In-cylinder combustion detection based on logarithmic instantaneous angular successive speed ratio

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Abstract. Performance of an internal combustion (IC) engine directly depends on quality of combustion. A direct way to detect the combustion is mainly done by measuring in-cylinder pressure by a pressure measuring sensor. However, sensor's cost is very high and its installation on the cylinder head is a tricky assignment. Therefore, in this paper, IAS signal measured from the output shaft, has been used to detect the combustion inside the engine cylinder. The advantage of IAS signal is that it is less noisy compared to other engine responses like vibration signal, acoustic signal etc. In IC engine, the speed fluctuation during power stroke is higher as compared to suction, compression and exhaust. Based on this idea, IAS signal based algorithm has been developed to detect combustion in a single cylinder four stroke spark ignition engine.

1. Introduction
Reliability of an internal combustion (IC) engine depends on the continuous power output and it depends on many factors such as stoichiometric air fuel ratio, compression ratio, spark energy, exhaust gas recirculation, ignition energy of air fuel ratio etc. [1]. Hence, any one of these becomes incorrect, then power output will not be continuous. Therefore, detection of combustion is an important issue in area of IC engine's combustion monitoring. Combustion diagnosis has historically done by measuring directly in-cylinder pressure by a pressure sensor [2]. However, the pressure sensor is very costly and installation of it on the engine cylinder head is a difficult task. Therefore, researchers are diagnosing the combustion by other means. These responses are vibration signal, speed signal, acoustic signal etc. The vibration signal is analysed by different researchers [3-5] to estimate in-cylinder pressure variation by the researchers [6]. In one paper [7], it has been reported that acoustic signal is amalgamation of combustion noise and structural noise. Researchers [8] have also tried to take apart mechanical noise from the combustion noise in time and frequency domain. Although, the mechanical noise and combustion noise occurred at distinctive time instances, still taking apart of them is quite difficult. Therefore, rotational speed or instantaneous angular speed (IAS) signal has also
been used for in-cylinder pressure estimation and combustion related fault detection. Most importantly, the IAS signal is contaminated by less structure borne and air borne noise. Moreover, the IAS can be measured by low cost speed measuring devices like optical encoder, magnetic encoder. Due to these advantages, the IAS signal has been analysed to reconstruct in-cylinder pressure by different techniques such as mathematical modeling [9], linear correlation [10], and neural network [11] etc. Yang et al. [12] have compared in-cylinder pressure variation with instantaneous angular speed fluctuation ratio. IAS signal is also used to identify misfiring in spark ignition engine by Ponti [13]. Tagliatela et al. [14] have identified fuel leakage in four stroke four cylinder diesel engine. Charles et al. have detected misfiring [15] and fuel injection time variation [16] in 16 and 20 cylinder diesel engine. Roy at al. [17] have detected combustion single cylinder spark ignition engine by combining complementary ensemble empirical mode decomposition and IAS signal.

Here, in this paper, the idea is that the speed fluctuation will be higher during power stroke rather than suction, compression and expansion. Thus successive speed ratios will be higher during power stroke than others. These successive speed ratios can be measured in logarithmic domain as logarithmic instantaneous angular successive speed ratios (LIASSRs) and used to detect in-cylinder combustion in a four stroke single cylinder gasoline engine.

2. Theory

2.1 Instantaneous angular speed

Nowadays the speed of a rotating machine is mostly measured by optical encoder. The encoder generally produces pulse signal and number of pulses in one revolution depends on the number of optical slots in the encoder is called resolution of the encoder. The time duration of each pulse remains constant while the speed of rotating machine is constant. However, in reality, achieving constant speed in rotating machine is simply difficult. Even a newly installed machine does not remain free from defect. The defects could be manufacturing defect, machining defect etc. Therefore, speed of the machine does not remain constant. While this varying speed is measured by an encoder, produces frequency modulated (FM) pulse signal. Hence, estimated speed from this frequency modulated signal is called instantaneous angular speed (IAS). There are various technique to achieve IAS from this encoder signal are mentioned in the literatures [18]. However, frequency domain technique measures better IAS with lower computation time. The frequency modulated pulse signal [19] can be written as

\[ y(t) = \sum_{i=1}^{n} A_i \sin[2\pi (2i-1) f_c t + b_m(t)] \]  

Where,

\[ f_c = N f_r \]  

\[ b_m(t) = \sum_{n=1}^{m} B_m \sin[2\pi f_m t + \beta_m] \]

Where, \( A_i, f_c, b_m(t) \) are \( i^{th} \) amplitude, carrier frequency, modulating signal and initial phase of the pulse signal. \( f_r \) is rotational frequency, \( f_m \) and \( f_v \) amplitudes and frequency of the modulating signal. \( N \) is resolution of the encoder. The encoder signal is filtered by a band pass filter around the \( 1^{st} \) carrier frequency and band pass filtered signal can be written as

\[ y(t) = A_i \sin[2\pi f_c t + b_m(t)] \]  

The width (2\( B_w \)) of band filter is decided by the following equation [18]

\[ B_w = f_h + N f_v \]

Where \( f_h \) and \( f_v \) are highest frequency and small frequency variation in the band width. Further, the band pass filtered signal \( (y_f) \) can be analytically represented as \( z(t) \) by Hilbert transform
\[ z(t) = A_1 e^{j[2\pi f_c t + \sum_{m=1}^{n} \theta_m \sin(2\pi f_m t + \beta_m)]} \]  

(6)

Now, estimated IAS from the analytical signal \( z(t) \) can be written as

\[ \text{IAS} = \frac{1}{N} \frac{d\varphi(t)}{dt} = 2\pi f_r + \frac{1}{N} \sum_{m=1}^{n} 2\pi B_m \cos \left[ 2\pi f_m t + \beta_m \right] \]

(7)

2.2. Logarithmic instantaneous angular successive speed ratio

In internal combustion engine, the in-cylinder pressure varies with different strokes. The pressure increases during combustion process and influences the speed variation. The speed variation will be higher during combustion process than other processes like suction, compression, and exhaust. Therefore, successive speed ratios will be closer to one during suction, compression, and exhaust. The ratios will be far from one during combustion process. This ratio will be much more predominant in logarithmic domain. Therefore, the ratio in logarithmic domain is called as Logarithmic Instantaneous angular Successive speed ratios (LIASSRs). Hence, LIASSRs can be written as

\[ r_l = \log \left[ \frac{\omega_l + 1}{\omega_i} \right] \]

(8)

2.3. Wavelet packet transform

Wavelet packet transform (WPT) [20] is an extension of discrete wavelet transform (DWT). In DWT, only approximate coefficients are decomposed into the next level. Whereas, in WPT, both approximate and detail coefficients are decomposed into the next level. Thus the technique gives better time frequency resolution. The wavelet function is time frequency function and it is defined as

\[ W^0_n(t) = 2^{j/2} W^n (2^j t - j) \]

(9)

Where, \( i, j \) are integers and represent scale and translation parameter, respectively. \( n \) is oscillation parameter. Hence, first two wavelet functions can be defined as

\[ W^0_{0,0} = \phi(t) \]

(10)

\[ W^1_{0,0} = \psi(t) \]

(11)

Where, \( \phi(t) \) and \( \psi(t) \) are scaling function and wavelet function, respectively. When \( n=2,3,\ldots \), then the function can be written in following relationship

\[ W^{2n}_{0,0} = \sqrt{2} \sum h(j) W^n_{1j} (2t - j) \]

(12)

\[ W^{2n+1}_{0,0} = \sqrt{2} \sum g(j) W^n_{1j} (2t - j) \]

(13)

Where, \( h(k) \) and \( g(k) \) are high pass and low pass filter associated with earlier mentioned scaling and mother wavelet functions. Thus, wavelet packet function generates normal orthogonal basis in precise frequency band and computes wavelet packet coefficients of a signal \( x(t) \) in that frequency band by inner product of \( x(t) \) and wavelet functions. Thus, the wavelet packet coefficients can be defined as

\[ c^n_l(j) = \{ x(t), W^n_{lj} \} = \int_{-\infty}^{\infty} x(t) W^n_{lj} dt \]

(14)

Here, \( c^n_l(j) \) is \( p^{th} \) set coefficients at \( j^{th} \) scale with \( k \) translational parameter. This decomposition produces \( 2^n \) number of sets of coefficients at \( j^{th} \) level. Thus, the signal \( x(t) \) can be written as

\[ x(t) = \{ c^n_l(j) | k = 1, 2, 3, \ldots , N \} \]

(15)

After \( j^{th} \) level decomposition, the width of wavelet packet coefficients will be

\[ \{ c^n_l(j) | k = 1, 2, 3, \ldots , N/2^j \} \]

(16)
Thus the sampling frequency is reduced by $2^j$. Each set coefficients are of $(p-1)Fs/2^n$ to of $pFs/2^n$ and produces wavelet packet tree. The tree can be written as

$$c_{l2m}^k(r) = \sum_{r=-\infty}^{\infty} h(r - 2k)c_{l+1}^{n+1}(r)$$

(17)

Hence, different frequency band signal can be reconstructed by setting the desired node's coefficients to zero.

3. Experimental set-up

The experimental set-up [17] (shown in Fig. 1) has a four-stroke, single cylinder gasoline engine (Honda G-300) which has the maximum rotational speed of 3600RPM with maximum rated power of 5kW. An Engine Performance Analysis software is connected through the internal control network which is applied in the control panel (shown in Fig. 2) to control the system test rig. The control panel is computerised. Different engine related parameters are displayed on the output hardware of the control panel. The displayed parameters are engine rotational speed, engine torque, air flow intake, and water flow rate. The gasoline engine can experience the external load through the cardan shaft which is connected through an eddy current dynamometer, whose specification is tabulated in Table 1. The engine has various sensors installed within to observe the varying responses of the engine. Incylinder pressure is obtained with the help of a Kistler charge type Piezoelectric pressure sensor. The specifications for the sensor are tabulated in Table 2. Number of thermocouples are positioned in the test rig to measure the air temperature and cooling water temperature at inlet and outlet.

![Figure 1](image)

**Figure 1.** (a) Experimental setup for four stroke SI engine, (b) Incremental rotary optical encoder.

**Table 1.** Technical specification of engine [17]

| Engine | HONDA G-300 |
|--------|-------------|
| Rated Power | 5HP @60 Hz |
| Rated Torque | 14 N-m @ 46.67 Hz |
| Cubic capacity cylinder | 272 C.C |
| Bore | 76 mm |
| Stroke | 60 mm |
| Connecting rod length | 73 mm |
| Compression ratio | 6.5:1 |
| Type | 4 Stroke, Single Cylinder, Air cooled, gasoline engine |
Table 2. Technical specifications piezoelectric pressure sensor [17]

| Specification          | Value                      |
|------------------------|----------------------------|
| Pressure range         | 0-100 bar                  |
| Sensitivity            | 40 mV/bar                  |
| Shock                  | 2000g                      |
| Operating temperature range | -50 to 300 degree Celsius |

A mechanical device (an orifice meter) is fitted to measure the air flow rate to the cylinder. The flow rate of cooling water going to the dynamometer is measured by a turbine flow meter. A calibrated burette is used to measure the fuel consumption rate and the dynamometer arm is being put with the external load with the help of a strain gauge load cell. The rotational speed of the crank shaft at output is observed by an incremental rotary encoder (E50S8-360-3-V-5). The pulse signals obtained from the encoder with the help of an oscilloscope and saved in a personal computer for further analysis.

4. Results and Discussion

Three speeds have been selected for the analysis. The encoder signal has been acquired during steady state condition with sampling rate of $10^5$ Hz. The sampling has been considered based on literature [18].

$$Fs > 4[Nf_r + f_h + Nf_v]$$
$$Fs > 4[360 \times 40 + (20 \times 40 + 360 \times 0.5)]$$
$$Fs > 61520Hz$$ (18)

Where $f_h$ is considered up to 20 multiples of rotational frequency and small frequency variation is 0.5 Hz. Estimated IAS from encoder signal during 2100 RPM and 4.8 Nm load has been shown Fig. 3(a) and frequency spectrum of IAS has been shown in Fig. 3(b). The frequency spectrum contains combustion frequency, rotational frequency and their harmonics. Hence, the spectrum can reveal the occurrence of combustion. However, online condition monitoring needs combustion cycle by cycle. Therefore, the IAS signal has been filtered by WPT. At first the signal has been decomposed up to 8th level by using db10 wavelet [20]. Thus, frequency content of $n^{th}$ node will be $(n-1) \times 10^5/2^9$ to $n \times 10^5/2^9$. Therefore the first node will contain the signal of 0-195.31 Hz. Hence, the signal has been
reconstructed by setting the other node's coefficients to zero (except 1st node). The reconstructed IAS has been shown in Fig. 4. However, the filtered IAS is unable to detect combustion properly.

![Figure 3](image1.png)

Figure 3. (a) Estimated IAS signal, (b) Frequency spectrum of IAS signal during 2100 RPM and 4.8 Nm load.

![Figure 4](image2.png)

Figure 4. (a) IAS signal, (b) Filtered IAS signal, (c) in-cylinder pressure signal during 2100 RPM and 4.8 Nm load.

![Figure 5](image3.png)

Figure 5. (a) Estimated LIASSR signal, (b) Frequency spectrum of LIASSR signal during 2100 RPM and 4.8 Nm load.
Next LIASSRs has been estimated from IAS signal and is called as LIASSR signal. The LIASSR signal and its frequency spectrum are shown in Fig. 5(a) & (b). The spectrum contains combustion frequency, rotational frequency and their harmonics.

Figure 6. (a) LIASSR signal, (b) Filtered LIASSR signal, (c) in-cylinder pressure signal during 1800 RPM and 4.8 Nm load.

Figure 7. (a) LIASSR signal, (b) Filtered LIASSR signal, (c) in-cylinder pressure signal during 2100 RPM and 4.8 Nm load.

Figure 8. (a) LIASSR signal, (b) Filtered LIASSR signal, (c) in-cylinder pressure signal during 2400 RPM and 4.8 Nm load.
Hence, LIASSR has been filtered by same WPT based technique, as earlier mentioned. Three speeds have been selected for the analysis. The speeds are 1800 RPM, 2100 RPM, and 2400 RPM, respectively. Corresponding each speed one load (4.8 Nm) has been considered for the analysis. Fig. 6-8 show filtered LIASSR and in-cylinder pressure during 1800 RPM, 2100 RPM, and 2400 RPM respectively. The filtered LIASSR shows higher speed fluctuation during combustion.

5. Conclusion
The paper utilizes IAS signal to detect combustion in spark ignition engine. Hence, IAS signal has been filtered by using time frequency domain (wavelet packet transform) technique to monitor the combustion continuously. However, direct filtering of IAS signal is unable to detect combustion properly. Therefore LIASSR has been estimated from IAS signal and filtered by WPT based technique. The technique can detect the combustion more efficiently.

References
[1] Heywood J B 1988 Internal combustion engine fundamentals (New York: McGraw-Hill)
[2] Mobley C 1999 SAE Paper No. 1999-01-0544
[3] Lyon R and DeJong R 1984 J. Vib. Acoust. 106 17
[4] Gao Y and Randall R B 1999 Mech. Syst. Sig. Process. 13 709
[5] Antoni J, Daniaire J and Guillet F 2002 J. sound vib. 257 815
[6] Kamin’ski T, Wendeker M, Urbanowicz K and Litak G 2004 Chaos 14 401
[7] Jeong-Guon I, Kim H, Lee S and Shinoda K 2009 Appl. Acoust. 70 347
[8] Delvecchio S, Bonfiglio P and Pompoli F 2018 Mech. Syst. Sig. Process. 99 661
[9] Citron S J, O’Higgins J E and Chen L Y 1989 SAE Paper No. 890486
[10] Moro D, Cavina N and Ponti F 2002 J. Eng. Gas Turbines Power 124 220
[11] Johnsson R 2006 Mech. Syst. Sig. Process. 20 1923
[12] Yang J, Pu L, Wang Z, Zhou Y and Yan X 2001 Mech Syst Signal Process 15 549
[13] Ponti F 2008 J. Eng. Gas Turbines Power 130 1
[14] Taglialetela F, Lavorgna M, Mancaruso E and Vaglieco B M 2012 Mech. Syst. Sig. Process. 38 628
[15] Charles P, Sinha J K, Gu F, Lidstone L and Ball A D 2009 J. sound vib. 321 1171
[16] Charles P, Sinha J K, Gu F, and Ball A D 2010 Mech. Syst. Sig. Process. 24 841
[17] Roy S K and Mohanty A R 2017 Measurement 98 60
[18] Gu F, Yesilyurt I, Li Y, Harris G and Ball A D 2006 Mech. Syst. Sig. Process. 20 1444
[19] Li B, Zhang X and Wu T 2018 ISA Trans. 74 245
[20] Fan X and Zuo M J 2006 Gearbox 2006 Mech. Syst. Sig. Process. 20 966