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Automatic Selection of a Suitable Coherence Frequency Domain

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Abstract – The improvement of techniques which allow pinpointing of leaks in pipe transportation networks is a priority for companies and authorities around the world. The flow of liquids (water) trough a pipe generates specific auditive (noise) signals. If the pipe has leakage points or other faults, then we face problems of liquid loss. The liquid which comes out of the pipe generates specific leak signals transmitted in the material of the pipe and in the liquid which is inside the pipe. These leak signals contain parasite information coming from other noise sources like pipe elbows or junctions. The signals must be filtered in order to determine the best frequency domain in which they should be analyzed and to remove any unwanted frequencies. The domain of interest must be the one where the signals are most coherent. At the same time, the limits of the filter must be determined in an automatic way in order to ease the work of the person who uses the application. After the domain of interest is found, the Cross Correlation Function (CCF) between the signals can be calculated in order to determine the delay between the two signals. This paper presents a way in which one can establish the frequency domain which is most suitable for analyzing leak signals. We are interested to show that the quality of the CCF grows after the automatic filtering process is used. The programs used in this paper were implemented with the help of Matlab 7.5 functions.

Keywords - leak detection, leak location, coherence, Matlab, automatic filtering, Cross Correlation Function.

I. INTRODUCTION

The flow of water trough a pipe generates specific auditive (noise) signals. If the pipe has leakage points or other faults, then we face problems of liquid loss. These problems must be solved, by locating with precision, the position of the leaks. The position of the leak, must be found with the highest accuracy. When dealing with pipes that are very long (measuring kilometers), the leaks must be located with an error of a few meters (less than 5 meters).

The analysis of data sequences (noise signals from pipe leaks) must be done in that frequency domain in which the signals are most coherent. Because the signals produced by leaks contain information belonging to other noise sources, the process of pinpointing the leak can be complicated. The person who uses a tool for leak location (leak noise correlator) must use the correct filtering settings. By means of filtering, one can remove the frequencies which are of no interest and analyze only the frequencies belonging to the leak.

The pipe material is an important factor when dealing with the frequency domain which is specific for a leak. For metallic pipes (steel, copper), the frequency range which is of interest is up to 5kHz. [1] Leaks in plastic pipes should be studied for frequencies which range up to a few hundred Hz.[2] It is not useful to use these broad frequency ranges, but rather to try and determine which is the best interval in which the signals should be analyzed. Finding the most suitable frequency interval should be an automatic process.

After determining which interval is best for analyzing the signals generated by water leaks, we can proceed with the calculation of the CCF.

II. SIGNALS CHARACTERISTICS

An experimental metallic pipe installation was used for generating the leak signals. The piezoelectric sensors (*MMF-KD13*) were placed on both sides of the leak (at 3m and 1m) on a straight part of the pipe in order to avoid possible perturbations which appear at pipe elbows.

Several pairs of signals were acquired for different water debits trough the leak. It is expected that when dealing with small leaks (small leak debits), the spectral power distribution of the signals should cover higher frequencies. For larger leaks and larger debits, the spectral distribution should cover lower frequencies.

The signals were amplified (*M60T* amplifiers) and then transmitted to a data acquisition board (*NI USB9215A*) for analog to digital conversion. The sampling frequency at which the signals were

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acquired was *Fs =15 kHz*. Each signal file contains 131072 samples. The sampling period is *Ts = 66.6 µs*. Each signal sequence lasts *8.73* seconds.

The following table, shows the recorded pairs of leak signals, for different water debits and their amplification factor.

Signal Pair	Leak Debit [l/min]	Amplification [dB]
1	0,20	60
2	0,25	60
3	0,35	60
4	0,85	60
5	1,06	60
6	2	20
7	2,76	40
8	3,87	20
9	4,27	40
10	5,26	40
11	6,09	20
12	8,27	20

Table 1. Acquired Leak Signal Pairs

The following images show segments (16384 samples) from pairs of such signals for 8.27 l/min and 4.27 l/min leak debit.

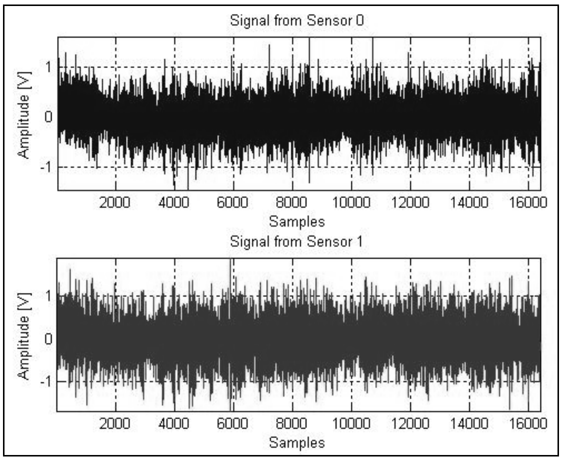

Fig.1. Experimental Leak Signals – 8.27 l/min

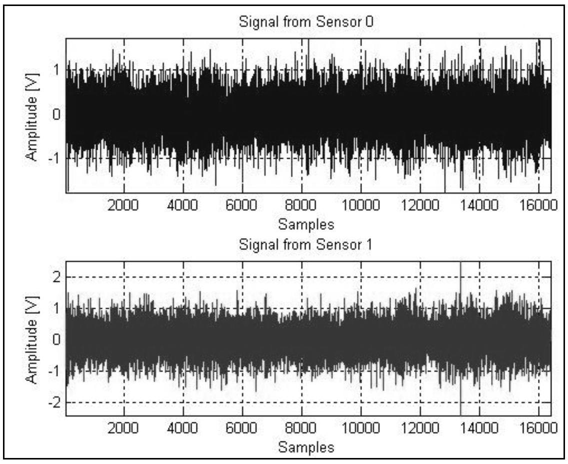

Fig.2. Experimental Leak Signals – 4.27 l/min

When the signals were acquired, the frequencies above 6kHz were removed because this range is sufficient for our purpose and aliasing does not occur. These signals contain low frequency components which are vibrations of the experimental installation. They are called modal vibrations and interfere with the leak detection process. These oscillations can be seen in the signals or in the CCF. They are removed by using a FIR filtering for frequencies lower than 500Hz. By filtering these modal components, the signals become stationary. The stationarity problem of the signals is not the purpose of this paper, however this is the reason for removing all the frequencies up to 500Hz.

The linear power spectral density (PSD) of the signals contains frequencies in the range 500Hz – 6kHz and was calculated by using the Welch method (the Periodogram method) implemented in Matlab with the *pwelch* function[8].

The CCF between these signals tells the difference in the arrival times for the two signals. The leak noise reaches the closest sensor first. The highest peak of the CCF is of interest. The fact that it is to the right or to the left of the central point of the CCF indicates which signal is closest to the sensors. We are interested in the quality with which the maximum peak stands out in the CCF.

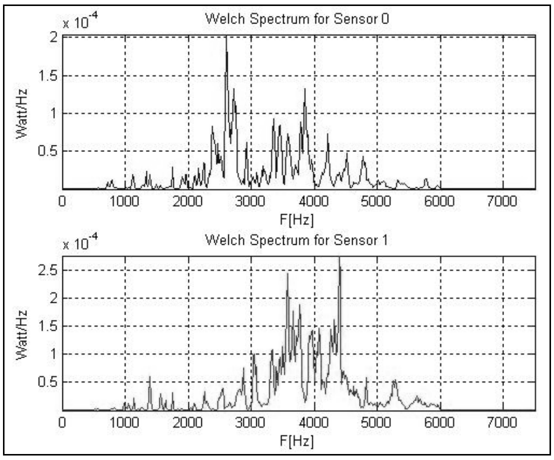

Fig.3. Experimental Leak Signals PSD – 8.27 l/min

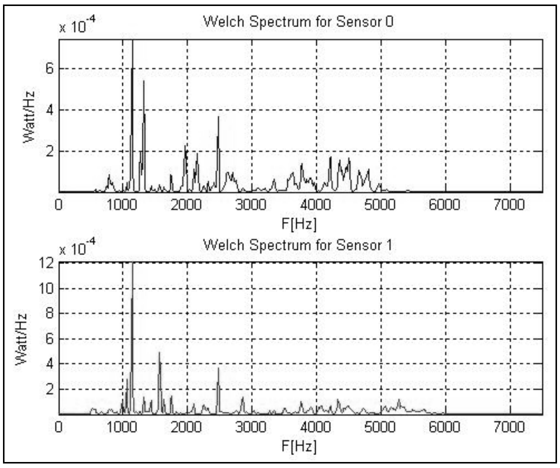

Fig.4. Experimental Leak Signals PSD – 4.27 l/min

III. AUTOMATIC INTERVAL SELECTION

The CCF is calculated with the help of the Matlab *xcorr* function. Because the speed of the noise signal in the metallic pipe is very high and the distances between the leak and the sensors are short, we only used 500 samples from each signal for the CCF computation.

The results of this computations are presented below and the CCF are calculated for the above signals which contain the entire frequency range from 500Hz – 6kHz.

At the moment we are not concerned with the delay indicated by this maximum peak, but with the quality of the representation. We are interested to see with what quality this peak stands above the rest of the CCF peaks.

The maximum peak of the CCF is located 15 samples to the right of the central point. An algorithm [4] was used to calculate the quality coefficient of the CCF maximum peak. This algorithm compares the maximum peak value of the CCF with other peak values located 100 samples to the left and to the right of the maximum peak. For the above example this quality coefficient is Q = 3.52 which is accepted as a good value (greater than 3).

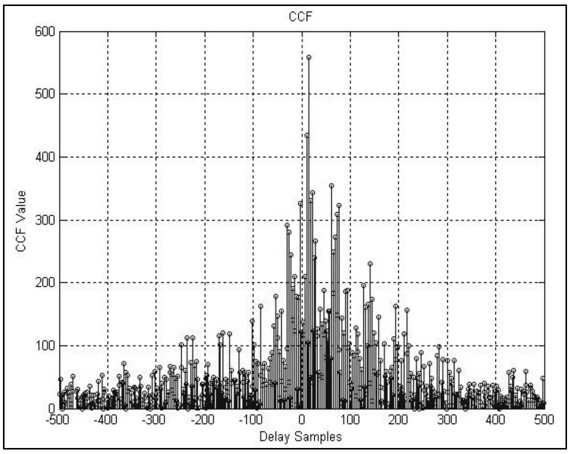

Fig.5. CCF – 8.27 l/min

In the following image (Fig.6), the CCF and the quality coefficient Q are calculated for the case where the leak debit is 4.27 l/min.

The quality of the CCF is poorer because of other noise sources and because of lower leak debit. We can see the maximum peak positioned to the right of the central point but the calculated quality coefficient is Q = 2.23. A quality Q higher than 3 is considered suitable so further improvements for the CCF are required.

A useful method of seeing in which frequency domain the signals are similar is to calculate the magnitude squared coherence function.[8] This calculus can be implemented in Matlab with the help of the *mscohere* function. In the following images (Fig.7, Fig.8) we present the calculated coherence functions for the signals acquired for 8.27 l/min and 4.27 l/min leak debit. As we can see from the images it is quite difficult to establish which is the domain of interest. The coherence functions have many fluctuations and it is not possible to determine with accuracy a most suitable domain of analysis. We can improve the quality of the coherence representation by passing it trough a low-pass filter.

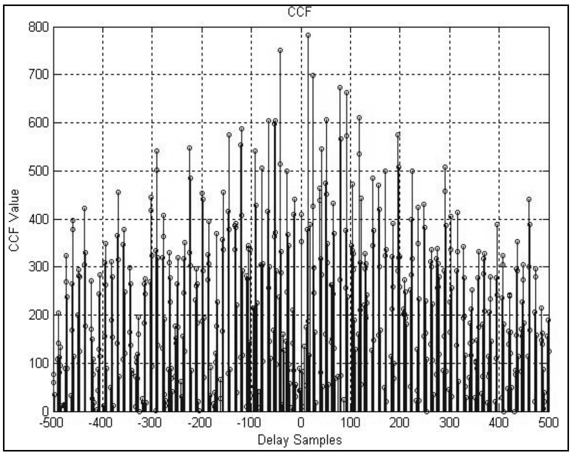

Fig.6. CCF – 4.27 l/min

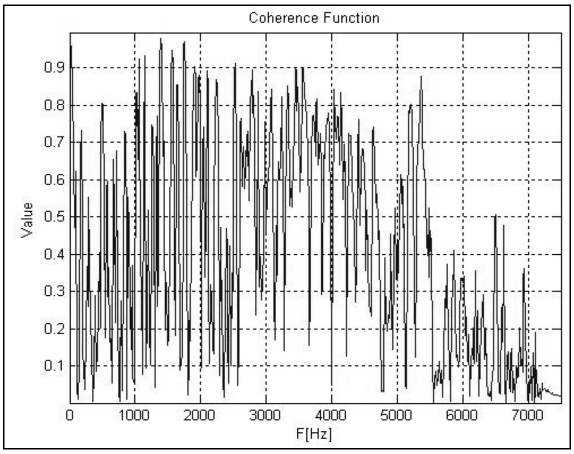

Fig.7. Coherence Function – 8.27 l/min

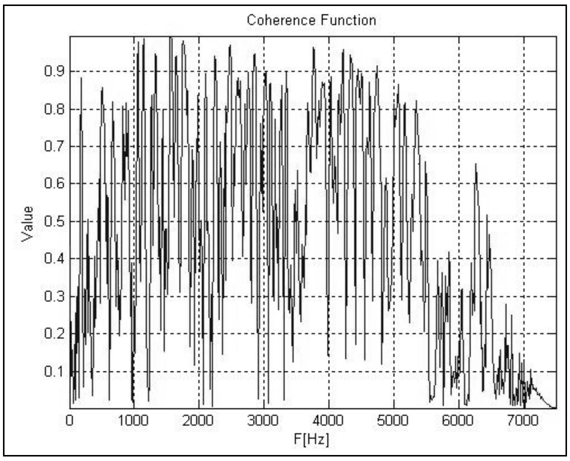

Fig.8. Coherence Function – 4.27 l/min

The limit of the filter can be established by looking at the representation of this function. In Fig.9. and Fig.10. the we can see that the coherence functions were low-pass filtered in order to improve (smoothen) their aspect.

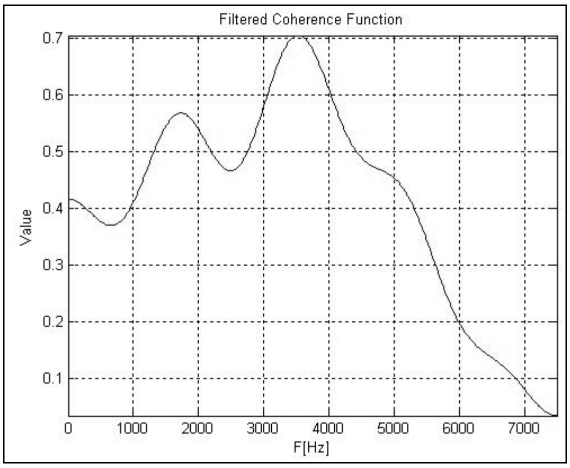

Fig.9. Improved Coherence Function – 8.27 l/min

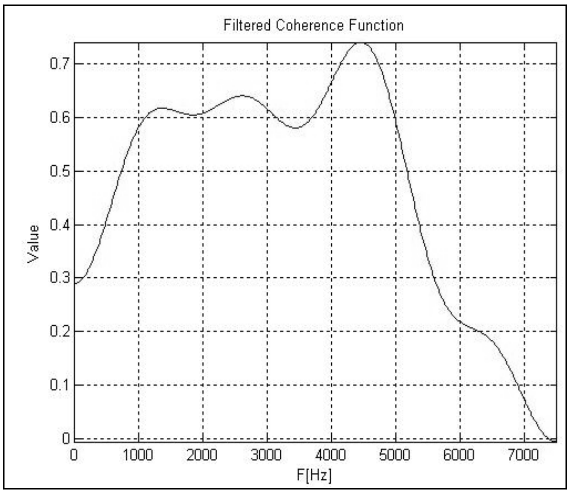

Fig.10. Improved Coherence Function – 4.27 l/min

It is important to see which intervals we can choose in order to improve the Q coefficient. For the proposed interval selection algorithm, we have chosen two intervals. In the following image, the filtered coherence function for the signals at 8.27 l/min leak debit is divided into these two intervals.

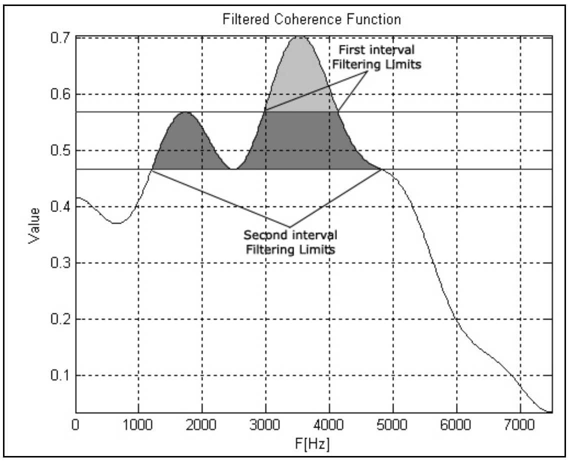

Fig.11. Improved Filtered Coherence Function Intervals – 8.27 l/min

The selection of these intervals was performed in an automatic manner. For the filtered coherence function we calculated the first derivative and the zero-crossings of this derivative. Each crossing tells where we can find a peak in the calculated coherence function. The two chosen intervals are: the one that contains values around the maximum point of the coherence function, but the values should be greater than the value of the second highest peak and a larger interval containing the first two highest peaks in the coherence function.

For the second pair of signals, the selected intervals are presented below. We can see that for the second filtering interval, the coherence function reaches a minimum, lower than the peak situated outside the interval at about 1.3kHz. The shape of the filtered coherence function is different because the debits are not the same. This presence of lower coherence values in this interval is not problematic. As we will show, the quality of the CCF will seriously improve when filtering the signals between the limits of this interval.

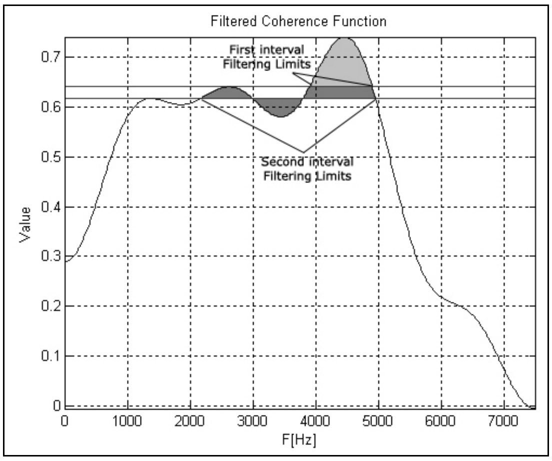

Fig.12. Improved Filtered Coherence Function Intervals – 4.27 l/min

IV. EXPERIMENTAL RESULTS

In order to see if the presented method gives better results, we should calculate the CCF function and the Q coefficient.

The following table shows the values of the Q coefficient for the CCF between the filtered signals.

Leak Debit [l/min]	Filtering Interval [Hz]	Q
8.27	2982 - 4137	2.98
8.27	1228 - 4824	3.25
4.27	3918 - 4897	2.88
4.27	2178 - 4941	3.57

Table 2. Filtering Intervals and calculated Q coefficients

As expected, when we have a narrow filtering interval, the quality of the CCF becomes smaller. There are few frequencies which compose the signal and the results are not accurate. If we set the filter settings as indicated by the second interval, there is a significant quality growth when dealing with the signals for 4.27 l/min leak debit. For the first pair of signals there is a slight quality decay, however the method brigs improvements for the problematic CCF calculations.

In this case, the choice of a larger interval is a good way to improve the quality of the calculated CCF. The following image presents the improved CCF, calculated for the leak signals at 4.27 l/min leak debit and filtered with the limits [2178Hz – 4941Hz]. When comparing the CCF from Fig.6. and the CCF from Fig.13., we can see the benefits that this method of automatic filtering interval selection brings. Other methods can be applied in order to obtain further improvements (signal whitening). For the first pair of signals, the first representation of the CCF is accurate enough.

We need to look at the results obtained for the filtering between the limits of the two intervals and decide which interval provides the best quality coefficient.

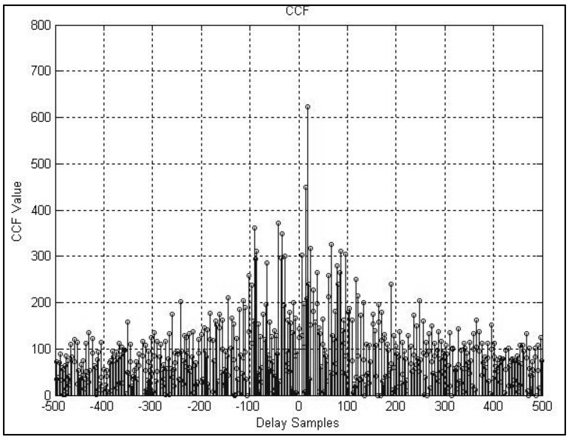

Fig.13. Improved CCF – 4.27 l/min

For the signal pairs presented in Table.1., we have calculated the CCF and the results are presented in the next table. The filtering interval was between 500Hz – 6kHz.

Signal Pair	Leak Debit [l/min]	Q
1	0,20	1.83
2	0,25	2.13
3	0,35	3.05
4	0,85	2.48
5	1,06	2.85
6	2	2.56
7	2,76	3.22
8	3,87	2.68
9	4,27	2.23
10	5,26	4.28
11	6,09	4.38
12	8,27	3.52

Table 3. CCF quality coefficients before the automatic filtering.

If we accept the fact that a Q = 3 is an accurate quality value, then we must look at the pairs where the quality of the CCF does not meet these requirements and try to improve the quality as much as we can.

Signal Pair	Leak Debit [l/min]	Q
1	0,20	2.79
2	0,25	2.28
3	0,35	3.05
4	0,85	2.63
5	1,06	3.14
6	2	2.67
7	2,76	3.50
8	3,87	2.78
9	4,27	3.57
10	5,26	4.11
11	6,09	2.99
12	8,27	3.25

Table 4. CCF quality coefficients after the automatic filtering

The quality of the calculated CCF can be seen in the next image. For Q coefficients which have a low value, the method of automatic filtering brings an improvement. However, if the CCF quality is accurate enough (Fig.5.), there is no need to apply the method because we can see that it brings no advantages.

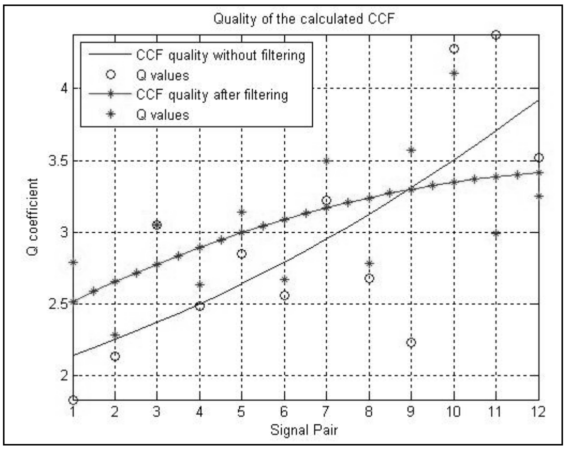

Fig.14. Quality of CCF before and after filtering

V. CONCLUSIONS

The process of automatic selection of filtering intervals is important because it can help us improve the quality of the calculated CCF. The way in which we can obtain the frequency intervals where the signals resemble each other is to study the magnitude squared coherence function.

The coherence function shows many fluctuations and irregularities if we use it in a primary form. In order to obtain a smoother coherence function and to be able to determine the intervals, we must use a low-pass filtering process. Passing the calculated coherence sequence trough this filter provides a smoother representation of the coherence and we are able to see which frequency intervals are suitable for us.

If we determine a suitable filtering interval we are able to use in the CCF calculus those frequencies which are of interest to us. The selection of the interval should be automatic. The user of the application has to choose between the calculation of the CCF without signal filtering or with the filtered signals. For this application, the two chosen intervals are the one that contains values around the maximum point of the coherence function, but greater than the value of the second highest peak and a larger interval containing the first two highest peaks in the coherence function.

If applied to the acquired signals, the method shows improvement for CCF that are not accurate without filtering. In Fig.6. we have shown a CCF in which the maximum peak (indicating the time delay in samples) is not clearly emphasized. It was shown that in the case of using the automatic selection of filtering intervals, the maximum value of the CCF was clearly emphasized (Fig.13.). This fact is important when we deal with establishing the position of the maximum value.

`However, it can be seen that if the initial CCF has a good quality (Fig.5.), it is not always useful to apply the method. The user should choose to apply this method, which in the case of already accurate CCF, may or may not bring advantages. In Fig.14 it can be seen that the method helps when dealing with CCF with an initial low quality coefficient.

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