On the tip-timing signal decomposition to the turbine blade vibration sources identiffication

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Abstract
An expert system aided method of the blade-tip signal decomposition to the turbine blade vibration sources identiffication is presented. The method utilizes a multi-valued diagnostic model based on the discrete wavelet transform. Proposed algorithm consists of four stages: – signal decomposition into low- and high-frequency components (approximations and details), – approximations and details parameterization, – multi-valued encoding of parameters obtained at the second stage, – an expert system use to the turbine blade vibration sources identiffication.

1. Introduction

Blade-Tip Timing (BTT) is one of the methods applied in the rotating machinery diagnostics [3, 4, 10, 11, 14]. The main kinds of sensors used are capacitive, inductive, eddy-currents, and optical.
In Air Force Institute of Technology (AFIT) extensive research on inductive sensors have been carried out [8, 9, 10, 11,13] because information obtained from thereof is usefull for many purposes, not only time of blade arrival extraction [5, 6, 10].
The inductive sensor signal and descrete wavelet transform are main components of presented method of blade sources vibration identification. The algorithm consists of:
– signal decomposition into low- and high-frequency components (approximations and details),
– approximations and details parameterization,
– multi-valued encoding of parameters obtained at the second stage,
– an expert system of the turbine blade vibration sources identiffication.
The examples use the real-world data gathered with the inductive sensor developed in AFIT.

2. The discrete wavelet transformation of the blade-tip signal measured by an inductive sensor

The discrete wavelet transform (DWT) is performed using so-called dyadic scales *a* and positions *b* based on powers of two [12].

$$C\left(a,b,s(t),\Psi(t)\right)=\int_{-\infty}^{\infty}s(t)\frac{1}{\sqrt{a}}\Psi^{*}\left(\frac{t-b}{a}\right)$$
$$\mathrm{a}\in\left\{2^{1},\ldots,2^{m}\right\};\mathrm{b}\in\left\{2^{1},\ldots,2^{m}\right\} \quad (1)$$

where:
s(t) – blade-tip signal;
C – wavelet transform coeefficients;
Ψ- wavelet function;
m – decomposition level.

Fig. 1 shows the results of the inductive signal s=s1s1A [10] decomposition into low- and high-frequency components (the approximations a1 – a8 and details d1 - d8)

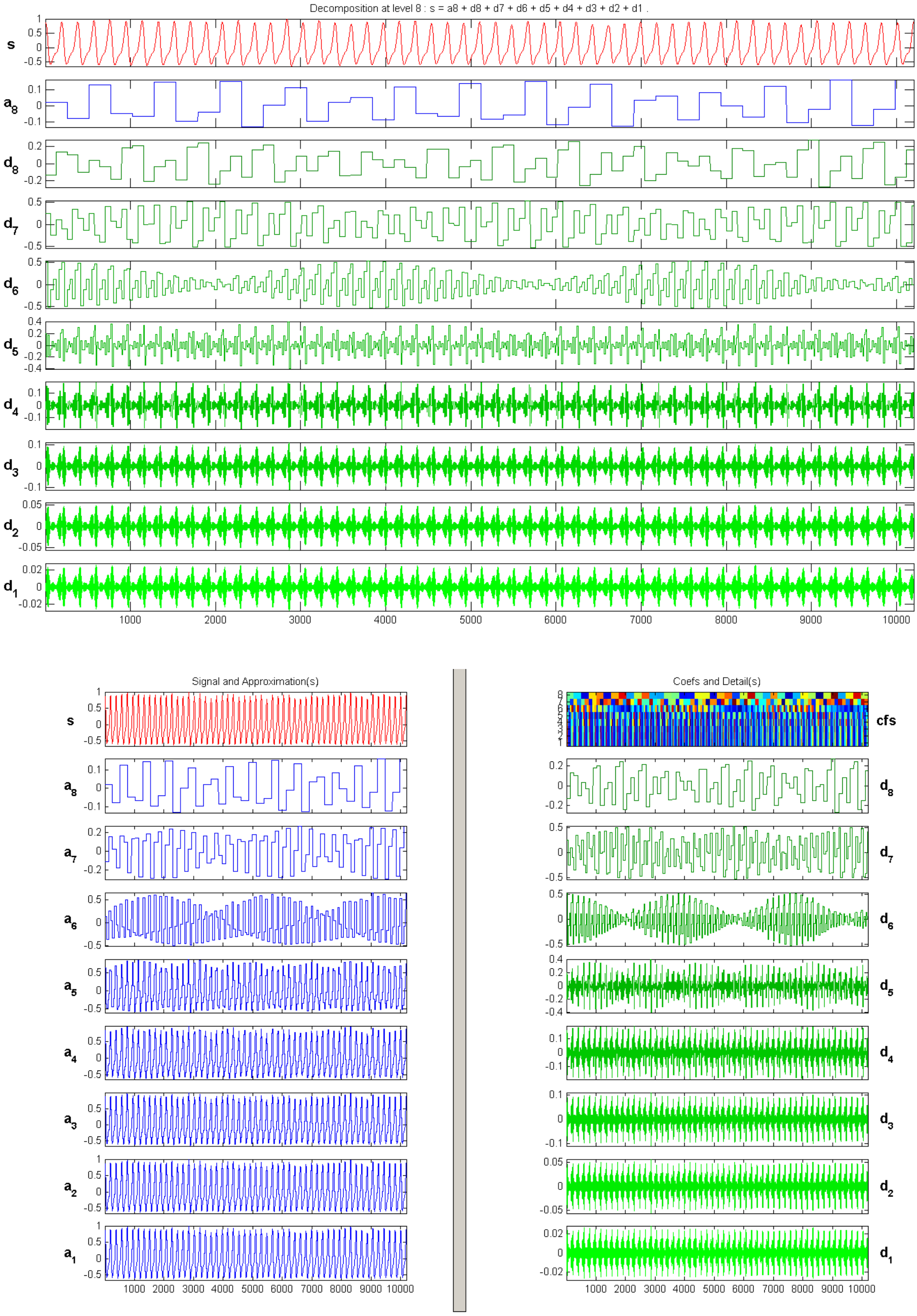


Fig. 1. The signal s=s1s1A decomposition (wavelet – Haar, level – 8)

3. The discrete wavelet coefficients parameterization

For the sake of resoning simplification the descrete wavelet coefficients should be parameterized [1]. At the first attempt the statistic characteristics are employed – Table 1.

Table 1 The statistic characteristics of the approximations and details (signal s1s1A wavelet – Haar, level – 8)

	a1	a2	a3	a4	a5	a6	a7	a8
x1 (mean)	0,00	0,01	0,01	0,02	0,02	0,05	0,07	0,10
x2 (median)	-0,22	-0,31	-0,45	-0,62	-0,73	-0,73	0,59	-0,25
x3 (max)	1,40	1,98	2,77	3,86	4,92	6,14	3,94	3,09
x4 (min)	-0,91	-1,29	-1,81	-2,48	-3,36	-3,95	-3,33	-2,07
x5 (std)dev	0,67	0,95	1,34	1,87	2,50	2,95	2,06	1,58
x6 (L2 norm)	47,94	47,89	47,72	47,11	44,56	37,17	18,33	9,88
	d1	**d2**	**d3**	**d4**	**d5**	**d6**	**d7**	**d8**
x1 (mean)	0,00	0,00	0,00	0,00	0,00	-0,02	0,03	-0,06
x2 (median)	-0,01	-0,01	-0,03	-0,09	-0,27	-0,73	-0,82	-0,75
x3 (max)	0,04	0,11	0,03	0,76	2,22	4,18	5,99	4,34
x4 (min)	-0,02	-0,06	-0,17	-0,46	-1,15	-2,76	-4,75	-3,07
x5 (std dev)	0,01	0,04	0,11	0,32	0,86	1,98	3,64	2,47
x6 (L2 norm)	1,02	2,03	4,04	7,99	15,29	24,97	32,34	15,44

During the resoning process one can use encoded (2) parameters rather than their accurate values – Table 2.

$$X_C = \begin{cases} \ldots \\ k-1 \quad dla \quad x \in [x_{k-1}, x_k),\ k \le K \\ \ldots \\ \ \ 1 \qquad dla \quad x \in [x_1, x_2) \\ \ \ 0 \qquad dla \quad x \in (x_{1\_}, x_1) \\ -1 \qquad dla \quad x \in (x_{2\_}, x_{1\_}] \\ \ldots \\ -(k_\_ - 1)\ dla \quad x \in (x_{k_\_}, x_{(k_\_-1)}],\ k_\_ \le K_\_ \\ \ldots \end{cases} \tag{2}$$

$$gdzie: \quad \ldots < x_{k_\_} < \ldots < x_{1_\_} < x_1 \ldots < x_k < \ldots$$

Table 2 The multi-valued representation of the approximations and details

	a1	a2	a3	a4	a5	a6	a7	a8	d1	d2	d3	d4	d5	d6	d7	d8
X1 (mean)	-1	-1	-1	-1	-1	0	1	1	0	0	0	0	0	-1	1	-3
X2 (median)	0	0	-1	-1	-1	-1	2	0	0	0	0	0	0	-2	-2	-2
X3 (max)	-2	-1	-1	0	0	1	0	-1	-1	-1	-1	-1	0	0	1	0
X4 (min)	1	1	0	-1	-1	-2	-1	0	0	0	0	0	0	-1	-2	-1
X5 (std)dev	-2	-2	-1	0	0	1	0	-1	-1	-1	-1	-1	-1	0	1	0
X6 (L2 norm)	0	0	0	0	0	-1	-2	-2	-2	-1	-1	-1	0	1	1	0

An integer code (Table 2) represents the range of parameter's values which can be interpreted in the field of analysis. For further research the set of the approximations and details' parameters can be appropriately adjusted. Formal methods for multi-valued problem representation analysis are shown in [2].

4. The multi-valued diagnostic-decision model

From the vibration analysis point of view ratating machinary is a non-linear, multi-frequency resonance system. All kinds of vibration form combination of forced and natural resonant vibrations. Forced vibration can be effected by [13]:
- internally generated forces and power;
- unbalance;
- external loads;
- ambient excitations.

An multi-aspect analysis using an expert knowledge and the real signal measurments should be performed to establish the system of blade vibrations sources identification based on discrete wavelet transform
At first the sets of the vibration sources *V* and frequencies *F* known to the experts are defined:

$$V = \{v_1, v_2, ..., v_{N_v}\}; \qquad F_V = \{f_{v1}, f_{v2}, ..., f_{vN_v}\} \tag{3}$$

The second stage consists of the sets of wavelets and wavelet scales selections. Because of rough relationship between the wavelet central frequency and the Fourier frequency of vibration source the measured signal decimation (integer d or rational d/u, where: d – downsampling, u – upsampling) is essential – Table3.
Fig. 2 presents wavelet decomposition of the signal s1s56A (a 56th decimated signal s1s1A – Fig. 1). The patterns for some scales show that the signal decimation is usefull in the identification of the sources frequences beyond standard dyadic wavelet scales.

Table 3 An example of wavelet Haar pseudo-frequencies

scale	decimation		
	1	24	56
	wavelet pseudo-frequency		
2	2.4903e+05	1.0376e+04	4.4469e+03
4	1.2451e+05	5.1881e+03	2.2235e+03
8	6.2257e+04	2.5940e+03	1.1117e+03
16	3.1128e+04	1.2970e+03	5.5586e+02
32	1.5564e+04	6.4851e+02	2.7793e+02
64	7.7821e+03	3.2425e+02	1.3897e+02
128	3.8911e+03	1.6213e+02	6.9483e+01
256	1.9455e+03	8.1064e+01	3.4742e+01

A combination of wavelet type, wavelet scales and signal decimation describes the analytic experiment ID_{AE}.

$$ID_{AE} = \langle wavelet, scale, f_{s0}, D, f_w \rangle \tag{4}$$

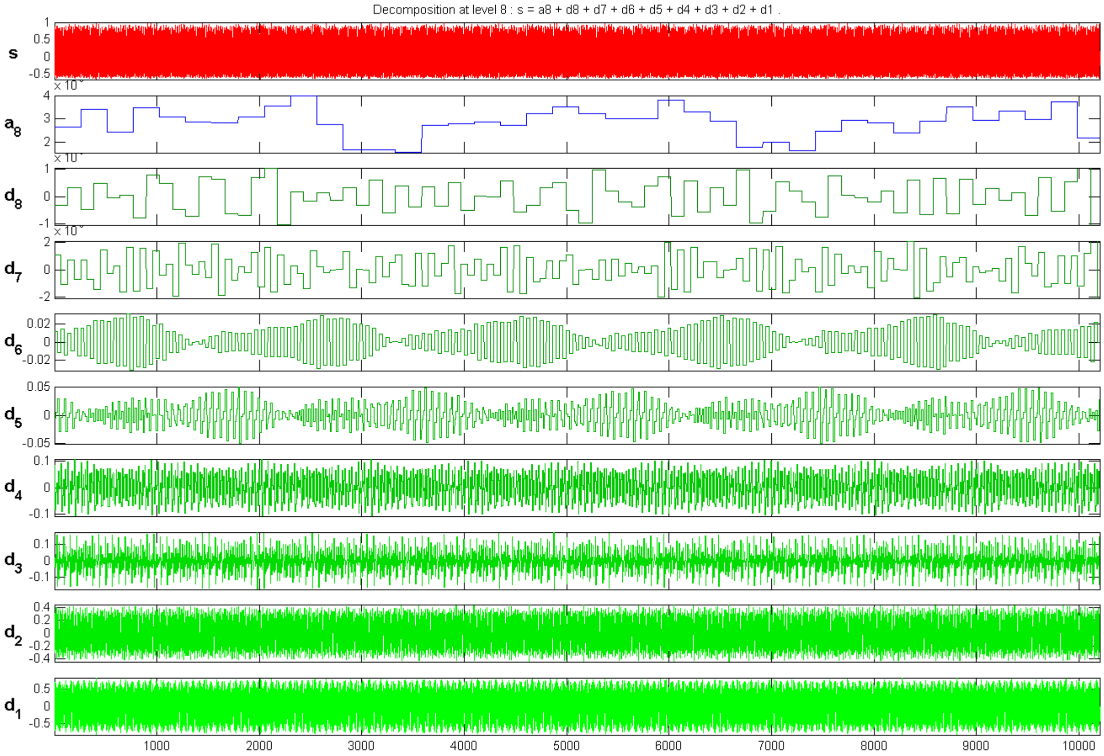
where:
f_{s0} – blade-tip signal sampling frequency,
D – sampling decimation,
f_w – wavelet pseudo-frequency.

The wavelet pseudo-frequency is described as follows:

$$f_w = \frac{f_{wc} f_{s0}}{aD} \tag{5}$$

where:
f_{wc} – wavelet central frequency [12].

According to (4) ordered in ascending wavelet pseudo-frequency blade-tip signal is analyzed and results are presented in the form of Table 1 and after encoding – in the form of Table 2 – the multi-valued diagnostic decicion model.



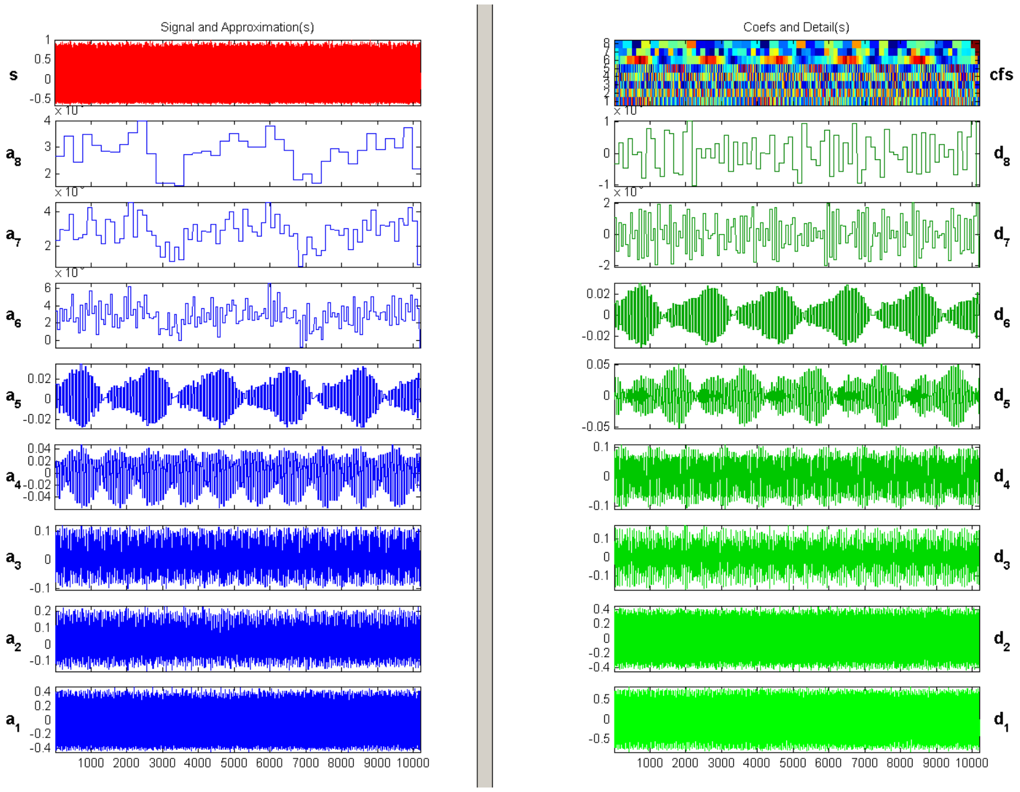


Fig. 2 The signal s=s1s56A decomposition (decimation – 56, wavelet – Haar, level – 8)

5. The expert system of the turbine blade vibration sources identiffication

The multi-valued diagnostic-decision model obtained at previous stage is the formal knowledge representation ready to use in the rule-based expert system [1, 7]. An expert system consists of two components:

- knowledge base;
- knowledge source (one or more)

The knowledge base includes knowledge sources declarations and block control which starts the system.

```
knowledge base vibroSources

 sources
   //declaration of knowledge source used

   vibroS1:
     type kb
 end; // sources

control

   // automatic launch of control block
   run;

   // adding new facts based on Table 2



   addFact( _, X1a1, -1);
   addFact( _, X2a1, -0);
   addFact( _, X3a1, -2);
   addFact( _, X4a1, 1);
   addFact( _, X5a1, -2);
   addFact( _, X6a1, 0);

   addFact( _, X1d1, 0);
   addFact( _, X2d1, 0);
   addFact( _, X3d1, -1);
   addFact( _, X4d1, 0);
   addFact( _, X5d1, -1);
   addFact( _, X6d1, -2);

           ...

   addFact( _, X6d8, 0);

   // start resoning
   solutionWin( yes );
   solve(… );

end;  // control
end;   // knowledge base
```

Knowledge source consists of two parts:

- facets;
- rules.

In facets block the variables are defined – their type and admissible set of values taken.

knowledge source *vibroS1*

facets
single no ;
vibS;

X1a1:
val oneof {-2, -1, 0, 1, 2};

...

end*; // facets*

rules
001: vibS = "v1" if
X1a1 == -1 & X2a1 == -0 & X3a1 == -2 & X4a1 == 1 & X5a1 == -2 & X6a1 == 0 & X1d1 == 0 & X2d1 == 0 & X3d1 == -1 & X4d1 == 0 & X5d1== -1 & X6d1== -2;

end*; // rules*

end*; // knowledge source*

The extended rule form is as follows:

$$vibS = v_1 \; if \quad f_w \simeq f_{v1} \; and \; X1a1 = -1 \; and \; X2a1 = 0 \; and \; ...X6a1 = 0 \; and \; ... \tag{6}$$

where:
vibS – decision variable taking values from *V* (3),
X1a1 – attribute taking values from Table 2.

During the resoning the expert system tries to confirm all vibration sources *V*. As the result the variable *vibS* includes only values v_i for which confirmation is successful.
In further development certainty factors of rules and conclusions should be taken into account.

6. Conclusions

The blade vibration sources identification method presented in the paper exploits an expert knowledge of signal processing in the rotating machinery diagnostics. The use of discrete wavelet transform localizes computations to the limited set of sources frequencies. Multi-valued representation of the wavelet transformation's results in natural way leads to rule-based expert system. On the other hand an expert system supports existing and new knowledge from real-world experiments. It is crucial for knowledge validation and removing artefacts (edge effects, cone of influence,…) from the resoning process.

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