- Torsional Output of Piston Engines -

The torsional pounding that piston engines apply to the stuff they run

In order to design machinery which will be driven by piston engines, it is necessary to understand the nature of the output those engines produce. Unlike a turbine or an electric motor, a piston engine does not produce a smooth output, but a very "lumpy" one, the degree of lumpiness depending on the number of cylinders and the evenness of the firing order. The following subsections present an explanation of piston engine torsional excitations.

Piston engines are often referred to as "Internal Combustion" (IC) engines, which is something of a misnomer. The "IC" really stands for INTERMITTENT COMBUSTION.

As a result of that intermittent combustion and the piston motion described on a previous page, a piston engine is a vibration machine. It generates horizontal and vertical shaking vibrations, fore and aft rocking moments, and torsional excitations galore. The torsional component of the output is the subject of this discussion.

SINGLE CYLINDER ENGINE

Consider how a 4-stroke piston engine operates. During each 720° of crankshaft rotation, each cylinder in a contemporary 4-cycle piston engine produces a torque output during roughly 140° of crankshaft rotation, and requires torque input during the remaining 580° of rotation. The general shape of this instantaneous torque characteristic is well-known and is illustrated in Figure 1.

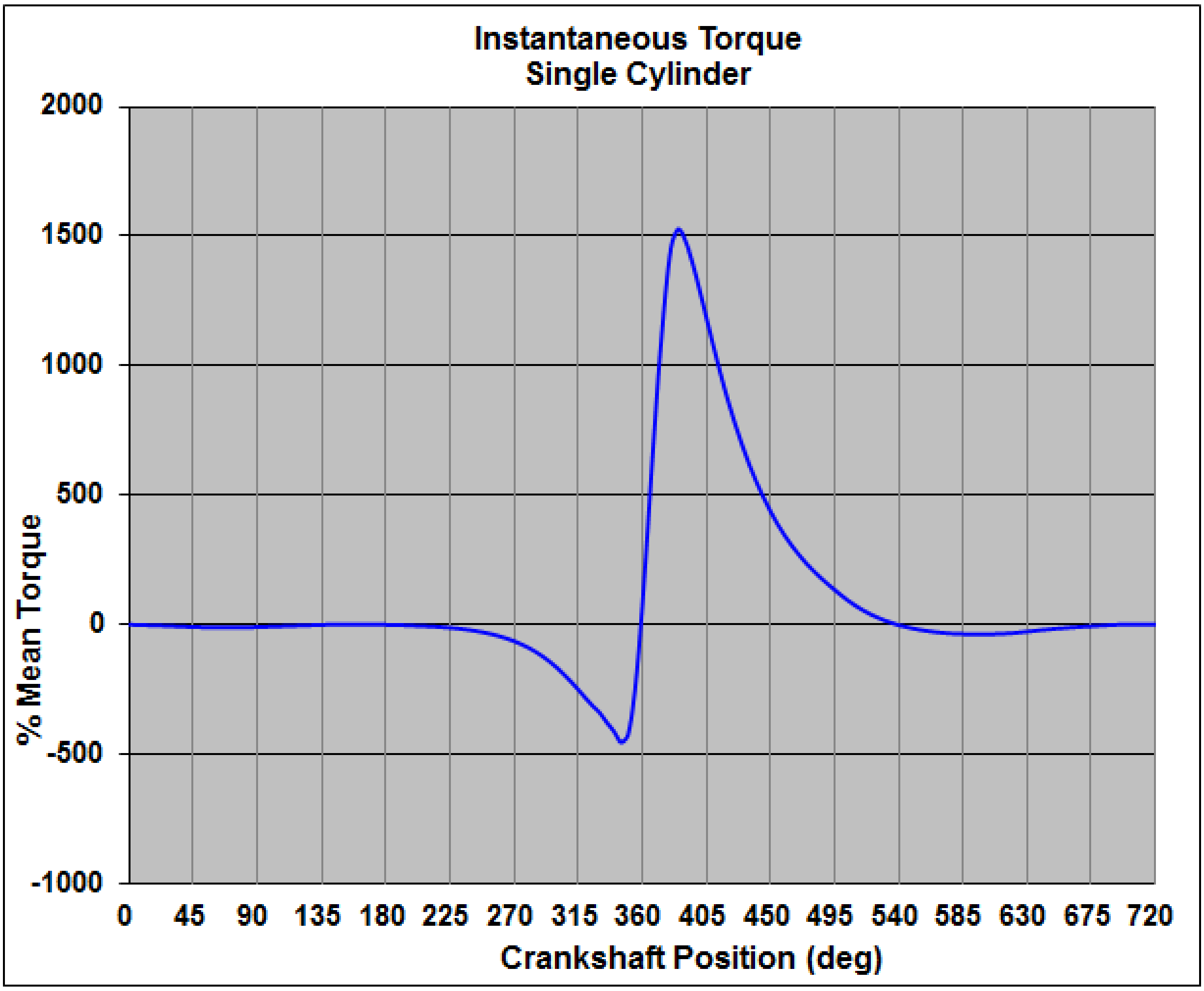

Figure 1

Notice that the peak value of torque output is approximately **15 times** greater than the mean torque output of the engine (the torque which the dynamometer measures). Also notice that the torque curve contains a negative peak (valley) which is nearly **5 times** the mean engine torque. Kind of impressive that your lawnmower engine stays together, isn't it?

Now, let's examine the torque characteristics of various configurations of multi-cylinder engines. The following charts are representative of full throttle operation of various engine configurations, and show the waveform of the torque curve which each engine applies to whatever is connected to the crankshaft output flange. The torque values are displayed as a percentage of mean torque.

These charts were prepared by mathematically superimposing the single-cylinder data shown in Figure 1 in order to show the effect of various engine layouts. Be mindful, however, that although these curves were mathematically generated, they do not represent some form of engineering fantasy. They bear a remarkable similarity to actual data we have taken from instrumentation installed across the load cell on an engine dynamometer.

On any given engine, the shape and amplitude of the signal can vary from those shown, depending on the specific details of engine. However, the fact remains that piston engine output consists of peaks and valleys, and the peaks *greatly exceed* the measured torque of the engine.

You may notice that, in general, as the number of cylinders increases, the peak amplitudes decrease and the waveform tends to become more approximately sinusoidal.

This section presents *"even-fire"* engines as well as a few common *"odd-fire"* engines. An *even-fire* engine is one in which the firing of each cylinder is separated from its predecessor by the same angular travel of the crankshaft. An *odd-fire* engine is one in which each cylinder fires at a different rotational spacing from its predecessor. Odd-fire engines are interesting because they produce more complex excitation resulting from the uneven pulse spacing and also because closely-adjacent pulses couple in unexpected ways, which can raise the amplitudes of the excitations and of the harmonics.

FOUR CYLINDER ENGINE

In a standard inline or horizontally-opposed even-fire four-cylinder engine, one cylinder fires every 180° of crankshaft rotation. The waveform in Figure 2 the instantaneous torque curve for an even-firing 4-cylinder engine, measured at the output flange of the crankshaft.

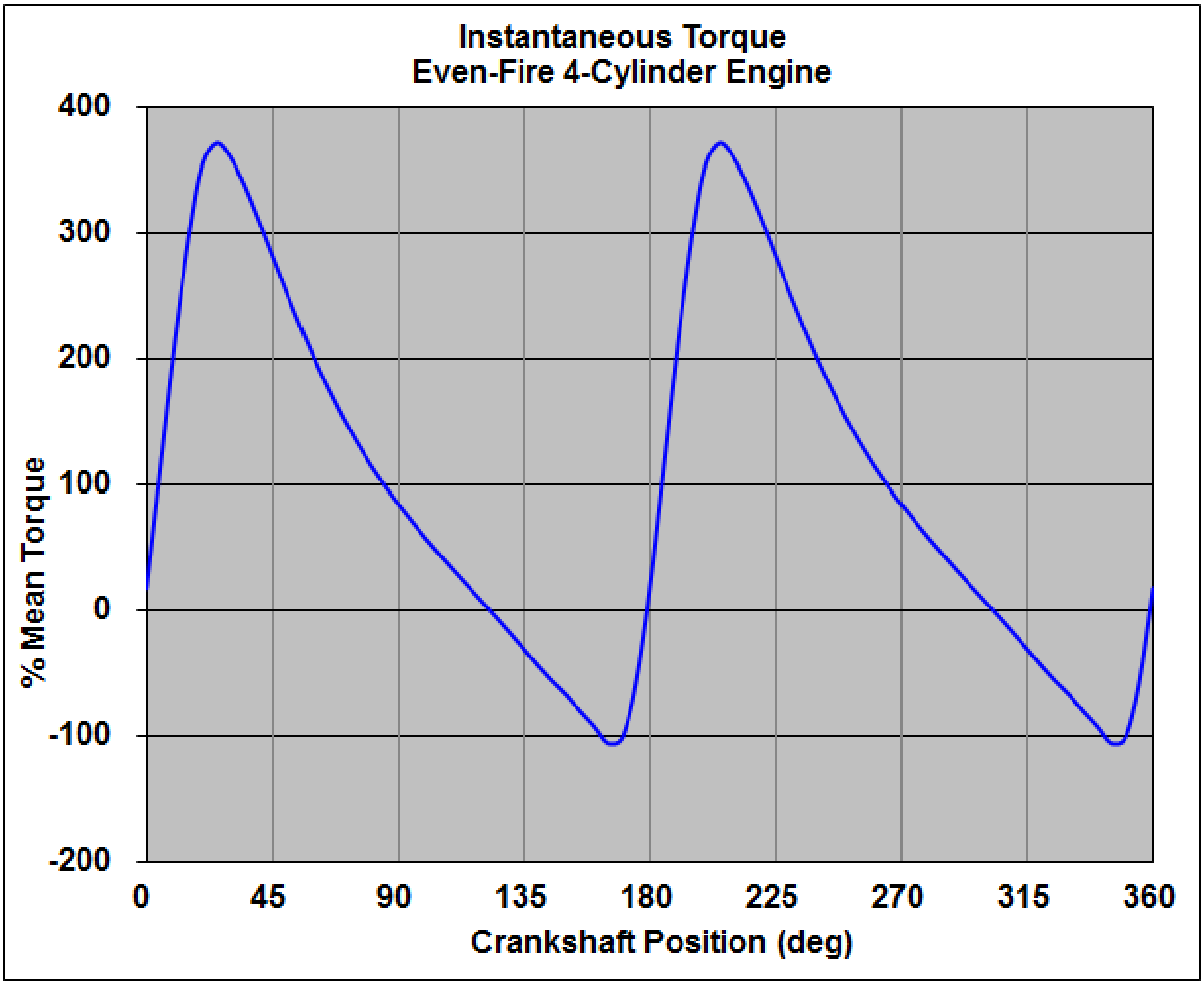

Figure 2

Note that the waveform in Figure 2 contains two torque peaks which are nearly 300% above mean torque, and two torque valleys which are about 200% below mean torque. This waveform is an example of "second order" excitation, because there are two complete up-and-down torque pulses (cycles) per rotation of the crankshaft.

Note that this waveform approximates a sawtooth, and there is a small negative "blip" at the bottom of the valley, which means that the engine output contains a complex mixture of harmonic orders. The shape of the waveform and the torque reversals make it quite apparent that the metal-prop designers have done an amazing job.

EVEN-FIRE SIX CYLINDER ENGINE

In a standard 6-cylinder engine with inline, horizontally-opposed, or a 60° V layout, one cylinder fires every 120° of crankshaft rotation. (One variant of the GM 90°-V-6 has a split-pin crankshaft which incorporates a 30° offset between adjacent rods to implement an even 120° firing spacing). Figure 3 shows the torque waveform of an even-fire 6-cylinder engine, which is a "third-order" excitation, one which has three peaks per revolution.

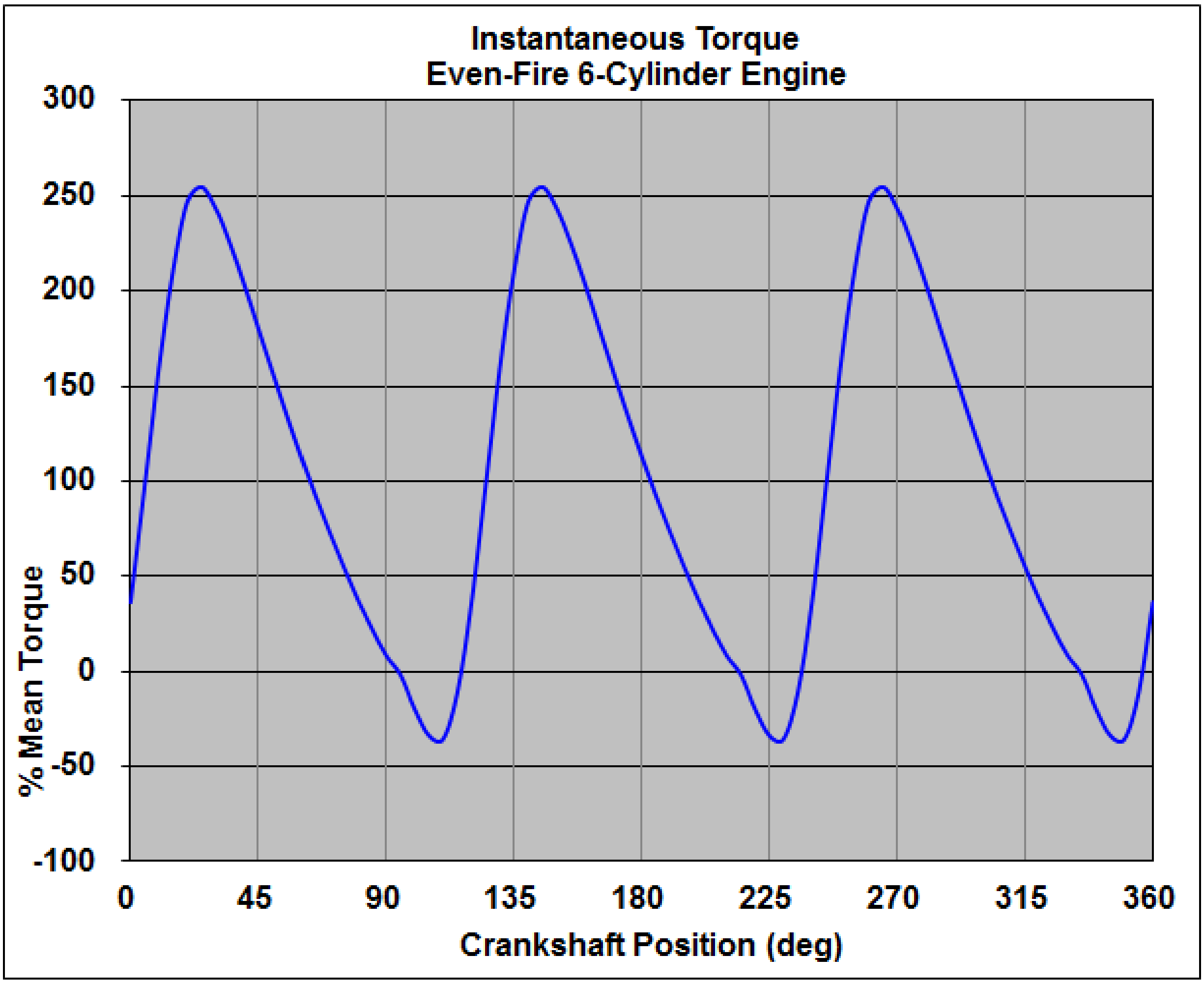

Figure 3

Note that, as a result of more closely-spaced power pulses, the amount that the peaks exceed the mean is less than in the 4-cylinder example, and although the valleys still dip below zero, the negative amplitude is reduced. Also notice that the waveform still resembles a sawtooth curve, and has some irregular shaping in the negative-pulse valley, indicating the presence of complex harmonics.

ODD-FIRE SIX CYLINDER ENGINE

An example of an odd-fire engine is the GM 90°-V6 with the "common-pin" crankshaft (conceptually, a small-block Chevy V8 with cylinders 3 and 4 cut out). This version of the V6 is often used in performance applications because the common-pin crank is quite a bit stronger than the split-pin crank used in the even-fire GM 90°-V6 engines..

With this layout, the firing impulses are unevenly spaced and occur at crankshaft rotation intervals of 150°-90°-150°-90°-150°-90°. This engine produces a complex mixture of torque excitation, as shown in Figure 4.

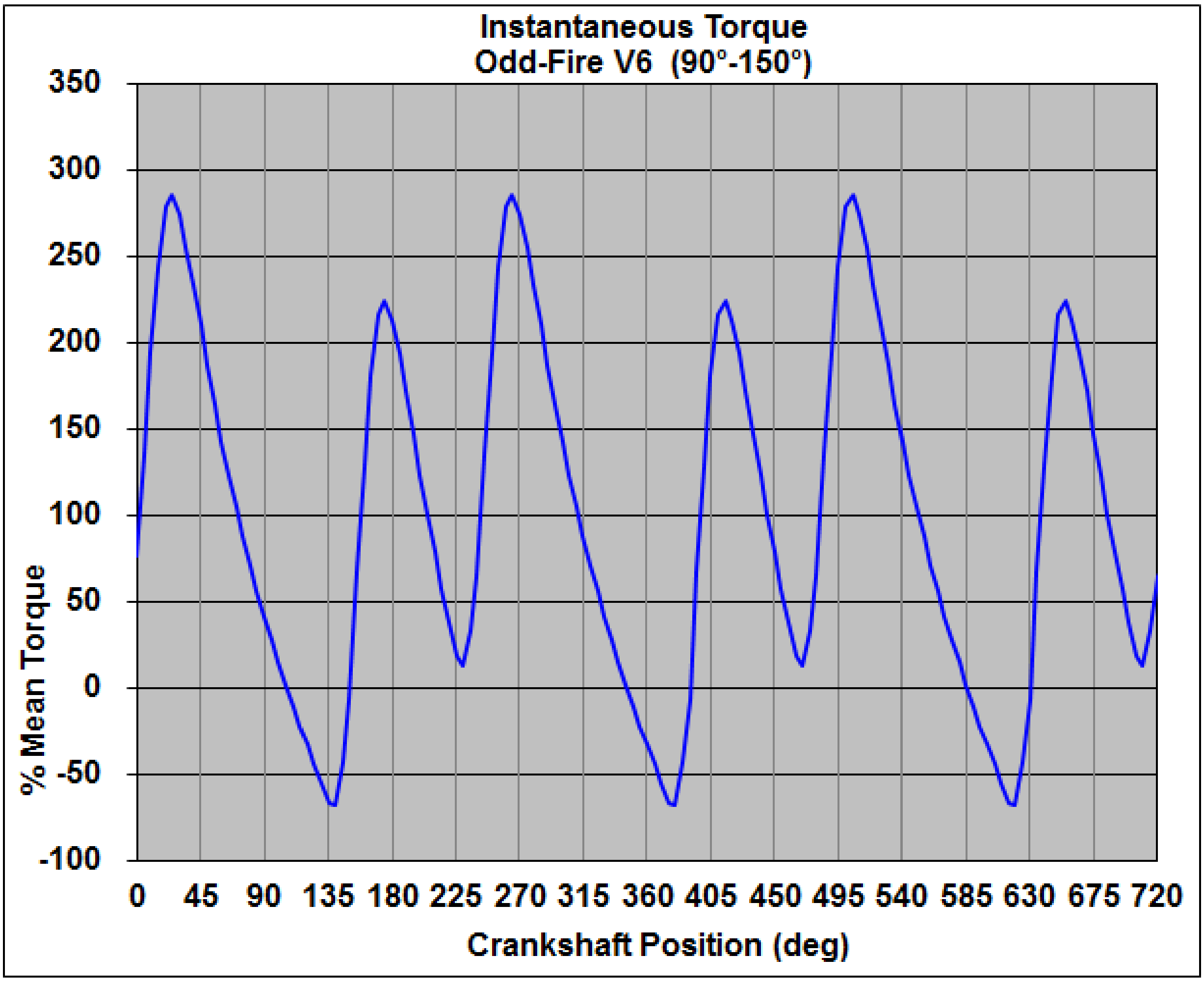

Figure 4

From a torsional standpoint, this engine is terrible. It exhibits adjacent-pulse coupling, uneven spacing between adjacent peaks and significant dips into the negative torque range. This particular curve contains large excitation components of the 1.5, 2.4 and 4th order (and others) which can be difficult to suppress. High-output odd-fire V-6's have been known to shatter the strongest of dynamometer driveshafts in a rather short time.

EVEN-FIRE 8-CYLINDER ENGINE

In a standard layout V8 engine, one cylinder fires every 90° of crankshaft rotation. Figure 5 shows the instantaneous torque characteristic of this type of engine. This is a "fourth order" excitation, which at an 800 RPM idle, produces 53 pulses per second (Hz), and at 5000 RPM, produces 333 pulses per second (Hz).

Note that in this layout, as a result of the closely-spaced power pulses, the valleys do not dip below zero.

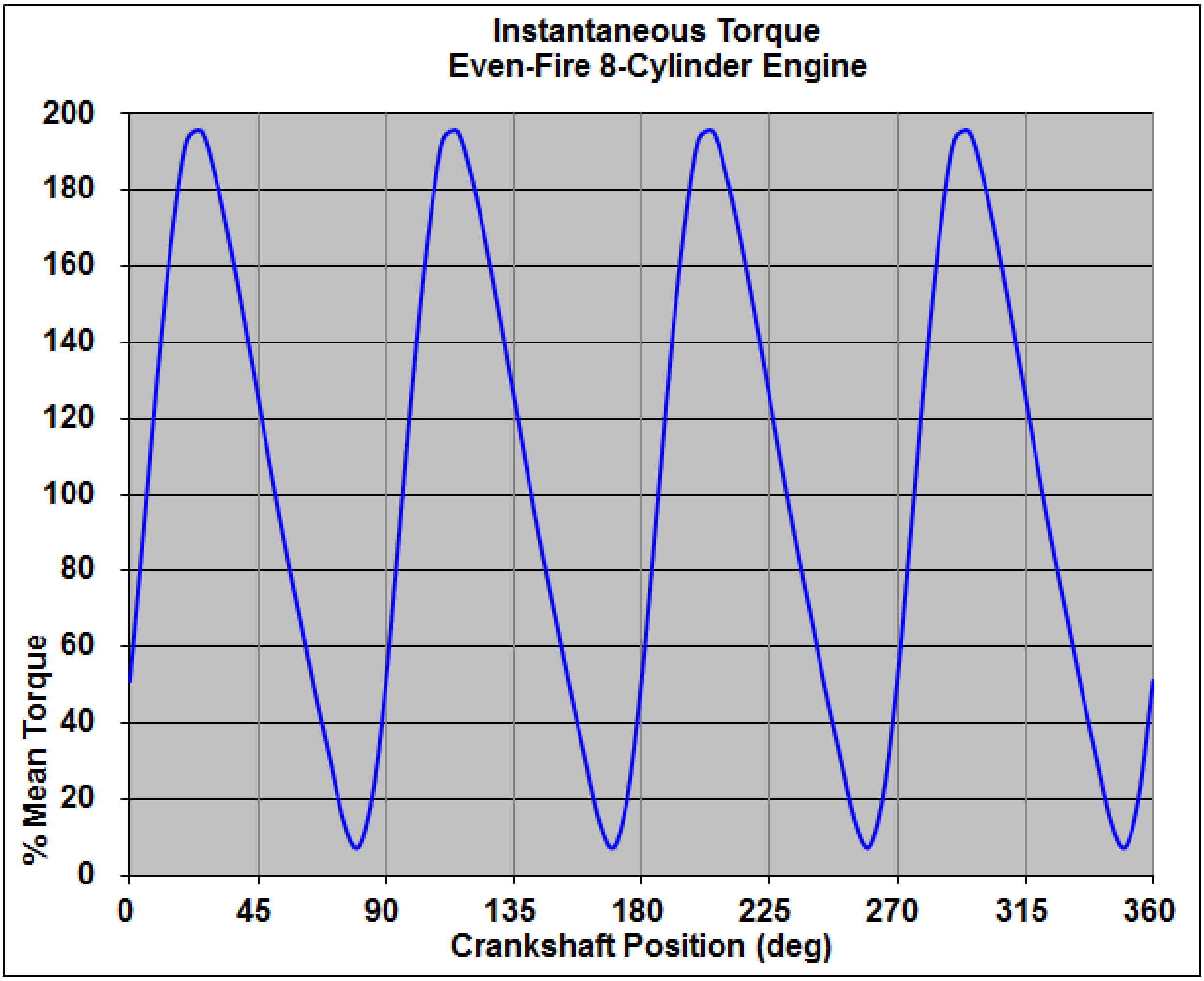

Figure 5

Figure 5 shows the peak torque amplitude to be roughly twice the mean torque of the engine. This particular engine produces a mean torque of 625 lb.-ft. at a specific RPM, but at that mean torque value, the instantaneous torque peaks are about 1235 lb.-ft. and the valleys are about 68 lb.-ft. Note that the waveform still has somewhat of a sawtooth appearance, although more rounded than previous examples.

EVEN-FIRE 12 CYLINDER ENGINE

In a 60° V-12, 120° V12, or horizontally opposed 12-cylinder engine, one cylinder fires every 60° of crankshaft rotation, producing six power pulses per crankshaft revolution. Figure 6 shows the instantaneous torque characteristic of this type of engine. Note that in this layout, as a result of even-more-closely spaced power pulses, the peaks only extend about 40% above mean and the valleys extend only 40% below mean.

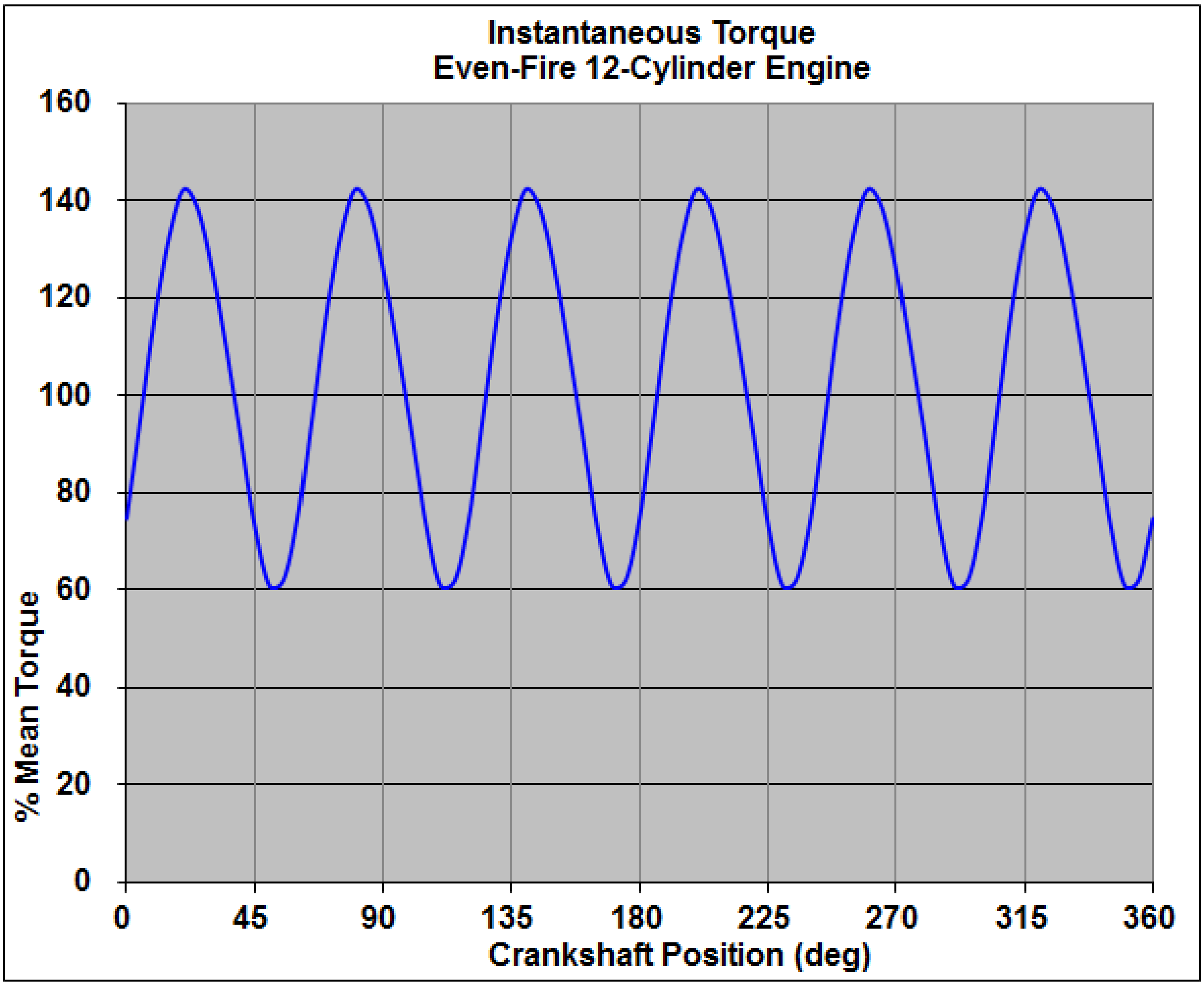

Figure 6

This waveform is the type generated by the Allison and Merlin V-12's which powered a significant number of successful WW2 aircraft (P-38, P-39, P-40, P-51, P-63, Spitfire, Hurricane, Lancaster, etc.).

ODD-FIRE V-12 ENGINE

Certain examples of odd-fire engines exhibit an unexpected characteristic: when one cylinder follows its predecessor very closely, the successor pulse combines with its predecessor pulse to produce a single larger torque pulse, and the output waveform changes to the order of an engine with half the number of cylinders. Therefore the excitation frequency is half what an evenly-spaced engine with the same number of cylinders produces, and the amplitude is considerably greater.

A specific example of that phenomenon is the V-12 engine being used in a certain warbird replica. That odd-fire engine is, in essence, a pair of in-line six-cylinder engines, physically separated 90° from each other, sharing a common 120° crankshaft. It has a 90°-30°-90°-30° firing impulse spacing, which produces the output waveform shown in Figure 7.

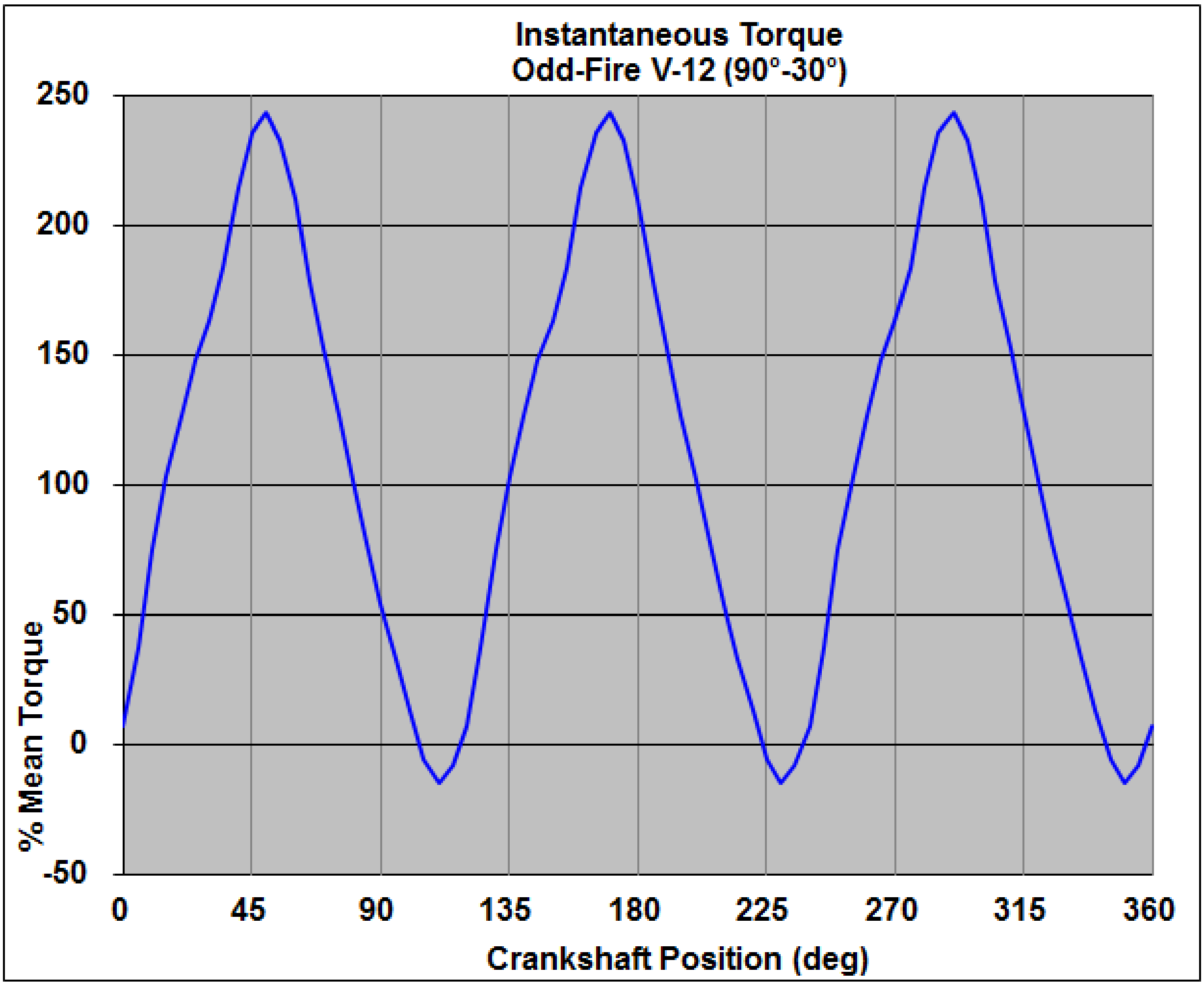

Figure 7

Notice how the cylinder which follows its predecessor by only 30° combines with the predecessor to produce a 3rd order wave-form instead of the clean 6th order of an even-fire V-12.

The torque peaks of this engine are roughly 140% of the mean torque instead of the 40% commonly expected from an even-fire V-12 (Allison, Merlyn, etc. as shown in Figure 6), and the valleys extend below zero (roughly -120% of mean torque). Also notice that the pulse shape looks less like a sine wave and more like a sawtooth wave. This shape suggests that there are some complex harmonic components in the excitation.

The substantial difference between this engine and an even-fire V-12 could lead to some very unpleasant surprises if the PSRU system was not designed with the torque signature of this specific engine in mind. The saving graces, in this case, might be the fact that (a) the PSRU on this particular engine is a knockoff of the Orenda™ PSRU, which is extremely hefty, but has begun to exhibit problems in service above 150 hours, and (b) the V-12 package is delivered with an MT 4-blade composite prop, which is quite forgiving of large amounts of torsional excitation. Only accumulated service will show whether this PSRU is up to the job.

Recently, we have seen several of these PSRU's apart for inspection and repairs after approximately 100-125 hours of in-flight service.. As a result of those inspections, the builders group contracted with EPI to manufacture a retrofit mechanism for all of the kits in existence to prevent the catastrophic departure of the propshaft from the gearbox. The vibration problems remain as yet unsolved (The proper solution was deemed to be "too expensive").

Source:

http://www.epi-eng.com/piston_engine_technology/torsional_excitation_from_piston_engines.htm