

# MEASUREMENTS AND STANDARDS OF MECHANICAL MOTION QUANTITIES

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## Summary

This paper discusses the interrelationship between important problems of life support and those in the fields of measurement of mechanical motion quantities and gravimetry. It reviews methods and means for measuring mechanical motion quantities, taking into account the vector nature and other specific features of the quantities to be measured, and the metrological characteristics of the means for measuring mechanical motion quantities. There is a brief description of standards, including their main units and systems. It also reviews the direction of metrological investigations.

## 1. Introduction

Finding a solution for some problems in the field of mechanical quantity motion measurement and gravimetry and establishing standards are necessary to solve many important problems of the global life support system. Each of these problems is connected, in its own way, to various life support systems. Technological progress and directions in the development of civilization make this connection more and more intimate. For example, without solving some of the problems related to the building of measuring instruments and standards used for the control of testing of nuclear weapons, their global proliferation is the most important problem of humankind.

The most important of these problems are considered in the following sections. The means for measuring mechanical motion quantities within appropriate wide ranges of amplitude and frequency values are required. For example, linear acceleration measurements are taken even now in the range from  $10^{-11} \text{ m s}^{-2}$  to hundreds of thousands  $\text{m s}^{-2}$ , angular velocity measurements in the range from  $10^{-9} \text{ rad s}^{-1}$  to  $10^{-10} \text{ rad s}^{-1}$  to tens of thousands  $\text{rad s}^{-1}$ , angular and linear displacements from  $10^{-4}$  angular seconds and units of angstrom, respectively, and so on. Now let us discuss the main means and systems for measuring mechanical motion quantities in their interrelationship with the global problems of life support.

### 1.1 Motion of a Solid Body in the Circumterrestrial and in Outer Space

Ground transportation (automobiles and trucks, trains, ships), air transport, spacecraft, and submarines, performing their useful functions, are dangerous for operating and attending personnel, and for bystanders (in the case of accidents and catastrophes). That is why there are two basic problems in the construction of such vehicles: a) outfitting these vehicles with orientation and control systems to ensure their motion in a predetermined manner with the required accuracy; b) control of parameters, specifically, mechanical motion quantities, aimed at the prevention of accidents. Inertial control systems, satellite navigation systems, astronavigation systems, and so on are built to solve the first problem. Special control-and-measuring systems, for example, systems for the control of engine vibration parameters, are used to solve the second one. In both cases, the units for measuring the mechanical motion quantities and those for orientation determination play an important, and sometimes decisive, role.

### **1.1.1. Geophysical Problems**

A few categories of geophysical problems can be singled out.

### **1.1.2. Problem of Earthquake Forecasting**

Among a great number of methods used to solve this problem, seismic methods are the most effective. There are regional, national, and global seismic networks, the basic components of which are high-sensitive, wide-range seismometers and seismic stations. Development of this equipment, methods, and units for ensuring its measurement traceability is a serious task for modern instrument-building and metrology.

### **1.1.3. Problem of Nuclear Test Control**

In terms of equipment, this problem is quite similar to earthquake forecasting. However, the necessity of distinguishing between natural earthquakes and artificial nuclear explosions—first of all, low-power underground nuclear explosions—imposes additional requirements on the seismic equipment used.

### **1.1.4. Prospecting for Mineral Resources**

Seismic methods are some of the most important ones in prospecting, too. The main method in this field is the one based on the analysis of seismic waves generated by artificial sources and reflected from rocks lying at different depths. It is necessary, therewith, to study large surfaces of the Earth, the shelf, the bottom of seas and oceans, with the result that one has to use hundreds of seismic sensors (receivers) during a single measurement. Specific requirements for seismic receivers and the means for ensuring their measurement traceability are connected with the necessity of singling out the useful small-amplitude components of a seismic signal from the noise, on one hand, and of making a cheap and small-sized receiver, on the other. The contradiction of these requirements leads to practical difficulty for solving this problem.

### **1.1.5. Machine-Building—Technological Processes**

Machine-building in the broad sense (machine-tool industry, aircraft industry, shipbuilding, and so on) is based, along with others, on two groups of systems: a) systems controlling the moving parts of machines and assemblies, and b) systems controlling the mechanical motion quantities of both moving and fixed parts of machines. The latter are necessary to attain the high technological parameters of machines. One can take, as an example, systems for the vibration control of turbines, the corresponding systems of program-controlled machine tools, and systems for measurement and control of the mechanical motion quantities in working out nanotechnologies. These systems make use of a wide range of measuring instruments for linear and angular displacements, velocities, and accelerations (accelerometers, vibrometers, linear and angular velocity sensors, and so on).

### **1.1.6. Construction**

The most demonstrative example is antiseismic construction, where sensors of mechanical motion quantities are used during tests that simulate earthquakes of varying strength.

### **1.1.7. Medicine—Health Protection**

Vibrations, overloads, and other factors affecting humans during job-related and other activities can often cause illness (vibration sickness, for example). The corresponding standards set the permissible level of such effects. The conditions of human life influenced by these harmful factors are controlled by a group of sensors of mechanical motion quantities, first of all by vibrometers and accelerometers.

The above list of systems and problems, which could be extended further, shows that units for measuring mechanical motion quantities in the process of human life should be widely used. The diversity of these problems, and the differing requirements of the systems used to solve them, have led to the development and application of a significant number of measuring instruments. These instruments differ in the quantities to be measured and their technological and metrological characteristics, mass and overall dimensions, power consumption, and cost. This has led to the need for a significant number of various instruments.

## **2. Quantities to be Measured—Intercommunication of the Mechanical Motion Quantities**

The motion of a solid body is characterized by the motion of its center of mass. It is completely determined by three linear displacements of the center of mass and by three turning angles around the center of mass. The mechanical motion quantities of a solid body are linear and angular displacements of its center of mass and all their time derivatives (displacement, velocity, acceleration, sharpness, and so on). The mechanical motion quantities are vector quantities, so they can be measured by one of two methods:

- determination of the corresponding vector modulus and the angles characterizing the position of these vectors in the chosen reference system
- determination of the vector components by the axes of the chosen reference system

The intercommunication of mechanical motion quantities can be divided into spatial and time intercommunications. The spatial intercommunication concerns the intercommunication of linear and angular mechanical motion quantities measured by means of measuring instruments located and oriented on an object in a certain way.

A similar intercommunication of mechanical motion quantities should be taken into account when setting the measuring instruments on an object. Because one cannot usually afford to locate all measuring instruments close to the center of mass of an object, in estimating the measurement results one should account for the influence of additional cross components of linear mechanical motion quantities on the instruments measuring the angular ones, and for the appearance of additional components due to the angular motions of an object in the output signal of instruments measuring the linear

mechanical motion parameters. Corrections are applied, if necessary. The same intercommunication can be used to improve the measurement accuracy.

The time intercommunication of mechanical motion quantities is an integral-differential relationship. Two methods for the determination of a mechanical motion quantity are possible, in principle. With the first method it is measured directly, and with the second it is determined by differentiation and integration of the known mechanical motion quantity. For example, the motion of a moving platform is measured using an interferometer, and then its acceleration is found by means of double differentiation. The integration or differentiation operations are performed directly in the instrument or by using a computer.

The characteristic of a quantity to be measured is chosen depending on a measurement problem. Thus, for example, in the investigation of polyharmonic vibrations the root mean square (r.m.s) and maximum values present the greatest interest for strength and reliability analysis; in the investigation of slowly varying motions, the instantaneous and integral (at the specified time interval) values are important; and in the investigation of shock processes, the maximum value, shock process time, pulse front, and so on are important.

The methods for measuring mechanical motion quantities can be divided into two groups:

- Absolute (inertial) methods are based on the law of inertia, which is valid for classical mechanics, where mechanical motion quantities change in inertial space. Inertial space is a space where Newton's laws are valid. It does not rotate around "immovable stars" that are so far from the Earth that their position can be considered fixed for solving these or those technical problems.
- Relative methods are those in which the mechanical motion quantities of one coordinate system are measured relative to the other.

In measuring mechanical motion quantities a reference system must be chosen depending on a specific measurement problem. Thus, in determining the mechanical motion quantities of the ship components relative to the ship itself as a solid body (e.g., vibration parameters of the ship hull), the reference system is connected to the ship. When solving navigation problems, one usually uses: a) an inertial coordinate system connected to the solar system; b) an inertial coordinate system with the reference point in the center of the Earth, which does not rotate around the inertial space; c) a coordinate system connected to the Earth, e.g., the well-known geographical system with the reference point in the center of the Earth.

In measuring mechanical motion quantities the measurement uncertainty depends, in the general case, not only on the uncertainty of the measuring instruments, but also on the uncertainty of the reference system construction, and on the accuracy of adjustment of the measuring axes of instruments by the reference system axes.

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### **Biographical Sketch**

**Prof. A. Ye. Sinelnikov** was born in 1934. He graduated from the Institute of Aviation Instrument Building in 1952. He defended two theses, in 1964 and in 1985. In 1991 Dr. Sinelnikov received the title of professor. The Presidium of the Russian Academy of Science awarded him the State scientific scholarship for outstanding scientist in Russia for the period 1994–1996. Dr. Sinelnikov is a laureate of the Prize of the Russian Federation Government (1998). He has four government awards. He is the author of more than 170 research works including his reports at international congresses, symposia, and conferences. He is a member of Russian and foreign scientific councils and committees. The main direction of his research activities is metrology in the field of measurement of mechanical motion quantities and gravimetry.