Predictive
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Technologies

The Multiple Cycles of a 4-Stroke IC Inline 6 Cylinder Engine

ENGINE POLYGRAPH®
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Engine Polygraph and Engine Angel

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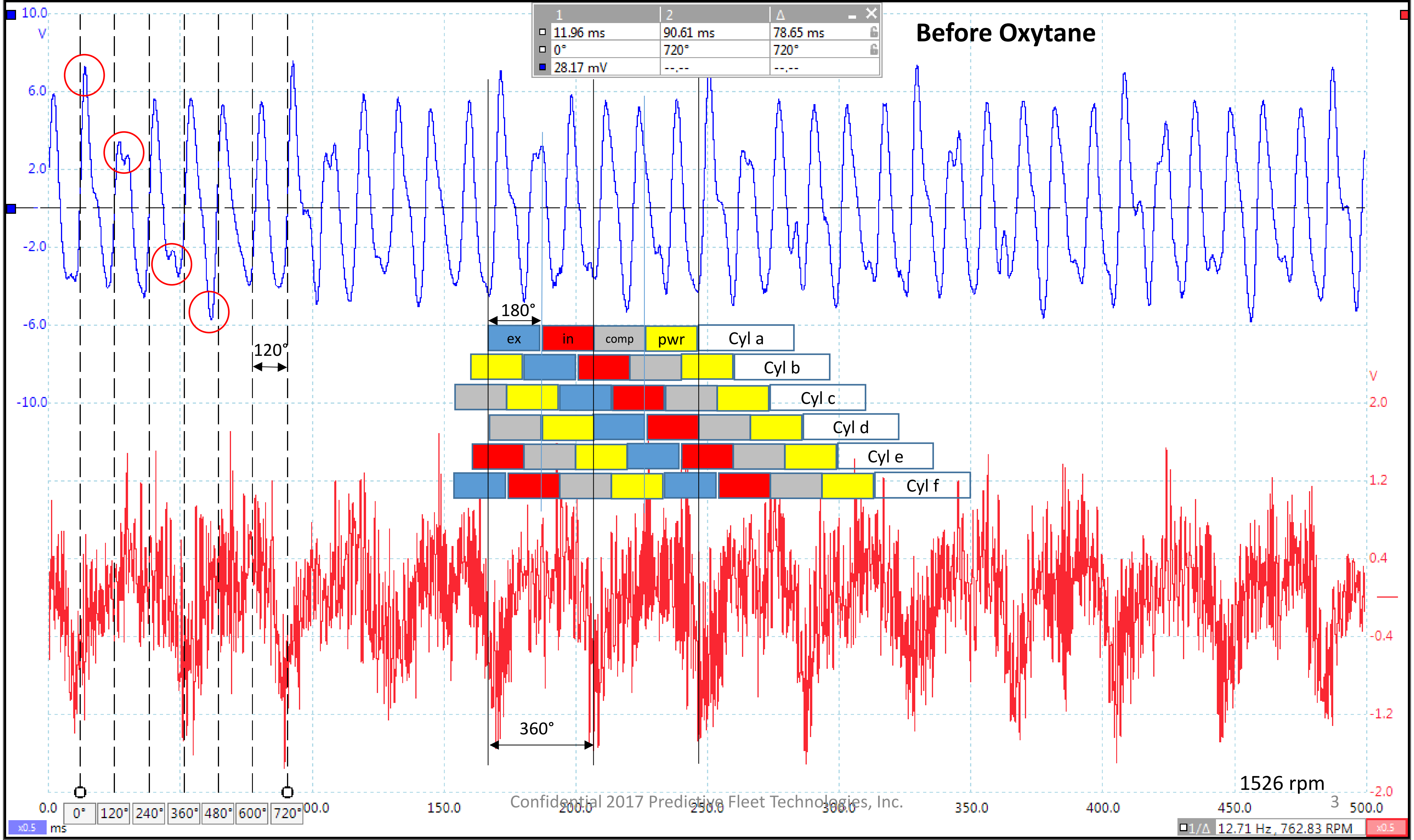
Cycles

- A 4-stroke engine has a cycle of 2 revolutions (720°) of the crankcase to repeat after each cylinder has fired once; ‘chronic’ problems will repeat each 720°.
- For each stroke-type (intake, compression, power, exhaust), an Inline 6-cylinder engine repeats every 720°/6 = 120° (if the engine is running properly)
- For each revolution of the crankcase, the PCV valve has a 3-cylinder cycle, the shape depends on the firing order (assuming the PCV valve is near the center of the intake manifold).

We will describe the major features of the IC engine and the effect on the appropriate signature features.

Before Oxytane



1	2	Δ
11.96 ms	90.61 ms	78.65 ms
0°	720°	720°
28.17 mV	--.--	--.--

1526 rpm

The diagram on the previous page has several areas:

1. The signature has an exhaust waveform (wavy line) in blue in the upper half of the diagram. It displays the voltage reading from a SenX FirstLook® piezoelectric sensor; the voltage is proportional to the ‘instantaneous’ pressure at the sensor (with hose into the engine ‘tailpipe’).

2. The red portion in the bottom half displays the crankcase voltage reading from a SenX FirstLook piezoelectric sensor; it is proportional to the ‘instantaneous’ pressure at the sensor (sampling the pressure via the oil dipstick tube.

3. The center diagram presents the identification of the stroke that each cylinder is in while the engine goes through its 2-revolution cycle. Each stroke takes 180° rotation of the crankshaft. The vertical dashed lines on the left show time periods of the cycle when each cylinder is expected to have its exhaust valve open. Since the engine is a 6-cylinder, each time period aligns with (720°/6 = 120°) rotation.

The ‘cylinder’ rows stacked in the center of the diagram are in firing order [a - f] with the upper-most row in the ‘lead’.

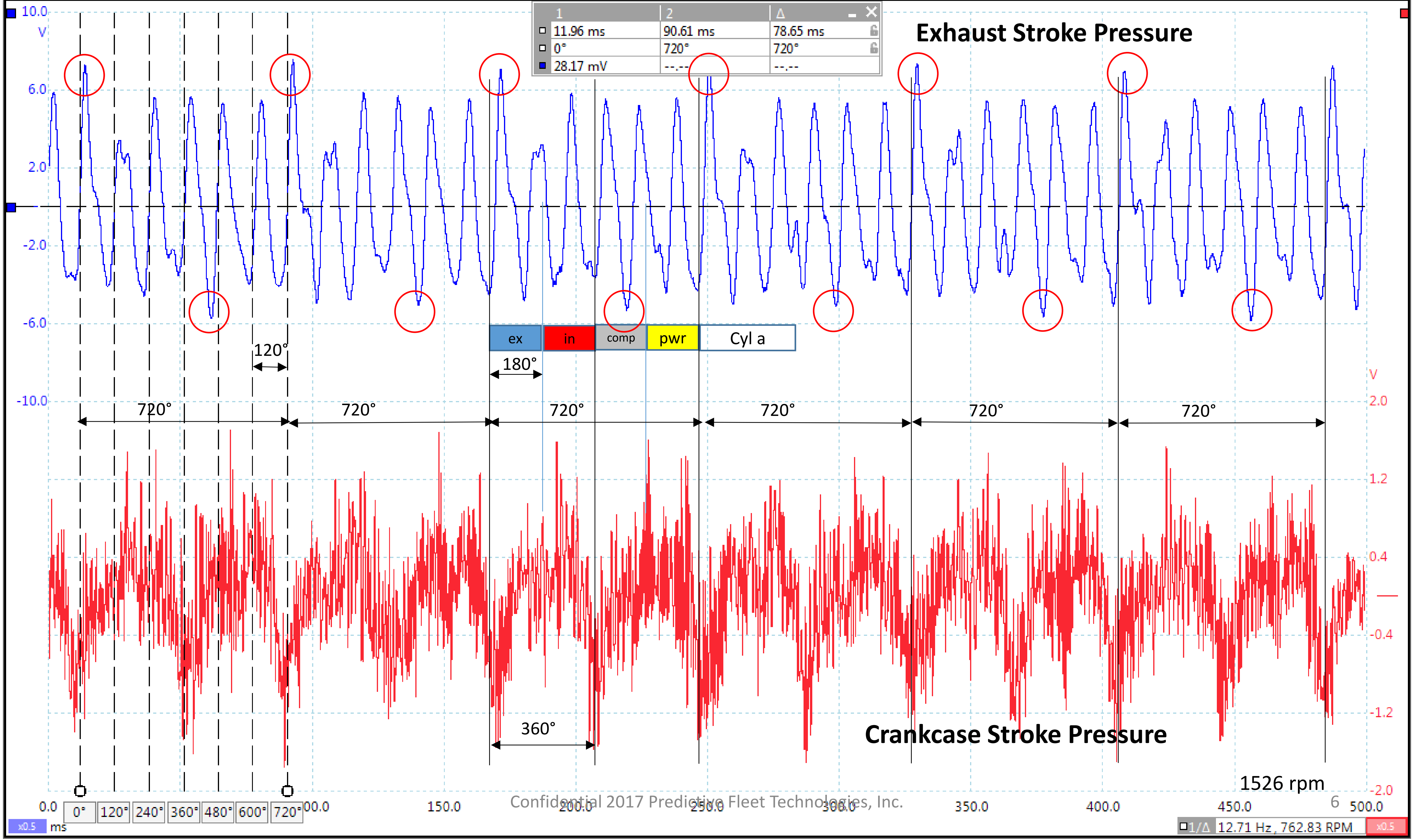
Engine Exhaust Cycles (720°)

The overall engine cycle (720°):

- Defects in cylinder waveforms (red circles) help define the 2-revolution cycle when each cylinder experiences each stroke once (assuming that each cylinder does not experience the same defect to the same intensity).
- Shown in the center of the blue waveform in the diagram on next page

The cylinder stroke cycle (120°):

- Each cylinder has one exhaust stroke during the 720° cycle, causing a 120° mini-cycle as each piston moves most of its exhaust out of the associated cylinder
- On the far left side of diagram on next page

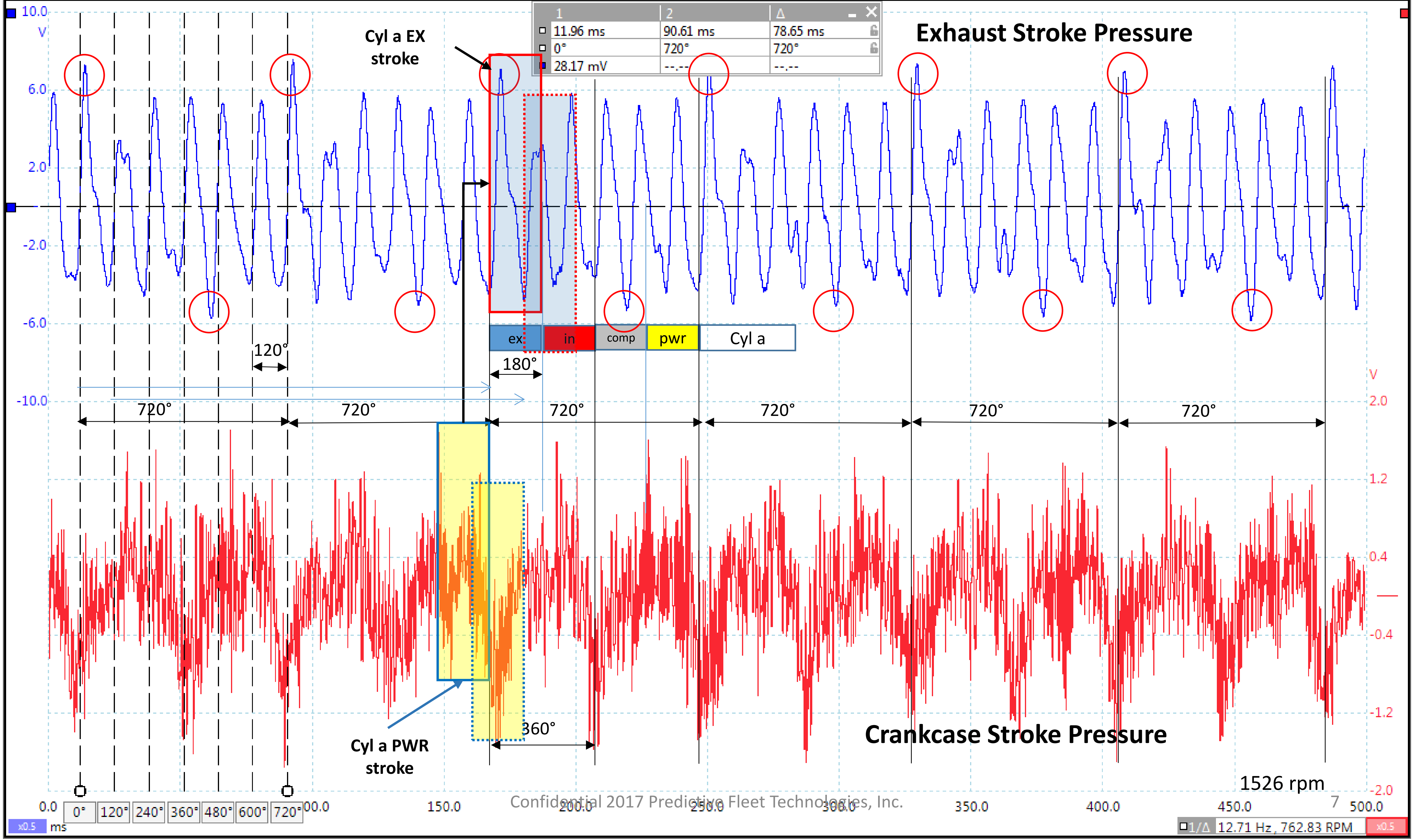


1	2	Δ
11.96 ms	90.61 ms	78.65 ms
0°	720°	720°
28.17 mV	--.--	--.--

Exhaust Stroke Pressure

Crankcase Stroke Pressure

1526 rpm



Exhaust Stroke Pressure

Cyl a EX stroke

Cyl a PWR stroke

Crankcase Stroke Pressure

1526 rpm

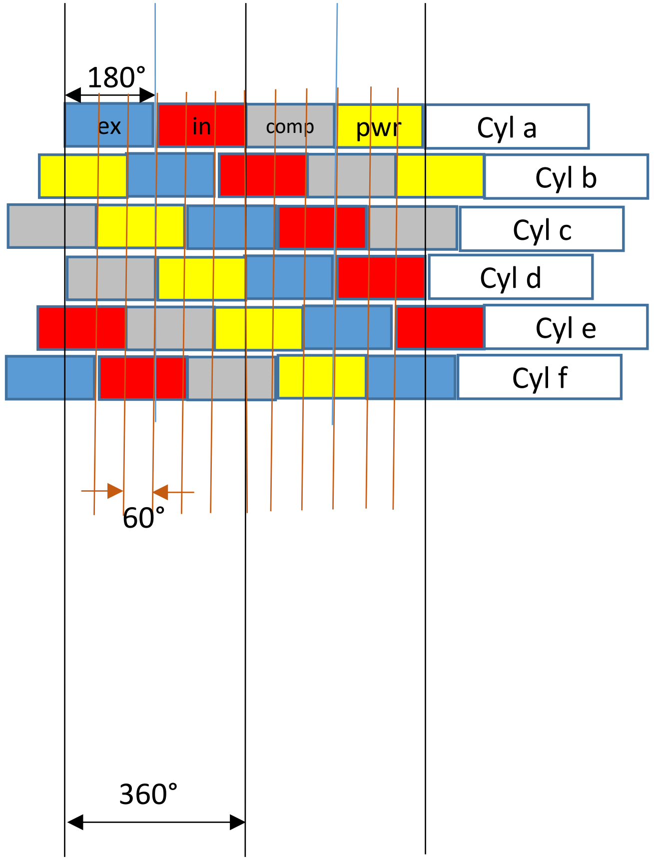
1	2	Δ
11.96 ms	90.61 ms	78.65 ms
0°	720°	720°
28.17 mV	--.--	--.--

12.71 Hz , 762.83 RPM

Cylinder Offsets

When the 4-strokes of each cycle are stacked in firing order, we see that each cylinder is ‘doing something’ at each instance.

- The 720° cycle is split into 180° stroke sections and also into 120° cylinder sections. This provides a set of 12 x 60°sections.
- The exhaust (blue) in a good engine has 2 cylinders with partially open exhaust valves 2/3 of the time. In the middle third of the stroke, when the piston is moving the fastest, only one cylinder is exhausting.

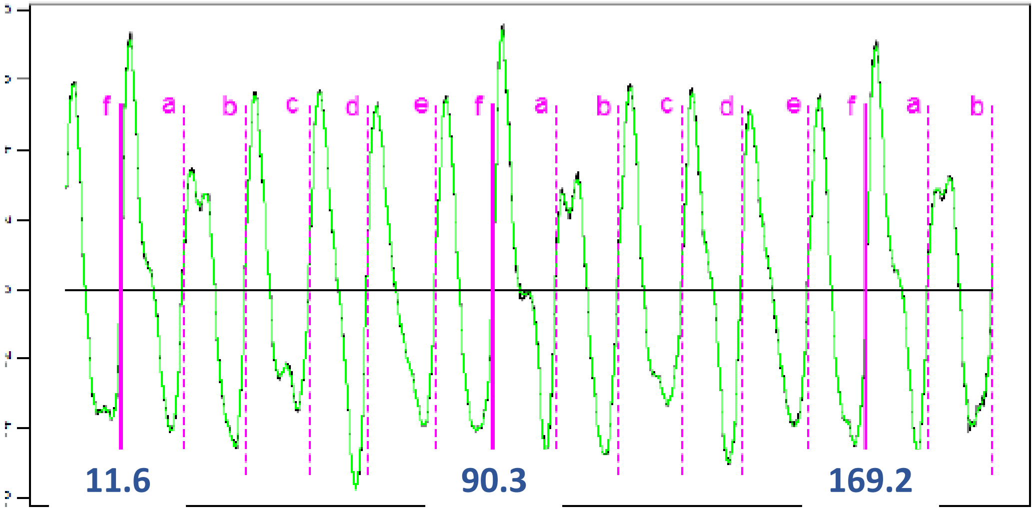


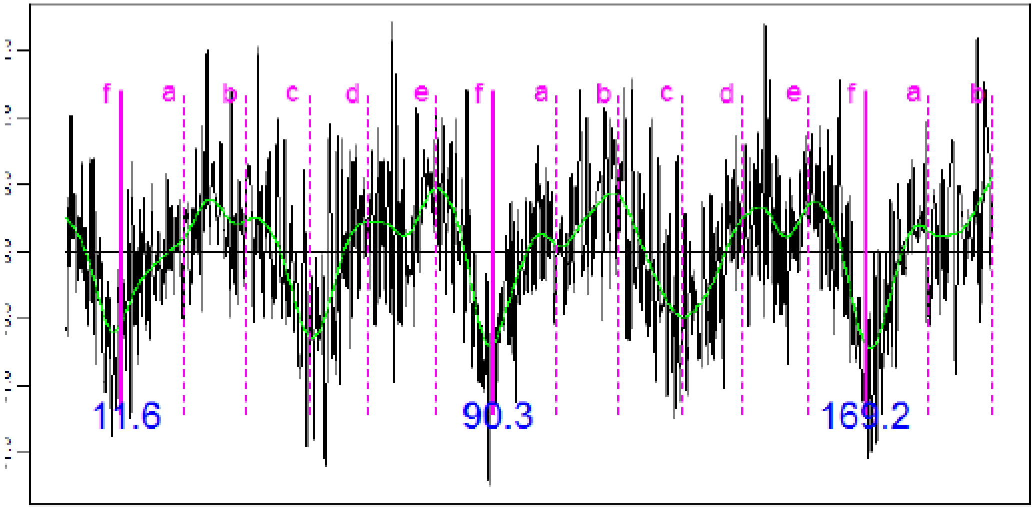
Pressure Wave vs. Higher Frequency ‘Vibrations’

On the right, we show the same signature, but have separated the very low frequency ‘pressure’ wave (green lines) from the higher frequency black ‘vibrations’. The numbers in blue are ms from the beginning of the signature. The main frequency in the exhaust is determined by the (90.3-11.6) = 87.7 ms cycle time divided by 6 cylinders = 14.6 ms = 0.0146 s which corresponds to 1/0.0146 s = 68.5 Hz.

The crankcase has a ‘valley’ (vacuum) every 360°.

The exhaust signature has very little ‘vibration’, but the crankcase curve has quite a bit of low frequency ‘rumble’ and a number of black regions of high frequency ‘scrape’ (metal on metal).





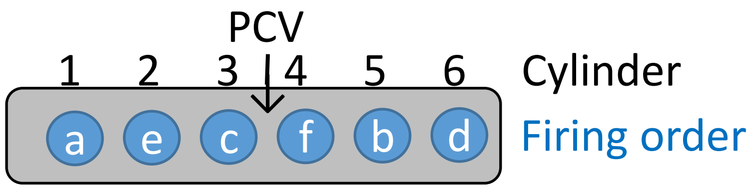
Engine Crankcase Cycles (360°)

There are a number of factors affecting the crankcase pressure during the 720° cycle:

- The intake manifold is pulling ‘air’ through the PCV valve from the crankcase whenever an intake valve is open; the ‘pull’ depends on how close the PCV is to the open intake valve and how fast the piston is moving down.
- The compression stroke can cause ‘blow-by’ near the TDC of the stroke pushing air (maybe with fuel) around the piston and rings into the crankcase.
- Combusting gases can ‘blow-by’ the rings during the power stroke to increase the pressure in the crankcase.
- The intake stroke can cause ‘air’ to be pulled from the crankcase directly into the cylinder around the rings.

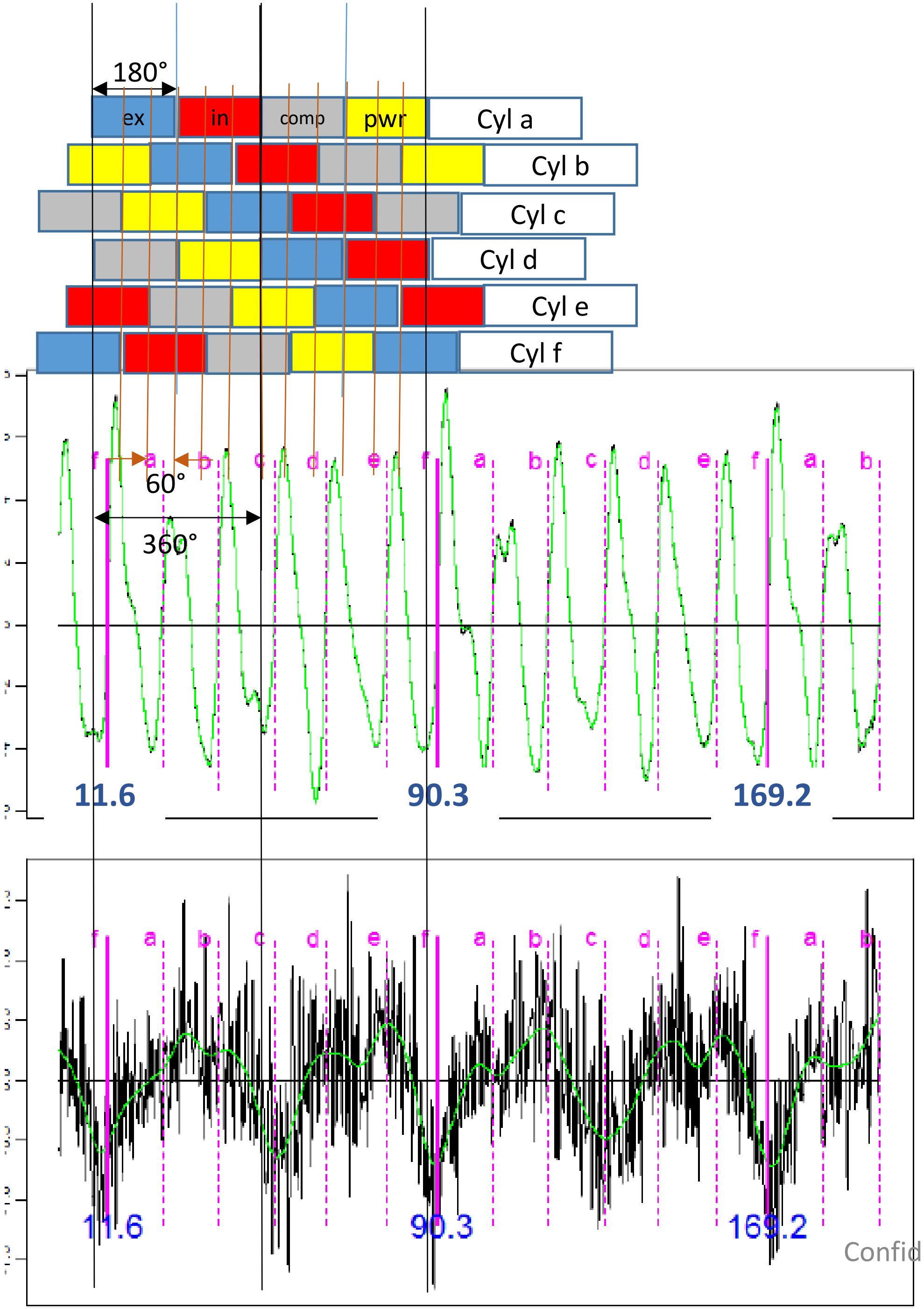
Intake Manifold on an Inline 6 Diesel

- The firing sequence of almost all I-6 diesels is ‘1-5-3-6-2-4’
- We do not know which peak of the signature belongs to the cylinder 1 since we do not have an electronic signal when any particular cylinder ignites.
- Cylinders 3 & 4 are nearest the PCV so should pull the most vacuum in the crankcase; 1 & 6 are the furthest - weakest; and 2 & 5 are intermediate.



b	f	d	a	c	e	?
c	**a**	**e**	b	d	**f**	?
d	b	f	c	e	a	?
e	c	a	d	f	b	?
f	d	b	**e**	**a**	c	?

The numbers are the cylinder assignments made by the manufacturer of the engine block. The letters are possible identifications of the peaks of the exhaust signature.



Notice that d & e are ‘intaking’ while a & f are exhausting for the 60° before the 11.6 ms vertical marker. There is a **deep** vacuum in the crankcase right before 11.6 ms on the green pressure curve. The **deep** suggests that cyl **e is either cylinder 3 or 4**.
During b’s exhaust, the first 60° has only cyl f in intake stroke followed by f & a for weak pull into the intake manifold. So **f is likely cyl 1 or 6**.
During c’s exhaust, a & b are intaking and the vacuum increases; so **a is either 2 or 5**.

Continuing on, while d is exhausting, b is in intake with a strong vacuum. So **b is 4 or 3**.
While e is exhausting, c and d are intake with weak pull as c takes over. **So c is 5 or 2**.
While f is exhausting, d & e are intaking with strong vacuum, so **d is 5 or 2**

Notice the cycle: **deep-weak-medium** and then **deep-weak-medium** cycles.

Diagnosing this Signature

This signature is from a C14 Caterpillar 2003 engine with 1,300,000 miles. It was brought in because the vehicle produced a 78 opacity test.

Notes on the ‘before’ signature

Exhaust curve observations:

- Each engine cycle has one peak that exceeds the others and one that is much less than the others. This is typical for ‘mis-fire with fuel’ when the power stroke before the low exhaust ‘peak’ doesn’t burn the fuel so the fuel goes out the exhaust. Then when the unburnt fuel hits the catalytic convertor (or other ‘hot spot’ in the exhaust), it flashes with the exhaust from another cylinder. This results in a spike that would occur a short time **after** the mis-fire exhaust – NOT before it.

But in this case, the high peak immediately **precedes** the mis-fire exhaust stroke, so there is more to the story.

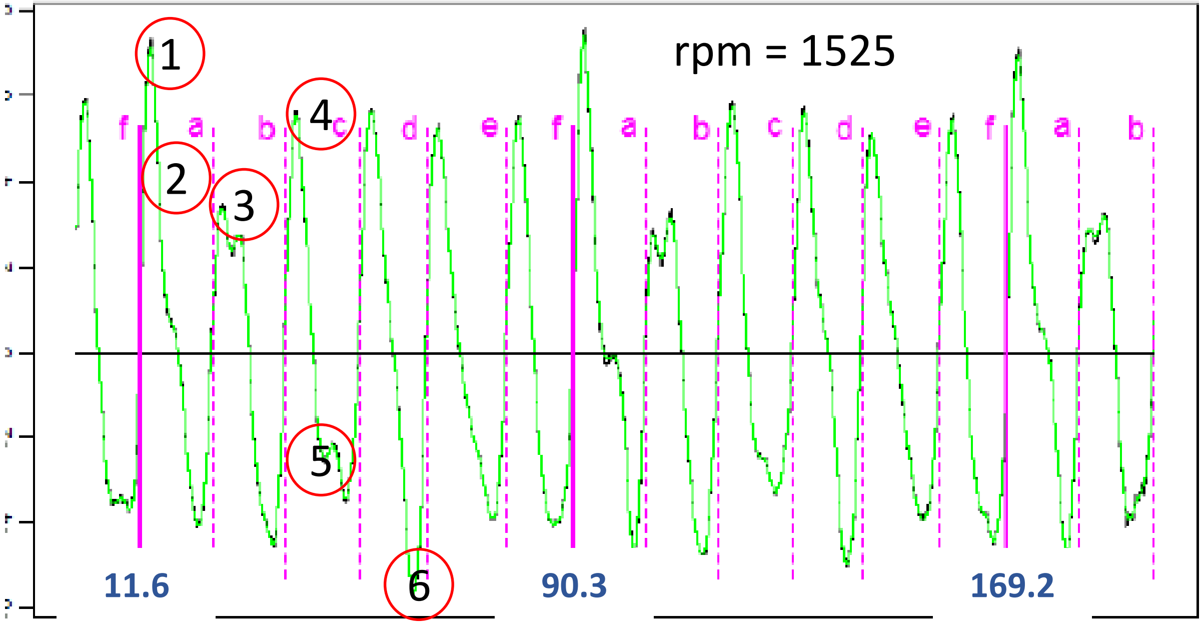
- ‘Forks’ at the peak of a cylinder indicate valve overlap at the exhaust closing (and intake valve opening early while the exhaust is still open.
- ‘Forks’ at the bottom valley indicate the intake valve closing and the exhaust valve opening with overlap.

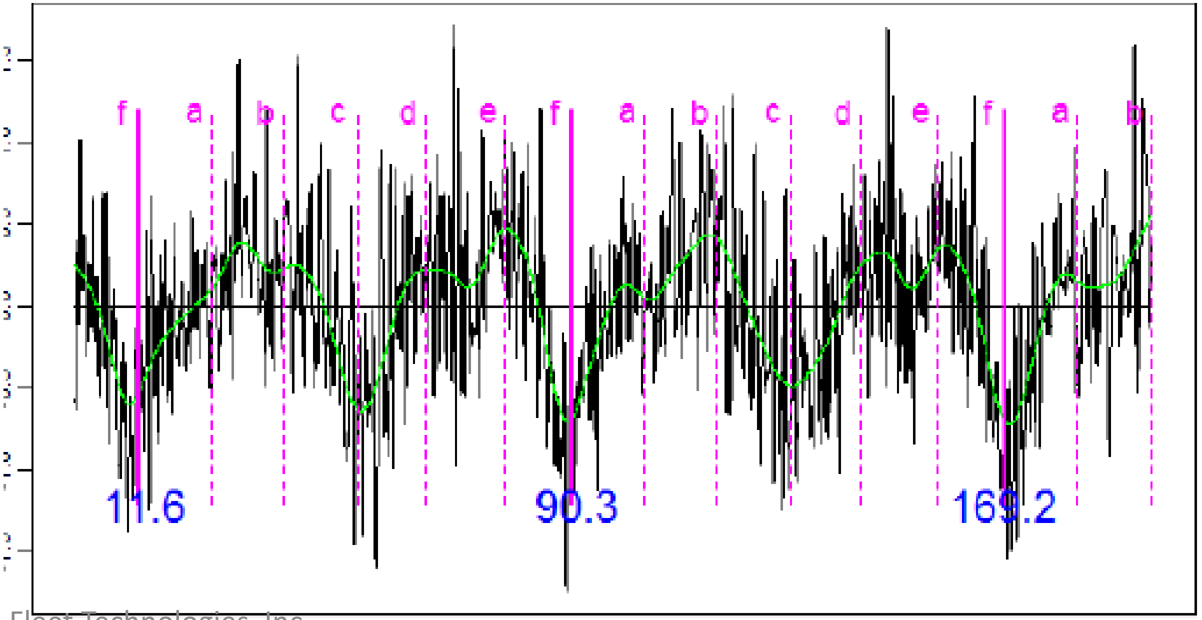
So we **hypothesize** that the cylinder in exhaust stroke, b, on the next page has an exhaust valve that cannot close very completely (not even tight enough to give a characteristic high frequency when a **little** carbon prevents a tight seal).

The exhaust in the a-b-c is not highly correlated with d-e-f, so there are some issues either with the PCV valve or possibly blow-by. But this looks minor compared with the valve issue with cylinder b.

Proposed Diagnosis

1. In the time when a is exhausting, b is in its power stroke. But b is a mis-fire because the exhaust valve partially open would not allow the poor compression to cause ignition.
2. Because b can't ignite and its exhaust valve is partially open, fuel is flowing with the air out the exhaust and is (poorly) burning, increasing the peak of a's exhaust with a lot of soot.
3. Now b starts its exhaust opening the exhaust valve while the piston pushes out some more air as a mis-fire pulse.
4. Nothing yet bothered c so it gives a healthy exhaust after its power stroke.
5. Near the midpoint of c's exhaust, b is now in its intake stroke, giving the hump in c's exhaust before c's exhaust was closed.
6. Near the mid and end of d's exhaust, the vacuum of b's intake is maximum and pulls some vacuum through the partially open exhaust, enhancing the exhaust after d's main pulse of exhaust was completed.





Possible Causes

1. A quite large amount of carbon might be preventing b’s exhaust valve from closing.
2. The valve spring on b might be very weak or broken.
3. The exhaust valve might be defective: chipped lip or cracked.
4. The valve lash for b’s exhaust valve might be way off.

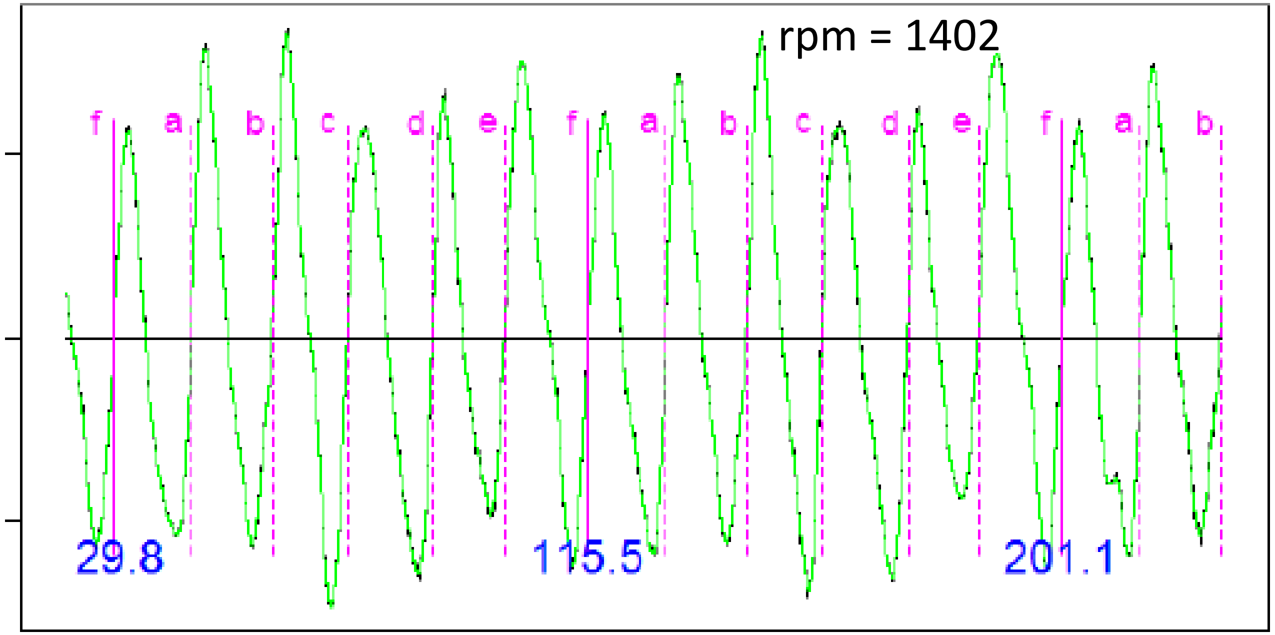
Suggested Solution

- Cheapest possible solution is to put a fuel additive (Oxytane) in the tank and drive the vehicle (ideally with a load) for 30 minutes.
- If that doesn’t help, open the valve cover and investigate the other possible causes.

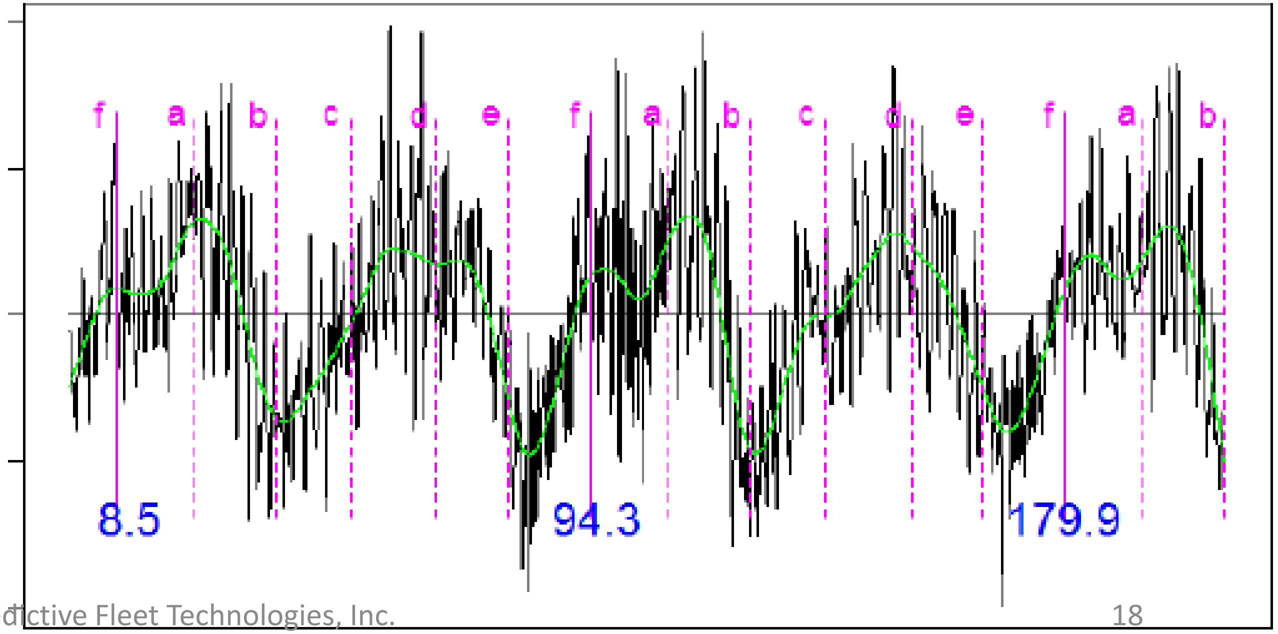
The Oxytane was used and the ‘After’ signature was run. It is shown on the next page.

Pressure Curves After Oxytane

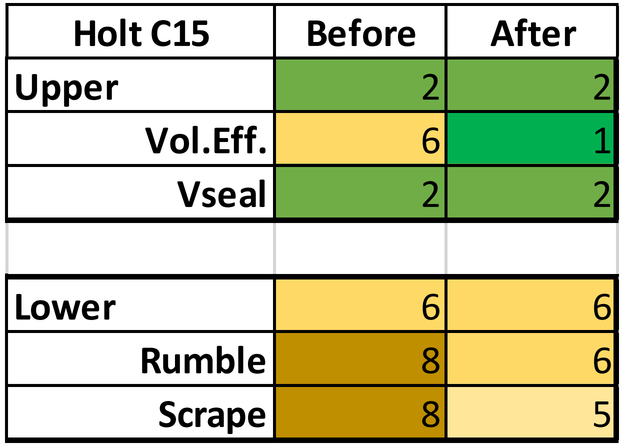
On right, we show the signature for the same engine after Oxytane has been added to the fuel and the vehicle driven for [½ hour ?]. Although not perfect, it is much better (the exhaust valve is closing tight). And the fuel is burning much cleaner in the restored power stroke.



- There is significant improvement in the exhaust uniformity.
- The rpm in the after is lower than the before, but the peak pressures are greater in the after.
- The crankcase has not improved noticeably.



New Engine Polygraph version Scores



Holt C15	Before	After
Upper	2	2
Vol.Eff.	6	1
Vseal	2	2
Lower	6	6
Rumble	8	6
Scrape	8	5

← No mechanical change

← Significant improvement

← No mechanical change

← Some improvement

Spectral Analysis of the Signatures

Background

- When engines run at 1500 rpm, the engine cycles occur at 750 per min => (750/60 s) = 12.5 Hz. There are Ncyl pistons, so the frequency of piston oscillations is Ncyl * 12.5 Hz = 75 Hz. This is the order of magnitude for valves, connecting rods, and other parts that are ‘centimeters’ in size. A defect in one cylinder presenting in one stroke (4-stroke engine) would be at 12.5 Hz
- The bearings in the connecting rods are on the order of magnitude of several mm, so the frequency of rotation of a journal bearing with 12 bearing around the journal should be on the order of 250 for a defective bearing to present itself – the bearing will rotate at least 10 times for each revolution
- Corrosion and cavitation pits on moving parts (e.g., cam lobes) are on the order of 1 mm and the travel in one rotation of the crankshaft might be 100 mm suggesting a frequency of a defect to be 2500 Hz.
- A piston with 85 mm stroke travels 170 mm in (1/25) second or 4,250 mm/s during one rotation of the crankshaft. The surface without lubrication has defects in the metal on the order of 0.6 mm so we can expect the frequency of noticing such defects to be about 4250/.06 = 7083 Hz
- All of these numbers are proportional to the engine rpm.