The RC30 Sound

1. Preamble

The 1987 to 1990 Honda VFR750R (RC30) has a sound that is almost as well known as the paint scheme. The engine sound has been described by various superlatives. I like to think of it as a very complex musical note. Like all sounds it can be sampled, broken down and analyzed. I will attempt to perform a simplified audio analysis of the sound emanating from an RC30 exhaust system. With all such analysis assumptions must be made in order to make things simple enough to work with. Unless otherwise mentioned, the following statements and assumptions were employed for the analysis:

- The sound waves emanating from the discharge of the exhaust system are directly related to the combustion inside the cylinders of the engine
- The sound waves are independent of the configuration of the exhaust system.
- Simple cylinder pressure versus time relationship
- The microphone used has flat frequency response. This is not true, however it tends to be offset by the response of the human ear. A more correct statement of the assumption is that the sound pressure level delivered by the microphone output is more or less proportional to frequency response of the human ear. In our case the errors should be minimal if the data appear to support this assumption
- The sound picked up by the microphone is only that of the combustion. This is not a great assumption but the other "noise" does tend to be overwhelmed by the exhaust sound
- Free field sound.
- Analysis is required only in the lower end of the human audio frequency response.
- Engine is operated unloaded for sampling.

2. The basics of combustion noise analysis

A reciprocating Otto Cycle engine ignites each cylinder once for every two revolutions of the crankshaft. The primary frequency of the sound produced by such a series of combustion explosions is described by a simple formula:

$F = (n)(s)/120$

Where:
F = Frequency (Hz, or cycles/sec)
n = Quantity of cylinders firing at equal spacing (unitless)
s = Crankshaft angular speed (rev/min, or RPM)
120 = constant of proportionality (RPM/Hz)

Example 1:
For a single cylinder four-stroke engine idling at 1000 RPM the first fundamental frequency is:

$F_0 = (1)(1000 \text{ RPM})/120 = 8.3 \text{ Hz}$

The frequency of 8.3 Hz is not detectable by the human ear though other senses can pick up this frequency if it is loud enough. Regardless of relevance I will avoid performing an analysis where the frequencies are below that of the human ear's comprehension. I will analyze the sound at as reasonably high RPM as I can. For this analysis I will, somewhat arbitrarily, set the engine speed to be 9000 RPM. This allows both the sounds to be heard, and sound samples to be obtained. I could set the engine speed at the rated maximum of 12,500 RPM, but operating an engine under no load at that speed is not recommended.

Example 2:
For a four-cylinder engine firing the cylinders equally spaced (every 180 degrees of crank rotation) at 9000 RPM the first fundamental frequency is:

$F_1 = (4)(9000)/120 = 300$ Hz

This frequency is detectable by the human ear, as would be the (higher) overtones. 9000 RPM looks like a reasonable frequency as a standard for the work at hand.

3. Approximation of the RC30 sound

Prior to reviewing any audio samples I like to approximate the actual sound either by using mathematics, experience, or just intuition. I think a combination of all three is welcome here. In Part 1 it was assumed the sound is related to the combustion. This assumption is now utilized. Sound is merely an alternating pressure wave, as most already know. The pressure fluctuations producing the sound come from the alternating combustion pressure inside the cylinder. If I approximate the combustion pressure I should have a direct link to the sound. I didn't feel like drilling into an RC30 cylinder head and installing a pressure transducer so I took a simpler approach.

I obtained a typical cylinder pressure versus crank angle diagram. This would provide the data needed to generate the predicted sound source. These curves vary significantly, with most having more than one peak pressure, but this one was simple enough to duplicate to make it useful. A useful time domain curve is one that will allow a better understanding of any actual time domain samples and the resulting spectrum extraction from it. One feeds the other.

Figure 1 shows the cylinder (combustion) pressure chart I will use as a basis.

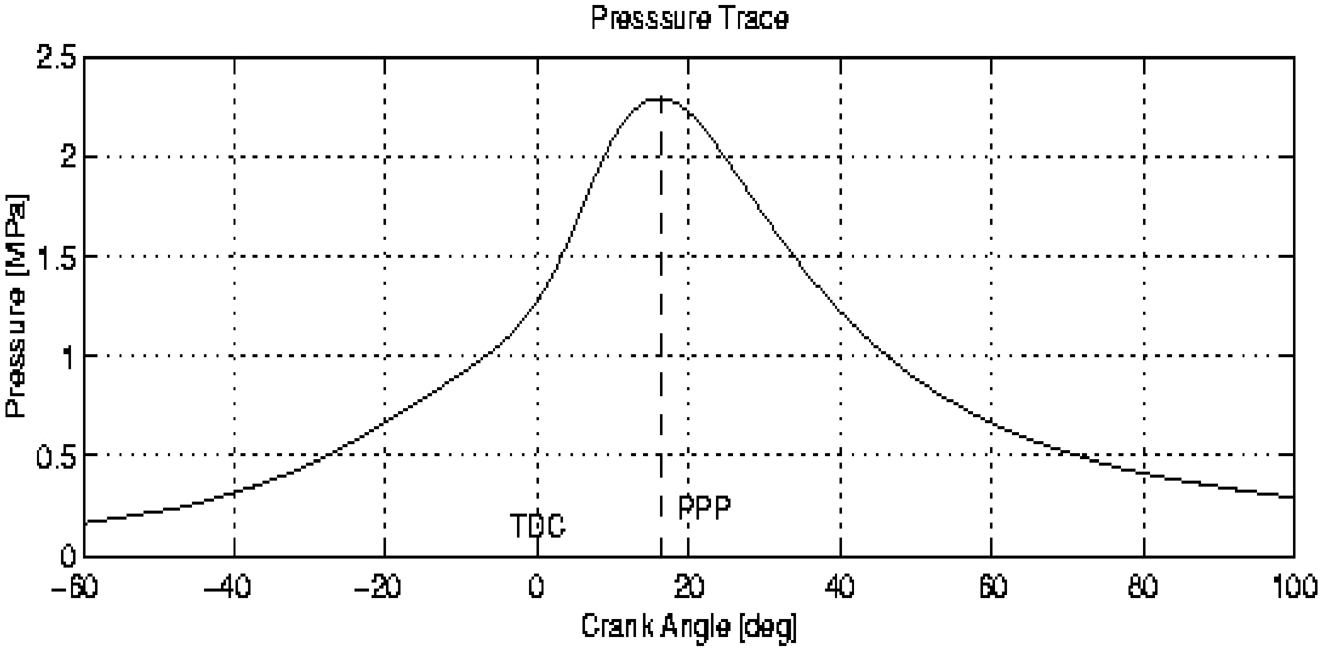

Figure 1 – Typical four-stroke cylinder pressure curve

After reproducing the curve in Figure 1 with one data point every 5 degrees I had something I could work with as shown in Figure 2. It should look like the curve in Figure 2, and it does. It has a few bumps from data interpretation but it's acceptable for the purpose.

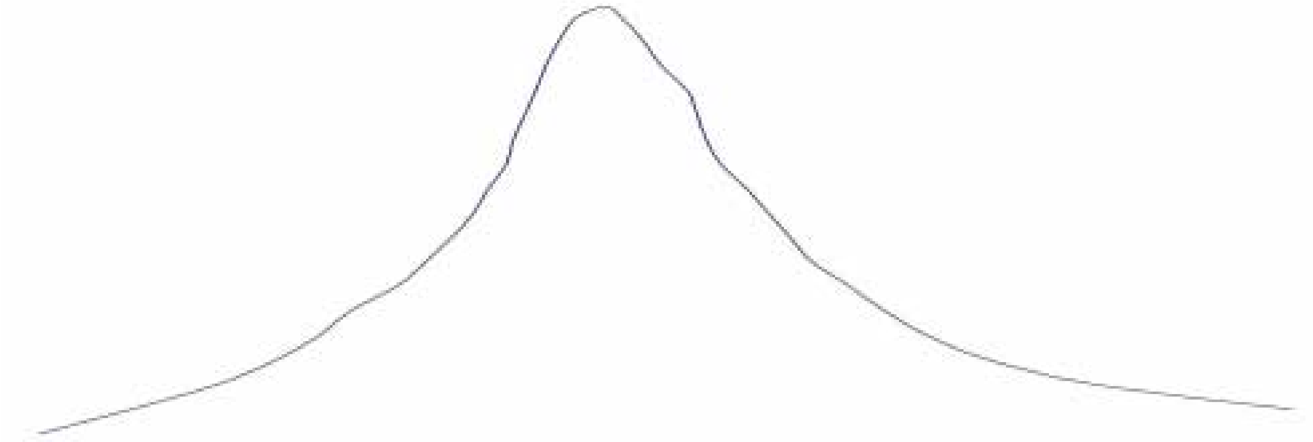

Figure 2 - Reproduced typical four stroke cylinder pressure curve

The curve in Figure 2 doesn't tell us much at all about the RC30 sound yet. I need to add up a sequence of these curves in the appropriate order to have a "look" at the RC30 sound.

The RC30 uses what is called a big-bang crankshaft to dictate the firing order. Another term for the crankshaft layout is 360-degree, due to the crankpins being separated by 360 degrees of crankshaft rotation. Either term is acceptable and interchangeable with the other. The chart in Figure 3 sequentially describes the big-bang firing order. Note I am not concerned with ignition timing, I am only concerned with the cyclic sequence of ignition.

Crank Angle (degrees)	Cylinder Firing
0	#1 (LR)
90	#4 (RF)
180	
270	
360	#3 (RR)
450	#2 (LF)
540	
630	
720 / 0	#1 (LR again)

Figure 3 - RC30 big bang firing order

Combining Figure 2 and Figure 3 supplies a simplified sound source to have an initial “look” at the sound with. The results of the combination are shown in Figure 4.

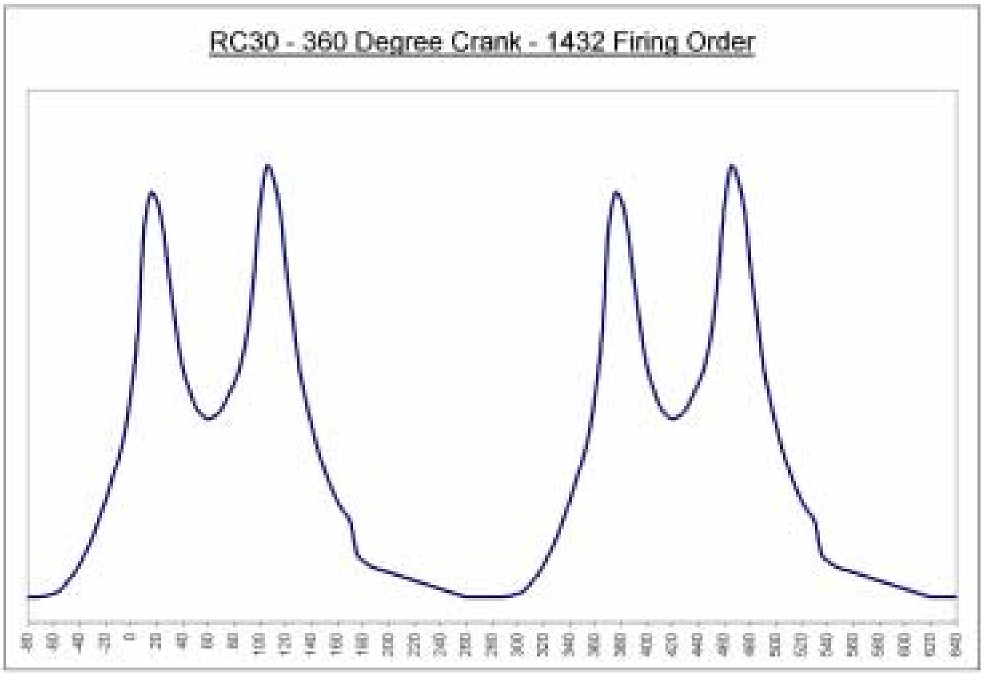

Figure 4 – Simulated big bang sound source

So far this appears to be logical, but some basic analysis of Figure 4 is in order. Without doing a fast Fourier transformation (FFT) to get into the frequency domain I can still check the first fundamental frequencies.

Example 2 works quite accurately if the firing order is spaced at exactly 180 degrees of crankshaft rotation, like that for many in-line 4 cylinder engines. The RC30 does not function this way as stated and as Figure 3 and Figure 4 indicate. By visual inspection I see that Figure 4 has the combustion in cylinders 1 and 4 occurring only 90 degrees apart as shown by the first two small bumps in Figure 4. Similarly the combustion in cylinders 3 and 2 occurs at only 90 degrees crank angle separation. Combustion (to be interpreted as a audio pressure pulse) that occurs every 90 degrees results in an effectively higher frequency than just 4 cylinders firing. This 90-degree firing pattern doesn't actually occur continuously, but nonetheless it should contribute significantly to the audio spectrum. This is analogous to an 8 cylinder engine firing at even spacing.

Using Formula 1 at 90 degree firing sequence at the previously assumed 9000 RPM I can calculate this new frequency.

A simulated N value needs to be calculated first.

$N = (2*360)/90 = 8$ as a value to use in formula 1 (the hypothetical 8 cylinder engine)

$F_2 = (9000)(8)/120$

$F_2 = 600$ Hz

Again by visual inspection from Figure 4 I can also see there is another predominant frequency. This one being represented by the large rise in Figure 4 that occurs every 360 degrees. This is analogous to a twin cylinder engine.

$F_3 = (9000)(2)/120 = 150$ Hz

I now have audio frequencies I expect to be generated by an RC30 while operating at 9000 RPM. The world is extremely complicated and sound is no different. There are many overtones, resonations, damping and background noise happening at once. In spite of all the audio complications my experience tells me the following frequencies should, if not dominate, be quite prevalent in the frequency spectrum of the sound.

F_1	300	Hz
F_2	150	Hz
F_3	600	Hz

Figure 5 – Calculated fundamental frequencies at 9000 RPM

The frequency that may not be as present as the others is F_1, the 300 Hz frequency calculated in Example 2. This would be due to the statement that it is, on average, the cylinder firing frequency. This frequency is a bit less “real” than F_2 or F_3. F_1 may also be present as an overtone of 150 Hz, as could F_3.

In effect Figure 5 is the result of a rudimentary FFT analysis on the assumed sound source. As previously stated I would use mathematics, experience, or just intuition. These should never be underestimated. More eloquently stated by William Thomson as "Do not imagine that mathematics is hard and crabbed, and repulsive to common sense. It is merely the etherealisation of common sense."

I now do a quick check on the frequencies in Figure 5. I will mathematically, very basically, add the frequencies and plot them with crank angle on the abscissa, though time could just as logically be used for graphing purposes. This is simply graphically restating what has already been mentioned, only serving as a visual representation of the calculations.

Assuming a sinusoidal function and the three frequencies of 150 Hz, 300 Hz and 600 Hz all with equal gain I arrive at a predicted sound source shown in Figure 6.

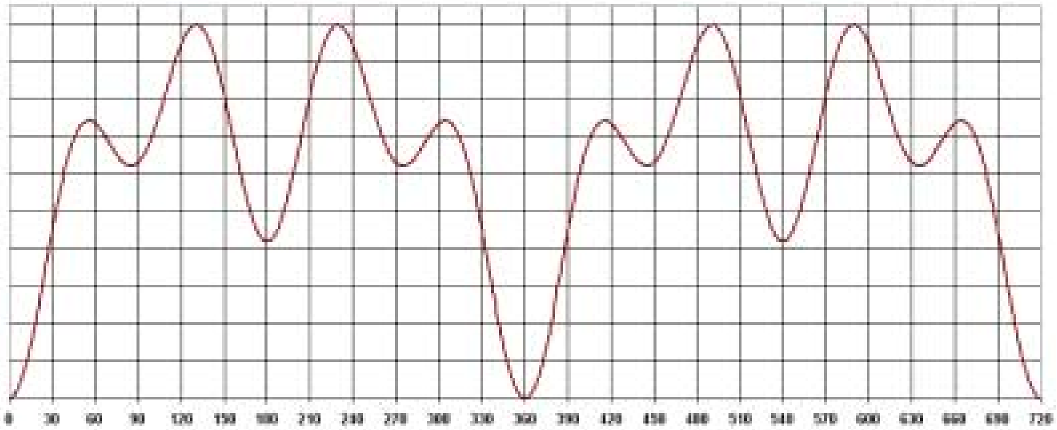

Figure 6 – Simulation of three fundamental frequencies

The curve in Figure 6 should look somewhat like the assumed curve in Figure 4. My assumptions of sinusoidal waveforms and equal gains will account for the differences but essentially they look similar. By adjusting the gains (multipliers) to account for the different contributions of each frequency it may be possible to have the curves more comparable. The following factors were used to adjust the curve of Figure 6.

150 Hz → Multiplier of 2
300 Hz → Multiplier of 1
600 Hz → Multiplier of 0.75

The adjusted curve is shown as Figure 7

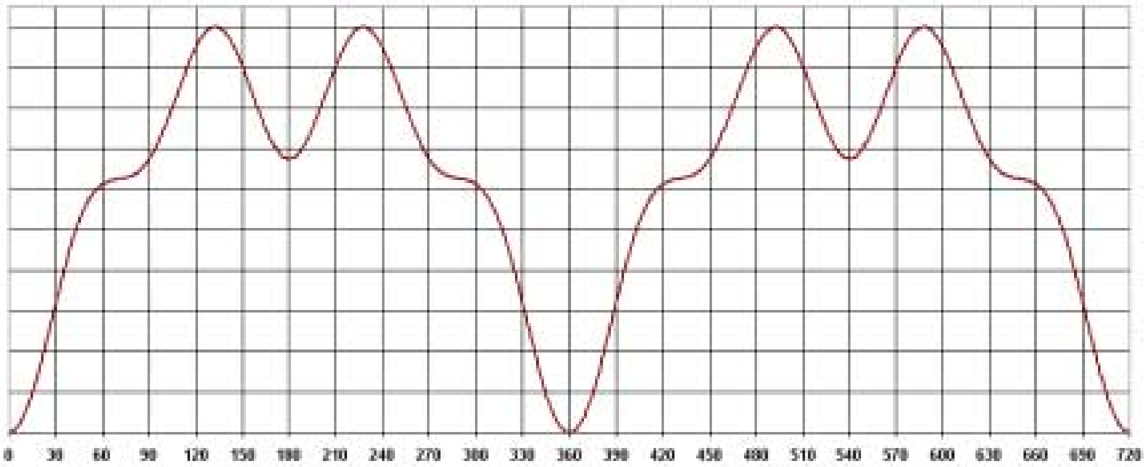

Figure 7 – Adjusted simulation of three fundamental frequencies

I am now satisfied that the rudimentary calculations on fundamental frequencies were correct for the purposes of this analysis and have comfort in the knowledge of what is causing the discrepancies. I haven't determined the actual gains of each frequency; I've just shown that the shape can be manipulated by adjusting the gains.

4. RC30 sound sampling and analysis

It is now time to analyze actual audio samples of the RC30. I used my own motorcycle and audio sampling equipment to obtain a time domain audio samples for analysis. The microphone was situated about 2 meters behind the motorcycle in as good of a free field as I could muster and directed at the exhaust discharge.

I took various sound samples and feel that the largest error in the samples is the ability to hold a constant RPM during the audio sample. Some fluctuation in the RPM is inevitable though a good review of the data in the time and frequency domains can determine if such error is significant. To have the ability to easily compare the audio samples with those of Figures 4, 6 and 7 it is necessary to perform a Fast Fourier Transformation (FFT) on the time domain audio samples. A desktop computer and some studio mixing software were used to perform the FFT, and any manipulation of data. FFT analysis requires a large amount of data points in order to arrive at meaningful low frequency results. The audio samples were taken at 48000 Hz and taken for approximately 5 seconds. All samples and data are based on the same 9000 RPM.

In the time domain an audio sample over a period of about 0.025 seconds looks like Figure 8:

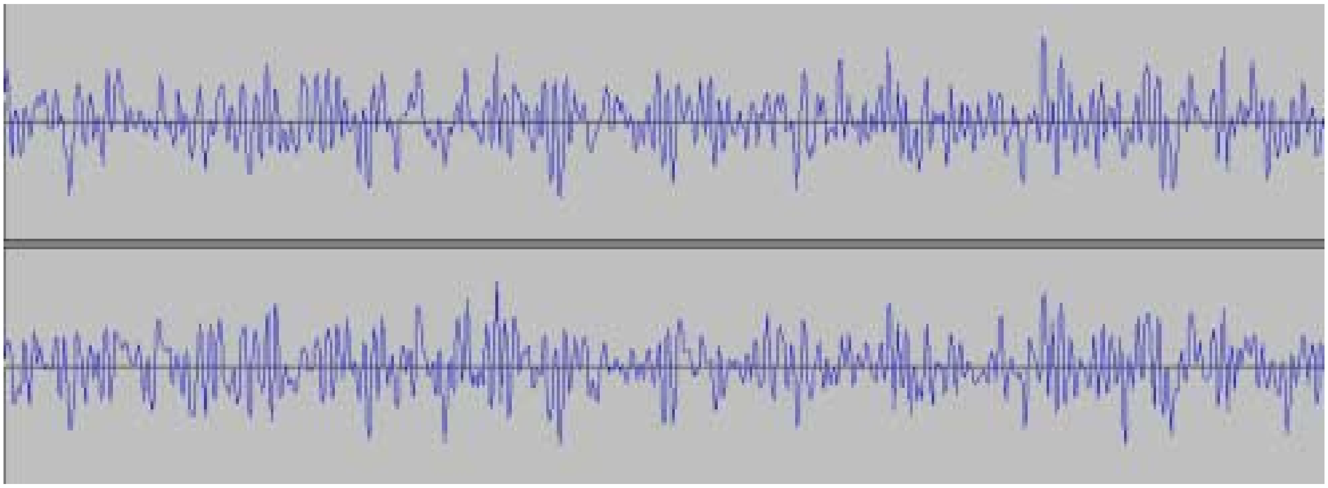

Figure 8 – Typical audio sample at 9000 RPM (0.025 seconds)

Figure 8 is impossible to decipher without the use of a computer due to the noise levels. Using the computer and the mixing software I performed some manipulation of the time domain audio sample. The test equipment was stereophonic so I combined the left and right channels for a monoraul signal

I wanted to have a look at the raw (now mono) signal to see if it bore any resemblance to figures 4 and 7. Since I am in the time domain at 9000 RPM I can calculate how long it would take for all cylinders to fire once each, that being 720 degrees of crank rotation.

T = (2 rev) / (9000 rev/min) x (60 sec / 1 min) = 1/75 of a second. Approx 0.013 seconds.

Zooming in on a 0.013 second long sample of the time domain sample gives me Figure 9.

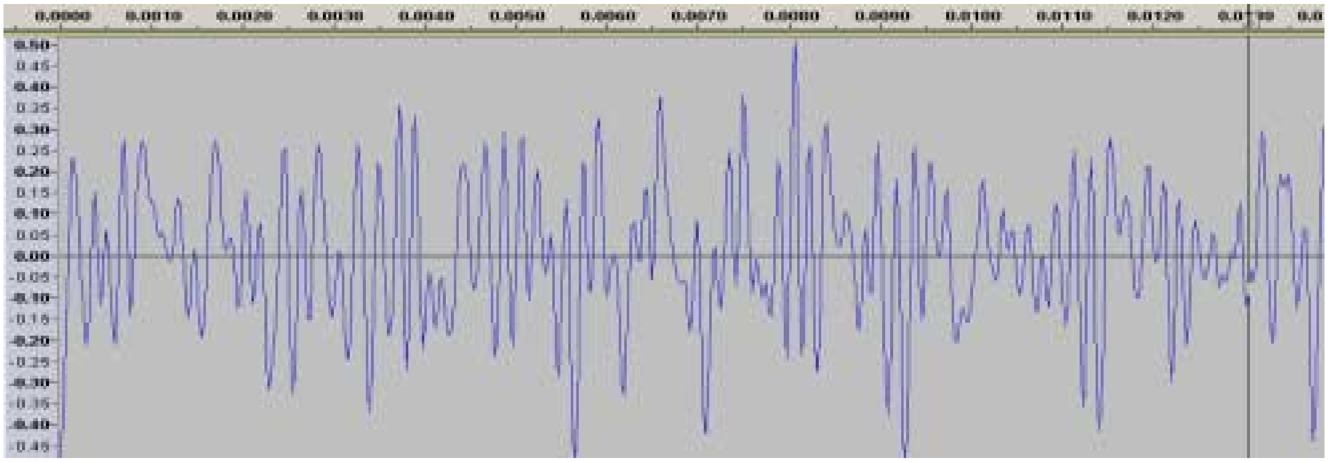

Figure 9 – Two crank rotations at 9000 RPM

Figure 9, as could be suspected, bears no immediate resemblance to Figure 4 or Figure 7. The major reason for this discrepancy is noise. Many other frequencies are present in the audio signal from gear noise to muffler tuning effects. The use of a simple (nice smooth shape) cylinder pressure curve will result in underestimation of noise also. Multiple large and small spikes in a real cylinder pressure curve will add much of the noise seen in figure 9. I will now remove the bulk of unwanted frequencies with filters. I am really concerned with the range from about 100 Hz to, I am presupposing, about 1100 Hz

After applying 24 dB filters at 100 Hz (high pass filter) and 1100 Hz (low pass filter) and normalizing the signal the time domain response looks like Figure 10.

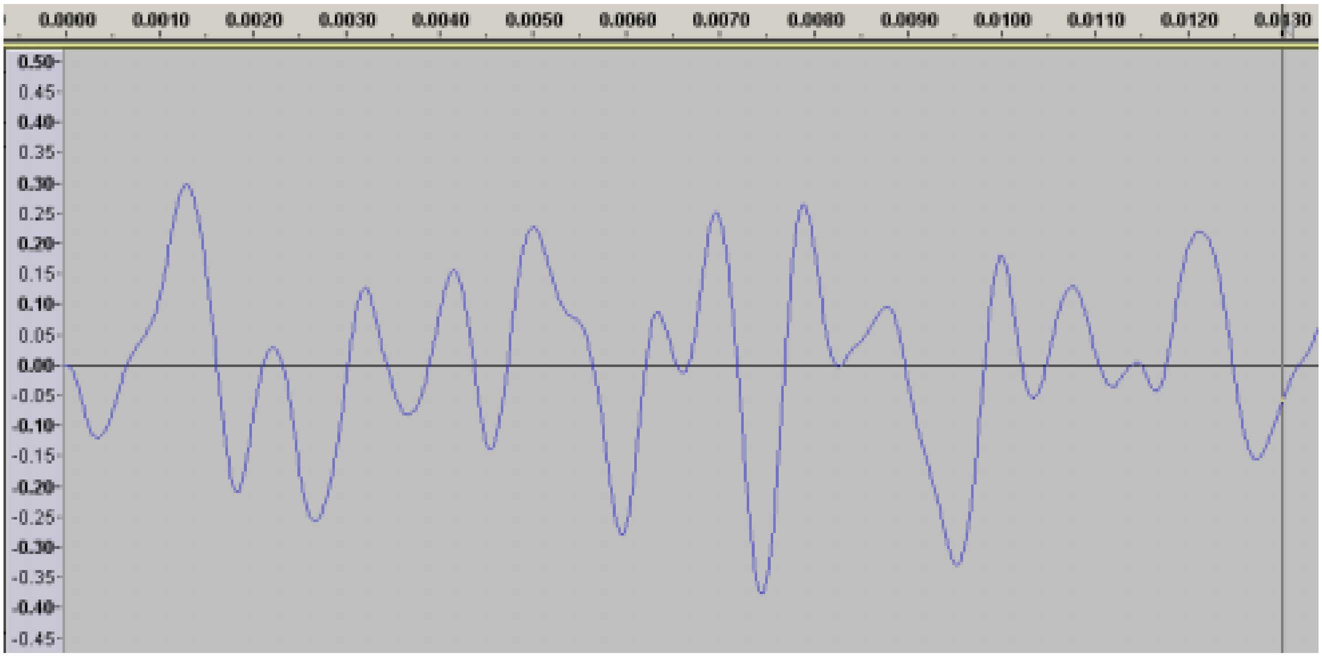

Figure 10 – Two crank rotations at 9000 RPM with filters applied

The waveform of Figure 10 shows that there must be additional frequencies present in the sound signal within the range of frequencies I am concerned with. The 150/300/600 Hz frequencies are obviously not the only ones present, however obvious they may become.

After performing an FFT the frequency domain of Figure 10 becomes Figure 11.

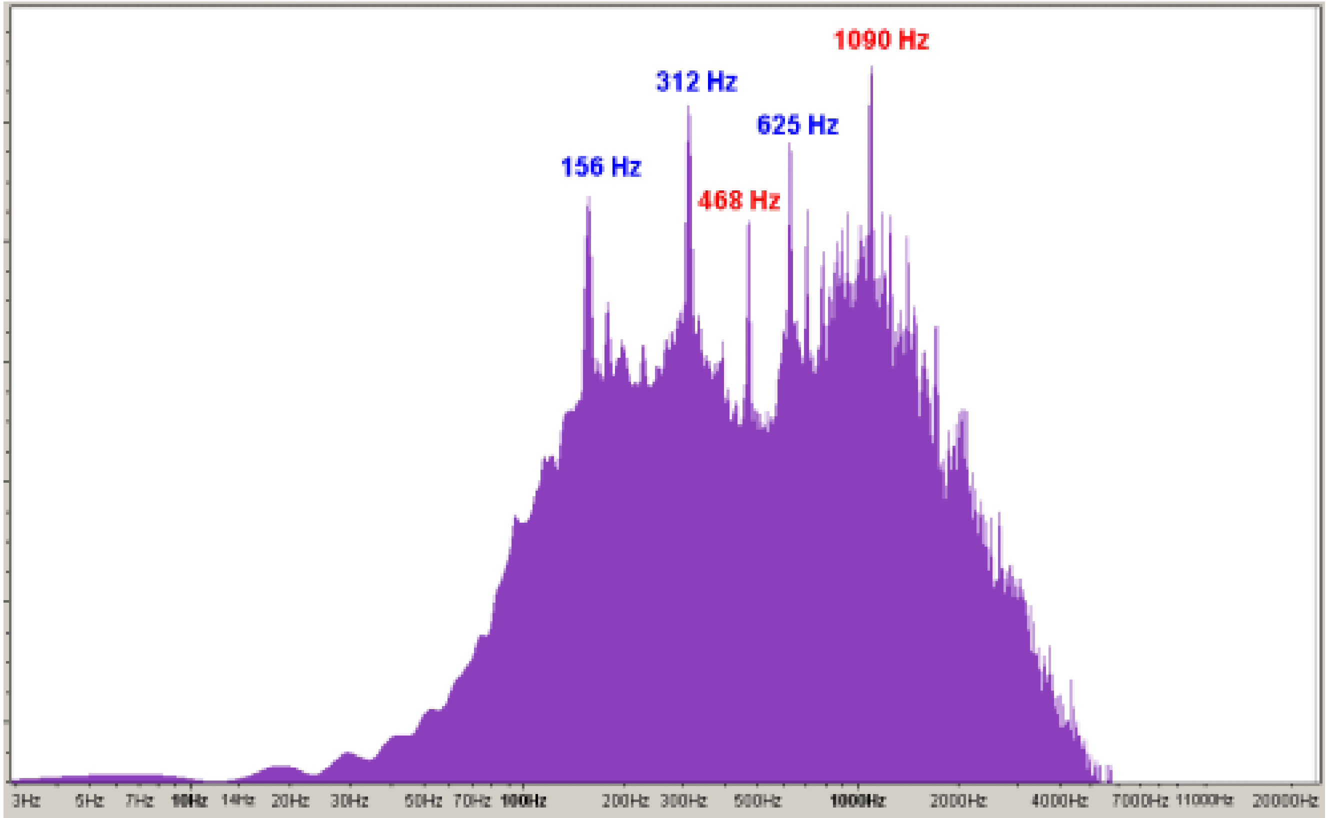

Figure 11 – Filtered RC30 frequency response at 9000 RPM (actual 9360 RPM)

The three frequencies of Figure 5 are present and are represented in blue. Note the frequencies are slightly higher than calculated as I was, on average, apparently holding the RPM slightly above 9000 RPM. The estimated actual RPM would be:

(156Hz/150Hz) x 9000 RPM = 9360 RPM.

The 468 Hz and 1090 Hz were not initially predicted, but are not surprising to see present in the frequency spectrum. To attempt to calculate where these are coming from would likely be an arduous task and involve dissecting the muffler and taking a lot of other audio or vibration measurements. My experience tells me these are probably generated by the muffler's resonance.

The initial predicted frequencies are all multiples of 150 Hz. The 468 Hz and 1090 Hz are probably odd order multiple of this 150 Hz base frequency.

Using the actual sampled base frequency of 156 Hz:

468 Hz / 156 Hz = 3

1090 Hz / 156 Hz = 7.

So it appears these are quite likely being generated by an open pipe due to the half wave (odd order) resonance. The muffler and exhaust system is a logical source of these resonant frequencies. Nothing else on the motorcycle is capable of generating the audio power necessary to produce these spikes at 468 Hz and 1090 Hz. In summary I have 5 dominant frequencies (note these are factored down to the desired and assumed 9000 RPM). Nature likes symmetry, these frequencies are all obviously related and it is dictated by the crankshaft arrangement. You could estimate the predominant frequencies for other engine speeds by diving the below values by 9000 and then multiplying them by the engine RPM under consideration.

150	Hz
300	Hz
450	Hz
600	Hz
1050	Hz

Figure 12 – Actual frequencies corrected to 9000 RPM

It is now easy to generate these frequencies in Figure 12 using software and, after having gains and phase corrections, artificially generate the RC30 sound at 9000 RPM or any other speed after factoring.

5. Closure

Without an in depth knowledge of sound and the brain's perception of sound it is difficult to explain why the RC30 sound is gratifying to listen to, versus the annoying, to some, sound of a screaming in-line 4 cylinder with an even firing order. The best way to explain why the big bang sound is more pleasing than an even fire sound is to make an analogy. The sound of an RC30 is analogous to that of a vacuum tube amplifier. An even firing order 4 cylinder is analogous to that of a transistor amplifier. Even those that are not musically trained will nearly always prefer the sound of vacuum tube amplifier to that of a transistor amplifier due to the distortion created by the vacuum tube. Vacuum tubes generate even order harmonics of the original frequency giving them what is often referred to as a "warm" sound. The RC30 sound possesses this same warmth as a result of the multiples of a single base frequency, in our case 150 Hz at 9000 RPM. Where the big bang crankshaft produces multiple frequencies, an even fire 4 cylinder tends to have less discrete dominating frequencies. Transistor amplifiers tend to amplify only the original frequency. Transistors are technically more accurate than vacuum tubes, but that doesn't make them more pleasing to the human cortex. If you want this same effect in your house I recommend a McIntosh tube amplifier for your stereo. Similarly, if you play guitar I don't have to tell you how a Mesa Boogie sounds compared to a cheap transistor guitar amp.