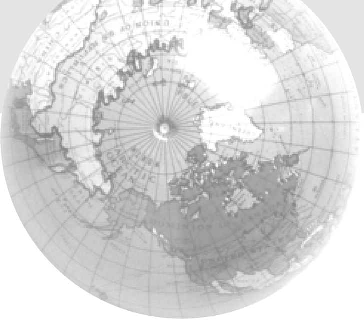

You will find the figures mentioned in this article in the German issue of MTZ 03|2007 beginning on page 164.

Die neue Motocross-Motorengeneration von KTM
in den Hubraumklassen 450 cm^3 und 480 cm^3

The New Motocross Engine Generation from KTM

in the 450 cm^3 and 480 cm^3 Displacement Classes

Developing two displacement variations, KTM has revamped its range of engines especially for the MX1 and MX3 motocross classes. After a 36-month development period, a unique engine with a 450 cm^3 displacement has been created, which – by enlarging the bore – forms the basis for a 477.5 cm^3 displacement for the MX3 class. The Otto (i.e. 4-stroke combustion) engine with four-valve technology is a brand new proprietary development by KTM featuring exceptional characteristics and an especially broad usable rpm range.

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1 Introduction

KTM is competing in two displacement classes with a new engine generation that has been developed exclusively for the motocross sport for the very first time and is ready for these special demands. The basic engine is a one-cylinder, 4-stroke Otto engine with a displacement of 450 cm^3. The engine is installed perpendicular to the direction of travel, is liquid-cooled and exclusively equipped with an electro-starter. This represents a revolution in the motocross sport, since these engines have previously always been started with a manual kickstarter **Figure 1**.

The counterbalancing is done via two short balancer shafts, which, due to their optimal position, minimize the alternating torque at high speeds and thereby make a broad, usable rpm range possible. The four-valve head with two overhead cams and rocker arms offers – in combination with the large valves – the perfect conditions for an optimum gas exchange and high intermediate pressures, even at high speeds. A modern 41 mm flat slide carburetor prepares the mixture. The engine's power is transmitted via a primary drive gear, a multi-disk wet clutch, the 4-gear sleeve transmission, as well as via a roller chain to the rear wheel. The engine impresses with its broad power band, enormous rev-capacity, its spontaneous responsiveness and its very high peak performance. The powerplant achieves 42.5 kW at 9500/min and reaches a maximum torque of 49 Nm at 7500/min. The maximum rpm of the new engine is 11,800/min.

2 Development Goals and the Concept Definition

Unlike for other motorcycles, the overall package is ultimately decisive in choosing the engine concept for a racing bike. A light and small engine chock-full of torque is a requirement for producing a compact motocross motorcycle with excellent riding characteristics, low weight and high agility, **Figure 2**. For the first time ever, KTM's design concept incorporates no manual starting mechanism such as a kickstarter. The bike starts with an electric starter only.

The displacement of 449 cm^3 or 477.5 cm^3, and the power and performance that can thus be achieved, is a result of the FIM regulations for the MX1 and MX3 motocross classes. The demand for a high power output with exceptional spontaneity, yet low weight and small designed space, leads to a single-cylinder motor for the required displacements. Diverse concept studies show a clear preference for single-cylinder engines; they are clearly superior to the multi-cylinder engines when it comes to compactness and the overall package. The chosen arrangement of the balancer shafts for the engine, as well as the fully integrated E-starter, results in a great centralisation of the masses. The short-stroke design featuring a 97-mm bore and 60.8-mm stroke (the 477.5 cm^3 engine has a 100-mm bore with the same stroke), in combination with the four-valve cylinder head (in which the valves are operated by two overhead camshafts and rocker arms, similar to the system in the KTM 250 SX-F) assist its performance and speed-oriented design. The extremely low moving masses operated by the rocker arm permit greater degrees of freedom in the valve timing and valve lift.

The intake ports' design is oriented exclusively toward an optimum charging of the cylinder to achieve a high power output. The demand for maximum power and performance, spontaneity, as well as greater reliability regarding the sometimes extremely contrary ambient influences in the motocross sport, result in the use of a 41mm flat slide carburetor. The entire engine is mounted on ball bearings to minimise the friction losses, as well as for the sake of reliability in the event of a momentary drop in oil pressure. Wet-sump lubrication is employed in the engine in such a way that the transmission and the clutch are dipped only slightly into the oil bath. The most vital engine statistics are compiled in the **Table 1**. The demands on the basic engine are increased by the goals regarding the bike's performance, as well as the demand for the greatest reliability and easy maintenance.

3 The Basic Engine

The engine housing is divided vertically and is made from the sand-cast aluminium alloy EN AC-Si7 Mg 0.3 S T6. The cylinder is sealed radially within the housing by two O-rings; this design omits the need for a gasket. The cylinder sleeve is die-cast entirely of aluminium and has a Nikasil coating on the contact surface. Cylindrical roller bearings are used as the crankshaft's main bearing, which are made with a shoulder in the outer ring to minimize the overall width to the axial retainer.

The oil filter is positioned in front of the crankshaft, and beneath the crankcase and transmission is an oil pan, which is separated from the transmission by a partition. This minimises churning losses. The oil pumps are found down below, along with the transmission shifting unit. The seal between the right and left halves of the housing and of the clutch covers is achieved with a liquid seal. Moulded seals are used to seal the chain housing, the valve cover and the clutch's outer cover. The engine is positioned within the vehicle using a bolt in the frame above the oil filter, a bolt beneath the crankshaft, an engine mounting with the swing arm bearing, plus the cylinder head is bolted to the frame by means of head braces.

3.1 Crankshaft Drive and Mass Balancing

The assembled crankshaft with a forged crank web, **Figure 3**, is installed at a right angle to the direction of travel and supported by two roller-bearings. The crank web is made of 16MnCr5 and the crank pin of 15 CrNi6. The ignition is mounted to the left of the direction of travel; the rotor has a sliding component for rpm detection and for the ignition signal. Mounted on the same stub shaft are the freewheel as well as the starter wheel, which is operated by an intermediate wheel and a slip clutch from the electro-starter, as well as the drive wheel for the left balancer shaft, which also bears the timing train's lower rear sprocket.

The primary drive wheel is on the right crankshaft stub and also bears the drive wheel for the right balancer shaft, which simultaneously operates the drive for the water pump. Counterbalancing the free inertia forces of the first order is reduced by 50 % on the crank web and by 30 % on the two balancer shafts. The positioning of the balancer shafts near the crankshaft axis minimizes the mass moments. The weight-optimized, forged, box-in-box piston is connected to the crankshaft by a forged connecting rod. A compression ring and a one-piece oil scraper ring comprise the piston ring package.

3.2 Cylinder Head and Valve Train

The unfinished blank for the cylinder head is gravity die-cast, followed by a heat treatment. The small valve angles (10.5° on the intake side and 12.5° on the exhaust side) and the centrally positioned spark plug result in a very compact combustion chamber with a compression ratio of 12.5:1.

The operation of the four valves per cylinder unit is accomplished by means of DLC-coated, friction and wear-optimized rocker arms, plus two overhead camshafts, **Figure 4**. This weight-optimized construction permits very high valve accelerations and consequently forms the basis for high mean effective pressures. To adjust the valve clearance, custom-ground shims are used, which are inserted into the valve spring retainer. The valve clearance is checked at appointed service intervals. As viewed from the direction of travel, the drive for the camshafts comes from the crankshaft via the left balancer shaft, which uses a rear sprocket to drive a timing chain. The timing chain is guided over a tensioning and a guiding blade and operates both camshafts by means of another twin wheel. A maintenance-free, hydraulic chain adjuster takes care of the chain tension. A double-layered metal gasket serves as a cylinder head gasket.

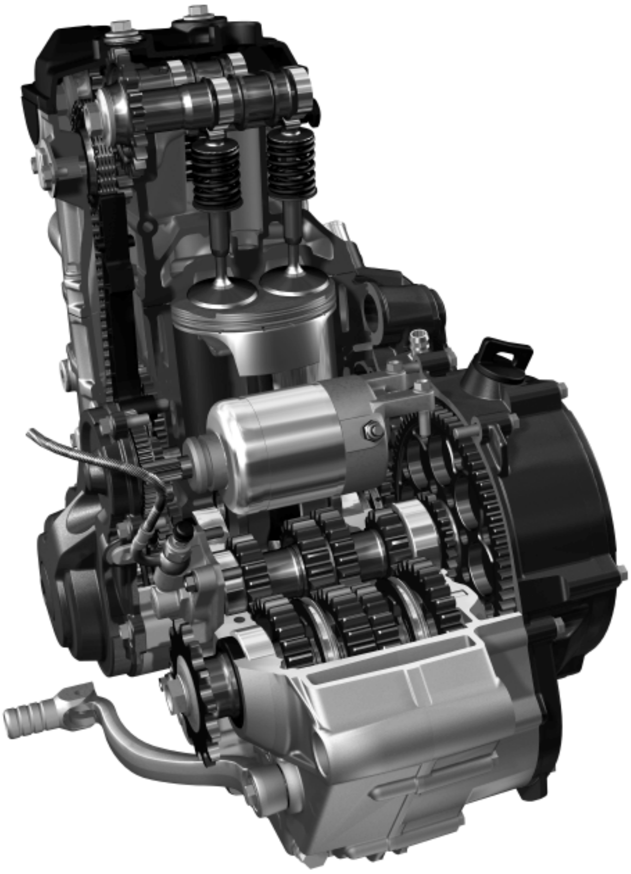

Figure 2: Engine cross section

3.3 Valve Train/ Charge Cycle

This very short-stroked design with a stroke/bore ratio of 0.627 makes high rpms and large valve diameters (40/32 mm) possible. The available surface is utilized in its entirety. The valve-surface ratio AIntake/ AExhaust of 1.56 is also designed for a high flow rate at rpms of >10,000/min. The shock absorber-determined positioning of the mixture preparation unit and the airbox necessitates an intake port that emerges from the cylinder head at a 11° angle. This means that the individual ports are not symmetrical. In order to ensure good responsiveness, the intake ports were designed to attain the desired power goals with the smallest possible cross-sections and lengths, **Figure 5**.

The intake port was designed with a flow diversion of approx. 45° (port/valve angle) and a wide separation. On the exhaust side, the port to minimize heat introduction into the cylinder head and to improve the responsiveness is also designed to be short and of small volume. Although racing engines need not meet exhaust emissions regulations, the intake ports were designed as tumble ports with average specifications, for good responsiveness under part load conditions. In spite of that, good flow rates were able to be achieved for the large bore.

In order to fulfil the desired functional characteristics for the power output, a charge cycle design was sought that was a compromise between peak performance with a high rev capacity and good torque at low speeds. Due to its great stiffness and low moving masses, the rocker arm valve drive with titanium valves enables substantial valve lift and acceleration, **Figure 6**.

This makes large opening sections possible at a comparatively shorter opening duration, which has a positive effect on the torque at low speeds, in spite of its design for high peak performance at rpms of over 9000/min. The valve overlap can also end up being a bit less. This approach keeps the residual gas content low and thereby also improves the responsiveness at low rpms.

Despite valve pockets for the intake and exhaust valves that are about 2.8 mm deeper, the combustion chamber was able to be kept compact thanks to the small valve angles (10.5°/12.5°) and the mostly flat piston heads. The inflow area around the intake valves is built to permit maximum charging. Quench areas were planned between the intake valves as well as the exhaust valves. The spark plug sits centrally and nearly vertically (4°) within the combustion chamber. A slight opening between the intake and the exhaust valves enables a compression of 12.5:1 to be achieved.

3.4 Oil and Water Circuits

The lubrication of the engine is accomplished via wet-sump lubrication, in which all rotating parts are positioned higher than the oil level during normal operations. 3 oil pumps are in operation per shaft. The two suction pumps as well as the pressure pump are made of the plastic compound PEEK and are operated by means of a common, continuous drive shaft via the clutch's gear wheel and intermediate gear.

The three Trochoid pumps move a total of 1.3 litres of oil through the engine. Two suction pumps draw oil and blow-by gasses from the crankcase. The pumps – each with a diameter of 36 mm and a width of 13 mm – are sized so that a vacuum of up to 0.4 bar is created in the crankcase. This aspirated mixture serves to lubricate the transmission and moves from there into the oil pan, thus effectively reducing the pistons' pump losses. The pressure pump's flow rate is approx. 15 l/min at maximum engine speed; the mean operating pressure is approx. 2.5 bar. From the pressure pump, the oil reaches the oil filter through a pressure control valve, which is designed as a ball valve. The pressure control valve allows a maximum of 4 bar in the pressure line when the engine is cold.

The conrod bearing is supplied with pressurized oil that is centrally injected into the crankshaft. The pressurized oil initially reaches the front piston injection nozzle through bore holes in the crankcase, and reaches the cylinder head through bore holes in the cylinder. It supplies lubrication to the chain adjuster, the rocker arm shafts and the camshafts' bearings, plus it lubricates the contact surfaces between the camshafts and the rocker arms via 4 injection openings. Pressurized oil is then supplied to the second piston injection nozzle, in addition to an axial supply for the lubrication and cooling of the clutch, **Figure 7**.

The crankcase ventilation is accomplished via the primary pinion, which functions as a centrifugal separator. The gas is discharged via the crankshaft and then through the clutch cover. The cooling circuit is perfectly adapted for the operational and package demands. The coolant pump is integrated into the clutch cover on the right hand side and is directly operated by the right balancer shaft. The coolant flows through the clutch cover and into the cylinder via a water pump cover with a large storage volume; the water outlet is located to the right of the exhaust flange and leads via a T-piece into two radiators, flowing lengthwise through them. This dual coolant flow is reunited within the water pump cover. The cooling system's total capacity is 1.2 litres. The coolant flow through the engine is CFD-computed to ensure optimal cooling and is optimized accordingly in the process.

3.5 Clutch and Transmission

The hydraulically operated multi-disk wet clutch sits on the transmission's input shaft and is driven by a spur gearing of the crankshaft. 9 friction-lining disks, plus 8 steel disks serve as torque converters between the driven outer clutch hub and the clutch hub. To lessen load alternation clunks, the clutch wheel is connected to the outer clutch hub by absorbing elements. The contact force for the disc package is applied by six pressure springs; the defined oil supply is provided via a throttle bore in the housing in front of the transmission input shaft **Figure 8**.

The claw-shifted 4-gear transmission, **Figure 9**, is integrated into the engine housing and consists of the transmission input shaft, the output shaft, the gear trains, two shifting rings and the shifting mechanism. Grooved ball bearings and roller bearings bear the shafts in the crankcase. The shifting of the individual gears is carried out sequentially by means of shifting torsion-proof shifting rings positioned on the output shaft. The foot shift lever, the shift shaft and the shifting ratchet turn the selector drum. Milled shift tracks shift the forged shift forks and thus the shifting rings along the output shaft, thus inserting the corresponding gears. A shifting star and an index lever ensure the precise gear position.

The gears are specially graduated for their intended purpose, **Figure 10**. A roller chain performs the power transfer to the rear wheel.

4 Peripherie

4.1 Suction System

The length of the intake pipe was kept relatively short at 65 mm, which is validated by the overall vehicle package. A 41 mm Keihin was chosen for the carburetion system. The decisive reasons for this choice were good throttle response at low loads, a quick cross section release, low weight, simple set-up and great robustness – for motocross use as well. The airbox is not a self-contained part like in automobile engines, but instead is an assembly of several functional motorcycle parts, to save weight. The fenders, the side panels and the bottom of the seat comprise the corpus of the airbox. A washable, plastic foam air filter closes the box on the engine-side.

4.2 Exhaust System

Single-cylinder engines react very sensitively, forfeiting torque in the lower speed range due to the strong pulsations and the large overlap with increased exhaust counter pressure. That's why close attention was paid to fine-tuning the engineering of the flow and the shafts in the 450 SX-F's exhaust system. In comparison to the street-homologated engines, larger, open cross sections can be designed for racing engines, due to the more moderate noise emissions regulations. A catalytic converter for the secondary treatment of exhaust gases is not necessary for motocross racing bikes. The exhaust system is designed as a single pipe featuring an absorption silencer. The manifold has a length of approx. 885 mm and an inner diameter of 43 mm, which widens conically to 48 mm after the 180° arc, **Figure 11** and **Figure 12**.

In terms of the charge cycle, this concept proved to be the best compromise between peak performance and torque at low speeds. Empirical tests on an engine test bench yielded a very good correlation between measurement and calculation, so the proposed system will be employed in the series with only minor manufacturing modifications.

The second, essential design criterion was the weight. The exhaust system was consistently designed to minimize weight. So titanium with a wall thickness of 1 mm was chosen as the material for the manifold. The weight of the titanium manifold is 558 g and therefore about half the weight of a comparable stainless steel manifold. The connecting flanges have very thin walls and are designed as an insertion system with spring attachments. This type of connection is very light, vibration-proof and can be very quickly disassembled for servicing. The silencer's construction as an absorption silencer was also chosen for weight reasons and because of its negligible exhaust counter pressure. It is comprised of a perforated inner tube with deeply drawn, multi-surfaced, stainless steel silencer caps with an aluminium outer casing. The acoustical absorption is accomplished with long-stranded fibreglass wool. The silencer weighs only 2380 g.

The design goal in developing the combustion was a minimal tendency to knock at full throttle at high compression and a sufficiently fast combustion, even under part load conditions with high residual gas levels. The latter is important to give the engine the greatest possible spontaneous responsiveness at low speeds (accelerations out of tight turns). That is why the intake port volume was minimized and the carburetor placed close to the valves. Thus, together with the quick-reacting acceleration enrichment, a very high level of responsiveness can be achieved. The engine achieves a peak performance of 42,5 kW at 9500/min, which corresponds to a specific power output of 96 kW/l. The maximum torque of 49 Nm is reached at 7500/min. This amounts to 109 Nm/l and a mean effective pressure of 13.7 bar. The engine has a broad power band in spite of its power output per litre. 90 % of the maximum torque lies between 4500 and 10,000/min.

5 Functional Characteristics

The overall engine design leads to the desired result – a very harmonious power output. Lots of torque at low rpms, in combination with high peak performance and a very high rev capacity result in an outstanding availability of power for the rider. The engine's exceptionally spontaneous power development and good traction are also extremely persuasive. Just the performance data alone point to a thoroughbred racing engine that is especially agile due to its minimal flywheel mass. The electrostarter is a noteworthy advantage, because engine-stalling falls and bumps happen all the time in the heat of racing battle.

6 Summary

With its new MX engine generation featuring an E-starter, KTM is pursuing a new concept in the MX1 and MX3 classes that sets new standards, thanks to an overall concept that is ingeniously planned, optimised and racing-oriented. The single-cylinder engine exemplifies the best concept to bring this entire package to fruition. With the optimally installed balancer shafts and extremely light components in the performance unit, the compact engine convinces with its negligible vibration level, high performance and enormous rev capacity. An important contribution to the dynamics is its low weight, which, in spite of the battery and E-starter, is only 104.9 kg incl. oil and coolant. ■