Investigating complex patterns of blocked intestinal artery blood pressure signals by empirical mode decomposition and linguistic analysis

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Characteristics of Bio-signals

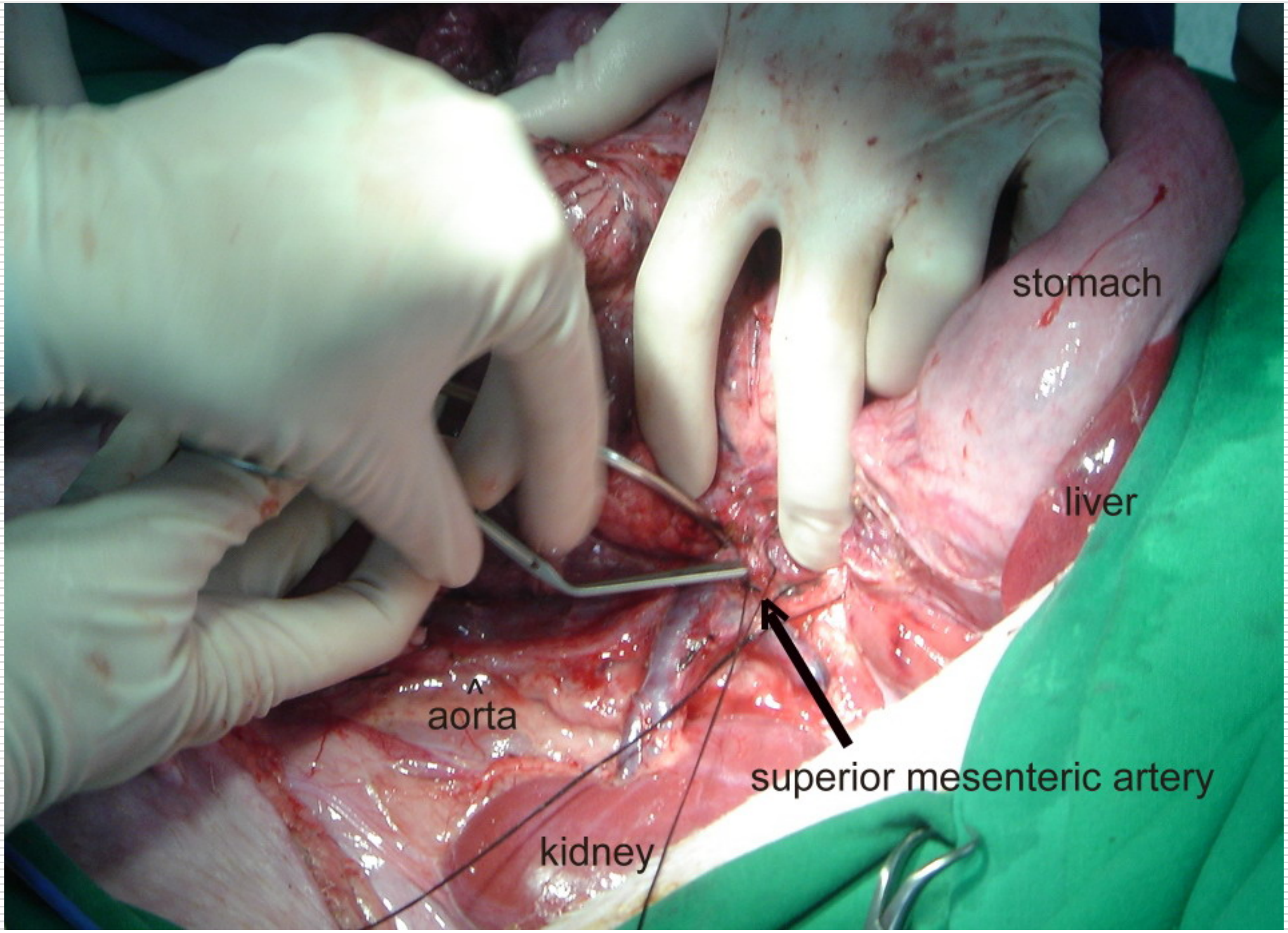
- Bio-signal are nonlinear and non-stationary time series.
- Bio-signal are complex and difficult to be presented precisely by conventional tools.
- The local characteristic parameters are not easy to be discovered when the dynamic changing of bio-signal cannot be extracted.

Material for analysis

- An intestinal artery blocking surgical operation was conducted to a pig.
- The surgical operation was conducted by the surgical team of Far Eastern Memorial Hospital.
- Pig’s intestinal artery was clamped for simulating the situation of intestinal embolism.
- Clamping was released for simulating the normal situation.

The surgical operation was conducted by the surgical team of Far Eastern Memorial Hospital

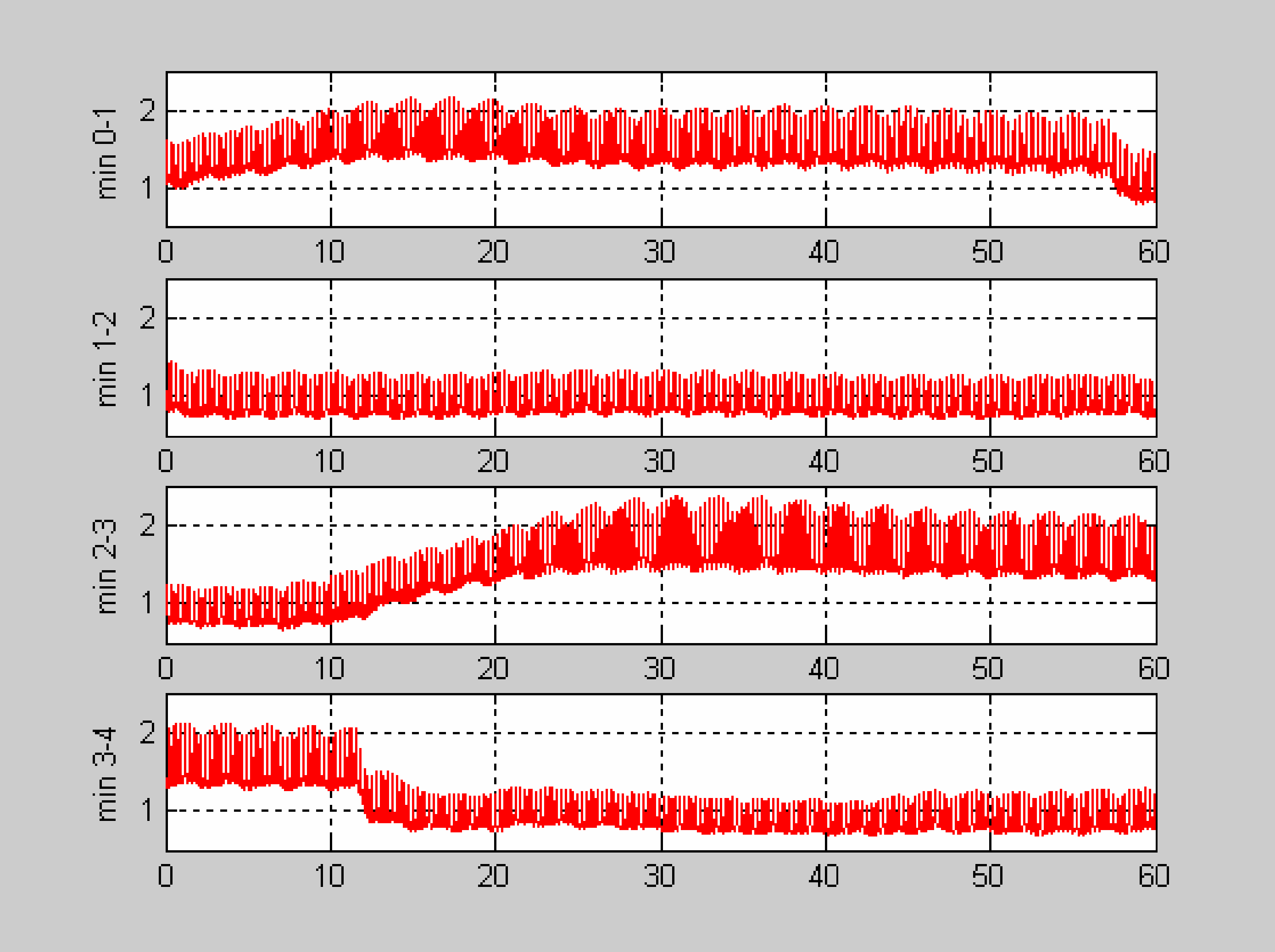
A photo of the surgical operation



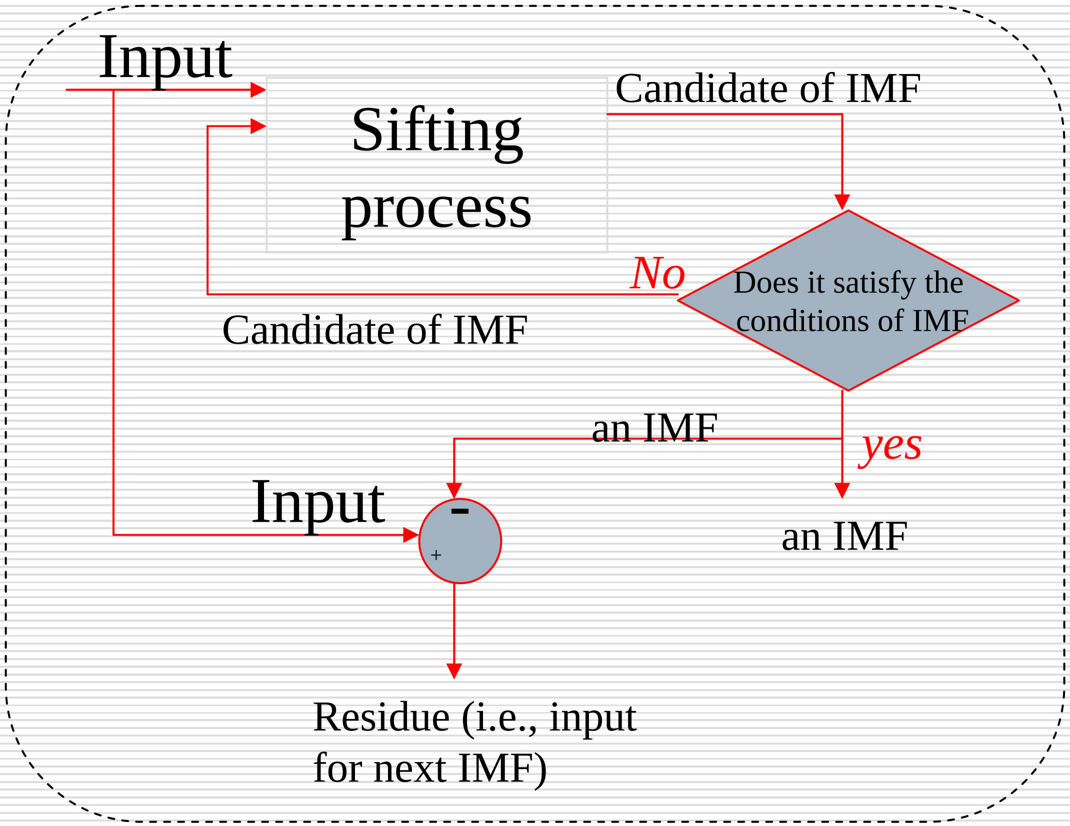
Recording the blood pressure signal

- Pig's intestinal artery was blocked by clamping at first minute.
- Clamping was relaxed at the second minute.
- Two time series datum for two different situations were simulated by clamping and relaxing.
- This procedure, including clamping and relaxing, was repeated two times consecutively .
- Totally, four-minute recording was recorded.

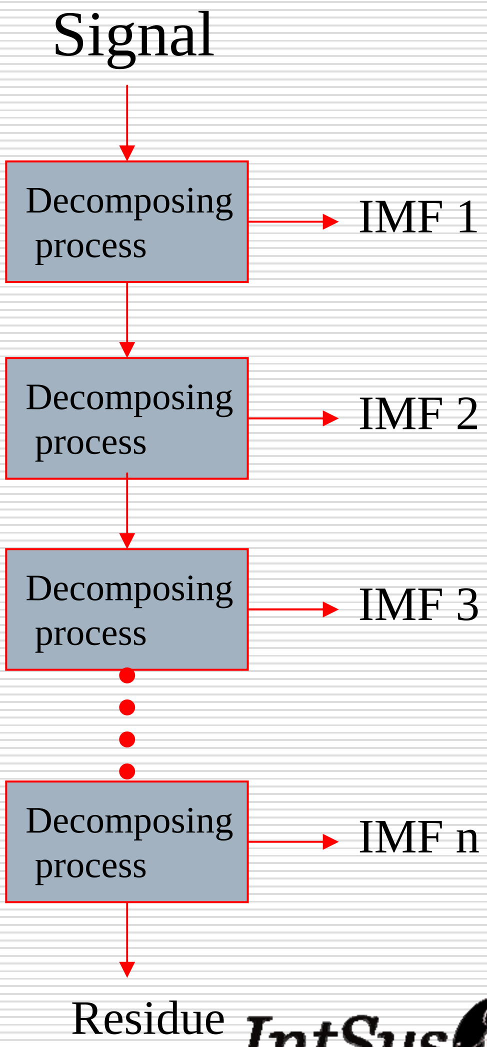
The original recordings of BP



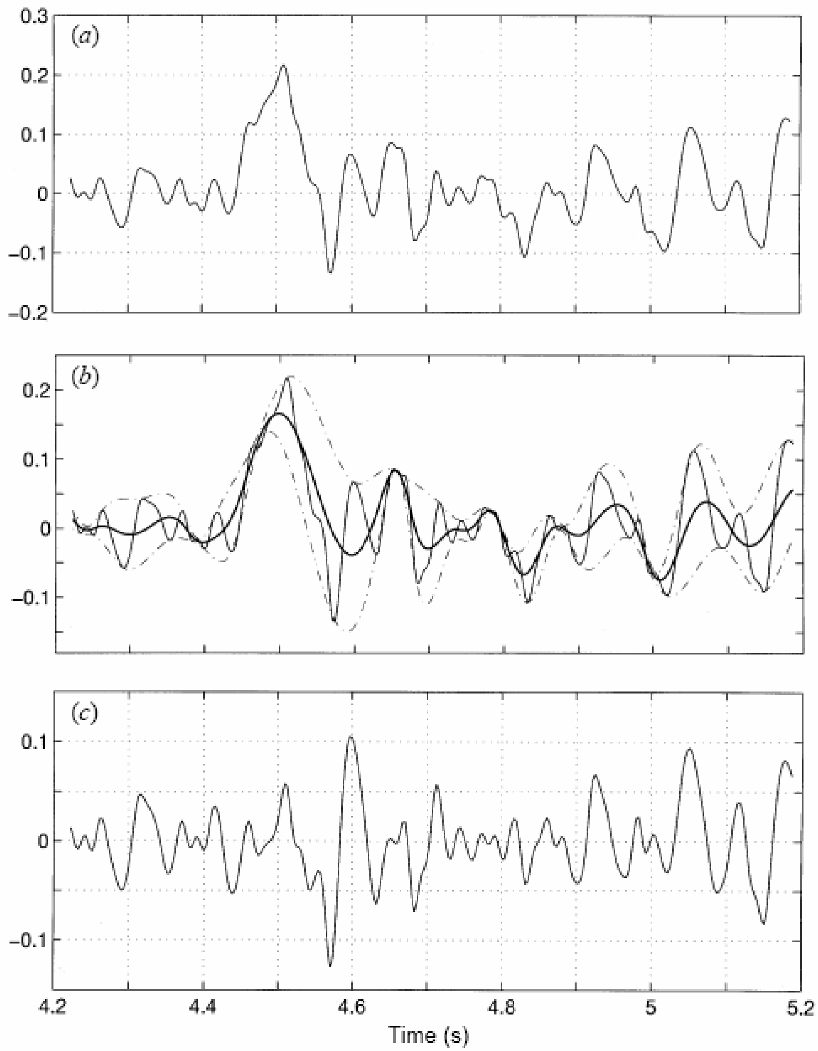
Quick preview of EMD



Schematic of a decomposing process



A Sifting Process



Two difficulties in EMD

- There are two difficulties in the original processing algorithm of EMD.

  - End effects: caused by the sensitivity of cubic spline, which is used to derive upper/lower envelop in sifting process.
  - Mode-mixing: unpredictable turbulence results mode shifting among intrinsic mode functions (IMFs).

How to Solve these Problems

EMD

with

End effects

solve

Wave Extension

with

Mode-mixing

solve

A noise assisted method of ensemble EMD (EEMD)

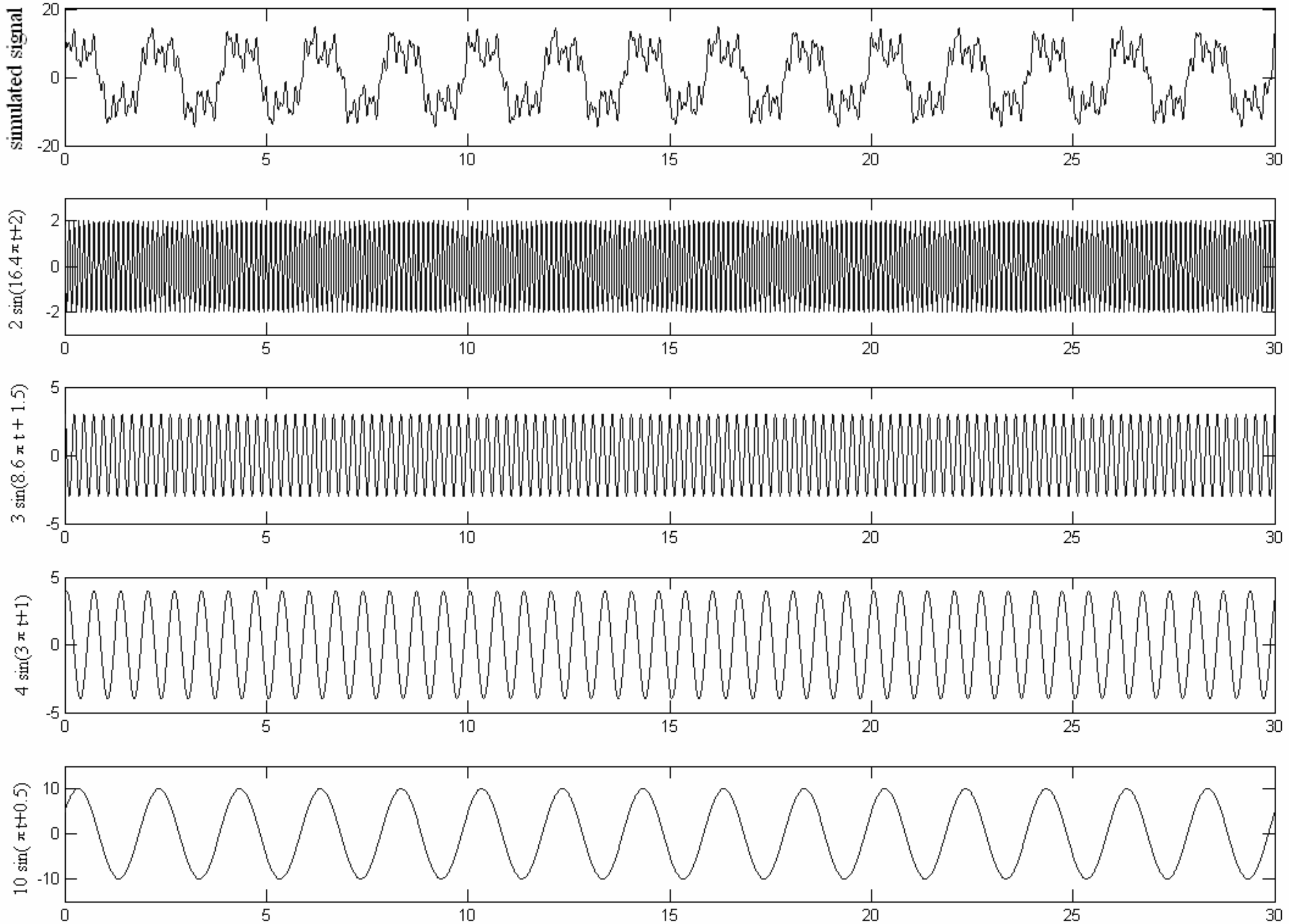
leave

Residue of added noises

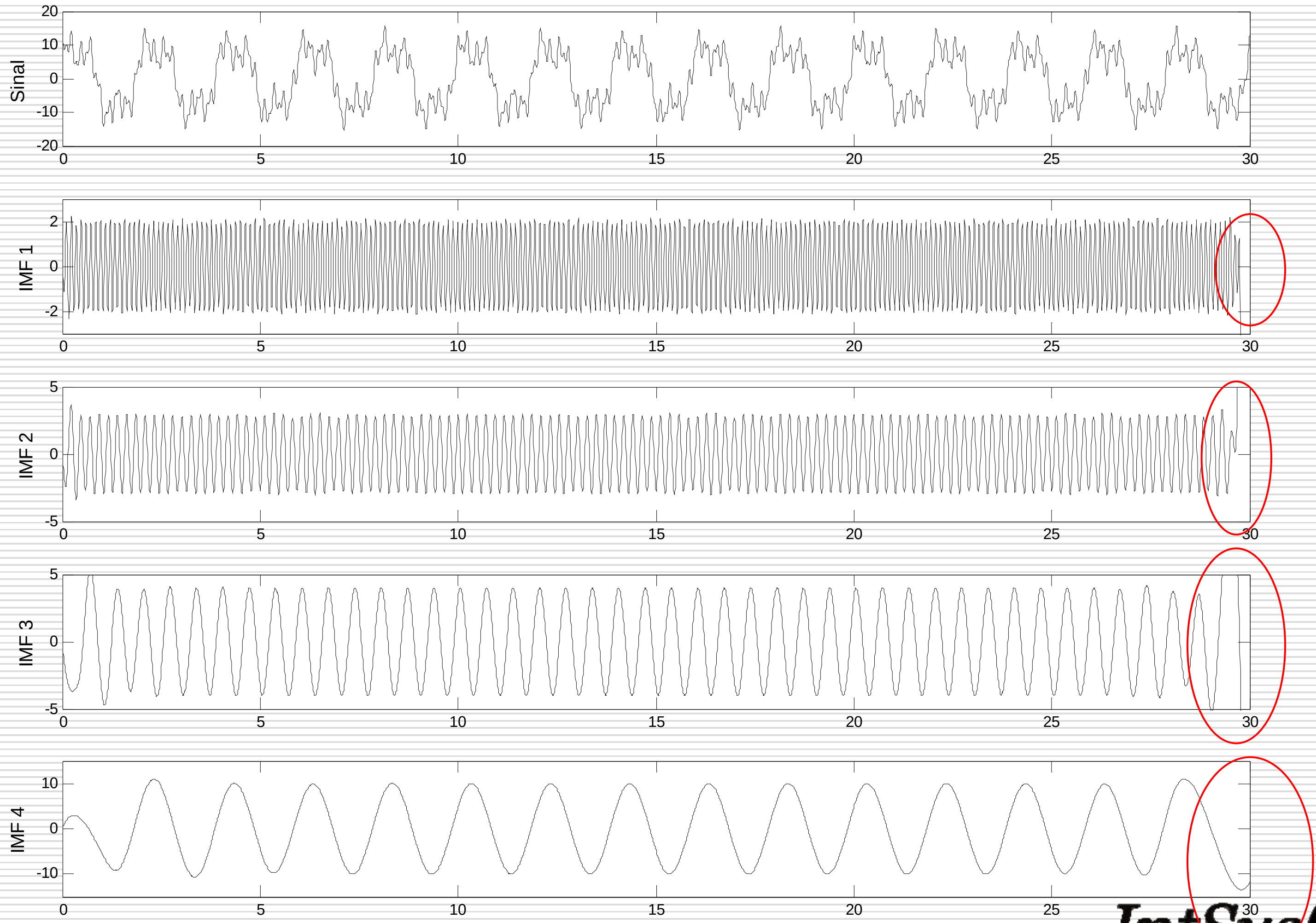
eliminate

A noise enhanced method of Complementary EEMD (CEEMD)

How to Solve End effects (via a Numerical Simulation)



End effects happening in These IMFs



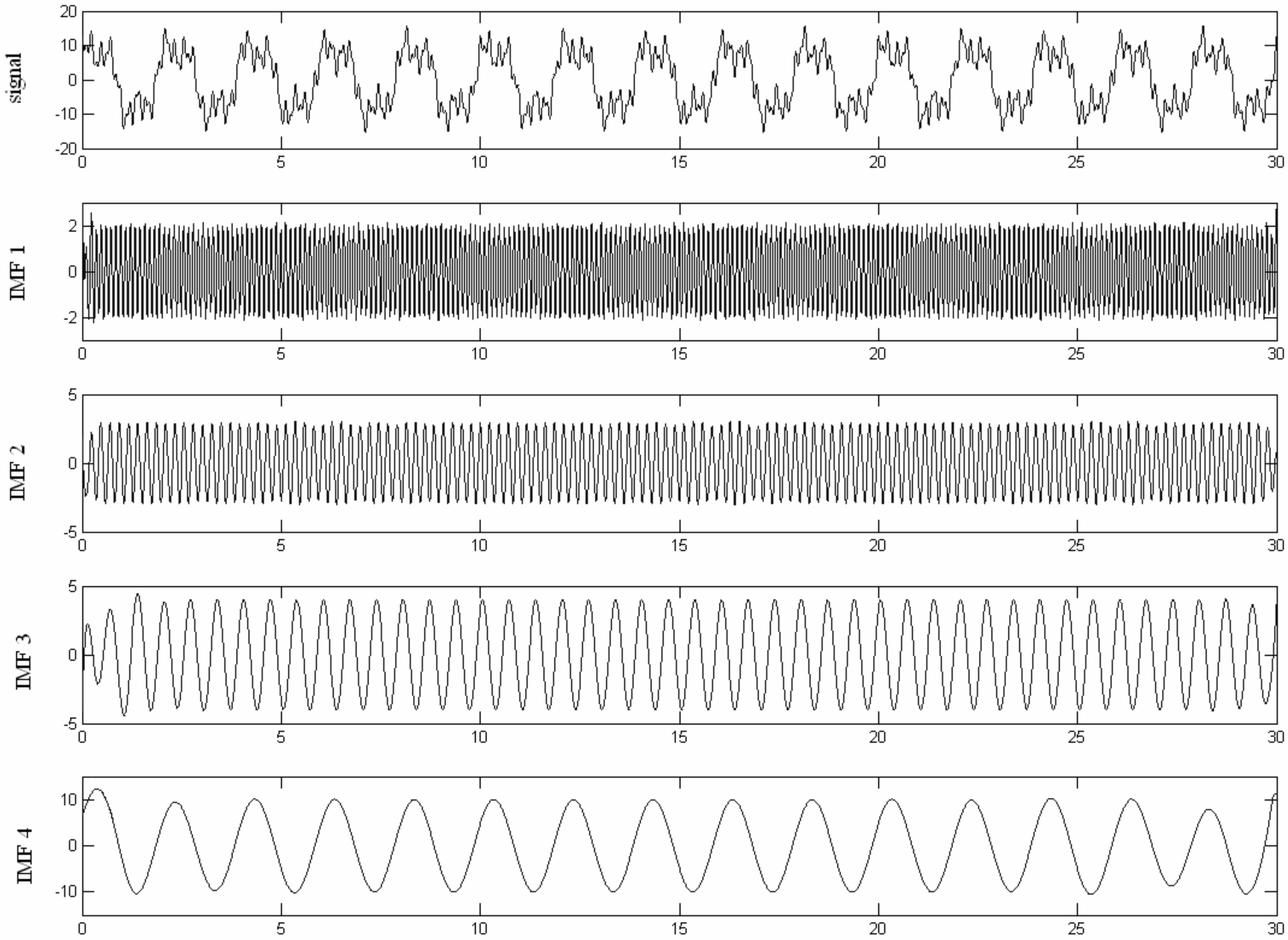
Wave Extension Method

In the wave extension method, the distortion can be reduced by extending both the beginning and end of the data using typical sine waves.

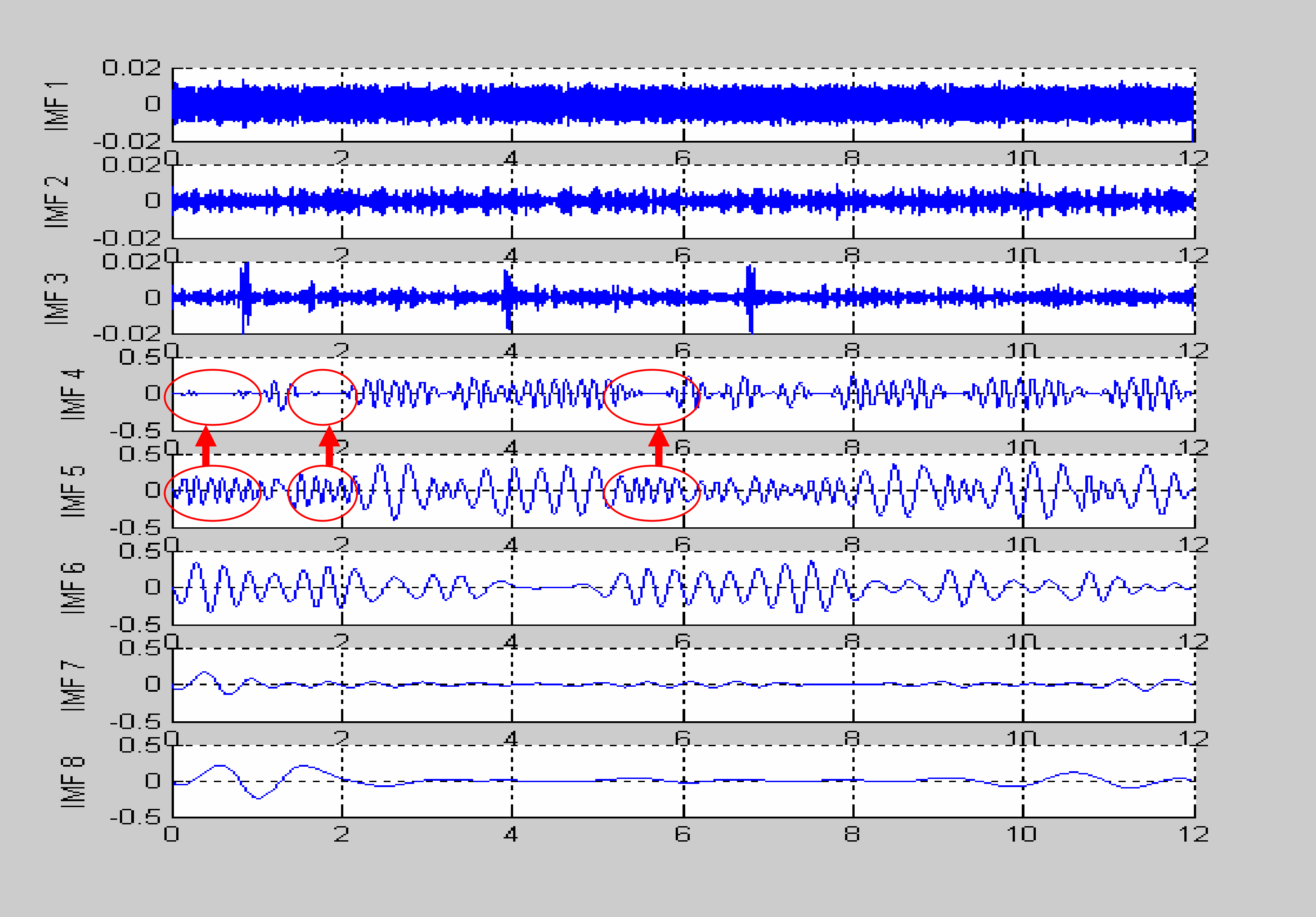
$$W_{extension} = A\sin\left(\frac{2\pi \cdot t}{p} + phase\right) + LocalMean$$

where *A* is the amplitude and *p* is the period of a typical sine wave, these two parameters (i.e., *A* and *p)* can be determined by the closest local extrama. A typical sine wave should be extended to the next minimum and maximum for both the beginning and the end of signal in every sifting process.

End Effects Reduced in These IMFs



Phenomenon of mode-mixing

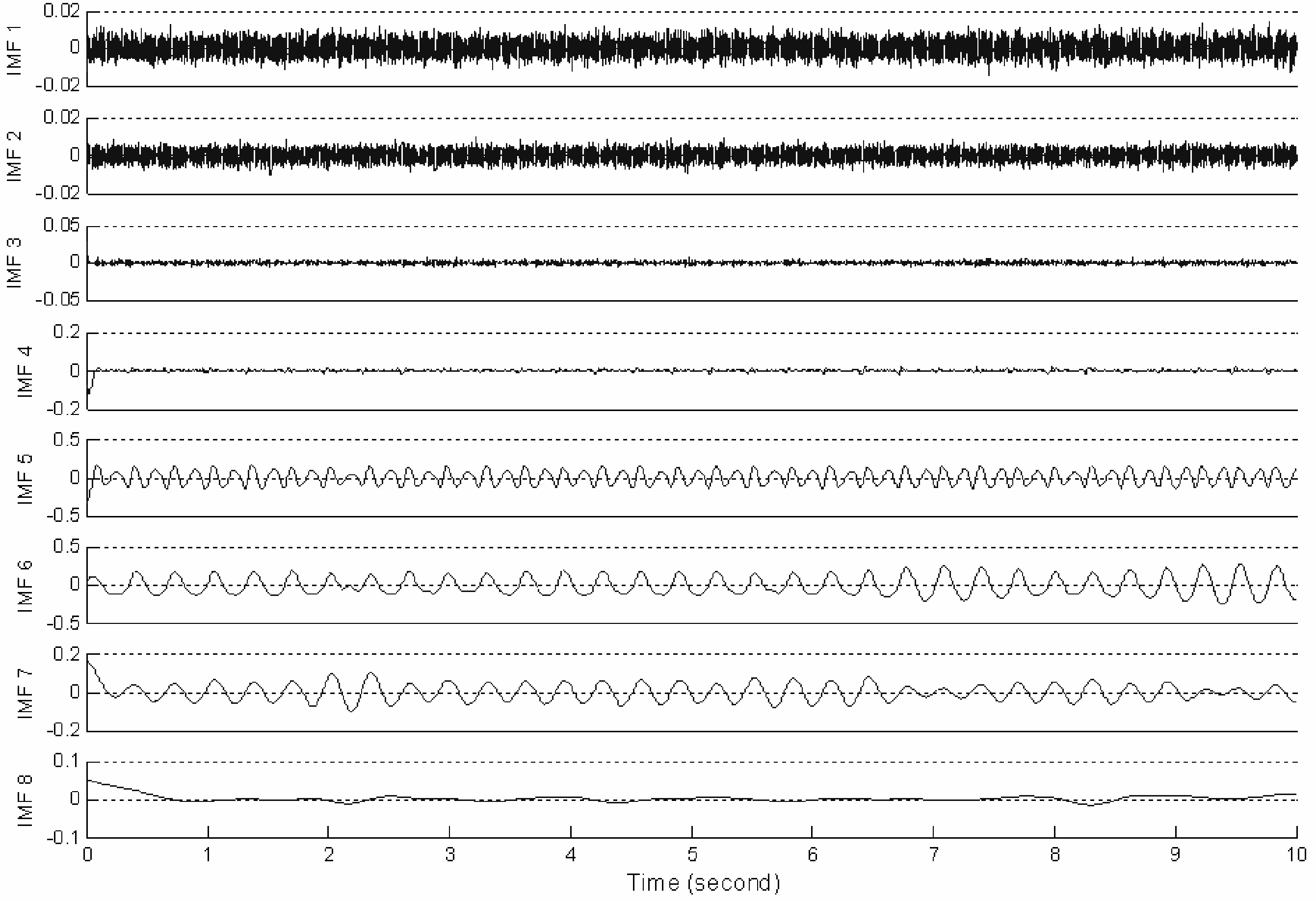


An example using a pig's blood pressure

A noise assisted method – ensemble EMD

In EEMD, a set of white noises with tuned amplitude (i.e., 0.1~0.2 time of the standard deviation of the original signal) are added to the original signal to generate a mixture of the signal and the added white noise. Therefore, we can derive a set of ensemble IMFs by averaging the IMFs decomposed from different mixtures.

IMFs decomposed from a pig's blood pressure by EEMD



Two difficulties of EEMD

Theoretically, the residue of added white noises is completely eliminated when numerous white noises have been used to generate the ensemble IMFs. Howerevr, there are still two difficulties for EEMD:

- It is impossible to complete the process of adding infinite white noises.
- It is time-consuming in the process of EEMD

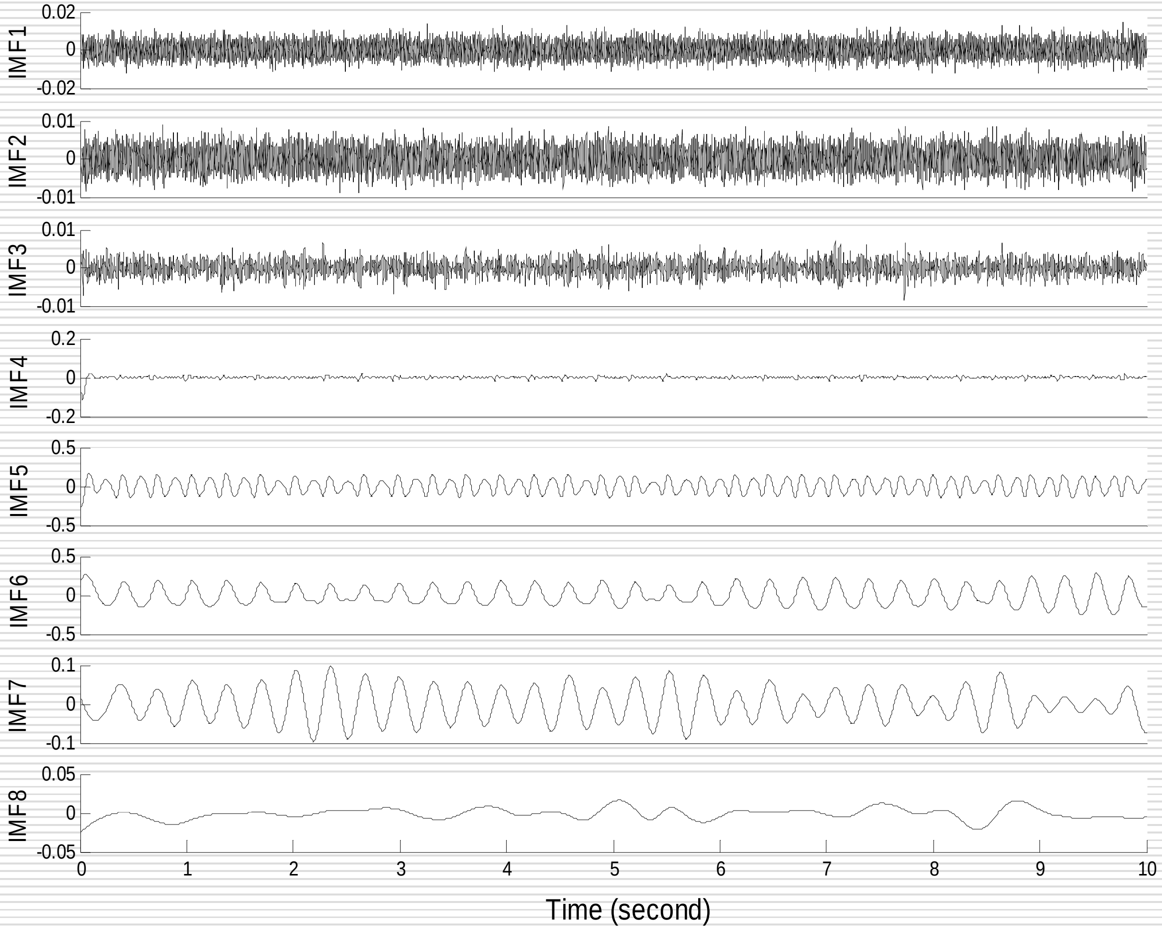
Complementary EEMD (CEEMD)

- CEEMD extends the concept of EEMD method by generating two sets of ensemble IMFs, ensemble IMFs with positive and negative residues of added white noises
- The final ensemble IMFs without residue of white noises can be derived by the following equation:

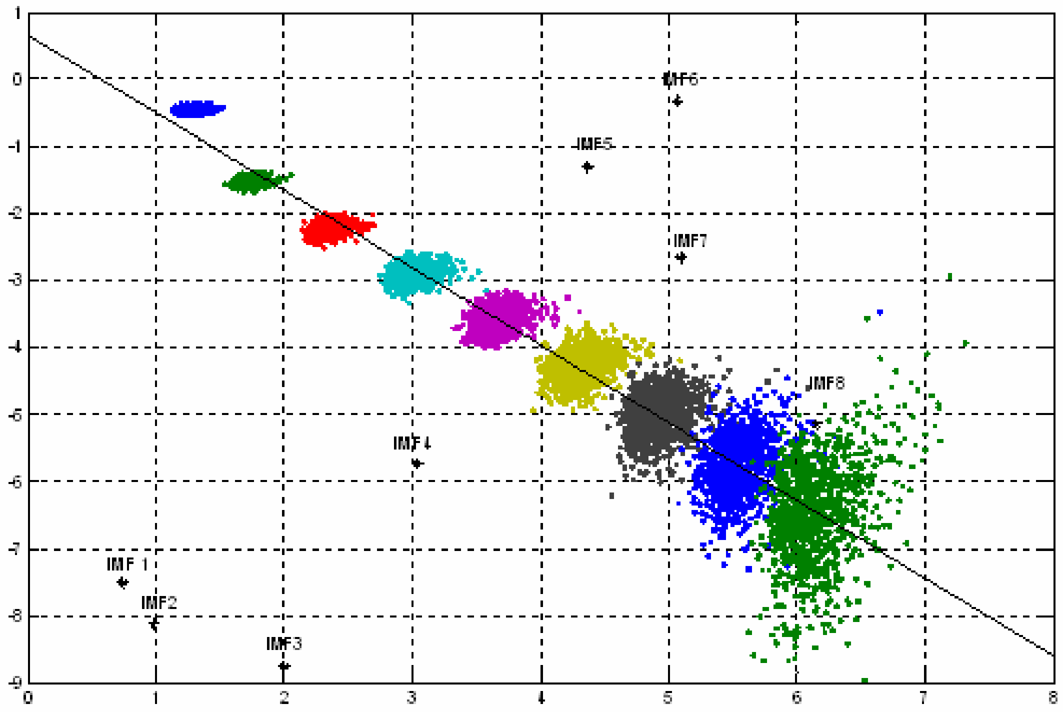
$$\begin{bmatrix} IMF_s \\ IMF_N \end{bmatrix} = inv\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} IMF_p \\ IMF_n \end{bmatrix}$$

Where *IMFp* is the ensemble IMF with positive residue of added white noises; *IMFn* is the ensemble IMF with negative residue of added white noises; *IMFS* is the final ensemble IMF without the residue of added white noises; *IMFN* is the part of ensemble IMF, which is contributed by the added white noises.

IMFs decomposed from a pig's blood pressure by CEEMD

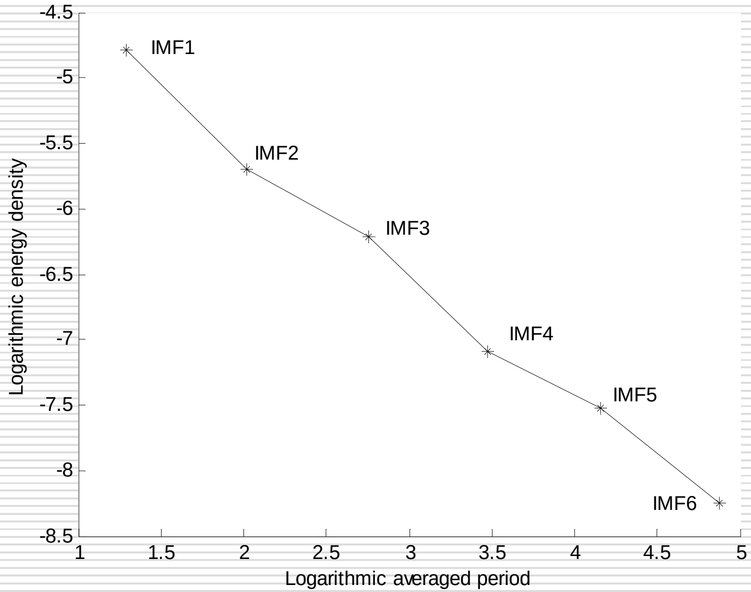


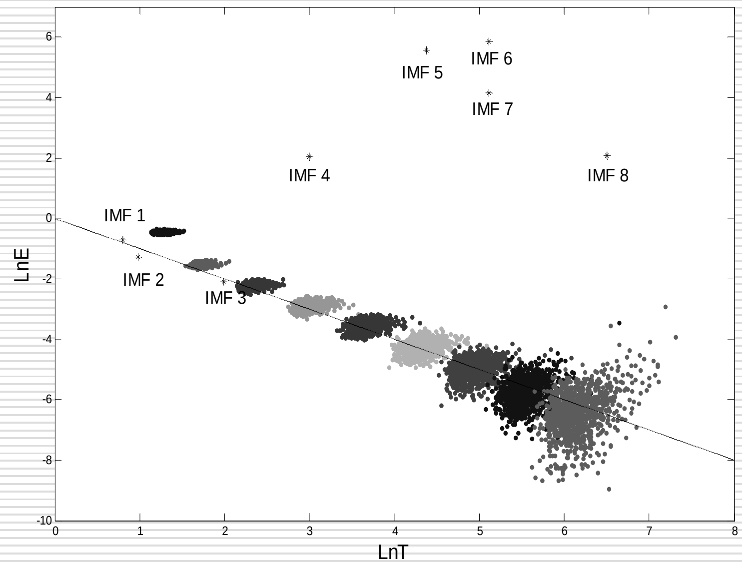
Which are the significant components for the original signal



Monte Carlo Verification

Energy density-averaged period plot for different signals

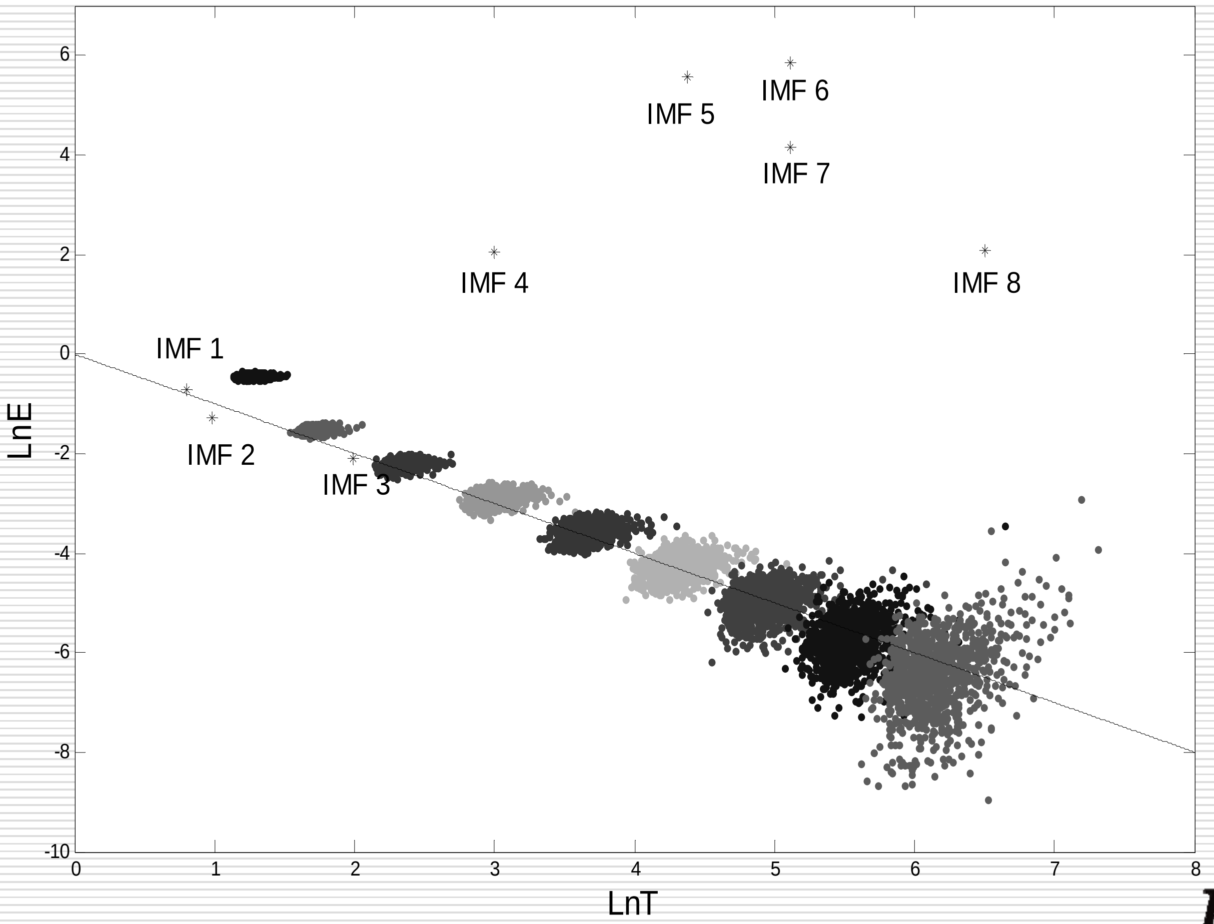




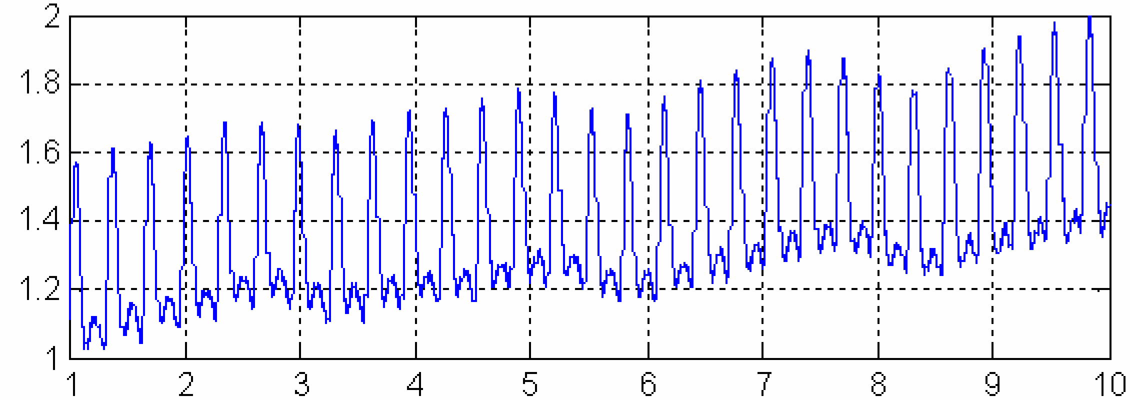
Energy density-averaged period plot
For a broad-band signal

Energy density-averaged period plot
For a narrow-band signal

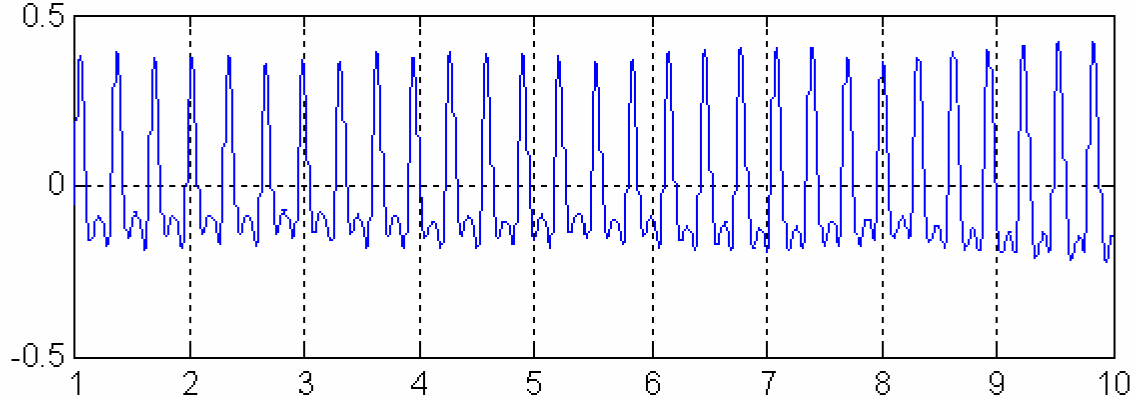
Reconstructing the main waveform and riding wave according to results of Monte Carlo verification



Reconstructing the main waveform

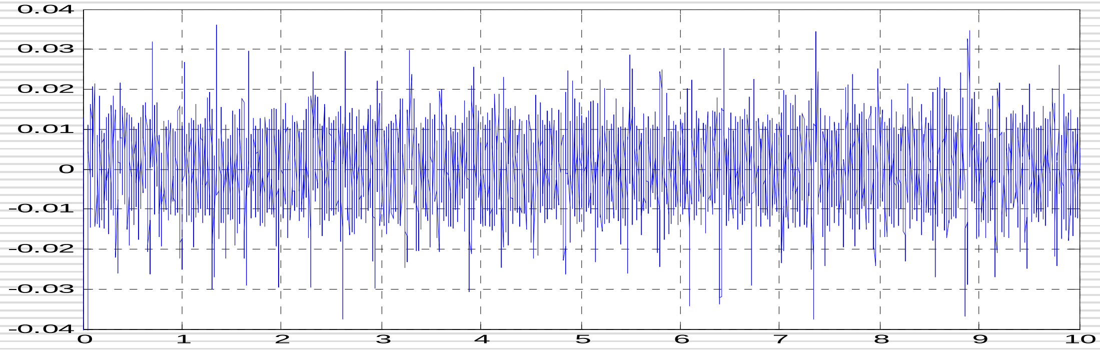


(a) IMF4~IMF8 & Residue signals

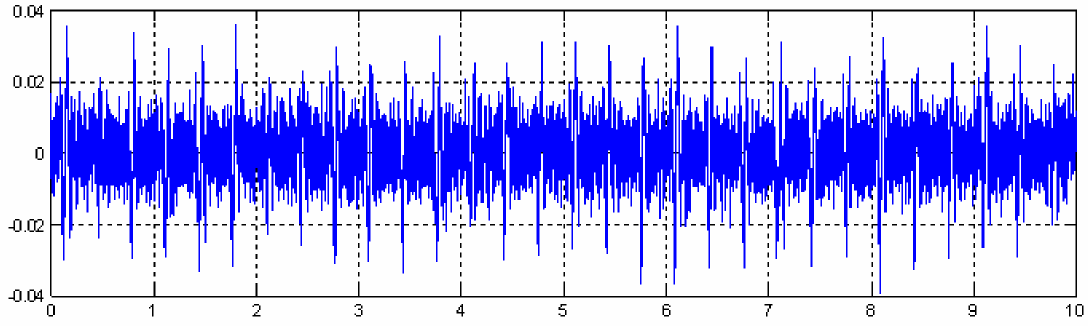


(b) IMF4~IMF8

The rest parts of original signal



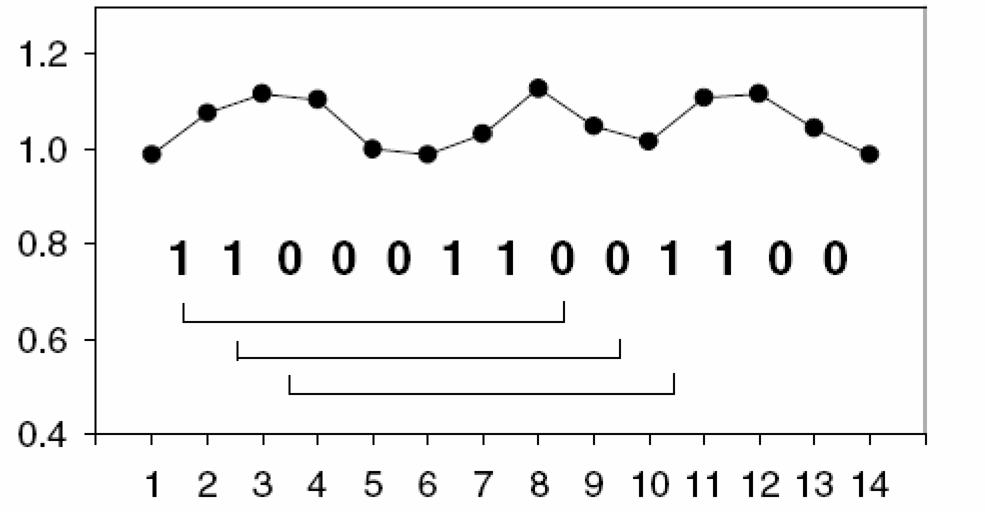
The reconstructed signal by IMFs 1-3 (experimental sample)



The reconstructed signal by IMFs 1-3 (control sample)

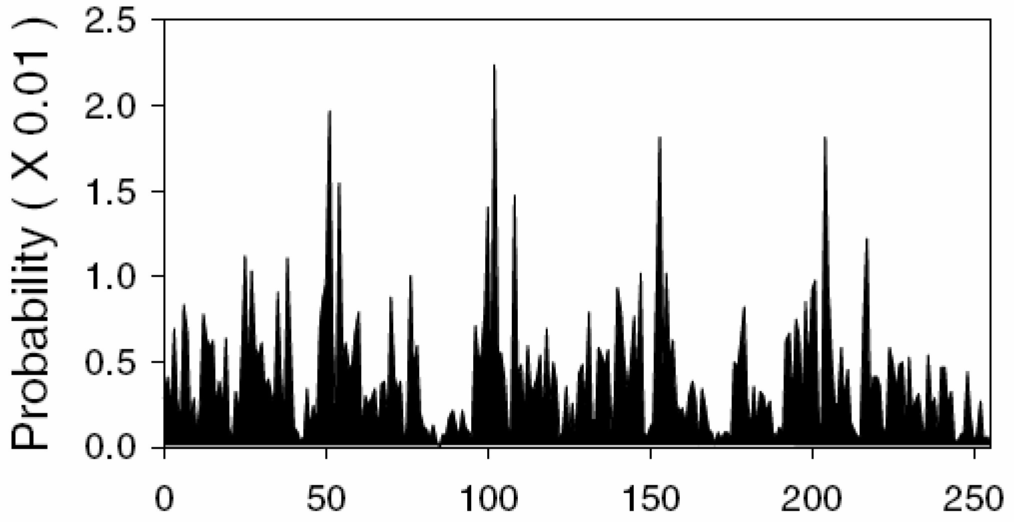
Linguistic analysis (I)

- The complex time series can be simplified via mapping time series to binary sequences, where the increase and decrease of voltage values are denoted by 1 and 0.
- Then, map successive binary sequence of length 8 called an 8-bit word. Each word represents a unique pattern of fluctuations in the time series.

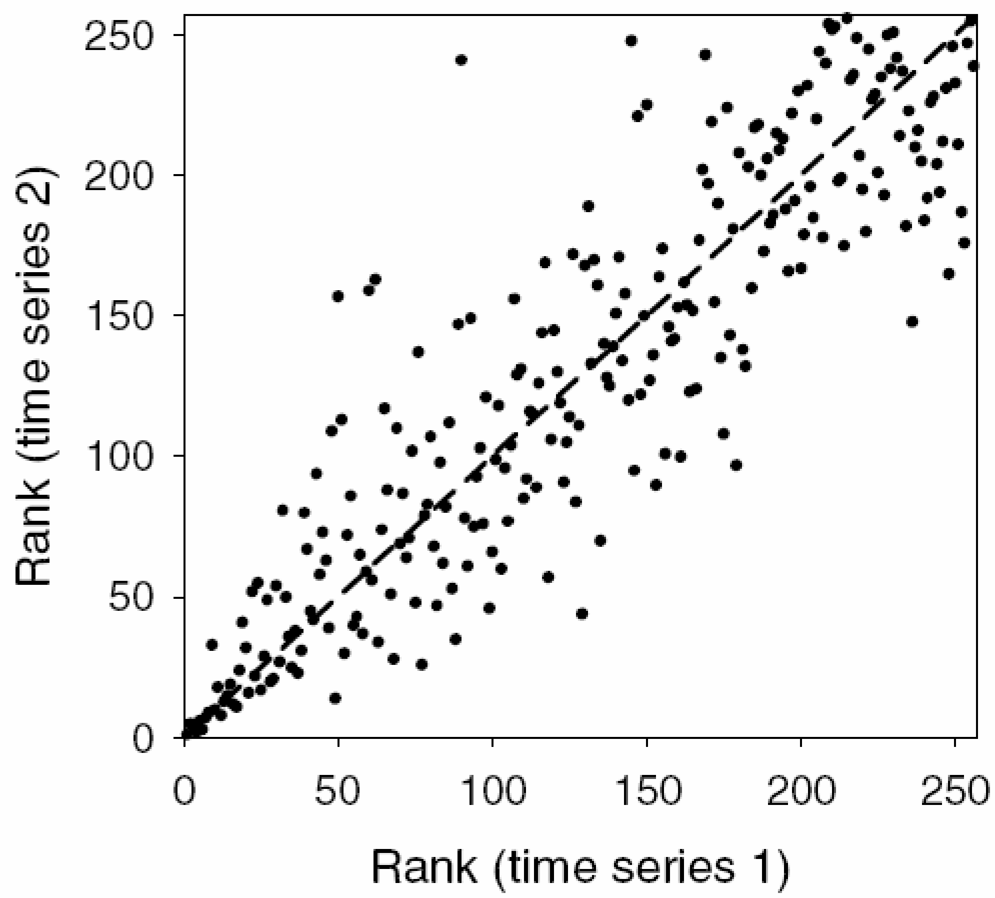


Linguistic analysis (II)

- By shifting one sampling point at a time, a collection of 8-bit words over the whole time series is derived.
- Count the frequencies of occurrences of different words and sort them according to descending frequency. Thus, the order ranks of frequency distribution is obtained.



Similarity between two time series (III)



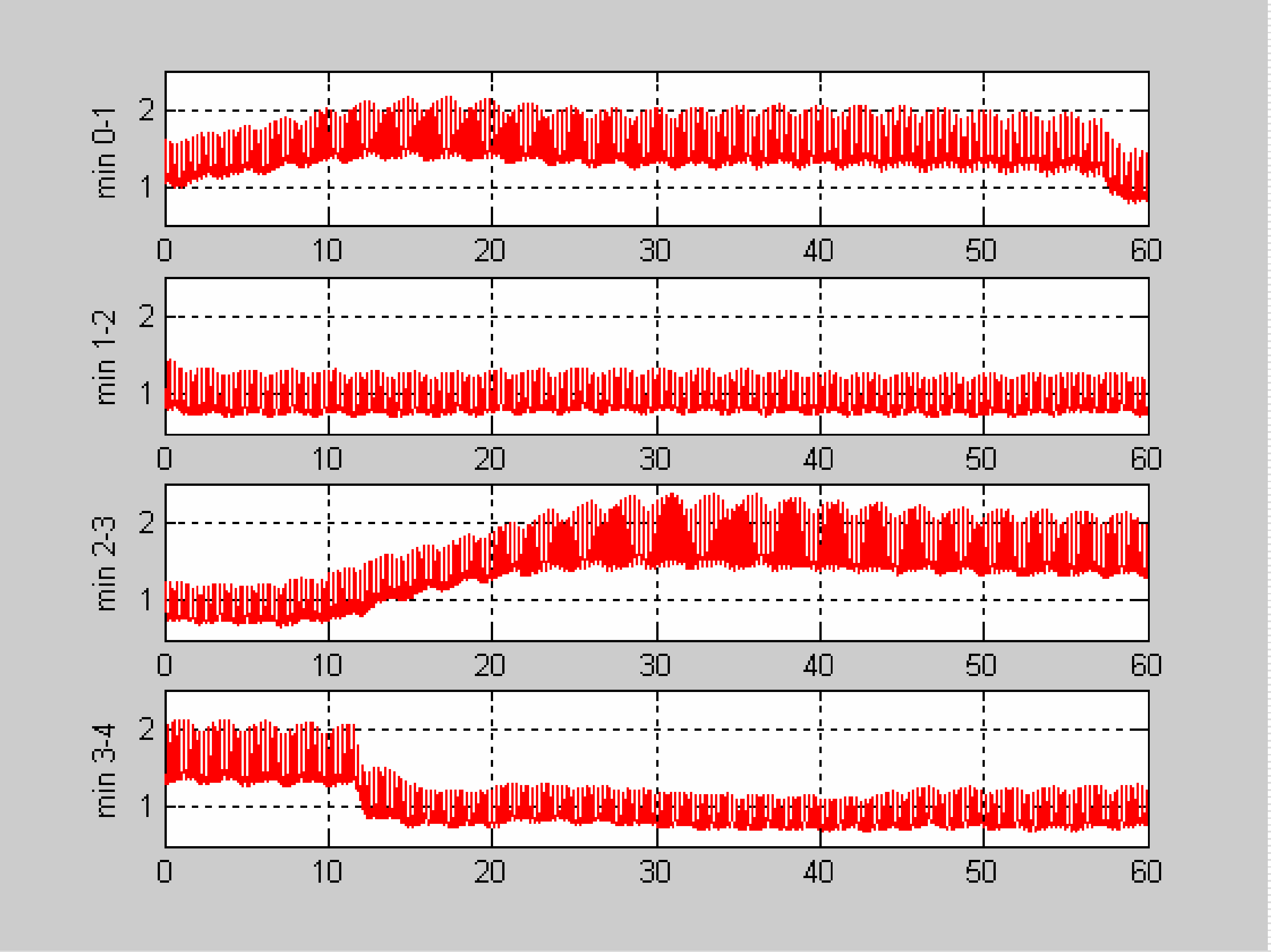
Quantitative measurement of Similarity

- Define a measurement of similarity between two time series, a weighted distance, *Dm*, between to symbolic sequences ,*S1* and *S2*.

$$D_m(S_1,S_2)=\frac{\sum_{k=1}^{2^m}\left|R_1(w_k)-R_2(w_k)\right|\cdot p_1(w_k)p_2(w_k)}{\left(2^m-1\right)\sum_{k=1}^{2^m}p_1(w_k)p_2(w_k)}$$

- Two time series with similar patterns of fluctuations have similar probabilities and ranks of words, and result a smaller distance. Contrastively, two time series with different patterns of fluctuations derives a bigger distance.

The original recordings of BP



Definitions of non-clamping and non-relaxing index

• Two extreme conditions (i.e., artery clamping and relaxing) are selected as two referent patterns.

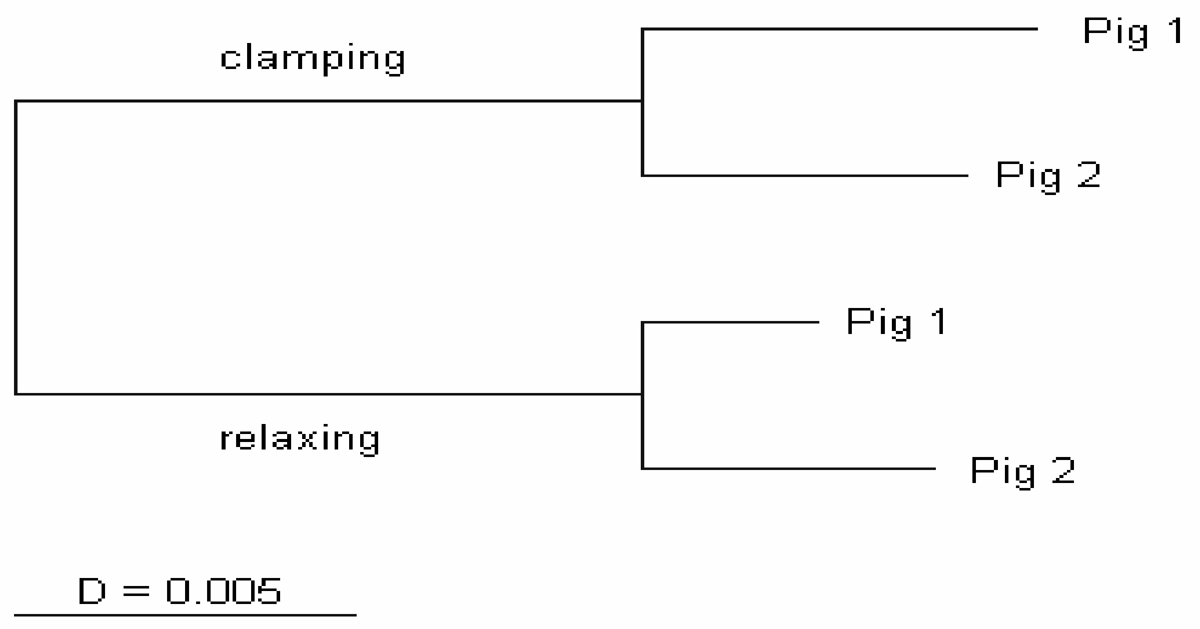
• Non-clamping index: the weighted distance between the sample and referent pattern of clamping

• non-relaxing index: the weighted distance between sample and referent pattern of relaxing.

Comparison between two sets of referent patterns extracted from two pigs

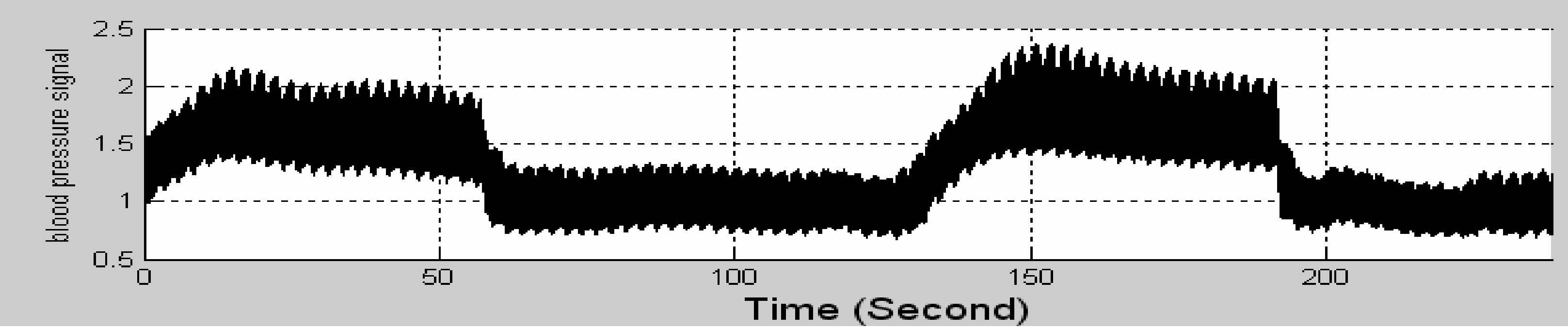
		Pig 1		Pig 2	
		Clamping	Relaxing	Clamping	Relaxing
Pig 1	Clamping	0	0.0268	0.0052	0.0265
	Relaxing	0.0268	0	0.0256	0.0060
Pig 2	Clamping	0.0052	0.0256	0	0.0250
	Relaxing	0.0265	0.0060	0.0250	0

Creating a phylogenetic tree via distant measurements among 4 referent patterns

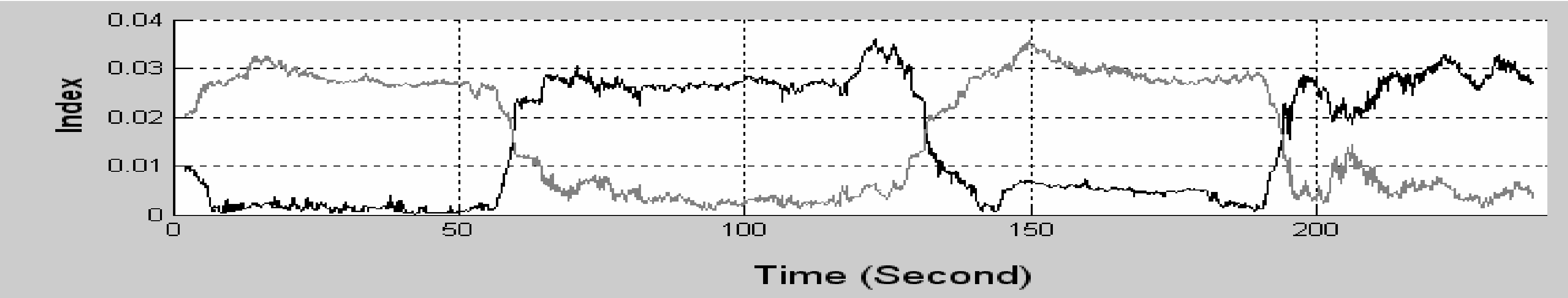


Results of non-clamping and non-relaxing indexes

(a)

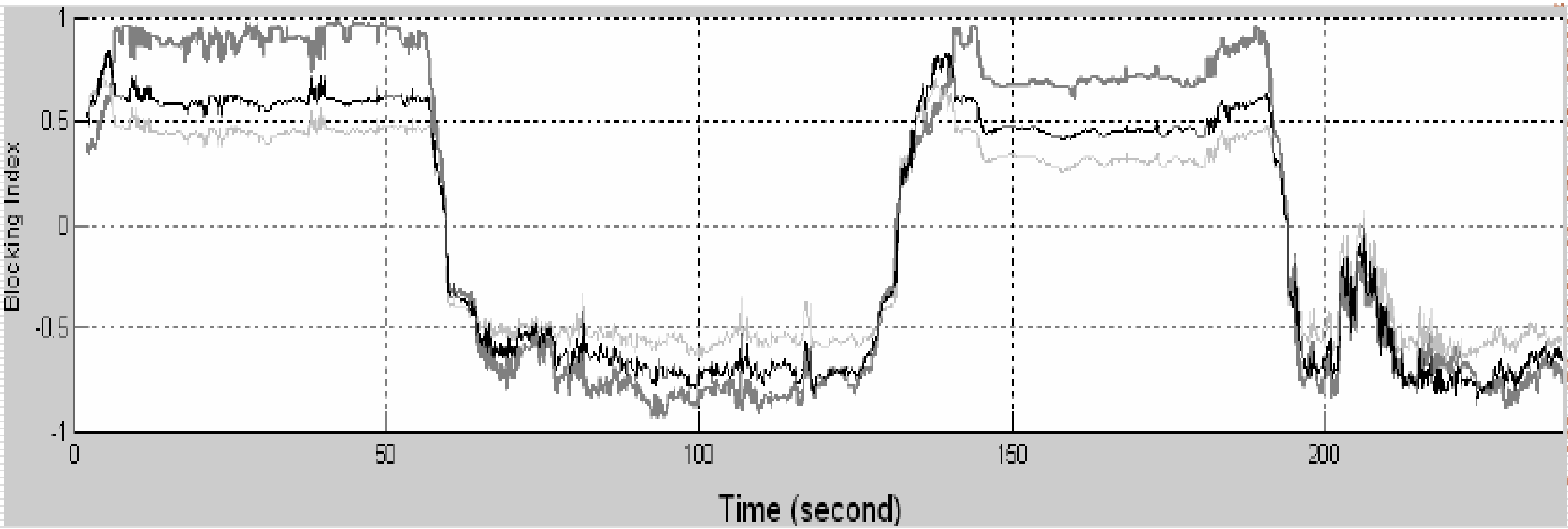


(b)



Analysis results using blocking index

$$I_B = \frac{(I_{NR} - I_{NC})}{(I_{NR} + I_{NC})}$$



Conclusions

- In this investigation, we propose an integrated procedure to verify the pattern of the riding wave of blood pressure signal using CEEMD and linguistic analysis.
- CEEMD was firstly proposed in this investigation, which overcomes the problem of time-consuming in the process of EEMD
- Monte Carlo verification was used to identify the noisy and dominant components of blood pressure.

Thanks for your attention!