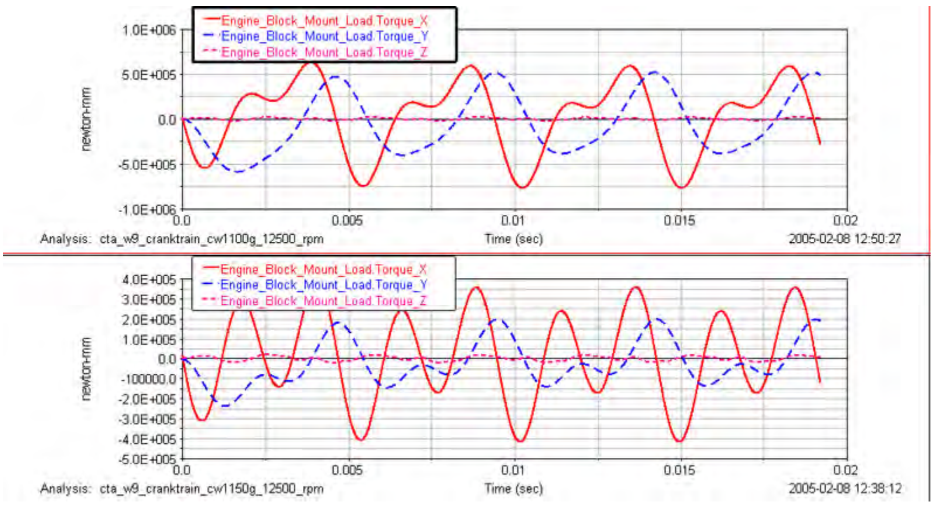

Figure 13: Engine block-mount load torque between two different counterweights.

The crankshaft is made of nitrided EN40B steel billet, see figure 14. Finite element analyse was made and the stress distribution can bee seen in figure 15. The short engine stroke gives a stiff crankshaft, which is needed since the crankpin is relative long in a W-engine, that share three connecting rods on one crank pin.

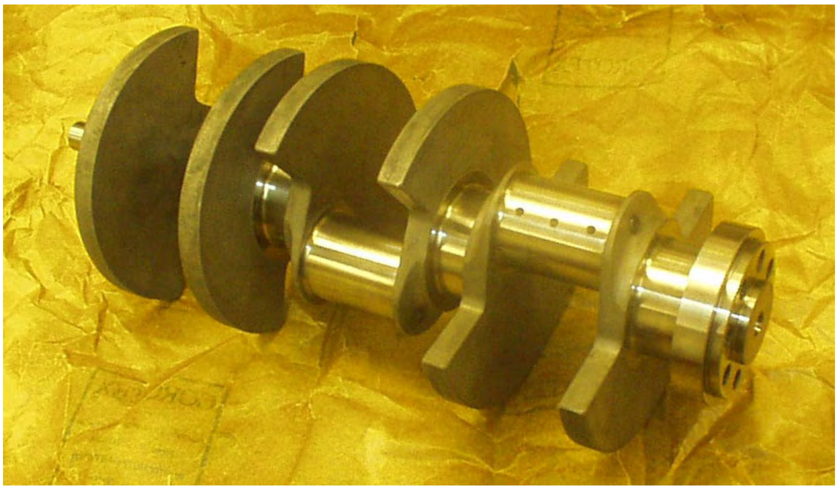

Figure 14: W-9 crankshaft.

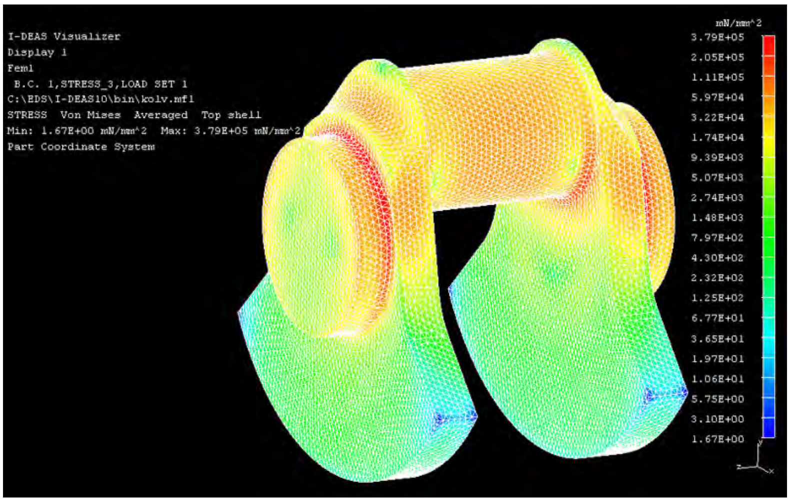

Figure 15: Crankshaft subjected to 5500 G with a threefold safety factor.

The connecting rod to stroke ratio is set relatively high at 2,44. Normal production engines have ratios between 1,6 and 2,0. The advantage with a high ratio is that the piston dwell longer at top dead center, giving longer time for the combustion to spread before the piston moves away, the G forces on piston and connecting rod is reduced, se figure 16. Piston skirt friction is also reduced [32] and the force-angle to the crankshaft is better. The drawback is increased weight of the connecting rod and considerations must be made to intake dynamics and valve events.

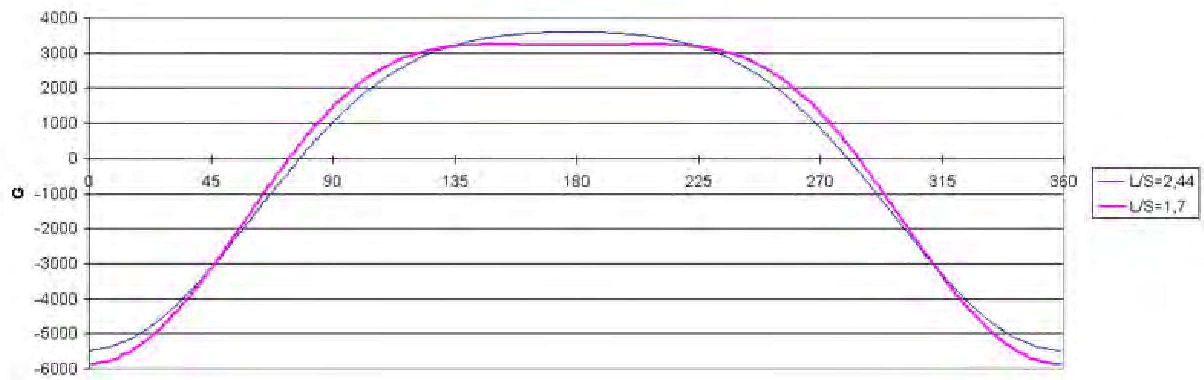

Figure 16: Piston acceleration during one crankshaft revolution, compared between two different connecting rod lengths, the stroke is unaltered.

The connecting rods are forged from 30CrNiMo8 steel, tempered to a yield strength of 1350 Mpa, and then fully machined in H-profile, se figure 17. The connecting rod bolts has a tensile strength around 1700 MPa.

Figure 17: H-profile connecting rods.

The connecting rod is finite element analyzed (FEA) to ensure a safe function, see figure 18.

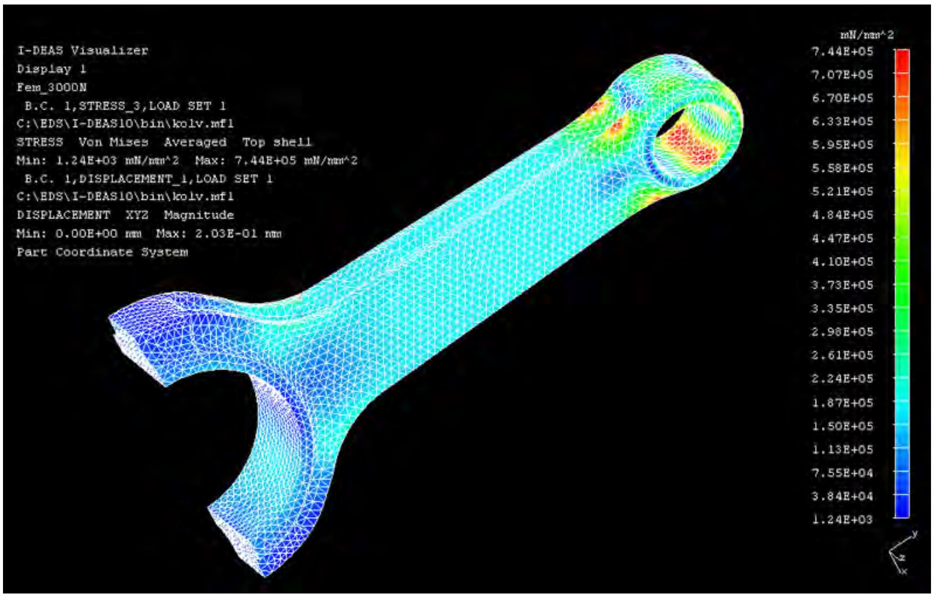

Figure 18: FEA of connecting rod with a tensile load of 5500 G, and twofold safety factor.

The piston and the piston rings in modern reciprocating engines account for the majority of the friction and power loss associated with the mechanical system [19]. To minimize friction losses the piston ought to be light-weighted and the piston rings ought to be thin. Coatings can also be used to reduce friction and wear [33], [34]. The W-9 piston is a short-skirt slipper type made in AA2618 aluminium. According to finite element analysis, figure 19, the piston was modified and 65 g from the dome and pin boss area was removed. This minimizes inertia loads and improves efficiency [35].

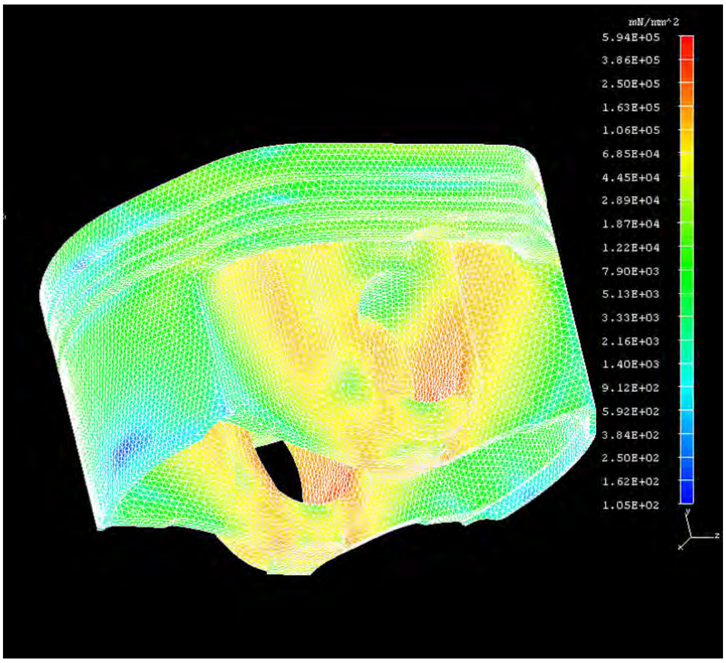

Figure 19: Finite element analysis of piston.

Figure 20: CAD image of the W-9 piston, unmodified piston, and machined piston.

4.4 Valve train

The valve lift is defined by integrating acceleration data for acceleration and jerk control. It was analyzed against a polynomial curve (third degree, without smoothing of ramp and main lift transitions) and a measured motorcycle camshaft. An acceleration based lift curve controls the forces and vibrations in the valve train [36], se figure 21.

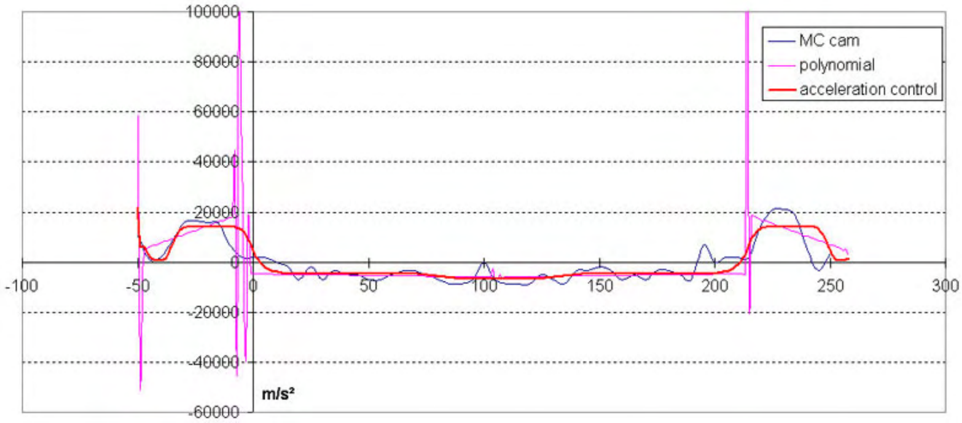

Figure 21: Acceleration comparison between different lift profiles.

The valve lift data was imported to ADAMS/Engine where a cam profile was generated. Further valve train analysis in ADAMS/Engine gave sufficient data for the required valve spring dimensions. In figure 22 a valve train simulation shows when the tappet force goes to zero (red line) i.e. the camshaft loose contact with the tappet/ valve.

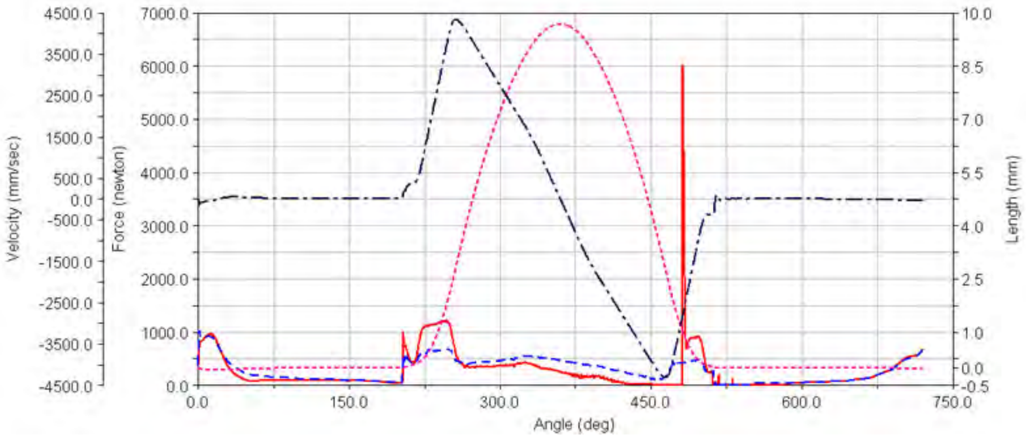

Figure 22: Valve train analysis in ADAMS/Engine, comparison between two valve springs tappet forces, valve velocity and valve displacement.

The camshafts are machined from billet, see figure 23. The cam profile data was used to machine a camshaft master for the cam grinder. The camshafts are made from high strength steel with yield strength around 1300 MPa.

Figure 23: Intake and exhaust camshafts for the W-9 engine.

4.5 Induction system

The intake valve size area is set to 32% of bore area. The intake channel is downdraft design. The throttle body is 46,5 mm and the intake is tuned for 10700 rpm, hereby a high engine power can be reached [18]. The intake duct length is calculated according to equation 3.1. The peaks and troughs in intake pressure can be calculated [12] as well. A power curve can also be established when empirical tests are used to calibrate these formula together with known brake mean effective pressure (BMEP) levels. Due to time constraints the intake length is fixed.
In figure 24, a power curve is estimated for the W-9 engine. Realistic BMEP levels of 15,7 bar at maximum torque, and 14,6 bar at maximum power speed is used in this curve.

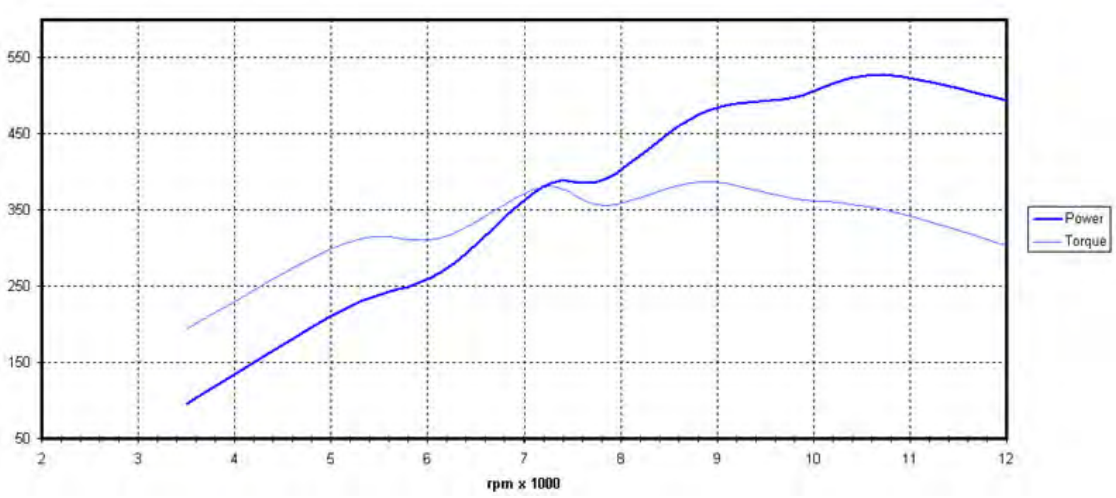

Figure 24: Estimated power and torque curve for the W-9 engine.

The intake runner and velocity stack are made in carbon fibre and can be seen in figure 25.

Figure 25: Carbon fibre parts for the W-9 engine.

4.6 Exhaust system

The exhaust valve size is set to 21% of bore area. The exhaust system is a 9-3-1 design. The primary exhaust pipe length is tuned for 9800 rpm according to equation 3.2. By tuning the exhaust for 9800 rpm it falls between two tuning peaks in the intake and broadens the power curve [12]. The primary pipes are conical from 38 mm to 42mm. The exhaust system is made of TIG-welded SS304 stainless steel thin-wall tubing (gauge 18 and 20), see figure 26 and 27.

Figure 26: 9-3-1 exhaust system in stainless steel.

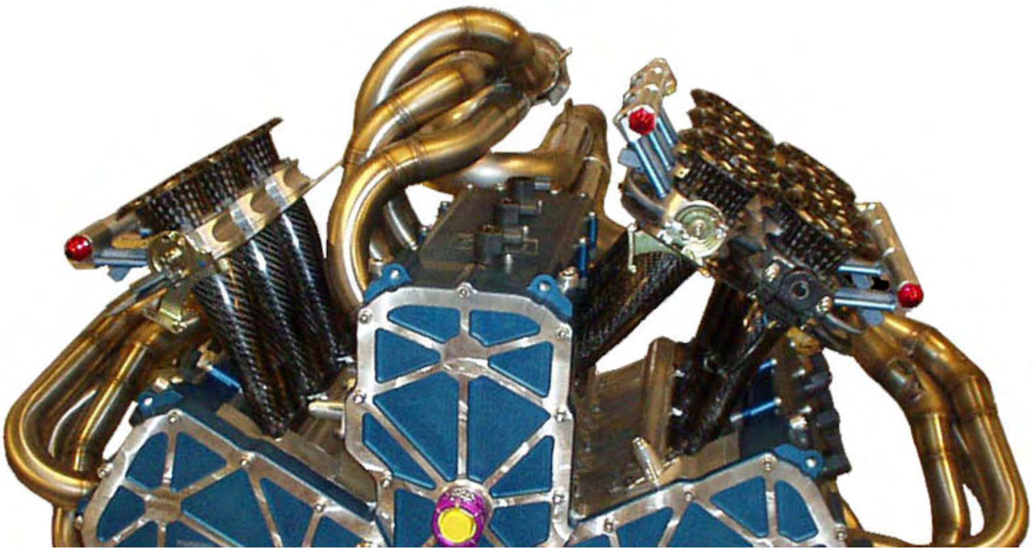

Figure 27: Sufficient clearance between exhaust and intake on the W-9 engine, compare with the Bugatti engine in figure 2.

5 Conclusions

In this thesis the fundamentals of engine design is described. By analyzing the properties of the lubrication system, cooling system, the crank train, the valve train, induction and exhaust system in theory and compare those data with known engine designs, the foundation for constructing a combustion engine from scratch was made.

Since W engines are quite rare, one can wonder why. The most likely answer is the increased manufacturing cost and problems concerning routing the exhaust from the middle cylinder row. By designing an engine with a narrow included valve angle, steep angled intake and exhaust ports, a long connecting rod to stroke ratio, the exhaust routing is no longer a problem, since it is far away from the adjacent cylinder row.

The advantage with a W engine is obvious, with a short and extremely compact engine block, a short and stiff crankshaft and less main bearings than a comparable engine it will lead to a lightweight and efficient engine package.
By using advanced computer software the dynamics and layout of the engine was analyzed, leading to that a nine-cylinder W-engine could be constructed from scratch in a comparable short timeframe. By modelling the whole engine in CAD-software, a perfect fitting of engine parts was made. The only part that had to be remade was the cam chain guides to get the right cam tension. By simulating the dynamics of moving parts in state-of-the-art MBS-software, where the kinematics and engine properties were included, appropriate crankshaft counter weight and valve springs could be chosen for a smooth and safe running engine.
The layout of the intake and exhaust system involves several empirical data from motorcycle engine tuning, where high power to engine displacement can be found.
The bore to stroke ratio is high and that leads to improved breathing capabilities at high engine speed, thus the power level can be relatively high compared to engine displacement.

The machining of the engine parts imposed some constrains, but the advances in CAM software lately, made the preparation relatively easy and fast. As an example, a CAM preparation from the CAD model that took a couple of hours some years ago, only takes just a couple of minutes today. During the CAD modelling process, it was vital to make the model suited for easy and fast machining. By using a four-axle CNC lathe, a minimum of indexing was required and tight tolerances could be kept. Throughout the machining process it was necessary to have careful measurements to keep the tight tolerances in important areas.
The measured engine weight of just 105 kg indicates the compactness of the design and will certainly give a superior power to weight ratio.

5.1 Future work

The engine will endure extensive testing in a dynamometer to verify all functions. Since the engine design is quite complex, one has to expect certain modifications.
If there is a need to improve the power of the engine, some more radical cam profiles and lighter valves can be deployed. If a broader power curve is needed some variable length intake stacks can be incorporated.

To increase the balance factor, lighter connecting rods can be chosen.

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