IMPROVING RECURRENCE-BASED FUNDAMENTAL FREQUENCY ESTIMATION BY USING IMAGE PROCESSING

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Abstract: *Fundamental frequency estimation based on representing the signal in phase space is simple and has good results. In this paper, we show that the results of this method can be improved by using image processing techniques on the recurrence plot. The goal of this image processing is to reduce the effect of noise. The results we present in this paper show clear improvements in the noise behavior of the method.*

1. INTRODUCTION

Estimating the fundamental frequency of a signal is an important topic especially in speech processing, where it is known as pitch detection. But its usefulness does not end there, as periodic signals are being used in various fields, e.g. communications, non-intrusive measurement techniques.

The real problem consists in the fact that the analyzed signal is not perfectly periodic. If the signal would be periodic, determining its fundamental frequency would be a simple task. But the signals we are interested in are in fact quasi-periodical. The cause of this fact is either noise, either the nonlinearity of the system that generated the signal.

There are three classes of methods for estimating the fundamental frequency [1]:

– time-domain methods
– frequency-domain methods
– statistical methods.

In this paper we deal with a method from the first of these three classes, namely time-domain methods. More precisely, we study a method that is based on representing the signal in phase space.

Although our method [2] is very similar with the method described in [3], the way we developed it allows some improvements. We study in this paper the improvements obtained by processing the image of the recurrence plot (RP) [4] before computing the sum of its diagonals.

We remind in the next section the essence of our method. We present then an image processing technique for denoising the recurrence plot and we make a brief analysis of the effect of noise on the RP, in order to obtain some indications concerning the choice of the parameters for the image processing technique. We follow with showing some results and we close the paper by pointing out conclusions and directions for future work.

2. RECURRENCE-BASED FUNDAMENTAL FREQUENCY ESTIMATION

In [2], we proposed a fundamental frequency estimation method that is based on the global quantification of the diagonals of the recurrence plot. More precisely, we performed a normalized summing of the RP diagonals:

$$SD(\tau) = \frac{1}{N-\tau}\sum_{i=1}^{M-\tau}\Theta(\varepsilon - \|\vec{v}_i - \vec{v}_{i+\tau}\|). \quad (1)$$

By using another approach, the author of [3] obtains a similar expression for what he calls "the periodicity histogram". As our approach consists in a quantification of the RP, it can be performed also after processing the RP first. The motivation for this can be seen in [5], where we showed that the effect of noise can be reduced by image-processing the RP.

The following section presents an image processing technique that is well suited for this task, and it also discusses the choice of the parameters.

3. IMAGE PROCESSING FOR DENOISING THE RECURRENCE PLOT

In order to reverse the effect of noise-generated spreading of points [5] in the RP, we propose the following processing:

$$R_{i,j}^{(new)} = \begin{cases} 1, & if \quad \dfrac{\sum_{l,c=1}^{2P_s+1} R^{(old)}_{l(=\overline{i-P_s,i+P_s}),c(=\overline{j-P_s,j+P_s})} \cdot M_{l,c}}{(2P_s+1)^2} \geq P_t \\ 0, & if \quad \dfrac{\sum_{l,c=1}^{2P_s+1} R^{(old)}_{l(=\overline{i-P_s,i+P_s}),c(=\overline{j-P_s,j+P_s})} \cdot M_{l,c}}{(2P_s+1)^2} < P \end{cases} . \quad (2)$$

In the previous equation: R is the recurrence plot, M is the mask, P_s is a parameter related to the size of the mask (which is $2P_s+1$), and P_t is a parameter that sets the black point density threshold.

We point out that a black point in the RP corresponds to a value of 1 in R. Figure 1 shows an example of a mask with a P_s of 3.

1	1	1	0	0	0	0
1	1	1	1	0	0	0
1	1	1	1	1	0	0
0	1	1	1	1	1	0
0	0	1	1	1	1	1
0	0	0	1	1	1	1
0	0	0	0	1	1	1

Fig. 1 Example of a mask with P_s = 3

This image processing technique identifies the areas that have a diagonal black point density of at least P_t. Figure 2 shows an example.

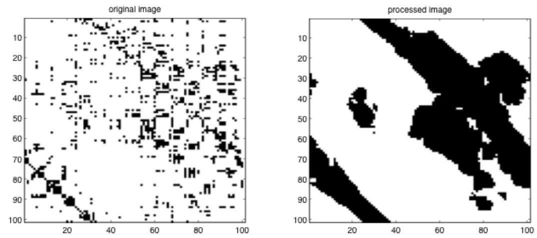

Fig. 2 Illustration of the image processing technique, for P_s = 7 and P_t = 0.1

The choice of the P_t parameter should take into account the way noise affects the distribution of black points along the diagonals in the RP. One way to study this consists in measuring the black point density, D_p, in the areas surrounding the diagonals of interest (marked in Figure 3), and then taking the average of the results.

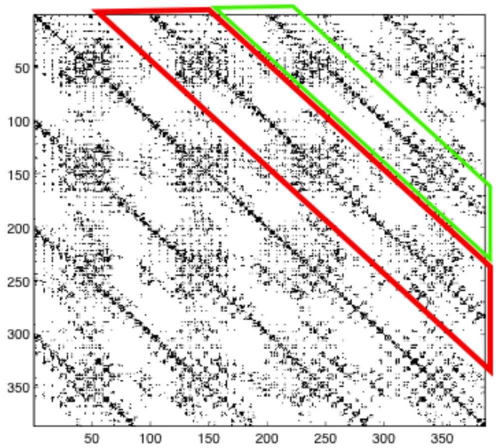

Fig. 3 Areas for computing the black point density in the recurrence plot

Figure 4 illustrates the results of this operation, for a SNR (signal-to-noise ratio) that varies between -20dB and 30dB.

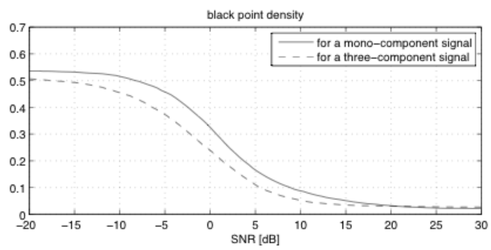

Fig. 4 Variation of D_p with SNR, for two different signals (a mono-component one, and a three-component one)

It can be noticed that D_p varies in a similar manner, even if the two signals are very different. For high SNR, the black point density is low, while for low SNR, the black point density is high. Therefore, a proper choice for P_t should take into consideration the value of D_p. We discuss in the next section our choice for the P_s and P_t parameters, and we present some results concerning the effect of this image processing.

4. RESULTS

Experimentally, we noticed that by choosing P_s to be greater than one third of the fundamental period of the signal, we obtain unsatisfactory results. Ideally, P_s should be as small as possible, for the computations to be fast. On the other hand, a P_s that is too small does not provide a good filtering of the RP. A good compromise can be obtained by choosing P_s to be between 5% and 10% of the expected fundamental period of the signal. Considering the last discussion in the previous section, we chose for P_t a value of $0.75D_p$.

Figure 5 shows the results we obtained using this choice for the parameters, for a sinusoidal signal.

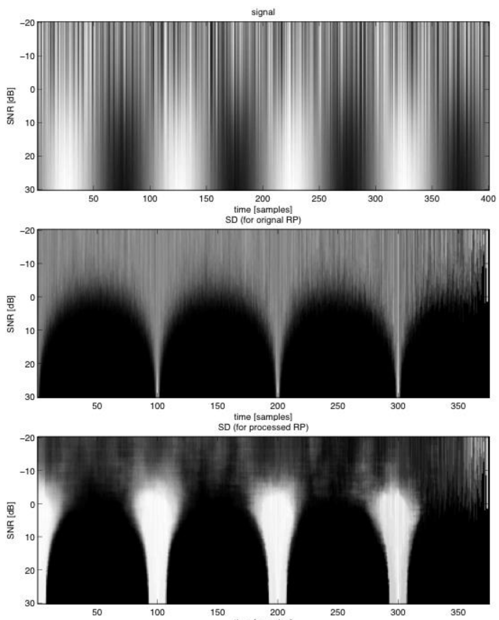

Fig. 5 Results obtained for a sinusoidal signal: (top) signal, (middle) original SD, (bottom) SD obtained for processed RP

We obtained Figure 6 by repeating the same tests for a signal composed of three sinusoidal components.

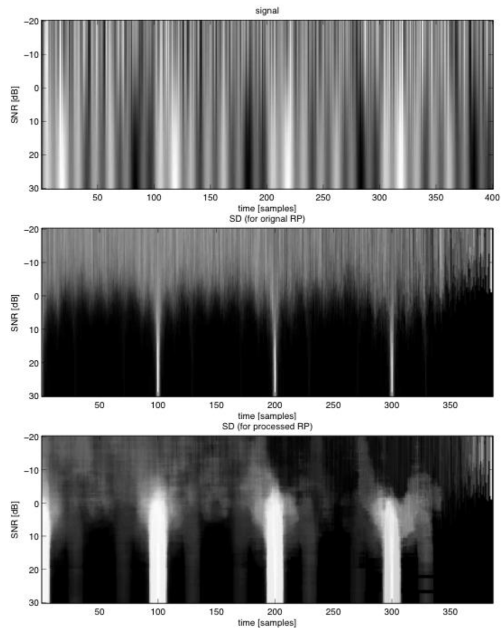

Fig. 6 Results obtained for a three-component signal: (top) signal, (middle) original SD, (bottom) SD obtained for processed RP

The previous figures show clearly that the technique we proposed for filtering the recurrence plot improves with at least 5dB the noise behavior of *SD*.

5. CONCLUSION

Recurrence plot analysis can be very helpful in fundamental frequency estimation, and although phase space representation of a signal has been used for a while in this field, improvements can still be made.

This paper shows one such improvement. We showed that with fairly simple image processing, the effect of noise on the RP can be reduced. This leads to improvements in the noise behavior of the measures derived from it, which can be further used for fundamental frequency estimation.

We must note, however, that our choice for the parameters that were used for image processing was somewhat empirical. Even better results might be obtained for a more adapted choice of these parameters. A good estimation of the noise level that is present in the signal might be useful for this task.

Besides these, future work might regard finding other image processing techniques that could better reverse the effect of noise on the recurrence plot.

6. ACKNOWLEDGEMENT

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