

KNOCK DETECTION USING WAVELETS

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ABSTRACT: *Knock as a phenomenon limits the efficiency of engines. An accelerometer based approach is used for conventional knock detection. The energy of knock samples is used to signal advance/delay of the spark. This approach inherently uses a Fourier Transform based approach. In this paper we propose that knock can be taken as a transient signal and thus a Wavelet Transform based approach might be more appropriate as compared to a Fourier Transform approach. Whether this approach can enable knock detection using fewer samples needs further exploration.*

KNOCK

Knock is the phenomenon of spontaneous incomplete ignition ahead of the spark. It produces a crackling noise and harmful emissions (mostly NO_x). In gasoline engines, knock can be controlled using better fuel quality. Gas engines are not totally knock-free as natural gas has different gases with variable knock-resistance. This requires more reliable knock detection as compared to gasoline engines.

We briefly describe here the two common methods used for knock detection:

i) Cylinder pressure method:

A washer – type cylinder pressure sensor is placed under the spark plug of each cylinder to measure the cylinder pressure. This sensor is capable of detecting high frequency signals such as knocking and cylinder pressure trace. This sensor along with a band-pass filter provides an accurate knock signal. Also it shows excellent durability considering the harsh environment it is placed in. The only shortcoming of this method is that since it is placed inside the engine cylinder, it raises concerns regarding the engine cylinder's reliability.

ii) Accelerometer method: This method uses accelerometry (vibration measurement) to measure knock. This method is widely used in the industry due to its simplicity. Knock sensor consisting of a piezoelectric material is used. The knock sensor is normally placed in the engine block or the cylinder head. The piezoelectric element is tuned to the engine knock frequency. It generates corresponding voltage on sensing pressure or vibrations. This voltage (electric signal) is sampled using an ADC. The data is passed through a decimation filter which does band- pass filtering. The filter output is integrated to get knock energy. The knock energy is concentrated in a narrow frequency band and is a property of engine cylinder topology. A low pass filtering is also performed to get rid of the resonant frequency of the knock sensor. This ensures that energy of knock only is measured. Accurately detected knock energy is compared against a threshold, which is a predetermined based on engine characteristics and result of calibration, to make the decision of knock or no-knock. [The threshold may be based on the noise energy.] This

serves as a feedback for controlling spark/piston retardation which finally leads to knock control.

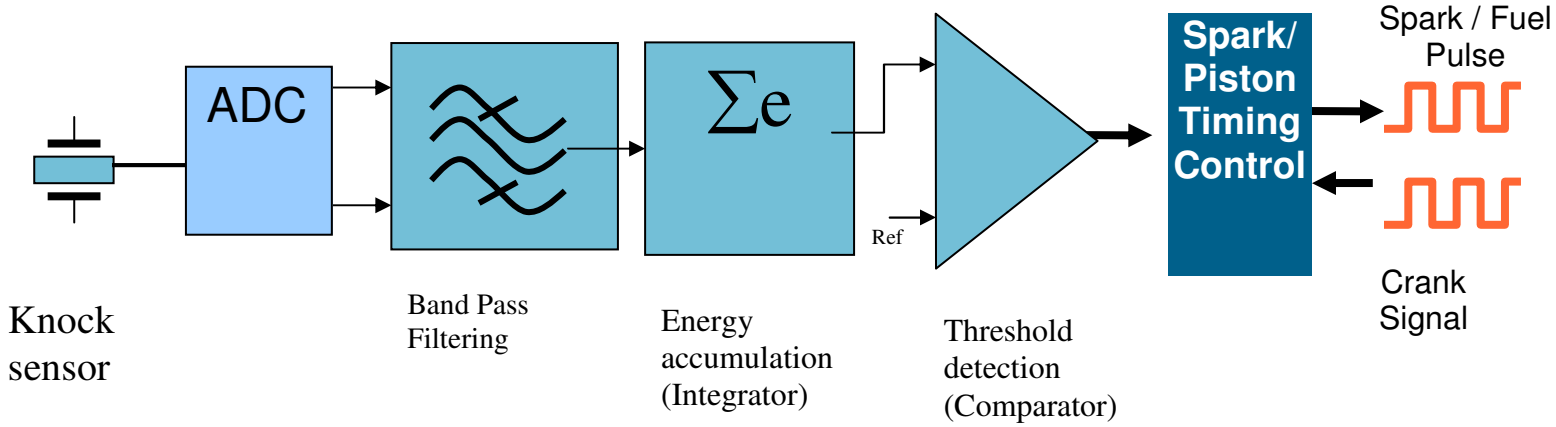


Figure 1: A commonly used knock detection method[6]

To summarize, in the present system of knock detection, engines are first calibrated. Samples are taken for noise and the energy is estimated by simple accumulation, this constitutes the threshold value for knock energy comparison. Samples are then taken during knock and again the energy is estimated in the knock frequency band. The energy of knock samples is then compared with the energy of noise samples or threshold. If this ratio is greater than a threshold, knock is said to occur. The onset of knock is also estimated based on this threshold. *(The threshold may need to be increased /decreased slightly to account for marginalities).*

KNOCK DETECTION USING WAVELETS

From algorithmic perspective, the computational resources used for knock detection depend on the number of samples used for knock detection. Also, a good knock algorithm should work under noisy conditions which are encountered in most of the real life engines. In this section, we present a method which we think can address the later concern better than the existing system of knock detection.

From real engine data (Figure 3), we infer that knock can be treated as a transient with low SNR. Also, the knock information in the signal is not uniform. It is localized heavily in samples where knock happens and fades as we move away from this instant. Wavelets give better resolution in both time and frequency. This makes them suitable for detecting components of a signal which are localized in time. This makes wavelets suitable for knock detection

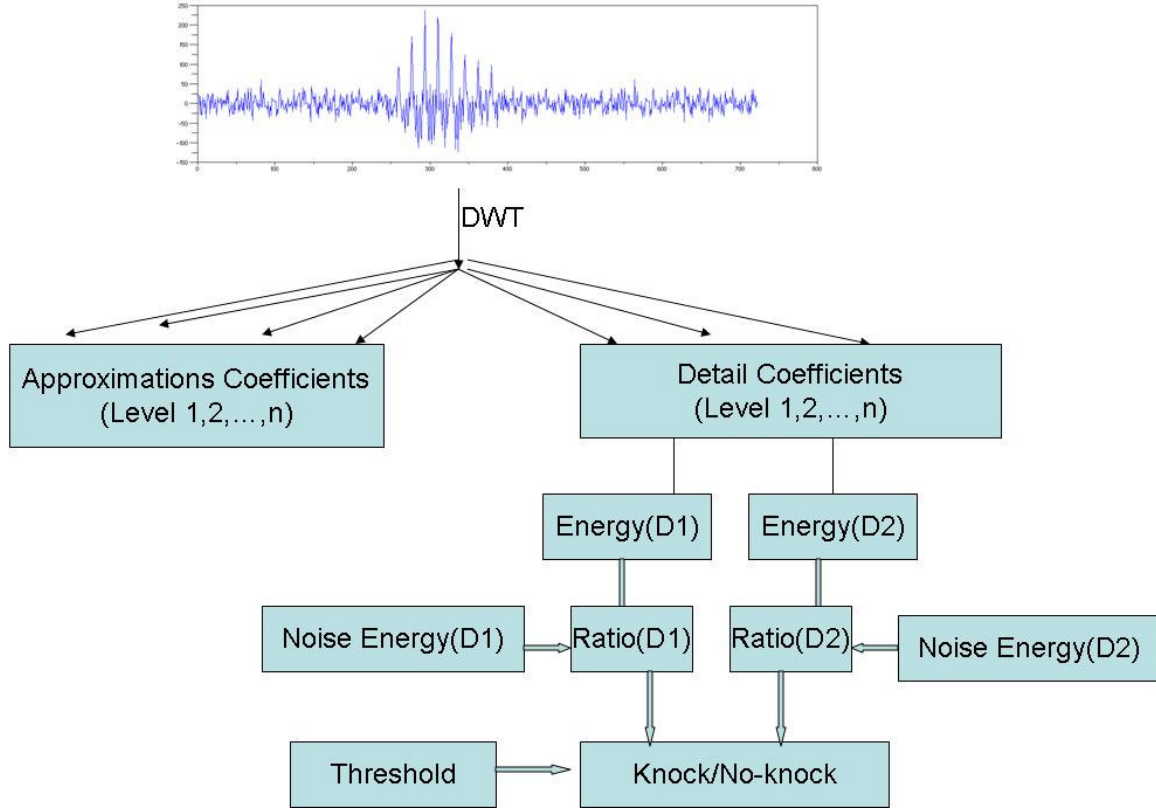


Figure 2 Proposed Knock detection method

The proposed method for knock detection consists of the following steps:

1. The ADC samples for a given knock window are down sampled at a rate F_s (F_s should be such that we can clearly determine details and approximations of interest. F_s should also ensure that there is no aliasing happening due to the higher resonant frequencies).
2. The samples are fed to a Wavelet Transform module (which can be implemented using FIR filters and down sampling).
3. Energy is computed to the required detail and approximation.
4. Energy thus computed it then compared with the corresponding detail and approximation levels energy for noise.
5. These ratios are used for indicating knock.

6. **[Adaptive]** When the SNR are high for a given level, de-noising for both signal and noise before comparing the energies can be done. This helps in getting better ratios then using simple energy ratios in the presence of heavy noise.

Figure 2 illustrates the steps mentioned above. Note that Details D1 and D2 have been selected as examples only. Suitable details for a particular engine and operating conditions need to be selected based on calibration.

Some considerations:

1. Note that de-noising may be necessary since SNR is very low (from Figure-3 peak amplitude of knock is almost half of signal peak amplitude). Thus simple Comparison of energy of signals might not be a good indicator. Local estimation of variance can help in achieving better SNR gain than estimation during noise samples.

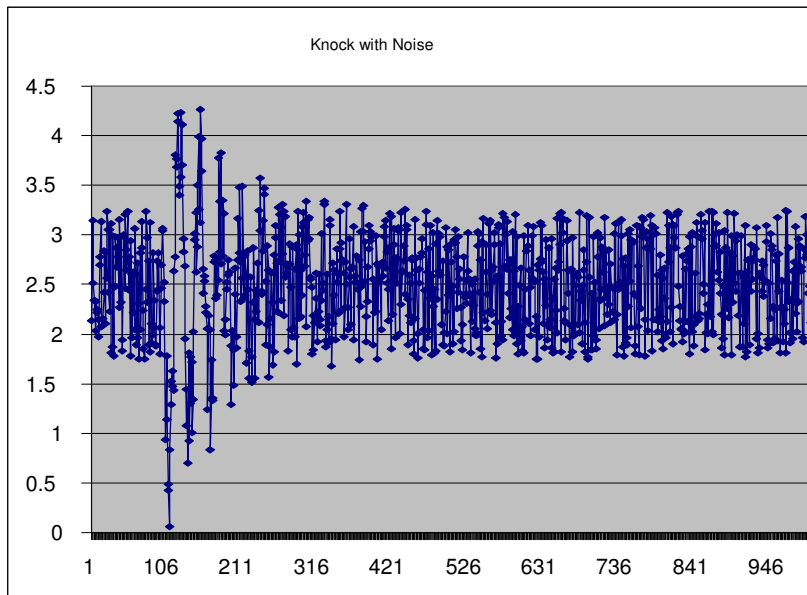


Figure-3 Knock with Noise [6]

2. **[Adaptive]** The sampling rate (F_s) is chosen so that we get the frequencies of interest in proper details and approximation levels. Since the frequencies of interest change with rpm (refer to Figure 2), we may need to change the sampling frequency (F_s) so that we get the new frequencies in the proper details/approximations.

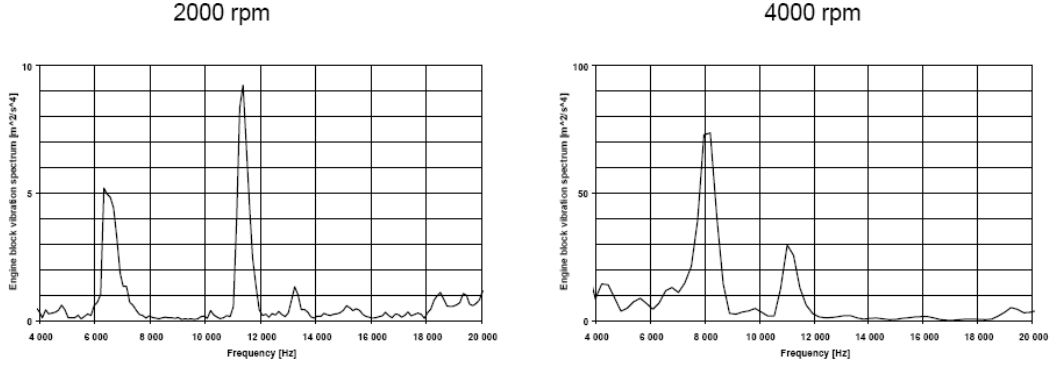


Figure 3 Variation with Knock Spectrum with engine speed [3]

3. At higher frequencies, the higher harmonics may also be included in the knock indication. For this, we use the other details. As these details might have lower SNR, we use de-noising here.

EXPERIMENTAL SETUP

For our analysis, we use a representative knock signal similar to [4]. Our knock signal consists of a fundamental at 7Hz and harmonics at 14Hz and 21Hz. We also have a 35Hz resonant frequency. The sampling rate is 120Hz. This sampling rate is chosen such that we get the knock energy of interest in details d3 and d4. Gaussian white noise is added to this signal. The combined knock signal can be expressed as:

$$y(\alpha) = A_0 e^{-d\alpha^2} (\cos(c\alpha + \phi) + 0.707 \cos(2c\alpha + \phi) + 0.5 \cos(3c\alpha + \phi) + \cos(5c\alpha + \phi)) + w_\sigma(n)$$

Where

- $A_0 e^{-d\alpha^2}$ represents the amplitude modulation
- $\cos(c\alpha + \phi)$ represents the phase of the knock signal and
- $w_\sigma(n)$ represents white Gaussian noise of standard deviation σ
- In our analysis, $A=240$, $c=14\pi$ (fundamental knock frequency), $d=2$

We add noise of different standard deviations. This helps in simulating knock signals under wide range of SNR. We use the *wavedec* function from *scilab* for 4-level wavelet decomposition of the knock signal. We find that the knock signal transients are clearer in the wavelet details D3/ D4 (this will vary from case to case). We de-noise these details using soft –thresholds. The threshold used is 1.5 times the mean standard deviation of the detail. Next, we observe the energy ratios for wavelet details of knock signal and noise before and after de-noising.

RESULTS:

i) $\sigma = 20$

Knock signal

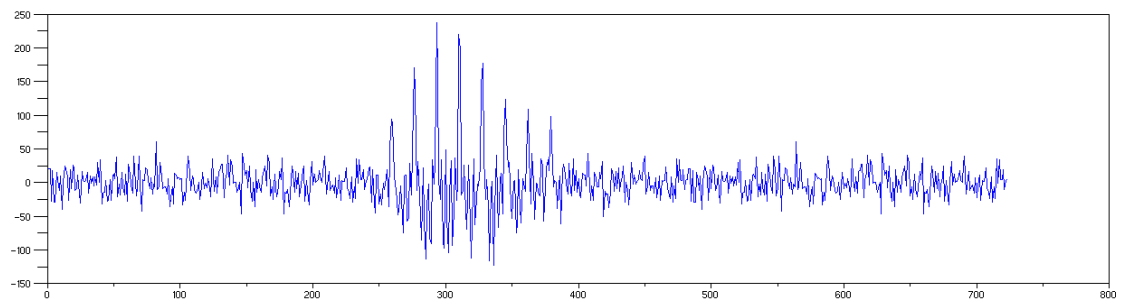


Figure 4 Knock signal with A=240, sigma=20

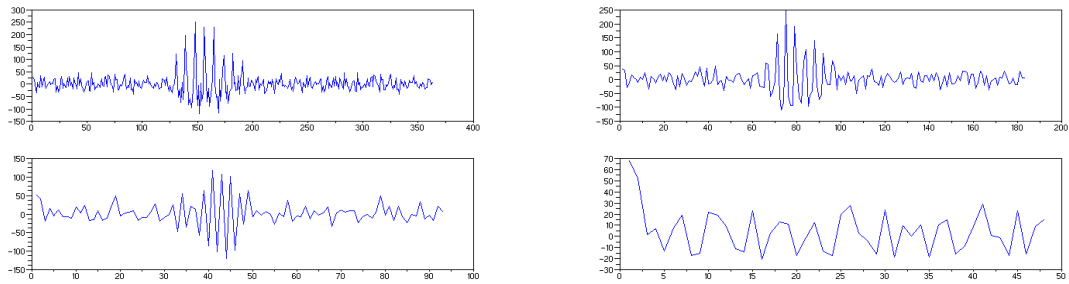


Figure 5 4- Level db4 Wavelet decomposition: Approximation coefficients

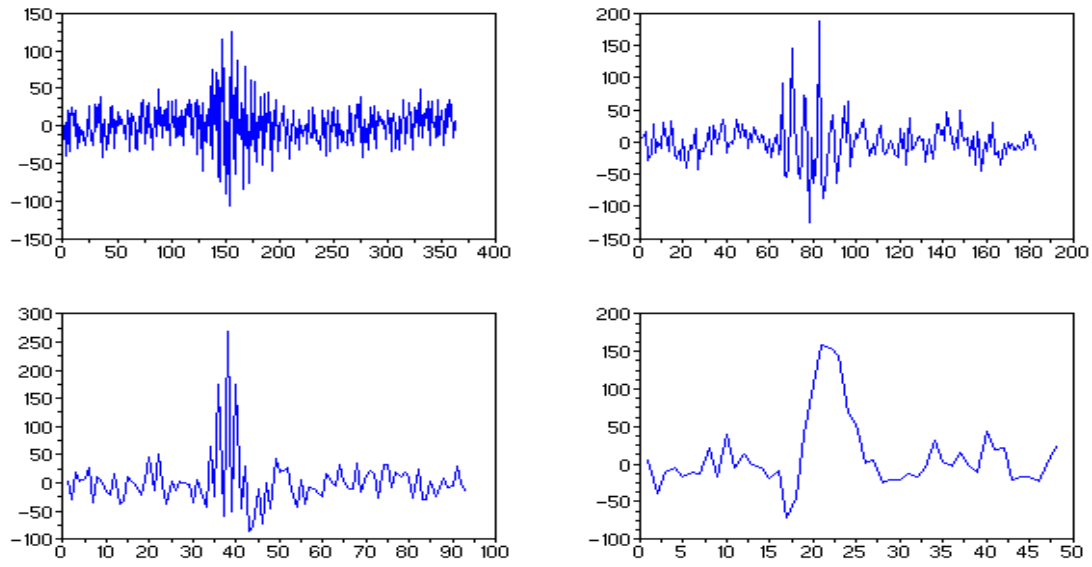


Figure 6 4-Level db4 wavelet decomposition: Detail coefficients

We show the wavelet analysis of noise signal now:

Approximation coefficients (4-level wavelet decomposition)

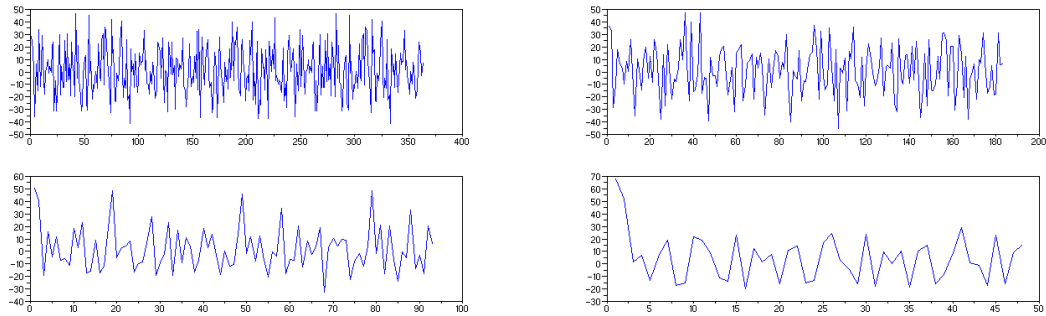


Figure 7 4-Level db2 Wavelet decomposition of noise signal : Approximation Coefficients

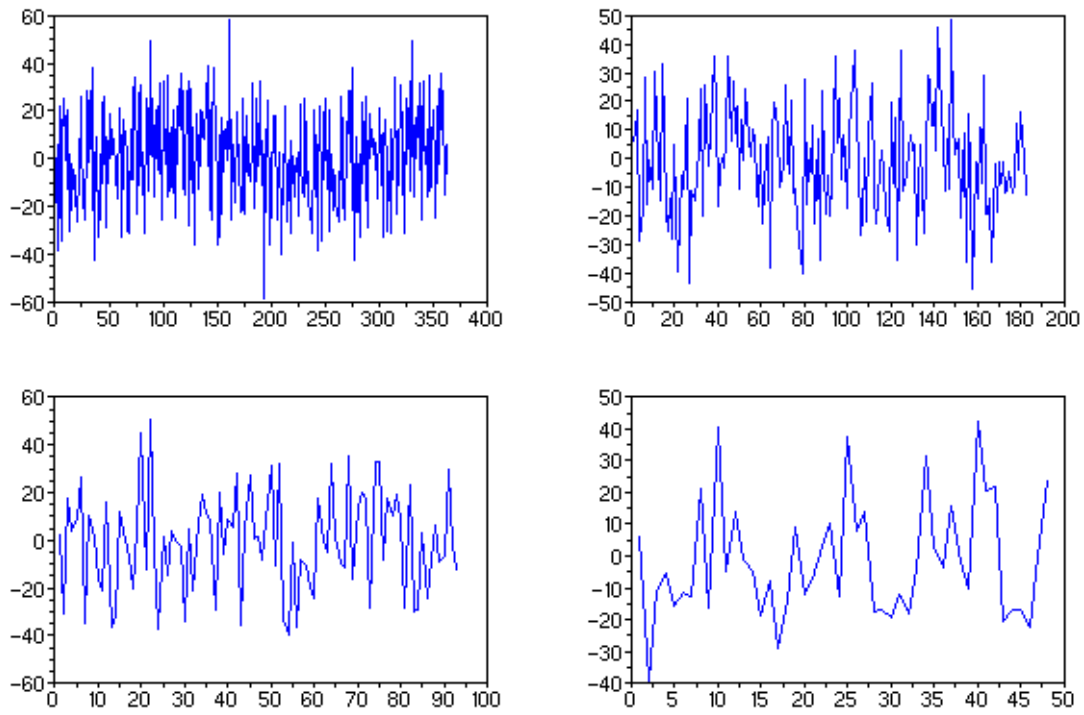


Figure 8 4-Level Wavelet decomposition of noise: Detail Coefficients

For an indication of noise, we use the ratio of details d3 and d4 for noise and signal.

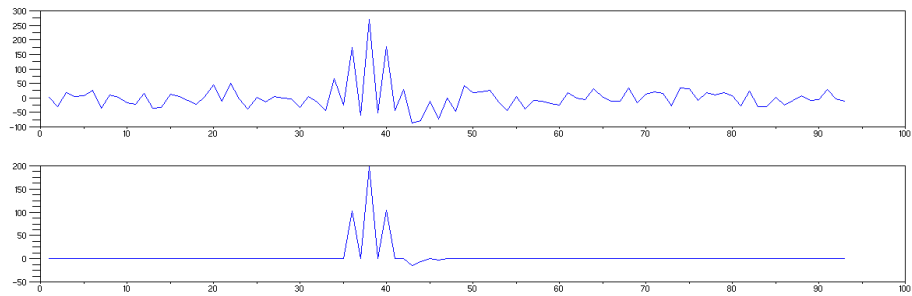


Figure 9 Raw(top) and de-noised detail D3 for knock signal

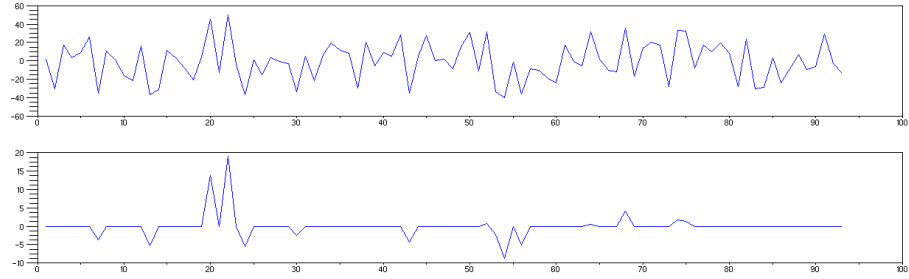


Figure 10 Raw(top) and de-noised detail D3 for noise signal

ii) raw and de-noised d4 for signal

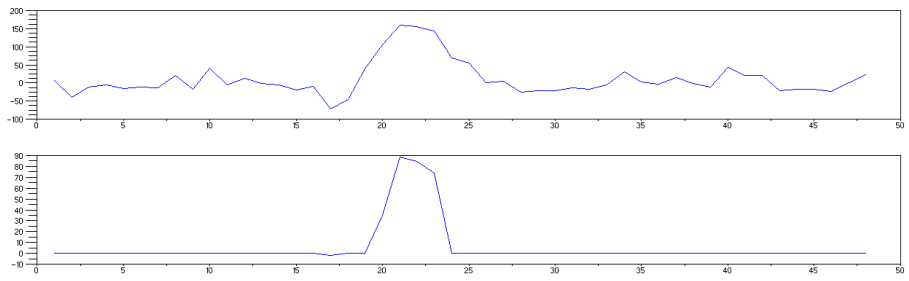


Figure 11 Raw and de-noised detail D4 for knock signal

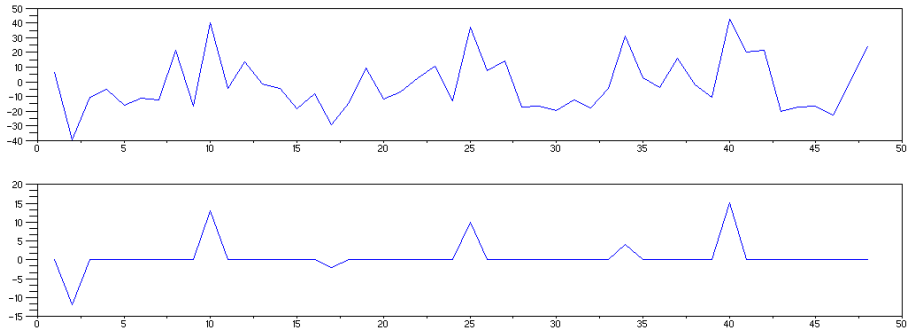


Figure 12 Raw and de-noised detail D4 for noise

Energy ratio of raw detail d3 for signal and noise = 5

Energy ratio of de-noised detail d3 for signal and noise = 78

Energy ratio of raw detail d4 for signal and noise = 6

Energy ratio of de-noised detail d4 for signal and noise = 32

ii) $\sigma=50$

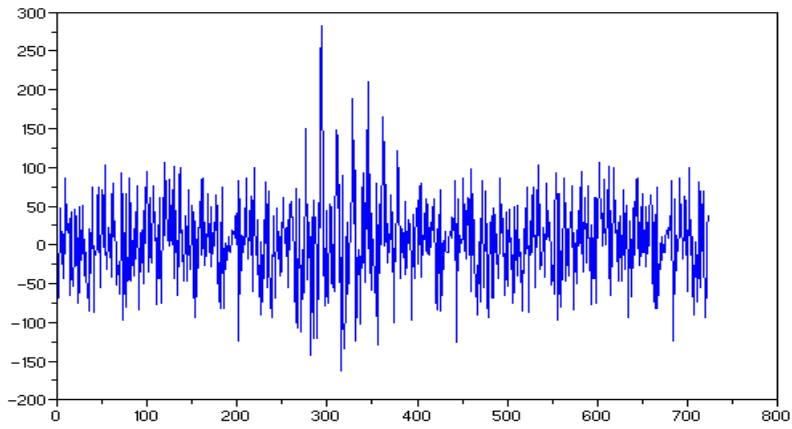


Figure 13 Knock signal with $A=240$ and $\sigma=50$

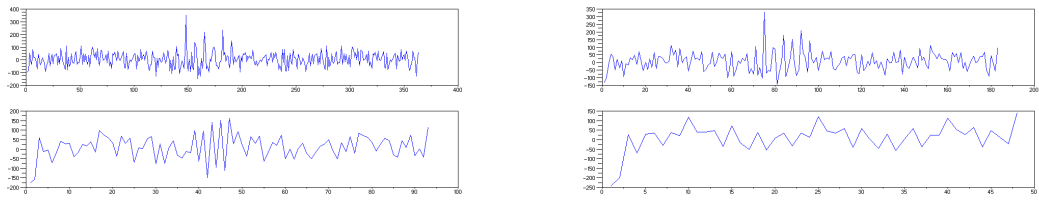


Figure 14 4-Level Wavelet decomposition of knock signal: Approximation Coefficients

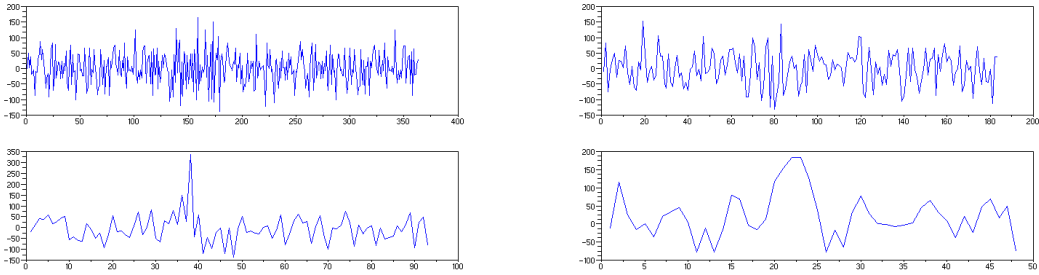


Figure 15 4-Level Wavelet decomposition of knock signal: Detail coefficients

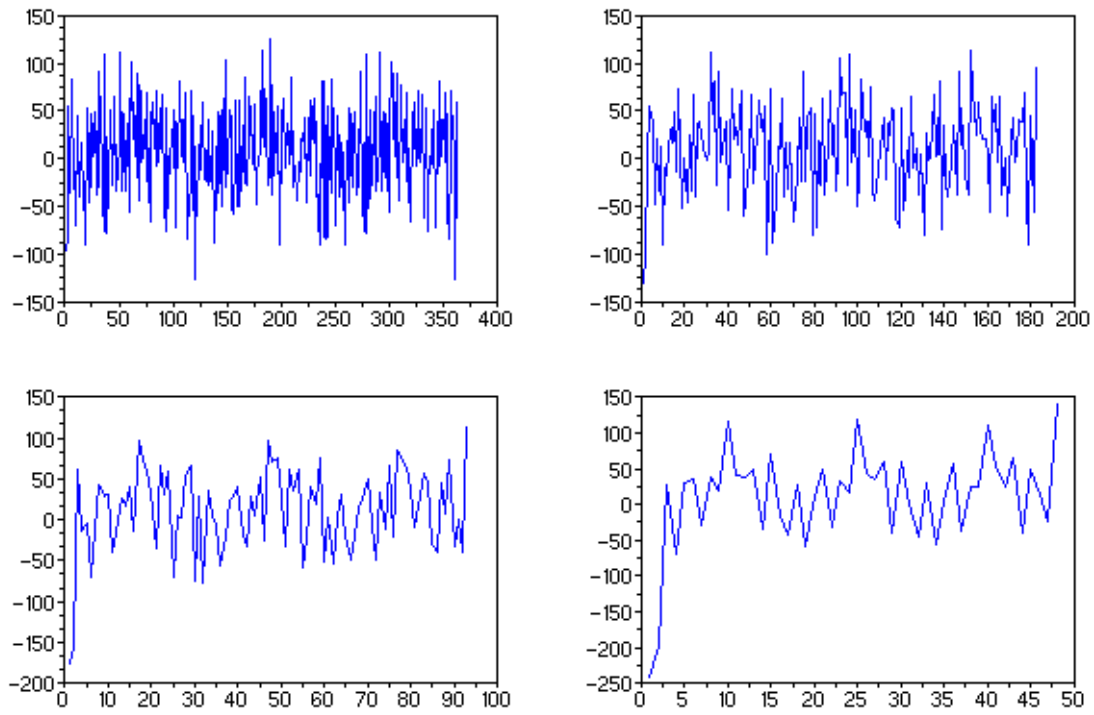


Figure 16 4-Level Wavelet Decomposition of Noise: Approximation coefficients

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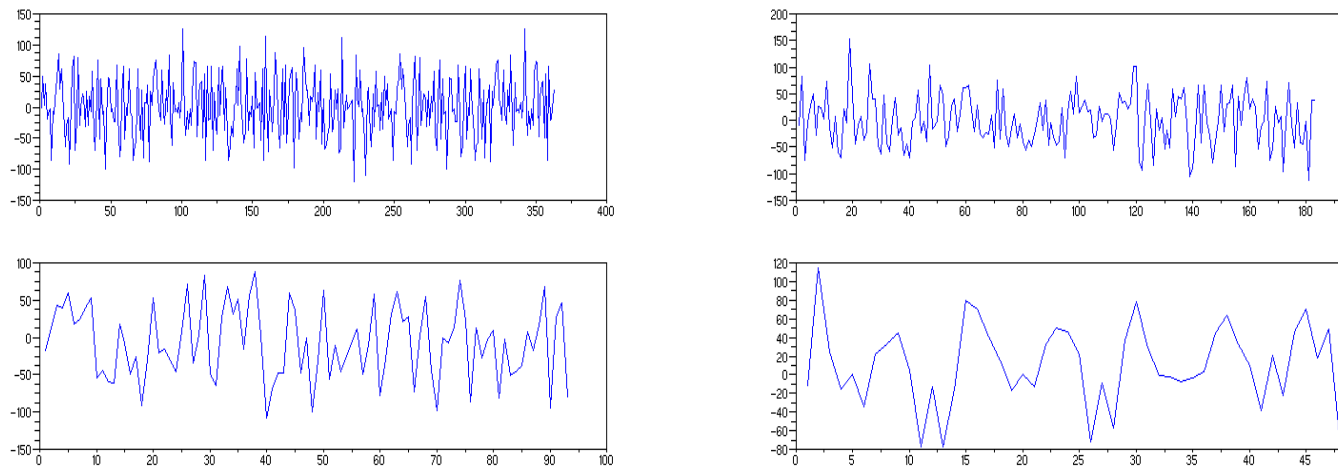


Figure 17 4-Level Wavelet Decomposition of noise: Detail Coefficients

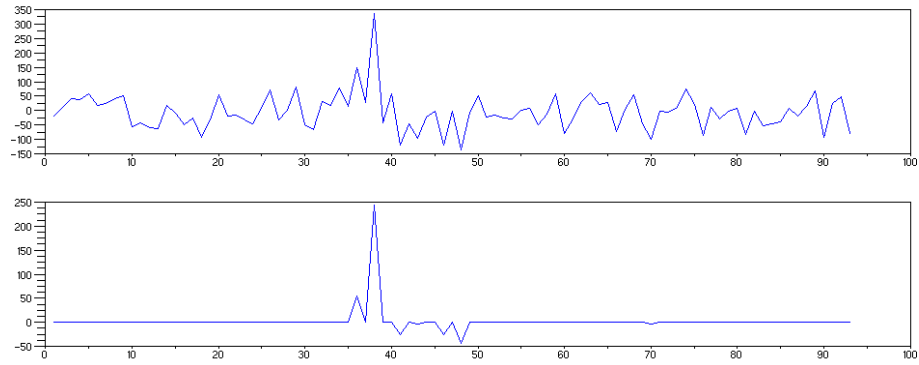


Figure 18 Raw and de-noised detail D3 for knock signal

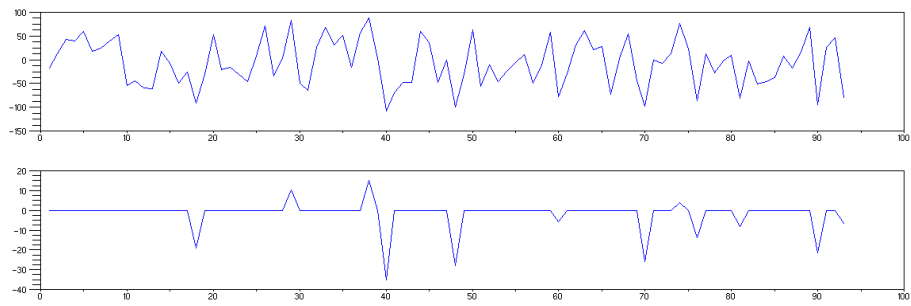


Figure 19 Raw and de-noised detail D3 for noise

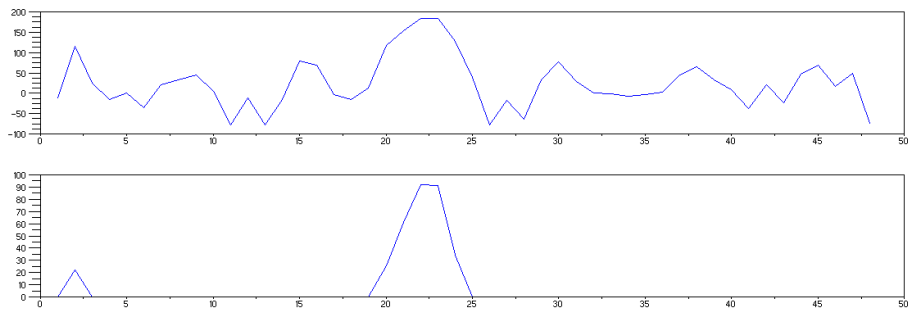


Figure 20 Raw and de-noised detail D4 for signal

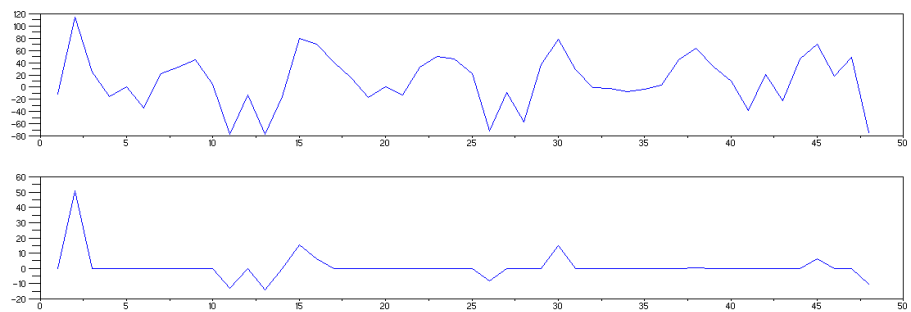


Figure 21 Raw and de-noised detail D4 for noise

Energy ratio of raw detail d3 for signal and noise = 1.65
Energy ratio of de-noised detail d3 for signal and noise = 15.6

Energy ratio of raw detail d4 for signal and noise = 0.86
Energy ratio of de-noised detail d4 for signal and noise = 0.17

DISCUSSION

Table 1 shows the ratio of details of signal with those of noise. As the noise increases, these ratios drop. For $\sigma=30$, we may choose D3 or D4 ratio as an indicator since the energy ratios are quite high. However, for $\sigma = 80$, we might use a criteria that when ratio for both D3 and D4 are greater than 1.2 (say), then we indicate knock. This can prevent false detection. Moreover, if either D3 or D4 has very low SNR, we may switch to the other detail as an indicator.

$\sigma = 80$		$\sigma = 30$		$\sigma = 20$	
D3	D4	D3	D4	D3	D4
1.29	1.21	2.10	2.97	5.60	4.28
1.34	1.18	2.50	3.90	3.40	6.11
1.28	1.54	3.30	2.29	4.80	5.40
1.22	1.13	2.89	3.30	7.00	3.50
1.25	1.54	2.80	2.72	7.60	5.94
1.24	1.83	2.22	2.37	4.54	3.92
1.33	1.38	3.17	2.43	3.80	5.57
1.27	1.50	3.00	4.49	5.06	4.74

Table 1 Ratio of detail energies of signal and noise

If we choose to use de-noising on a detail, it becomes necessary to compare the de-noise signal energy behavior with that of de-noised noise signal itself. This is needed to make sure that we are using the correct measure on the de-noised signal. Table 2 shows the energy of de-noised (D3) of signal and de-noised detail (D3) of noise for $\sigma=20$ and $\sigma=50$. For a given SNR, we can select an appropriate threshold for de-noised signal detail energy using such data. For example, for $\sigma = 50$, we might choose 0.1. The de-noised signal energy is greater than this in most of the cases while the de-noised energies for detail D3 of noise is less than 0.1.

$\sigma = 20$		$\sigma = 50$	
D3(signal)	D3(noise)	D3(signal)	D3(noise)
1.7	0.02	0.16	0.076
1.26	0.029	0.31	0.0569
1.91	0.05	0.23	0.062
2.01	0.05	0.27	0.035
0.87	0.109	0.207	0.059

1.432	0.065	0.16	0.08
2.0	0.056	0.14	0.03
2.57	0.056	0.21	0.019

Table 2 Energy after de-noising for signal and noise

CONCLUSIONS

We conclude the following from the results presented above:

- i) **It is possible to detect knock using wavelet analysis.** Since, knock manifests itself in the form of a transient centered at the fundamental frequency and its harmonics, the appropriate wavelet details can be used for knock detection. In our analysis, details D3 and D4 are the details used since they include the fundamental and the 1st harmonic of knock signal (Figure 4 and Figure 13). The energy ratio of these details for knock signal and noise can be used to detect knock/no-knock.
- ii) If we choose to **include one or more harmonics in knock detection**, it is possible to choose a different level detail along with the present ones to aid in knock detection. Choosing **more than one detail** helps in more robust knock detection. For example, we can use only detail D3 or we can use only D4 or a combination of D3 and D4 for knock detection.
- iii) Under **reasonably low SNR** conditions, it is possible to do **wavelet based de-noising** for more reliable knock detection. The energy ratio for de-noised wavelet details is higher than for energy ratio for raw details of signal and noise. Table shows the energy ratios for many realizations of knock signal under different noise conditions.
- iv) We need to **choose an appropriate sampling rate** so that we get the knock signal of interest in a few details and reach this with the minimum level of decomposition. We may have to change the sampling rate with the rpm since the knock frequency or the harmonic of interest might shift with engine rpm and other operating conditions.
- v) Conclusions (ii) and (iii) above point towards an **adaptive knock detection** scheme. This can help in better knock detection by shifting between harmonics based on rpm, etc. De-noising of details helps in better energy ratios and thus more robust knock detection.
- vi) **[Future Work]** Efficient hardware implementation of this scheme is required. Further analysis is required to compare the computational complexity of the proposed method versus the existing method of knock detection.

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