Wave Phase-Sensitive Transformation of 3d-Straining of Mechanical Fields

I N Smirnov¹,²,³ and A A Speranskiy¹
¹Advanced Vector Analytics Ltd, Riga, Latvia
²Lomonosov Moscow State University, Moscow, Russia

E-mail: Ilyas@ava-labs.com

Abstract. It is the area of research of oscillatory processes in elastic mechanical systems. Technical result of innovation is creation of spectral set of multidimensional images which reflect time-correlated three-dimensional vector parameters of metrological, and/or estimated, and/or design parameters of oscillations in mechanical systems. Reconstructed images of different dimensionality integrated in various combinations depending on their objective function can be used as homeostatic profile or cybernetic image of oscillatory processes in mechanical systems for an objective estimation of current operational conditions in real time. The innovation can be widely used to enhance the efficiency of monitoring and research of oscillation processes in mechanical systems (objects) in construction, mechanical engineering, acoustics, etc. Concept method of vector vibrometry based on application of vector 3D phase-sensitive vibro-transducers permits unique evaluation of real stressed-strained states of power aggregates and loaded constructions and opens fundamental innovation opportunities: conduct of continuous (on-line regime) reliable monitoring of turboaggregates of electrical machines, compressor installations, bases, supports, pipe-lines and other objects subjected to damaging effect of vibrations; control of operational safety of technical systems at all the stages of life cycle including design, test production, tuning, testing, operational use, repairs and resource enlargement; creation of vibro-diagnostic systems of authentic non-destructive control of anisotropic characteristics of materials resistance of power aggregates and loaded constructions under outer effects and operational flaws. The described technology is revolutionary, universal and common for all branches of engineering industry and construction building objects.

1. Introduction

Vibration methods became of common usage in the sphere of test parameter measuring of mechanical systems. These methods are based on static models of experimental estimate of strength resource state according to two scalar jitter parameters such as amplitude and frequency. These elements are
emotional outer system indicators that reflect understanding of spatial deformation processes averaged and projected by scalar method. Monoscope monitoring provides only a capability to estimate systems and also it is entropy relative to insight. Because of it, the main reason of emergencies in critical infrastructure and of mass human presence is the lack of efficient equipment for monitoring of dynamic strength.

At the turn of XXI century in the context of state-of-the-practice of the idea to create vector phase-sensitive metrological means on the basis of computer technologies, there was a breakthrough opportunity of spatial updating of the outlined anisotropically hard dynamically-sized portraits. This opportunity allows estimating by direct method the deflected modes and vibration test parameters of the monitoring objects. The method, which is fundamental and flexible for all fields of machine building and construction industry, has been developed and implemented. This method represents innovative IT for environmental safety.

Deficiency of the known methods is that they do not allow reconstructing time-correlated multidimensional images of metrological and estimated spectral parameters of oscillatory processes in mechanical systems.

In order to effectively use the advantages of the substantial increase in informativity of the oscillatory measurements in mechanical systems attained through application of vibration accelerometers and 3D-receivers of mechanical oscillations, it is necessary to create multidimensional systematic interlinked spectral images of test parameters in oscillatory processes, which are adequate to physical and fundamental laws of researched and controlled natural phenomena and processes. It would resolve the problem of enhancing the efficiency of research and evaluation of oscillatory processes in mechanical systems. Technical solution to the posed problem is the method of reconstruction of multiparameter images of oscillatory processes in mechanical systems. Creation of systematic interlinked multiparameter, multilevel, hierarchically organized cybernetic images of oscillatory processes (both superficial and volumetric) in mechanical systems is the main result of implementation of this innovation.

2. Description of the method
Solution to the posed problem is the method which implies creation of sets of three-dimensional elliptic images (hodographs) of linear vibration acceleration vectors and/or vibration speed vectors, and/or vibration displacement vectors in places where the sensors (3D-receivers) are installed on the monitored object based on synchronously measured spatial and dynamic (time-varying) components of test parameters’ vectors, accumulation of spectral arrays consisting of the measured and estimated (including approximated) vector and scalar values in the specified range of mechanical oscillations frequencies, application of measured and estimated test parameters on 3D-model of monitored object, 3D-reconstruction of spectral sets of spatial elliptic hodographs of time-varying deformation vector parameters, defining the characteristic parameters of external forces and their relative positioning against measuring points through a correlation between values and direction of axes of deformation vector hodograph, as well as defining stress-strain states.

Metrological and estimated vector parameters are physically interlinked through tensor connection, these parameters are fundamental, integral and systemic and they form a stable aggregation of attributes which reflect dynamic homeostasis of monitored object adequately to the physical nature. An integrated reconstruction image of oscillatory processes in an object can be used in the course of further monitoring of the object.
Technical result is the creation of spectral set of multidimensional images which reflect time-correlated three-dimensional vector parameters of metrological, and/or estimated, and/or design parameters of oscillations in mechanical systems (Holospectrum). Reconstructed images of different dimensionality integrated in various combinations depending on their objective function can be used as a homeostatic profile or cybernetic image of oscillatory processes in mechanical systems for an objective estimation of the current operational conditions in real time.

The specified above technical result of the method of reconstruction of oscillatory process images is accomplished through the device which contains a space-time measurements module, module of synchronization of space-time measurement transformation, digital memory module, module of spectral processing of measured vector parameters, module of reconstruction of the measured parameters, module of standardized matrixes of tensor transformations, module of estimated test parameters of mechanical oscillations, module of reconstruction of object’s 3D-model, module of reconstruction of multi-parameter images of oscillatory processes, module of visualization of the reconstructed parameters, registering module, and the module which organizes system interaction of all modules. Innovation can be widely used to enhance the efficiency of monitoring and research of oscillation processes in mechanical systems (objects) in construction, mechanical engineering, acoustics, etc.

The method is illustrated by figures 1 and 2 where the structure of measurement and buildup of test parameters of mechanical oscillation is schematically pictured. Reconstruction module of multi-parameter images of oscillatory processes in mechanical systems is displayed in figure 2. The method of reconstruction of multi-parameter images of oscillatory processes in mechanical systems is carried out as follows.

A spectrum of wave oscillations produced by external forces in the form of forces and moments’ actions or by internal pathologies of structure’s material, propagating on a contour surface and through the whole volume of the monitored object, influences sensing elements of the 3D-receivers of mechanical oscillations installed in the measuring points on a contour surface of an object. Metrological tool carries out the inverse tensor transformation of deformation spectrum acting upon it as well as carries out space-time measurement of superimposition of components of spectral set of metrological parameters in the Cartesian coordinate system of the receiver. Measured analog parameters are transformed synchronously into the digital form and are entered into a digital unit for further spectral processing (filtration) and vector-phase reconstruction of elliptic metrological parameters. In order to retain the linearity of interlinked metrological and estimated test parameters, it is necessary to standardize the measurements relative to maximum values defined by technical characteristics of metrological tools and estimated coefficients of transformation of physical quantities.

Multidimensional interlinked space-time set of the estimated and metrological parameters of oscillatory processes makes up an essence of object’s cybernetic image and defines the degree of its adequacy to mechanical oscillations spectrum, produced in nature. Further, subject to the posed problem, the current values of test parameters are calculated based on spatial measurements, allowing evaluation of the dynamic condition (homeostasis) of an object. Inside the modules of visualization and registration of the reconstructed parameters both graphic vector images (including elliptic images) and scalar images are formed, allowing analyzing and effectively evaluating current homeostatic condition of an object.
Reliability of a cybernetic image of an object is supported by synchronous system interaction of all modules that generate, process, register, store and display sets of estimated metrological parameters of oscillatory processes.

| Module 1: Measuring System (3D-receiver of linear mechanical oscillations) |
|-------------------------------|-------------------|-------------------|
| Measuring point                | Contour surface   | 3-D frame         |
| Volumetric array of measuring points (3D-receivers) |

| Module 2: Measurable Components of Test Parameters |
|---------------------------------|-----------------|-----------------|
| Cartesian projections of 3D-superimposition of frequency spectrum in a measuring point |
| Frequency spectrum of Cartesian projections of vector measurement of contour (surface) array of measuring points |

| Module 3: Transfer of Measured Components (modules 2, 3, 4, 5) |
|-------------------------------------------------------------|
| Synchronous data transmission, analog-to-digital transformation, input into processor and storage of accumulated measured space-time components |

| Module 4: Metrological Task (modules 6, 7) |
|------------------------------------------|
| Spectral vector decomposition and standardizing of measured space-time components |

| Module 5: Reconstruction (modules 8, 9, 10) |
|------------------------------------------|
| Calculation and spectral reconstruction of superimposition of space-time elliptic hodographs of oscillation processes test parameters |

| Module 6: Calculations Arrangement (modules 11 -15) |
|---------------------------------------------------|
| Organization of intra-processor interaction, storage and registration of sets of measured and estimated test parameters |

**Figure 1.** Structure of measuring and generating of test parameters in mechanical oscillations.

The project is delivered on the basis of such new IT as vector-phase method of multivariate spatial-temporal updating deformation fields via 3D-phasebalanced tensor – transformation of strength parameters of the monitoring objects. Software and hardware using vector vibration transducer are...
meant for estimate, supporting and safety systems in the building industry, in the sphere of fuel transfer, thermal and nuclear power industry, in air-space, heavy and machine industry, geological engineering, hydroacoustics and defectoscopy.

Comparative informativeness of scalar and vector-phase methods measurements of multivariate spatial-temporal updating deformation fields is presented in the picture (figure 3). Graphical symbols: red – block of spatial-temporal of instantaneous vectors of deformation fields, green – block of monoscope scalar projectures of instantaneous vectors.

Main objects of application of the method are dynamic aggregates and mechanisms, power static constructions, hydroacoustic systems, natural objects of anthropogenic type.

**Figure 2.** Reconstruction module of multi-parameter images of oscillatory processes in mechanical systems.

Designations in figure 2: 1 – 3D-receivers of mechanical oscillations, 2 – three-channel blocks of synchronous amplification and transformation of the charge, 3 – device/block of synchronous transfer of measured components of mechanical oscillations parameters, 4 – device/block of synchronous analog-digital conversion and input of components of mechanical oscillations parameters into processor, 5 – digital storage unit for measured components of mechanical oscillations parameters, 6 – module of spectral processing of the measured components of mechanical oscillations parameters, 7 – module of standardized matrixes of tensor transformations, 8 – module of spectral reconstruction of elliptic hodographs of test space-time parameters in measuring points, 9 – module of reconstruction of object’s 3D-model, 10 – module of reconstruction of multi-parameter images of oscillatory processes, 11 – module of visualization of test parameters, 12 – registering module, 13 – module of synchronization of transformation of space-time measurements, 14 – module of organization of system interaction of all modules, 15 – information transfer and management bars.

### 3. Application examples

#### 3.1. Comparison of informativity 1D and 3D methods

Vector vibroacoustic metrology method and laboratory production technology of vector vibration transducer is developed. Russian company «GAZprom» has developed, implemented and tested Vector Diagnostic Automated System (VDAS) of compressor station gas compressor units.
3.2. Static construction

Description of experiment: simple plywood construction 190x190x720 was placed on a vertical vibrating table. Frequency of the vibration was 50Hz. The platform was fixed on four dampers. Measurements were taken at different points of the structure (1-7 in figure 4).

There were two modes:
1- well fixed and dampened structure
2- one dampener removed forming an imbalance on one of the pillars

Figure 4. The structure used in the experiment; 1…7 – Measuring Point.
The presented data show that a perfectly balanced structure has its homeostatic holospectrum portrait in the band set elliptic trajectories having general directions of semi-axes, and a common plane. Adding an imbalance to the system at the same frequency band results in an unrelated set of elliptic trajectories, indicating more degrees of freedom, as well as an increase of the energy level of the structure. The energy level is characterized by the sum of areas of the resulting elliptic trajectories (Holospectrums). Depending on the task this situation can be analysed on deeper levels.

**Figure 5.** Box without mass.  
**Figure 6.** Box without mass, damper removed.  
**Figure 7.** Box with mass, all dampers in stand.

4. Conclusion
In this article we have considered new approach to monitoring of buildings and constructions. A new approach to analysis of spectral data well-known as holospectrum approach was also considered. It demonstrates the simplicity of 3D data through elliptical vibrations portraits. Holospectrum analysis also allows us to estimate the energy fluctuations at the real physical measurement point. That in turn allows evaluating how the energy of external influences spread in the building and how much of it is stored in it. Thus, we can also evaluate the residual and accumulating stress and strain in buildings and metal structures.
5. References
[1] Zhilin P A A 1996 New Approach to the Analysis of Free Rotations of Rigid Bodies ZAMM Mech Z 76 p 4
[2] Qu L, Liu X, Peyronne G and Chen Y 1989 The holospectrum: A new method for rotor surveillance and diagnosis Mechanical Systems and Signal Processing 3 (3) 255–261
[3] Du* R and Yeung K 2004 Fuzzy transition probability: A new method for monitoring progressive faults, Part 1: the theory Engineering Applications of Artificial Intelligence 17 457–467
[4] Braun S (eds) 2001 Encyclopedia of Vibration (USA: Academic Press) p 1685
[5] Strommen E N 2013 Structural Dynamics Springer p 521
[6] Levitskij D N, Maljutin D V and Speranskij A A 2006 Novyj Tip Sredstv Izmerenija Vibrouskorenija dlja Dostovernogo Prostranstvennogo Monitoringa (Izvestija VUZov: Neft' i gaz) No. 4 p 87–95
[7] Cernant A A, Speranskij A A, Kobjakov I B and Maljutin D V 2006 Vektornyj vibromonitoring – instrument obektnoj volnovoj tomografii v stroitel'stve, BST, No.12 p 52–64

Acknowledgments
This research was supported by grant RFBR project No. 14-01-31444 and Russian President Grant MK-7776.2015.1, NSH-4595.2014.1