DIGITAL ORDER TRACKING ANALYSIS FOR ROTATING MACHINERY MONITORING. THEORY AND IMPLEMENTATION

Aleksandr PETROVSKY, Andrew STANKEVICH, Mirosław OMIELJANOWICZ, Grzegorz RUBIN

Politechnika Białostocka, Wydział Informatyki, 15-351 Białystok, Wiejska 45A
Tel. 085-746-91 48, palex@wi.pb.edu.pl,
mirekmo@wi.pb.edu.pl , gregor@wi.pb.edu.pl,

Summary

This paper presents a brief of properties and rules of digital order tracking analysis in diagnosis of rotary machines. The classical methods of order spectrum analysis are also provided. The main part of given paper is description of new approach of method for digital tracking analysis. The most important thing is a way of choosing samples for logical change of regular sampling in time domain by regular sampling in angle domain. The low-order filter based method is used. Presented paper shows design of such filter and the results of simulations and experiments. At the end short brief of expert systems idea for diagnosis of rotary machines was shown.

Keywords: digital order tracking analysis, vibrodiagnostic, real time.

CYFROWA RZĘDOWA ANALIZA ŚLEDZĄCA DO MONITORINGU MASZYN OBROTOWYCH. TEORIA I IMPLEMENTACJA

Streszczenie

W prezentowanej publikacji przedstawiono w skrócie zasady i cechy cyfrowej rzędowej analizy śledzącej w diagnostyce maszyn obrotowych. Wskazano, także klasyczne metody wyznaczania widma rzędowego. Zasadniczą częścią publikacji jest opis autorskiej metody prowadzenia cyfrowej analizy śledzącej. Najistotniejszą innowacją jest sposób wyznaczania próbek pozwalający na logiczną zmianę równomiernego próbkowania sygnału w dziedzinie czasu na równomierne próbkowanie w dziedzinie drogi kątowej. Metoda polega na zastosowaniu tzw. filtru niskich rzędów. W przedstawionej pracy opisano sposób projektowania takiego filtru oraz pokazano wyniki symulacji i eksperymentów. W zakończeniu przedstawiono krótko ideę systemu ekspertowego do diagnostyki maszyn wirujących, wykorzystującego opracowaną metodę.

Słowa kluczowe: cyfrowa analiza śledząca, wibrodiagnostyka, czas rzeczywisty.

1. VIBROACUSTIC SIGNALS AND REALTIME ANALYSYS

Vibroacoustic phenomenon (VP) in general are dynamic mechano-acoustic phenomenon [3, 7] which occurs with machines and moving devices or having elements in motion. Such phenomenons are vibration, air sound and material, pulsation of rounding machine work space [6, 4]. Projection of vibroacoustic phenomenons are vibroacoustic signals (VS) generated by any kind of electronics sensors.

In practice aspects of VS [7] the widest domain of appliance seems to be diagnostic, a specially during „on time" in real-time of work. The classical methods such as, signal decomposition using band filters, estimation of power spectrum density isn't acceptable diagnostic result in periods of unstable device work. It occurs when VP, so VS too, temporarily loose its stationary property. Such situation have place during speedup or breaking down of rotary machines eg. rotor, electric engine, plane and ships engines. In most of cases this stage of work isn't analyzed, because it's temporary and unstable state. However in causes, when we work with big objects, where run-up and run-down procedure is complicated, information of that period of work have very important practical meaning. It is early fault detection, so serious damage can be avoided.

Instability of signals is very big difficulty of measurement and analysis, so no one from classical time, amplitude or frequency characteristic will be useful. That shows spectrum map (fig. 1a), where placement of spectrum lines moves with every next measurement and not allows for correct estimation. The range of observed spectral component changes too. With the lowest rotations, all to the 8-th harmonic are visible but with the highest only to the 5-th harmonic. In this cases changing domain of analysis is demand [2, 13, 16], that the results have stable character and allows do analysis. Such possibility can be achieved using order domain versus frequency domain. In this approach observed signal (fig. 1b) can be analyzed in the same way like classic invariable picture of frequency spectrum. In order domain points on Y-axis presents x-time of current speed of rotary object so spectral lines of signal component (functions of rotary speed of engine) will be stationary.

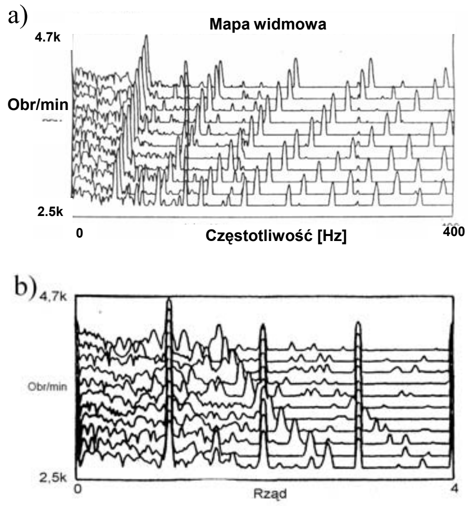

Fig. 1. Frequency spectrum of VS signal with increasing rotary speed and order spectrum of VS signal with increasing rotary speed

2. VIBROACOUSTIC SIGNALS ANALISYS MADE AS ORDER TRACKING ANALYSIS

The main work algorithm of measurement devices worked in order domain analysis are well known from publications [1, 2, 13], many companies like Hewlett-Packard, Bruel & Kjaer, Oros. The algorithm of work flow presents as follows:

a) measure and store the arrival times of each synchronizing tachometer pulse simultaneously (depending of spectrum resolution);
b) calculate the new points of digital resampling time on the base of different rotation models and store them;
c) interpolate the stored measurement data in some optimum manner to obtain new samples at the desired time points;
d) compute the spectrum in the order domain using FFT or any other transformation.

The hardest operation is reconstruction of signal amplitude in the angle movements corresponding the same time moments with precision allowed to achieve demand spectrum dynamic. In paper [13] of Hewlett-Packard company, for signal amplitude reconstruction the interpolation in time domain filter was used. The main defect of such approach is the same amplitude-frequency characteristic in every new collected point corresponding the same angle movements. In the machine speeding up situation threshold frequency should move into high frequency, and when the machine slowing down – into low frequency. Given property makes constant non-removable defect which limits dynamic of the method. For signal amplitude reconstruction the specialists from Bruel & Kjaer company applying different [1, 2] solution: decimation and interpolation with partial multiplicity. That approach decimation factor must be change with non-stationary frequency of engine rotary, but there is problem with setting of current, demanded value of decimation factor which depends on dynamic of specific machine.

In the next chapter the algorithm of spectrum order determination with angle domain filtering usage was described, that eliminates problems in presented methods.

3. SPECTRUM TRACKING ANALYSIS BASED ON DIGITAL LOW ORDER FILTER

Digital order tracking analysis is very important in case of diagnosis of big rotating machines. Disadvantages of traditional methods implicated number of their improvements [12, 10]. The key moments in algorithms that computes order spectrum are how to calculate time points on equal angular movements and how to approximate rotation speed in this points. In presented method [11, 10] linear acceleration rotation speed model and low order filter are used.

3.1. Calculation of new digital resampling time points

In presented work one's assumed that the reference shaft is constantly accelerating during three successive phase marks. Denominate T_j time between i and $i+1$ phase marks and T_{j+1} between $i+1$ and $i+2$ phase marks and using lows describing rotating movements one's get:

$$t_i = -\frac{T_{j+1}^2+T_j^2}{2(T_j-T_{j+1})} \pm \sqrt{\left(\frac{T_{j+1}^2+T_j^2}{2(T_j-T_{j+1})}\right)^2 + \frac{i}{N}\frac{(T_{j+1}+T_j)T_jT_{j+1}}{T_j-T_{j+1}}} \quad (1)$$

where N – number of resampling points, i – current time point (in equation (1) before square root is chosen „-" if acceleration is negative, otherwise is „+").

3.2. Amplitude interpolation at the desired time point

Amplitude interpolation can be made using digital filter of low orders (LOF – Low Order Filter). On fig. 2a time changes of rotation speed are shown. On fig. 2b one's see data collected with constant discretization frequency (Ts=const.) and two time moments t_j i t_k, where amplitude should be resampled. To achieve this, rotation angle in points 1 to 5 and 11 to 16 are calculated. Then, central point of filter impulse response is set on interpolated time moment. Resampled value is equal to sum of the next signal points stored with constant sampling rate weighted with impulse response of LOF. The impulse response of LOF in angle domain is symmetric and has constant width (fig. 2c), but in time domain varies tracking rotation speed (fig. 2b). Resampling algorithm is as follow: 1). To calculate a revolution angle for t_j resampled point from beginning of a revolution j on the base of the linear model of object rotation. It should be noticed that the central point of impulse response of LOF is in a resampled point:

$$\varphi_{tj} = \omega_{oj} t_j + \varepsilon t_j^2 / 2, \qquad (2)$$

where: ω_{0j} – is initial angular rotation velocity of j revolution, ε - acceleration.

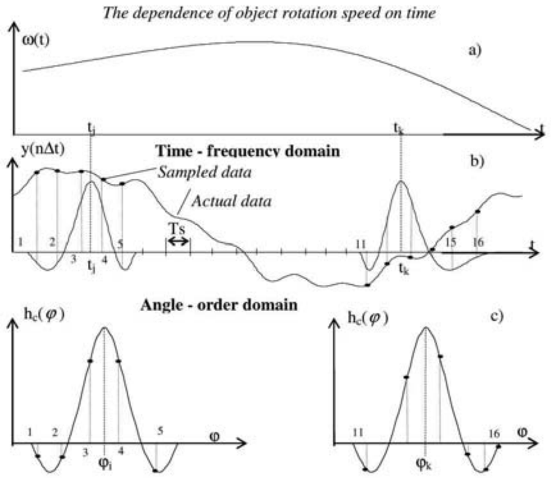

Fig. 2. Resampling amplitude method by the interpolation digital filter.

2. To calculate a current angle from beginning of *j-th* revolution for the nearest points stored with constant sampling time period to the resampled point on the base of the linear model of object rotation.

$$\varphi(nT_S) = \omega_{0j} nT_S + \varepsilon \frac{(nT_S)^2}{2}, \qquad (3)$$

where T_S – discretization period. If the *n-th* point concerns to the previous *(j-1)-th* revolution, then:

$$\varphi(nT_S) = -2\pi + \omega_{0j-1} nT_S + \varepsilon \frac{(nT_S)^2}{2} \qquad (4)$$

In addition to check up the angular distance from the resampled point up to some *i-th* nearest point stored with constant sampling time period, whether the angular distance is no more than half of length of the impulse response. The length of the impulse response of LOF is

$$\varphi_h = \frac{2\pi(N_h - 1)}{N \cdot L},$$

where N_h – number of points in impulse response, N – number of resampled points, L – number of phase markers. Now then it should be:

$$-\frac{\pi(N_h - 1)}{N \cdot L} \le \varphi(nT_S) - \varphi_{t_i} \le \frac{\pi(N_h - 1)}{N \cdot L} \qquad (5)$$

3). To calculate according expression (1) the value of the impulse response of LOF with angle defined on the step #2 for the signal points stored with constant sampling frequency.

$$\varphi_{t_i}(nT_S) = \frac{N \cdot L}{N_h}\left(\frac{\pi(N_h - 1)}{N \cdot L} - \varphi_{t_i} + \varphi(nT_S)\right) \qquad (6)$$

4). To calculate resampled y_{ti} of a signal in *i-th* point as a sum input signal points stored with constant sampling frequency weighted with impulse response:

$$y_{t_i} = \frac{\sum_n h_{t_i}(nT_S) x(nT_S)}{\sum_n h_{t_i}(nT_S)} \qquad (7)$$

where $x(nT_S)$ – input signal. The summation in (7) is conducted for all of *n*, for which the inequality (5) is executed. The given division of the resampled signal amplitude on a size equal to sum of impulse response points is necessary to take account of the change of the impulse response length of LOW in time domain.

In presented resampling method low pass order filter with constant impulse response in angle domain is used. This fact eliminates methodological errors present in other methods. Additional advantage is that in further calculations only important part of spectrum is considered. As were shown, cut-off frequency in magnitude response in frequency domain of the LOF automatically tracks rotation speed changes.

4. SYNTHESIS OF LOW ORDER FILTER

The requests, which the LOF should satisfy are as follow:

1). The cut-off order of a filter should be selected from the required maximum order. In the generally case the normalized cut-off order of a LOF can be selected as: $p_C=2p_{max}/(N \cdot L)$, where p_{max} – maximum order in signal spectrum, $N \cdot L$ – total number of resampled points.

2). The request to pass-band ripple of order response characteristics is selected according to a required dynamic range of the analyzer, as generally during revolution the acceleration of object rotation can be not to constant, then the passband ripple of order response will be perceived as a noise, which to reduce will be impossible without knowledge of the law of the acceleration change. For a required dynamic range D_T, [dB], the passband ripple is estimated by the following expressions:

$$\delta_1 = \pm 20 \cdot \lg(1 - 10^{-D_T/20})$$

$$\delta_1 = \pm 100\% \cdot 10^{-D_T/20}$$

For example, for a required dynamic range 70 dB will have δ_1= ±0,032% or δ_1 = ±0,003 dB. Also the stop-band ripple of a order response should be selected not bigger than significance DT.

3). The ratio between pass-band, stop-band and transition band should be selected according to minimum to possible impulse response points number, as this number determines computing complexity of the resampling amplitude algorithm.

Thus, the problem of a low order filter synthesis is formulated as: Let on the set of orders $E_l \in (-L, L)$, the function is given *B(l)* and the order of transfer function *H(l)* of a nonrecursive filter (FIR) $H(l) = \sum_{k=0}^{N_h-1} h_k \exp(-jkl)$. Where *l* - current order.

It is required to find the vector $\mathbf{h}^* = [h_0, h_1, ..., h_{N_h}]^T$ such, that

$$\min_{\mathbf{h}} \max_{l \in L} \left| B(l) - \sum_{k=0}^{N_h-1} h_k \exp(-jkl) \right| = \max_{l \in L} \left| B(l) - \sum_{k=0}^{N_h-1} h_k^* \exp(-jkl) \right| = \delta^*$$

otherwise

$$\max_{l \in L} \left| B(l) - \sum_{k=0}^{N_h-1} h_k \exp(-jkl) \right| \Rightarrow \max_{\mathbf{h}} = \delta^*$$

The set E consists of the pass-band and stop-band of the desired filter. Thus, we have got the Chebyshev approximation problem. To solve for the filter parameters, we can use the Remez [8] exchange algorithm. The continuous impulse response of the LOF is determined according to the trigonometrical interpolation method [11]:

$$h(\varphi) = \frac{a_0}{2} + \sum_{l=1}^{\frac{N_h-1}{2}} \left[a_l \cos\left(2\pi l \frac{\varphi}{\vartheta_d N_h}\right) + b_l \sin\left(2\pi l \frac{\varphi}{\vartheta_d N_h}\right) \right] \quad (8)$$

where $\vartheta_d = 2\pi/(N \cdot L)$ – sampling period (angle), N_h – number of points of impulse response, ϑ_d - continuous angle ($0 < \vartheta_d < \vartheta_d N_h$),

$$a_l = \frac{2}{N_h} \sum_{q=0}^{N_h-1} h_q \cos\left(2\pi l \frac{q}{N_h}\right), \quad (9)$$

$$b_l = \frac{2}{N_h} \sum_{q=0}^{N_h-1} h_q \sin\left(2\pi l \frac{q}{N_h}\right) \quad (10)$$

where h_q - q-th point of the LOF impulse response.

On fig.3a – 3c impulse responses of the LOF in time domain are shown. The parameters are: ω_0=0, ε=200 rad/sec^2, N_h=33, T=10^{-3}s_c for N=64 points. On figures following labels are used: n –number of point, h1, h32 i h64 – accordingly impulse response in time domain for 1-th, 32-th and 64-th resampling point on the second rotation revolution. From fig. 3 it is visible that by machine run-up, impulse response in time domain is non-symmetric and its length (measured by number of points) decreases.

The magnitude characteristic of the LOF in the frequency domain for the given example is shown on the fig. 3d. The line 1 corresponds to the first resampled point, the line 2 - 32-th, and the line 3 - 64-th resampled points for equal transitions on the second revolution respectively. From fig. 3d it is visible, that LOF has a magnitude response in frequency domain with tunable cut-off frequency, and this frequency displaces in high-frequency area owing to run-up of object. Therefore, the offered filter realizes automatic tracking for the change of the object rotation velocity in the correspondence with the required model of the object rotation velocity.

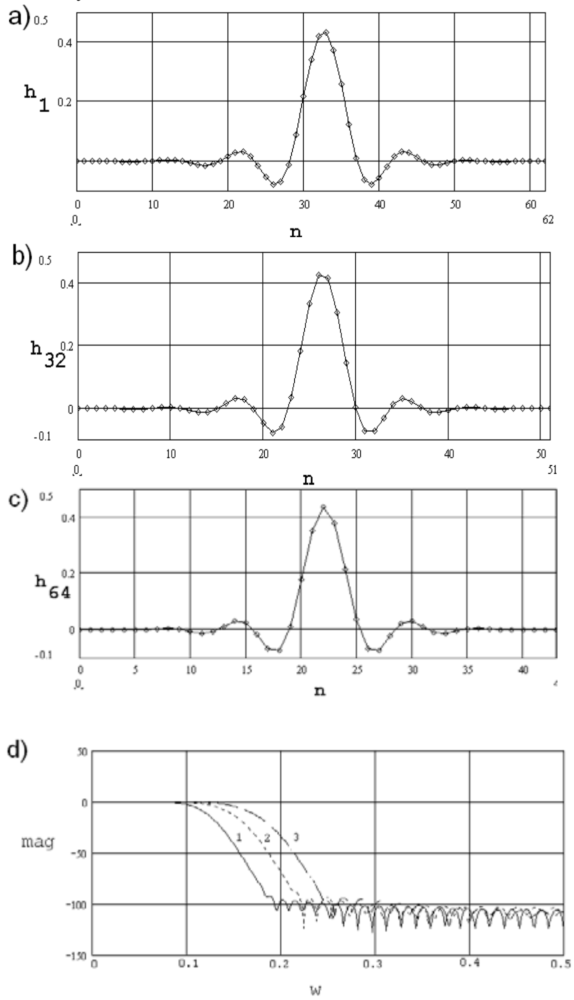

Fig. 3. a) Impulse response on the 1-st resampling point, b) on the 32-th point, c) on the 64-th point, d) magnitude response of the LOF in frequency domain.

5. SIMULATION AND TESTS

Algorithm of the developed spectral tracking analysis consist of following stages:

1. To measure some adjacent time intervals between phase markers on the object rotor. Number of intervals is find from expression *(L*N)/2 = Pmax*, where *Pmax* – maximum order required in spectral map. If spectral resolution *1/k* is needed, it is necessary to collect data throughout *k+1* revolutions.
2. To calculate time moments on equal angle movements of the rotor of the object.
3. To resample amplitude in time moments from stage 2.
4. To calculate spectral map using FFT algorithm. With purpose of a illustration of method work the simulation modeling of process of a unstable rotation is performed. Linear and sine wave are chosen as the law of time variation of object rotation speed. It includes run-up and run-down

stages of object. The following signal was used as the simulation signal:

$$x(t) = \sin[\varphi(t)] + 0{,}25\sin[10\varphi(t)],$$

where:

$\varphi(t) = \omega t + \varepsilon t^2/2$ - by linear changes,

$\varphi(t) = \omega_c t - \frac{a}{b}\cos(at) + \frac{a}{b}$ - by sinusoidal changes (a, b – signal parameters, ω_c – stationary rotation speed).

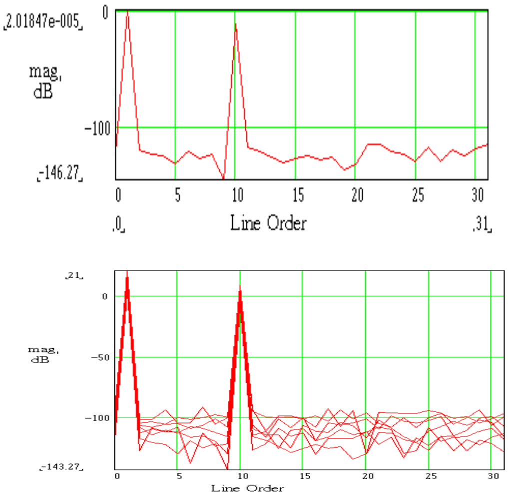

Fig. 4. The spectral map in order domain by linear velocity changes for one revolution (upper fig.) and for six revolutions (lower fig.).

Some simulation results are shown on fig. 4 and fig. 5. The simulation experiments depict that proposed method provides stable spectral line despite of velocity changes even by non-linear case.

By non-linear rotation speed changes spectrum noise component increases because of differences between modeled and real rotation speed.

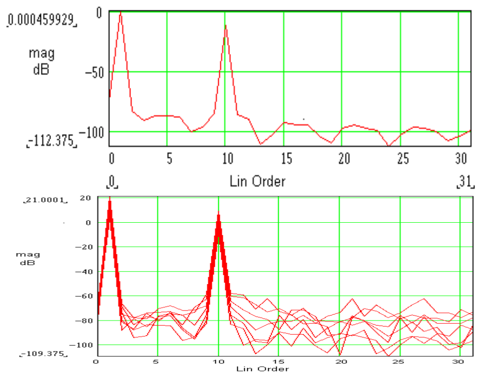

Fig. 5. The spectral map in order domain by sinusoidal velocity changes for one revolution (upper fig.) and for six revolutions (lower fig.).

For checking of the method it was also made a test of an asynchronous electric engine in the stage of start-up and some time later in the stage of rated load. The range of generated frequencies was closed to vibrations of symmetrical engine with 24 slots of stator. The testing results are shown on the fig. 6.

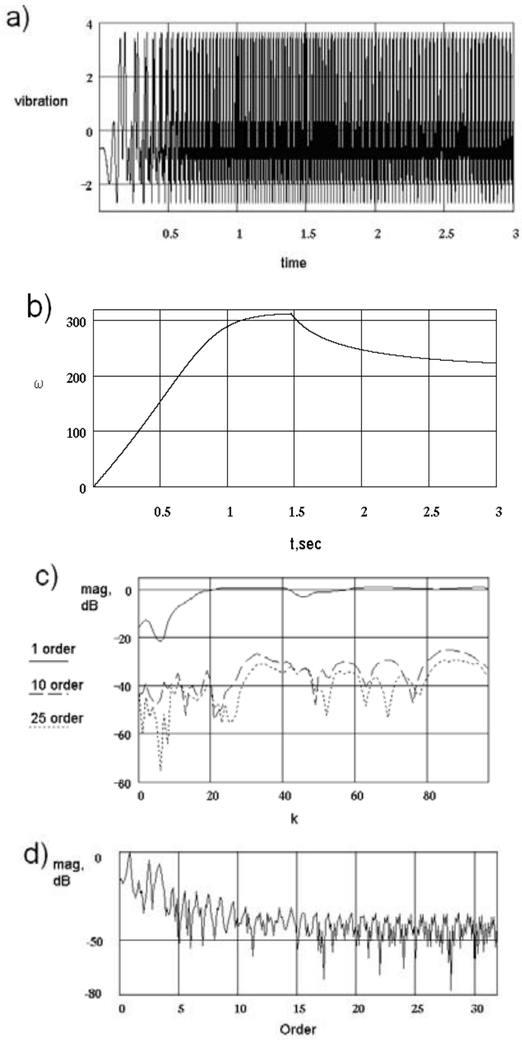

Fig. 6. a) The vibration signal of an electric engine, b) the dependence of object rotation speed, c) the dependence of the 1-th, 10-th and 25-th order amplitude upon number of revolution, d) spectral map in order domain.

6. EXPERT SYSTEM

Proposed method gives possibility of diagnosis rotary machines at instable environment.

Supplementing proposed approach by spectral analysis, there is possible to create automated diagnosis system [12] inclusive all cycle of rotary machines work. During the research the idea of such system was developed. The decision mechanism based on fuzzy-logic methods. The system is implemented in an objectoriented language C++. The object-oriented approach is used because it provides a rich structure for describing frames. The fuzzy reasoning algorithm and knowledge representation in this system are based on the results of the paper [9]. Each hypothesis is expressed as a frame, witch is organised as a hierarchy through a system of superlinks and sub-links. The rules about a hypothesis are attached in the associated frame. There are two kinds of rules. One is used for diagnosis, the other is for meta-knowledge. A grammar in Backus-Naur Form (BNF) for the rules are given below:

Rule:= rule-name IF [conditio] then conclusion cf(f) [rel(f)]
Condition:= fullpremise {relation fullpremise}
Fullpremis:= [sign] premise [weight(f)]
Relation := AND/OR/ADD/REL
sign:=NOT
conclusion:=[sign]premis/rule-name1 {rule-name}
premise:= string/(numeric-variable relation-op value)/string IS string-val)
numeric-variable:=string
relation-op:=>/</=
value:=decimal number
string-val:=string
f[-1,+1]
rule-name:=rule-name1/rule-name2
rule-name1:=r+digital number
rule-name2:=M+digital number
** bold letters denote keywords*

The rule is formulated in a class with the data and operations encapsulated in the rule class. The data include rule name, rule type, certainty, conjunction, conclusion, related factor and a premise list for the variable number of premises. The operations about the rules are written as methods. They include **getNumberofPremise()**, which will get the number of premises in a rule; **getnthPremise()** which will get the content of the *n*th premise; and so on. The definition of the diagnostic rule class is presented in the following view:

class: DiagRule
suoperclass: Rule
data:
ruleName:
ruleType: RULE_DIAG
pemiseList:
certainty:
preRelation:
relatedFact:
conclusion:
methods:
virtual readData()
getNumberofPremise()
genthPremise()
rulename()
ruletype()
certainty()
prerelation()
releatedfact()
conclusion()

A premise is also expressed as a class. It includes premise type, attribute name, relation between premises, weight for the premise and attribute value such as *increase*, *small*, *0.12* and so forth. An instantiation of the premise class is executed as follows:

class: Numeri premie
super-class: premie
premie-type: pre-num
attribute-name: the thickness of LVwall
relation: ADD
weight: 0.3
attribute-value: incrase
function: match()
certainty: 0.7

Each premise object may have its own **match** method to calculate the degree of match between the premise and findings. The certainty fact for a premise is calculated by the algorithm and filled in the certainty slot during the run time. In the system, the frames, rules and even premises are all expressed as classes. During the reasoning process, they are instantiated into objects. This objects will be created and deleted dynamically. The fuzzy reasoning algorithm is used to calculate an uncertainty measure for the conclusion.

7. CONCLUSION

Developed method of digital tracking analysis for monitoring industry machines working in runup and run-down phases and during big frequency instability, eliminates methodology inaccuracy caused by applying polynomial interpolation or interpolation filter in frequency domain. The filter works in order domain has constant order of cut-off (similarly frequency threshold) and choose only that part of order spectrum which is important for the next processing. Impulse response of the given filter is function of rotation angle and constant in this domain. After transformation of given characteristics into domains, time and frequency appropriately, the shape of them changes together with rotary speed change. In the case of frequency characteristic the cut-off frequency automatically fits to changes of speed of rotary machine rotations. In the case of impulse response the progress and the count of non zero points changes. The changes character depends on established model of rotary speed changes. Applying proposed method and appropriated parameters of interpolating filter (Low Pass Filter) the spectrum dynamics more than 100 dB can be achieved (polynomial interpolation or interpolation with frequency domain filter gave dynamics about 70-80 dB). Computation complexity is a defect of proposed method. It can be resolved using efficient microprocessors DSP or distributed arithmetic technology.

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Alexandr PETROVSKY received the Dipl. Ing. degree in computer engineering, in 1975, and the Ph.D. degree, in 1980, both from the Minsk Radio-Engineering Institute, Minsk, Belarus. In 1989, he received the Doctor of Science degree from The Institute of Simulation Problems in Power Engineering, Academy of Science, Kiev, Ukraine. In 1975, he joined Minsk Radio- Engineering Institute. He became a Research Worker and Assistant Professor; and since 1980, he has been an Associate Professor at the Computer Science department. From 1983 to 1984, he was a Research Worker at the Royal Holloway College and the Imperial College of Science and Technology, University of London, London, UK. Since May 1990, he has been a Professor and Head of the Computer Engineering Department, the Belarusian State University of Informatics and Radioelectronics, and he is with the Real-Time Systems department, Faculty of Computer Science, Bialystok Technical University, Poland. Recently, his main research interests are acoustic signal processing, such as speech and audio coding, noise reduction and acoustic echo cancellation, robust speech recognition, and real-time signal processing. He is a Member of Russian A. S. Popov Society for Radioengineering, Electronics, and Communications, and an Editorial Staff Member of the Russian journal Digital Signal Processing, AES, IEEE, EURASIP.

Ph. D. **Andrew STANKEVICH** was born in 1958 in Minsk, Belarus. In 1980 graduated Minsk Radiotechnology Institute of Digital Counting Machines. In years 1982-1992 worked at Bielarusian State Academy Institute of Experimental Physics. From 1992, he works in Bielarussian Sate University of Informatics and Radiotelecom-munication in Digital Machines Department. The area of scientific research is: digital signal processing, digital machines design, technical system modeling.

Ph. D. **Mirosław OMIELJANOWICZ** is employed in Computer Science Department at Bialystok Technical University. The main work is computer architecture, implementation of DSP algorithms in real-time and vibroacoustic signal processing into FPGA devices and DSP processors.

M. Sc. **Grzegorz RUBIN** is employed in Computer Science Department at Bialystok Technical University. The main work is digital vibroacoustic signal processing algorithm realization into FPGA devices and Petri Nets modeling.