N92-27740

PROGRESS OF MAGNETIC SUSPENSION SYSTEMS AND MAGNETIC BEARINGS IN THE USSR

Kuzin A.V.
Moscow Aviation Technological Institute

SUMMARY

This paper traces the development and progress of magnetic suspension systems and magnetic bearings in the USSR. The paper describes magnetic bearings for turbomachines, magnetic suspension systems for vibration isolation, some special measuring devices, wind tunnels and other applications. The design, principles of operation and dynamic characteristics of the systems are presented.

INTRODUCTION

Due to increase of range, speed and operation life of moving objects, gain in accuracy of instruments and machines and growth of rotational speeds of their individual elements, the problem of improving the quality of bearing assemblies and suspensions becomes ever more acute.

Modern bearings should meet the following requirements: they must have capacity for long-duration and stable operation in any environment at low and high speeds, should have moments close to zero, and must consume a small quantity of energy; they should be easily producible and not too expensive. Quite a number of different bearings and suspensions, to one degree or another, satisfy some of the above-mentioned requirements.

These problems find their most exhaustive solution in electromagnetic suspensions (EMS) in which the weight of a suspended body and loads acting on it are counterbalanced by the magnetic field strength.

Free levitation of bodies in an electromagnetic field ensures functioning of suspensions at super-high speeds bringing about extremely small disturbing moments. The service life of EMS is determined mainly by the operation life of electronic equipment whose failure-free performance may last for dozens of years. Absence of contact, wear, noise and vibrations, ability to function in vacuum and corrosive mediums, wide temperature range, and low energy demand offer conditions for provision of high accuracy and operating longevity of instruments and devices incorporating EMS and make EMS ever more perspective.

Theoretical studies in the field of noncontact electromagnetic suspension began (approximately) in 1839 when English scientist Earnshaw proved that a static system of bodies which repel one another or have an attraction for each other, with a force inversely proportional to the square of the distance between them, is unstable (ref. 1).

Exactly one century later (in 1939) Brounbeck corroborated this inference, except that in his opinion stable spatial suspension of bodies in stationary magnetic and electric fields is possible but refers only to bodies having relative magnetic permeability or relative dielectric permittivity less than a unit (ref. 2).

Arkadiev V.K. was the first Russian scientist who demonstrated electromagnetic suspension. He suspended a permanent magnet measuring 4 × 4 × 10 mm and weighing about 1.2 g in the space above the concave surface of a superconductive metallic disk whose diameter was 40 mm and was immersed in a vessel filled with liquid helium (ref. 3). Ponizovsky V.M. (Perm State University) (ref. 4) was one of the first Russian scientists who put into practice magnetic suspension with an external control system. Following American scientist J. Beams (ref. 5) in 1957 he built up an EMS set for suspension of steel balls whose diameters were from 2 to 5 mm. The balls were rotated in a vacuum by means of a rotating magnetic field with the aim of conducting strength tests of steel balls and various coatings. Ponizovsky V.M. has been engaged in research work in the field of EMS for more than 20 years. One of his essential achievements manifested itself in double magnetic suspension of ferromagnetic rotors which is described in his work (ref. 6) and one version of which is presented on fig. 1. 1,2 - suspended rotors; 3,4 - servo systems of control of currents in solenoid 7 containing movable magnetic core 9 and damper 10, and in solenoid 11 containing core 12; 5,6 - rotors position inductive pickups.

The double magnetic suspension may be used for studying stability of motion of a liquid between two spheres rotating at different angular velocity and for studying stability of fluid film on the surface of a rotating sphere.

During the last two decades the main achievements in the field of magnetic suspension have been connected with creation of new precision measuring instruments of control systems and navigation of moving objects, high-speed turbomachines and electric machines using magnetic bearings, effective vibration isolation systems incorporating EMS and EMS intended for windtunnel studies.

EMS OF GYROSCOPIC INSTRUMENTS

Cardinal improvement of accuracy of gyroscopic devices can be attained through replacement of conventional suspensins by noncontact suspensions.

Many works are devoted to the discovery of stability conditions of a solid body (a gyroscope, rotor in particular) in noncontact suspension. Such interest in this problem is connected with the principal nature of stability of a solid body in noncontact suspension.

Passive noncontact suspensions in which the stability of the equilibrium position of a solid body is ensured by the special choice of parameters of resonant circuits that were studied rather minutely.

In their book (ref. 7) the scientists of the Moscow Technical College (MTC) discuss the questions of theory and application of instrument EMS. They generalize the principles of construction of EMS, analyse main alternative schemes and designs, offer methods of study and the designing of power, dynamic and moment characteristics. Figs. 2 and 3 present designs of two-axle octapole and three-axle magnetoresonant suspensions used in gyroscopic instruments of the moment and attitude sensors type, the floated integrating gyroscope type, and the gyroscopic accelerometer type.

Quite a number of works are devoted to analysis of noncontact suspensions incorporating servo systems changing the field of forces of a suspension depending upon position of the body (refs. 8-16).

For twenty years the scientists of the Scientific Research Institute of Applied Mathematics and Cybernetics affiliated with the Gorky State University have been studying and designing nonbearing assemblies for measuring instruments.

Fig. 4 presents a functional diagram of the magnetic suspension which is employed by gyrocompass (refs. 9, 10). In this instrument the sensing element consists of a nonmagnetic rod, the upper part of which accommodates ferromagnetic sphere 1 and the lower part carries hydrochamber 2 with a fast moving rotor, 3 - body position pickup; 4 - controller; and 5 - electromagnet. In the mock-up of this suspension a body whose mass was 1-1.5 kg was suspended, being attached to a ferromagnetic sphere whose mass was 70-120 g.

Fig. 5 presents a functional diagram of the magnetic suspension used in torque magnetometer (ref. 11) in which ferromagnetic sphere 3, whose mass is 20-200 g, and which is tested for anisotropic properties, is suspended in the field of two coaxial electromagnets 1, 2; 4 - body position pickup; and 5 - controller.

Fig. 6 presents a functional diagram of the instrument in which magnetic suspension is used for noncontact suspension of sensing element 1, whose mass is 0.5-1.5 kg, by attaching it to two ferromagnetic spheres 2, 3 in the field of two coaxial electromagnets 4, 5 (ref. 17).

A peculiarity of the regulation processes in electromagnetic suspension devices is the natural instability of the suspended object. Existence of limitations for value of control voltage on windings of electromagnets leads to limited domain of the object's stability in space and to limited range of permissible external disturbances. Domain of states of stability in space is one of the most important characteristics of systems having a naturally unstable object of control which determines optimization for synthesis of control algorithms (ref. 12). In papers (refs. 13-17) the authors synthesize control algorithms for magnetic suspension systems presented on figs. 4, 5, 6 in accordance with the criterion of maximum domain of stability of the object which is suspended in space, make analysis of different systems of control with allowance for non-linearity of characteristics of power amplifier, and discuss rigidity dependences and values of permissible external disturbances induced by system parameters.

Fig. 7 shows a block diagram of a magnetic suspension optimum control system; the diagram is reduced to dimensionless form (ref. 17), where 1 - transfer frunction of the object being suspended; 2 - electromagnet; 3 - power amplifier; 4 - transfer function of optimum controller; 5 - link of electromagnet x_3 current negative feedback; x_4 displacement of the object; T - ratio of electromagnet time constant to selected scale of time coinciding with the object time constant; and p - differentiation statement.

Stability of a rotor in electromagnetic suspension with allowance for sluggishness of its circuits is analysed in a paper (ref. 18) in which the authors discovered the condition of damping of nutation oscillations of the rotor. In ref. 19 the author discusses nonlinear reasonances occurring with combined radial, axial and angular oscillations at different frequencies, where energy transfer between motions of a gyroscope rotor takes place.

Noncoincidence of the rotor shape of a noncontact gyroscope with a sphere provokes occurrence of moment relative to the centre of the mass of the rotor and therefore induces gyroscope drifts. Calculation of moment of forces applied to an ellipsoidal rotor in electromagnetic suspension is demonstrated in ref. 20. The moment of forces applied to a rotor whose shape differs little from spherical form is calculated in refs. 21-23.

The questions of gyroscope dynamics with noncontact suspensions arranged on a vibrating mounting are discussed in refs. 24-26.

Increase of mass and dimensions of structural elements of magnetic suspensions and application of resilient suspension for attachment of a useful load to the suspended body necessitate consideration of the resilient properties of a structure when designing suspension stabilization systems. Usage of a regulator synthesized without allowance for these properties may lead to diminution of domain of attraction, i.e., a region of absolute stability of the equilibrium state in the phase space of variables of the system which is always limited due to instability of the object of regulation and limitedness of control, and even to loss of stability of the equilibrium state. In ref. 27 the author, assuming that the power characteristicsof an electromagnet are linear, synthesizes the control algorithm of the system of stabilization (of magnetic suspension) with allowance for resilient properties of its construction, providing maximum domain of attraction and absolute stability of the equilibrium state. The author discusses a three-mass model of magnetic suspension which takes into account the elasticity of the bearing and suspended body (fig. 8). A characteristic feature of the controller providing maximum domain of attraction and absolute stability in the discussed case when only clearance and current are measured, necessitates introducing additional correction of sensor signals which occurs when second order active filters tuned to the particular frequencies of elastic vibrations of the bearing and suspended body are used.

In ref. 28 the author gives quantitative estimates of permissible application of the simplest magnetic suspension regulator which does not allow for elasticity of mounting in a two-mass model.

The application of gyroscopes to noncontact suspensions is not limited by navigation and control of moving objects. Such gyroscopes are used in delicate physical experiments, in particular, for measurement of the effects of the general theory of relativity onboard a satellite which is free from drift. In this case it is necessary to measure gyroscope drift equal to 7 seconds of arc a year. Such exceptional accuracy requires taking account of extremely small moments acting on the gyroscope. In particular, when analysing motion of the rotor it is necessary to take into account the oscillations of atoms inside the body of the gyroscope, i.e., to determine the so called heat barrier to gyroscope accuracy. Refs. 29 and 30 are devoted to solving this problem.

Ref. 31 is devoted to determining the principal vector and principal moment of forces acting on a confined superconductive body in a magnetostatic field.

The approximate calculation procedure of the power characteristics for suspension of a cryogenic gyroscope which allows us to obtain final formulae for forces and rigidity of suspension in a case when supporting coils of unspecified form are used, is suggested in ref. 32.

SYSTEMS OF MAGNETIC SUSPENSION IN FINAL-CONTROL DEVICES DESIGNED FOR ORIENTATION OF SPACE VEHICLES (SV)

Nowadays there is widespread application of magnetic suspension, i.e., inertia engine-flywheels allowing stabilization and changes of angular position in space without use of a propulsive mass which is always limited onboard satellites and is replenished with difficulty. Space Vehicles (SV) move in the conditions of space where damping is absent.

The basis of an electromechanical orientation control system consists of rotating the inertia mass-flywheel.

When the engine rotates the flywheel, then, according to the law of conservation of momentum the SV should rotate in the opposite direction at an angular velocity as low as the moment of inertia of the flywheel is in comparison with the moment of inertia of the SV. The main disadvantages of the systems with inertia flywheels are limited operation life and aptitude to enter saturation mode. The first disadvantage is explained by the presence of friction parts in bearings, and the second drawback is referred to maximum permissible rotational speed. These considerations have induced designers of inertia flywheels to give paramount importance to the questions of increasing the operation life and rotational speed accompanied by reduction of energy consumption, mass and dimensions of the system. Since the mass of the flywheel is in reverse relationship to rotational speed, there is a tendency to choose maximum possible speed of rotation.

Operation life of ordinary bearings is a function of the number of revolutions, and as in all phenomena connected with friction, it is characterized by wide scatter of the value of mean-time-between failures and value of moments of friction. Here selection of proper lubrication is of great importance. Usage of liquid or gas lubrication in cosmos conditions requires construction of hermetic casing, the mass of which may constitute a considerable part of the system's total mass.

There is potential for application of magnetic bearings in the gyroscopes and flywheels of space vehicles' attitude control systems. About twenty five years ago a group of specialists with the All-union Scientific Research Institute of Electromechanics (ASRIE, Moscow) under the leadership of academician Sheremetievsky N.N. began research works on an EMS problem for orientation of space vehicles. The result was the creation of an original spherical electromotor-flywheel for the orientation system of orbital station "Salut-5" and powered gyroscopes which are successfully used in the orientation system installed in orbital station "Mir" (refs. 33, 34, 35).

Fig. 9 displays an actuator device of the attitude control system where 1 - a support-free spherical rotor-flywheel of a three-axle electromotor acts as three flywheels simultaneously. The system of electromagnetic suspension incorporating electromagnets 2 through 7 creates an electromagnetic field which solely holds the flywheel in support-free state at the centre of the stator body of three collector-free electromotors: 8, 9, and 10. The spherical flywheel has a number of advantages in comparison with conventional flywheels fitted along three axes: it allows control of angular motion of SV about three axes simultaneously, it is not connected with the body gyroscopically, and it has lesser mass and dimensions.

The main parameters of a spherical electromotor-flywheel (ref. 36) are mass - 230 kg; rotor diameter - 0.64 m; rotation speed - 800 r.p.m.; maximum kinetic moment - 200 Nms; control moment - 3 Nm.

Further development of endeavors in this direction will be creation of an electromagnetic bearing for high-speed powered gyroscopes. Main parameters are mass of gyroscope - 160 kg; rotor diameter - 0.4 m; rotation speed - 10000 r.p.m; kinetic moment - 1000 Nms; control moment -200 Nm;and precession angle - unlimited.

The system of automatic protection of EMS has been worked out in the ASRIE and was used for protection of a number of big-size rotor mechanisms with magnetic suspension of the rotor, such as an electro-gas blowing system for gas-cooling nuclear reactor "EG-90/1.25" (P=1500 kW, n=3000 r.p.m.; Mr=1500 kg), turbo-compressor for gas main "GPA-C-16"(P=16000 kW, n=5300 r.p.m.; Mr=1200 kg), diametral fan "DV" (P=100 kW, n=3000 r.p.m.; Mr=300 kg) (ref. 37).

EMS may be successfully used as a ball support of the dynamic stand designed for physical modelling of different flight conditions of SV under space conditions. The dynamic stand is a movable platform which accommodates tested equipment including power units imparting angular motion. Suspension of the dynamic stand platform should provide three rotary degrees of freedom and absence of resistance to angular motion, i.e., real conditions in which a space vehicle operates. Nowadays the dynamic stand platform is suspended mainly with the aid of spherical gasdynamic bearings having significant disturbing moments. Application of an electromagnetic bearing in the dynamic stand allows it to have disturbing moment which is far smaller than in the case when gasdynamic bearings are used. In the Moscow Aviation Institute specialists from the Electrical Engineering Department have designed and constructed a magnetic bearing for the dynamic stand which at a suspending mass of 1000 kg has adverse friction moment not exceeding 0.3 g.cm at lateral rigidity of 6000 N/m; i.e., its performance satisfies the requirements specified for dynamic stands of SV (refs. 38-40).

MAGNETIC SUSPENSION FOR TURBOMACHINES

Modern level development of engineering puts forward more and more contradictory requirements for bearings of rotor machines, which in a number of cases are practically unrealisable if we use existing rolling-contact bearings and plain bearings. First of all there is a substantial increase in rotational speed and operation in extreme conditions; second, there is a reduction of noise and vibrations, a gain in accuracy of rotation, an increase in operation life, and a decrease of mass dimensions and losses from friction. Magnetic bearings with an external control system are regarded as an alternative to existing rolling-contact bearings and plain bearings. Owing to the absence of mechanical contact there is no necessity for lubrication. The bearings can operate in a vacuum or in corrosive mediums as well as over a wide range of temperatures; there are no friction problems of wear, or noise; these bearings allow development of maximum rotational speeds, and it is worth mentioning that the operation life of magnetic bearings does not depend on rotational speed; it is determined only by the operation life of the control system that may amount to several dozen years. The control system ensures high accuracy of rotation (tenth fractions of micron), high rigidity at static loads (2000 N/μm), active damping of oscillations, low requirements to accuracy of balancing and assembly of rotor, easy control of static and dynamic rigidities.

The research works package of the Pskov Branch of the Leningrad Polytechnical Institute scientific group is devoted to creation of magnetic bearings for a high-speed grinding electrospindle (refs. 41-45). Super-high-speed grinding allows us to raise labour productivity, increase operation life of tools and ensure higher quality of the work surface. Fig. 10 displays the block diagram of a designed experimental model of a high-speed electrospindle with active magnetic bearings (AMB). The model was designed on the basis of a production-type grinding electrospindle 3W-120/0.4 (120000 r.p.m.; 0.4 kW) by means of substitution of active magnetic bearings for ball bearings. The driving part of the spindle consists of an induction motor having stator 6 and squirrel-cage rotor 12. Radial AMB consists of trunnion 13 fitted on shaft 1, the core of stator 3 with windings 4 and inductive pickup 5 of radial translations of the trunnion. The stator core is stacked sheets of electrical-sheet steel and has eight poles. Axial AMB consists of two ring electromagnets, 7 and 9, ferromagnetic disk 8 fitted on the shaft, and inductive pickup 10 of axial translations of the rotor. When suspension is switched off, or in emergencies, the rotor rests on emergency bearings 2 and 11 with bronzegraphite inserts. Fig. 11 shows the block diagram of a radial magnetic bearing coordinate *Y* optimum regulator ensuring minimum integral square error of regulation in the presence of limitation of the maximum value of the integral square manipulated variable in transient processes in the absence of disturbances. $K_1, K_2, T_1, T_2, T_3, T_4, T_5$ - synthesized parameters of the regulator; I_{iv}, V_{iv}, - variable components of signals; I_{ic}, V_{ic} - direct components of signal; $\beta = I_{2c}/I_{1c}$ (ref. 44).

The production test results of the electrospindle model with AMB in operations of high-speed grinding prove the high efficiency of AMB.

There is potential for AMB application in metal-cutting machine tools where usage of super-speed cutting regimes allows considerable decrease in wear of tools and improves accuracy of the work surface. The results of research work relating to development of the high-speed spindle of a metal-cutting machine tool using magnetic bearings which is carried out in the Experimental Science Research Metal-cutting Machine Tools Institute, Moscow are presented in refs. 46-49.

Today there is an actual problem, i.e., the problem of AMB application in cooling life-support system turbines of flying vehicles where for development of maximum efficiency, rotational speed of the rotor should amount to 150000-180000 r.p.m. Research work relating to this theme was carried out in the Moscow Aviation Institute and the results of the work are presented in refs. 50-53.

MAGNETIC SUSPENSION OF NONCONTACT ELECTRIC MOTORS

Beginning in 1970 a scientific group of the Electric machines department of the Moscow Energetics Institute has been engaged in development and study of magnetic suspension of high-speed rotors of high-frequency electric motors with the aim of increasing their operational life. Such studies were needed because with the increase of rotational speed, operation life of rolling-contact bearings dwindles sharply to several hundred hours. Air-gas-cushion (aerostatic and aerodynamic) bearings are rather difficult to manufacture and, as a rule, for their normal operation they need an air compressor and air purifiers to clean air from moisture and dust. The scientific group suggested a design of magnetic suspension of a high-speed rotor in a rotating magnetic field (ref. 54), which has two functions simultaneously: it provides magnetic suspension forces of the rotor and creates electromagnetic moment of rotation as in an ordinary electric motor.

In accordance with this principle scientists have developed magnetic suspension of a disk-type rotor of a front electric motor (fig. 12) and of a cylindrical rotor of an electric motor (fig. 13) (ref. 55). On fig. 12 two stators (1 and 2) flank two-core disk-type rotors (3 and 4) of the face motor. Its active parts are connected by means of a hollow non-magnetic bush (5) inside which shaft (6) is rigidly secured. The rotor represents a bobbin designed to take up yarn. During starting and/or stoppage the rotor rests on safety bronze rings (7) and safety ball bearings (8) whose outer races do not contact the stator during magnetic stabilization of rotor position. The mass of the rotor is 1 kg. Fig. 13 displays a block diagram of a combined magnetic suspension of a one-core rotor of a longitudinal axis autoregulation motor: 1, 2 - upper permanent magnets; 3, 4 - lower permanent magnets; 5 - electromagnet; 6 - rotor position inductive pickup; 7 - core of stator with winding; 8 - rotor; and 9 - shaft.

The suggested suspension of the rotor in a rotating magnetic working field with an autoregulation resonance circuit has the following advantages: economical operation, simplicity of design and suspension regulation scheme, absence of complicated control servo systems and special structural assemblies for rotor magnetic suspension. Feasibility of magnetic suspension of a rotor in a working rotating field was experimentally substantiated in 1973.

VIBRATION ISOLATION DEVICES WITH MAGNETIC SUSPENSION

In many cases the EMS may help essentially to solve the problem of vibration isolation of objects exposed to dynamic or kinematic vibrational and impact actions. At present mechanical elastic couplings prevail in vibration isolation engineering. When mechanical couplings are objectionable and therefore are replaced by electromagnetic suspension, in many cases it becomes necessary to provide effective protection of a suspended object against vibrations. High efficiency of EMS vibration isolation devices may be secured through implementation of wide potentialities of formation of desired dynamic suspension characteristics by the selection of proper algorithms to regulate voltages and currents of windings of power electromagnets in accordance with the characteristics of motion of the suspended object and mounting. Not many papers (refs. 56-61) are devoted to studies of EMS vibration isolation properties and to the development of vibration isolation devices incorporating EMS.

In ref. 56 the authors analyse types, characteristics and perspectives of application of magnetic vibration isolators.

In ref. 61 the author discusses vibration isolation properties of EMS devices of different designs. He has established dependences of these properties on parameters and transfer functions of stabilization circuits.

A group of scientists from the Scientific Research Institute of Applied Mathematics and Cybernetics has developed vibration-isolated magnetic suspension of a body with a ferromagnetic disk. Refs. 57-59 contain a description of the design and a functional diagram of the system of automatic regulation of magnetic suspension of a body which is suspended in a magnetic field by means of a ferromagnetic disk attached to it; diameter of the disk is 300 mm and clearance between the disk and electromagnet is 5 mm. Experimenters suspended a body, mass 10 kg, with watt consumption being 100 W. The frequency of body oscillations in the horizontal plane was 0.25-1 herz. Fig. 14 presents a diagrammatic representation of the suspension: A - front view; B - top view; 1 - electromagnets; 2 - first channel pickup coil; 3 - coils of pickups of the second and third channels; 4 - suspending body; and 5 - conductive disk.

The functional diagram of the suspension control system is shown on fig. 15; it consists of three channels: channel 1 - body vertical stabilization and two identical channels 2, 3 - stabilization of the body according to angle of inclination and stabilization of the body in accordance with displacements in directions going via opposite electromagnets ЭМ. Each channel has its own inductive pickup Д. Signals of pickups Д are transduced by amplifying-and-converting links УП into voltages of direct current, the value and polarity of which are determined by values and directions of displacements of the body along corresponding coordinates. To ensure stability channels 2 and 3 are supplemented with forcing links Ф and channel 1 is provided with correcting feedback OC responding to the sum of currents of ЭМ. УМ - power amplifiers. T - links time constants; p - differentiation statement.

The suspension, if recommended for application in vibration isolation of instruments when mounting, is exposed to horizontal oscillations.

Present-day main features of gravimetric measurements consist of stringent requirements as to their accuracy. This is attributed to the fact that changes of gravitational force are small and from the pole to the equator they do not exeed 0.5%. The biggest anomalies do not exceed 0.05% of the value of free-fall acceleration. Urgency is attached to the problem of measuring gravitational force on a moving base (ship, aircraft, etc.). The specifics of a moving base assume that measurements are made against the background of inertia interferences, the value of which are considerably higher than variations of free-fall acceleration. One of the main methods of eliminating the influence of inertia interferences is suppression of the interferences by means of vibration isolation devices. On the strength of equivalence of gravitational and inertia forces it is principally impossible to derive a desired signal from gravimeter readings, i.e. to segregate free-fall acceleration from disturbing accelerations. For separation of inertia acceleration and free-fall acceleration scientists exploit their differing characteristics. Accelerations of motion change with relatively high frequency, whereas free-fall acceleration changes slowly. Using this phenomenon we may apply frequency filtering of the disturbances.

Vibration isolation of a ballistic gravimeter using an interferrometric method of measurements may be effected by installing an auxiliary corner reflector on the vibration damper which has the capacity for filtering low frequencies.

The Kharkov Scientific Research Metrology Institute, in cooperation with the Moscow Aviation Institute, has developed a vibration isolation device in which, for construction of the vibration damper, the initiators suggested the use of a solenoid magnetic suspension effecting the elastic coupling of the isolated object with the vibrating base and possessing a significant extent of tractive characteristic and zone of stable equilibrium in the absence of an external system of regulation (ref. 60). Fig. 16 displays a diagram of a ballistic gravimeter, showing 1 - accelerometer; 2 - vibration damper; 3 - regulator; 4 - auxiliary corner reflector; 5 - interferometer; 6 - ballistic unit; 7 - test body; 8 - electromagnetic centering system; 9 - laser; and 10 - photodetector. The accelerometer senses disturbed motion of the isolated object and reacts accordingly; from the accelerometer output the signal, via the filter of upper frequencies, enters the input of the correcting circuit which produces the law of control of feedback force action regulating the position of the movable part of the vibration damper. The regulator is a proportionally-integrally-differential regulator. The regulator incorporates an accelerometer in which elastic coupling of the inertia element with the body is effected with the aid of a magnetic support with a resonant circuit. For damping of motion of the inertia element all mechanical coupling is filled with oil. The accelerometer has small weight and dimensions. The developed vibration damper incorporates a combined system of electromagnetic centering with resonant circuits and additional active electromagnetic damping which ensures horizontal stabilization of the movable part of the vibration damper, having a weight of 200 g and an initial clearance of 0.15 mm at accelerations equal to 0.1 g. Design of the device also allows angular stabilization, the factor which is rather important for interferential methods of measurements. An experimental test of the vibration damper in conjunction with the ballistic gravimeter has shown that the vibration damper eliminates the effect of inertia interferences, thus permitting improvement of accuracy of determination of free-fall acceleration under real test conditions by 2.5-7 times.

SYSTEMS OF MAGNETIC SUSPENSION FOR WIND TUNNELS

Absolute absence of mechanical contacts with the suspended object (test model) allows us to solve the principal problems of aerodynamics which cannot be solved by conventional means: measurement of aerodynamic loads acting on the model without the effect of mechanical supporting devices, wake studies, study of base pressure, etc.; these opportunities stimulate growing interest to EMS engineering (ref. 62).

At present there are two systems of electromagnetic suspension for wind tunnels in the USSR. One was constructed in 1983 as a result of a collaboration between the Moscow Aviation Institute and the Central Aero-Hydrodynamic Institute and was intended for studies of models with six degrees of freedom in a subsonic wind tunnel, the working part of which measured 400 mm × 600 mm (ref. 63).

The second system was created in the Moscow Aviation Institute in 1989; it is designed for laboratory investigations and for the development of magnetic suspension technology. The suspension has six degrees of freedom and its working part measures 300 mm × 400 mm. Fig. 17 displays a model suspended in the suspension system of the Moscow Aviation Institute (ref. 64).

Both systems comprise seven electromagnets which are arranged as shown on fig. 18.

The optical system for determination of model position is based on usage of photodiode regions. Rays of light of special form cross the model as shown on fig. 19. Position of the model can be calculated by measuring the position of the model shadow on the surfaces of the detectors. The original design of the sensitive system (ref. 65) ensures determination of vertical and horizontal displacements of the model in one optical channel (fig. 20).

Both systems of electromagnetic suspension have analog control systems. Their design adopted control algorithms which provide maximum domain of stability of the suspended object in the presence of limitations of control actions (refs. 66, 67). Model roll stabilization is effected by passive means.

All electromagnets have copper windings with natural cooling and are provided with bipolar transistorized power sources. In the process of calibration, known values of static forces and moments are applied to the model and position of the model and currents of electromagnets are measured. Aerodynamic loads are computed by means of a digital minicomputer on the basis of established empirical dependences between currents of electromagnets, position of the model and external loads (ref. 68).

The current research efforts are directed at realization of the following technical problems:

1. Tests of models at high angles of attack, dynamic tests;

2. Development of a digital control system;

3. Perfection of means and methods of measurements.

MAGNETICALLY LEVITATED TRAINS

Nowadays there exists an essential problem - to create a new principal means of ground transport, the characteristics of which would be as follows: unlimited speed of movement, high economy index, absence of pollution and a minimum of noise emission. The solution of this problem is connected with high-speed ground transport (HSGT) using magnetic levitation.

Since 1976 the USSR has been addressing the problem of HSGT. Up to 1980 general areas and geographical directions of HSGT introduction were defined. Models of various systems were constructed and tested, such as linear engines and magnetic suspension systems as well as their feeding and control parts, and general normal and alarm breaking power supply systems. Also, there were elaborations of technical assignments for experimental carriages of 40 tons weight and for prototypes with electromagnetic suspension EMS added with one-side linear asynchronous engine OLAE and with electrodynamic suspension system EDS added with linear synchronous engine LSE. Experimental HSGT-system "HE-01" was created in the city of Novocherkassk. The system "HE-01" has L-way with permitted loading of 10 tons, air gap is 0.02-0.025 m, EMS, the number of electromagnets is at four each; the lifting force of the electromagnetic system is 29.4 kN; the side force - 14.72 kN.

The prototype for HSGT in Ramenskoye city has a track of 600 metres in length for motion testing. In 1979 the first in the USSR with a carriage of 10 tons weight on constant magnets was tested at a distance of 120 metres.

From 1980 on that prototype and the main parts of new devices of HSGT were tested. In 1985 an experimental carriage of 14 tons weight with EMS was created. In 1986 complex testing began on a prototype route, and a speed of 30 km per hour was reached.

The main technical characteristics of the USSR's HSGT systems which are working out in the USSR are given in table 1 (refs. 69, 70). Here "Soyus-E" is HSGT-train with EMS and OLAE, "Soyus-D" is HSGT-train with EDS and LSE.

CONCLUSION

The presented article reflects the main technical applications and the main directions of development of magnetic suspension systems and magnetic bearings but it does not pretend to completely cover the discussed problem. The analysed advantages of magnetic suspension systems and ever more increasing requirements to bearing assemblies of instruments, mechanisms and machines promote wider and wider introduction of noncontact systems of magnetic suspension.

The author expresses his gratitude to Dr. R. A. Kilgore (NASA Langley) and to the Organizing Committee of ISMST for their support and for giving us the opportunity to present this work to the Symposium.

Table 1.

Parameters	Parameters'Value for HSGT-systems		
	HE - 01	Soyus-E	Soyus-D
Size, m : - length	4.12	25	25
- width	1.77	3.6	3.6
- height	1.48	4.2	4.2
Number of carriages in train	1	up to 10	up to 10
Carriage mass, tons	3	40	40
Maximum speed, km per hour	50	400	400
Number of passengers in train armchairs	2	870	870
Working period of time in a day, hours	-	18	18
Duration of stand, min	-	3	3
Passenger passing ability in a day, passenger-km	-	5.48	5.48
Acceleration when starting, m. per sq.sec.	-	up to 1	up to 1.5
Slowing down when braking, m. per sq.sec.: - normal	-	up to 1	up to 1
- alarm	-	up to 3	up to 3
Traction power, mW	-	50	50

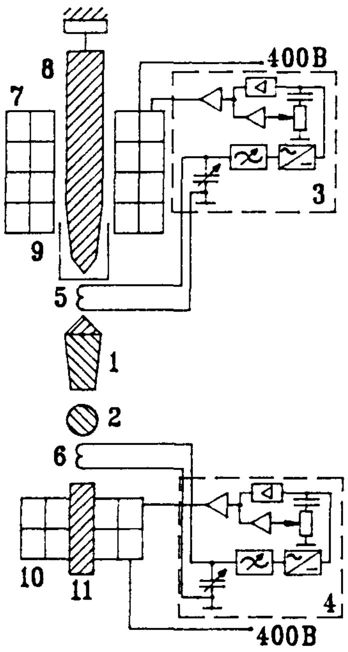


Fig. 1

Double magnetic suspension

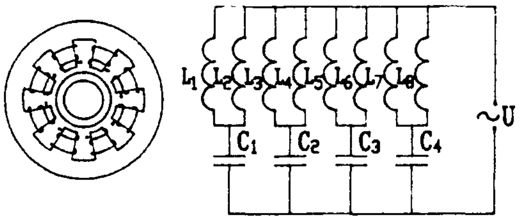


Fig. 2

Two-axle magnetoresonant suspension

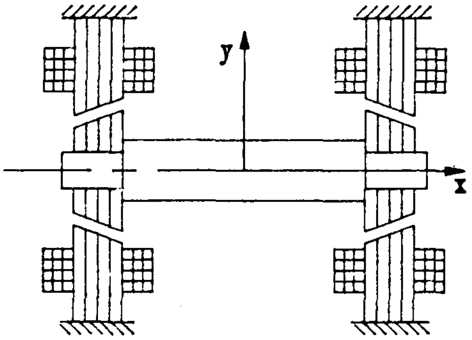


Fig. 3

Three-axle magnetoresonant suspension

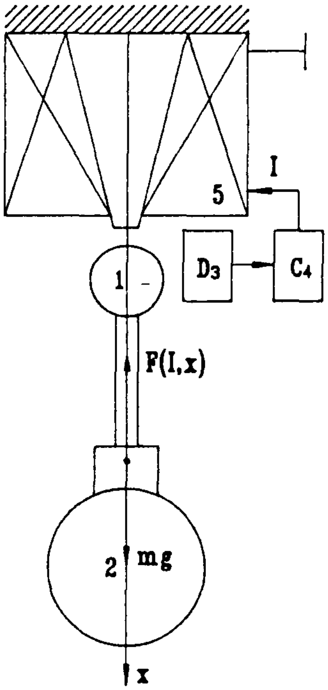


Fig. 4

EMS for gyrocompass

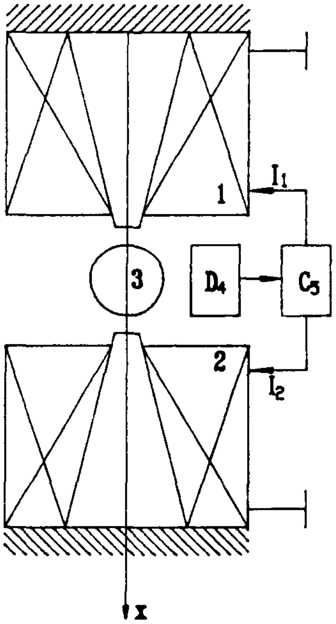


Fig. 5

EMS for torque magnetometer

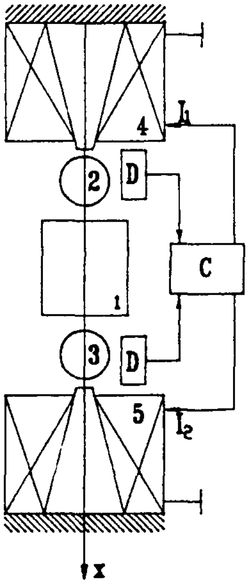


Fig. 6

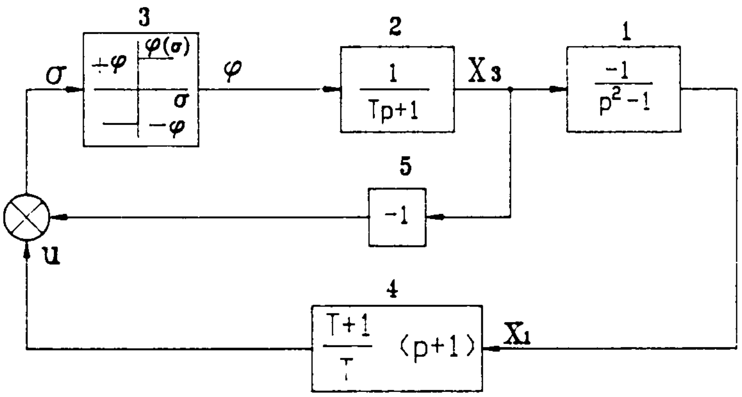


Fig. 7 Block diagram of EMS optimal control system

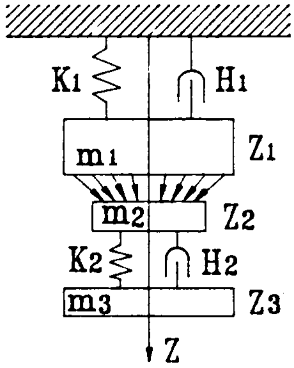


Fig. 8 Three-mass model of EMS

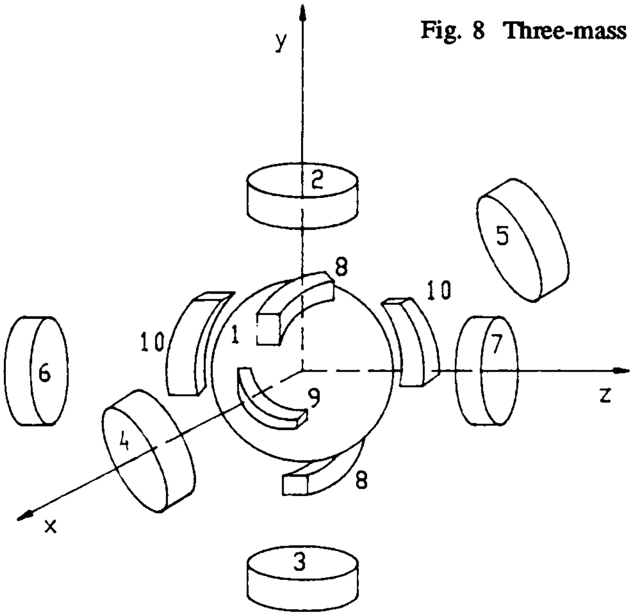


Fig. 9 An actuator device of the attitude control system for orientation of space vehicles

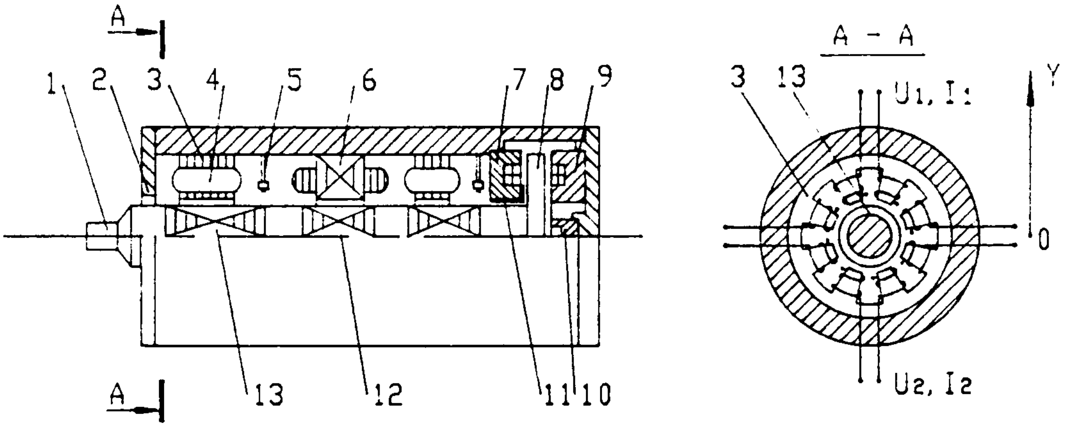


Fig. 10

Block diagram of high-speed electrospindle

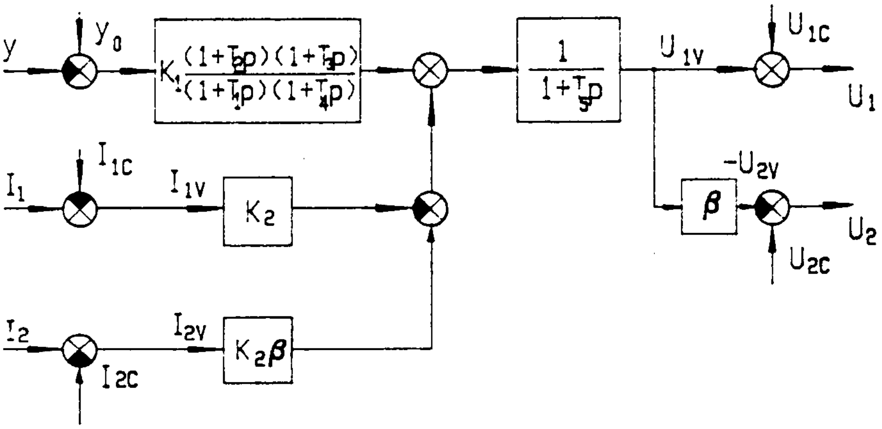


Fig. 11

Block diagram of a radial magnetic bearing coordinate Y optimum regulator

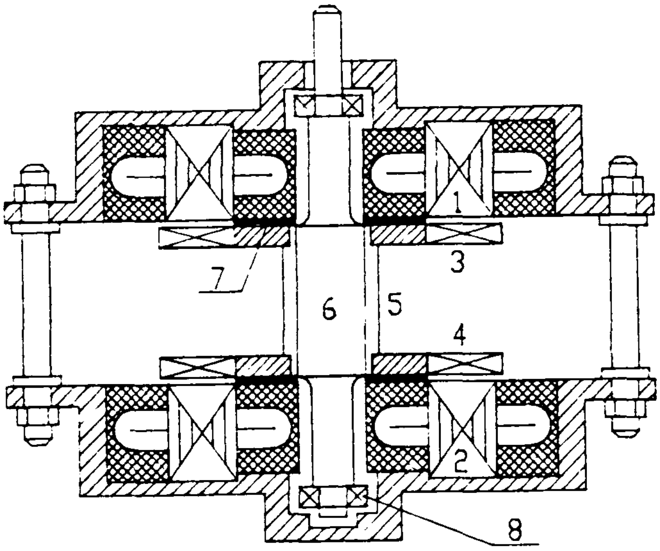


Fig. 12

EMS of disk-type rotor of front electric motor

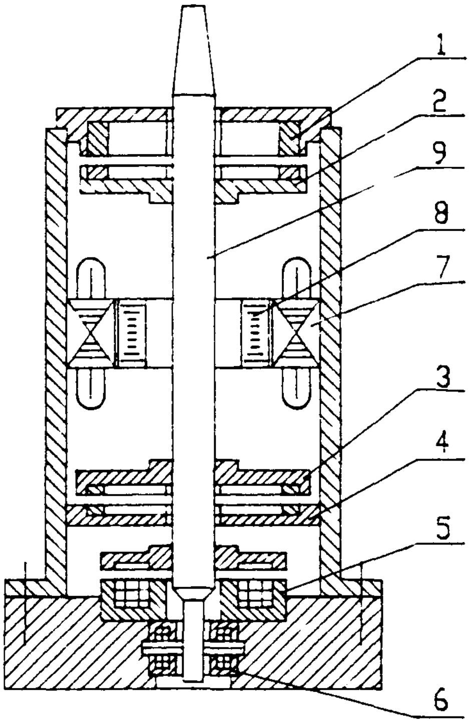


Fig. 13

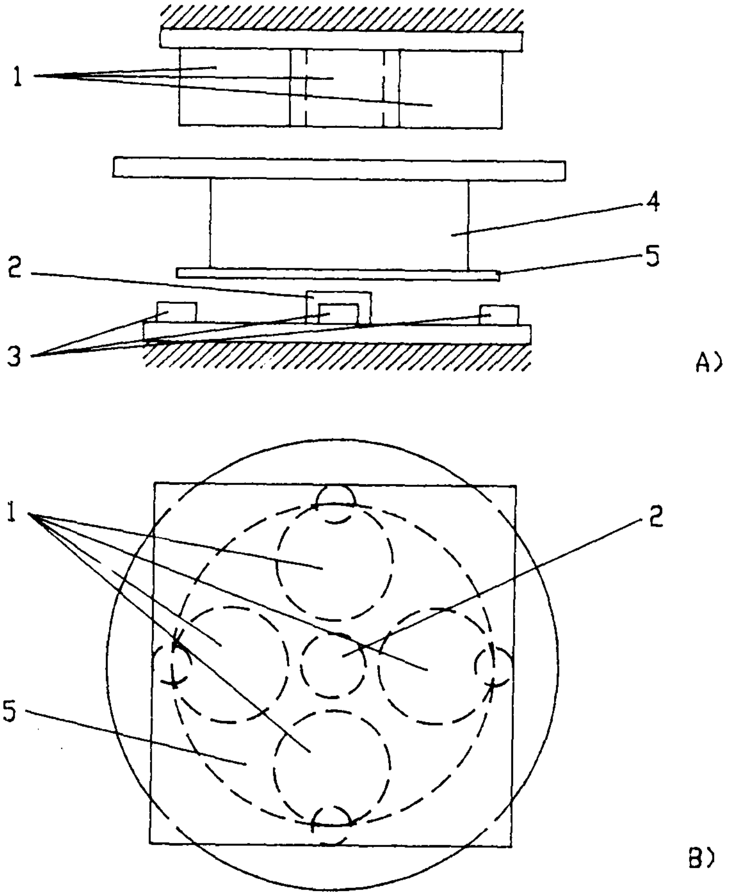
EMS of cylindrical rotor of electric motor

Fig. 14

Vibration isolation EMS of body with ferromagnetic disk

A) Front view

B) Top view



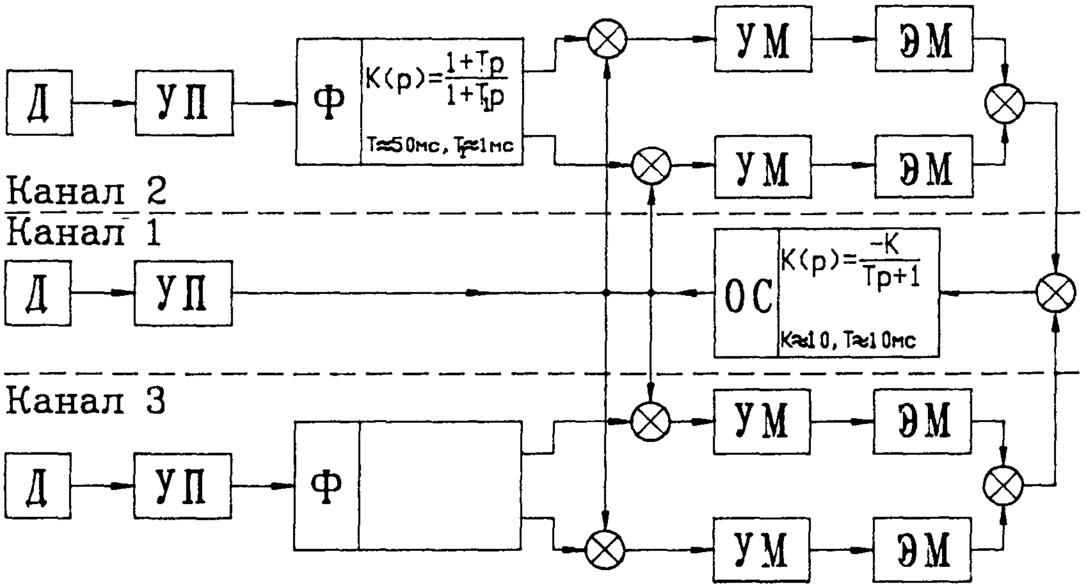


Fig. 15

Functional diagram of the suspension control system

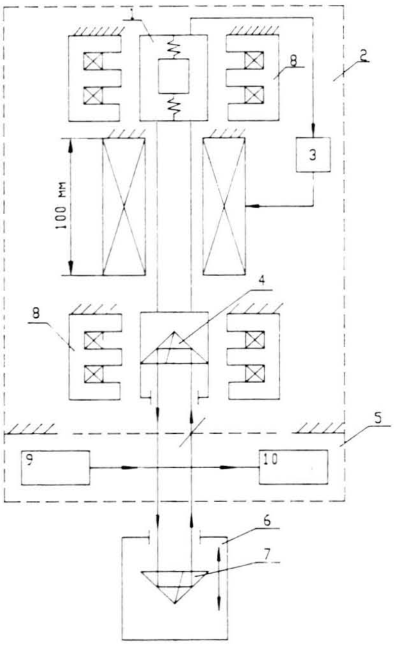


Fig. 16 Vibration isolation of a ballistic gravimeter

Fig. 17 Model suspended in suspension system of the MAI

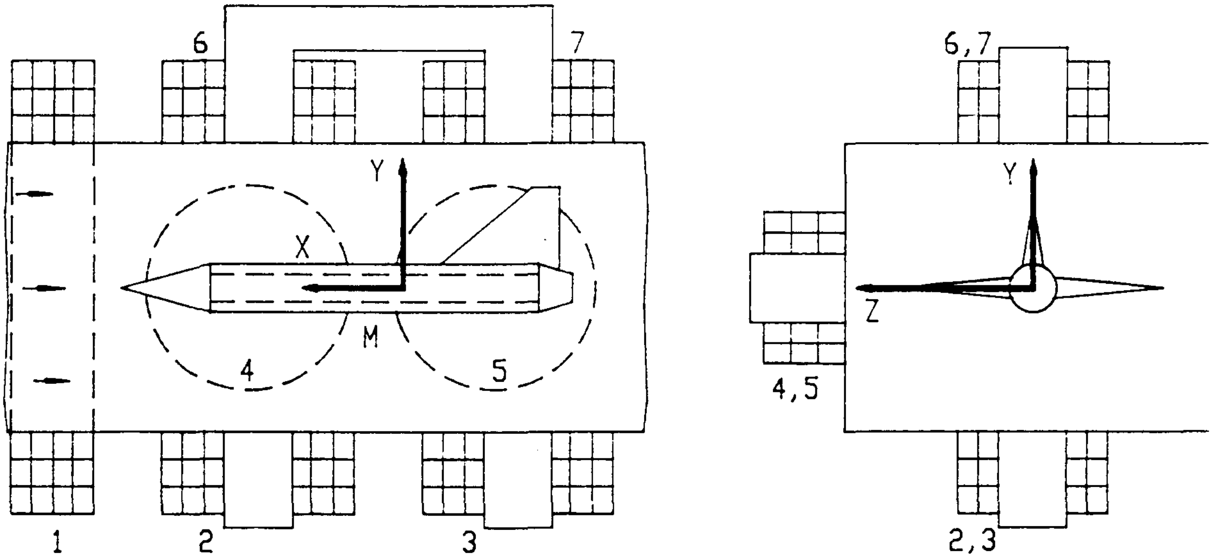


Fig. 18 EMS for wind tunnel

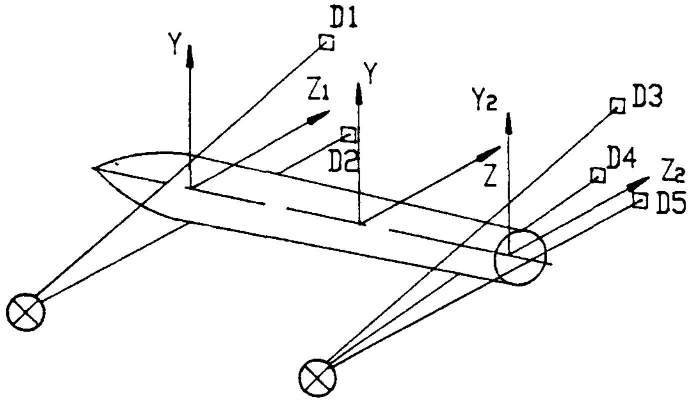


Fig. 19 Position sensing system

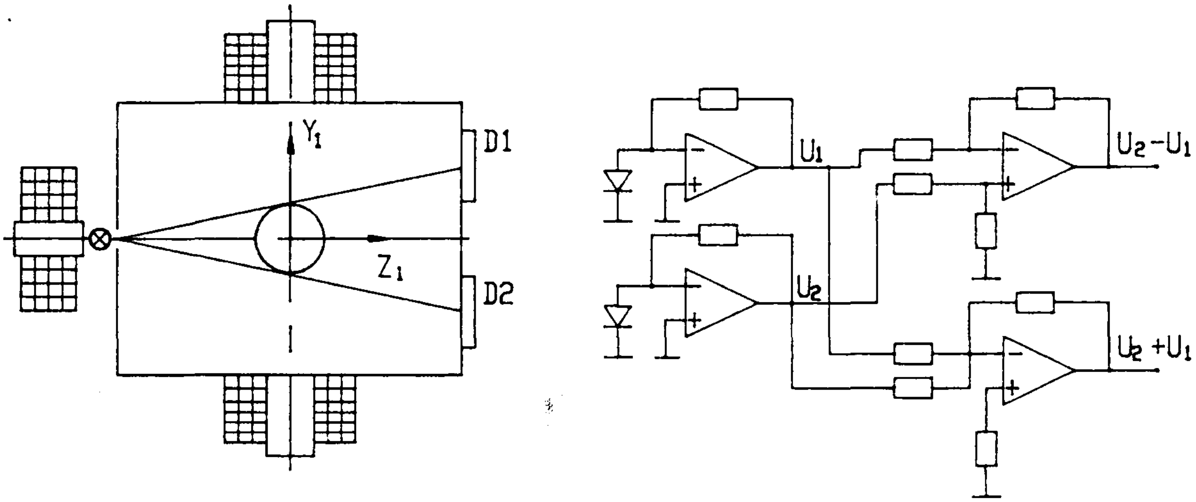


Fig. 20 Signal processing

REFERENCES

1. Earnshaw S. On the Nature of the Molecular Forces - Transactions of Cambridge Philips Society - 1842 - v.7.
2. Brounbeck W. Freischuebende Korperin Electrischen und Magnetischen Feld. - Ztschr. f. Physik. - 1939 - Bd 112 - H.7, 8.
3. Arkadiev V.K. A Floating Magnet. - Nature - 1947 - v.160.
4. Ponizovsky V.M. Induction of Large Centrifugal Fields // - Instruments and Technique of Experiment (ITE). - 1957 - No.7 - pp. 69-72.
5. Beans J.W., Joung J.J., Moore J.W., Journal of Applied Physics - 1946 - v.17.
6. Ponizovsky V.M. Double Magnetic Suspension of Ferromagnetic Rotors // ITE - 1976 - No.1 - pp. 181-183.
7. Osokin Y.A., Gerdy V.N., Maikov K.A., Stankevitch H.H. Theory and Application of Electromagnetic Suspensions - Moscow (M.): Machine Building. 1980 - 288 p.
8. Vyshkov Y.D., Ivanov B.I. Magnetic Bearings in Automatics - M.: Energy - 1978 - 160 p.
9. Voronkov V.S., Pozdeev O.D., Sandalov V.M. On Dynamics of Magnetic Suspension // Transactions of Colleges, Electromechanics - 1974 - No.10 - pp. 1082-1089.
10. Ganiev R.F., Vorobiev V.M., Liuty A.I. Resonance Oscillations of Gyroscopic Systems - Kiev: Scientific Thought - 1979 - 186 p.
11. Denisov G.G., Posdeev O.D., Khimin Y.A. On Rotary Hysteresis in Variable Magnetic Fields // Transactions of Colleges, Physics - 1978 - No.5 - pp. 64-67.
12. Stepaniants G.A., Tararoschenko N.S. On Structure of Laws of Control Providing Absolute Stability of Control Systems with Unstable Object // Reports of Academy of Sciences of the USSR. - 1970 - No.4 - pp. 774-776.
13. Voronkov V.S., Posdeev O.D. Effect of High Frequency Disturbances on Operation of Magnetic Suspension // Transactions of Colleges, Electromechanics - 1979 - No.9 - pp. 945-950.
14. Voronkov V.S., Pozdeev O.D. Optimization of System of Stabilization of Magnetic Suspension // Transactions of Colleges, Instrument Engineering - 1979 - No.9 - pp. 53-57.

15. Voronkov V.S., Pozdeev O.D. Investigation of Systems of Stabilization of Magnetic Bearing // Transactions of USSR Academy of Sciences, Magnetics of Rigid Body (MRB) - 1980 - No.4 - pp. 30-39.

16. Voronkov V.S. Synthesis of System of Stabilization of Magnetic Suspension and Experimental Investigation of its Dynamics // Transactions of Colleges, Instrument Engineering - No.8 - pp. 32-37.

17. Voronkov V.S. Synthesis and Analysis of Systems of Stabilization of Magnetic Suspension: Author's Essay of Dissertation of Candidate of Technical Sciences - M. - 1982.

18. Sorin V.M. Stability of Rotor in Electromagnetic Suspension with Allowance for Sluggishness of its Circuits // Works of Leningrad Polytechnical Institute (LPI) - 1969 - No.307 - pp. 46-53.

19. Sorin V.M. Sone Types of Vibrations of Rotor in Electromagnetic Suspension // Works of LPI - 1982 - No.386 - pp. 94-98.

20. Sorin V.M. Moments Acting on Non-spherical Body in Electromagnetic Suspension // Engineering Journal, MRB - 1968 - No.2 - pp. 31-39.

21. Martynenko Y.G. Drifts of Electrostatic Gyroscope Provoked by Non-sphericity of Rotor // Transactions of USSR Academy of Sciences, MRB - 1970 - No.1 - pp. 10-18.

22. Urman Y.M. Moment of Forces Provoked by Rotor Non-sphericity in Cryogenic Suspension // Transactions of Colleges, Instrument Engineering - 1974 - No.11 - pp. 87-92.

23. Urman Y.M. Drifting moments provoked by rotor nonsphericity in suspension having axial symmetric field // Transactions of USSR Academy of Sciences, MIT - 1973 - No.1 - pp. 24-31.

24. Martynenko Y.G., Savchenko T.A. Resonance Motions of Gyroscope with Noncontact Suspension on Vibrating Base // Transactins of USSR Academy of Sciences, MRB - 1977 - No.6 - pp. 16-23.

25. Savchenko T.A. Stability of Motion of Gyroscope with Noncontact Suspension at Angular Vibrations of the Base // Transactions of USSR Academy of Sciences, MRB - 1979 - No.3 - pp. 7-14.

26. Savchenko T.A. Resonance Motions of Gryoscope with Noncontact Suspension in the Presence of Two-component Vibration of the Base // Transactions of USSR Academy of Science, MRB - 1980 - No.6 - pp. 9-16.

27. Voronkov V.S., Pozdeev O.D. Synthesis of System of Stablilization of Magnetic Suspension with Allowance for Elasticity of Elements of its Construction // Transactions of Colleges, Instrument Engineering - 1987 - No.2 - pp. 61-65.

28. Voronkov V.S. Analysis of Dynamics of System of Stabilization of Elastic Base Magnetic Suspension // Transactions of Colleges, Instrument Engineering - 1988 - No.7 - pp. 41-45.

29. Ishlinsky A.Y., Zhuravlev V.F., Klimov D.M. Heat Barrier of Accuracy of Gyroscopes Having Noncontact Suspension // Present-day Problems of Mathematics and Mechanics and Appendices - M.: Moscow Physicotechnical Institute - 1983 - pp. 21-28.

30. Kobrin A.I., Martynenko Y.G. Effects of Heat Oscillations of Crystal Lattice on Accuracy of Gyroscope in Noncontact Suspension // Moscow Energetics Institute (MEI) works. - 1983 - No.14 - pp. 10-15.

31. Ryabov A.B. Determination of Main Vector and Main Moment of Forces Acting on Superconductive Body in Magnetic Field // Transactions of USSR Academy of Sciences, MRB - 1969 - No.6 - pp. 34-37.

32. Zhuravlev V.F., Rudenko V.M. Refering to Analysis of Power Characteristics of Suspension of Cryogenic Gyroscope // Transactions of USSR Academy of Sciences, MRB - 1983 - No.1 - pp. 9-15.

33. Sheremetievsky N.N. Problems of Construction of Flywheel-motor (spherical type) for Control of Position of Space Object // Report to World Electrotechnical Congress - 1977 - p. 15.

34. Veinberg D.M., Vereschagin V.P., Danilov-Nitusov N.N., Sheremetievsky N.N. Systems of Magnetic Suspension in Executive Organs of Control of Orientation of Space Vehicles // Transactions of USSR Academy of Science, MRB - 1981 - No.3 - pp. 152-157.

35. Sheremetievsky N.N., Veinberg D.M., Vereshchagin V.P., Danilov-Nitusov N.N. Powered Gyroscope with Electromagnetic Bearings for the Orientation System of Orbital Stations // Transactions of USSR Academy of Sciences, Space Researches - 1983 - Vol. 21 - No.1 - pp. 10-16.

36. Sheremetievsky N.N. Electromechanics and Peace Cosmos // Electrotechnics - 1987 - No.6 - pp. 10-16.

37. Sheremetievsky N.N. Magnetic Suspension of Rotors of the Electric Machines and Mechanisms // Works of ASRIE - 1989 - Vol. 89.

38. Vyshkov Y.D., Zheltov V.P., Korobkov V.P. Identification of Power Characteristics of Electromagnets of Dynamic Stands // Works of Moscow Aviation Institute - 1974 - No.305 - pp. 74-78.

39. Vyshkov Y.D., Korobkov V.P. Moment of Electromagnetic Friction in Spherical Rotor Magnetic Suspension System. - In book: Automatization of Technological Processes in Different Branches of National Economy - Kuibishev - 1975 - pp. 279-280.

40. Vyshkov Y.D., Ivanov V.I., Korobkov V.P. Investigation of Braking Moments Acting on Spherical Rotor in Electromagnetic Suspension - In book: Present-day Methods and Means of Balancing of Machines and Instruments - Yaroslavl - 1976 - pp. 6-7.

41. Zhuravlev Y.N. Electromagnetic Forces in Conical Radial Thrust Electromagnetic Bearing // Electricity - 1982 - No.11 - pp. 61-63.

42. Zhuravlev Y.N., Vetlitsin A.M., Khmylko N.V. Experimental Investigation of Electromagnetic Bearings for High-speed Rotors // Machines and Tools - 1982 - No.5 - pp. 13-14.

43. Zhuravlev Y.N. Synthesis of Linear Optimum System of Control of Magnetic Suspension of Rigid Rotor // Science of Machines - No.4 - 1987 - pp. 49-56.

44. Zhuravlev Y.N., Khmylko N.V. Dynamic Optimization of Linear System of Control of Active Magnetic Bearing // Transactions of Colleges, Electromechanics - No.12 - 1987 - pp. 74-82.

45. Zhuravlev Y.N. Control of Dynamics of Flexible Rotor in Active Magnetic Bearings // Transactions of Colleges, Instrument Engineering - 1988 - No.6 - pp. 7-12.

46. Averianov O.I., Betin V.N., Eisenshtock G.I. System of Control of Electromagnetic Bearings of Spindle // Machines and Tools - 1985 - No.11 - pp. 19-20.

47. Vasiliev A.V., Betin V.N., Eisenshtock G.I. Eletromagnetic Bearings with External Automatic Stabilization // Machines and Tools - 1985 - No.9 - pp. 16-18.

48. Betin V.N., Eisenshtock G.I. Dynamic of Radial Motion Spindle on Magnetic Bearings // Machines and Tools - 1988 - No.5 - pp. 20-22.

49. Vasiliev A.V., Eisenshtock G.I. Calculation of Parameters of Electromagnetic Bearings // Machines and Tools - 1989 - No.2 - pp. 16-19.

50. Shleenkin L.A. Radial Electromagnetic Suspension of High-speed Rotors // Electromechanical. Electromagnetic and Electronic Devices of Systems of Electrical Equipment of Flying Vehicles - M.: Moscow Aviation Institute - 1984 - pp. 44-47.

51. Shleenkin L.A. Synthesis of System of Stabilization of Active Magnetic Bearing - In book: Electronic Devices of Systems of Electrical Equipment of Flying Vehicles - M.: Moscow Aviation Institute - 1985 - pp. 42-46.

52. Bushuev V.A., Kuznetsov V.V., Shleenkin L.A. Radial Magnetic Bearings of Electrospindels - In book: Electric Drive and Automatization in Machine Building - M.: All-union Correspondence-course Machine Building Institute - 1985.

53. Shleenkin L.A. Multichannel System of Stabilization of High-speed Rotor - In book: On-board Converters of Systems of Electrical Equipment of Flying Vehicles - M.: Moscow Aviation Institute - 1986 - pp. 13-18.

54. Sharov V.S., Galkin V.I. Gyromotor with Magnetic Suspension of Ferromagnetic Rotor // Works of MEI - 1974 - No.187 - pp. 128-131.

55. Sharov V.S. Features of Design of Magnetic Suspension of Rotors of High-speed Electromotors - M.: MEI - 1982 - p. 85.

56. Piatin Y.M., Taisov V.N. Magnetic Vibration Isolators. Types, Characteristics and Perspectives of Application // Works of MADI - 1978 - No.139 - pp. 90-92.

57. Vorobjev V.M., Vorobjev-Obukhov A.V., Dmitriev A.Y., Pozdeev O.D. Magnetic Suspension of Body with Ferromagnetic Disk // ITE - 1976 - No.5 - pp. 245-247.

58. Vorobjev V.M., Vorobjev-Obukhov A.V., Pozdeev O.D. Vibration Isolated Electromagnetic Suspension - In book: Vibration Isolation of Man-operator and Vibrations in Machines - M.: Science - 1977 - pp. 57-61.

59. Vorobjev-Obukhov A.V. Investigation of Stability of Magnetic Suspension with Ferromagnetic Disk // Transactions of Colleges, Electromechanics - 1978 - No.12 - pp. 1300-1305.

60. Shurubkin V.D. Investigation and Development of Ballistic Gravimeter Magnetic Suspension Vibration Damper, (the Gravimeter is Designed for Determination of Absolute Values of Free Fall Acceleration on a Movable Base): Author's Essay of Dessertation of Candidate of Technical Sciences - M.: Moscow Aviation Institute - 1981.

61. Vyshkov Y.D. Vibration Isolation Properties of Electromagntic Suspension Devices // Transactions of Colleges, Instrument Engineering - 1985 - No.9 - pp. 49-54.

62. Beliaev L.B., Shirmanov P.M. Magnetic Suspension of Models in Wind Tunnels // Reviews of Central Aero-Hydrodynamic Institute - 1979 - No.557 - p. 58.

63. Vyshkov Y.D., Kovalnogov S.A., Usachov V.N., Shapovalov G.K. Magnetic Suspension and Balance System for Low-speed Wind Tunnel // Scientific Notes of Central Aero-Hyrodynamic Institute - 1986 - No.4 - pp. 94-97.

64. Kuzin A.V. Magnetic Suspension System for Aerodynamic Researches // Instruments and Technique of Experiment - 1990 - No.4 - pp.

65. Kuzin A.V. Photoelectrical Sensors of the Magnetic Suspension Systems // Transactions of Colleges, Instrument Engineering - 1990 - No.4 - pp. 63-67.

66. Kuzin A.V., Vyshkov Y.D. Optimization of Control in Multicomponental System of Electromagnetic Suspension // Transactions of Colleges, Instrument Engineering - 1987 - No.11 - pp. 44-49.

67. Kuzin A.V. Synthesis of the Magnetic Suspension Stabilization System for the Models in Wind Tunnel // Transactions of Colleges, Electromechanics - 1990 - No.5 - pp. 48-57.

68. Vyshkov Y.D., Kuzin A.V., Usachov V.N. Force Measurement Using Electromagnetic Suspension of Boaded Object. Paper presented at the 2nd Conference, Force Measurements. Modern Methods and Means - Novosibirsk - 1986 - pp. 43-44.

69. Bocharov V.I. High-Speed Ground Transport with Linear Drive and Magnetic Suspension // M.: Transport - 1985 - 279 p.

70. Bocharov V.I. Transport with Superconductive Magnets // Rostov-na-Donu: University of Rostov - 1988 - 152 p.