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AN APPLICATION OF ORDER TRACKING PROCEDURE FOR DIAGNOSIS TECHNICAL STATE OF ROTOR SYSTEM IN SHUT-DOWN PROCESS

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Abstract

Vibration diagnostic tests of marine gas turbine engines are performed as a research of on-line and off-line types. On-line systems generally monitored one or two vibration symptoms, which asses the limited and/or the critical values of parameters and they, potentially, can warn and/or shutdown engines. Off-line Systems are usually used for vibration analysis during non-steady state of work. The paper presents a new method of vibration diagnostics of rotor bearing system of gas turbine systems. The study assumes implementation of characteristics of vibration signals during the shut-down process of the rotor. The shut-down process is non-stationary so the studies used the order tracking procedure. Identified orders constitute individual characteristics as a function of changes of the rotational speed and shut-down process time. These allow the observation of changes in the support rigidity of the rotor in the frequency domain and change the bearing resistance torque as a function of changing time of the shut-down process. The resulting characteristics are as reference fingerprints for each of the rotors. Changes in the characteristics of the primary evidence of the processes of wear. Changes in the stiffness of rotor supports make change the amplitude of orders and frequency of the resonance signals observed in the frequency domain - decreasing rotational speed. The bearing wear results in changes in the shut-down time between successive intervals of characteristic rotational speed and the total shut-down time.

Keywords: *dynamics, vibration, gas turbines, rotor vibration, shut-down process, order analysis*

1. Introduction

Diagnostics of rotor systems of gas turbine engines includes a wide range of parameters, controls and maintenance procedures. One of them is the control of unacceptable balance of rotors and technical state of bearing systems. Identification of different unbalanced states, determining its value and the accurate placements of corrective masses is commonly known. In the case of naval propulsion diagnostic procedures are limited for several reasons. The most important of these is the need to maintain a constant readiness to start the engine, associated with the tactical requirements. In addition, due to the fact that the engines are foreign construction, there is a lack of information on the structural parameters of the engine, reducing warranty, no spare parts readily available, etc. Similar problem occurs with diagnostics of bearing systems. Gas turbine engines work in the non-stationary states what includes changes of loads (different temperature of gas flow and lubrication oil) and changes of the rotational speed. This causes problems with unambiguous interpretation of the results of research and the creation of a database of diagnostic symptoms.

The use of vibration diagnostics makes the use of the engine more rational; from a technical point of view, especially towards vitality of service, which in effect will not withdraw, even a technically efficient ship, from service. Measurements and analysis of vibration parameters of marine gas turbine engines can be divided into:

– off-line (measurements performed in free-run mode, periodically),
– an on-line (real-time monitoring).

Both methods have their advantages and disadvantages. Off-line Systems are usually offered as very simple analysers – data collectors. Measurement path is determined in the collector interface, with preset measuring settings, so that an average technical staff, whose main task is a precise procedure, could perform the measurement. The analysis of measurement results is carried out off the ship, sending the results to the coast laboratory. Currently, there is not many off-line data collectors, who would engage in that precise diagnostic evaluation. The main advantage of such devices is their price. It should be emphasized that the data collectors are useful mainly to assess the go-state of vibrations of turbine engines.

On-line diagnosis of vibrations provides continuous surveillance of the technical condition of gas turbine engines, including registration, analysis, forecasting and alarming. It allows you to recognize the basic signs of changes in the technical condition with the possibility of analysing the trend of selected symptoms. On-line vibration systems usually work as part of a complex and symptomatic diagnosis of marine propulsion systems. The proper diagnosis of such structures, for example, turbine engine, depends on various issues, including how the measurement and processing of vibration signals was taken. Important in the further analysis is the fact that internal combustion engines in gas turbine propulsion ships do not run at a constant speed with compressor and turbine rotors.

This is the main reason for synchronizing the processing of selected parameters (of the signals) i.e. the rotational frequency of one or both of the engine rotors. This method allows you to identify the most common groups of rotor systems, which allows you to identify their failure. Damages to operating gas turbine engines can be categorized as follows:

- damage or crushing of first-stage compressors' blades or power turbine blades (rare),
- the appearance of unbalance, originating from heating or salinity,
- cracks sealing systems and leakage of lubricating oil to the inside of the drum rotor,
- lack of alignment between the gas-dynamic gas generator and power turbine,
- thermal damage to the combustion chambers – torsion of power turbine rotor,
- damage to the auxiliary engine mechanism.

Some failures can be resolved in the recorded spectra as a change in vibration frequency of rotating engine components, hence the introduction of a synchronous sampling of the transient engine operation, e.g. in the boot process or in the shut-down run.

The occurrence of non-stationary effects, typical for residual unbalance may be due to small, incremental damage whose symptoms may be poorly recognized in the early stages of development. The results of the identification of such phenomena sre exemplified in the article comparing the various methods of synchronous signal processing method such as PLD or Order Tracking. The presented method for identification of defects can be introduced into the turbine engine monitoring systems as a tool for early identification of unbalance [1, 8].

2. Autotracking procedure

The analysis the vibration of machines usually requires to estimate the rotational speed of the analysed machine. Usually the applied speed sensors require access to the rotating parts of machinery that often encounters problems or is even impossible. The autotracking is a new method where the fundamental frequency is extracted from the measured vibration signals. The method is based on Bayesian statistics. The major advantage is the possibility of performing rotational speed of the machine where no tacho signal is available.

The signal processing literature describes the problem of detecting periodic signals as a estimating the amplitude and phase of a number of harmonic components [6, 7]:

$$d_m(t) = a_{m,0} + [\sum_{k=1}^{K} a_{m,k} \cos(\omega_k t) + b_{m,k} \sin(\omega_k t)] + e_m(t), \quad (1)$$

where:

$e_m(t)$ – noise term with mean value equal zero,

a_k – next orders of the fundamental frequency.

When consider a segment of samples (Eq. 1) it can be formualted as linear problem [6, 7]:

$$\mathbf{d} = \mathbf{Gb} + \mathbf{e}, \tag{2}$$

where:
d – column vector of mesured data,
G – matrix represents cosines and sines,
b – column vector of amplitudes,
e – noise contribution.

Based on Bayes theorem the joint posterior probability density function (PDF) of the parameters in a model is equal to the likelihood of the data multiplied by the prior knowledge of the parameters divided by the evidence of the data. It can be written as [6,7,11]:

$$P(A/\boldsymbol{d}) = \frac{P(\boldsymbol{d}/A)P(A)}{P(\boldsymbol{d})}, \tag{3}$$

where:
A – model parameters;
$\boldsymbol{d}$ – data parameters.

Using Bayes theorem it is possible to calculate the posterior distribution of ω_0 conditioned on the measurement data. The autotracker calculates a sequence of probability spectra, giving the probability that a given frequency represents the RPM. By further statistics the final RPM profile is estimated. Using Pulse LabShop we have to give some inputs to the autotracker, main of them are the actual RPM range, the maximum acceleration [delta RPM/s] and the dominating orders/harmonics of the RPM manifest in the noise/vibration signal. Analyzing the run down processes (nonlinear) we have to give information about maximum rotational speed expected in the signal. Information about maximum deceleration and the dominating RPM orders usually can be find in technical documentation of machine or they may have been revealed during pre-analysis for example, in an FFT colour contour of a run-down. It is obvious that if no orders are visibly presented in the signal, it is not possible for the autotracker to calculate fundamental frequency and consequently the rotational speed will not be available. The next disadvantage of the autotracker is that it does not give any information about phase relative to the revolution. Moreover, due to the fact that the autotracker is based on statistics methods, it may encounter problems in cases which involving asynchronously rotating parts with closely separated or crossing RPM manifests. It should be noted that the most accurate method of estimating rotational speed is still the tachometer [10].

3. Order Tracking

Rotating machines produce repetitive vibrations and acoustic signals connected with rotational speed. These relationships are not always obvious with standard dynamic signal analysis (for example FFT) and especially in these cases the order analysis is very useful. The order analysis becoming a commonly used technique for analysis of vibrations generated in machines, where many vibrations are related to machine RPMs

The FFT process transforms time domain data to the frequency domain, creating a spectrum. Periodic signals in the time domain appear as peaks in the frequency domain. In order analysis the FFT transforms the revolution domain data into an order spectrum. Signals that are periodic in the revolution domain appear as peaks in the order domain. For example, in a six-cylinder four-stroke engine, gas-dynamic forces occur three times per revolution, peaks generated by this forces occurs in the third order in the order spectrum.

In order analysis, normally a signal from tacho probe is used as a tracking reference. It allows a measurement to be related to the revolutions of a rotating part in the machinery. In cases where it is impossible to get access to the rotating parts of the machinery it is possible to use the autotracker which provides the tracking reference. In this case, the fundamental frequency can be extracted indirectly from the measured vibration. It should be notice that still preferred source of tacho signal is tachometer.

In the order analysis spectral elements that are constant with frequency, for example resonance peaks are well visualized, this is the reason why order analysis is often first step in a trouble-shooting scheme, in order to investigate whether a vibration problem is resonance or other reasons.

The other typical uses of order analysis are:

- separation of rotational noise and vibration phenomena,
- investigation of instabilities in rotating machinery,
- identification of noise due to rotational vibrations.

Order analysis without tracking

Run-up and run-down tests without tracking can be made using a tacho signal and an FFT analyser. This is done by using a fixed sampling frequency and plotting the frequency spectra at certain fixed changes in the rotational speed of the machine. The amplitude as a function of RPM can be obtained by cutting slices at oblique angles from contour plots showing frequency spectra versus rotational speed. It is useful technique when one analyses lower order components and frequency smearing is insignificant. However, with high frequency components smearing may occur. This is the reason why order analysis with tracking is often used instead [10].

Order analysis with tracking

Order analysis uses order tracking, which involves measuring order spectra rather than frequency spectra. The Order analyser tracks the data by using re-sampling and interpolation and then performs an FFT measurement on the tracked data. This provides an order spectrum with the amplitude of the various orders as a function of the rotation frequency. As it was describe above using this technique means that an order component remains in the same analysis line independent of the rotational speed of the machine [5, 10]. Many functions can be calculated as a post-processing operation.

The main advantages of an order analysis using tracking are:

- order components remain in the same analysis line and thus the same position in the spectrum.
- the distance between spectral lines can be adjusted so that the order components are placed in the middle of a spectral line, it reducing bias errors connected with leakage when measuring the order components amplitude.

4. Object of researches, methodology of the measurement

The research work was conducted at the Laboratory of Marine Power Plant Operation in Polish Naval Academy on a test bed of turbine engine GTD 350 (Fig. 2). Engines of this type are mainly used to drive the helicopters, particularly helicopters MI-2, so many of them are still in operation. Engine GTD 350 has a nominal power P_{nom} = 235.4 kW, maximum power P_{max} = 294.2 kW, maximum power turbine speed is n_{tn} = 24000 rev/min, max speed of gas generator n_{wt} = 45000 rev/min, maximum compression π = 5.9, the maximum temperature of gases is t_s = 1243 K. Elements of the combustion chamber, turbine casing and a turbine driving the compressor are not cooled and there is no possibility of montage the vibration transducer due to too high temperature. For this reason, as transducer mounting location the engine block of the first stage compressor was chosen. The closest to the transducers sources of vibrations are as follows: first stage of compressor with 10 blades, second stage with 13 blades and third with 15 blades. The whole rotor of the engine is presented on Fig. 1. The on the test bench the engine power turbine shaft has a ratio of i=0.246. On the test bench engine power turbine shaft is coupled to a external reduction gear with ratio i_1 = 0235. Water brake guarantee load on the engine at full speed range.

During the measurements there were used three accelerometers mounted in three mutually perpendicular directions (Fig. 2), wherein for the further analysis only the signal obtained by the measurement in the direction V has been chosen. At the time of the measurement measured frequency band was limited to the frequency 12.8 kHz, the sampling frequency used was 32.768 kHz. There were applied a high-pass filter with cut-off frequency of 7 Hz.

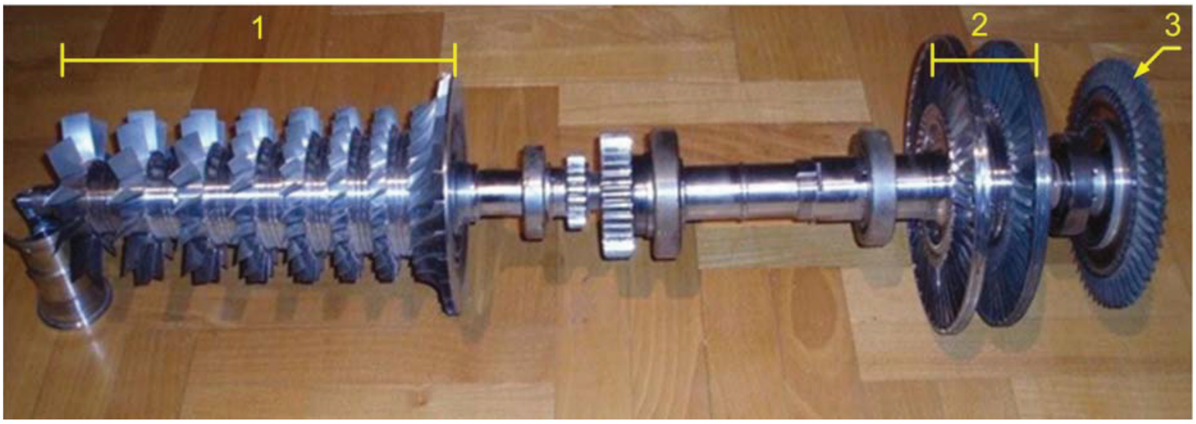

Fig. 1. Rotor system of GTD 350, 1– compressor consists of seven degrees of axial compressor and one radial, 2 - power turbine, 3 - turbine compressor (1+3– gas generator) [9]

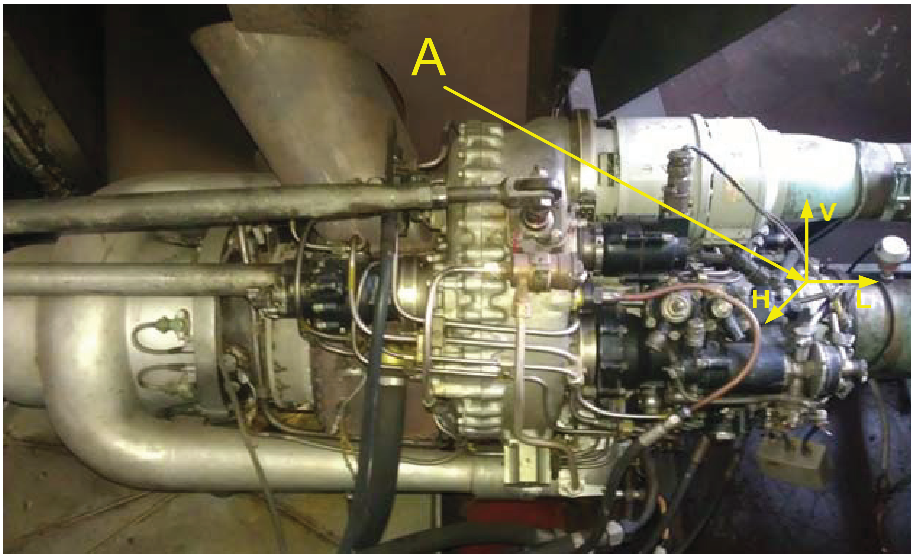

Fig. 2. GTD 350 turbine engine on test plate in laboratory of Polish Naval Academy. A – place of mounting the accelerometers

5. Analysis of results

Before the essential part of the analysis, results of the usefulness of estimation the rotational speed using the autracker method had been conducted. The course of the vibration signal obtained from the engine mounted tachogenerator was compared to the tacho signal obtained from vibration signal. Due to the fact that the voltage of tachogenerator exceeds the allowable measurement range of the testing equipment it was necessary to use the damper with attenuation of 20 dB. The results of both the speed waveform is shown in Fig. 3

As shown in the above figure (Fig. 3) in the steady state, speed of the compressor estimated using the procedure of autotracker are almost identical with the tachogenerator speeds (up to 9 s). However significant differences occur during run down of the engine, therefore speed profiles obtained with this method are not suitable for assessment of bearing systems by measuring the run down time. Of course, this inference refers only to this type of engines. Research conducted by the authors indicate that the speed obtained with this method for simpler rotating machinery (centrifuges, pumps) are almost identical with the values of speeds obtained by means of tachometers.

The next step of the analysis is the analysis of the results in the order domain. Due to the reason stated above as a tacho signal the signal from the tachogenerator was used.

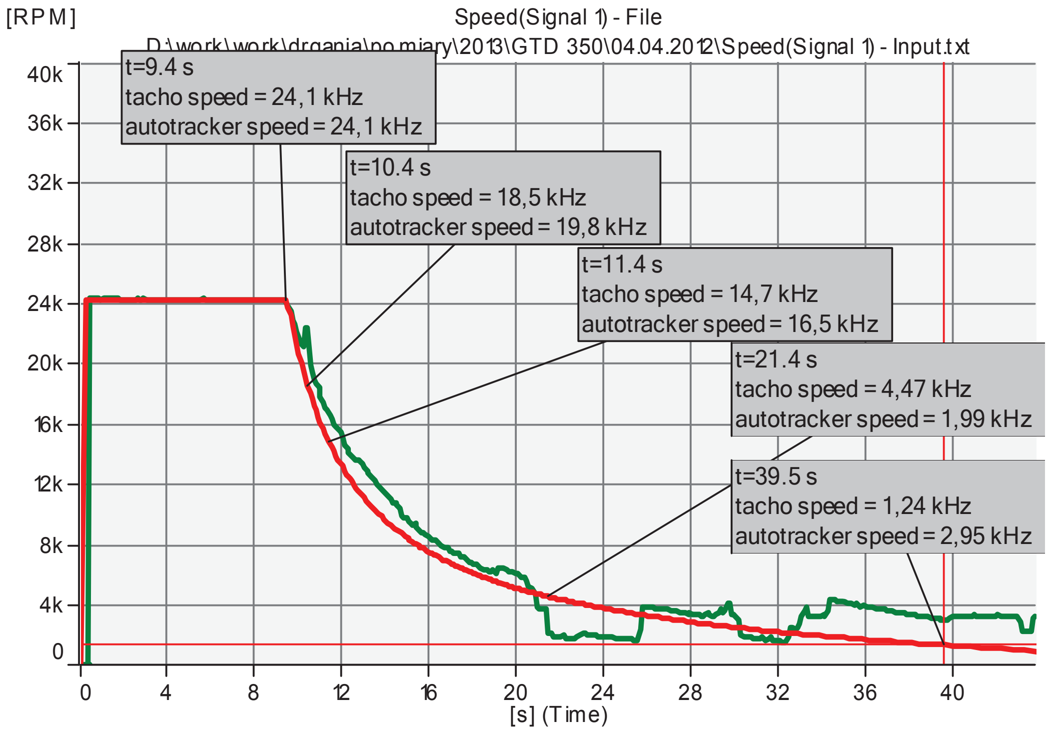

Fig. 3. Changes in speed of rotor compressor. Red colour indicates the speed curve recorded with tachogenerator, green show the speed of the vibration signal obtained using the procedure of autotracker

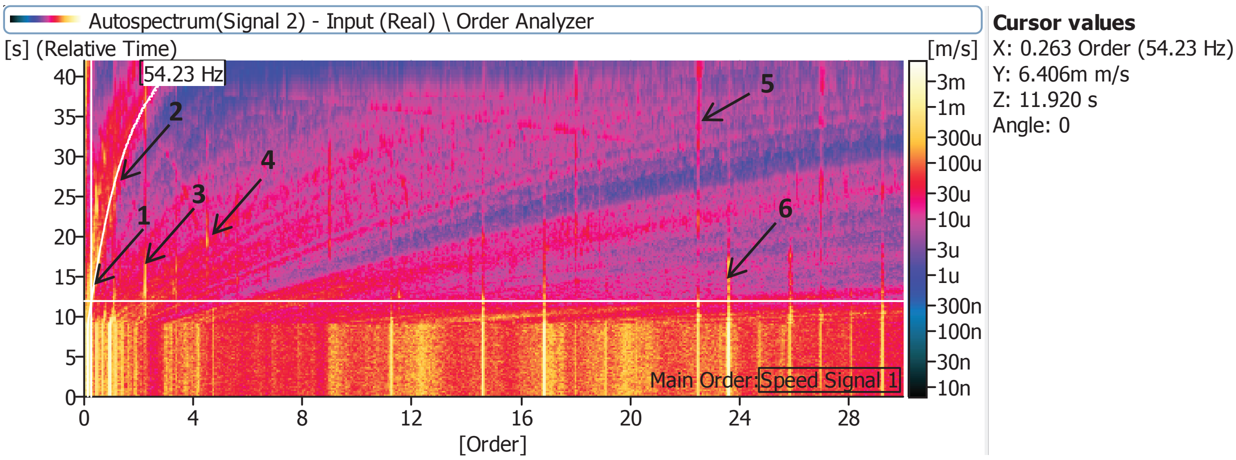

Fig. 4. Result of the order of the GTD 350 engine run-down, numbers 1-6 indicates the potential location of the resonances

Figure 4 presents a chart obtained by the order analysis with tracking. The first 30 rows was analysed with a resolution of 800 lines which allows the minimum spacing between orders as a d_{order}=0.0375. Numbers 1 to 6 indicates orders for further analysis. In this orders the boost of vibration velocity amplitude could be seen.

Figures 5 and 6 show slices through the orders of the values 0.225, 1.125, 2.250, 4.5, 22.5 and 23.650. Due to the high dynamics of amplitude in the various orders in Fig. 5 a logarithmic amplitude scale velocity had been used, in order to visualize the effect of resonance in Fig. 6 linear scale had been used. In Fig. three values are indicated they are values of resonance amplitudes much larger than the average amplitude of vibration velocity recorded for the order during normal operation of the engine. The graph presents clearly high utility of order analysis to detect resonances in the run-down process of machines.

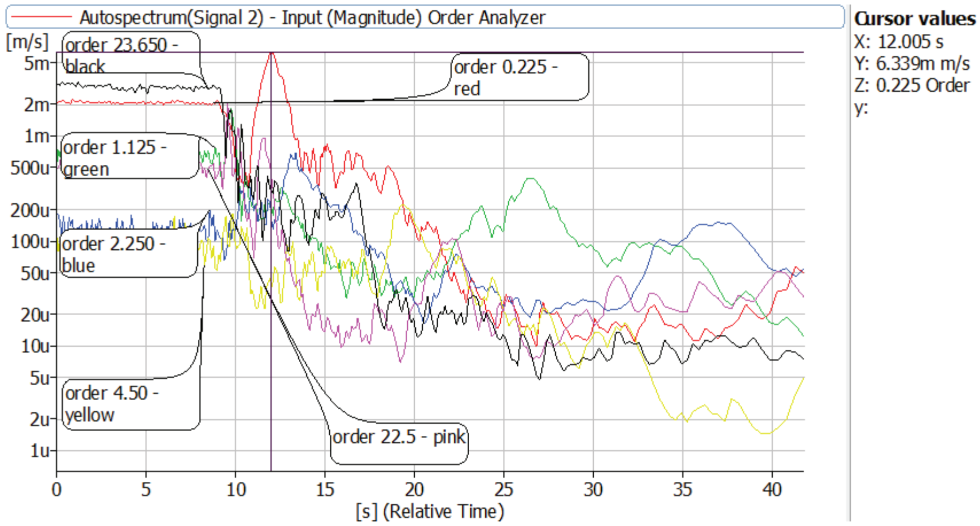

Fig. 5. Slices through the orders indicated on Fig. 4. The logarithmic scale of vibration amplitude velocity was used. All slices are 0.1 orders wide

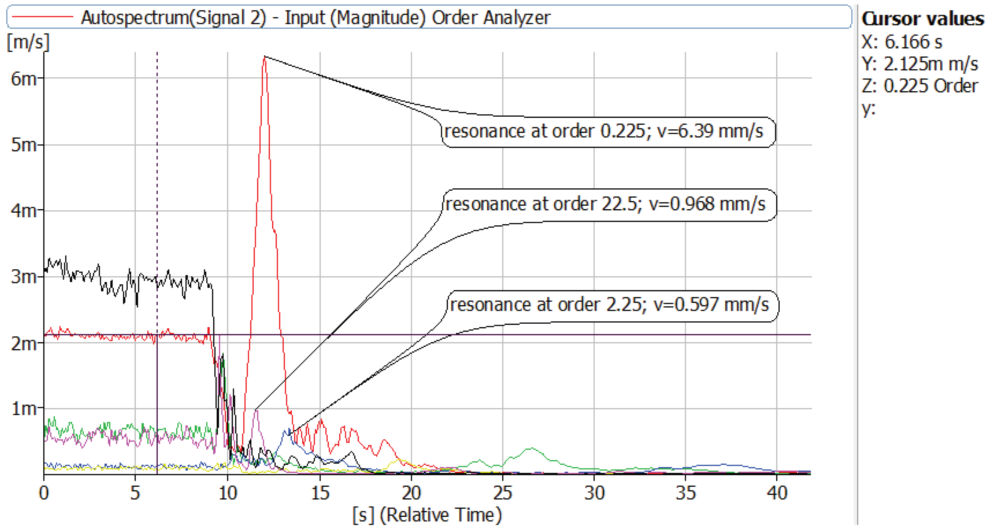

Fig. 6. Slices with use of linear scale of vibration velocity amplitude (resonances are more visible)

6. Conclusions

Referring to the construction of turbine engines in the rotary system the compressor and the power turbine rotors are not mechanically connected together and this is the reason why there is no strict relationship between the rotational speeds of this elements. As mentioned in the introductory chapters, in such cases, a very useful form of vibration analysis is the use of order analysis with the tracking procedures. The conducted analysis confirms usefulness of this method in detection of resonances of rotor systems. It should be also noted that the autotracker procedure is not good enough to accurately assess the speed in the range of complicated rotating systems. This is due to changes in order with decreasing rotor rotational speed.

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