Knock, Knock - Part 1

Knock destroys engines. But what is it, how can it be best measured, and how does it affect power?

By Tim White

In this exclusive 3-part series we'll cover the anatomy of knock (often called 'detonation') - looking at what it is, how it occurs, and what negative affects it has on engine performance. We'll explore the use of in-cylinder fibre optic pressure sensors, and later we'll prove the point by torturing a MoTeC-managed Toyota 3S-FE 2-litre engine on the dyno.

But first, some background.....

Knock

The spark-ignition engine has now been in service for more than a century. Throughout this time, gradual improvements have been made to the power output and fuel efficiency of engines. However, one limiting factor for this improvement has remained the same since early times. It is the phenomenon known as "spark-knock", or just "knock".

Knock is an abnormal combustion event in the engine, identifiable by its characteristic "pinging" sound. Prolonged knock causes erosion of the piston and cylinder and eventually results in catastrophic failure of the engine. In turbocharged engines, knock can destroy an engine within seconds. For these reasons, all commercial engines are designed to operate without knock. Knock restricts the performance of an engine chiefly by placing an upper limit on its compression ratio.

A higher compression ratio yields more efficient conversion of the fuel's chemical energy into useful work to drive the piston. Unfortunately, increasing the compression ratio also directly increases the engine's tendency to knock and so to subsequently destroy itself....

Whether a naturally aspirated engine will knock at a particular compression ratio depends primarily on the type of fuel used. The ability of a fuel to resist knock is specified by the fuel's octane number. A fuel with a high octane number is more knock resistant and allows the use of a higher compression ratio before knock occurs.

To maximize the durability of their engines, designers have limited the compression ratio to avoid knock occurring. This has directly limited the performance achieved. Yet in some racing formulas, the engine needs only to last for a short time: say two hours in a Grand Prix race. As long as the engine does not fail during the race, the damage inflicted in that short time is not a major concern. In this situation, the main design criterion for the engine is maximum power output rather than longevity. In Part 3 of this series we will look at the measured power output of an engine where knock is occurring, to see if in fact knock reduces power output in addition to causing other problems.

The Normal Combustion Process

This series of articles is concerned with a particular part of the four-stroke cycle: the ignition and subsequent combustion of the compressed fuel-air mixture. Ignition occurs as the piston nears the top of the compression stroke and combustion continues well into the power stroke.

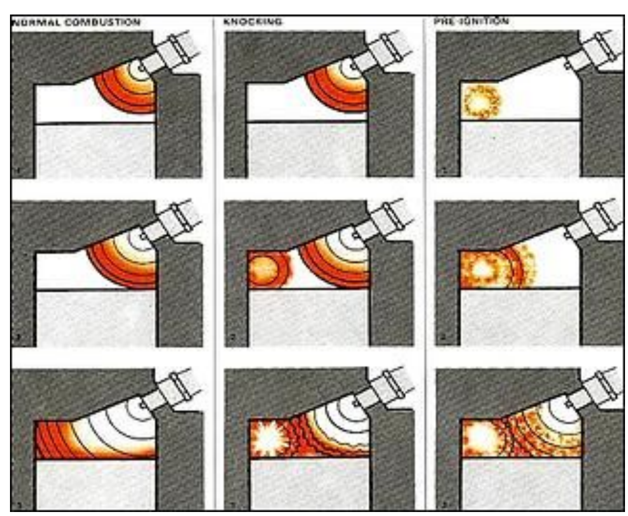
Normal combustion takes place in four stages:

Stage One is ignition and flame kernel growth which immediately follows the introduction of the spark into the combustion chamber.

Stage Two is flame development and occurs as the flame front grows in size. A sphere of flame grows and accelerates uniformly throughout the chamber. Turbulence in the combustion chamber will increase the rate of acceleration by increasing the surface area of the flame.

Stage Three, fully developed propagation, begins when the radius of the flame front reaches approximately 30mm. At this time the fully developed flame front travels across the chamber at a reasonably constant velocity

Abnormal Combustion



There exist several different forms of abnormal combustion where the combustion process does not follow the carefully planned order of events described above.

The particular case of interest in this series is "spark-knock", often abbreviated to "knock". Knock is the preferred name given to the noise that results from the spontaneous ignition of one or more portions of the unburned mixture - the "end-gas" - ahead of the normal flame front. This phenomenon is also often called "end-gas autoignition" and sometimes (incorrectly) "detonation".

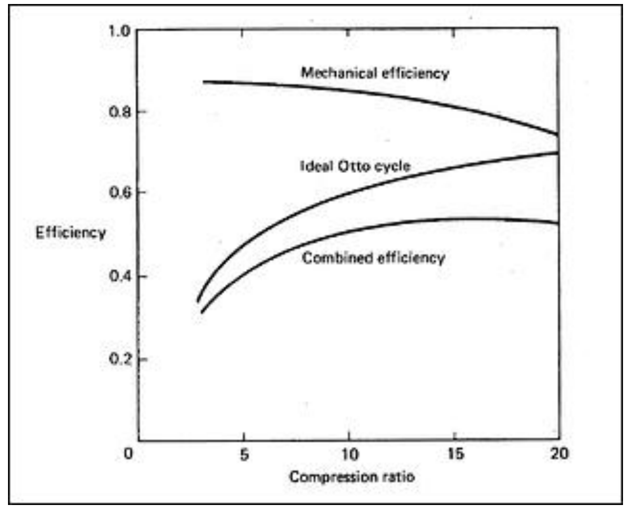
Knock is a concern because, when severe, it can cause quite extensive engine damage and inhibit both performance and efficiency. Even when it is not severe unlikely to cause damage, it is regarded, in passenger vehicles at least, as an objectionable source of noise. For these reasons, commercial engines are designed to operate without knock.

Factors Affecting Engine Power Output And Efficiency

The power output of an engine at a given speed is a proportional to the torque being developed. The torque developed depends on the amount of fuel-air mixture being burnt, and thus the energy released per cycle.

The amount of useful energy liberated by burning the charge is governed by the engine's overall thermodynamic and mechanical efficiency. Efficiency is often measured by finding the engine's Specific Fuel Consumption (SFC). This is a measure of how much power can be produced per unit of fuel per unit of time (eg grams per kilowatt hour). Amongst other factors, efficiency depends on the compression ratio and spark timing.

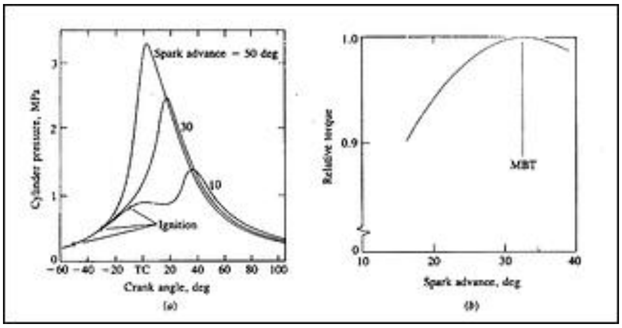
1. Compression Ratio



The compression ratio is the ratio between the volume of the gas in the cylinder before and after compression. For example, if the gas is reduced to one-ninth of its original volume, the compression ratio is 9:1. An increase in compression ratio, to a point, will increase the efficiency of conversion of the fuel's chemical energy to heat and then mechanical energy during the combustion process. As shown in this diagram, experimental work reveals that maximum engine efficiency occurs at a compression ratio of around 16:1.

In practice, however, the Highest Useful Compression Ratio (HUCR) is much less than this optimum of 16:1. As the compression ratio increases, so do cylinder pressures during combustion. Because of this, the higher the compression ratio is raised, the greater the tendency to knock. The value of the HUCR is primarily a function of the knock resistance of the fuel. A typical HUCR for a production car engine is around 9:1.

2. Ignition Timing



The combustion event must be properly located relative to the piston's top dead centre (TDC) to obtain the maximum torque, and thus power, at a given engine speed and manifold conditions.

In this example the middle curve on graph (a), with spark timing advanced 30° before top dead centre (BTDC), represents the optimum timing for this operating condition. If the start of combustion is progressively advanced before TDC (spark at 50° BTDC), the compression stroke work transfer from the piston to the cylinder gases increases. If the end of combustion process is progressively delayed by retarding the spark timing (spark advanced 10° BTDC), the peak cylinder pressure occurs later in the expansion stroke and is also reduced in magnitude. These changes both reduce the work transfer from the cylinder gases to the piston during the expansion (power) stroke.

The optimum timing, which gives the maximum torque, occurs when the magnitudes of the two opposing trends just offset each other. It depends mainly on the rate of flame development and propagation and the length of the flame travel path across the combustion chamber.

Timing that is either advanced or retarded from this optimum gives lower torque, and thus power at the given speed. In the above diagram, (b) shows the effect of variations in spark timing on brake torque for a typical spark-ignition engine. It can be seen that the maximum of this curve is quite flat. It is difficult to find the exact timing that results in maximum torque. In practice, the spark is often retarded to give a one or two percent reduction in brake torque from the maximum.

This value of spark timing is often called "Minimum advance for Best Torque" or "MBT". The term "minimum" is significant since the particular point of timing that corresponds to the one or two percent torque reduction is always obtained by **retarding** the timing from the optimum rather than advancing it. This is done because advancing the timing increases the likelihood of knock.

The spark timing at which knock occurs is called the "knock limit". The value of the knock limit depends chiefly on the engine's compression ratio and the fuel's resistance to knock. In practice, it may not be possible to advance the spark timing to MBT without knock occurring, since the knock limit may lie either before or after MBT (ie best torque may occur at an ignition timing where knock intrudes).

3. Fuel Quality

For a given engine, fuel type is the most important factor in promoting or preventing knock, or "end-gas autoignition". The ability of a fuel to resist end-gas autoignition is defined by the fuel's "octane number".

A fuel with an octane number of 100 has the same knock resistance as a pure sample of a particular type of hydrocarbon called "isooctane". At the other end of the scale, an octane number of 0 corresponds to a sample of pure "n-heptane". In Australia, regular unleaded petrol (ULP) has an octane number of 91. This means that ULP has the same resistance to knock as a blend of 91% iso-octane and 9% n-heptane. The octane number may be raised further still by the addition of lead compounds (such as tetra-ethyl lead) or, since the phasing out of lead, benzene compounds. A fuel of higher octane rating allows the use of a higher compression ratio and more advanced spark timing before knock will occur.

Next week: the anatomy of knock, and measuring its presence and severity with a fibre optic pressure transducer.

Knock, Knock - Part 2
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