Appendix A. Testing Log

Test #	Power	Valve	FB1	FB2	FT1	FT2	FT3	PZTBI	PZTBO	PZTTO	Refe-rence	Binary Data
5/15/2002												
001	off		Noise check									
002	off				× (1)	× (2)	× (3)	× (4)				
003	off							× (1)	× (2)	× (3)		
004	on	open	× (1)	× (2)				× (4)	× (3)			
005	on	open	× (1)		× (2)	× (3)				× (4)		
006	on	open	× (1)		× (2)	× (3)		× (4)				
5/16/2002												
00	on	open			× (1)	× (2)	× (3)	× (4)				×
01	on	open			× (1)	× (2)	× (3)			× (4)		×
02	on	open			× (1)	× (2)	× (3)			× (4)		×
03	on	open			× (1)	× (2)	× (3)			× (4)		×
04	on	open	× (1)	× (2)			× (3)		× (4)			×
05	on	open	× (1)	× (2)			× (3)		× (4)			×
06	on	open					× (3)	× (2)	× (4)	× (1)		×
07	on	open					× (3)	× (2)	× (4)	× (1)		×
08	on	open	× (1)	× (3)				× (2)	× (4)			×
09	on	open	× (1)	× (3)				× (2)	× (4)			×
5/17/2002												
007	on	shut	× (1)	× (2)				× (3)	× (4)			×
008	on	shut			× (1)		× (2)	× (3)	× (4)			×
009	on	open	× (1)	× (2)				× (3)	× (4)			×
010	on	shut	× (1)	× (2)				× (3)	× (4)			×
011	on	open			× (1)		× (2)		× (4) (PZTBS)		× (3)	×
012*	on	open	× (1)	× (2)		× (4)		× (3)				×
013*	on	open	× (1)	× (2)			× (4)	× (3)				×
015*	on	open	× (1)	× (2)			× (4)	× (3)				×
016*	on	open	× (1)	× (2)	× (4)			× (3)				×
017*	on	open	× (1)	× (2)			× (4)	× (3)				×
018*	on	open	× (1)	× (2)			× (4)	× (3)				×
019*	on	open	× (1)	× (2)			× (4)	× (3)				×
022*	on	open	× (1)	× (2)			× (4)	× (3)				×
023*	on	open	× (1)	× (2)			× (4)	× (3)				×
024*	on	open	× (1)				× (4)	× (3)			× (2)	×
025*	on	open	× (1)	× (3)			× (4)				× (2)	×
026*	on	open	× (1)	× (3)			× (4)				× (2)	×
5/18/2002												
027*	on	shut	× (1)	× (3)			× (4)				× (2)	
028*	on	shut	× (1)	× (3)			× (4)				× (2)	
029*	on	shut	× (1)	× (3)			× (4)				× (2)	
030*	on	shut	× (1)	× (3)			× (4)				× (2)	
031*	on	shut	× (1)	× (3)			× (4)				× (2)	
032*	on	shut	× (1)				× (4)	× (3)			× (2)	
033*	on	shut	× (1)	× (3)			× (4)				× (2)	
035*	on	open	× (1)				× (4)	× (3)			× (2)	
036*	on	open	× (1)				× (4)	× (3)			× (2)	
037*	on	open	× (1)				× (4)	× (3)			× (2)	
039*	on	open	× (1)				× (4)	× (3)			× (2)	
040*	on	open	× (1)				× (4)	× (3)			× (2)	

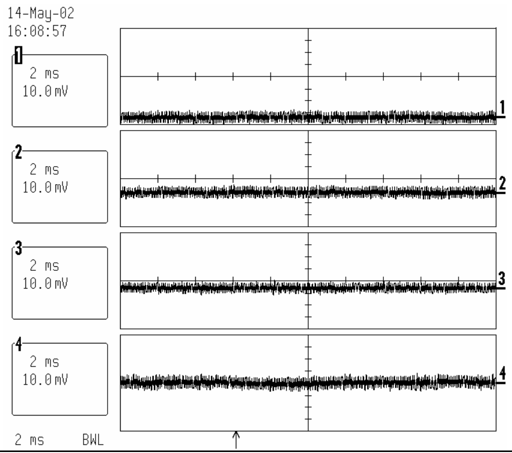
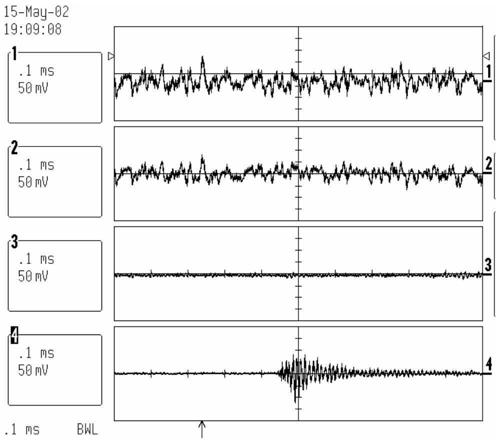
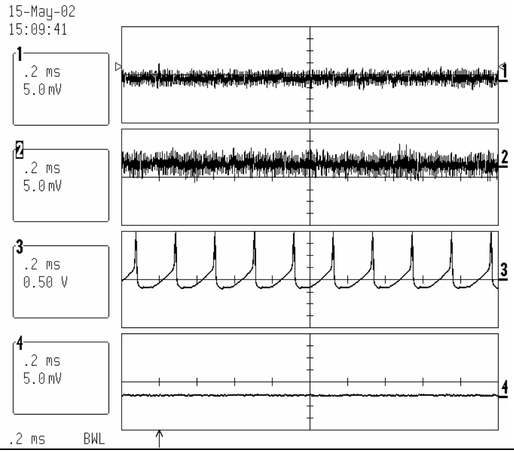
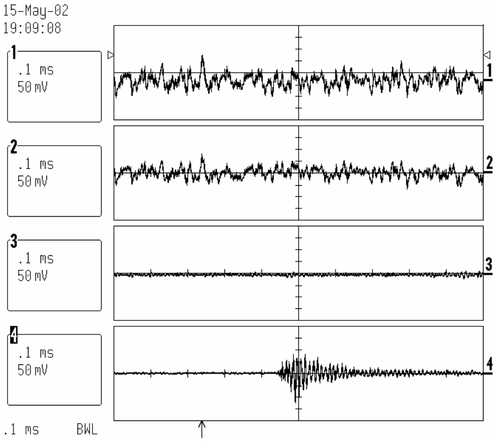
041*	on	open	× (1)				× (4)	× (3)			× (2)	
042*	on	open	× (1)				× (4)	× (3)			× (2)	
043*	on	open	× (1)				× (4)	× (3)			× (2)	
044*	on	open	× (1)				× (4)	× (3)			× (2)	
045*	on	open	× (1)				× (4)	× (3)			× (2)	

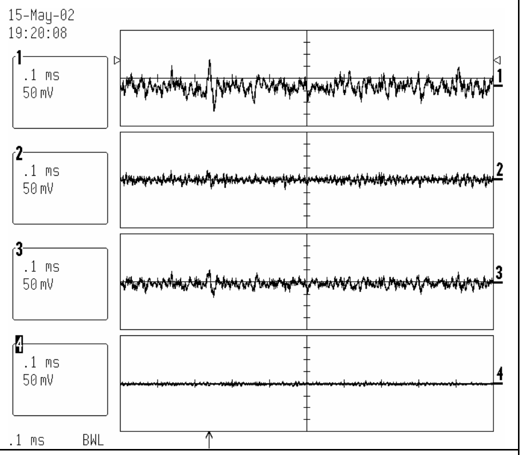
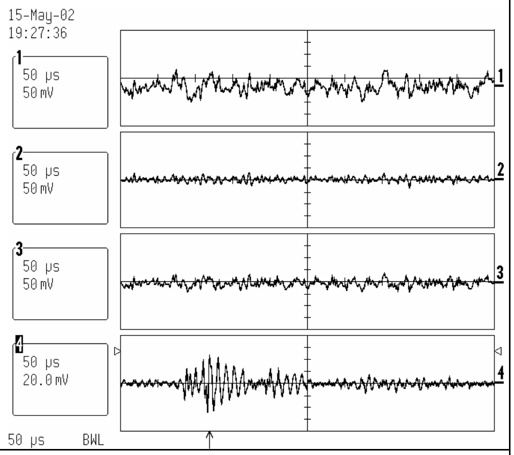
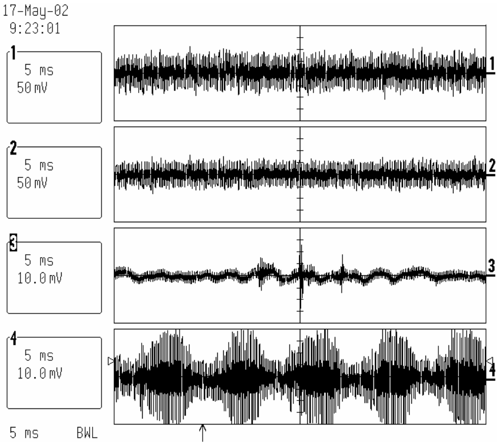
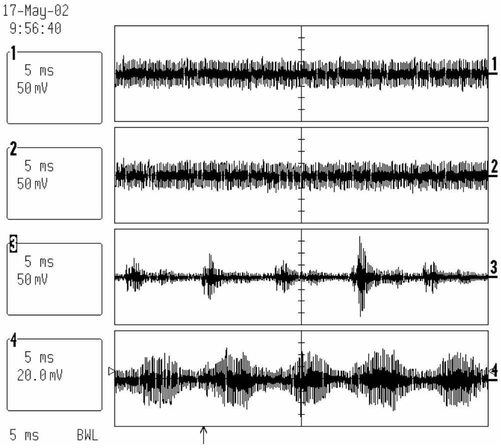
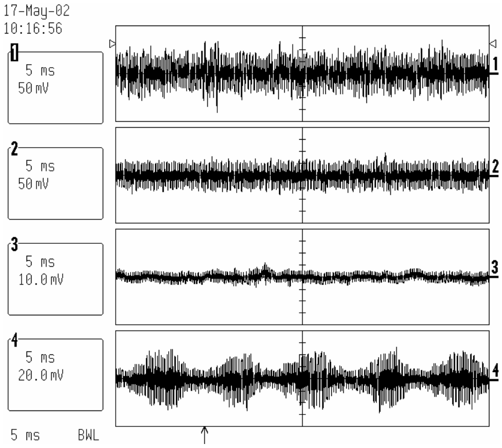
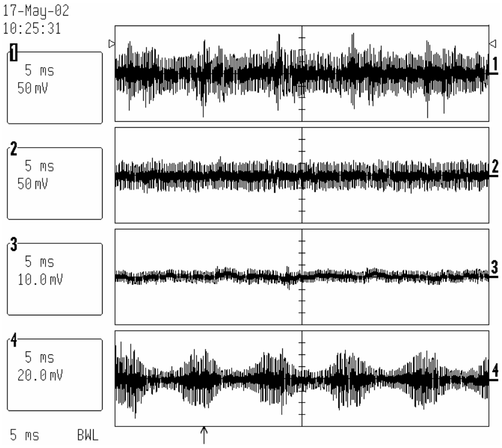
Note: 1. * besides the test number indicates the test was done with magnitude trigger setting.

2. All data have the screen shot graphs available, however only those with '×' in the Binary Data column have the data in binary format which we can further process.

Appendix B. Measurement data sets

The number in the title represents the test number as in Appendix A.

	001 (noise check)  	FT1 FT2 FT3 PZTBI	002 (no power, no fan) 
PZTBI PZTbtw PZTttw	003 (no power, no fan)  	FB1 FB2 PZTbtw PZTBI	004 (power on, fan off, valve open) 

PZTBI PZTbtw PZTttw	005 (power on, fan off, valve open) 	FB1 FB2 PZTbtw PZTBI	006 (power on, fan off, valve open) 
FB1 FB2 PZTBI PZTBO	007 (power on, fan off, valve shut) 	FT1 FT3 PZTBI PZTBO	008 (power on, fan off, valve shut) 
FB1 FB2 PZTBI PZTBO	009 (power on, fan off, valve open) 	FB1 FB2 PZTBI PZTBO	010 (power on, fan off, valve open) 

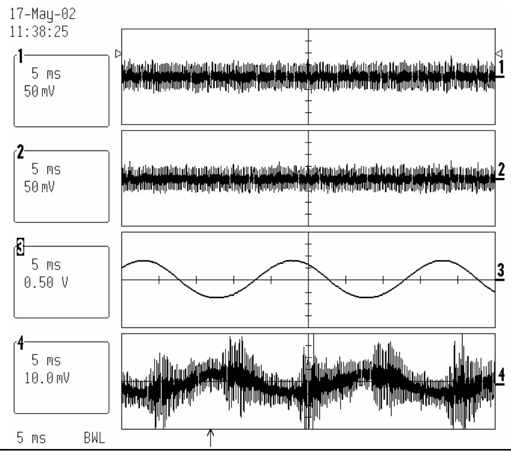
011 (power on, fan off, valve open)

FT1

FT3

Reference

PZTBS



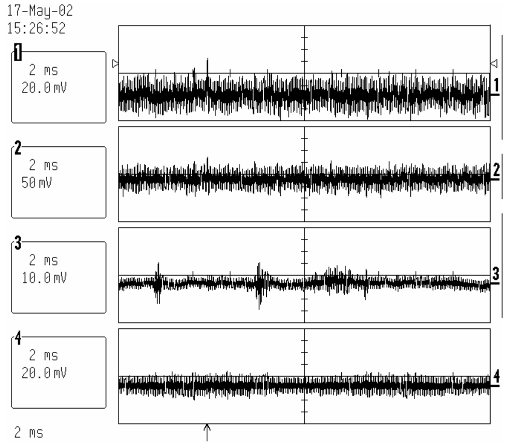
012 (power on, fan off, valve open)

FB1

FB2

PZTBI

FT2



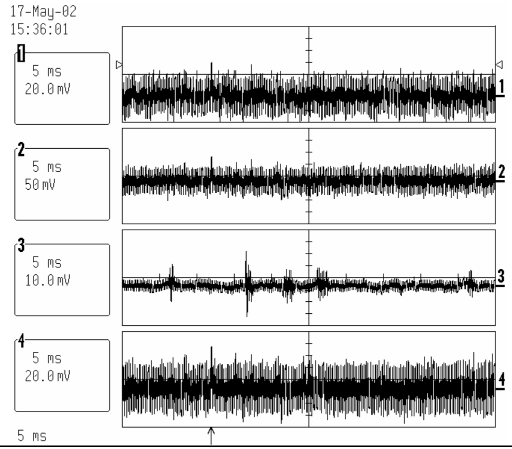
013 (power on, fan off, valve open)

FB1

FB2

PZTBI

FT3



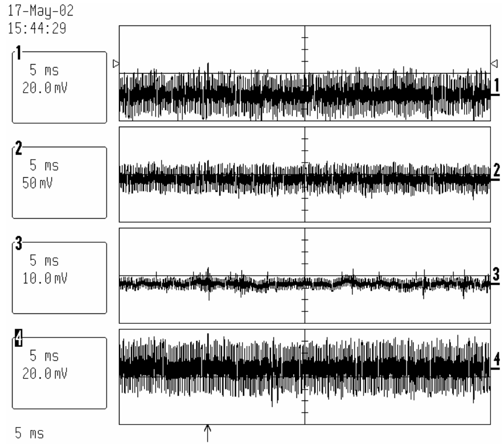
015 (power on, fan off, valve open)

FB1

FB2

PZTBI

FT3



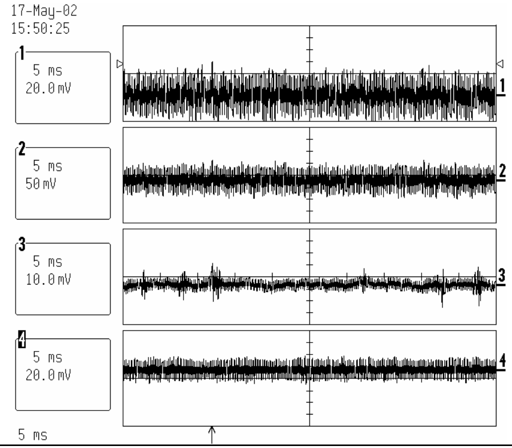
016 (power on, fan off, valve open)

FB1

FB2

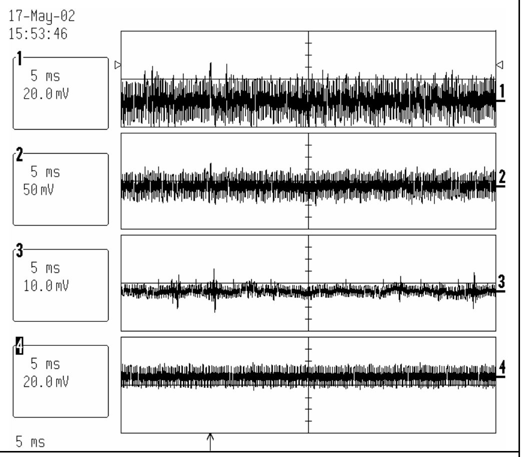
PZTBI

FT1



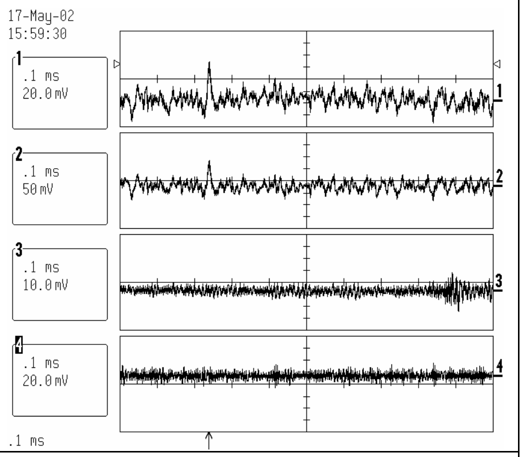
017 (power on, fan off, valve open)

FB1
FB2
PZTBI
FT3



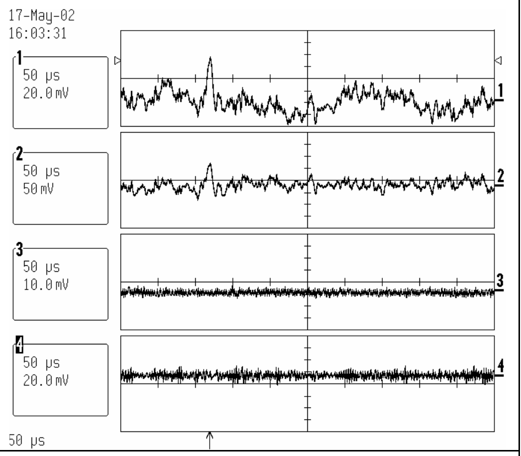
018 (power on, fan off, valve open)

FB1
FB2
PZTBI
FT3



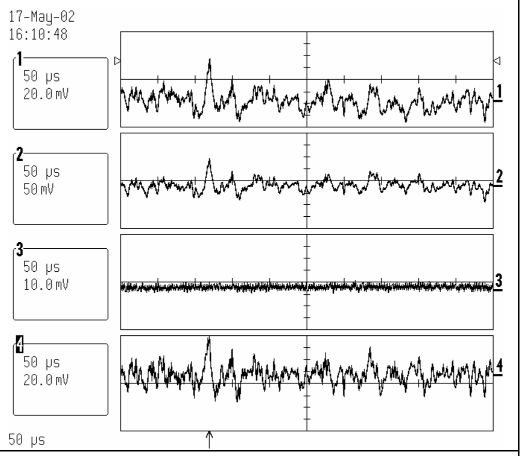
019 (power on, fan off, valve open)

FB1
FB2
PZTBI
FT3



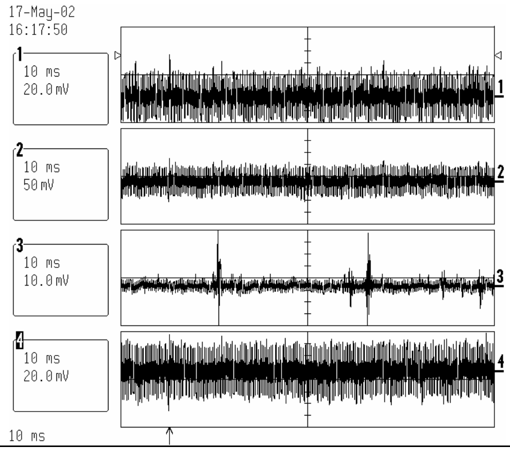
022 (power on, fan off, valve open)

FB1
FB2
PZTBI
FT3



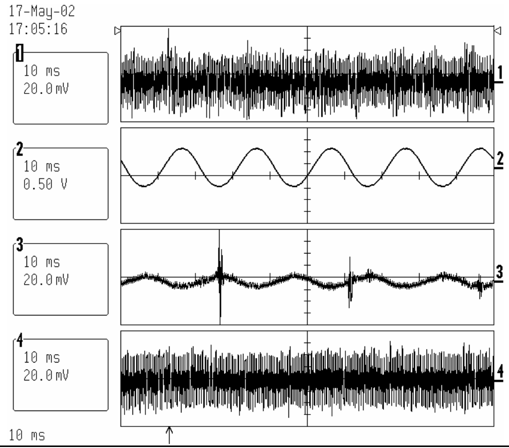
023 (power on, fan off, valve open)

FB1
FB2
PZTBI
FT3



024 (power on, fan off, valve open)

FB1
Reference
PZTBI
FT3



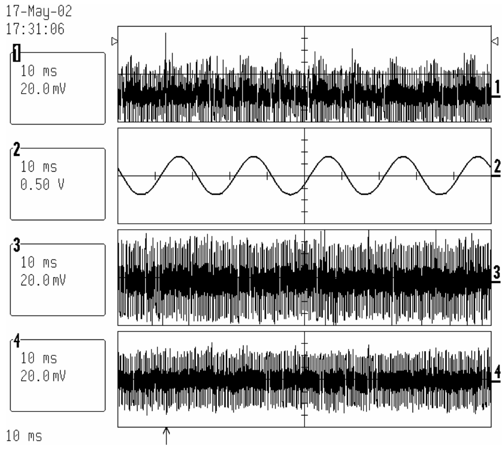
025 (power on, fan off, valve open)

FB1

Reference

FB2

FT3



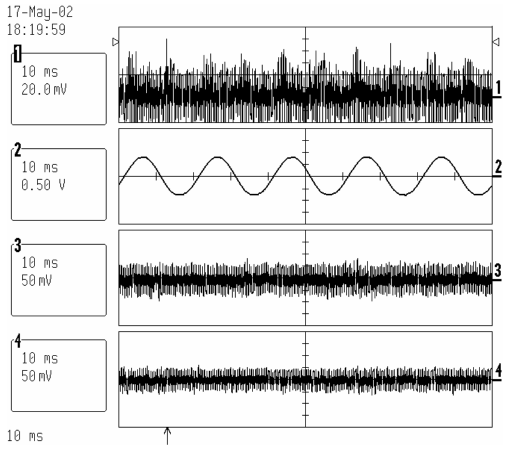
026 (power on, fan off, valve open)

FB1

Reference

FB2

FT3



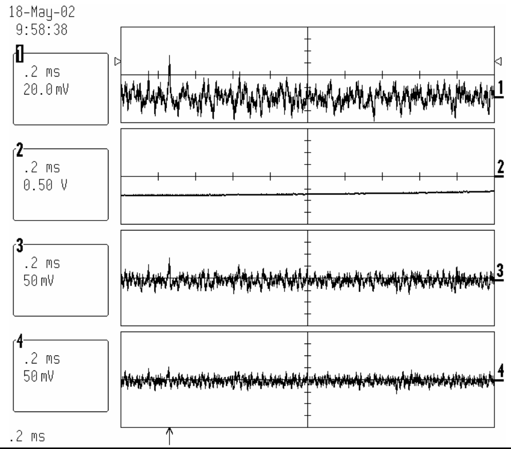
027 (power on, fan off, valve shut)

FB1

Reference

FB2

FT3



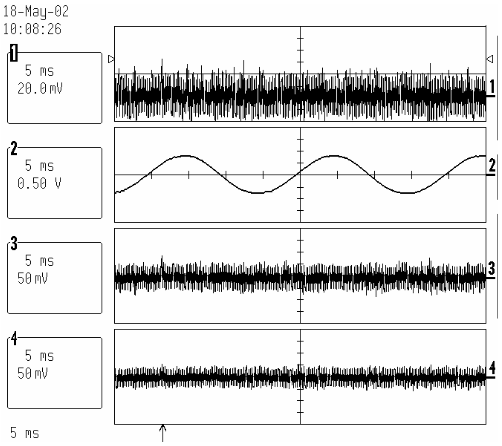
029 (power on, fan off, valve shut)

FB1

Reference

FB2

FT3



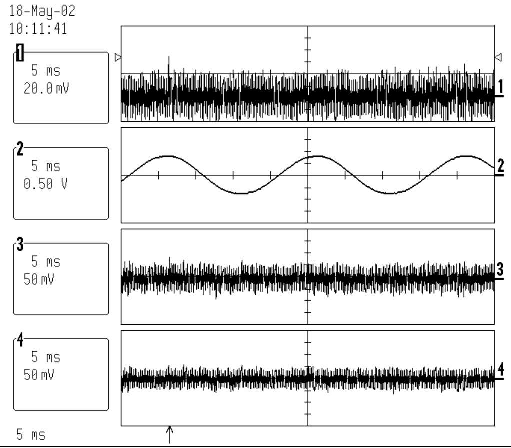
030 (power on, fan off, valve shut)

FB1

Reference

FB2

FT3



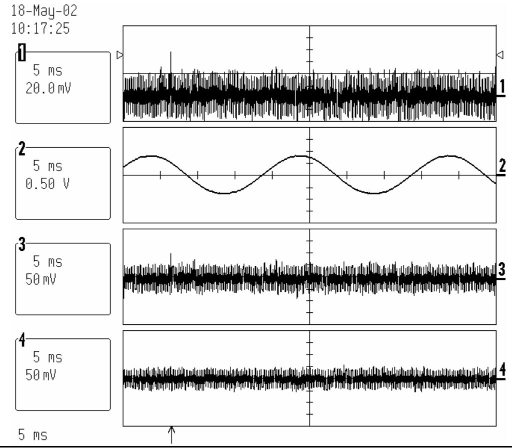
031 (power on, fan off, valve shut)

FB1

Reference

FB2

FT3



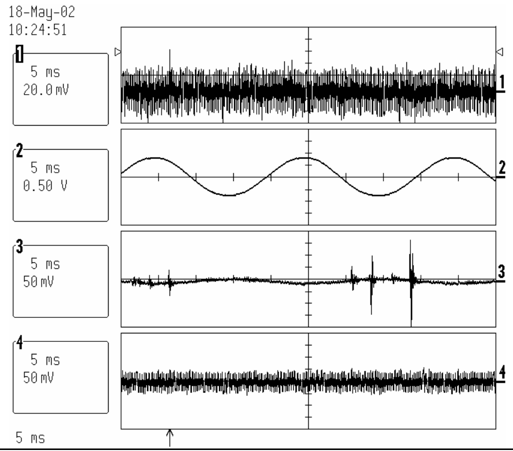
032 (power on, fan off, valve shut)

FB1

Reference

PZTBI

FT3



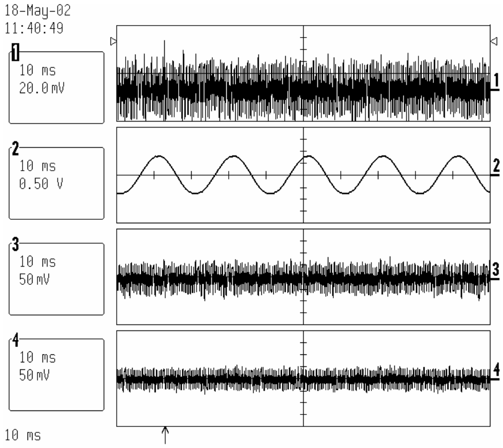
033 (power on, fan off, valve shut)

FB1

Reference

FB2

FT3



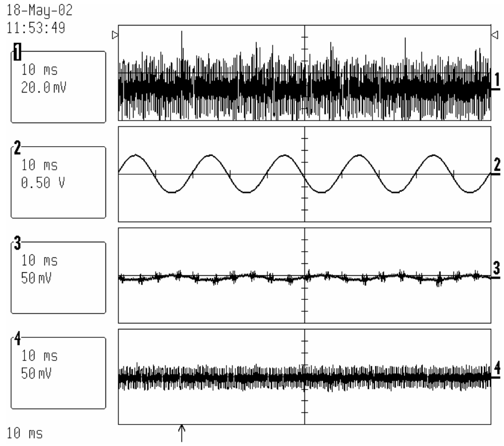
035 (power on, fan off, valve open)

FB1

Reference

PZTBI

FT3



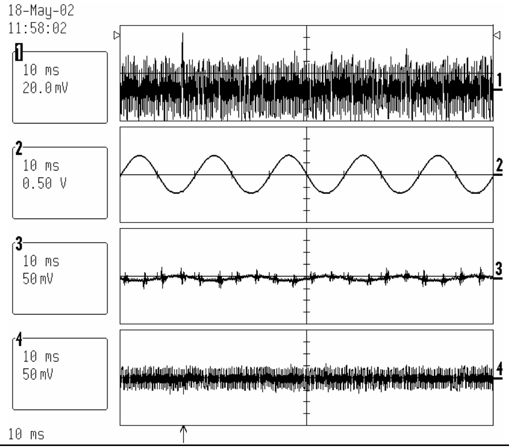
036 (power on, fan off, valve open)

FB1

Reference

FB2

FT3



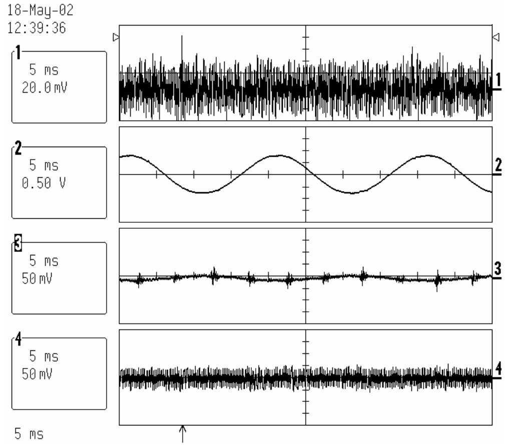
037 (power on, fan off, valve open)

FB1

Reference

PZTBI

FT3



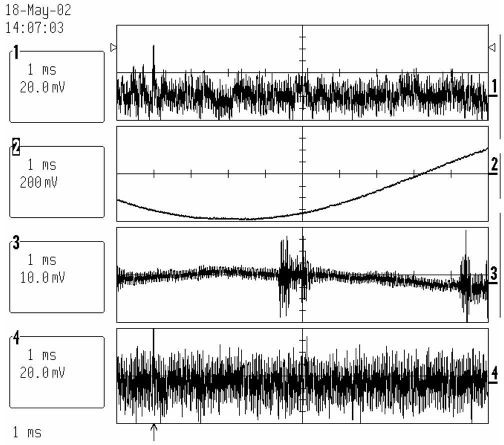
039 (power on, fan off, valve open)

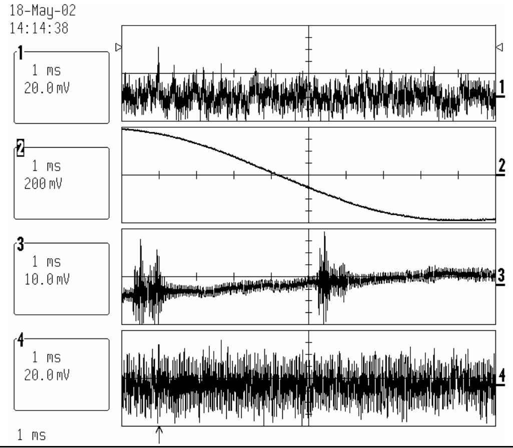
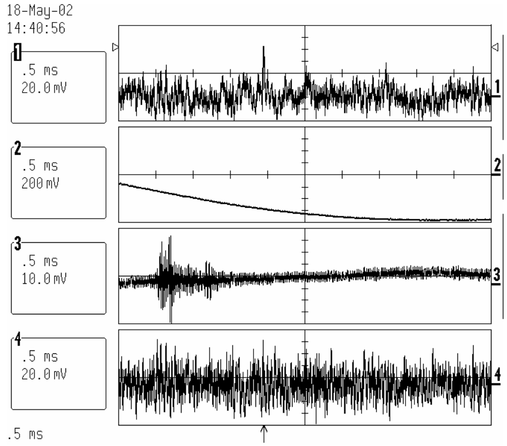
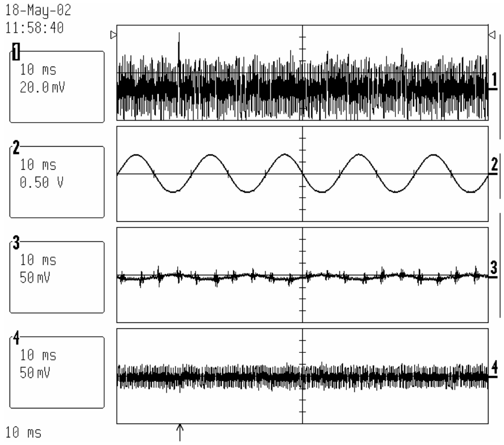
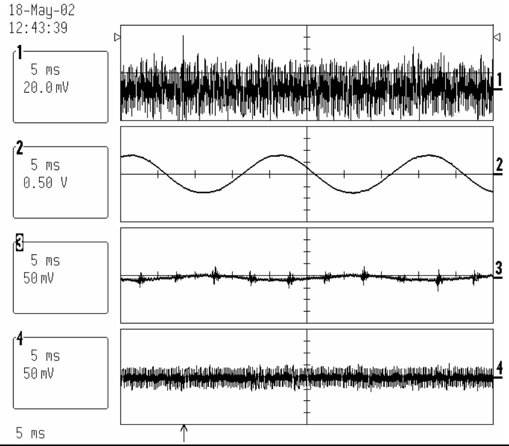
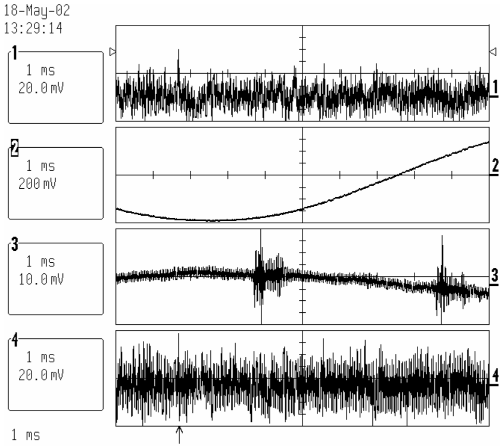
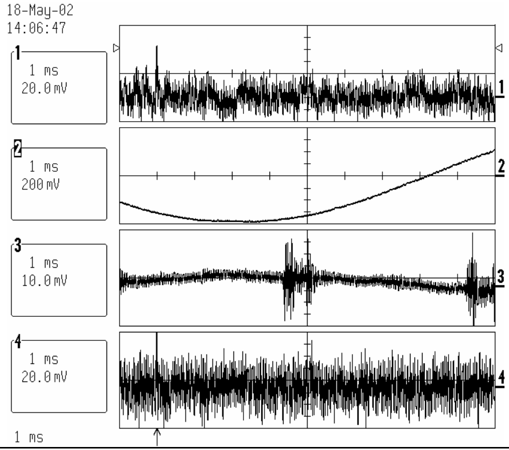
FB1

Reference

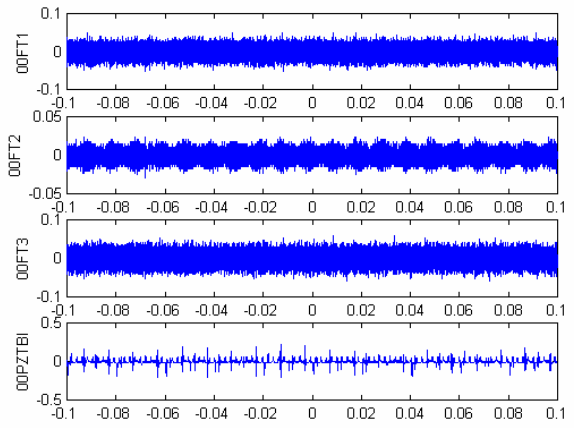
PZTBI

FT3

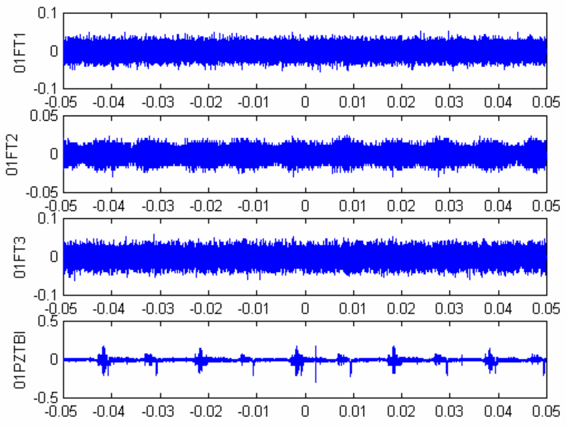


FB1	040 (power on, fan off, valve open)  	FB1	041 (power on, fan off, valve open) 
FB1 Refe-rence PZTBI FT3	042 (power on, fan off, valve open)  	FB1 Refe-rence PZTBI FT3	043 (power on, fan off, valve open) 
FB1 Refe-rence PZTBI FT3	044 (power on, fan off, valve open)  	FB1 Refe-rence PZTBI FT3	045 (power on, fan off, valve open) 

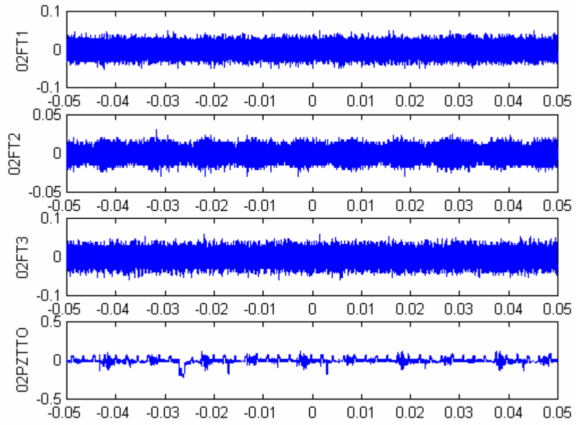
00



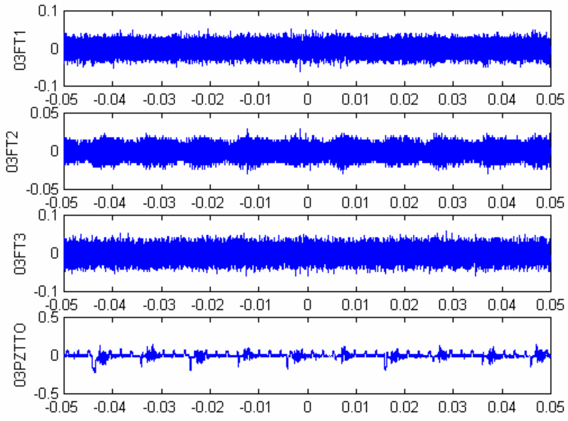
01



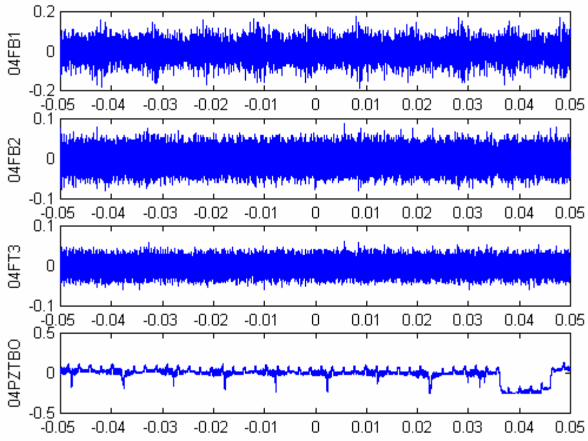
02



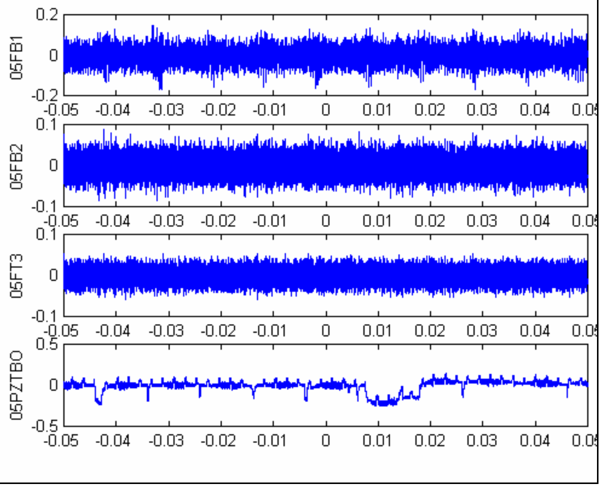
03



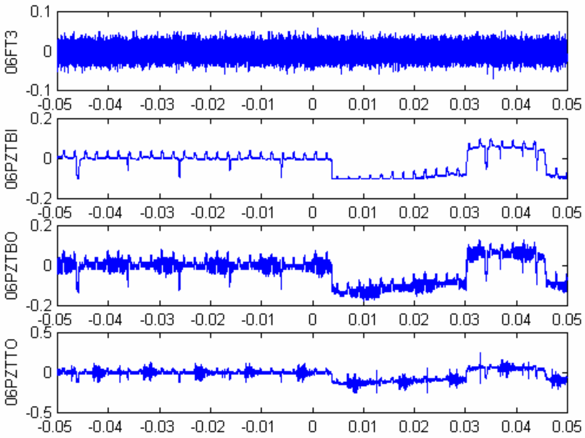
04



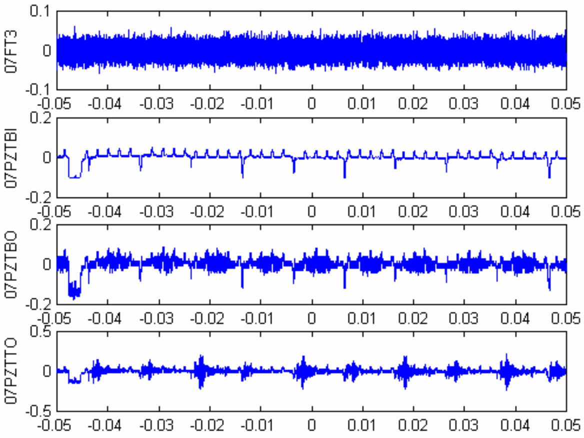
05



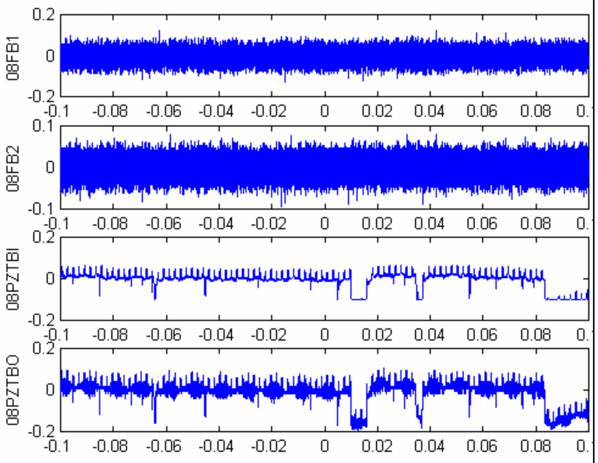
06


06FT3
06PZTBI
06PZTBO
06PZTTO
0.1
0
-0.1
0.2
-0.2
0.5
-0.5
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05

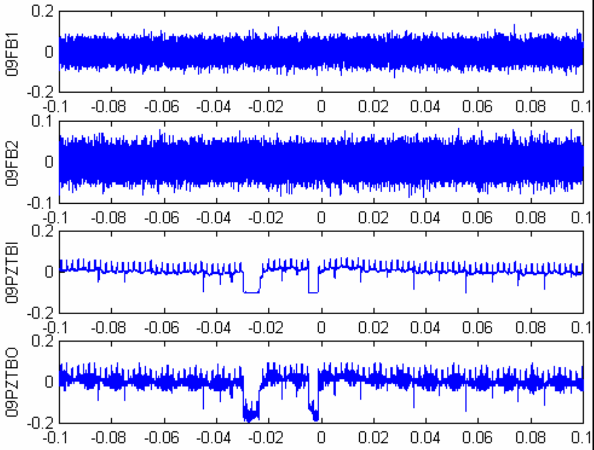
07


07FT3
07PZTBI
07PZTBO
07PZTTO
0.1
0
-0.1
0.2
-0.2
0.5
-0.5
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05

08


08FB1
08FB2
08PZTBI
08PZTBO
0.2
0
-0.2
0.1
-0.1
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1

09


09FB1
09FB2
09PZTBI
09PZTBO
0.2
0
-0.2
0.1
-0.1
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1

Appendix C. PZTBI measured signal, denoised signals and frequency spectrum of major burst group

Some other PZTBI examples are illustrated in Fig 62 to Fig 76.

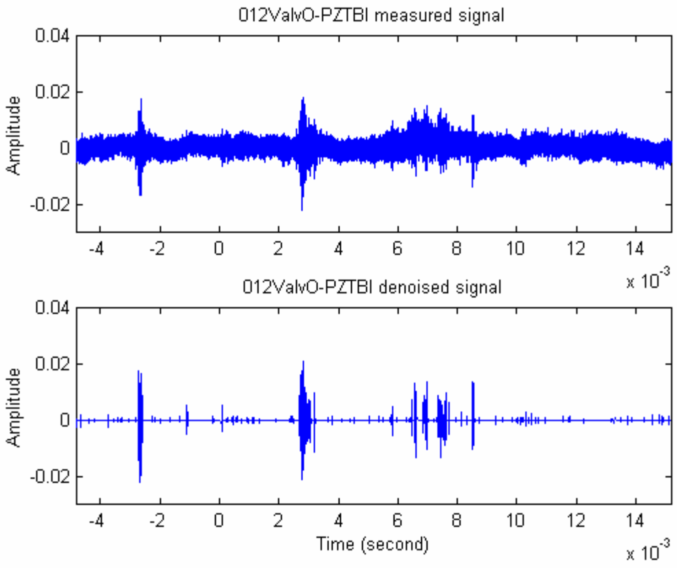


Fig 62. PZTBI (012) measured signal and denoised signal using wavelet-based transform

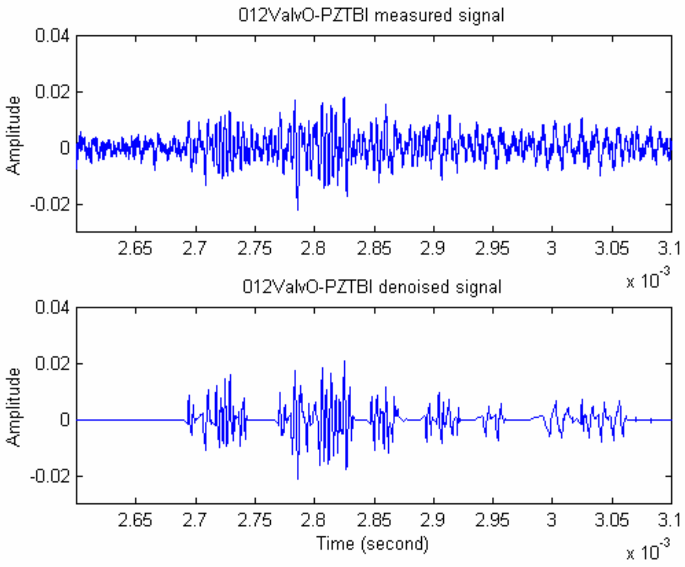


Fig 63. PZTBI (012) measured signal and denoised signal zoomed between 0.0026 and 0.0031 second

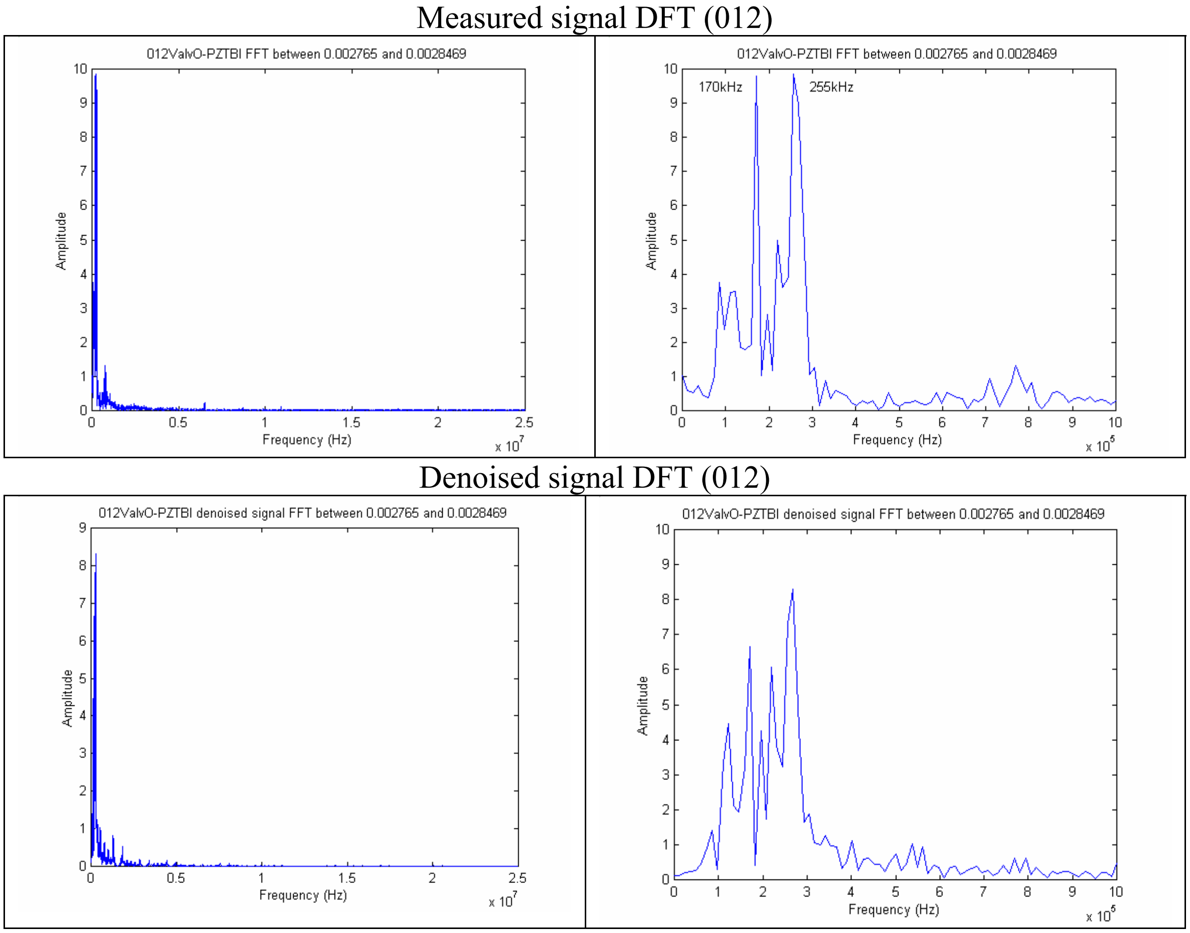


Fig 64. PZTBI (012) DFT of measured signal and denoised signal in the interval of 2.765 msec and 2.847 msec

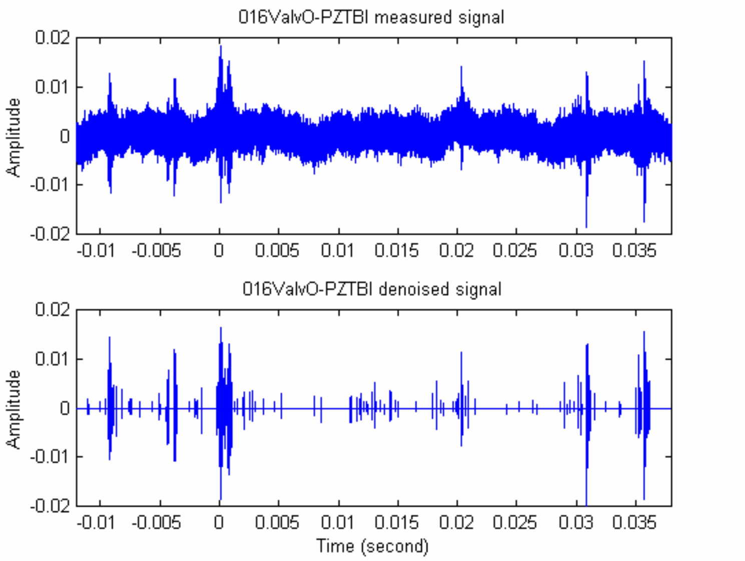


Fig 65. PZTBI (016) measured signal and denoised signal using wavelet-based transform

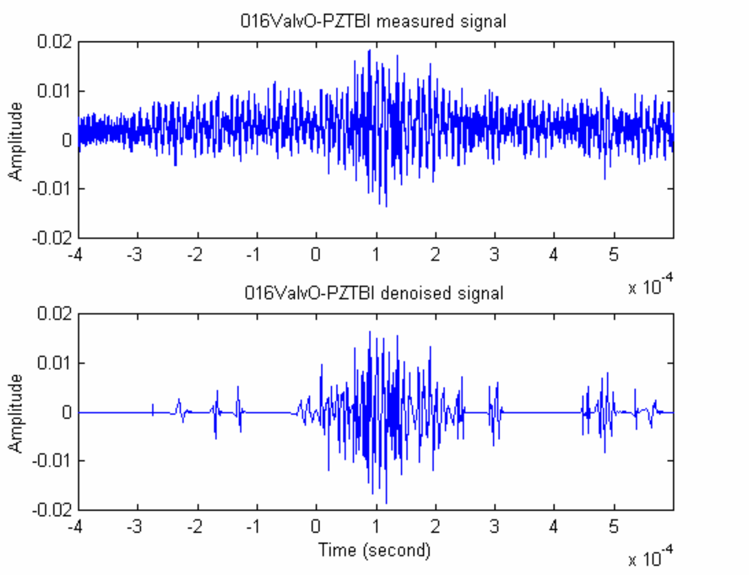
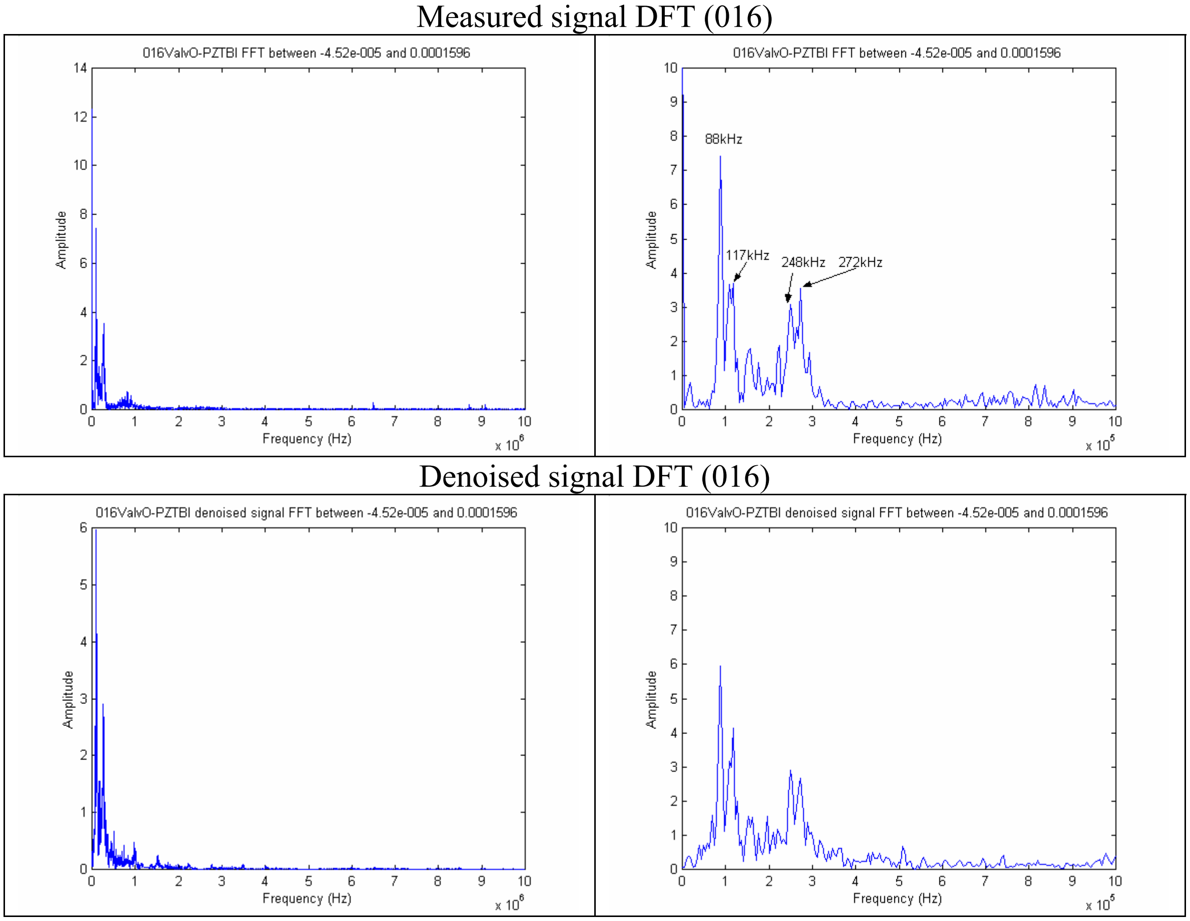


Fig 66. PZTBI (016) measured signal and denoised signal zoomed between -0.0004 and 0.0006 second


Measured signal DFT (016)

Denoised signal DFT (016)

Fig 67. PZTBI (016) DFT of measured signal and denoised signal in the interval of –0.0452 msec and 0.1596 msec

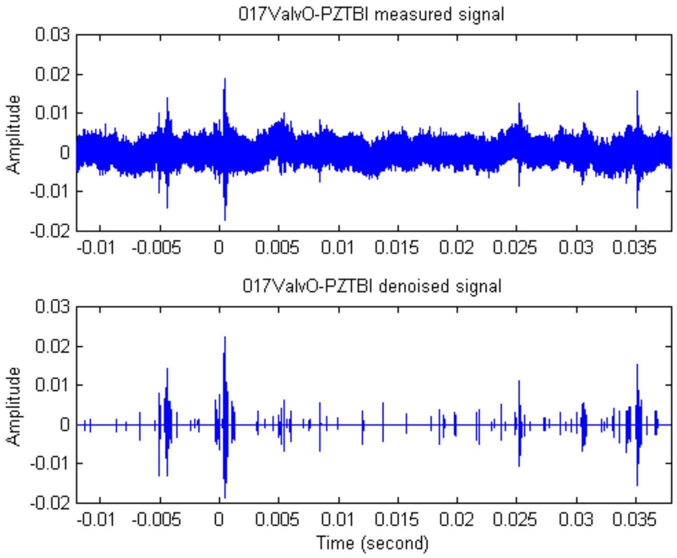


Fig 68. PZTBI (017) measured signal and denoised signal using wavelet-based transform

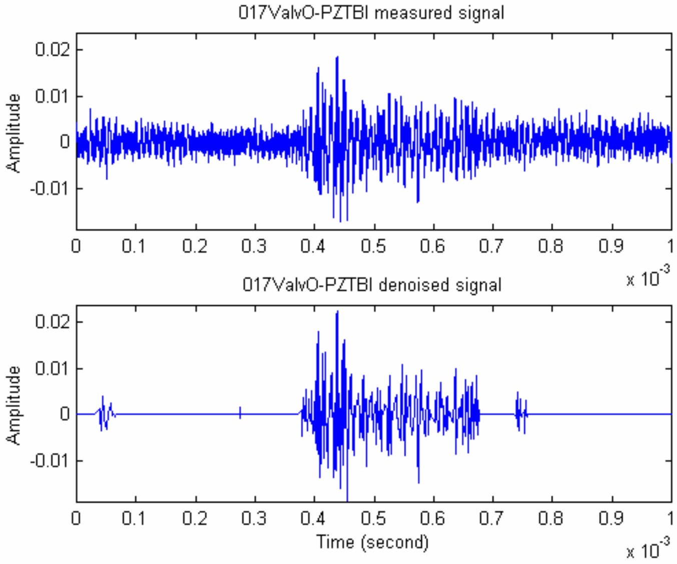
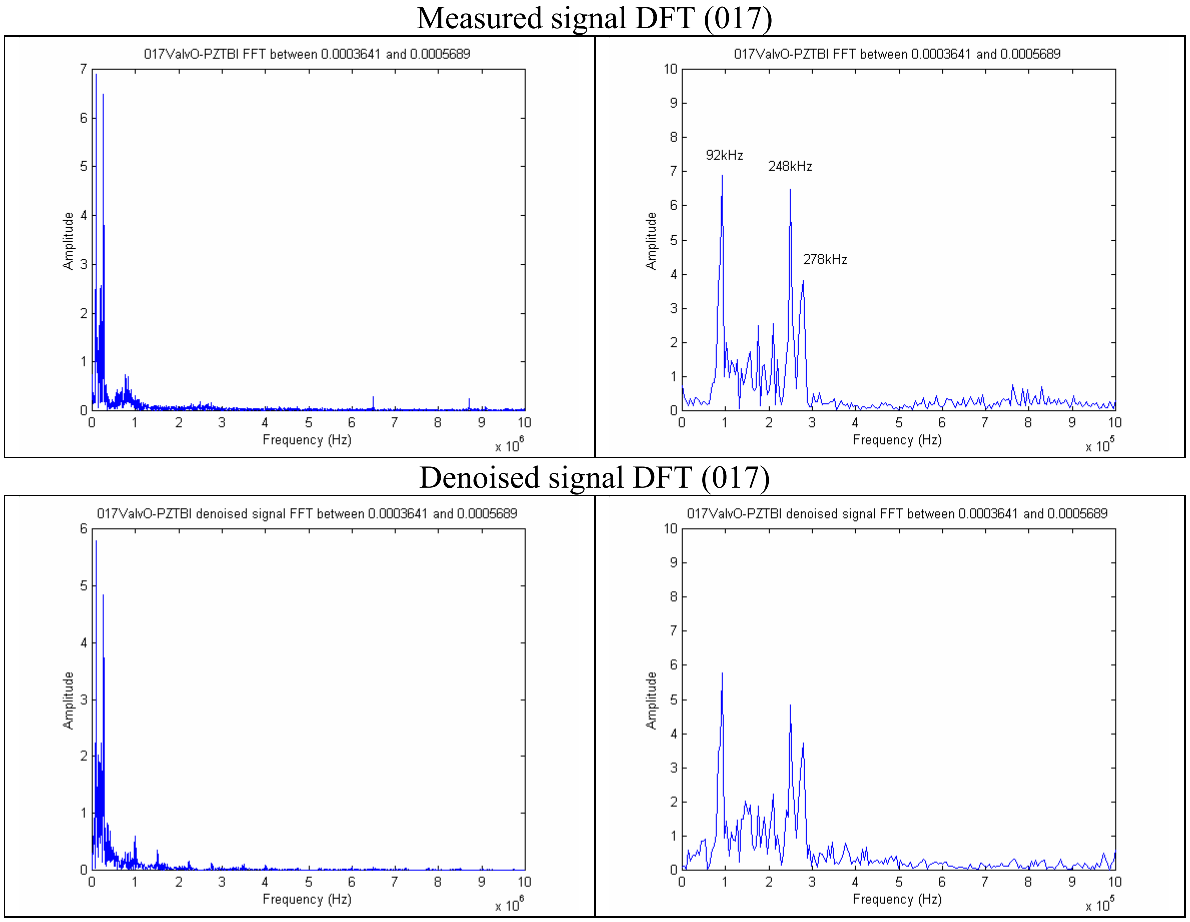


Fig 69. PZTBI (017) measured signal and denoised signal zoomed between 0 and 0.001 second



Measured signal DFT (017)

Denoised signal DFT (017)

Fig 70. PZTBI (017) DFT of measured signal and denoised signal in the interval of 0.3641 msec and 0.5689 msec

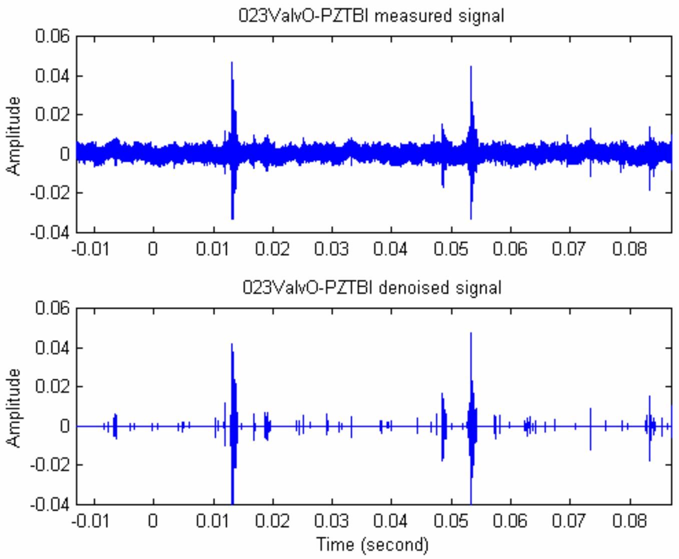


Fig 71. PZTBI (023) measured signal and denoised signal using wavelet-based transform

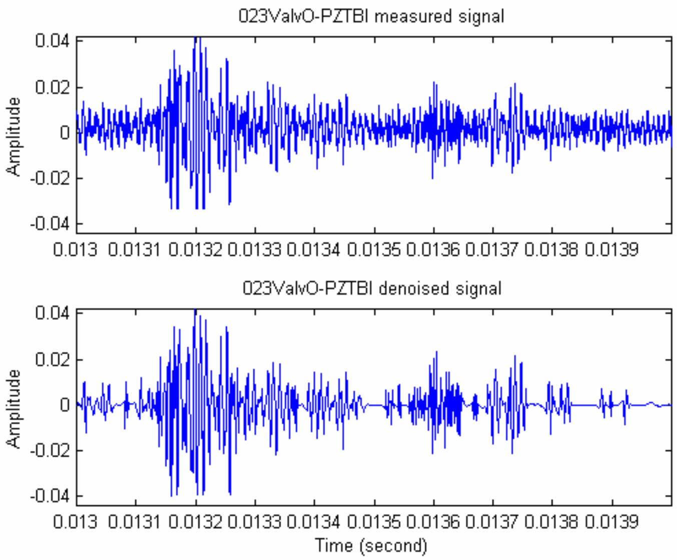
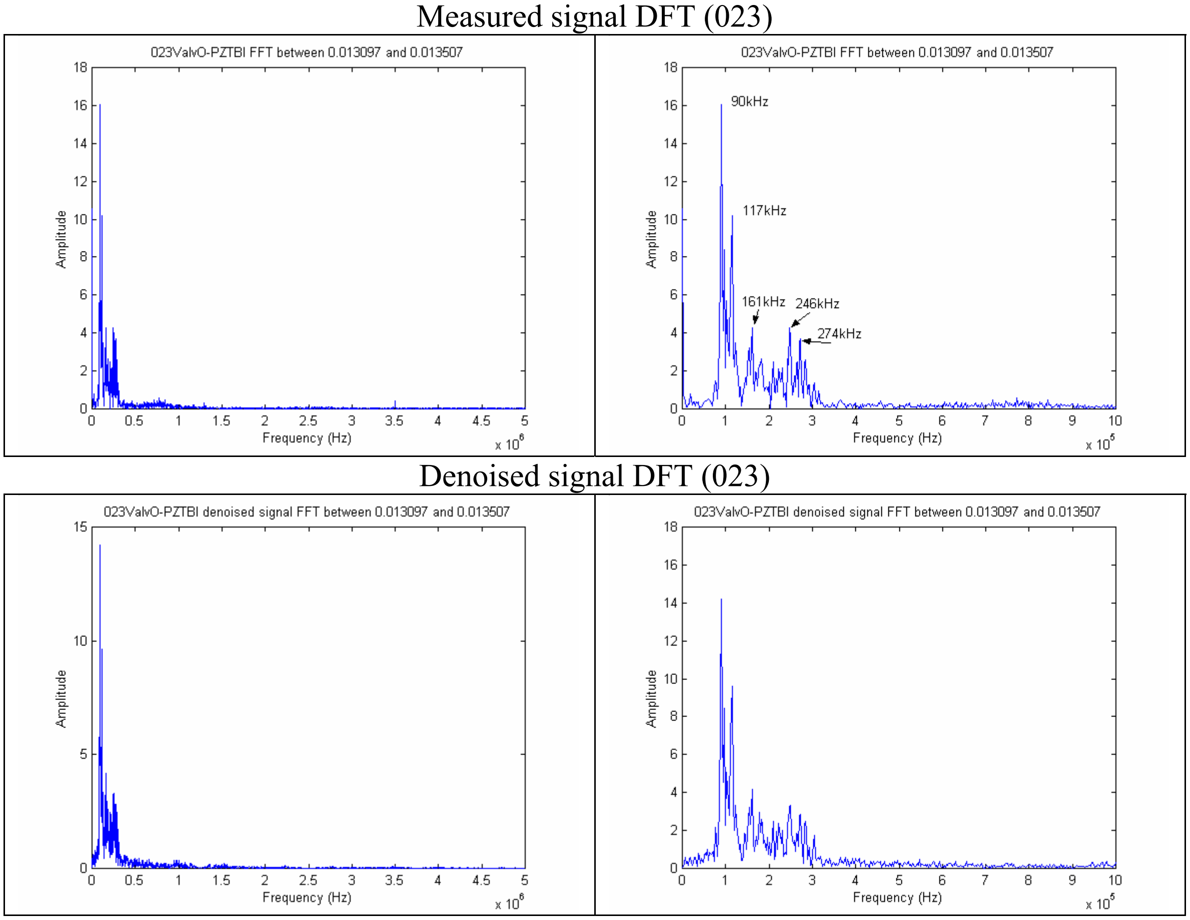


Fig 72. PZTBI (023) measured signal and denoised signal zoomed between 0.013 and 0.014 second


Measured signal DFT (023)

Denoised signal DFT (023)

Fig 73. PZTBI (023) DFT of measured signal and denoised signal in the interval of 13.097 msec and 13.507 msec

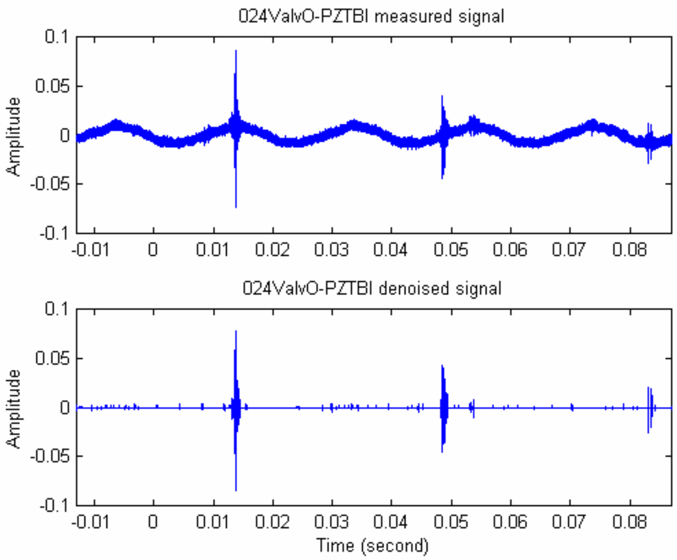


Fig 74. PZTBI (024) measured signal and denoised signal using wavelet-based transform

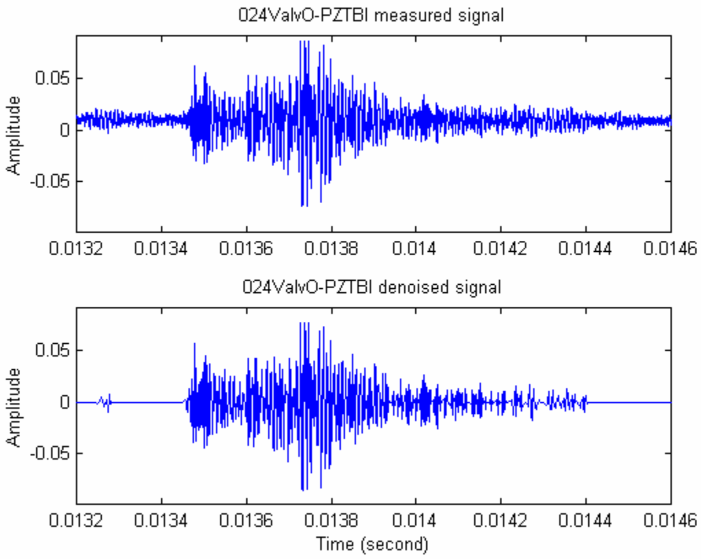
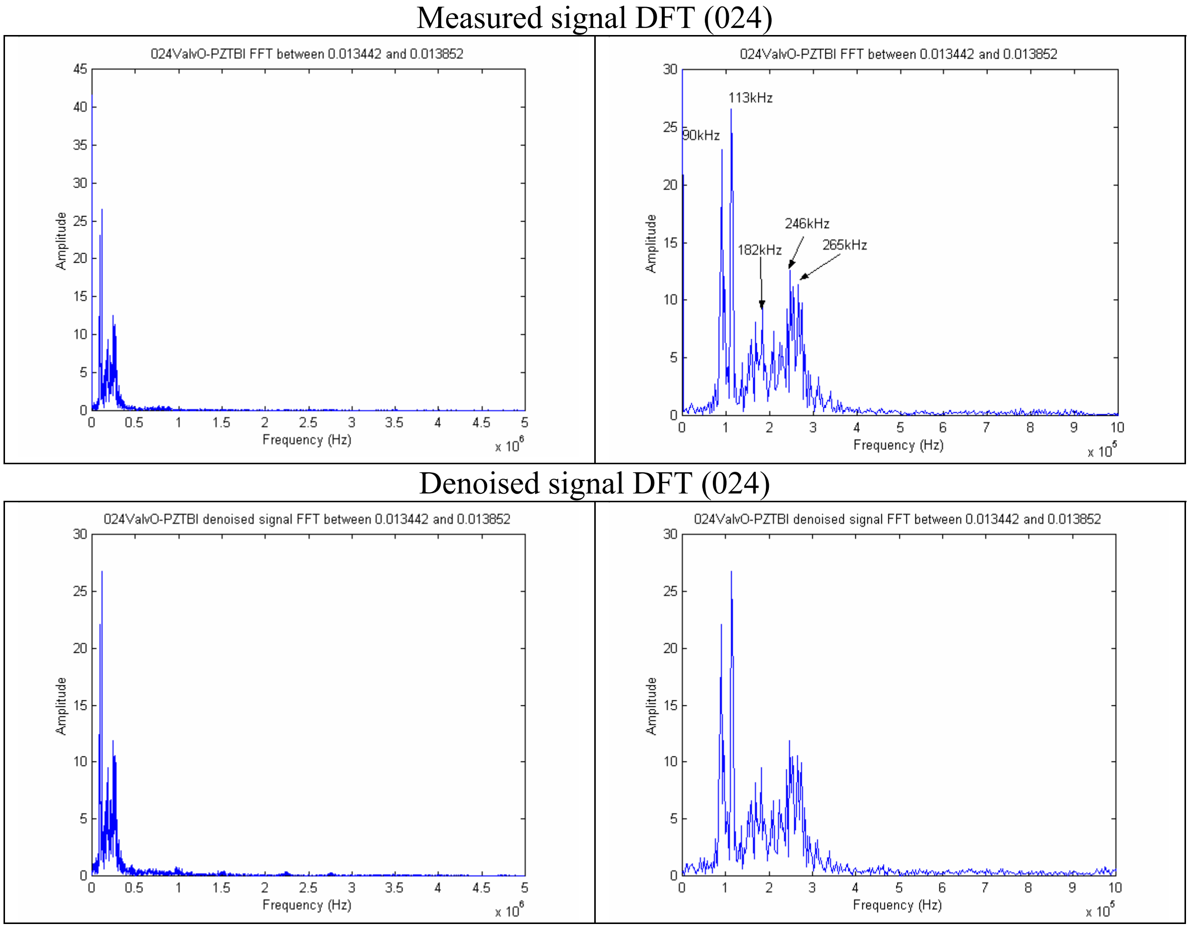


Fig 75. PZTBI (024) measured signal and denoised signal zoomed between 0.013 and 0.014 second


Measured signal DFT (024)

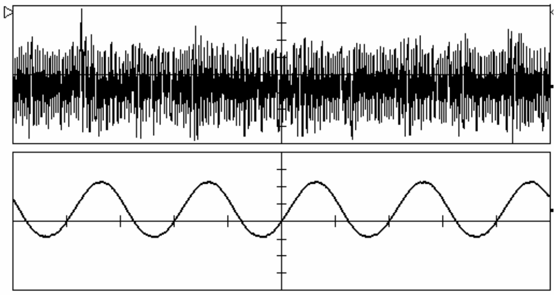
Denoised signal DFT (024)

Fig 76. PZTBI (024) DFT of measured signal and denoised signal in the interval of 13.442 msec and 13.852 msec

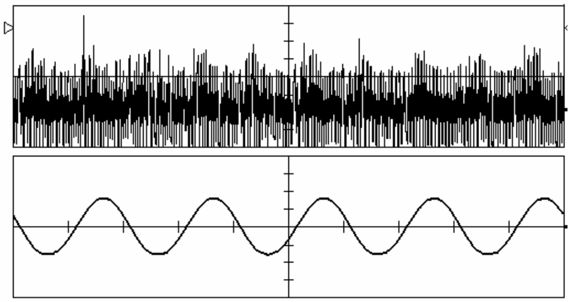
Appendix D. Signal occurrence phase measurement

Note: The sinusoids are 90° leading of transformer phase A voltage sinosoid. For ease of illustration of the PD signal occurrence phases, the following plots are the extraction of the data set in Appendix B.

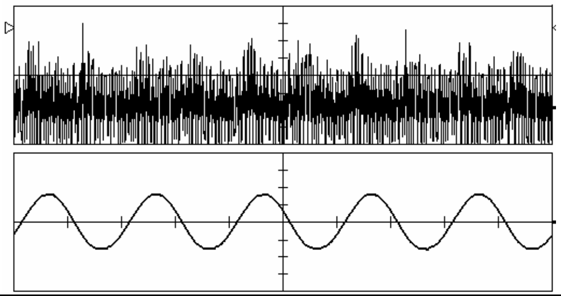
FB1 (024)



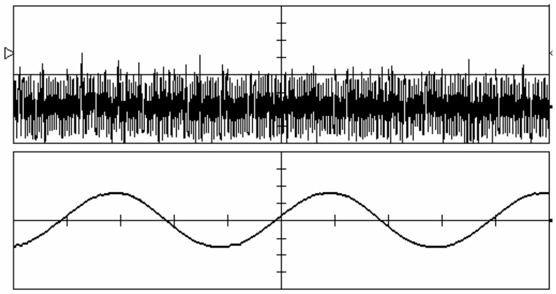
FB1 (025)



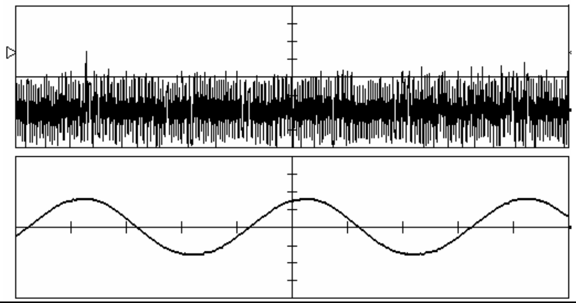
FB1 (026)

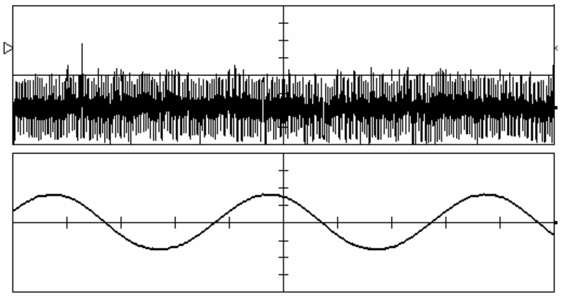
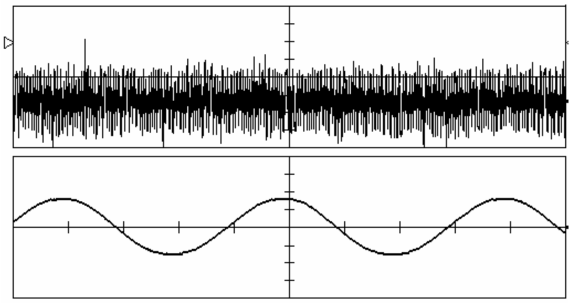
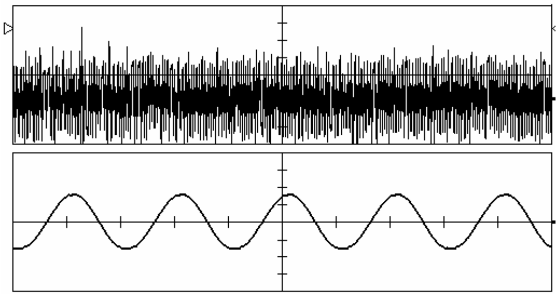
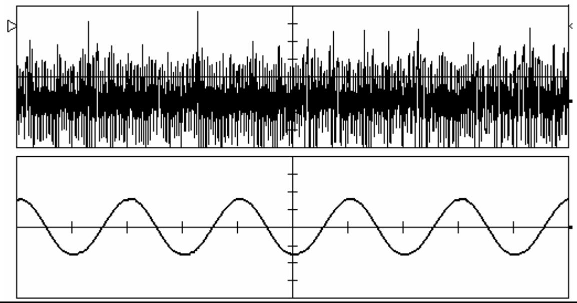
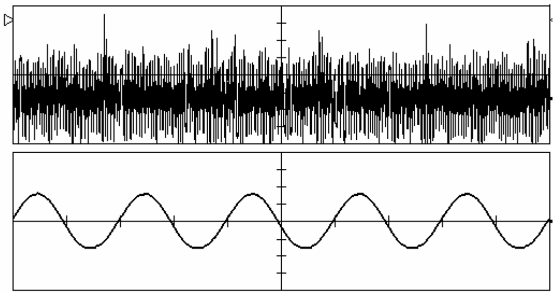
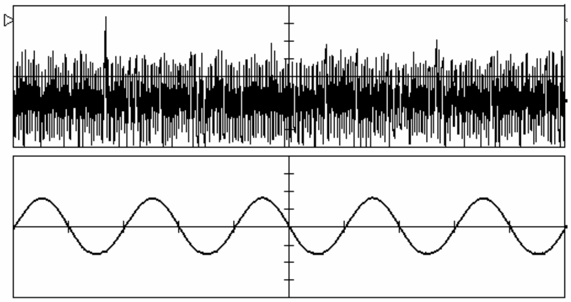
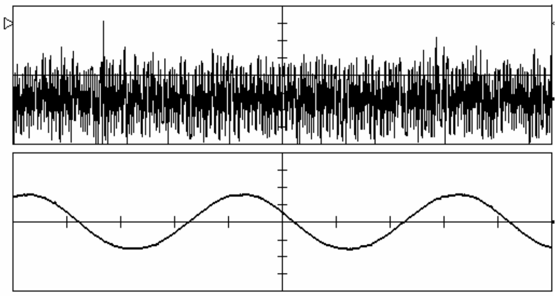
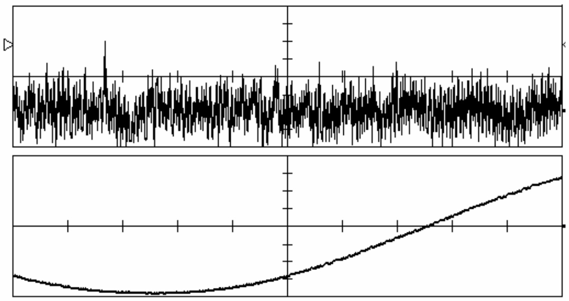


FB1 (029)

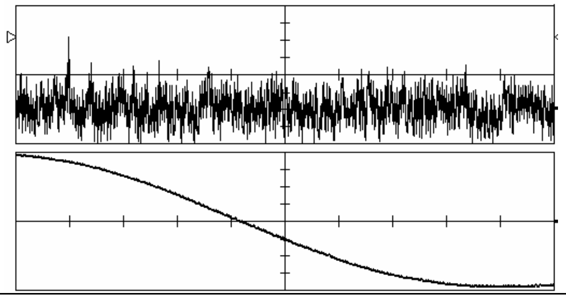


FB1 (030)

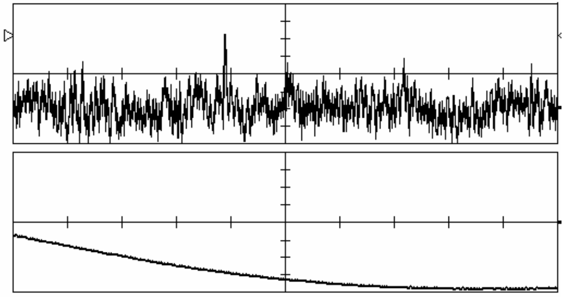


FB1 (031) 	FB1 (032) 
FB1 (033) 	FB1 (034) 
FB1 (035) 	FB1 (036) 
FB1 (037) 	FB1 (039) 

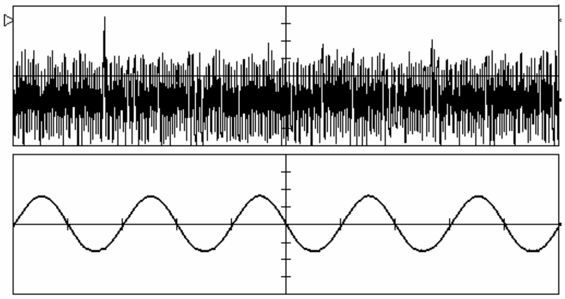
FB1 (040)



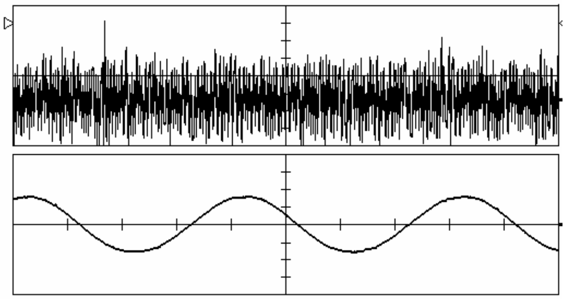
FB1 (041)



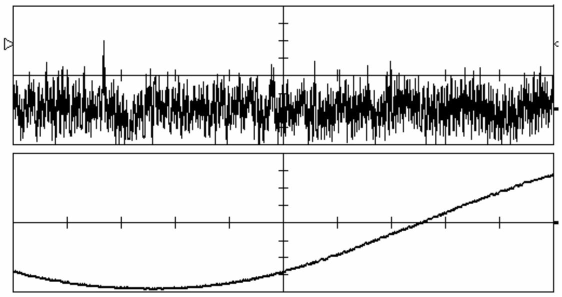
FB1 (042)



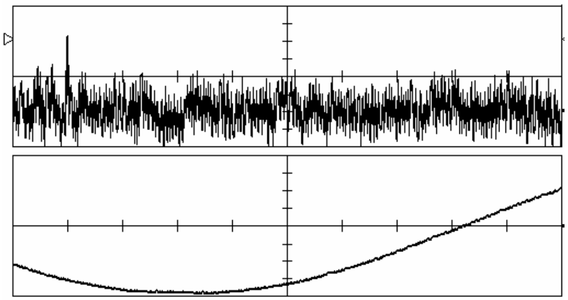
FB1 (043)



FB1 (044)



FB1 (045)



Appendix E. Matlab Codes

The following Matlab code performs the wavelet transform and the denoising process of the signal's time and magnitude data that stored in a mat file (Matlab's binary format). The user can specified the mother wavelet, levels of transform, numeric threshold limit, thresholding method (hard or soft), and an option whether to view denoising process. During the denoising process, the user can change the threshold limit. The processed data will append to the original data file.

<u>Wavelet decomposition Matlab code</u>

```
function data =
wavelet_tf(wfname,filename,N,Threshselect,thresh_method,viewdenoise)
% data =
wavelet_tf(wfname,filename,N,Threshselect,thresh_method,viewdenoise)
% Inputs:  wfname - wavelet name
%          filename - input signal file name
%          N - level of wavelet transform
%          Threshselect - threshold limit:could be specified by the
multiples of standard
%                         deviation or automatic. (e.g. 4, 5, or 'a')
%          thresh_method - threshold method ('h': hard, 's': soft)
%          viewdenoise - 1: view the denoise process
%                        0: no view on the denoise process
% Outputs: data - structure contains the denoised signal as well as the
original signal
%
% Written by Shu-Jen(Steven) Tsai
% Virginia Tech, Power IT Lab.  June,1,2002


eval(['load ',filename])
% specify number of levels to perform wavelet and method of wavelet
transform

% change the '_' in the filename to '-'
filenametitle = filename;
filenametitle(findstr(filenametitle,'_'))='-';
C_denoise = [];

% shrink data
zerotimeindx = min(find(data.time>0));
ampl = data.ampl;

% remove the points with zero magnitude
zeroamplindx = find(ampl==0)
for j=1:1:length(zeroamplindx)
   ampl(zeroamplindx) = (ampl(zeroamplindx-1)+ampl(zeroamplindx+1))/2;
end

% Perform wavelet transform
[C,L]=wavedec(ampl,N,wfname);
cumsumL = cumsum(L);
```

```
% generate 4 plots first
fid1 = figure; fid2 = figure; fid3 = figure; fid4 = figure; %fid5 =
figure;

% plot the results of wavelet transform of different level signal
maxnumofrowplot = 4; % the maximum number of plots in a row per figure
C_start_indx = 1;
for i=1:1:N+1
   C_end_indx = cumsumL(i);    % change the end index of each plot from
the generated L vector
   if (i/maxnumofrowplot <=1)
      figure(fid1)
      subplot(maxnumofrowplot,1,i)
   else
      if (i/maxnumofrowplot<=2)
         figure(fid2)
         subplot(maxnumofrowplot,1,i-maxnumofrowplot)
      elseif (i/maxnumofrowplot<=3)
         figure(fid3)
         subplot(maxnumofrowplot,1,i-2*maxnumofrowplot)
      elseif (i/maxnumofrowplot<=4)
         figure(fid4)
         subplot(maxnumofrowplot,1,i-3*maxnumofrowplot)
      elseif (i/maxnumofrowplot<=5)
         figure(fid4)
         subplot(maxnumofrowplot,1,i-4*maxnumofrowplot)
      end
   end
   plot(C(C_start_indx:C_end_indx))
   % find the noise threshold
   thdmethod = 'heursure';
   noise_thd = thselect(C(C_start_indx:C_end_indx),thdmethod);
   %xlabel(['Threshold by ',thdmethod,' is:',num2str(noise_thd)])
   if rem(i,maxnumofrowplot)==1
      title([num2str(N),'-level ',wfname,'.  ',filenametitle]); zoom on
   end
   a_level = num2str(N);
   if i==1  %average signal ylabeling
      if length(a_level)>=2
         h = ylabel(['a_',a_level(1),'_',a_level(2)]);
         set(h,'Rotation',0,'FontSize',11)
         ylabel_text = ['a_',a_level(1),'_',a_level(2)];
      else
         title([num2str(N),'-level ',wfname])
         h = ylabel(['a_',a_level]);
         set(h,'Rotation',0,'FontSize',11)
         ylabel_text = ['a_',a_level];
      end
   else     % detailed signal ylabeling
      d_level = num2str(N-i+2);
      if length(d_level)>=2
         h = ylabel(['d_',d_level(1),'_',d_level(2)]);
         set(h,'Rotation',0,'FontSize',11)
         ylabel_text = ['d_',d_level(1),'_',d_level(2)];
      else
         h = ylabel(['d_',num2str(N-i+2)]);
         set(h,'Rotation',0,'FontSize',11)
         ylabel_text = ['d_',d_level];
      end
   end
   % use the thresholding method to denoise on the detailed signal the
thresholding value is
   % determined by calculating the standard deviation of the detailed
signal and set 4.5 times
   % the standard deviation to denoise it.
   % we first plot the original with the calculated thresholding lines
and prompt in the command
   % line if we want to proceed.
   % we then will store the new denoised data to a new vector

   if ~isstr(Threshselect)
      std_d = std(C(C_start_indx:C_end_indx));
      thresh = Threshselect*std_d;
      titletxt = [filenametitle,' Thresholding value is set at
',num2str(Threshselect),' \sigma (',num2str(thresh),')'];
   else
      thresh =
mean(C(C_start_indx:C_end_indx))/0.6745*sqrt(2*log(C_end_indx-
C_start_indx+1));
      titletxt = [filenametitle,' Thresholding value is set at
',num2str(thresh)];
   end

   if i==1
      fid_n = figure;
      fid_n_denoise = figure;
   end
   figure(fid_n);
   subplot(N+1,1,i)
   plot(C(C_start_indx:C_end_indx))
   hold on
   plot(thresh*ones(length(C(C_start_indx:C_end_indx)),1),'r--')
   plot(-1*thresh*ones(length(C(C_start_indx:C_end_indx)),1),'r--')
   %title(titletxt)
   h = ylabel(ylabel_text);
   set(h,'Rotation',0)


   % perform thresholding on the signals
   if 0
   if (viewdenoise==1)
      denoise = input('Would you want to denoise the signal (y/n)?
','s');
      if lower(denoise)=='y'
         new_d =
wthresh(C(C_start_indx:C_end_indx),thresh_method,thresh);

         figure(fid_n_denoise)
         subplot(N+1,1,i),plot(new_d);
         ylabel_text = strcat(ylabel_text,'''');
         h = ylabel(ylabel_text);
         set(h,'Rotation',0)
         shg
         %pause(1)
      elseif lower(denoise)=='n'
         new_d = C(C_start_indx:C_end_indx);
      else
         disp(['Unrecognized selection!!'])
      end
   end
   end

   new_d = wthresh(C(C_start_indx:C_end_indx),thresh_method,thresh);
   if 0
   % added for faster PZT data processing 06/19/2002
   if (i==1)
      new_d = C(C_start_indx:C_end_indx);
   else
      new_d = wthresh(C(C_start_indx:C_end_indx),thresh_method,thresh);
   end
   end

   %close(fid_n);
   C_denoise(C_start_indx:C_end_indx) = new_d;
   C_start_indx = C_end_indx+1;  % change the next start index in C
end


% reconstruct the denoised signal and append the information to the
'data' structure
data.wavelet.method = wfname;
data.wavelet.levels = N;
data.wavelet.thresholdmethod = thresh_method;
data.wavelet.levellength = L;
data.wavelet.decomp = C;
data.wavelet.decomp_denoise = C_denoise;
data.ampl_denoise = waverec(C_denoise,L,wfname);
eval(['save ',filename,' data -append']);
close(fid1),close(fid2),close(fid3),close(fid4)
close(fid_n),close(fid_n_denoise)
```

PD occurrence Matlab code

```
% PD phase plots
% to remove the radius text, go to polar.m file and comment out line
112-114
% the following are the angles of the PD occurence (in degree) from
024-045 sets
x =
[50,90,130,125,100,300,225,260,250,100,250,300,230,265,250,40,45,225];

figure,polar(x/180*pi,ones(1,length(x)),'o')
title('PD occurance location (in reference to phase A sinusoid and no
shift)')

figure,polar((x-90)/180*pi,ones(1,length(x)),'o')
```

```
title('PD occurance location (in reference to phase A sinusoid with -
90^o shift)')

figure,polar((x-90-310)/180*pi,ones(1,length(x)),'o')
titletxt[40] = ['PD occurance location (in reference to phase A
sinusoid with -90^o shift'];
titletxt[40] = ['and time delay of -310^o)'];
title(titletxt)
```