Cyclic Variability in SI Engines

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The most widely-used measure of the combustion cyclic variability or combustion quality is defined through measurements of combustion chamber pressure as a function of the crank angle. Therefore, prior to indulging in a brief description of the cyclic variability, its possible causes and adverse effects, it is imperative to visualize and understand combustion chamber pressure behavior. The in-cylinder pressure after the valves are closed changes primarily due to changes of volume as piston moves and to the net amount of the fuel chemical energy release given to the trapped mass in the form of the heat. Typical averaged cylinder pressure traces for different spark timing of 45, 29, and 8 crank angle degrees before top dead center (TDC) are shown in Figure 1. Assuming that 29 degrees is the optimum spark timing (called MBT timing or spark time at which maximum (brake) torque occurs) then traces A and C are advanced and retarded with reference to the MBT case respectively. Note that each curve in this figure is an average of sufficiently large number of individual cycle pressure traces. But how do individual single-cycle traces look like when compared to the mean trace? Figure 2 attempts to give an impression of how individual traces behave. This behavior is referred to as cyclic variability. It is essential to note that traces in Figure 2 all have the same ignition timing. In other words, combustion is spark-initiated at the same time and the differences observed are not due to variations in spark timing. Indeed if not informed of this fact one is tempted to attribute such behavior to changes in combustion initiation as traces in Figure 1 suggest.

What is the problem with such a behavior? After all, the world is full of variations and we learn to appreciate diversity. There are several major problems with having such a cyclic variability in cylinder pressure. First, it causes losses in both power and efficiency. This is because engine spark timing is set at the MBT value determined for the average cycle (Figure 2). However, some cycles behave as if they were advanced (cycle 1 in Figure2) and some retarded (cycle 4). This leads to lowered power as well as efficiency. Second, extremes of the cyclic pressure traces set the lean limit and knock limit of operations of an engine design. For example, the cycle number 1 in Figure 2 is the fastest burn and appears as though it were spark-advanced. It is this cycle that is most susceptible to knock should that occur and hence this extreme defines the knock limit of operation, fuel octane requirement, and the maximum compression ratio of that engine design. The slowest burn cycle similar to the extreme cycle number 4 in Figure 2 is the one to fail first should the engine be operated under the lean fuel/air mixture condition and hence determines the lean limit of operation. Here, ìto failî means that either spark is unable to start the flame or even if initiated it is extinguished prior to having a chance to completely burn the mixture. Third, emission issues and in particular control of nitric oxides are severely affected by the large cyclic variability. This is because an engine with large cyclic variability cannot tolerate sufficiently-high exhaust gas recalculation (EGR) for nitric oxide emission control. Finally, variations in cylinder pressure causes variations in engine output torque which is directly related to vehicle derivability.

What are the causes? After many years of research the followings are considered as causes of cyclic variability. In general, any factor that accelerates the combustion rate leads to lower engine cyclic variability. For example, inclusion of multiple spark plugs and port and chamber design changes to enhance turbulence (faster flame burning rate) are measures that reduce variability. Also, changes in location, size, growth rate of the initial flame kernel and its interaction with chamber walls affect variability. The major causes, however, are proposed to be variations of the in-cylinder mixture motion at the time of the spark and variations in mixing between the incoming fresh fuel/air charge and the gases left from the previous cycle (residual gases) cycle by cycle and especially near the spark plug. For the stoichiometrically -fueled engine at low load and MBT operation the cyclic variability is correlated to cyclic variations in the amount of the fuel burned per cycle.

How do we measure the extent of the cyclic variability? Although there are several ways to quantify, the most widely used parameter is the so-called covariant of the indicated mean effective pressure (imep). The imep is the work per cycle, calculated by integrating the pressure as a function of the cylinder volume, divided by the piston displacement volume. This process is repeated for a large number of individual consecutive cycles and the ratio of the standard deviation of the imep numbers to the mean value as a percentage is the covariant of the imep. For further reading on this subject the readers are invited to resort to Internal Combustion Engine Fundamentals by J. B. Heywood, as a good starting point, and to SAE Technical Papers 810020, 890884, 902142, and 902143.

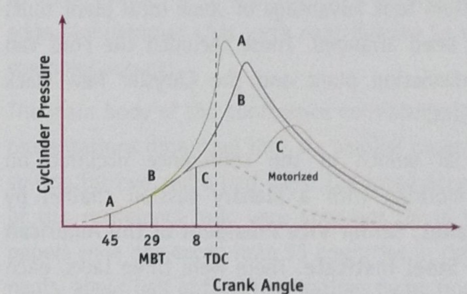

Figure 1: Mean cylinder pressure as a function of crank angle at the same engine speed. Spark timing for A, B, C are at 45, 29, 8 degrees before TDC respectively. A, B, C curves are for fired and dashed curve is for motored (nonfired) cases.

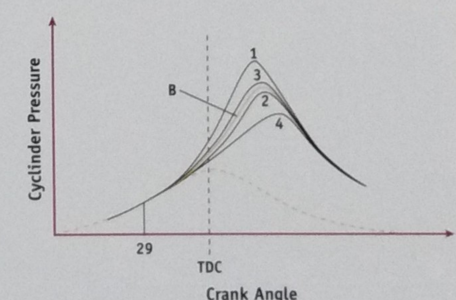

Figure 2: Pressure traces for several consecutive cycles at a fixed spark timing of 29 degrees before TDC indicating cyclic variability.

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