Monitoring of Diesel Engines using Acoustic Emission (AE) and Canonical Correlation

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Abstract. The high temporal resolution of AE offers great promise in the on-line monitoring of complex machines such as diesel engines. One difficulty in realising this potential is the deconvolution of disturbances arriving at a sensor from multiple sources, each of which has a distinct temporal structure (i.e. not an impulse) and a distinct location in the engine. Current methods exploit the propagation aspect of AE and use multiple sensors to locate sources in time and space, but these can be awkward to implement in a way that could be applied automatically in an embedded system.

This work seeks to implement the temporal and spatial location of AE using a specially adapted thresholding technique followed by canonical correlation between three sensors. A set of experiments was performed on a 76 kW four cylinder, medium HSDI Perkins diesel engine running at a range of speeds using three Acoustic Emission (AE) sensors whose relative arrival times for various simulated source positions were carefully pre-calibrated. Applying the thresholding technique, followed by canonical correlation allows the separate identification of parts of the AE signal in the complex area where sources involved in injection, inlet valve opening and combustion are operating.

Introduction

A number of authors have commented on the capacity of AE to provide detailed temporal and spatial monitoring information for a variety of phenomena, including those relevant to machinery. A good example of such an application is in diesel engines, where multiple sources (injection, firing, valve opening in each cylinder) occur in a succession which is strongly dictated by the (known) engine cycle [1]. It has been shown that, even in quite small engines, a small array of sensors can be used to reconstruct the time series at a particular location (e.g. an exhaust valve on a given cylinder) and that each such "spatially located time series" can be used for monitoring purposes [2].

Such an approach, however, depends on a shaft encoder, which allows for in-cycle and between-cycle variations in engine speed to be taken into account as this can be important when attempting source location over the short distances involved in engines [3]. Even then, the resolution and response time of most encoders are on the limits of what is required to separate the closest signals (temporally and/or spatially), for example those occurring at TDC in a small engine.

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This paper explores a new AE signal processing approach, canonical correlation analysis (CCA), traditionally used in learning applications, particularly image recognition [4]. Canonical correlation analysis (CCA) finds the optimum linear relationship between two multidimensional variables, and can be seen as an extension of Principal Component Analysis, where principal components are first identified from a data set and CCA is a kind of cross-correlations between the PCs of two (or more) data sets [5]. Here we apply the method to the problem of separate source identification over an approximately 20-degree crank angle window around TDC for a small HSDI engine using the time- (or crank angle-) series recorded at pairs of sensors. There is some controversy around the precise nature of the sources in this window [6, 7], but potential candidates include the mechanical parts of the injector, the flow thought the injector nozzle, waves in the injector lines associated with rapid valve openings and closings and, of course, the firing process itself.

Experimental method

The approach is applied to a Perkins T1004, 76 kW, 4 litre, four-stroke, four cylinder, turbocharged, high speed direct injection (HSDI) diesel engine which utilises a Bosch VE diesel injection pump and four multi-hole, long stem, single spring Lucas injectors. Three broadband Physical Acoustics Corporation (PAC) Micro-80D AE sensors were used with operating frequency range of 0.1-1MHz, resonant at 325 kHz and 650 kHz. Each sensor was connected to a PAC-1120A preamplifier which included a band pass filter over the range of 0.1-1 MHz. Data were acquired by using a 12-Bit, 10 MS/s/ch, simultaneous sampling multifunction DAQ card (NI PCI-6115). An Omron, 360 pulse per revolution shaft encoder was coupled to the fuel injection pump in order to record its angular position synchronously with the AE.

The test data were generated by running the engine with the sensor array shown in Figure 1 installed; AE Sensor 1 on the protruding body of Injector 1, and AE Sensors 2 and 3 on similar flat areas on the cylinder head adjacent to Cylinders 1 and 3, respectively. The engine was run with no load at five different throttle positions of the injection pump associated with five camshaft speed ranges around 420, 530, 735, 995 and 1130 rpm. At each speed range, five records were captured at a sampling rate of 2.5 MHz for one second, corresponding to between seven and nineteen cycles depending on the engine speed. Sensor AES1 used 8dB total signal gain while both AES2 and AES3 required a total signal gain of 14dB.

Results and analysis

Figure 2 shows typical raw AE records, re-sampled into the angle domain. Although the method can be demonstrated amply without re-sampling, the behaviour of the correlation is clearer in this domain since it removes in-cycle and between cycle variations in speed and so links clearly the mechanical events with the AE generated.

Figure 2(a) demonstrates clearly one aspect of the interpretation problem, which is that the cylinder TDC "signatures are relatively (but not perfectly) reproducible from cycle to cycle and also that these signatures look very different in overall amplitude and in detailed structure when viewed from different sensor positions. By the same token, seen more clearly in Figure 2(b), the nominally identical signatures for each cylinder differ greatly in both magnitude and in detail when viewed from a given sensor position. Figure 2(b) also shows the individual engine events which may generate AE at or around the cylinder head and it is clear that there could be contributions from more than the cylinder which is at TDC. Thus, the signal interpretation is a complex issue, even in a confined part of the time- (or angle-) series, requiring knowledge of the signal attenuations form a range

of possible source positions to a range of possible sensors positions as well as careful calibration of sensors [8].
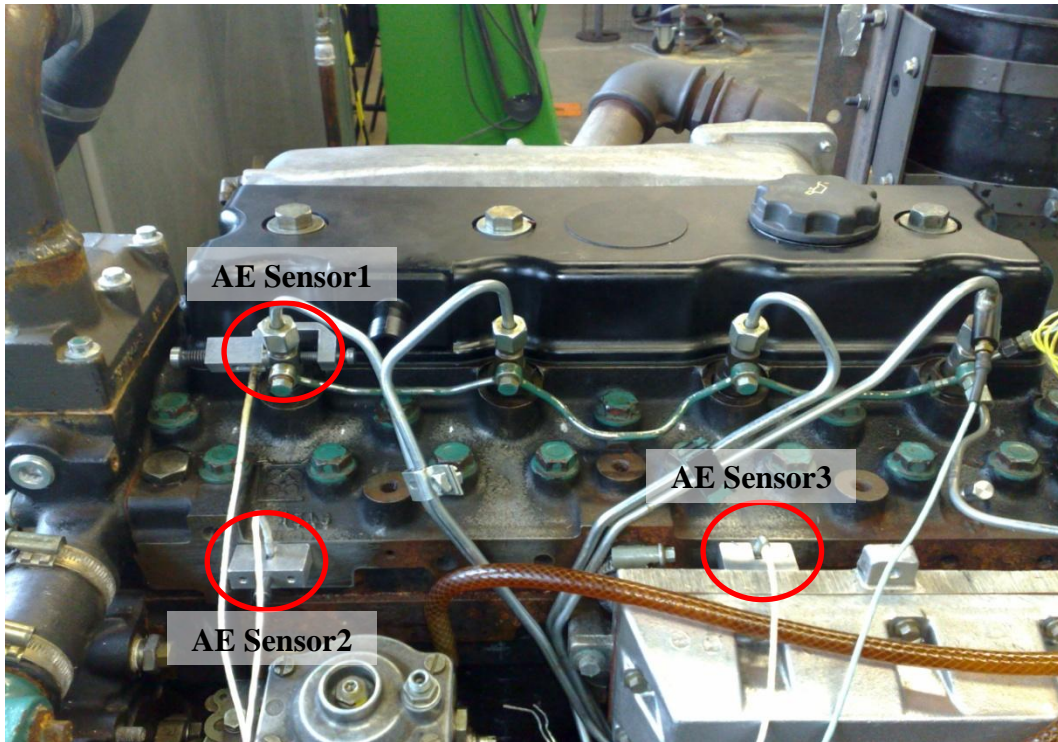
Figure 1: Sensor array set up for Perkins T1004 diesel engine.

**(a)**   **(b)**
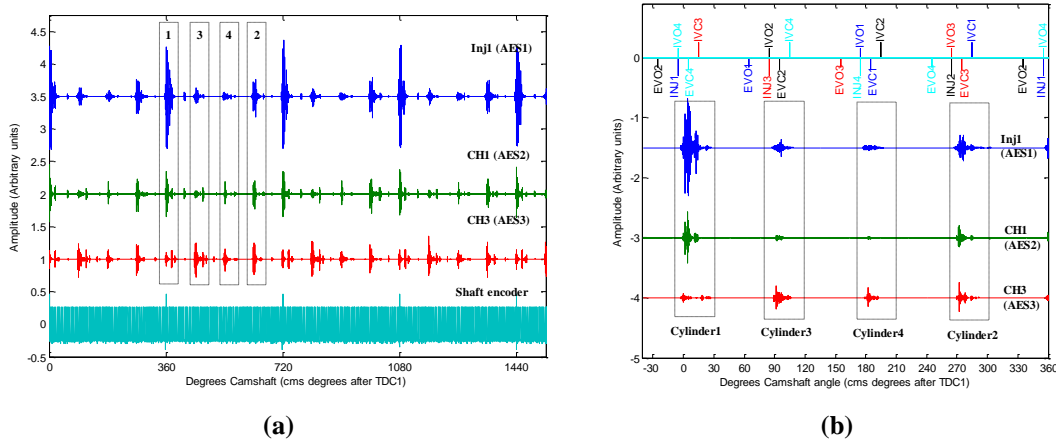
Figure 2: Re-sampled raw AE in the angular domain recorded at the three sensor locations (a) four complete engine cycles at a camshaft speed of 997 rpm and (b) for one complete engine cycle at a camshaft speed of 736 rpm.

As mentioned above, canonical correlation analysis (CCA) finds the best linear relationship between two multidimensional variables. Here, a proprietary algorithm was used to correlate across pairs of the sensor positions, and a search carried out to find the angular separation between the angle-series or parts of them. The operation of the algorithm can be demonstrated most easily between sensors CH1 and CH3, because they are relatively distant from each other, with a consequent expected time separation for the same

event and because they are on a similar type of position to each other (on the flat face of the cylinder block) so that propagation paths are similar, although of different lengths [8].

Figure 3 shows the two angle series for a particular cycle for the window from -10° to +35° around TDC of cylinder 1, Figure 3(a), along with the best correlation coefficient between the series as a function of angle shift, Figure 3(b). As can be seen, the best correlation is obtained for an angle shift of about -4.5°, but there are subsidiary peaks at around -2°, +0.1° and 14°. Other cycles show a similar pattern, but there is some variation between which of the first three peaks is the highest, although the 14° peak is always present and is always the smallest. It might also be noted that even the best correlation coefficients are only about 0.45. Figures 3(c) and 3(d), show the angle series overlaid on each other and the ambiguity in matching the two series becomes obvious, due to the relative movement of peaks between the series, and the fact that the series are of different lengths in the crank angle domain.

(a)

(b)

(c)

(d)
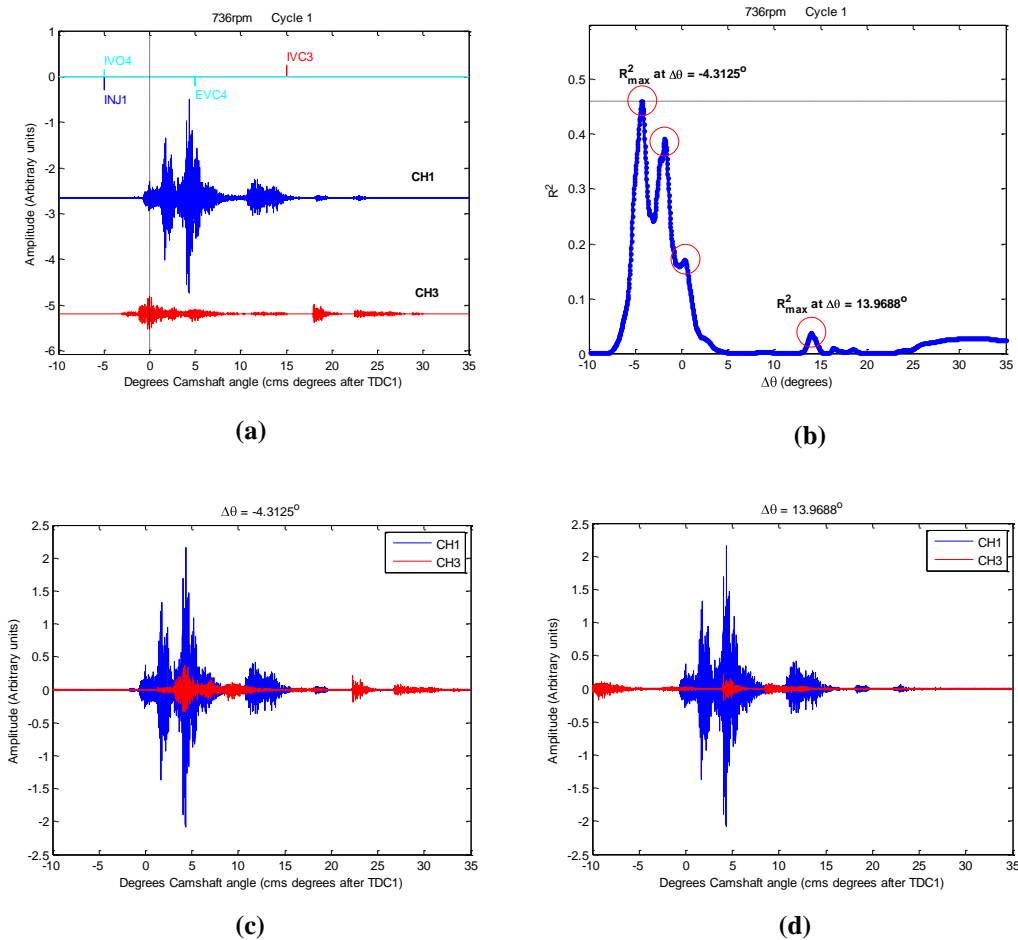
Figure 3: Canonical correlation for angle difference for single sample of TDC1; (a) angle-series recorded at CH1 and CH3 (b) correlation coefficient for various angle shifts, (c) and (d) overlays for largest and smallest peaks.

Figure 4 shows the approach applied more generally across the data, compared with a more conventional energy analysis.
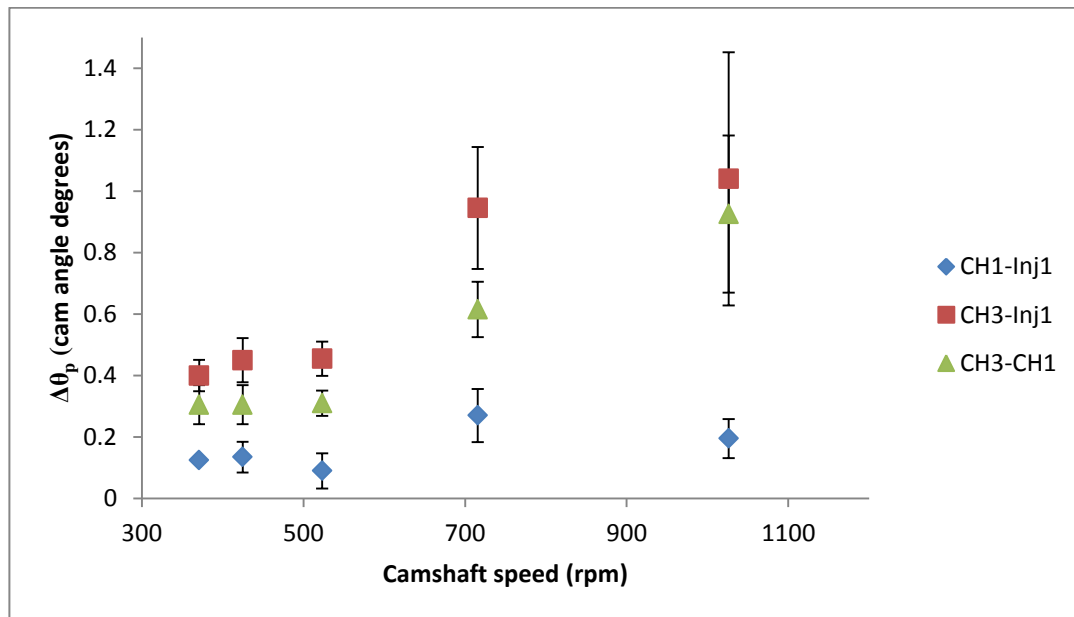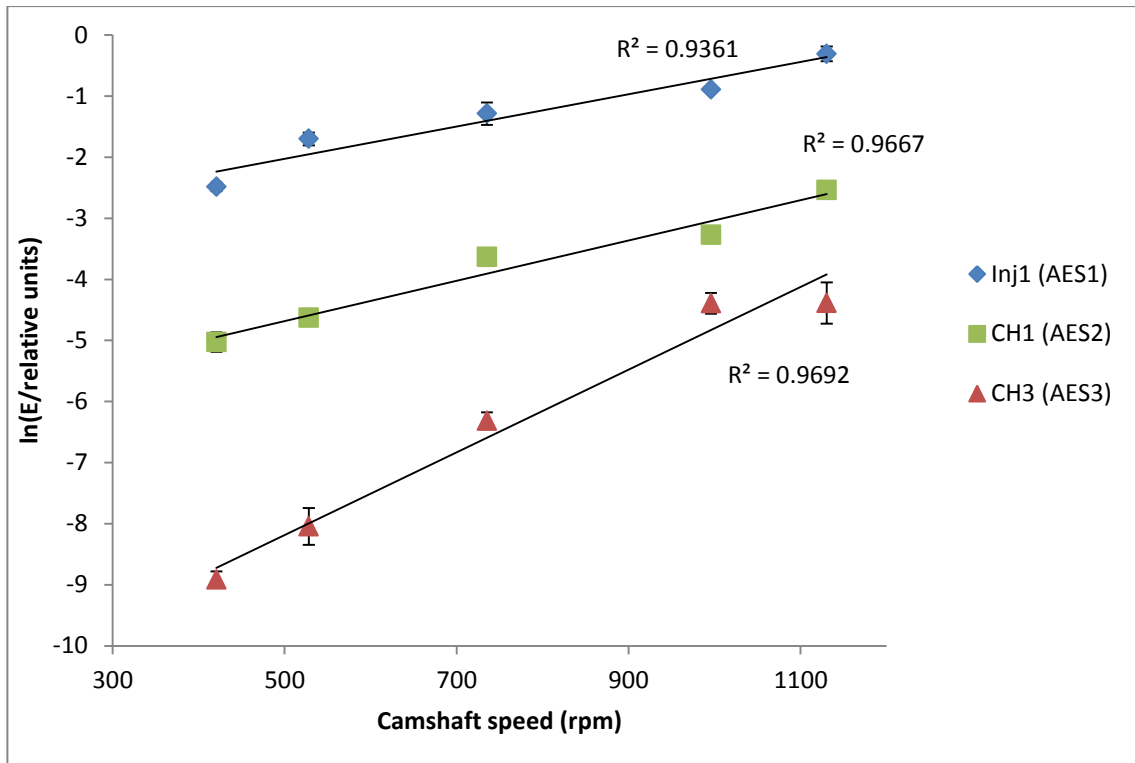
Figure 4: Canonical correlation compared with energy analysis across the range of camshaft speed investigated.

It can be seen from Figure 5 that the angle shift for the sensor mounted at CH3 is significantly greater than that between the two sensors mounted at cylinder 1, confirming that much of the source is nearer these latter two sensors. More interesting still is that the

angular shift cylinder 3 and cylinder 1 increases with engine speed, which cannot be accounted for by injection or ignition advance. It therefore seems likely that different parts of the TDC1 window come from different sources whose energies vary relatively with engine speed. In order to assess this, the TDC1 window was divided (somewhat subjectively) into three sub-windows as illustrated in Figure 5.
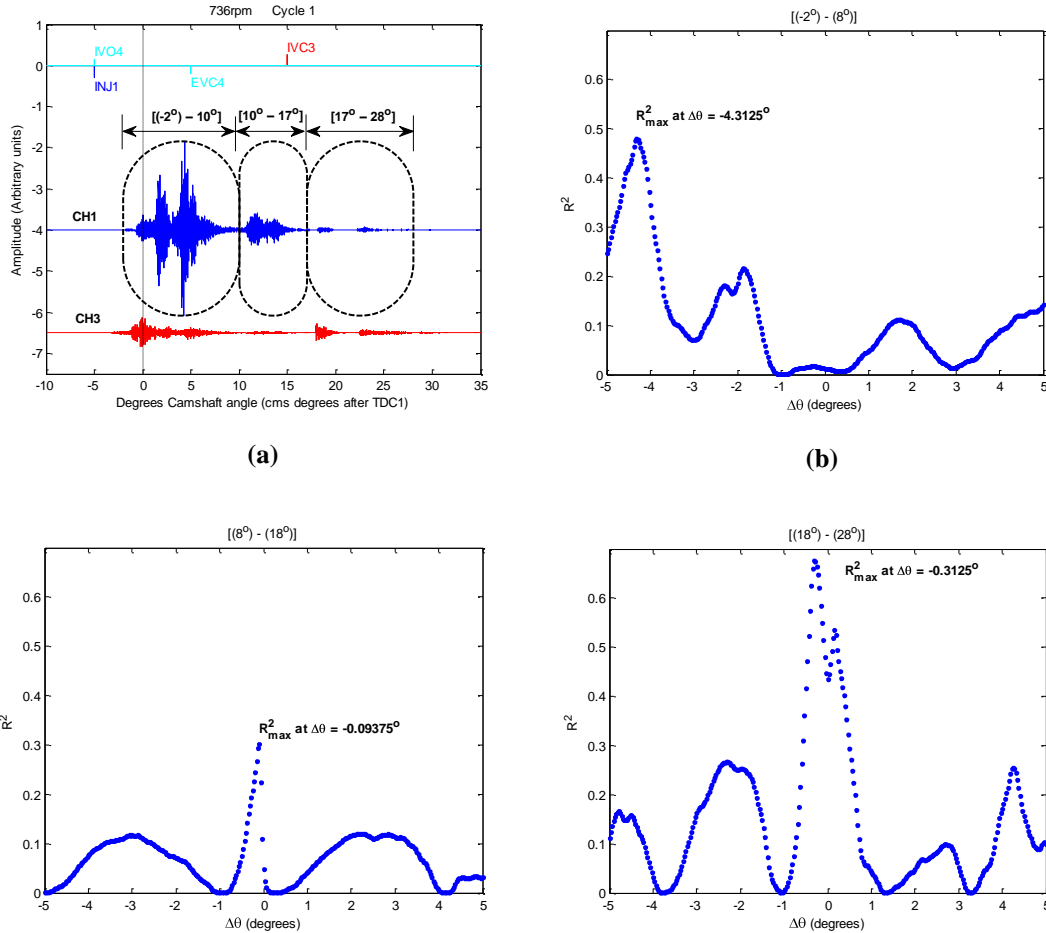
Figure 5: Canonical correlation for angle difference for single sample of TDC1 analysed in Figure 3, this time segmented into three windows. (a) angle-series recorded at CH1 and CH3 (b), (c) and (d) correlation coefficients for Windows 1, 2 and 3, respectively.

As can be seen from Figure 5, each of the sub-windows has a markedly different angle shift at which the correlation coefficient is maximum, and also the values of the correlation coefficient at maximum are, in general, higher than they are in Figure 3. Figure 6 shows the same detailed analysis for a second cycle and comparing this with Figure 5 reveals some interesting features about the detailed signals. Firstly, and not surprisingly, the maximum correlation coefficient for Window 1 is enhanced for the split signal, although there is still an ambiguity over which angle gives the best fit. This may be due to inconsistencies in the signal, or, perhaps, due to the window containing more than one source. Window 2 contains a very low signal at CH3 and the results cannot be relied upon; for example the $+0.4°$ shift in Figure 6 is obviously a correlation between Window 2 at CH1 and Window 3 at CH3. Finally, there is a remarkable similarity in the angle difference and magnitude of the maximum correlation coefficient for Window 3 in both cycles, this showing a slight lag at CH3. However, the amplitude of the CH3 signal is higher than that at CH1 (unlike for the other two windows), suggesting that the source is nearer to CH3, which would give a positive angle difference. Since the distance between the two bursts in

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Window 3 seems to be different at the two sensor positions, perhaps this window could also be split. It certainly seems, by inspection, that the first burst in Window 3 at CH3 is in advance of that at CH1 which might indicate that it, at least, is due to a pressure wave in the fuel line associated with the IVC3 event in the engine map.
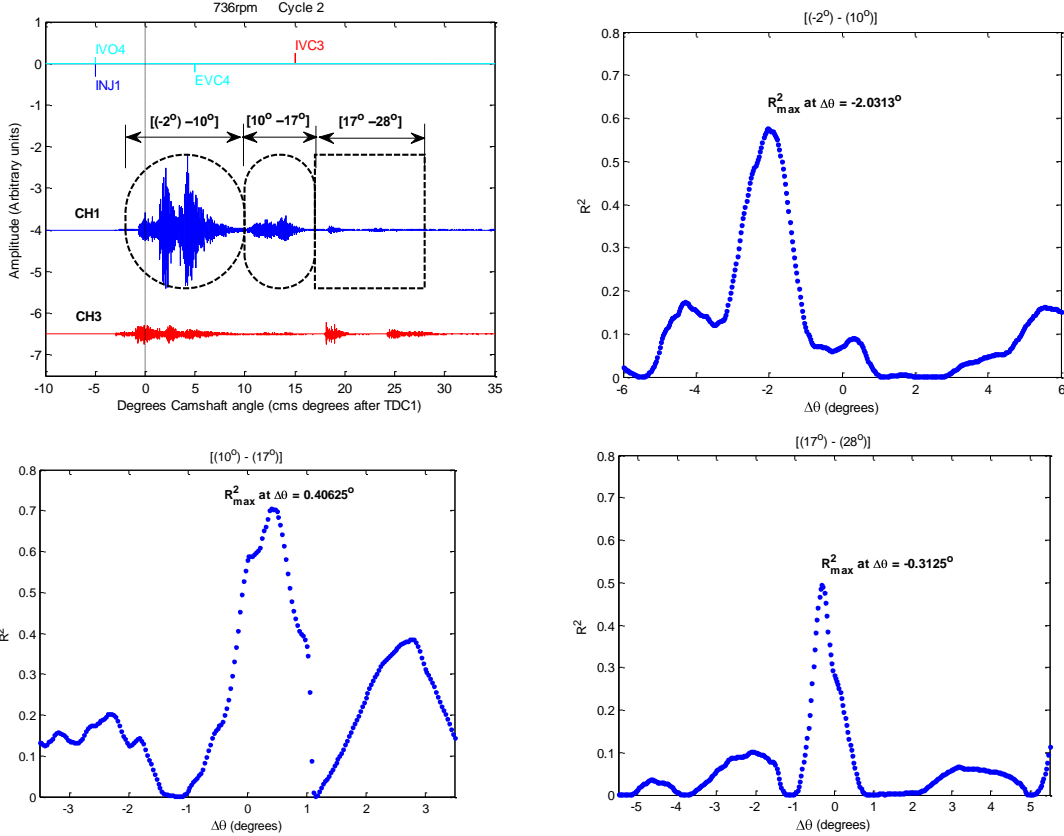
Figure 6: Canonical correlation for angle difference for an alternative sample of TDC1 segmented into three windows. (a) angle-series recorded at CH1 and CH3 (b), (c) and (d) correlation coefficients for Windows 1, 2 and 3, respectively.

Conclusions

A new method of processing multi-source, multi-sensor AE data is demonstrated on some records from three sensors mounted on the cylinder head of an HSDI engine. The study shows that canonical correlation has the capacity to add to more conventional time-based analysis, allowing time (or angle) differences between different parts of a signal recorded at two sensors to be identified.

The ability to have a dynamic measure of phase as well as energy adds considerably to the potential for automated source location in machinery and moves closer to spatial location of time-series in mechanically-regulated AE records.

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