Feature Extraction from a Crankshaft Instantaneous Speed Signal of an Automotive Power Unit using Cepstrum Analysis

Ismail El Yacoubi and Stephen Samuel

Abstract

Internal combustion (IC) engines are the most common power unit technology found in road vehicles. The process of combustion within IC engines is directly linked to the output torque and overall powertrain performance. This work presents a method of analysing the parameters of cylinder pressure and crankshaft instantaneous speed signals obtained from a turbocharged, 4-stroke, 4-cylinder, 1.6 Litre, spark ignition, gasoline direct injection engine at various speed and load operating conditions. Whereas cepstrum analysis is used in the present work to extract critical features characterising the combustion process. Cepstrum analysis showed that the location of maximum heat release can be directly obtained from the quefrency of the instantaneous crank speed. This paper presents a systematic scheme for applying cepstrum for obtaining combustion features from the instantaneous crank speed signal.

Introduction

Combustion analysis

Internal combustion (IC) engines are the most common powertrain type used in the automotive sector. The principle behind IC engines is the production of mechanical power from combustion to be transmitted to the output shaft as a torque. However, powertrain manufacturers are nowadays required to comply with stringent emission requirements and increased demand for vehicles with improved performance and fuel consumption. These restrictions introduced various research work in powertrains development. One common area of research in IC engines is the improvement of the combustion process since it affects the overall performance of the engine [1].

Combustion is the process of burning air and fuel inside an IC engine cylinder to create a thrust force acting on the piston and therefore rotate the crankshaft and transmit power to the output source. This process involves various parameters and stages affecting the overall efficiency of the cycle. The air-fuel mixture experiences compression and expansion processes during combustion which can be examined using cylinder pressure data. Cylinder pressure is an important parameter in combustion analysis given its direct link to the output power produced by the engine [2].

The use of cylinder pressure is well known in the history of IC engines research from Rassweiler and Withrow paper [3] published in 1938 detailing a methodology of sorting pressure fluctuations due to combustion, in addition to the development of combustion mathematical models such as Wiebe function [4] in the 1960s. Cylinder pressure have been used to gain information on spark timing [2], information on peak pressure [5], heat transfer and thermal efficiency [6]. The settings of the mechanical and pneumatic control systems of IC engines before the 1970s were based on these cylinder pressure parameters. Later on in the 1970s, the advancements in the automotive sector led to the introduction of electronic control systems based on different sensors feedback for IC engines knowns as the Engine Control Unit (ECU). Therefore, research in the use of cylinder pressure information for optimising the Engine control systems have gained interest. The improvement of the electronic control of parameters such as injection and spark timing using gained information on cylinder pressure results in a better combustion process and therefore improved power and lower emissions. For example, Hsu [7] and Heywood [2] showed methods of using cylinder pressure measurements and the first law of thermodynamics to develop mathematical models of heat release rate estimation for a given engine cycle. Hsu [7] then demonstrated a structured approach to use heat release models in developing a method for improving fuel injection control and therefore fuel consumption in IC engines. The uses of cylinder pressure information are also found in partial burning and misfire control applications [8], the optimisation of fuel injection by using a closed-loop control algorithm based on cylinder pressure data [9], as well as applications in identifying the presence of engine knocking during the combustion process [5, 10, 11].

Another parameter used for combustion analysis research is the crankshaft instantaneous speed. This signal is crucial as it represents the output feedback due to the pistons firing from the cylinder. The pistons and the crankshaft are linked by the connecting rod and therefore the linear travel of the piston directly affects the rotational displacement of the crankshaft. This relation leads to the conclusion that pressure fluctuations inside the combustion chamber will affect the variations of the crankshaft instantaneous speed signal. The number of cylinders also plays an important role in determining the smoothness of the crank speed signal, the higher the number of firing cylinders, the smoother it is for the power delivery process.

The relation between cylinder pressure and the crankshaft instantaneous speed signal is well known in the literature, for example, Wang, Yang and Ouyang [12] used the crankshaft instantaneous speed signal and the cylinder pressure signal of a single cylinder to characterise the cylinder by cylinder indicated torque. The results of this research showed that it is possible to use this method to estimate with good accuracy the indicated pressure torque, which can be utilised to determine features such as the location with respect to the crank angle of maximum torque during combustion, as well as the value of indicated mean effective pressure (IMEP). An approach to estimate indicated torque information using the crankshaft speed signal was also attempted by Rizzoni [13]. Additional methods of estimating IMEP based on the crankshaft instantaneous speed signal are found in the literature as well [14, 15]. The crankshaft instantaneous speed signal was also previously used to recompose cylinder pressure data using artificial neural networks [16] and for cycle-by-cycle cylinder pressure estimation [17, 18, 19].

Overall, it is shown that the use of cylinder pressure and the crankshaft instantaneous speed presented useful applications in the automotive sector. However, due to the complexity and cost associated with obtaining direct cylinder pressure measurements, such measurement transducers are not used in production engines. Whereas cylinder pressure transducers can only be found in engines used for research and development purposes. Therefore, a current limitation in production engines is the inability to integrate a live cycle-by-cycle input of cylinder based pressure and heat transfer changes in the ECU for performance optimisation. Therefore, the development of a method for extracting such live cycle-by-cycle changes from the crankshaft instantaneous speed to be used for engine control optimisation applications for production IC engines can present a solution to the current live condition monitoring limitations of the combustion chamber. Hence, the scope of the present work.

Cepstrum analysis

Cepstrum analysis is a signal analysis method that has many applications in fields such as harmonics, fault diagnosis for mechanical systems [20] and speech analysis [21]. Cepstrum analysis can distinguish an echo from its original signal by using Fourier transforms (FFT). FFT is used to convert time domain data to a frequency domain. The benefit of the FFT approach is to allow a simpler identification of the main frequencies present in the original time domain.

The resulting frequency domain after FFT computations is also known as the power spectrum. Whereas, Cepstrum can be identified as the power spectrum of the logarithm of the power spectrum [22]. cepstrum is an anagram of the spectrum. The initial concept of cepstrum was published in 1963 before the publication of the FFT computation method in 1965 by Bogert, Healy and Tukey [23]. By considering a time domain signal given by x(t), the cepstrum of x(t) can be represented mathematically by the following equation [22]:

$$|C| = \mathrm{IFFT}(\log|\mathrm{FFT}(x(t))|) \qquad (1)$$

Cepstrum analysis is capable of separating a time domain signal from its echo, as well as detecting signal harmonics which makes this method a practical tool in a variety of fields including engineering. By taking the Fourier Transform of the logarithm of a frequency domain, the resulting plot is known as the quefrency domain. According to Oppenheim and Schafer [22], the quefrency domain contains information on the signal periodicity. The terminology quefrency was assigned to the cepstrum results by Bogert, Healy and Tukey [23]. The purpose of proposing this terminology is to reduce the confusion between the spectrum domain representing frequency and the cepstrum domain representing quefrency. Quefrency is represented by a time unit. However, the quefrency domain carries information regarding both time and frequency components within the original signal [24]. Therefore, this method has a significant advantage over FFT given that the conversion from time domain to frequency domain using FFT results in the loss of information on time components in the frequency domain.

Applications of cepstrum analysis are found in the literature in papers such as [24] and [25]. For example, Morsy and Achtenova [25] used cepstrum as a method for identifying vehicle gearbox faults. This was achieved by performing cepstrum computations on a gearbox vibration signal. The quefrency domain obtained after this process clearly identified the quefrency peaks corresponding to the sidebands time period of the pinion and the gear. A fault was then identified in the pinion given the high amplitude of this quefrency component in the cepstrum plot. Morsy and Achtenova [25] paper demonstrated the advantages of cepstrum analysis in gearbox fault detection over the limitations of frequency domain analysis only. Similar previous research in the literature have also proved the effectiveness of cepstrum analysis in gearbox fault detection [26, 27, 28]. Whereas, [24] used cepstrum analysis for applications within IC engines and showed that this method is a practical tool to analyse the rates of fuel injection in the powertrain system of heavy duty commercial vehicles. This was embodied in the ability to extract periodic signal noise features, as well as the hydraulic system features and its effect on fluid borne frequencies using cepstrum analysis.

Methodology of work

Experimental process

The specifications of the test engine can be found in table 1. For the present work, a Piezo-electric sensor integrated within the spark plug is used to obtain cylinder pressure data. The justifications behind choosing a piezo-electric sensor are related to improved reliability and reduced cost purposes in comparison to other intrusive sensors [5]. The crankshaft instantaneous speed data are collected using a rotary encoder 360 pulse per rotation. Figure 1 shows a schematic illustration of the locations where the sensors are installed within the engine, respectively. Whereas, Table 2 shows the detailed description of the sensors used.

Table 1: Experimental engine specifications

Parameter	Value
Bore diameter	77 mm
Stroke length	85.8 mm
Connecting rod length	138.4 mm
Number of cylinders	4
Compression ratio	10.5
Pistons firing order	1 – 3 – 4 – 2
Fuel injection type	Gasoline Direct injection
Induction type	Turbocharged and intercooled

Table 2: Table of experimental instruments

Data	Measurement instrument
Cylinder pressure	Kistler Spark plug mounted Type 6118C Piezo-electric pressure transducer with the measuring range up to 200 bar
Crankshaft instantaneous speed	Rotary Encoder with 360 pulse per rotation with AVL Indiset© Advanced Data Acquisition system

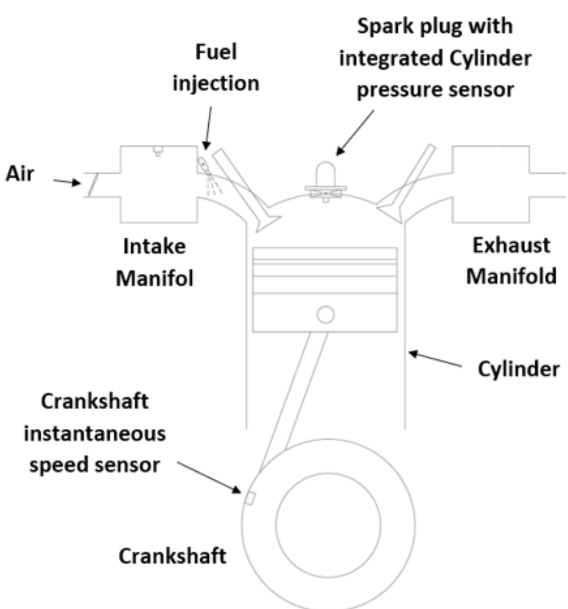

Figure 1: Schematic diagram of the experimental engine showing the locations of data collection sensors

Signal post processing methodology

The signal analysis methodology consists of applying Cepstrum analysis to the in-cylinder pressure trace and Crankshaft instantaneous speed signals. Cepstrum is used in this work of the purpose of extracting features within the signals. Cepstrum results will be illustrated in the form of quefrency domain plots. For the present work, a MATLAB software file provided by Zhivomirov [29] is used to perform Cepstrum analysis. The MATLAB file used provides an integrated Hanning window for smoothing. The advantage of using a Hanning window consists of reducing the effect of signal noise on the results [24, 30].

Results and discussion

Combustion signals

The resulting in-cylinder pressure trace and crankshaft instantaneous speed signals collected from the experimental engine testing are shown in figures 2 and 3, respectively. the plots shown in figures 2 and 3 are the average of 15 measured full engine cycles at 1600 RPM speed condition with 3 loading cases 40 Nm, 60 Nm and 100 Nm. In the present work, the experimental data were collected for 4 speed operating conditions at 1600, 2000, 2800 and 3200 RPM. For each speed case, 3 loading conditions 40 Nm, 60 Nm and 100 Nm were chosen. Therefore, the total number of cases collected from the experiment is 12 operating conditions. Figures 2 and 3 show the cylinder pressure and instantaneous crank speed signals only at 1600 RPM at 3 loading conditions.

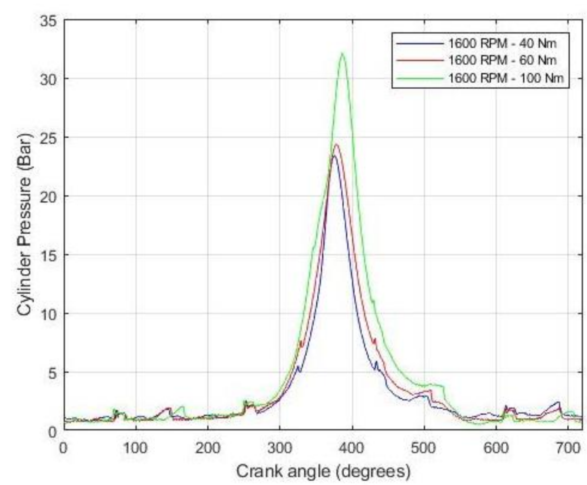

Figure 2: An illustration of cylinder pressure signals at 1600 RPM for 3 loading conditions 40 Nm, 60 Nm and 100 Nm

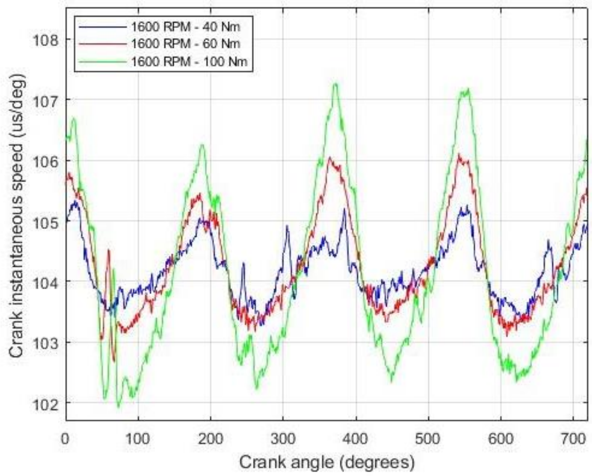

Figure 3: An illustration of crankshaft instantaneous speed signals at 1600 RPM for 3 loading conditions 40 Nm, 60 Nm and 100 Nm

Cepstrum analysis

Cepstrum analysis is a signal processing method within which the Fast Fourier Transform is applied to a signal, followed by taking the logarithm of the resulting frequency domain and then taking the inverse FFT afterwards. Therefore, It is important that the sampling frequency chosen for cepstrum computations adheres to Nyquist principle in order to avoid signal aliasing given that FFT is part of the process [31].

For this project, the sampling frequency is determined following equation 2:

$$f_s = \frac{N \times 360}{60} \quad (2)$$

N represents the speed in RPM at which the engine is running. Table 3 shows the sampling frequency fs used for each engine speed operating condition.

Table 3: A table showing the sampling frequency used for each engine speed condition during cepstrum analysis

Engine speed in RPM	Sampling frequency (f_s) in Hz
1600	9600
2000	12000
2800	16800
3200	19200

Cepstrum was computed for the first 15 consecutive engine cycles and for various speed and loading conditions. Figure 4 illustrates an example 15 consecutive cycles signal of the crankshaft instantaneous speed at 2000 RPM and 40 Nm. Whereas an example of the cepstrum results of in-cylinder pressure trace and crank instantaneous speed signals for the 2000 RPM and 40 Nm case is demonstrated in figure 5. It can be seen that a group of dominant quefrency peaks are present within both cylinder pressure trace and crank instantaneous speed quefrency domains at the same location with respect to the horizontal quefrency axis. The presence of these peaks indicates a pattern of periodicity within the original time domain data. It is also noticed that these dominant frequencies are equally spaced. For the case of 2000 RPM and 40 Nm, the spacing between the peaks highlighted in figure 5 is found to be 60 milliseconds (ms). This time period is directly related to the speed condition at which the engine is operating and represents the period of a full engine cycle, i.e. two full crankshaft revolutions. To calculate the equivalent RPM relevant to each cepstrum plot the equation below can be used:

$$\text{Equivalent RPM} = \frac{1}{A \times 0.001} \times 2 \times 60 \quad (3)$$

In equation 3, “A” represents the quefrency spacing in milliseconds (ms) between the dominant peaks within the cepstrum plots.

as demonstrated in table 4, the spacing between the dominant peaks is found to be the period of a full engine cycle for the 1600 RPM, 2800 RPM and 3200 RPM speed conditions as well. The effect of varying torque operating conditions on the reliability of this finding was also tested. Figure 6 illustrates the first dominant cepstral peak for the 2000 RPM crankshaft speed signal at three different loading conditions. It can be seen that the change in loading does not affect the main cepstral peak location. This is found to be true for all the other speed conditions as well.

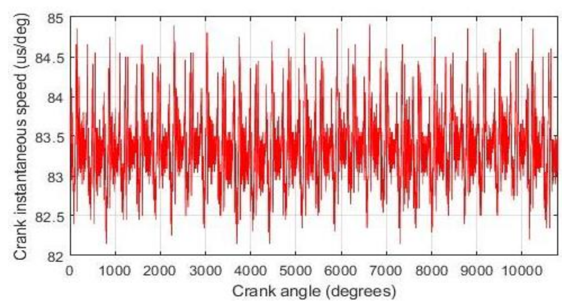

Figure 4: An illustration of 15 consecutive cycles of the crankshaft instantaneous speed signal at 2000 RPM and 40 Nm operating conditions

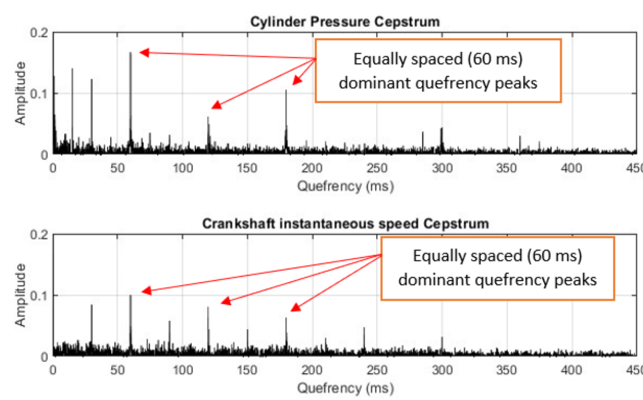

Figure 5: Cepstrum plots of cylinder pressure and crankshaft instantaneous speed at 2000 RPM and 40 Nm operation conditions

Table 4: The equivalent RPM of the quefrency spacing within the cepstrum plots for 4 engine speed operating conditions

Engine speed in RPM	Quefrency spacing between the dominant peaks in ms	Equivalent RPM
1600	75	1600
2000	60	2000
2800	42.85	2800
3200	37.5	3200

Overall, it can be concluded that cepstrum is capable of detecting periodicity and significant signal harmonics within IC engines. This is embodied in the detection of dominant cepstral peaks equally spaced within the cepstrum plots of in-cylinder pressure trace and crank speed signals with the quefrency spacing representing the engine cycle period at the operating speed of the given data. It was also deduced that the periodicity shown in quefrency spacing which is related to operating speed of the engine is unaffected by a fluctuation in torque conditions given that the speed is fixed.

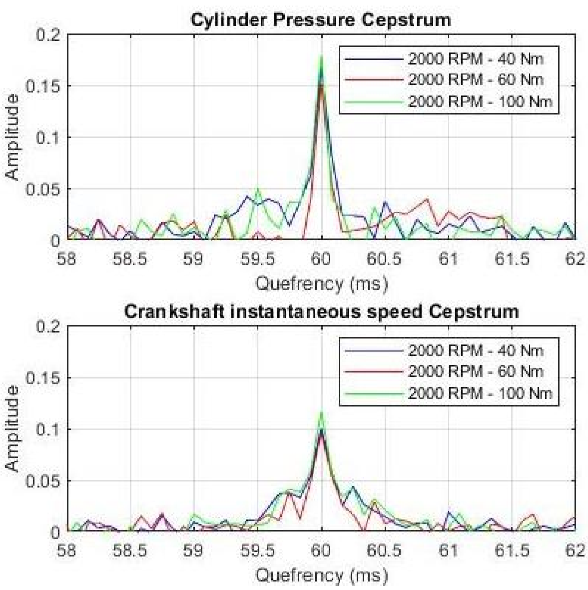

Figure 6: Zoomed first dominant cepstral peak of cylinder pressure and crank speed cepstrum plot for a fixed speed at 2000 RPM and 3 different loading cases

Therefore, cepstrum analysis can have useful applications in fault detection within IC engines. This can be implemented by monitoring the cepstral peaks location along with the quefrency spacing within the targeted signal to be compared with the expected theoretical periodicity at a given engine operating condition. If the quefrency spacing does not match the expected engine cycle time period for a certain speed, this might signify that a fault within the sensors or the engine mechanical system is present. Moreover, it was seen from the results shown in figure 5 that the dominant cepstral peaks signifying the main periodicities within the data have the same locations for in-cylinder pressure trace and crank speed signals. This was true for all the other speed operating conditions. This leads to conclude that it is possible to get the main quefrency peaks location of a cylinder pressure signal indirectly from the crankshaft instantaneous speed cepstrum plot, which can be a non-intrusive method for extracting cepstral information within cylinder pressure data. Therefore, the complexity and high costs associated with installing a cylinder pressure sensor for direct measurements of the combustion process can be avoided. Using cepstrum analysis, changes to the cepstral peaks of cylinder pressure can be estimated from the quefrency plot of the crankshaft rotational speed signal by monitoring the location of quefrency peaks occurrence.

Further analysis of the cepstrum plots revealed the presence of a second group of peaks in addition to the first group of dominant peaks within the crankshaft instantaneous speed cepstrum. The quefrency values associated with these peaks were found to match the timing at which the piston reaches the top dead centre (TDC) at the end of the compression stroke. Figure 7 shows the locations of this group of peaks within the crankshaft instantaneous speed cepstrum at 2000 RPM and 40 Nm.

The order of these peaks in the cepstrum domain is aligned with the order of the consecutive cycles used as an input for the cepstrum computations. This means that the first cepstral peak from this group of peaks matches the time period at which the piston reaches TDC at the end of the compression stroke during the first cycle. Similarly, the next cepstral peak within this group matches the same TDC time period during the following cycle. This is very useful given that it implies that cepstrum can separate each engine cycle and allow feature analysis per specific cycle corresponding to a certain quefrency peak location from the chosen group of consecutive cycles used as an input for the simulation process. However, it can also be seen from figure 7 that the amplitudes of the quefrency peaks corresponding to the timing of the piston at TDC at the end of the compression stroke decrease as the peaks order increase. For case in figure 7, the ability to extract any cepstral peak and its associated cycle features after the 5th TDC quefrency peak is significantly reduced. To overcome this limitation, a bigger sample of consecutive cycles must be used as an input for the simulation process. Figure 8 shows an illustration of two quefrency domains of a crankshaft instantaneous speed signal at 2000 RPM and 40 Nm. The first quefrency domain is the result of the cepstrum computation of 15 consecutive cycles. Whereas the second quefrency domain is the result of the cepstrum computation of 30 consecutive cycles. It can be seen in figure 8 that using more consecutive cycles data as an input results in the detection of more cepstral peaks corresponding to the TDC time period during combustion of each cycle. However, the time required to compute the cepstrum of larger sets of consecutive cycles is more significant in comparison to a smaller sample. Therefore, this approach can be optimised based on the ideal number of cycles for the given computation time limitations for each research or commercial application.

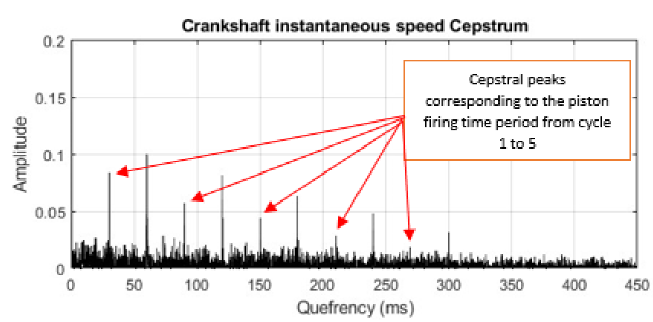

Figure 7: Cepstrum plot of the crankshaft instantaneous speed signal for the 2000 RPM and 40 Nm

Further analysis of the group of peaks with a quefrency corresponding to the TDC time period during combustion demonstrated that it is possible to extract more combustion features within each cycle from the cepstral peaks sidebands. For example, figure 9 illustrates a zoomed plot of the first cepstral peak with a quefrency value of 30 ms corresponding to the TDC timing at the end of the compression stroke during the first cycle. It is noticed that the right sideband of this cepstral peak has a value of 30.33 ms. The comparison of this value with the time stamp location during combustion of maximum heat release occurrence revealed that the quefrency value of the right sideband of the first cepstral peak approximately matches the location of maximum heat release occurrence during the first cycle at 2000 RPM and 40 Nm, i.e. 30.33 ms ≈ 30.45 ms. This is an important finding signifying that it is possible to extract the location of maximum heat release directly from the quefrency information available within the cepstrum plot of the crankshaft instantaneous speed signal.

In order to test the reliability of this finding, the same strategy was applied to different operating conditions. This strategy consist of estimating the heat release rate of each chosen operating condition by applying the first law of thermodynamics for estimating rate of heat release from measured cylinder pressure:

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} \times p \times \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \times V \times \frac{dp}{d\theta} \qquad (4)$$

In equation 4, Q, V and γ represent the total heat release, combustion chamber volume and the specific heat ratio. Whereas p represents the instantaneous cylinder pressure at each crank angle and is obtained from the experimental cylinder pressure data gathered during this work using a piezoelectric transducer. The experimental location of maximum heat release is then deduced to be the time in milliseconds (ms) corresponding to the crank angle at which dQ/dθ peaks. This experimentally obtained value was then compared to the quefrency value of the right sideband of each cepstral peak representing the TDC time period of the same experimental cycle for the specified operating conditions. All quefrency information extracted using this method are from the crankshaft instantaneous speed cepstrum plots only. An illustration of the comparison results for different operating conditions can be found in figures 10, 11, 12 and 13. It can be seen that for all the first 5 five cycles at all the operating conditions shown, the location of maximum heat release extracted from the cepstrum plot of the crankshaft instantaneous speed signal matches the maximum heat release location obtained experimentally very closely.

This finding demonstrates the suitability of cepstrum analysis in extracting combustion features of heat release from the crankshaft instantaneous speed signal as opposed to the direct method using measured cylinder pressure data. Therefore, this systematic methodology using cepstrum provides a cost-effective strategy for obtaining the maximum heat release location given the high cost associated with using cylinder pressure piezoelectric transducers for research or commercial purposes.

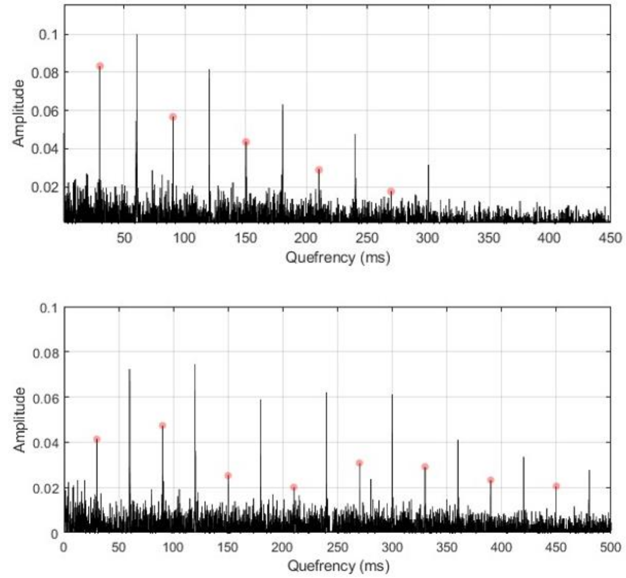

Figure 8: A comparison between the crankshaft instantaneous speed cepstrum plot at 2000 RPM and 40 Nm of 15 consecutive cycles (Top plot) and 30 consecutive cycles (Bottom graph) showing more cepstral peaks (Dotted in red) with a quefrency matching the TDC time period for the 30 consecutive cycles case

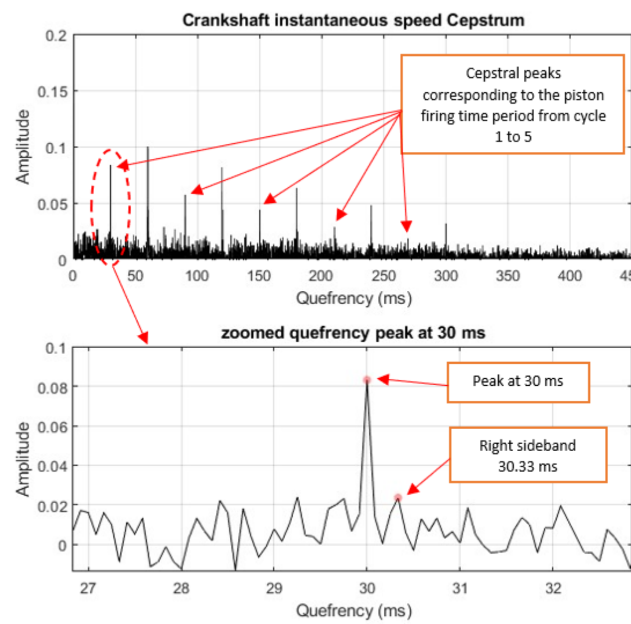

Figure 9: Crankshaft speed signal cepstrum plot (Top) for the 2000 RPM and 40 Nm operating conditions with a zoomed plot (Bottom) of the first cepstral peak at 30 ms

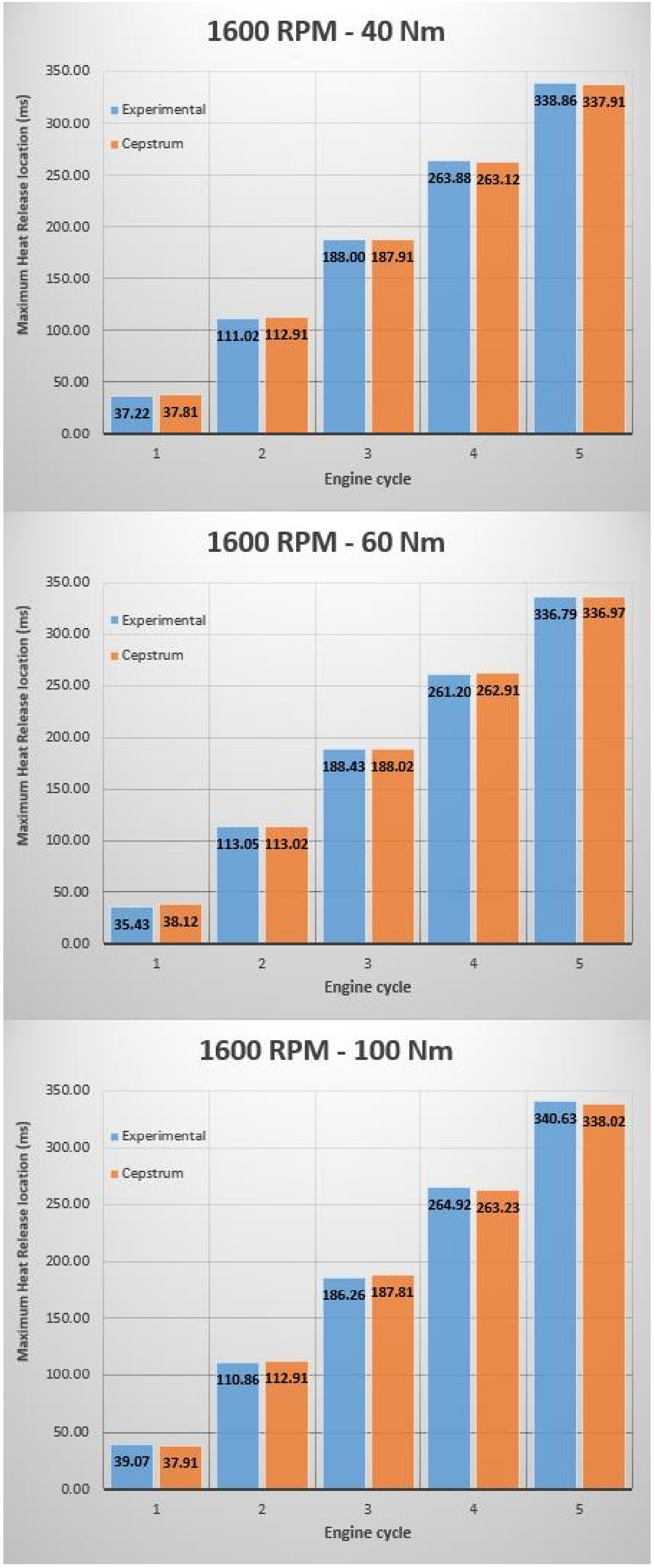

Figure 10: A comparison between the experimental and cepstrum extracted location of the maximum heat release for the first 5 engine cycles at 1600 RPM for 3 loading conditions 40 Nm, 60 Nm and 100 Nm

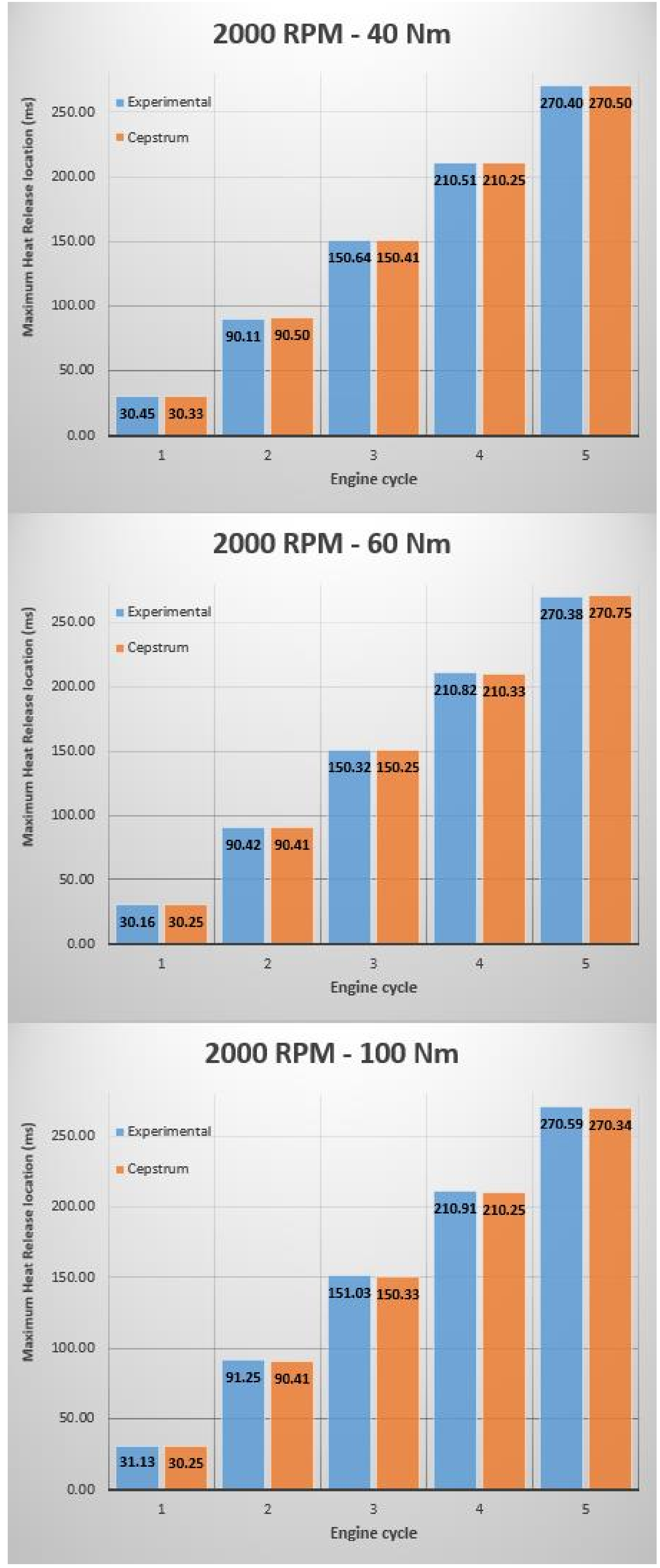

Figure 11: A comparison between the experimental and cepstrum extracted location of the maximum heat release for the first 5 engine cycles at 2000 RPM for 3 loading conditions 40 Nm, 60 Nm and 100 Nm

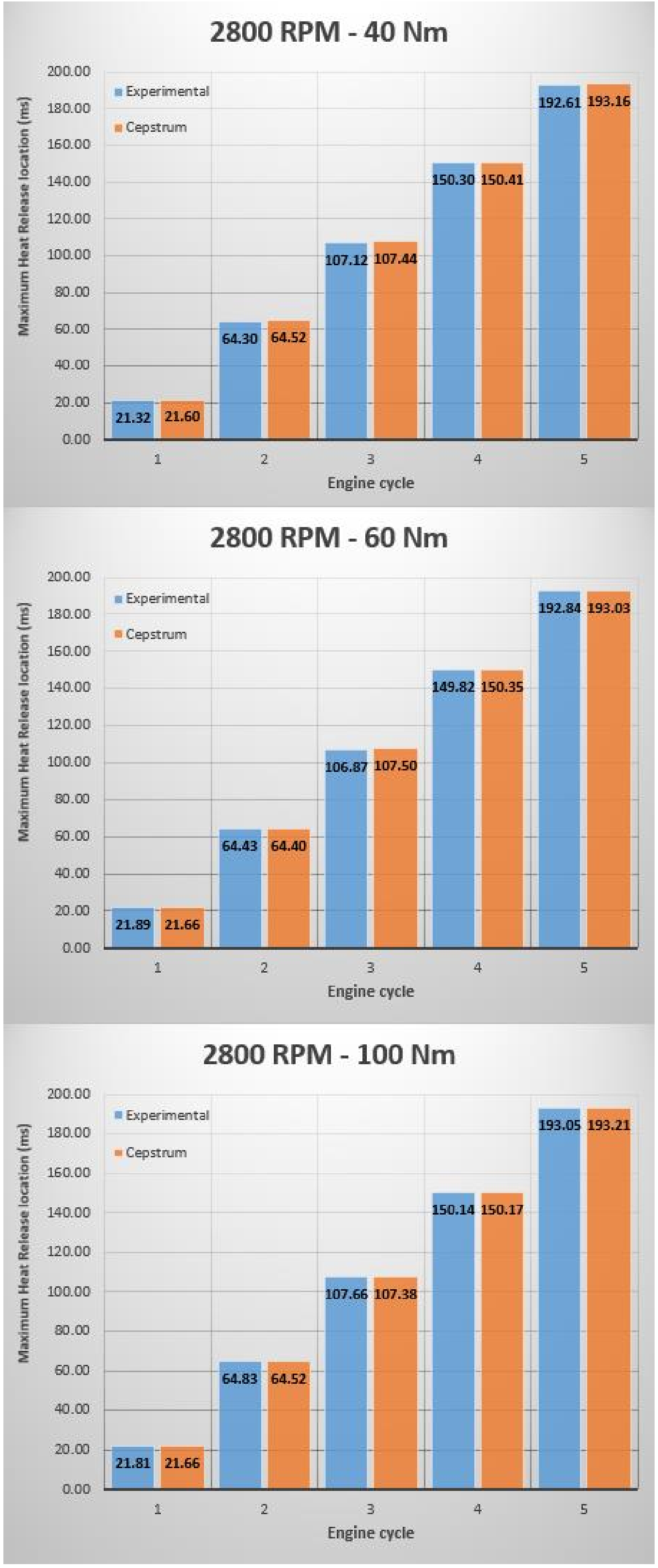

Figure 12: A comparison between the experimental and cepstrum extracted location of the maximum heat release for the first 5 engine cycles at 2800 RPM for 3 loading conditions 40 Nm, 60 Nm and 100 Nm

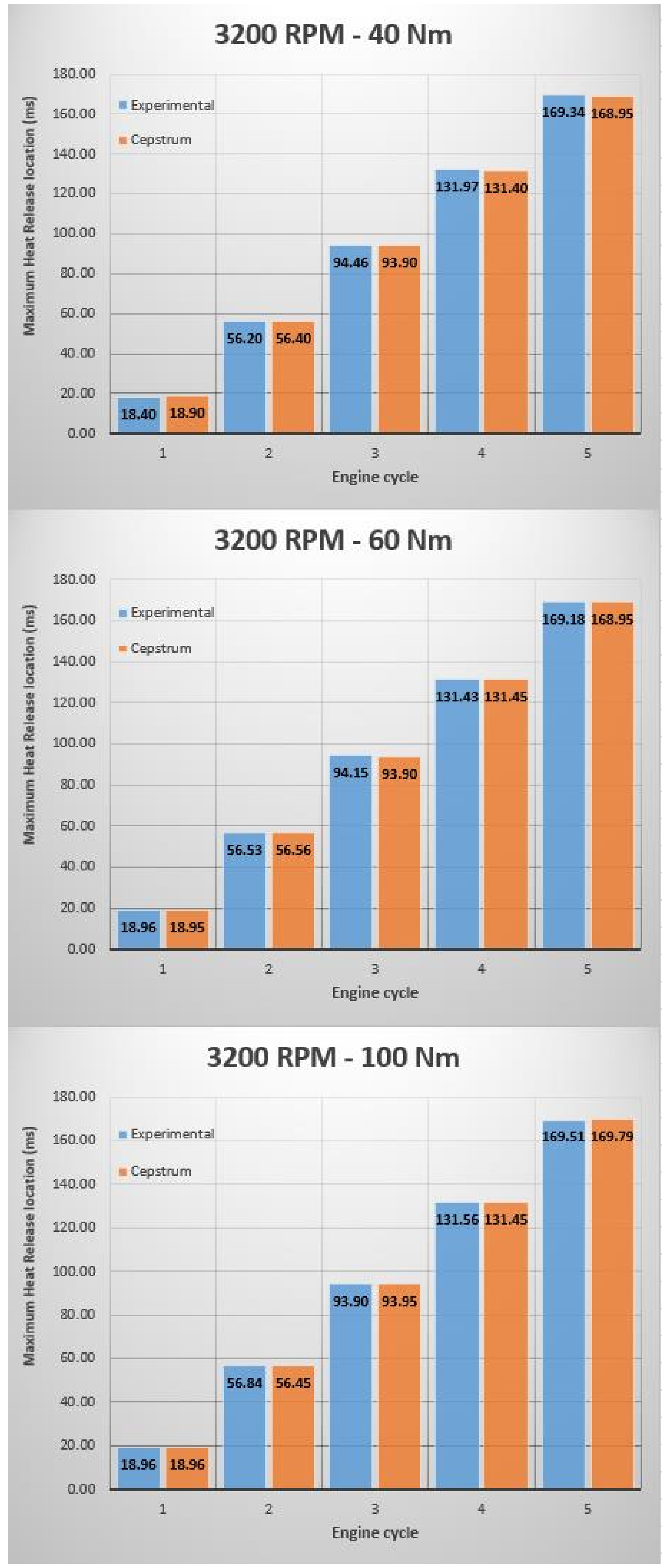

Figure 13: A comparison between the experimental and cepstrum extracted location of the maximum heat release for the first 5 engine cycles at 3200 RPM for 3 loading conditions 40 Nm, 60 Nm and 100 Nm

Conclusions

Cepstrum analysis can be employed to obtain combustion features from a crankshaft instantaneous speed signal. The features extracted using cepstrum analysis can be used for cylinder pressure reconstruction and other engine control applications.

One of the main findings of this work is the extraction of maximum heat release location from the crankshaft instantaneous speed signal using cepstrum analysis. Therefore, the crankshaft instantaneous speed signal with cepstrum analysis can be a cost-effective way of extracting in-cylinder combustion features for deriving heat release characteristics without the need of using cylinder pressure sensors for direct measurements.

References

1. El Yacoubi, I. and Samuel, S., "Frequency Coupling Analysis in Spark Ignition Engine Using Bispectral Method and Ensemble Empirical Mode Decomposition," SAE Technical Paper 2022-01-0481, 2022, doi:10.4271/2022-01-0481.

2. Heywood, J., *Internal Combustion Engine Fundamentals*, 1st ed. (New York [etc.]: McGraw-Hill, 1988), 1-10, ISBN: 0-07-028637-X.

3. Rassweiler, G. and Withrow, L., "Motion Pictures of Engine Flames Correlated with Pressure Cards," SAE Technical Paper 380139, 1938, doi:10.4271/380139.

4. Ghojel, J., "Review of the development and applications of the Wiebe function: A tribute to the contribution of Ivan Wiebe to engine research," *International Journal of Engine Research* 11(4): 297-312, 2010, doi:10.1243/14680874JER06510

5. Sellnau, M., Matekunas, F., Battiston, P., Chang, C., et al., "Cylinder-Pressure-Based Engine Control Using Pressure-Ratio-Management and Low-Cost Non-Intrusive Cylinder Pressure Sensors," SAE Technical Paper 2000-01-0932, 2000, doi: 10.4271/ 2000-01-0932.

6. Worret, R., Bernhardt, S., Schwarz, F., and Spicher, U., "Application of Different Cylinder Pressure Based Knock Detection Methods in Spark Ignition Engines," SAE Technical Paper 2002-01-1668, 2002, doi:10.4271/2002-01-1668.

7. Hsu, B., "Heat Release, Cycle Efficiency and Maximum Cylinder Pressure in Diesel Engine—The Use of an Extended Air Cycle Analysis," SAE Technical Paper 841054, 1984, doi:10.4271/841054.

8. Cesario, N., Tagliatatela, F., and Lavorgna, M., "Methodology for Misfire and Partial Burning Diagnosis in SI Engines," *IFAC Proc.* 39 (16): 1024-1028, 2006, doi: 10.3182/20060912-3- DE-2911.00176.

9. Jorques Moreno, C., Stenlåås, O., and Tunestål, P., "In-Cycle Closed-Loop Combustion Control with Pilot-Main Injections for Maximum Indicated Efficiency," *IFAC-PapersOnLine* 51(31): 92-98, 2018, doi:10.1016/j.ifacol.2018.10.018.

10. Horner, T., "Knock Detection Using Spectral Analysis Techniques on a Texas Instruments TMS320 DSP," SAE Technical Paper 960614, 1996, doi: 10.4271/960614.

11. Kirsten, M., Pirker, G., Redtenbacher, C., Wimmer, A. et al., "Advanced Knock Detection for Diesel/Natural Gas Engine Operation," SAE Int. J. Engines 9(3): 1571-1583, 2016, doi: 10.4271/2016-01-0785.

12. Wang, J., Yang, F., and Ouyang, M., "Cylinder by cylinder indicated torque and combustion feature estimation based on engine instantaneous speed and one cylinder pressure through error similarity analysis," SAE Technical Paper 2015-01-1249, 2015, doi:10.4271/2015-01-1249.

13. Rizzoni, G., "Diagnosis of individual Cylinder Misfires by Signature Analysis of Crankshaft Speed Fluctuations," SAE Technical Paper 890884, 1989, doi: 10.4271/890884.

14. Lida, K., Akishino, K., and Kido, K., "IMEP Estimation from Instantaneous Crankshaft Torque Variation," SAE Technical Paper 900617, 1990, doi:10.4271/900617.

15. Taraza, D., "Accuracy Limits of IMEP Determination from Crankshaft Speed Measurements," SAE Technical Paper 2002-01-0331, 2002, doi:10.4271/2002-01-0331.

16. Taglialatela, F., Lavorgna, M., Mancaruso, E., and Vaglieco, B., "Determination of combustion parameters using engine crankshaft speed," *Mechanical Systems and Signal Processing* 38 no. 2 (2013): 628–633, doi: 10.1016/j.ymssp.2012.12.009.

17. Ali, S., and Saraswati, S., "Cycle-by-cycle estimation of cylinder pressure and indicated torque waveform using crankshaft speed fluctuations," *Transactions of the Institute of Measurement and Control* 37(6): 813-825, 2015, doi: 10.1177/0142331214549093.

18. Seuling, S., Hamedovic, H., Fischer, W., and Schuerg, F., "Model Based Engine Speed Evaluation for Single-Cylinder Engine Control," SAE Technical Paper 2012-32-0044, 2012, doi:10.4271/2012-32-0044.

19. Citron, S., O'Higgins, J., and Chen, L., "Cylinder by Cylinder Engine Pressure and Pressure Torque Waveform Determination Utilizing Speed Fluctuations," SAE Technical Paper 890486, 1989, doi: 10.4271/890486.

20. Randall, R., "A history of cepstrum analysis and its application to mechanical problems," *Mechanical Systems and Signal Processing* 97(2017): 3-19, 2017, doi: 10.1016/j.ymssp.2016.12.026.

21. Noll, A., "Cepstrum pitch determination," *The journal of the acoustical society of America* 41(2): 293-309, 1967, doi: 10.1121/1.1910339.

22. Oppenheim, A.V. and Schafer, R.W., "From frequency to quefrency: A history of the cepstrum," *Signal Processing Magazine, IEEE* 21(5):95-106, 2004, doi: 10.1109/MSP.2004.1328092.

23. Bogert B.P., Healy M.J.R. and Tukey, J.W., "The Quefrency Analysis of Time series for Echoes: Cepstrum, Pseudo-

Autocovariance, Cross-Cepstrum, and Saphe Cracking," *Proc. Symp. Time Series Analysis*, M. Rosenblatt (Ed.) 209-243, 1963.

24. Stojanovic, S., Tebbs, A., Samuel, S., and Durodola, J., "Cepstrum Analysis of a Rate Tube Injection Measurement Device," SAE Technical Paper 2016-01-2196, 2016, doi:10.4271/2016-01-2196.

25. Morsy, M., and Achtenova, G., "Vehicle Gearbox Fault Diagnosis Based On Cepstrum Analysis," *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering* 8(9): 1533-1539, 2014, doi: 10.5281/zenodo.1095903.

26. Zhang, X., Zhou, R., and Zhang, W., "Improved local cepstrum and its applications for gearbox and rolling bearing fault detection," *Measurement Science and Technology* 30(7): 075-007, 2019, doi: 10.1088/1361-6501/ab1235.

27. Benkedjouh, T., Chettibi, T., Saadouni, Y., and Afroun, M., "Gearbox fault diagnosis based on mel-frequency cepstral coefficients and support vector machine," *In IFIP International Conference on Computational Intelligence and Its Applications* 220-231, 2018, doi: 10.1007/978-3-319-89743-1_20.

28. Li, H., and Ai, S., "Application of order bi-cepstrum to gearbox fault detection," presented at 7th World Congress on Intelligent Control and Automation 2008, Chongqing, 25-27 June, 2008.

29. Zhivomirov, H., "Cepstral Analysis with Matlab Implementation," http://uk.mathworks.com/matlabcentral/fileexchange/44632cepstralAnalysis-matlab-implementation accessed June. 2022.

30. Childers, D.G., Skinner, D.P., and Kemerait, R.C., "The cepstrum: A guide to processing," Proceedings IEEE 65(10):1428-1443, 1977, doi:10.1109/PROC.1977.10747.

31. Cerna, M., and Harvey, A., "The fundamentals of FFT-based signal analysis and measurement," National Instruments: 1-20, Jul. 2000.

Definitions/Abbreviations

IC – Internal Combustion

ECU – Engine Control Unit

IMEP – Indicated Mean Effective Pressure

CA – Crank Angle

TDC – Top Dead Centre

FFT – Fast Fourier Transform

RPM – Revolution per minute

Nm – Newton meter

ms – milliseconds