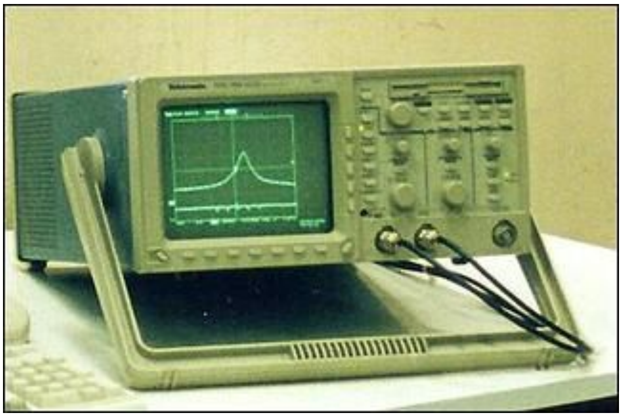
Knock, Knock - Part 2

Identifying and measuring knock.

By Tim White

Spark-knock is a particular type of abnormal combustion in an engine cylinder. It is not the only type of abnormal combustion that can occur; however, in all forms of abnormal combustion there is some extraneous ignition source, which results in more than the one single, smooth flame front propagating through the cylinder.

Abnormal combustion may take many forms. The two main types are 'knock' and 'surface ignition'. Both types are of concern since, when they are severe, they can cause quite extensive engine damage and also inhibit performance and efficiency. Even when not severe and when unlikely to cause damage, they are regarded - in passenger vehicles at least - as an objectionable source of noise.



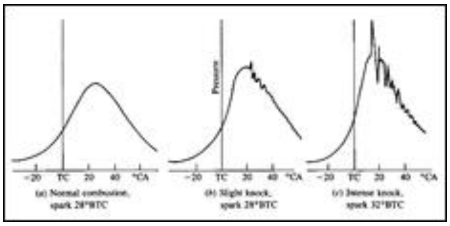
Knock is the preferred name given to the noise that results from spontaneous ignition of the end-gas ahead of the normal flame front during combustion. It is thus a direct consequence of the spark ignition. Knock that follows normal spark ignition is called "spark-knock" to distinguish it from knock which has been preceded by surface ignition, although it is usually abbreviated to just "knock". When knock occurs, energy is released from the fuel to the cylinder in the form of heat and pressure much more rapidly than in normal combustion.

Surface ignition begins entirely differently to knock. It occurs when the fuel-air mixture is ignited by coming into contact with a hot spot somewhere in the combustion chamber. Typically this may be an overheated exhaust valve or spark plug, a glowing combustion chamber deposit or by any means other than the spark plug. Its occurrence is completely independent of the primary ignition source (the spark plug).

Since the spontaneous ignition causing knock is governed by the temperature and pressure history of the end gas and therefore by the phasing and rate of development of the flame, various combinations of knock and surface ignition may occur. Surface ignition is a problem that can be solved by appropriate attention to engine design, fuel and lubricant quality. In contrast, knock is an inherent constraint on engine performance and efficiency since it limits the maximum compression ratio that can be used for any given fuel.

Here we're concerned with the special case of end-gas autoignition known as knock. This is the spontaneous ignition of parts of the charge which are not in contact with either the advancing flame-front from the spark plug, or the combustion chamber walls.

Historical Knock



Knock is best defined and identified as the sound associated with vibrating pressure waves created by the burning of some part of the mixture in advance of the normal flame front. The abnormal burning in advance of the flame front creates a measurable rise in pressure that is always steeper and often earlier in the combustion cycle than normal. Under some conditions, this gradual pressure rise becomes a pressure spike with a peak value much higher than normal. This is illustrated here.

The knocking phenomenon can be traced back to the first days of combustion engineering in piston engines. Nickolaus Otto, the inventor of the of the four-stroke spark-ignition engine, pointed out in his records a strong noise while the internal combustion process destroyed his engine(!). Yet the event was not given serious consideration until Kettering in the USA and Ricardo in the UK recognised that this particular characteristic of the combustion process limited the compression ratio at which an engine could be operated.

In 1913, Sir Harry Ricardo made the first useful findings on the subject. He found that knock caused significant increases over normal combustion pressures in the cylinder. Ricardo stated that the damage inflicted on the engine's internal components was a consequence of the pressure rise associated with knock. He also found that knock occurred **after** the spark ignition. The knocking phenomenon then became known as "spark-knock" to distinguish it from other knocking noises produced by an engine. For convenience, the term "knock" is still used.

Much of what is known about combustion in engines comes from the analysis of photographs of the combustion event. These photographs are taken with high-speed cameras in specially modified engines equipped with glass windows in either the cylinder or the head to allow the combustion event to be viewed. Early attempts proved to be of little value, and it was Miller who in 1941 first developed the ultra high-speed camera capable of producing useful results. Miller also analysed his photographs and many of his findings and theories regarding the exact nature of how knock occurs were corroborated by later research.

Two Competing Theories

There is still much debate on how knock actually occurs. Since Miller's time, two differing theories have existed as to the exact way in which the spontaneous combustion of the end-gas occurs. These are the "autoignition" theory and the "detonation" theory. The major difference between these two theories lies in how the end-gas region is ignited rapidly enough in the short time available to create the vibrations associated with knock.

- **Autoignition Theory** relies on the compression of the end gas by an infinite series of sound waves, which are caused by the normally burning gas. The resulting rise in temperature and pressure causes the end gas to spontaneously ignite.

- **Detonation Theory** attributes the compression and subsequent ignition to an intense compressive shock wave travelling through the end gas at supersonic velocity.

In recent times, researchers have begun to make decisions as to which type of knock actually occurs. The two groups remain polarised by the respective theories. Miller actually proposed a combined theory (autoignition plus detonation waves) which stated that both end-gas compression methods exist to some degree in all cases. He identified which type of knock was occurring by the pitch of the resulting sound.

Knock of a relatively low pitch was caused by simple autoignition of the end-gas at a rate too slow to produce audible gas vibrations. Knock of a high pitch indicated a detonation wave in the after-burning gases behind the flame front. Knock containing both high and low pitched tones were the result of autoignition followed by the development of a detonation wave.

Whilst a combined theory seems quite feasible, many researchers today accept only one theory or the other. Most accept the autoignition theory.

Causes Of Knock

As discussed, for a given engine the type of fuel is the most important factor in promoting or preventing end-gas autoignition. The following guidelines show how various engine operating parameters affect the fuel octane requirement of an engine. The higher the octane requirement, the more likely an engine is to knock for a given fuel.

Parameter	**Effect On Octane Requirement** (ON = octane number)
Spark advance	1 ON per 1 degree Spark Advance
Intake air temperature	1 ON per 7 Kelvin
Air/Fuel ratio	Peaks at around 5% rich of stoichiometric Decrease of around 2 ON per A/F ratio around peak
Intake Pressure	3-4 ON per 10 kPa
Compression Ratio	5 ON per CR
Exhaust back pressure	1 ON per 30kPa
Coolant temperature	1 ON per 10 Kelvin Similar effect for head and block temperature

For naturally aspirated engines, the two main design and tuning parameters given in the table are the compression ratio and the spark advance. For an engine at wide open throttle (maximum inlet manifold pressure) and normal operating temperature; these two parameters, if increased, are then proportionally the most likely to produce knocking combustion.

Detection Of Knock

There are several ways of detecting when knock is occurring in an engine. Only some methods, however, are capable of measuring the knock intensity.

1. Sound of Knock Knock is audible when more than about 10% of total engine cycles knock. The human ear is the most obvious and readily available device to detect knock. The ear is surprisingly sensitive and routinely used in determining the octane requirement of an engine. The sound of knock is best described as a sharp metallic "ping". This sound is caused by the high pressure and frequency waves impacting against the cylinder walls, giving rise to a ringing knock as though they had been struck by a light hammer. The ringing noise is worsened by the way in which the energy of the pressure wave is not completely absorbed when it first contacts the chamber wall. Instead, the wave is only slightly diminished and then reflected back across the chamber, continuing this process until all the energy is lost to the engine structure as vibration or dissipated through the gas.

2. Sight and Pressure of Knock A high-intensity flash is observed in the cylinder when knock occurs. This facilitates the use of optical probes and ionisation detectors to measure at least the presence of knock if not its intensity. Much of what we know about combustion today has come from the analysis of photographs taken using high-speed cameras as first successfully developed in 1941. More recently, as the technology has become widely available, direct measurement of cylinder pressures during combustion has been used to study knock. Direct pressure measurement allows the study of the actual intensity of knock. The piezoelectric pressure transducer has been the standard sensor for some time. Typical pressure traces from a cylinder experiencing knocking and non-knocking operation were shown earlier.

A major obstacle in developing feasible combustion pressure sensors has been to overcome sensor performance degradation caused by high combustion temperatures and strong electromagnetic interference (EMI). So far, due to inherent material limitations, conventional piezoelectric type combustion pressure sensors cannot operate over 200°C without water-cooling. In addition, signal conditioning electronics must usually be located near the sensor head to combat the strong EMI and stray capacitance loading effects of spark-plug leads.

The last decade has seen the emergence of the fibre-optic pressure transducer. Fibre-optic sensors prove themselves operationally viable in high temperature conditions. EMI immunity makes them suitable for applications such as engine combustion pressure monitoring. Engine tests performed with the fibre-optic sensors demonstrate signal-to-noise performance comparable to piezoelectric transducers for a sensor of much smaller size. The sensor output is more temperature stable than a piezoelectric transducer and the total cost of the equipment is also less.

For these reasons, the shown fibre-optic transducer was used for the measurements made here. It was small enough to be mounted in a specially modified spark plug. The sensor head (coloured red) has a diameter of just 2.8mm, the thread has a diameter of 3.5mm. The sensor is connected to its electronic module by the blue fibre-optic cable. This module connects directly to DC power and an oscilloscope.

It is important to note that once knock occurs, the pressure distribution across the combustion chamber is no longer uniform. Pressure transducers located in different parts of the chamber will record different pressure levels at a given instant until the wave propagation associated with knock has been damped out. A comprehensive study of the exact nature of knock would require several pressure transducers; each located in different parts of the combustion chamber. Such work was beyond the scope this testing and so a single transducer was used.

3. Determination of Knock Intensity

A simple method is based on the Maximum Amplitude of the Pressure Oscillations (MAPO) during knock. As the name implies, this method simply involves measuring the maximum amplitude of the pressure oscillations that occur during knock. The oscillations for analysis are typically obtained by passing the cylinder pressure data through a bandpass filter centred on 6kHz.

Owing to its simplicity, and its use by other distinguished researchers, the MAPO method was adopted for use in analysing the results from the measurements presented here. While a bandpass filter was not used, the direct measurement of the amplitude of pressure fluctuation was found to still give a very good indication to the intensity of knock. The increase in amplitude of pressure fluctuations corresponded well to an increase in the audibility of knock. Analysis of the pressure traces produced indicates that the frequency of knock was between 5 and 6 kHz.

A classification was developed for describing the intensity of knock that occurred in the test engine. This classification is shown here:

Knock Intensity	**Maximum Amplitude Of** **Pressure Oscillation**
Trace Knock	MAPO of 60 kPa (0.6 bar) At least 10% of cycles knocking
Medium Knock	MAPO of 150 kPa (1.5 bar)
Heavy Knock	MAPO of 300 kPa (3 bar)

Engine Damage Caused By Knock

The main reason that knock is a concern in engines is because of the severe mechanical damage it can cause. For this reason perhaps more work has been done on analysing the damage that knock causes than any other aspect of the phenomenon. Engine damage that results from excessive exposure to knock is quite distinctive. Upon first inspection the surface has the appearance of being sandblasted. Further analysis reveals the type of damage to be very similar to that caused by hydraulic cavitation.

This damage results from two sources: increased heat transfer rates and increased pressure resulting from accelerated combustion.

There is a theory that the pressure waves associated with knock scour away the protective boundary layer of relatively stagnant gas adhering to the combustion chamber walls. As a result, the heat energy from combustion is lost to the cylinder walls and piston at a rate much higher than usual. The amount of heat lost to the engine in this way may be up to three times the normal amount. The greater heat transfer to the chamber walls raises their temperature. The extra heat weakens the material on the surface and this high-temperature weakening is then combined with extremely high local pressures from the knock pressure wave, causing the surface to erode. Local pressures of over 180 Bar (over 2600 psi!) have been recorded in test engines, at frequencies of up to 250 kHz.

The usual failure is the result of erosion of the piston head at the position of the last part of the end-gas to burn. In extreme cases, the temperature in the cylinder may rise high enough to cause actual melting of part of the head of an aluminium alloy piston. An explanation for this is that the aluminium alloy commonly used for pistons (precipitation hardened) may actually continue to age (becoming more brittle and prone to erosion) when subjected to high temperatures and repeated knocking operation. With repeated exposure to knocking, brittle fracture will occur and the piston will catastrophically break.

Effect On Emissions

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                                Run Results
                     Test Data   Composite Standard   Test Result
Parameter
HCgpm....................  0.159        0.800            Pass
COgpm....................  2.962       15.000            Pass
NOxgpm...................  0.812        2.000            Pass
CO2gpm................... 265.116
O2gpm....................  1.697
Purge (liters)...........    N/A        1.000            N/A
Fuel economy (MPG).......  52.81

Test time................May 26, 2000  2:23 PM
Test length..............240 Seconds
Overall result...........Invalid (due to speed excursion(s))
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As may be expected, the abnormal combustion associated with knock leads to a higher output of undesirable emissions. Quantitative data from a test is given here.

Carbon Monoxide (CO) levels may increase significantly with knock. This is attributed to a reduction in volumetric efficiency owing to higher combustion chamber wall temperatures. It therefore becomes a problem particularly with modern EFI engines using manifold pressure sensing to determine the fuel injection quantity. In these engines, the mixture will become richer during knock.

Hydrocarbon(HC) emissions do not seem to be greatly affected. Even though knocking combustion is incomplete in that the fuel is not fully oxidised, the fuel is still oxidised to some extent (which results in the higher CO emissions). Heavy knock may also cause the stagnant boundary layer to be removed from the cylinder walls. This layer contains high levels of HC's which during knock are mixed in with the rest of the cylinder gases and burned. In some cases, this may actually lower HC emissions compared to non-knocking operation where the boundary layer remains intact.

Oxides of nitrogen (NOx) significantly increase. This is attributed to the higher combustion temperatures that occur during knock. The higher temperatures result in an increased rate of NOx formation.

Noise

Knock is an objectionable source of noise commonly known as "pinging". In recent times much emphasis has been placed on noise control as well as emissions control in automobiles. The sound of knock is now louder than ever before in comparison to other vehicle noises. This is another reason that manufacturers of both engines and fuel wish to avoid knock in vehicles using their products. Many motorists feel that pinging is the result of a poorly designed engine or low quality fuel.

Power Loss With Combustion Knock

Knock primarily occurs under wide-open-throttle (WOT) operating conditions. It is thus a direct constraint on engine performance.

Most sources agree that knock lowers the efficiency of an engine by increasing the rate of heat transfer to the cylinder walls during combustion. Whilst several sources deal qualitatively with the loss of power and efficiency during knock, very few give good quantitative results. It is agreed by most that detonation results in a considerable amount of heat transfer to the walls of the combustion chamber. Since there is no more heat release by the fuel in the combustion process, this is heat that in normal combustion would be converted into useful work to drive the piston.

Moderate to heavy knock reduces the power output and efficiency of an engine. This is caused by a higher proportion of the chemical energy contained in the fuel being lost to the combustion chamber walls during knocking operation than for normal combustion. This leaves less energy to be converted to useful work.

Next week: Torturing the knocking Toyota 4A-FE engine on the dyno.

Knock, Knock - Part 1
Knock, Knock - Part 3

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