Chapter 6

EXTRACTION OF LINEAR PREDICTIVE, SPECTRAL AND STATISTICAL PARAMETERS OF AE SIGNAL

6.1 INTRODUCTION

The advantage of AEDAPS over conventional instrumentation is that it provides the flexibility of converting the instrument as a parameter extractor for user specified set of parameters. In this section we explore this feature of AEDAPS by considering three separate streams of parameters -viz.- linear predictive, spectral and statistical analysis of the signal. The emphasis is on the instrument capability and implementation aspects. Detailed study with artificially generated defects under a controlled environment could determine the physical significance of these new set of parameters proposed.

6.2 ON-LINE EXTRACTION OF LP COEFFICIENTS USING AEDAPS

In linear prediction the observed signal is modeled as the output of an excitation signal passing through an all-pole filter, whose coefficients represents the system through which the excitation signal is passing through [Markel & Gray 1976]. This technique is widely used in speech analysis, where it can be shown that the coefficients computed at sufficiently small intervals can effectively represent the signal and hence can be used for speech coding, synthesis and recognition [Paliwal 1993].

Unlike the case of speech signals where the signal production mechanism justifies the usage of the technique, the applicability of LP to the Acoustic Emission case doesn’t have a strong theoretical basis. However, in order to determine the behavior of the analysis scheme to the signals actually acquired, we have applied the scheme to the AE signal, with the sensor resonant frequency taken as the excitation signal and the system gain set to equalize the energy of the observed and predicted signal within the interval of prediction. The results are summarized below:

- Fairly low LP order is sufficient to give good LP fit.
- For an LP order of 6, the error energy is less than 40 dB than the signal energy, indicating that the scheme is a good coder for the AE signal.

At first sight, the above conclusions might look very promising. However one should bear in mind that choice of the resonant frequency as the excitation signal and enforcing the condition that the energy of observed and predicted signals are equal in each interval of prediction is the major factor responsible for the match. This is illustrated in Fig 6.1 that gives the result of applying linear prediction on the theoretical model of the AE signal given by equation (2.12). The graph in red is the modeled curve. Graph in blue is the excitation signal amplified within each interval of estimation to equalize the observed and predicted energy. Graph in magenta is the LP signal with 6 coefficients.

It is observed that increasing the LP order to 10 will equalize the LP signal with the excitation signal. However, the observed deviation from the modeled AE signal persists. This can be reduced only by increasing the number of intervals of prediction. This indicates that the observed closeness of the original and LP predicted signal has more to do with the energy equalization scheme than to linear prediction. This aspect is further amplified in section 6.5.
where the energy profile parameter set is compared with the theoretical AE parameter set.

The coefficient extraction is repeatedly enabled corresponding to short intervals.

![Fig 6.1(a): Theoretical AE Signal (Red) and The excitation (Blue)](image)

![Fig 6.1(b): Result of LP analysis with above excitation. Green gives LP Signal.](image)

Fig 6.2 gives the result of LP analysis on an AE signal extracted during a pressurization of titanium gas bottle. Note that there is good resemblance with the corresponding results of the theoretical case illustrated in Fig 6.1. Moreover, it was seen that increasing the LP order doesn’t reduce the residual error.

The spectral parameters are of primary importance in investigations related with the energy profile of the AE event in various spectral bands [Oppenheim & Schafer 1989]. This can give valuable insight into the nature of the physical processes leading to the observed signal, especially in cases where a broad band sensor is used.

AEDAPS can extract the power spectrum of the AE signal on-line [George Varkey 1998]. Since the AE signal picks up from and dies down into the zero baseline, a weighting function prior to the spectral computation is not really necessary. However, the short duration of the signal puts a serious limitation on the available resolution of the spectrum. This may be overcome by zero padding the signal to the required length prior to the Fourier Transform phase.
The spectral characteristics of the sensor has a dominant role in determining the corresponding characteristics of the acquired signal. Thus, usage of a wide band sensor is essential in serious theoretical studies.

Fig 6.3 gives a typical time domain signal and its power spectrum computed by AEDAPS. The sensor used in this case was a 150 KHz resonant sensor and the effect of the sensor can be predominantly seen on the spectral plot.

Fig 6.3 : Time Domain Signal (Top) and Spectrum (Bottom) of an AE signal from an HPM Structure.

In the actual applications, the low sensitivity of the wide band sensors is not normally acceptable. In order to determine the behavior of the spectral analysis scheme to these signals, we have computed the power spectrum of observed AE signal in actual experiments with such sensors. The results are summarized below:

- As expected, the sensor resonant frequency dominates the spectral characteristics.
- The analysis scheme is effective in some type of materials (for e.g., HPM bottles) and is ineffective in many others. Generally, one can say that, in cases where the observed signals dies down fast, the analysis gives uncorrupted spectral functions. In other cases, the multiple reflections of the same signal circulating around the surface seriously distorts the observed spectrum. This aspect is further illustrated in the practical situations given in section 7.4.

6.4 ON-LINE EXTRACTION OF CORRELATION COEFFICIENTS

The correlation coefficient of an AE signal with itself (auto) and with its adjacent channels (cross) indicates the (self or cross) similarity of the signals being correlated and could be used for many different purposes [Dowdy & Wearden 1991]. For example, the lag with the maximum autocorrelation is indicative of the occurrence of the first reflected signal. Similarly, the lag with maximum cross correlation to an adjacent channel relates to the difference in the arrival time of the same signal at these sensor locations, and along with the event time can be used for determining the flaw location.

AEDAPS can extract the correlation coefficients on-line. The computation for one lag involves the N “multiply and accumulate” operations, where N is the sample size of the shorter signal. The number of lags should be judiciously determined so as not to overshoot, the on-line timing constraints.

If the attenuation of the signal over the medium is low, the conventional duration computation will fail and we will get most of the durations equal to the HDT parameter. This is shown in Fig 6.4 below that gives the plot of the duration parameter in case of a pressurization test of a Titanium Gas Bottle.

The x-axis is the time and the y-axis is the duration of the observed events. Blue color is used for channel 1 and red color for channel 2. From the accumulation of the scatter points towards the top of the curve, we can say that most of the events are saturated in the time plane and was actually terminated by the hardware HDT parameter setting. Examination
of the typical time domain plot of these signals given in Fig 6.5 illustrates this point further.

![Fig 6.4: Scatter diagram of duration parameter of AE signals from a Titanium Bottle Pressurization test.]

In these cases, the maximum lag of the autocorrelation gives a better estimate of the actual event duration.

The lag corresponding to maximum cross correlation can give an estimate of the time differential of the first p-wave arrival of same signal at the sensors. Assuming the velocity of the signal over the medium is \( v \), the distance between the point of emission to the sensors are \( d_1 \) and \( d_2 \), and the event times recorded at the sensors are \( T_1 \) and \( T_2 \), we have the relation:

\[
T_2 - T_1 + \frac{1}{f} = \frac{(d_2 - d_1)}{v}
\]

(6.1) \( T_2 - T_1 + 1/f = (d_2 - d_1)/v \)

Where \( l \) is the lag of maximum cross correlation and \( f \) is the sampling frequency. Since \( v \) and \( f \) are known constants, and \( T_1 \) and \( T_2 \) are provided by the AEDAPS hardware, the differential distance \( (d_2 - d_1) \) can be determined from the maximum lag. The distance differential from a number of sensor pairs can uniquely determine the flaw location [Barsky & Hsu 1985].

If \( N \) is the number of signal elements in the shorter event and \( L \) is the number of lags needed, computation of maximum lag requires:

\[
(6.2) \text{Time}_{\text{lag}} = L * N * \text{MAC}_{\text{time}} + L * \text{COMP}_{\text{time}}
\]

where \( \text{MAC}_{\text{time}} \) is the time needed for a multiply and accumulate operation and \( \text{COMP}_{\text{time}} \) is the time needed for a comparison. If \( f \) is the sampling frequency, the time required for generating \( N \) samples is \( N/f \) and the ratio \( P_1 \) of the processing time to generation time is given by:

\[
(6.3) P_1 = \frac{L * f * \text{MAC}_{\text{time}} + L * f * \text{COMP}_{\text{time}}}{N}
\]

If \( N \) is large, the second term in 6.3 can be ignored. On a 50 MHz TMS320C40, the MAC operation could be completed in one clock while operating from the internal memory of the processor. However, in the case of AEDAPS, external memory access and hence additional cycles is required. Considering the other overheads for computation, \( \text{MAC}_{\text{time}} \) in (6.3) should be taken as 100 ns. If \( R_{\text{active}} \) is the ratio of total time to the Ae active time, the overflow condition (for a single processor) becomes:

\[
(6.4) L > 10^8 R_{\text{active}}/f
\]

(6.4) places a severe restriction on the number of lags that can be computed in any practical situation. Note that the maximum lag needed can be determined by the geometrical consideration of the signal propagation of the structure under test and hence it will be parameter supplied by the source location software. In situations where the limitation put by (6.4) is not acceptable to the number of lags required, the only option is to parallelise the cross correlation computation algorithm. Since each of the lag could be computed in parallel to
other lags, it is fairly straight forward to parallelise the correlation computation. For example, the correlation for the first half of the lags could be computed by one processor and the that of the second half could be computed in parallel by another. Since the computed lags are parameters send by the DAP to the SAPS, the actual comparison and flaw location calculation will be computed by the SAPS system. Fig 6.6 gives the general arrangement.

\[(6.5) \mu_r = \frac{\sum (x_i - \mu)^r}{n}\]

where, \(\mu\) is the signal mean. In the case of AE, \(\mu\) may be taken as zero.

The second moment (rms) is computed by AEDAPS as part of the standard set of parameters. The third moment gives the skewness of the AE event and can be used as an alternate to the conventional \(R_t/D\) (rise-time/duration) parameter. The fourth order moment (Kurtosis) also could potentially be used for defect classification.

Computation of the higher order statistics using AEDAPS is rather straight forward. Since TMS320C40 is a floating point DSP, the issues relating to overflow in the computation of higher order terms doesn’t arise. The number of multiplications can be grouped together, so that the computational load per sample is proportional to \(\sqrt{r}\).

Fig 6.6 : Parallel Arrangement for Computation of Cross Correlation with 4 nodes.

From the intuitive point of view, this set-up indicated in 6.7 could be extremely useful in determination of flaw locations of flaws in pipelines. Detailed study with simulated flaws and environmental noise can bring out the usefulness of the proposed analysis method.

6.5 ON-LINE EXTRACTION OF SKEWNESS AND KURTOSIS

AEDAPS can extract a number of statistical parameters on-line. These include the moments of the signal and the signal median [Miller & Freund 1987].

The \(r^{th}\) order moment \(\mu_r\) of the signal is given by: