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Spectral Fault Recovery Analysis Revisited With Normal and Abnormal Heart Sound Signals

V. ELAMARAN[1], N. ARUNKUMAR[1], AHMED FAEQ HUSSEIN[2],
MARIO SOLARTE[3], AND GUSTAVO RAMIREZ-GONZALEZ[3]
[1]School of EEE, SASTRA Deemed University, Thanjavur 613401, India
[2]Bio-Medical Engineering Department, Faculty of Engineering, AL-Nahrain University, Baghdad 10072, Iraq
[3]Telematics Department, University of Cauca, Popayan 190001, Colombia

Corresponding author: Gustavo Ramirez-Gonzalez (gramirez@unicauca.edu.co)

ABSTRACT The computation of fast Fourier transform (FFT) plays a vital role in all fields of science and engineering, especially in the medical domain. Spectral results of the data convey more information to the clinicians to take handy decisions during the diagnosis. If a problem happens during the computation of FFT, the incorrect results misinterpret the information and hence the suggestions and decisions by practitioners would be the useless one moreover, it may yield harmful result to the patients. This paper deals with how to recover the spectrum from the faulty one with the heart sound case reports. The heart sound recording is the phonocardiogram (PCG) signal. Stethoscopes are commonly used to hear the heart sound for diagnosis. The two PCG signals of normal and abnormal subjects in each were analyzed in this paper. The normal subject produce clear lub and dub sounds, where the abnormal subject produce a kind of whistling or swishing sound in middle which may be due to the problem of septal defect in a heart. This paper analyzes four PCG signals spectrally with fault and the recovered ones along with the execution time results in each using Matlab R2016b tool.

INDEX TERMS FFT, fault recovery, heart sound, normal PCG, abnormal PCG.

I. INTRODUCTION

A common declaration is that the digital signal processing (DSP) subject is difficult for undergraduate engineering students. The sole objective of this study is to break the ice through hands on experiments to comprehend fundamentals behind the fast Fourier transform (FFT). Even though the students have ample command on engineering mathematics course, due to the shortage of application instances, interpreting Fourier theory and the learning of discrete-time signals and systems turn uninteresting for the scholars group [1], [2]. The DSP techniques are frequently used in a day-to-day living via numerous devices. The noisy signals should be removed in discrete-time signal processing through often by smoothing, which can be achieved through the design of simple moving average filters. The information and understanding about the input signal frequencies is essential to design an appropriate filter. The grasping DFT concepts can aid a lot for the filter design excessively [3]–[6].

The heart is an important organ with a normal size about 12 cm long (base-to-apex) and 8 cm wide. Its main tasks are to spill the deoxygenated blood to the lungs in which the exchange of carbon dioxide-oxygen takes place, and to spill the oxygenated blood to the whole body. The right and left sides are the two functional sides of a heart which are separated by the septum. They are further divided into chambers. The left-sided chambers contain the left atrium and the left ventricle; the right-sided chambers contain the right atrium and the right ventricle [7], [8]. Figure 1 shows the cross section of a human heart. The chambers are separated by unidirectional valves which control the blood flow too. The right atrium and right ventricle are separated by the right atrioventricular (AV) valve; the left atrium and left ventricle are separated by the left AV. The right ventricle and pulmonary artery are separated by the semilunar pulmonic valve; the left ventricle and aorta are separated by semilunar aortic valve. The vibrations of from bumpy blood flow, heart's walls and valves are heard as heart sounds through a stethoscope. During the cardiac cycle, the heart's walls and valves are flexible as they move in response to pressure [7], [8].

The heart sound (HS) is an important physiological signal in the human body for the diagnosis of clinical auscultation. During the cardiac cycle, two basic heart sounds (S1 and S2) are produced from a normally functioning heart [3]–[7]. These sounds are caused due to the blood acceleration

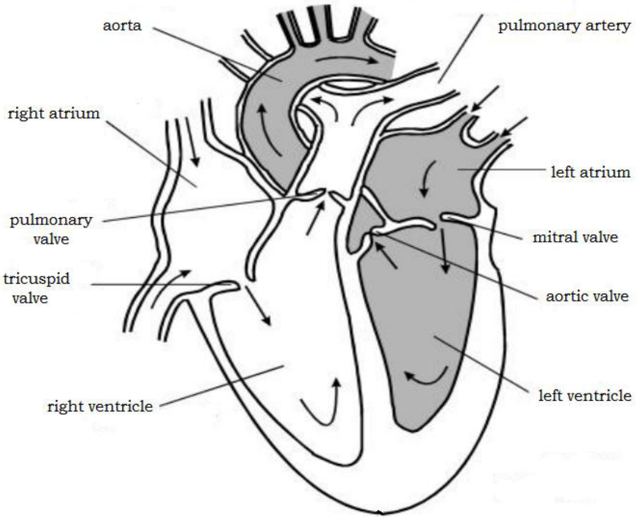

FIGURE 1. Human heart cross section.

or deceleration in the heart's chambers. The "lub" sound belongs to the S1 portion and the "dub" sound belongs to the S2 portion, and hence "lub-dub" sounds occur in a heart. Even an ordinary person can hear and identify or distinguish the different heart beats such as normal heartbeat, fast heartbeat, slow heartbeat and irregular heartbeat [8]–[11].

Heart sound or phonocardiogram (PCG) signals do have high similarity with the electrocardiogram (ECG) signals [9]–[13]. The heart sounds are produced due to the blood acceleration or deceleration in the heart's chambers. In ECG, during the cardiac cycle, the activation of the atria belongs to P wave; the activation of the ventricles belongs to QRS complex; the recovery wave belongs to T wave [12]–[16] . The ventricular contraction is the reason for the first heart sound "S1". This S1 sound occurs at the same time as the QRS complex in the ECG signal with a low frequency band about 10 – 120 Hz. The second heart sound "S2" is due to the closing scenario of the pulmonary and aortic valves, which occurs during the end of the T wave in the ECG signal. The S2 sound frequency is normally higher than that of the first sound with a low frequency band about 10 – 200 Hz [14]–[17].

Healthy people need a normal heart rate. "Tachycardia" is the term that belongs to the abnormal heart rate (above normal) and the "bradycardia" term belongs to the below normal heart rate. For example, the athletes should have the heart rate between 50 to 70 beats per minute; the heart rate of adults should be in the range between 70 to 90 beats per minute; Childs heart rate should be in the range between 80 to 100 beats per minute; new born babies heart rate should be around 130 beats per minute [18]–[24].

This paper is organized as follows. Section 2 contains the fault recovery equations involved in this study during the stage one and two and Section 3 includes simulation results of faulty and fault recovered PCG signal spectrums with the execution time in each respectively. The conclusions are finally described in Section 4.

II. MATERIALS AND METHODS

The different windows are described here. The spectral and SNR analysis on normal and abnormal heart sound signals are done using these windows and the results are discussed for a comparative study in the next section.

A. FAULT RECOVERY DURING THE FIRST STAGE

The discrete Fourier transform (DFT) expressions using decimation-in-time FFT algorithm are given as,

$$\begin{aligned} X(k) &= Even(k) + W_N^k\, Odd(k) \\ X(k+\frac{N}{2}) &= Even(k) - W_N^k\, Odd(k) \\ k &= 0,\,1,\,2,\,\ldots,\,\frac{N}{2}-1 \end{aligned} \tag{1}$$

By mistake, if the even samples are replaced with odd samples and vice versa, the DFT expressions will have to be recovered by solving the above equations – as follows [25],

$$\begin{aligned} E(k) &= \frac{X(k) + X(k+\frac{N}{2})}{2} \\ O(k) &= \frac{X(k) - X(k+\frac{N}{2})}{2}\, W_N^{-k} \end{aligned} \tag{2}$$

Finally, to recover the DFT results, these even and odd DFT expressions – as in Equation (2) – are exchanged appropriately as follows [25],

$$\begin{aligned} Xrec(k) &= \frac{X(k)-X(k+\frac{N}{2})}{2}\, W_N^{-k} \\ &\quad + \frac{X(k)+X(k+\frac{N}{2})}{2} W_N^{k} \\ Xrec(k+\frac{N}{2}) &= \frac{X(k)-X(k+\frac{N}{2})}{2}\, W_N^{-k} \\ &\quad - \frac{X(k)+X(k+\frac{N}{2})}{2} W_N^{k} \\ k &= 0,\,1,\,2,\,\ldots,\,\frac{N}{2}-1 \end{aligned} \tag{3}$$

B. FAULT RECOVERY DURING THE SECOND STAGE

During the second stage, the DFT equations using decimation-in-time FFT algorithm are expressed as,

$$\begin{aligned} Even(k) &= EvenEven(k) + W_N^{2k}\, EvenOdd(k) \\ Even(k+\frac{N}{4}) &= EvenEven(k) - W_N^{2k}\, EvenOdd(k) \\ Odd(k) &= OddEven(k) + W_N^{2k}\, OddOdd(k) \\ Odd(k+\frac{N}{4}) &= OddEven(k) - W_N^{2k}\, OddOdd(k) \\ k &= 0,\,1,\,2,\,\ldots,\,\frac{N}{4}-1 \end{aligned} \tag{4}$$

By mistake, if the even-even samples are replaced with even-odd samples and vice versa; also if the odd-odd samples are replaced with odd-even samples and vice versa, the DFT expressions will have to be recovered by solving the above equations – as follows:

$$\begin{aligned}
EvenEven(k) &= \frac{Even(k) + Even(k+\frac{N}{4})}{2} \\
EvenOdd(k) &= \frac{Even(k) - Even(k+\frac{N}{4})}{2} W_N^{-2k} \\
OddEven(k) &= \frac{Odd(k) + Odd(k+\frac{N}{4})}{2} \\
OddOdd(k) &= \frac{Odd(k) - Odd(k+\frac{N}{4})}{2} W_N^{-2k} \\
k &= 0,\ 1,\ 2,\ \ldots,\ \frac{N}{4} - 1 \qquad (5)
\end{aligned}$$

Finally, to recover the DFT results, these even and odd DFT expressions – as in Equation (5) – are exchanged appropriately as follows,

$$\begin{aligned}
Even(k) &= EvenOdd(k) + W_N^{2k}\ EvenEven(k) \\
Even(k+\frac{N}{4}) &= EvenOdd(k) - W_N^{2k}\ EvenEven(k) \\
Odd(k) &= OddOdd(k) + W_N^{2k}\ OddEven(k) \\
Odd(k+\frac{N}{4}) &= OddOdd(k) - W_N^{2k}\ OddEven(k) \\
k &= 0,\ 1,\ 2,\ \ldots,\ \frac{N}{4} - 1 \qquad (6)
\end{aligned}$$

Then the final DFT outputs are obtained using the above even and odd DFT expressions – as follows,

$$\begin{aligned}
Xrec(k) &= Even(k) + W_N^{k}\ Odd(k) \\
Xrec(k+\frac{N}{2}) &= Even(k) - W_N^{k}\ Odd(k) \\
k &= 0,\ 1,\ 2,\ \ldots,\ \frac{N}{2} - 1 \qquad (7)
\end{aligned}$$

C. FAULTS DURING THE THIRD STAGE

During the third stage, the DFT equations using decimation-in-time FFT algorithm are expressed as,

$$\begin{aligned}
&EvenEven(k) \\
&\quad = EvenEvenEven(k) \\
&\qquad + W_N^{4k}\ EvenEvenOdd(k) EvenEven(k+\frac{N}{8}) \\
&\qquad = EvenEvenEven(k) \\
&\qquad - W_N^{4k}\ EvenEvenOdd(k) EvenOdd(k) \\
&\qquad = EvenOddEven(k) + W_N^{4k}\ EvenOddOdd(k) \\
&EvenOdd(k+\frac{N}{8}) \\
&\quad = EvenOddEven(k) \\
&\qquad - W_N^{4k}\ EvenOddOdd(k) OddEven(k) \\
&\qquad = OddEvenEven(k) + W_N^{4k}\ OddEvenOdd(k) \\
&OddEven(k+\frac{N}{8}) \\
&\quad = OddEvenEven(k) \\
&\qquad - W_N^{4k}\ OddEvenOdd(k) OddOdd(k) \\
&\qquad = OddOddEven(k) + W_N^{4k}\ OddOddOdd(k)
\end{aligned}$$

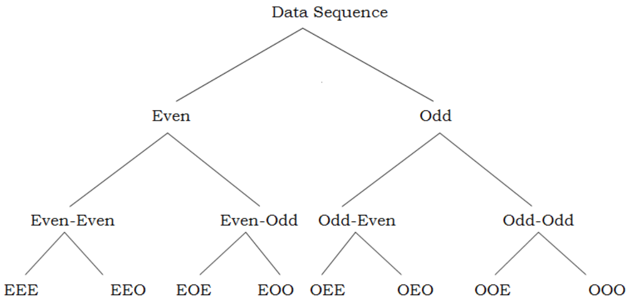

FIGURE 2. **Data sequence partition during the third stage.**

$$\begin{aligned}
&OddOdd(k+\frac{N}{8}) \\
&\quad = OddOddEven(k) - W_N^{4k}\ OddOddOdd(k) \\
&k = 0,\ 1,\ 2,\ \ldots,\ \frac{N}{8} - 1 \qquad (8)
\end{aligned}$$

The motivation for the analysis of fault recovery during the third stage is as illustrated in Figure 2.

Similarly, during the third stage, the even-even-even samples are replaced by mistake by even-even-odd samples and vice versa; even-odd-even samples are too replaced by mistake by even-odd-odd samples and vice versa. Also, the odd-even-even samples are by mistake replaced by odd-even-odd samples and vice versa; the odd-odd-even samples too are replaced by mistake by odd-odd-odd samples and vice versa. the DFT expressions will have to be recovered by solving the above equations – as follows,

$$\begin{aligned}
EvenEvenEven(k) &= \frac{EvenEven(k) + EvenEven(k+\frac{N}{8})}{2} \\
EvenEvenOdd(k) &= \frac{EvenEven(k) - EvenEven(k+\frac{N}{8})}{2} W_N^{-4k} \\
EvenOddEven(k) &= \frac{EvenOdd(k) + EvenOdd(k+\frac{N}{8})}{2} \\
EvenOddOdd(k) &= \frac{EvenOdd(k) - EvenOdd(k+\frac{N}{8})}{2} W_N^{-4k} \\
OddEvenEven(k) &= \frac{OddEven(k) + OddEven(k+\frac{N}{8})}{2} \\
OddEvenOdd(k) &= \frac{OddEven(k) - OddEven(k+\frac{N}{8})}{2} W_N^{-4k} \\
OddOddEven(k) &= \frac{OddOdd(k) + OddOdd(k+\frac{N}{8})}{2} \\
OddOddOdd(k) &= \frac{OddOdd(k) - OddOdd(k+\frac{N}{8})}{2} W_N^{-4k} \\
k &= 0,1,2,\ \ldots,\frac{N}{4} - 1 \qquad (9)
\end{aligned}$$

Finally, to recover the DFT results, these even and odd DFT expressions – as in Equation (9) – are exchanged appropriately as follows,

$$\begin{aligned}
EvenEven(k) &= EvenEvenOdd(k) \\
&\qquad + W_N^{4k}\ EvenEvenEvenk)
\end{aligned}$$

$$
\begin{aligned}
EvenEven(k+\frac{N}{8}) &= EvenEvenOdd(k) \\
&\quad - W_N^{4k}\, EvenEvenEven(k) \\
EvenOdd(k) &= EvenOddOdd(k) \\
&\quad + W_N^{4k}\, EvenOddEven(k) \\
EvenOdd(k+\frac{N}{8}) &= EvenOddOdd(k) \\
&\quad - W_N^{4k}\, EvenOddEven(k) \\
OddEven(k) &= OddEvenOdd(k) \\
&\quad + W_N^{4k}\, OddEvenEven(k) \\
OddEven(k+\frac{N}{8}) &= OddEvenOdd(k) \\
&\quad - W_N^{4k}\, OddEvenEven(k) \\
OddOdd(k) &= OddOddOdd(k) \\
&\quad + W_N^{4k}\, OddOddEven(k) \\
OddOdd(k+\frac{N}{8}) &= OddOddOdd(k) \\
&\quad - W_N^{4k}\, OddOddEven(k) \\
k &= 0, 1, 2, \ldots, \frac{N}{8} - 1 \qquad (10)
\end{aligned}
$$

III. RESULTS AND DISCUSSION

In this study, the four recording of the heart sounds, i.e. phonocardiogram (PCG) signals are used. It includes two normal and two abnormal heart sound signals.

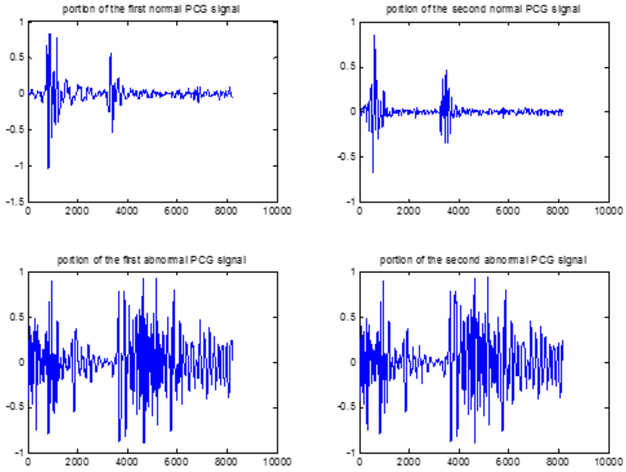

FIGURE 3. The two normal and abnormal PCG signals.

A. PCG SIGNAL DATASET

The four patient PCG signals are considered here in which two are normal ("pecnorm1.dat" and "pecnorm2.dat") and the other two are abnormal ("pecab1.dat" and "pecab2.dat") heart sounds. The abnormal signals had the problem of ventricular septal defect [22]. In the heart sound, during the systole period, the blood leak may happens from the left ventricle to the right ventricle because of a hole – is known as "septal defect". The four PCG signals are shown in Figure 3. From the figure, it reveals that the abnormal heart sounds do have murmur effects.

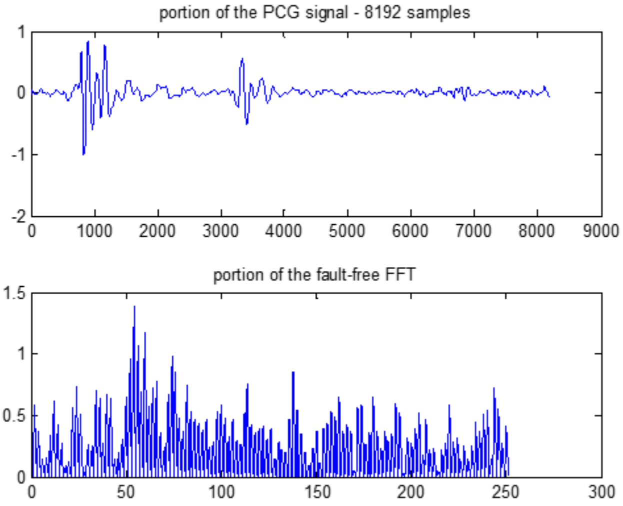

FIGURE 4. The portion of the PCG signal and its fault-free FFT during the first stage.

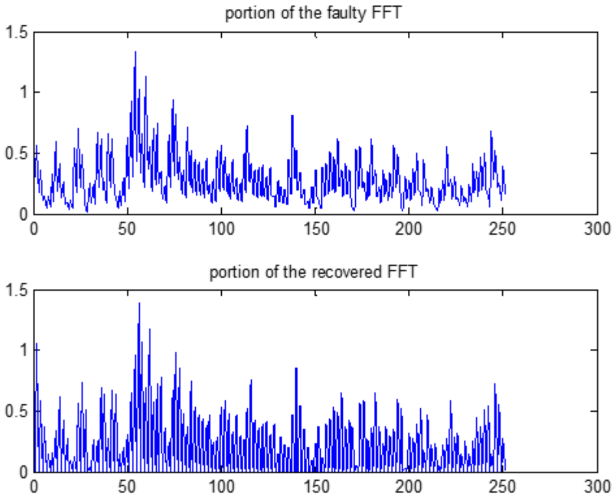

FIGURE 5. The portion of the faulty and recovered spectrums during the first stage.

B. FAULTY AND RECOVERED SPECTRUM RESULTS – DURING THE FIRST STAGE

For the sake of space, the second abnormal PCG signal ("pecab2.dat") is used for interpretations [22]. The portion this PCG signal contains 8192 samples and its fault-free FFT are shown in Figure 4. For the sake of simplicity again, the only portion of the FFT is visualized, not the whole spectrum. During the first stage, if the hardware pickups even samples instead of odd samples and vice versa, there will be error in the spectrum. Using the equations mentioned, the errors are recovered and the resulting spectrums, both the faulty and fault-free are illustrated in Figure 5.

C. FAULTY AND RECOVERED SPECTRUM RESULTS – DURING THE SECOND STAGE

Let us consider the hardware pickups samples correctly i.e. without any error. But during the second stage,

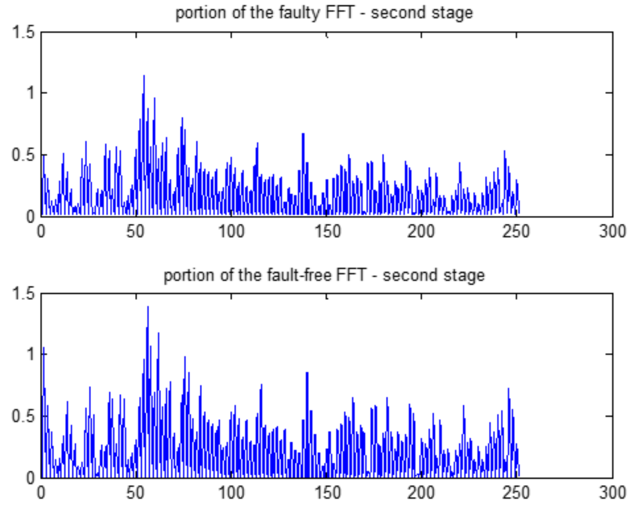

FIGURE 6. **The portion of the faulty and recovered spectrums during the second stage.**

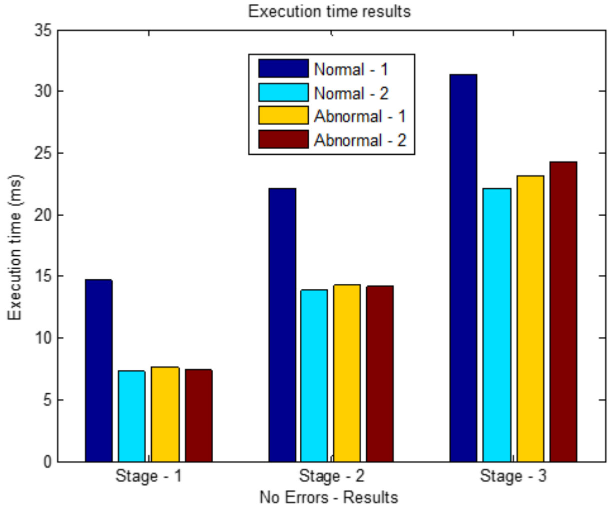

FIGURE 7. **Execution time with no errors.**

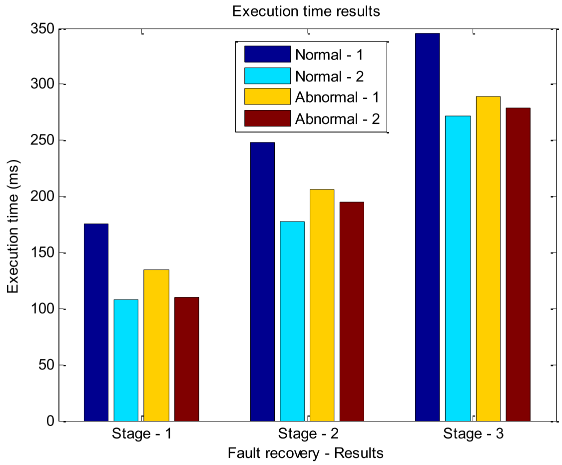

FIGURE 8. **Faulty recovery execution time results.**

the even-even samples are replaced with even odd samples and vice versa. Also, the odd-odd samples are replaced with odd-even samples and vice versa. The corresponding faulty and recovered spectrum results are illustrated in Figure 6.

D. EXECUTION TIME RESULTS

The experiments of faulty and fault-recovery spectrums have been conducted for the stage one and two respectively. These experiments have been carried out on 2.5 GHz processor with 8 GB RAM. The execution time results with no errors and using fault recovery method on two normal and two abnormal PCG signals are illustrated in Figures 7 and 8 respectively.

IV. CONCLUSIONS

The detailed faulty and fault recovered spectrums are dealt in detail in this study with the first, second, and third stages. The spectrum results of both faulty and recovered ones are analyzed in detail along with the execution time comparisons. The faulty spectral information would misread the data or information in a big way. Hence, the fault recovery of spectral information is required and hence this work becomes significant for the clinicians to pinpoint the disease for the patients suitably. This work can further be extended to genomic signal processing, audio and speech signal processing, two-dimensional signal processing, etc.

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