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(FOUO 3/81)

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AERONAUTICAL AND SPACE

FLIGHT TESTS OF HELICOPTERS

Moscow LETNYYE ISPYTANIYA VERTOLETOV in Russian 1980 (signed to press 28 Aug 80) pp 2-3, 396-399

[Annotation, foreword and table of contents from book "Flight Tests of Helicopters", by Aleksandr Ivanovich Akimov, Leonid Mikhaylovich Berestov and Rostislav Aleksandrovich Mikheyev, Izdatel'stvo "Mashinostroyeniye", 2,700 copies, 400 pages]

[Text] The problems of flight tests and their postulation are considered in the book and the methods of flight tests to determine and reduce to controlled conditions the flight data of helicopters with various types of engines are justified. Methods of determining characteristics of stability and controllability during flight are outlined. The theoretical bases and methods of flight-strength tests are considered. Attention is devoted to processing and analysis of the test results.

The book is intended for engineering and technical personnel engaged in development, tests, finishing and operation of helicopter technology.

Foreword

Among all types of experimental investigations of aviation equipment, flight tests reveal most fully the principles of complex processes of the interaction of the flight vehicle (LA), its units and systems, the medium in which the LA functions and of the person controlling this vehicle. Therefore, flight tests are not only important in themselves as a means of checking and developing aviation equipment, without which introduction into operation is impossible, but they are also an exceptionally effective means which contributes to proper formation of the engineering ideology of specialists involved in both development of LA and their operation and in scientific research.

The sections of the book devoted to flight tests and aerodynamic investigations (Chaptesr 1-7) were written by A. I. Akimov, those on flight dynamics (Chapters 8-14) were written by L. M. Berestov and those on strength (Chapters 13-18) were written by R. A. Mikheyev.

The authors feel it their duty to note especially the important role of V. V. Vinitskiy, Yu. A. Garnayev, A. A. Dokuchayev, Ye. F. Milyutichev, A. I. Mukhi and others in the investigations.

The authors express gratitude to S. B. Bren, who was responsible for general scientific supervision of the investigations and who rendered important assistance in the work on the book, and to reviewer A. V. Nekrasov for a number of valuable comments.

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AEROELASTIC STABILITY OF FLIGHT VEHICLES

Moscow AEROUPRUGAYA USTOYCHIVOST' LETATEL'NYKH APPARATOV in Russian 1980 (signed to press 30 Jul 80) pp 2-5, 230-231

[Annotation, foreword, introduction and table of contents from book "Aeroelastic Stability of Flight Vehicles" by Aleksandr Ivanovich Smirnov, Izdatel'stvo "Mashinostroyeniye", 1220 copies, 232 pages]

[Text] The dynamic problems of aeroelasticity--classical flutter of high- and low-aspect wings (straight and swept), of the tailplane, fuselage and of the entire vehicle as a whole and also flutter of thin panels and shells--are considered in the book. Problems of stalling flutter are analyzed.

The book is intended for engineering and technical personnel involved in problems of aeroelasticity.

Foreword

This book is a logical continuation of one published previously by the author [A. I. Smirnov, "Aerouprugost'. Chast' I. Staticheskiye zadachi aerouprugosti" (Aeroelasticity. Part I. Static Problems of Aeroelasticity), Moscow Aviation Institute, 1971] and is devoted to the dynamic problems of aeroelasticity in applications to flight vehicles.

A great deal of attention is devoted in the book to the physical pattern of the phenomena under discussion and to postulation of the problem. However, unlike the cited reference, main attention is turned to analysis and discussion of the results of solving individual problems rather than to a description of different methods of solving one or another problem. Each problem is usually formulated in the form and is solved by the method which the author feels are most convenient for one reason or another.

The limitations imposed by the framework of the book's volume and by the author's scientific interests were naturally reflected both in the style of the exposition and in selection of the dynamic problems under discussion.

The author is grateful to the collective of the Department of the Moscow Aviation Institute imeni S. Ordzhonikidze and its head Academician I. F. Obraztsov for advice and friendly assistance in the book.

The author is also grateful to the collective of the Department of Design and Strength of Flight Vehicles of the Moscow Institute of Civil Aviation Engineers, who sent their comments on the manuscript.

Doctor of Technical Sciences, Professor V. I. Protopopov performed important work in review of the book, for which the author expresses his deep gratitude.

Introduction

Interest in dynamic problems has intensified appreciably during the past few years in all fields of technology and specifically in aviation. One should apparently seek an explanation to this on the one hand in the desire to develop optimum designs and on the other hand to improve the mechanical properties of materials, to increase the dimensions of flight vehicles and to intensify operating modes.

A modern flight vehicle is usually a combination of sufficiently flexible structural components (wing, fuselage and tailplane), the natural motions and deformations of which determine to a significant degree their load during operation. As a result it becomes necessary to take these motions into account, which determines the formulation of the dynamic problem.

Taking the dynamic effects into account appreciably complicates the equations of elastic equilibrium of flight vehicle components due to the presence of yet another independent variable--time t. Thus, even for the simplest one-dimensional structural component the differential equations of euilibrium will no longer be ordinary equations, as in the case of the static problem, but equations in partial derivatives, the methods of solving which have still not been adequately worked out. For problems of aeroelasticity, the latter circumstance is also complicated by the fact that the corresponding differential or integral operators will be non-self-adjoint operators with complex eigenvalues, while the theory of these operators has been rather poorly worked out.

Systematic theoretical and experimental investigations of the dynamic problems and specifically of the flutter problem, were first begun in the Soviet Union in the early 1930s. Conversion from the biplane to the monoplane aircraft had begun by this time in the aviation of almost all countries, flight speeds increased appreciably and the number of accidents for unexplained reasons increased significantly.

Investigations were carried out primarily by workers of TsAGI [Central Institute of Aerohydrodynamics imeni N. Ye. Zhukovskiy] and the main results were obtained by this institute which made it possible by the end of the 1930s to construct reliable flight vehicles safe from the viewpoint of loss of dynamic stability.

The main contribution to study of these problems was introduced at that time by the papers of M. V. Keldysh, M. A. Lavrent'yev, A. I. Makarevskiy, A. I. Nekrasov, L. I. Sedov, Ya. M. Parkhomovskiy, L. S. Popov, Ye. P. Grossman and many others.

A large part of the difficulties related to solution of dynamic problems was caused by the need to take aerodynamic loads into account. These nonconservative conditions are what determines the non-self-adjoint nature of the boundary value problem. Under these conditions the successful selection of the aerodynamic operator acquires especially important significance. The operator should meet two main requirements--the simplicity of the analytical structure and the adequacy of the real physical pattern of the effect of air flow on the supporting components of the flight vehicle in the sense of objective reflection. Otherwise, the process of problem-solving may be rather complex and the results of calculating critical parameters will be far from real values.

The aerodynamics of transient flow are complex and are as yet a still inadequately developed section of fluid dynamics. The equations of motion of a viscous compressible fluid (the Navier-Stokes equation) are rather complex. Precise solutions of these equations were found only for special cases, of low interest to aviation practice. In view of this, it becomes necessary to simplify the initial equations of motion. The simplifications reduce to adoption of additional hypotheses with respect to the physical properties of flow, the range of velocities, the nature of perturbed motion, the configuration of the flight vehicle and so on. As a result numerous and more limited ranges of transient flow theory arise which describe the behavior of an ideal compressible or noncompressible gas (devoid of viscosity) at subsonic, near-sonic, supersonic or hypersonic speeds, the aerodynamics of narrow wings and low-aspect wings, the aerodynamics of quasi-steady flow, the aerodynamics of thin bodies and many others.

Additional hypotheses, significantly constricting the framework of the investigation, permit one in a number of cases to find a comparatively simple expression for the aerodynamic effect of transient flow on the components of the flight vehicle suitable for practical calculations. An example may be extensive use of the hypothesis of quasi-steady flow or piston theory and its various modifications.

Problems of experimental investigation of the aeroelastic stability of flight vehicles, which comprise an extensive independent section, are not considered in the book.

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ELIMINATION OF VIBRATIONS IN AVIATION PIPING

Moscow USTRANENIYA KOLEBANIY V AVIATSIONNYKH TRUBOPROVODAKH in Russian 1980 (signed to press 14 Dec 79) pp 2-4, 155-156

[Annotation, foreword and table of contents from book "Elimination of Vibrations in Aviation Piping" by Vladimir Pavlovich Shorin, Izdatel'stvo "Mashinostroyeniye", 1,070 copies, 160 pages]

[Text] Problems of designing acoustic dampers intended to eliminate vibrations of the working medium in aviation piping systems are considered in the book. Methods of calculating the efficiency of dampers, of optimizing their characteristics and methods of experimental investigations of dampers are outlined. The book is intended for engineers involved in design of hydraulic and fuel systems of flight vehicles and engines, piping and automatic hydraulic systems of production units and transport vehicles. It will also be useful to scientific workers, students and graduate students of the corresponding specialties.

Foreword

An increase of flight speed, load-carrying capacity and maneuverability of flight vehicles is accompanied by a significant expansion of functional problems and by an increase of the output of hydraulic and fuel systems. The specific parameters increase and processes in automatic devices and hydraulic couplings are intensified when the structures of the systems are complicated and when the number of units and the length of piping are increased. At the same time, ever more rigid requirements on reliability are placed on hydraulic and fuel systems throughout the service life of the flight vehicle. In this regard the problem of prevention and elimination of vibrations of the working medium in piping systems becomes ever more timely.

Reducing the vibrational intensity of the working medium not only provides operational reliability of crucial assemblies of flight vehicles and engines, but is in some cases a necessary condition of their functioning.

It has been established that the main type of failure of piping is vibrational failure and one of the main sources of excitation of mechanical vibrations is pulsating flow of the working medium. Reduction of the pressure fluctuation amplitudes permits a reduction of strength reserves of piping and consequently a reduction of the mass of systems.

Flow fluctuation of the working medium is one of the causes of seal failure of connections.

The functional and parametric reliability of hydraulic systems is reduced to a significant degree due to the effect of pulsation on the sensing elements and actuating members of units. Variable pressure causes undamped vibrations of valves, slide valves and servo pistons, which in turn leads to premature wear of them and to the appearance of cold hardening and scoring on the working surfaces. The interaction of periodic processes in piping with the working members of mechanisms is one of the factors affecting their operating stability. Variable pressure in piping is a source of servo control unit errors and tracking system errors and is the cause of disruption of their initial adjustment.

Vibrational processes have a significant effect on the characteristics, efficiency and reliability of pumps.

Instability of the combustion process in liquid-fuel rocket engines at low and intermediate frequencies is related to periodic processes in the piping of the fuel-feed system. Vibrational processes in fuel-feed systems of gas turbine engines affect the working process in the combustion chamber, leading to deterioration of engine economy.

The problem of eliminating vibrations of the working medium is also timely for other systems, for example, for ship piping, the hydraulic systems of machine tools, ground transport and power engineering units, the pipeline systems of the oil and gas industry and heating and ventilation systems.

There are now several directions in solving the problem of prevention and elimination of vibrations of the working medium. One of them--the use of special dampers --is reflected in the book. This method of elminating vibrations is more promising and is gaining ever wider distribution in the systems of flight vehicles and engines.

The author is grateful to Candidate of Technical Sciences A. G. Gimadiyev, Candidate of Technical Sciences L. I. Brudkov and Candidate of Technical Sciences V. I. Sanchugov, who participated in solution of some specific problems. The author is also grateful to Doctor of Technical Sciences B. F. Glikman for a number of useful comments made in review of the manuscript.

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SURFACE TRANSPORTATION

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THEORY OF ELECTRODYNAMIC LEVITATION, MAIN RESULTS AND FURTHER PROBLEMS

Moscow IZVESTIYA AKADEMII NAUK SSSR: ENERGETIKA I TRANSPORT in Russian No 1, Jan-Feb 81 pp 72-91

[Article by V. M. Kochetkov, K. I. Kim and I. I. Treshchev, Leningrad and Moscow]

[Text] The principles of electrodynamic suspension (EDP) are well known [1]. A number of approximate and precise methods have now been worked out for calculating the characteristics of suspension. The results of calculations presented in existing publications show in their entirety the achievable characteristics of EDP and the advantages and disadvantages of this method compared to other noncontact methods of suspension of transport vehicles. Specifically, the prospects for use of EDP at high speeds (in the range of 250-500 km/hr) has been determined.

The literature on EDP and related problems is very extensive and includes no less than 250-300 titles. Attempts to systemize the results have been undertaken by several authors; we note first the extensive technical survey [2] and a number of papers of a survey nature devoted to individual problems of EDP [3, 4]. However, the indicated papers mainly have a technical orientation and the calculating-methodical aspect is not the main one for them. At the same time, a need has arisen for a survey where the presently known calculating methods would be summarized and problems of the theory of electrodynamic levitation would be considered from a unified viewpoint, in a sequential manner and in a unified system of notations with regard to the continuing investigations and optimization of suspension systems based on calculation of the forces of levitation, braking and stabilization acting on suspension. The compilers of this survey had in mind satisfaction of these requests.

Main attention was devoted to an outline of the calculating procedures, which in the authors' opinion, are rather extensive and effective. The details of considering the calculating methods are different--from a brief mention with reference to the publication to an outline expanded with respect to the original.

The given graphs are mainly illustrative in nature and one should turn to the primary source articles indicated in the bibliography for more complete calculating-numerical information. Due to the limited volume of the survey and the number of literary references, it was not possible to compile any kind of complete bibliography and far from all the authors working actively in the field of EDP theory and not all the articles and books which deserve mention are cited in the survey. However, the bibliography may be supplemented with inclusion of the bibliographies of those articles and collections which are indicated in this survey.

1. Levitation above an infinitely wide bed. The starting point for the entire subsequent outline is Maxwell equations without bias current:

$$\mathrm{rot}\,\mathbf{E} = -\partial \mathbf{B}/\partial t, \tag{1.1}$$

$$\mathrm{rot}\,\mathbf{B} = \mu_0 \mathbf{j}, \tag{1.2}$$

where B and E are the magnetic and electric vectors, j is current density and μ_0 is the permeability of free space.

Further, nonmagnetic media are considered for simplicity (the generalization for the case of media with constant permeability through bodies encounters no difficulties [5]). Having selected a coordinate system with quiescent bed for certainty, we have for current density

$$\mathbf{j} = \sigma \mathbf{E}, \tag{1.3}$$

where σ is the specific conductivity of the material.

The boundary conditions on the surface of a conductor for the magnetic vector have the form [6]

$$\mathbf{B}_i = \mathbf{B}_e, \quad \left(\frac{\partial}{\partial n}\mathbf{B}\right)_e - \left(\frac{\partial}{\partial n}\mathbf{B}\right)_i = [\mathbf{n}, \mathrm{rot}\,\mathbf{B}_i]. \tag{1.4}$$

Here $\partial/\partial n$ is the derivative in the direction of the outer normal end (with respect to the conducting zone) and the subscripts correspond to the maximum values in the domain of conductivity (i) and in the external space (e).

The following model corresponds to the suspension system: the conducting bed occupies the domain $-T < z < 0$ in the Cartesian coordinate system (x, y, z) and the system of conductors (electromagnets) which creates a magnetic field and which moves parallel to the boundary of the bed in the direction of the x axis at velocity v is located in domain $z \geq H > 0$.

In the domain that does not include the interfaces and sources, the following diffusion equation is valid for the magnetic field

$$\Delta \mathbf{B} = \mu_0 \sigma \partial \mathbf{B}/\partial t. \tag{1.5}$$

At constant velocity v we have $\partial/\partial t = -v\partial/\partial x$; therefore, (1.5) can be rewritten in the form [7]

$$\Delta \mathbf{B} = -\mu_0 \sigma v \partial \mathbf{B}/\partial x. \tag{1.6}$$

Solution of equation (1.6) with boundary conditions (1.4) permits one to find the field in the entire space and also the density of the eddy currents in the conducting domain. The force acting on the conducting circuit of the electromagnet can be determined either by integration of the forces acting on the elementary magnetic dipole

$$\mathbf{F} = I \iint_{S_k} (\mathbf{n}, \nabla) \mathbf{B} \, dS, \tag{1.7}$$

or by the reactive force with which the current circuit acts on the bed:

$$\mathbf{F} = -\int_{-\infty}^{\infty} dx \iint_{S} [\mathbf{J}(x,y,z) \mathbf{B}^0(x,y,z)] dS. \tag{1.8}$$

The following notations are used in formulas (1.7) and (1.8): I is the current of the electromagnet circuit, S_k is the surface subtended by this circuit, S is the cross-sectional area of the track bed, J is the density of the eddy currents in the bed, B is the field of eddy currents of the bed acting on the suspension electromagnet and B^0 is the field of the electromagnet acting on the eddy currents in the bed.

The value of B^0 in (1.8) is assumed to be known and the values of B and J in (1.7) and (1.8) can be determined from solution of (1.6). Besides B^0 itself, its normal derivative is also continuous for component B normal to the boundary of the conductor, according to (1.4). For this reason solution of equation (1.6) can be found for normal component B_z and the remaining components of this sector can be determined outside the conductor from the equation rot B = 0.

Turning from the magnetic vector to the Fourier representation[1]

$$\mathfrak{B}(\mathbf{k}, z) = (2\pi)^{-2} \iint_{-\infty}^{\infty} \exp(-i\mathbf{kr}) \mathbf{B}(\mathbf{r}, z) \, d\mathbf{r}, \tag{1.9}$$

we find from (1.6)

$$d^2\mathfrak{B}/dz^2 = \alpha^2 \mathfrak{B}. \tag{1.10}$$

The following notations are used in (1.9) and (1.10): $r = xe_x + ye_y$, $k = k_x e_x + k_y e_y$ (here and further e_x, e_y and e_z are the unit vectors in the direction of the corresponding axes), $\alpha = (k^2 - i\mu_0 \sigma k_x)^{1/2}$ for the domain of conductivity and $\alpha = k$ for a free space, $k = |\mathbf{k}|$.

Equation (1.10) has solutions of type exp ($\pm \alpha z$) and the coefficients in front of these partial solutions are found from the boundary conditions. The procedure of determining the coefficients which reduces to solution of a system of linear algebraic equations (inhomogeneous--due to consideration of the boundary conditions which include the source field) is very simple [8]. Let us devote main attention to the other problem, less illuminated in the literature--that of finding the Fourier transform of the source field which determines the inhomogeneous part of the mentioned system of equations.

With Coulomb calibration div A = 0, the vector potential of the currents has the known expression

$$\mathbf{A}(\mathbf{r}, z) = (\mu_0/4\pi) \int_V \mathbf{j}(\mathbf{r}', z') [|\mathbf{r}' - \mathbf{r}|^2 + (z' - z)^2]^{-1/2} d\mathbf{r}' \, dz',$$

where j is the current density vector and integration is carried out by the volume of the conductor with current.

Making use of the identity

$$\iint_{-\infty}^{\infty} \exp(-i\mathbf{kr}) [|\mathbf{r}' - \mathbf{r}|^2 + (z' - z)^2]^{-1/2} d\mathbf{r} = 2\pi \exp(-i\mathbf{kr}') \times$$

$$\times \int_0^{\infty} r J_0(kr) [r^2 + (z' - z)^2]^{-1/2} dr = \frac{2\pi}{k} \exp(-i\mathbf{kr}' - k|z' - z|),$$

for Fourier representation of the vector potential we have

$$\mathfrak{A}(\mathbf{k}, z) = (\mu_0/8\pi^2 k) \int_V \mathbf{j}(\mathbf{r}', z') \exp(-i\mathbf{kr}' - k|z' - z|) d\mathbf{r}' \, dz'. \tag{1.11}$$

Hence, the Fourier transform of the magnetic field of the source is found from the equality B = rot A and for Fourier representations in the rot operator, instead of derivatives $\partial/\partial x$ and $\partial/\partial y$, one should substitute the multipliers ik_x and ik_y.

Let the source be compiled from a set of conducting circuits L_n, each of which subtends some surface S_n and carries current I_n (n = 1, ..., M). The integral through the volume in (1.11) now reduces to the sum of the integrals through the conducting circuits. Using the identity valid for an arbitrary continuously differentiable function

$$\oint_{L_n} f \, d\mathbf{l} = \iint_{S_n} [\mathbf{n}', \operatorname{grad} f] dS,$$

where n' is the unit vector of the normal to surface S_n at the point of integration and introducing the vectors

$$\mathbf{N}_n = \iint_{S_n} \mathbf{n}' \exp(-i\mathbf{kr}' - kz') dS, \tag{1.12}$$

$$\varkappa = ik_x \mathbf{e}_x + ik_y \mathbf{e}_y + k\mathbf{e}_z, \tag{1.13}$$

we find for z < H, i.e., at a positive value of (z' - z) in (1.11),

$$\mathfrak{A}(\mathbf{k}, z) = (\mu_0 \exp(kz)/8\pi^2 k)\left[\varkappa, \sum_{n=1}^{M} I_n \mathrm{N}_n\right].$$

The Fourier representation of the magnetic field of the source can now be written in the form

$$\mathfrak{B}^0 = \frac{\mu_0 \exp(kz)}{8\pi^2 k}[\varkappa, \mathfrak{A}] = \frac{\mu_0 \exp(kz)}{8\pi^2 k}\cdot\left(\varkappa, \sum_{n=1}^{M} I_n \mathrm{N}_n\right)\varkappa. \qquad (1.14)$$

Hence, it follows that for a source of arbitrary form

$$d\mathfrak{B}^0/dz = k\mathfrak{B}^0, \qquad (1.15)$$

if the source is located above the conducting bed.

The values of N_n given by formula (1.12) are comparatively easily calculated for a wide range of circuit shapes. Thus, for a horizontally arranged rectangular circuit measuring 2b at z = h in the direction of motion and 2a in the transverse direction, we find [7]

$$\mathrm{N} = 4\exp(-kh)\frac{\sin bk_x}{k_x}\frac{\sin ak_y}{k_y}\mathrm{e}_z. \qquad (1.16)$$

The expressions for N at some other shapes of the circuit are indicated in [5, 9].

Finding the field of eddy currents is essentially simple with the known expressions for the Fourier transform of the source field. The component $\mathfrak{B}_z$ of the Fourier transform of field $\mathfrak{H}$ is determined from boundary conditions at z = 0 and z = -T and the inhomogeneous part of the derived system of equations contains the z-components of vectors $\mathfrak{B}^0$ and $d\mathfrak{B}^0/dz$ determined by (1.14) and (1.15). The remaining components are found from the equation rot B = 0 for the field of eddy currents at known value of $\mathfrak{B}_z$, which yields $\mathfrak{B} = \mathfrak{B}_z \varkappa^* / k$, where $\varkappa^*$ is a vector complex conjugate to (1.13). The described procedure of determining the Fourier transform of the field of eddy currents leads to the result

$$\mathfrak{B} = \varkappa^* \mathcal{R}(\mathrm{k}) \exp(-kz) \mathfrak{B}_z^0|_{z=0}/k, \qquad (1.17)$$

where

$$\mathcal{R}(\mathrm{k}) = \frac{k-\alpha}{k+\alpha}[1-\exp(-2\alpha T)] \Big/ \left[1-\left(\frac{k-\alpha}{k+\alpha}\right)^2 \exp(-2\alpha T)\right]. \qquad (1.18)$$

Now, turning from the Fourier transform of the field (1.7) to the original, we find the force acting on the electrodynamic suspension from formula (1.7). The corresponding transforms lead to the expression

$$F=\frac{\mu_0}{8\pi^2}\iint_{-\infty}^{\infty}\frac{\varkappa^*}{k}\mathcal{R}(k)\left(\varkappa,\sum_{n=1}^{M}I_nN_n\right)dk\sum_{n=1}^{M}I_n\iint_{-\infty}^{\infty}\exp(ikr-kz)(n,-\varkappa^*)\,dS=$$
$$=-\frac{\mu_0}{8\pi^2}\iint_{-\infty}^{\infty}\frac{\varkappa^*}{k}\mathcal{R}(k)\left|\left(\varkappa,\sum_{n=1}^{M}I_nN_n\right)\right|^2. \quad (1.19)$$

Formula (1.19) is a generalization of the known formulas for force F given in [5, 7-9].

Specific results were found in the greatest volume for the suspension electromagnet having the form of a rectangular conducting frame parallel to the bed boundary. Using expression (1.16) for this case, we find

$$F=-\frac{2\mu_0 I^2}{\pi^2}\iint_{-\infty}^{\infty}\frac{k\varkappa^*}{k_x^2k_y^2}\mathcal{R}(k)\exp(-2kh)\sin^2(bk_x)\sin^2(ak_y)\,dk. \quad (1.20)$$

This formula was first presented in [7] in somewhat different notation.

The described procedure for determination of force F corresponds to so-called normal-flow levitation systems for which unilateral arrangement of the source with respect to the bed is inherent. The problem of determining the eddy current field not only in the domain where the individual source inducing the currents is located but on the opposite side of the bed occurs for zero-flow type systems in which the sources are located on both sides of the bed [10]. Using optical terminology, one may accordingly talk about the reflection coefficient $\mathcal{R}(k)$ for the z-component of the Fourier transform of the field and about the transmission coefficient $\mathcal{P}(k)$ through the thickness of the bed. The reflection coefficient is given by relation (1.18) and the transmission coefficient is equal to

$$\mathcal{P}(k)=\frac{4\alpha k}{(\alpha+k)^2}\exp(-\alpha T)\Big/\left[1-\left(\frac{k-\alpha}{k+\alpha}\right)^2\exp(-2\alpha T)\right]. \quad (1.21)$$

The optical analogy for a bed of infinite width is very fruitful, especially in the case of laminated conductors whose properties vary along coordinate z. The productivity of this analogy is related to the possibility of using the easily developed methods of geometric optics. We note that the indicated approach corresponds to the physical essence of the processes descirbed by an equation of type (1.10); in optics an analogous equation determines the field of a plane wave impinging normally on the interface.

Let us return to derived formula (1.20). Taking the nature of evenness with respect to k_x and k_y of the value of α into account, we find that the components of force F in (1.20) distinct from zero will be only F_x and F_z. Subsequently, for lift F_z and the decelerating force $-F_x$ according to the established tradition, we introduce the notations:

$$F_L=F_z,\ F_D=-F_x. \quad (1.22)$$

Let us also introduce the levitation quality η, determining it by the relation $\eta = F_L/F_D$.

The equality of force F_y to zero for finite values of v (the limit $v \to \infty$ is discussed below) is not obligatory in the general case. The relation $F_y = 0$ is the consequence of the axial symmetry of the circuit with respect to the direction of motion with regard to expression (1.20). It is easy to show that arguments k_x and k_y of function N_n in (1.19) accordingly change to expressions $k_x \cos\phi + k_y \sin\phi$ and $k_y \cos\phi - k_x \sin\phi$ upon rotation of the conducting circuit by angle ϕ in plane (x, y) and a lateral force distinct from zero is found in this case even for a rectangular circuit with initial value of function N in the form of (1.16). Incidentally, the lateral force, like the deceleration force, approaches zero with an increase of speed. Actually, at $v \to \infty$ we have $|\alpha| \to \infty$ and (1.19) yields

$$F^0 = \frac{\mu_0}{8\pi^2} \iint_{-\infty}^{\infty} \frac{\varkappa^2}{k} \left| \left(\varkappa, \sum_{n=1}^{M} I_n N_n \right) \right|^2 dk = e_z F_L^0. \tag{1.23}$$

Taking the nature of the evenness of the integral expression with respect to k_x and k_y into account, we find that only the z-component of the force is distinct from zero in (1.23). The physical force F_L^0 is a repulsive force between a real source (a solenoid) and the same source arranged specularly with respect to plane z = 0 and fed in the opposite direction.

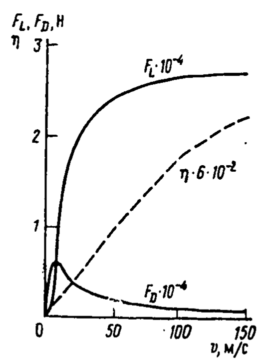

Figure 1. Characteristics of Suspension as a Function of Velocity With Respect to [10] at 2b = 1 meter, 2a = 0.3 meter, h = 0.2 meter, T = 2 cm and $I = 2.85 \cdot 10^5$ A

Key:
1. m/s

Formula (1.19) permits one to calculate the levitation characteristics not only for a single conducting circuit but for a system of conducting circuits (at M > 1). If all the circuits have identical shape and orientation, but are shifted in plane x, y by vectors d_n (n = 1, ..., M) with respect to the origin, then according to the definition of functions N_n with respect to (1.12) for the total circuits, we find

$$\sum_{n=1}^{M} N_n = N \sum_{n=1}^{M} \exp(-ikd_n), \qquad (1.24)$$

where N is vector (1.12) calculated for an unbiased circuit.

Substitution of (1.24) into (1.20) permits one to estimate the mutual effect of the circuits on the levitation characteristics.

The method used in finding formula (1.20) and which includes the use of a Fourier transform with respect to coordinates x and y for solution of an equation of type (1.6), is rather general. As indicated above, it is suitable for analysis not only of normal-flow systems, but also for zero-flow levitation systems. The use of it with respect to suspension systems in which, besides a conducting band under the source, there is also a ferromagnetic strip located above it (the use of an additional ferromagnetic strip is feasible at low speeds or when the vehicle stops [11]), is also possible.

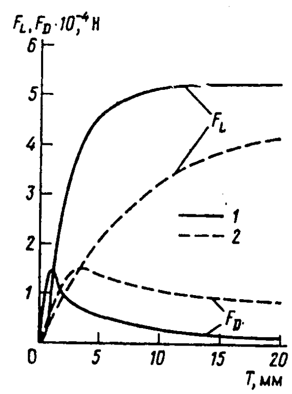

Figure 2. Effect of Thickness of Bed With Respect to [10] at 2b = 2 meters, 2a = 0.3 meter, h = 0.2 meter, I = $3 \cdot 10^5$ A; 1--v = 150 m/s; 2--v = 30 m/s

The suspension characteristics are determined by the dependence of the lift F_L and the deceleration force F_D on various parameters which give the shape and dimensions of the suspension electromagnet, the height of suspension, the thickness of the bed and travel speed. A considerable volume of calculating results is presented in [10]. Since the number of parameters which determines the suspension characteristics is rather high, it is impossible in the framework of a brief survey to give a complete picture of dependences of F_L and F_D on all parameters. However, the dependence on speed and the thickness of the bed, which may be regarded as typical for electrodynamic suspension systems, are presented below. The specific values of the suspension parameters are taken into account in the subscripts under the figure and the following notations are used in this case: 2a and 2b are the transverse and longitudinal dimensions of the conducting circuit (the suspension electromagnet), h is the height of suspension, T is the thickness of the bed, σ is the specific conductivity of the bed, v is the travel speed of the vehicle and I is the product of the current in the electromagnet by the number of turns. It is assumed equal to $3 \cdot 10^7$ 1/ohms·m (aluminum alloy) eyerywhere, where conductivity σ is not indicated.

The dependence on speed for lift, decelerating force and levitation quality is presented in Figure 1. At $v \gtrsim 50$ m/s, lift essentially ceases to depend on speed, whereas the levitation quality increases monotonically with an increase of v due to the fact that the decelerating force decreases by the law[2] $v^{-1/2}$ at large values of v.

The dependence of suspension characteristics on the thickness of the bed can be found on the basis of calculations by formula (1.20). The natural scale parameter here is the thickness of the skin layer δ, which is equal to $\delta = 2/\mu_0\mu\sigma\omega)^{1/2}$, where μ is the relative permeability equal to unity for nonmagnetic media, for fields variable in time with circular frequency ω. Although variation of the field is not periodic for electrodynamic levitation, however, one can determine the main harmonic from the time signal and one can then approximately estimate the thickness of the skin layer. This approach was used by a number of authors to find rough estimates.

The dependence of levitation characteristics on the thickness of the bed for a specific version of a suspension system is presented in Figure 2.

As recent investigations showed, the levitation quality of normal-flow levitation systems is bounded above by the value $0.5\ \mu_0\sigma vT$ and this value is independent of the shape of the conducting circuit [12]. It may be exceeded only by the zero-flow levitation systems investigated in [10].

The suspension characteristics for a levitation system using a ferromagnetic strip over a solenoid and an ordinary conducting band below it were studied in [11]. As indicated by calculations, this system provides adequate lift for low speeds v (and even at v = 0) and significantly greater lift compared to an ordinary levitation system at large values of v. The problem of calculation of levitation for systems using ferromagnetic strips is also considered in [5, 7, 10].

Papers [5, 9] are devoted to the problem of the mutual effect of the fields of adjacent suspension solenoids on suspension characteristics. The levitation characteristics are estimated in these papers for the total plane circuits having the form of matrix M X N in the general case. It is shown that their mutual effect is rather strong with close arrangement of the circuits and the total force cannot be calculated on the basis of calculations made for an individual solenoid.

An interesting calculating method is suggested in [13, 14]. An equation for the vector potential of the eddy current field is formulated for a thin conducting strip, i.e., for the practically most important case, and a solution of it is constructed. A method of calculating the forces acting not only on the conducting circuits but also on circuits with ferromagnetic cores and also on permanent magnets is described in the same source. Taking the ferromagnetic materials (without saturation) into account requires solution of a Fredholm equation of second kind for the density of the imaginary magnetic surface charges. According to the calculations, the lift acting on the conducting circuit can be almost doubled in the presence of a ferromagnetic core [14].

Summarizing the results, we note that on the whole levitation theory in approximation of a plane bed of infinite width has now been rather fully developed. The references cited above contain in total extensive material which represents different versions of calculating methods and also specific calculating functions for levitation systems of various type. Nevertheless, approximation of an infinitely wide bed itself is of limited applicability and can be used only for preliminary, approximate estimates.

2. Levitation above a continuous bed of finite width. The theory which permits one to calculate the forces on electrodynamic suspension with finite width of the bed is considerably more complicated. Nevertheless, effective calculating methods have now been worked out in this direction.

Let us briefly outline one of the possible approaches, following [6]. Let the conducting bed in plane (y, x) have an arbitrary cross-sectional shape S constant along direction x. Turning from equation (1.6) to the equation for the Fourier transform determined by the equality

$$\mathfrak{B}(k, y, z) = (2\pi)^{-1} \int_{-\infty}^{\infty} \exp(-ikx)\mathbf{B}(x, y, z)\,dx, \quad (2.1)$$

we find

$$\frac{\partial^2 \mathfrak{B}}{\partial y^2} + \frac{\partial^2 \mathfrak{B}}{\partial z^2} = (k^2 - ik\lambda)\mathfrak{B}, \quad \lambda = \mu_0 \sigma v. \quad (2.2)$$

Using the Green formula and boundary conditions (1.4) permits one to write the following integral equation for the Fourier transform of the field inside a conducting bed

$$\mathfrak{B}(P) = \frac{ik\lambda}{2\pi} \iint_S G(P, Q)\mathfrak{B}(Q)\,dS - \frac{1}{2\pi} \int_L [\mathbf{n}, \operatorname{rot} \mathfrak{B}] G\,dl + \mathfrak{B}^0(P). \quad (2.3)$$

Here P and Q are two points in domain S, the first of which is the observation point and the second of which is the integration point, n is the unit vector of the normal external to S, $\mathfrak{B}^0(P)$ is the Fourier transform of the field created by the electromagnetic suspension without regard to the conducting bed, $G(P, Q) \equiv K_0(|k|R)$, where K_0 is a MacDonald function and R is the distance between P and Q and L is the boundary of domain S.

The field inside the conducting domain can be found by solving equation (2.3), after which the field in the external domain is determined by quadratures without solving any equations. The force acting on suspension can now be determined on the basis of formulas (1.7) or (1.8) by the derived magnetic vector and the density of the eddy currents J is found by differentiation of the field inside the conducting domain.

Besides the equation for the magnetic field, one can also find equations of type (2.3) for an electric field [6] and also a system of equations for the scalar and vector potentials of the field.

We note that to calculate the force acting on the suspension, one does not at all have to find the Fourier original of the magnetic vector, but it is more reasonable to limit oneself to use of the Fourier transform B determined from an integral equation of type (2.3). Let us illustrate calculation of the force on the basis of formula (1.8). Turning from the value of J and B^0 to their Fourier transforms and using equation (1.2), we find

$$F = \frac{1}{\mu_0} \int_{-\infty}^{\infty} dx \iint_S \left[\int_{-\infty}^{\infty} \exp(ik'x) \mathfrak{B}^0 \, dk', \left[p, \int_{-\infty}^{\infty} \exp(ikx) \mathfrak{B} \, dk \right] \right] dS, \tag{2.4}$$

where $p = ike_x + e_y \frac{\partial}{\partial y} + e_z \frac{\partial}{\partial z}$.

Integrating in (2.4) with respect to x, we find the multiplier $2\pi\delta(k + k')$ and subsequent integration with respect to k' leads to the result

$$F = \frac{2\pi}{\mu_0} \int_{-\infty}^{\infty} dk \iint_S [\mathfrak{B}^0(-k, y, z), [p, \mathfrak{B}(k, y, z)]] dS. \tag{2.5}$$

The dependence of formula (2.5) on k in the integral expression is not oscillating in nature and therefore substitution of the variable3 $k = A \operatorname{tg} \phi$ may be used to calculate the quadrature with respect to k and the integral may then be calculated by the Gauss quadrature formulas with respect to ϕ in the range of $(-\pi/2, \pi/2)$.

Let us note the possible numerical methods of solving equations of type (2.3). A significant number of methods of numerical solution of integral equations is now generally known, but the use of many of them in practice for the equation under consideration is difficult by the bidimensionality of the quadrature and by the characteristic in the kernel. One can now hardly give a justified answer to the question of which method of solution is best. Let us limit ourselves to indication of the methods which were used in attempts at practical solution of equations (2.3). The method of nonlinear iteration [6] can be used for solution of this equation. However, the method of reduction to a system of linear algebraic equations based on approximation of representation of the integral by some quadrature sum is essentially simpler. Both methods were tested in practical calculations and, as it turned out, preference should be given to the second of them by universality and principal simplicity.

On the whole practical solution of equations of type (2.3) is related to a significant volume of programming operations and also requires the use of very high speed digital computers. For this reason the approximate methods of calculation of levitation are of significant interest with regard to finite transverse dimensions of the bed, based on solution of one-dimensional integral equations.

An effective method of calculating levitation above a thin bed (this is the more important case in the practical sense) is presented in [15]. A brief outline of this method is given below with use of the notations adopted in the given paper.

Let domain $0 < y < 1$, $-T < z < 0$ be occupied by a conducting bed which will be regarded as thin (T is shallow). The shallowness of the bed thickness permits one to disregard the z-component of the eddy currents and to consider only the currents flowing in planes $z = z_0$ and $z_0 \in [-T, 0]$. Let us introduce the value of eddy current density averaged with respect to z

$$\langle \mathbf{J} \rangle = \frac{1}{T} \int_{-T}^{0} \mathbf{J}\, dz. \tag{2.6}$$

Let us denote in similar fashion by the angular brackets the other averaged values. From Maxwell equations we find

$$\mathrm{rot}_z \langle \mathbf{J} \rangle = \sigma v \frac{\partial}{\partial x} \langle B_z \rangle. \tag{2.7}$$

This relation is identical to the z-component of the diffusion equation (1.6) when it is averaged. Instead of vector $\langle J \rangle$, let us introduce the scalar function of current V (x, y), assuming

$$\langle \mathbf{J} \rangle = [\nabla V, \mathbf{e}_z]. \tag{2.8}$$

Turning by use of a relation of type (2.1) from the function V (x, y) to its Fourier transfor[4] $\mathfrak{U}(k, y)$, let us write equation (2.7) in the following form

$$\frac{\partial^2}{\partial y^2} \mathfrak{U} - k^2 \mathfrak{U} = -ik\sigma v \langle \mathfrak{B}_z \rangle. \tag{2.9}$$

Here $\langle \mathfrak{B}_z \rangle$ is the averaged z-component of the Fourier transform of the magnetic vector. The magnetic field in a bed induced by eddy currents can be expressed by the current density using Biot-Savart law. Let us introduce the notation B_z^+ for the half-sum of the z-component of this field calculated at $z = 0$ and $z = -T$. At small values of T when the average (2.6) may be used instead of the true current desntiy, for a Fourier transform of value of B_z^+, one can find from the Biot-Savart formula the equality

$$\mathfrak{B}_z^+(k, y) = \frac{\mu_0 T}{4\pi} \hat{D} \left[\pi T \mathfrak{U}(k, y) - 2 \int_0^1 \mathfrak{U}(k, y') K_0(|k| \cdot |y - y'|)\, dy' \right] + \mathfrak{B}_z^0. \tag{2.10}$$

Here $\mathfrak{B}_z^0$ is the Fourier transform of an external source and D is a differential operator:

$$\hat{D} = \partial^2 / \partial y^2 - k^2. \tag{2.11}$$

To find the integral equation which determines function $\mathfrak{U}$, it remains to transform the right side of equality (2.9). According to equation (1.6), the z-component of the magnetic field in the Fourier transform satisfies the equation

$$-k^2\mathfrak{B}_z+\frac{\partial^2\mathfrak{B}_z}{\partial y^2}+\frac{\partial^2\mathfrak{B}_z}{\partial z^2}=-ikv\sigma\mu_0\mathfrak{B}_z. \tag{2.12}$$

The right side of the equation becomes larger at large values of σv realized in the suspension systems under consideration. Moreover, the derivatives with respect to coordinate z become larger due to the shallowness of the thickness of the skin layer. This permits one to assume that one can disregard the first two terms of the left side[5] in equation (2.12) and one can write this equation in the form

$$\frac{\partial^2\mathfrak{B}_z}{\partial z^2}=p^2\mathfrak{B}_z,\quad p=(-ikv\sigma\mu_0)^{1/2}. \tag{2.13}$$

Further writing the general solution of this equation in the form $\mathfrak{B}_z=C_1\exp(pz)+$ $+ C_2\exp(-pz)$ with arbitrary constants C_1 and C_2 and then calculating the averaged value of $\mathfrak{B}_z$ and the half-sum of values $\mathfrak{B}_z$ at z = 0 and z = -T, we arrive at the relation

$$\langle\mathfrak{B}_z\rangle=\frac{1}{T}\xi\mathfrak{B}_z^+,\quad \xi=\frac{2}{p}\,\mathrm{th}\left(\frac{pT}{2}\right). \tag{2.14}$$

If the derived expression for $\langle\mathfrak{B}_z\rangle$ is now substituted into the right side of formula (2.9), then equations (2.9) and (2.10) may be regarded as a system of equations for $\mathfrak{B}_z^+$ and $\mathfrak{U}$. However, it turns out that both these equations can be reduced to a single equation. This is achieved in [15] by using the following procedure. Let us introduce the function

$$\mathfrak{U}_0(k,y)=-\frac{iv\sigma\xi}{2T}\int_0^l\mathfrak{B}_z^0(k,y')[\mathrm{sh}(k|y-y'|)-\mathrm{sh}(ky-ky')-2\frac{\mathrm{sh}\,ky'}{\mathrm{sh}\,kl}\mathrm{sh}\,k(l-y)]dy', \tag{2.15}$$

which satisfies the equation $(\partial^2/\partial y^2-k^2)\mathfrak{U}=-ikv\sigma\xi\mathfrak{B}_z^0/T$ and boundary conditions $\mathfrak{U}_0=0$ at y = 0 and y = 1. The use of equations (2.9)-(2.11) and (2.14) now yields

$$\left(1+\frac{ikv\mu_0\sigma\xi T}{4}\right)\mathfrak{U}(k,y)=\mathfrak{U}_0(k,y)+\frac{ikv\mu_0\sigma\xi}{2\pi}\int_0^l\mathfrak{U}(k,y')K_0(|k|\cdot|y-y'|)dy'+\varphi(k,y), \tag{2.16}$$

where ϕ satisfies the equation $(\partial^2/\partial y^2-k^2)\varphi=0$.

Function V in (2.8) is determined with accuracy to the additive constant. The condition of equality of full current to zero through the cross-section of the bed permits one to determine the indicated constant so that functions V and $\mathfrak{U}$ are equal to zero at y = 0 and y = 1. Now writing the general solution for ϕ in the form $\alpha(k)\mathrm{sh}(ky) + \beta(k)\mathrm{ch}(ky)$ and determining the values of $\alpha(k)$ and $\beta(k)$ from the condition that $\mathfrak{B}_z$ is equal to zero at y = 0 and y = 1, we finally find

$$\mathfrak{U}(k,y)=\frac{2ikv\sigma\xi\mu_0}{\pi(4+ikv\sigma\xi\mu_0 T)}\int_0^l \mathfrak{U}(k,y')\Xi(k,y,y')\,dy'+\frac{4}{4+ikv\sigma\xi\mu_0 T}\mathfrak{U}_0, \qquad (2.17)$$

where

$$\Xi(k,y,y')=K_0(|k|\cdot|y-y'|)-[K_0(|k|y')\mathrm{sh}(k|l-y|)+ +K_0(|k|\cdot|l-y'|)\,\mathrm{sh}\,ky]/\mathrm{sh}\,kl.$$

Equality (2.17) is the desired Fredholm integral equation of second kind for the Fourier transform of the scalar current function. After determination of function V, the averaged density of the eddy currents is found by formula (2.8) and the force acting on the suspension is then determined by a quadrature of type (1.8). However, it is more convenient even in this case to express the force by functions in Fourier representation (see the derivation of formula (2.5) in this survey). Equation (2.17), being one-dimensional, is significantly simpler than equations of type (2.3).

Development of the outlined approach with respect to systems of more complex profile is given in [16], while a procedure important for practical calculations which accelerates derivation of the eigenfunction of the integral operator in equation (2.17) and which is based on separate calculation of the eigenfunction with even and odd summetry with respect to y regarding the center of the strip y = 1/2 on the basis of corresponding splitting of the initial integral operator, is described in [17].

The method of considering the limited dimensions of the bed is also given in [13], although use of it is demonstrated there (in terms corresponding to the levitation problem) only for the case when the width of the bed exceeds the transverse dimensions of the magnet by a value significantly greater than the height of the suspension.

The method of solving the problem of electrodynamic levitation on the basis of potential theory should be noted. In this method the Fourier transform of the magnetic field (2.1) is represented by contour integrals along the boundary of the domain of conductivity S and the integral expressions include unknown functions from the point on boundary S, while the kernels of the integrals are selected so that the equations for the magnetic field are automatically satisfied. Formulation of boundary conditions permits one to find a system of one-dimensional integral equations for the desired functions. The advantages of this method are essentially

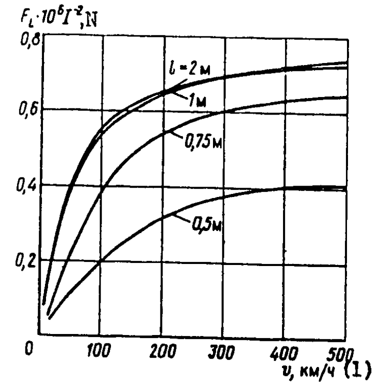

Figure 3. Dependence of Lift on Speed from [17] at 2a = 0.5 meter, 2b = = 3 meters, h = 0.3 meter, T = 2.54 cm and σ = 2.5·10^7 1/ohms·m

Key:
1. km/hr

obvious: the method is accurate and leads to one-dimensional rather than two-dimensional integral equations. However, numerical realization of this method of solving the problem encounters difficulties specifically related to the characteristics of the kernels in the integrals and no calculations have yet been made on the basis of the described method.

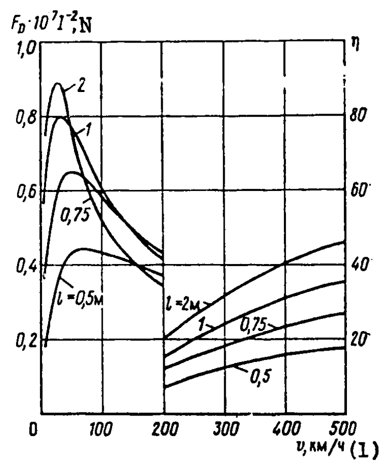

Figure 4. Dependence on Speed for Decelerating Force F_D (at v < 200 km/hr) and for Levitation Quality η (at v < 200 km/hr) [17] (the parameters of the system are the same as for Figure 3)

Key:
1. km/hr

The approximate numerical solution of the levitation problem can be found by the method of expansion of the source field and eddy currents in the bed to multidimensional Fourier series. This method is essentially very simple since differential equations of type (1.6) change to simple algebraic relations for individual Fourier harmonics, but numerical realization of this method requires solution of systems of linear equations of very high order found upon formulation of the boundary conditions. The disadvantage of the method is that the use of a Fourier series leads to the need to eliminate the effect of periodicity, called a discrete Fourier expansion. To do this, it is required that the value of the periods be high compared to the dimensions of the magnet and the transverse dimensions of the track structure. However, the role of high harmonics increases sharply in this case and calculations with high accuracy becomes difficult. Nevertheless, the use of a high-speed digital computer having large memory permits one to realize this method [18].

Let us present some numerical results for illustration. The finiteness of the width of the bed is reflected in two respects: the value of lift and decelerating force varies somewhat and a lateral force also occurs (with asymmetrical arrangement of the suspension magnet over the conducting strip). The type of dependence of lateral force and also additives to the lift and decelerating forces on the transverse displacement of the magnet is presented in [18]. A number of other data are presented in the same source with respect to the characteristics of levitation with regard to the finite width of the bed. We shall limit ourselves to illustration of the dependence of lift and decelerating force and also of levitation quality on speed with different width of the bed [17] (Figures 3 and 4).

According to the given data, consideration of the transverse dimensions of the bed is significant: the levitation quality at high travel speeds is appreciably dependent on the transverse dimensions of the bed even with a ratio of the width of the bed to the transverse dimensions of the vehicle magnet on the order of four. Nevertheless, the use of approximation of an infinitely wide bed is permissible with rough estimates of the forces and in this case Figures 3 and 4 can serve for an approximate estimate of the error related to this approximation.

More detailed numerical data related to parameters of suspension systems with regard to finite width of the bed can be found in the literature, references to which are given above.

3. Levitation using discrete track components. The use of discrete components in the form of individual turns along the travel route was suggested in the earliest papers on electrodynamic suspension. The method of calculating levitation above these structures is outlined in [19]. It is also suggested in the same source that a track structure of the "rope ladder" type be used as a possible modification of the discrete system (let us call a structure of this type in this survey a multilink chain, following the authors' terminology).

Let us separate discrete track structures into coil, zero-flow and multilink as a function of the nature of the inductive contact between the track circuits and the conducting circuits of the vehicle. These types of structures are shown in Figure 5. Structures a and b consist of individual circuits and a structure of type c has the form of two longitudinal buses connected by transverse jumpers. The moving circuit of the vehicle electromagnet is located between the turns of the track structure b or above the track components of structures a and c[6].

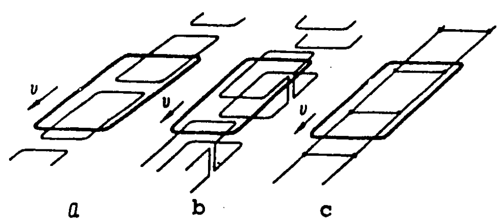

Figure 5. Diagrams of Suspension Using Discrete Track Structures: a--coil bed; b--zero-flow system; c--multilink chain

Reference [19] contains an inaccuracy related to selection of the type of dependence on the coordinates and time for interlinkage between the electromagnet circuit and the track circuit. A different approach to calculation of levitation for discrete structures free of the indicated deficiency is outlined below [20].

Let us first consider a track structure of type a and b (Figure 5). Let us number the links of the track structure by sequential integers k and some aribtrary circuit corresponds to the number k = 0. Let us pose the problem of finding current I(t) in this circuit. Let us introduce the following notations: I_0 is the current in the electromagnetic circuit on the vehicle, M(t) is the mutual inductance between the circuit k = 0 and the vehicle circuit, L is the natural inductance of the track circuit, R is its resistivity, M_k is the mutual inductance between the zero track circuit (k = 0) and the circuit with number k ≠ 0 and $I_k(t)$ is the current in the circuit with number k.

The following equation is valid for current I(t) in the zero track circuit

$$L\frac{dI}{dt}+RI+\sum_{k=1}^{\infty}\left(M_k\frac{dI_k}{dt}+M_{-k}\frac{dI_{-k}}{dt}\right)=-I_0\frac{dM}{dt}. \quad (3.1)$$

Kirchhoff's laws must be taken as a basis when considering a structure of type c. For unanimity, let us also call the link of this structure limited by adjacent transverse jumpers a track structure. If the notations $R_\perp$ and $R_{||}$ are accordingly used for the resistance of the transverse jumper and the section of longitudinal bus between two adjacent jumpers, the circuit impedance is equal to $R = 2(R_\perp + R_{||})$ and for current I in the longitudinal bus we find the equation

$$L\frac{dI}{dt}+RI-R_\perp(I_1+I_{-1})+\sum_{k=1}^{\infty}\left(M_k\frac{dI_k}{dt}+M_{-k}\frac{dI_{-k}}{dt}\right)=-I_0\frac{dM}{dt}. \quad (3.2)$$

Here I_k is the current in the longitudinal bus of the k-th circuit.

The current in the transverse jumper which separates the circuits with numbers k and k + 1 is equal to $K_{k+1} - I_k$. We note that the values of $M_1 = M_{-1}$ in (3.2) essentially do not have the meaning of mutual inductance coefficients since circuits with the number k = 0 and k = ± 1 have common current omponents. The value of $M_{\pm 1}$ is nevertheless easily found from Kirchhoff's law and is expressed by a combination of the mutual inductance of straight sections of the circuit.

To solve equations (3.1) and (3.2), let us use the Fourier transform:

$$I(t)=\int_{-\infty}^{\infty}\mathcal{J}(\omega)\exp(i\omega t)\,d\omega. \tag{3.3}$$

With uniform vehicle motion at speed v, current $I_k(t)$ in the circuit with number k corresponds to current I shifted by time kT = kl/v in the zero circuit, where l is the distancne between the centers of adjacent track circuits. Thus, the Fourier transforms of these currents are related by the relation $\mathcal{J}_k(\omega)=\exp(ik\omega T)\cdot\mathcal{J}(\omega)$. Equations (3.1) and (3.2) lead to the following expression for the Fourier transform of the current in the zero circuit:

$$\mathcal{J}(\omega)=-i\omega I_0\mathcal{M}(\omega)\left[R-2r\cos\omega T+i\omega L+2i\omega\sum_{k=1}^{\infty}M^k\cos k\omega T\right]^{-1}. \tag{3.4}$$

Here $\mathcal{M}(\omega)$ is the Fourier transform of the function M(t) and parameter r is equal to zero for track structures of type a and b, described by equation (3.1), and is equal to $R_\perp$ for a structure of type c. Using (3.3), we find the current I:

$$I(t)=-iI_0\int_{-\infty}^{\infty}\frac{\omega\mathcal{M}(\omega)\exp(i\omega t)\,d\omega}{R-2r\cos\omega T+i\omega\left(L+2\sum_{k=1}^{\infty}M_k\cos k\omega T\right)}. \tag{3.5}$$

Formula (3.5) is inconvenient for practical calculations for two reasons: the integral expression contains the Fourier transform $\mathcal{M}$;rather than the mutual inductance M itself; the presence of the multiplier exp ($i\omega t$) leads to difficulties in calculation of the quadrature. Therefore, I(t) may be represented in different form. Use of the convolution in the Fourier representation yields

$$I(t)=I_0\int_{-\infty}^{\infty}M(t-s)\,\Phi(s)\,ds, \tag{3.6}$$

where

$$\Phi(s)=\frac{-i}{2\pi}\int_{-\infty}^{\infty}\frac{\omega\exp(i\omega s)\,d\omega}{R-2r\cos\omega T+i\omega\left(L+2\sum_{k=1}^{\infty}M_k\cos k\omega T\right)}. \tag{3.7}$$

Then using the notations

$$\Phi_0(s)=-\frac{1}{2\pi L}\int_{-\infty}^{\infty}\exp(i\omega s)\frac{d\omega}{G(\omega)},\quad G(\omega)=1+2\sum_{k=1}^{\infty}\frac{M_k}{L}\cos k\omega T, \tag{3.8}$$

$$\Phi_1(s)=\frac{1}{2\pi L}\int_{-\infty}^{\infty}\frac{(1-\zeta\cos\omega T)\exp(i\omega s)\,d\omega}{G(\omega)\,[1-\zeta\cos\omega T+i\omega\tau G(\omega)]}, \tag{3.9}$$

we represent the function $\Phi(s)$ in the form of the sum $\Phi = \Phi_0 + \Phi_1$. The following notations are used in formula (3.9): $\tau = L/R$ and $\zeta = 2r/R$.

As indicated by calculations, sufficient accuracy is achieved in most cases when the inductive coupling only between adjacent track circuits is considered. In this case only the term M_1 is maintained in function G in (3.8) and (3.9). Let us further use the notation $q = -2M_1/L$. Since $|q| \ll 1$, we consider only terms of order q in formula (3.8):

$$\Phi_0(s)\simeq-\frac{1}{2\pi L}\int_{-\infty}^{\infty}(1+q\cos\omega T)\exp(i\omega s)\,d\omega=-\frac{1}{L}\Big\{\delta(s)+ +\frac{q}{2}[\delta(s+T)+\delta(s-T)]\Big\}. \tag{3.10}$$

For the value of Φ_1 we find

$$\Phi_1(s)=-\frac{i}{2\pi L\tau}\int_{-\infty}^{\infty}\frac{(1+q\cos\omega T)\,(1-\zeta\cos\omega T)\exp(i\omega s)}{(\omega-\omega_0)\,(1-\gamma\cos\omega T)}\,d\omega, \tag{3.11}$$

where $\omega_0=i/\tau$, $\gamma=(q\omega-\zeta\omega_0)/(\omega-\omega_0)$.

Since $|\gamma| < 1$, then using the equality

$$(1-\gamma\cos\omega T)^{-1}=\sum_{m=-\infty}^{\infty}\beta_m\exp(im\omega T),$$

where

$$\beta_m=\sum_{n=0}^{\infty}C^{n}_{2n+|m|}\left(\frac{\zeta}{2}\right)^{2n+|m|},$$

we can rewrite the expression for $\Phi_1(s)$ in the form

$$\Phi_1(s)=\frac{-i}{2\pi L\tau}\sum_{l=-2}^{2}p_l\sum_{m=-\infty}^{\infty}\sum_{n=0}^{\infty}C^n_{2n+|m|}\left(\frac{q}{2}\right)^{2n+|m|}\times$$
$$\times\int_{-\infty}^{\infty}\frac{(\omega-\zeta\omega_0/q)^{2n+|m|}}{(\omega-\omega_0)^{2n+|m|+1}}\exp[i\omega(mT+lT+s)]d\omega. \quad (3.12)$$

The following notations are used in (3.12): $p_0 = 1 - q\zeta/2$, $p_1 = p_{-1} = (q - \zeta)/2$ and $p_2 = -p_{-2} = -q\zeta/4$. The integral in (3.12) can be calculated by residue theory, after which we finally find

$$\Phi_1(s)=\frac{1}{L\tau}\sum_{l=-2}^{2}p_l\sum_{m=-\infty}^{\infty}\theta(mT+lT+s)\exp[-(mT+lT+s)/\tau]\times \quad (3.13)$$
$$\times\sum_{n=0}^{\infty}C^n_{2n+|m|}\left(\frac{q}{2}\right)^{2n+|m|}\sum_{k=0}^{2n+|m|}\frac{1}{k!}C^k_{2n+|m|}\left[\frac{(mT+lT+s)(\zeta-q)}{q\tau}\right]^k.$$

Here the symbol θ denotes a function equal to zero for negative independent variables and to one for positive independent variables.

The series with respect to m and n are rapidly convergent and thus the use of formulas (3.6), (3.10) and (3.13) permits one to calculate current I in the track circuit.

The method described above is accurate within the framework of the conditions used. However, one can find an approximate expression having very simple structure for the function $\Phi(s)$ in (3.6). Let us assume that the sum over k in (3.7) is limited to terms $k \leqslant N$ ($N = 1$ or $N = 2$ in practical calculations). Let us rewrite relation (3.7) in the following identical form:

$$\Phi(s)=-\frac{1}{2\pi L}\int_{-\infty}^{\infty}\exp(i\omega s)\,d\omega-\frac{1}{2\pi L}\int_{-\infty}^{\infty}\frac{\omega_0\exp(i\omega s)}{\omega-\omega_0}d\omega. \quad (3.14)$$

Here the value of ω_0 is determined by the relation

$$\omega-\omega_0=\omega+\frac{2\omega}{L}\sum_{k=1}^{N}M_k\cos\omega kT-iR/L. \quad (3.15)$$

The first integral in (3.14) yields $-\delta(s)/L$ and the second integral can be calculated on the basis of residue theory. The approximate value for the root of equation (3.15), closest to the point $\omega = 0$, has the value

$$\omega_0 = iR \Big/ \left(L + 2\sum_{k=1}^{N} M_k \operatorname{ch}\frac{kRT}{L}\right), \quad \frac{M_k}{L}\operatorname{ch}\frac{kRT}{L} \ll 1, \quad k \leqslant N. \tag{3.16}$$

Now calculating the integral in (3.14) from the residue at this point,[7] we finally find

$$\Phi(s) = \frac{1}{L}\{-\delta(s) + [\theta(s)\exp(-s/\tau_M)]/\tau_M\}, \tag{3.17}$$

where $\tau_m = i/\omega_0$.

Current I(t) in the track circuit, according to formula (3.6), is now written in the following simple form:

$$I(t) = -\frac{I_0}{L}\left[M(t) - \frac{1}{\tau}\int_0^\infty M(t-s)\exp(-s/\tau_M)\,ds\right]. \tag{3.18}$$

The force acting on the vehicle is found from the derived value of current I(t) by the formula

$$\mathbf{F}(t) = I_0 \sum_{k=-\infty}^{\infty} I(t-kT)\,\mathrm{grad}\,M_k^0, \tag{3.19}$$

where M_k^0 is the coefficient of mutual inductance between the vehicle electromagnet and the track circuit with number k, calculated with regard to the position of the vehicle at moment of time t.

The value of F(t) is a periodic function with period T. Values averaged by period may be introduced for lift and decelerating forces (F_L and F_D)

$$\langle F_{L,D}\rangle = \frac{1}{T}\int_0^T F_{L,D}(t)\,dt, \tag{3.20}$$

after which the levitation quality can be determined by the relation $\eta = \langle F_L\rangle/\langle F_D\rangle$.

Both methods of calculating current I(t)--the exact and the approximate--and in combination with formulas (3.19) and (3.20) fully solve the problem of calculating the levitation characteristics for discrete track structures. The described method is comparatively simple and is far superior in convenience of numerical realization to the methods based on direct solution of systems of differential equations for current in individual track circuits [21].

A number of interesting results related to discrete track structures have been found by colleagues of the Novocherkassk Polytechnical Institute [22], the

Leningrad Institute of Railway Transport Engineers [23] and others. It is impossible within the framework of the survey to dwell on the content of these investigations, mainly related to problems of calculation and optimization of suspension parameters.

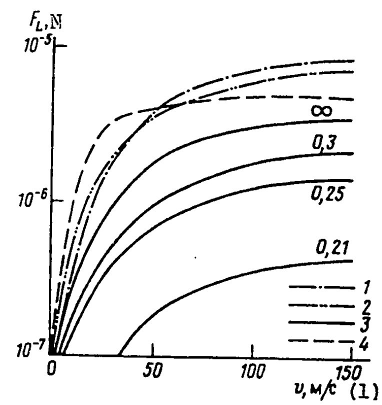

Figure 6. Dependence of Lift (the values of lift are given for current I = 1 A) on Speed for Discrete Type Track Structures: 1--multilink chain; 2--coil bed; 3--zero-flow system (the distance between turns of the track circuit is indicated in meters on the curves); 4--continuous track structure (T = 4 cm, h = 0.1 meter) [20]

Key:
1. m/s

The levitation characteristics for discrete track structures are presented in Figures 6 and 7. The given values correspond to the following parameters of the suspension system: length of track circuit is 1.8 meters, the width of the track circuit and the vehicle circuit is 0.6 meter, the spacing of the track circuit is 2 meters, the length of the vehicle magnet is 3 meters, the height of suspension is 10 cm, the cross-sectional diameter of the track circuit is 4 cm and the resistivity of the material of the track circuits is $3 \cdot 10^{-8}$ ohms·m. The dependence for a suspension with continuous aluminum strip 4 cm thick is presented in Figures 6 and 7 for comparison. We note that a height of suspension of 10 cm corresponds to distance between zero turn of the track structure and the vehicle circuit for a zero-flow system (Figure 5, b). The values along the y axis are plotted in logarithmic scale in Figures 6 and 7.[8]

We note that in the considered case, as in the version of a continuous bed, zero-flow systems provide high levitation quality (due to the low level of decelerating force). However, when estimating the real value of the levitation quality of these systems, one must take into account additional losses to eddy currents excluded from consideration in the described approximation of linear circuit theory. According to recent calculations, the indicated additional losses lead to a significant reduction of levitation quality [24].

Based on the outlined methods, one can compare the characteristics of different suspension systems, one can achieve partial optimization and so on. However, these problems are not included in this survey as going beyond the framework of the calculating-methodical problems considered in this paper.

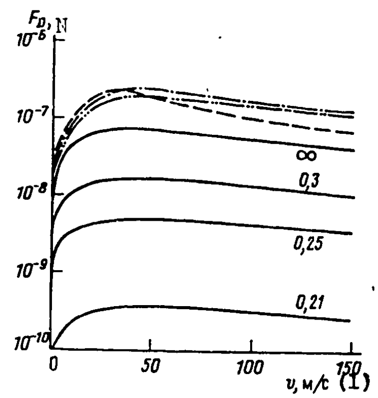

Figure 7. Dependence of Decelerating Force on Speed for Discrete Type Track Structures (the notations are the same as for Figure 6)

Key:
1. m/s

Conclusions. The outlined calculating methods encompass the aggregate of a significant range of problems related to calculation of the electrodynamic suspension characteristics. They are suitable for use not only in calculation of levitation but also in calculation of stabilization and dynamics of motion. Thus, the stabilization characteristics based on the use of shaped strips or discrete track circuits can be calculated by using the formulas given above in the corresponding sections; the initial equation for general problems of dynamics is the nonstationary equation of magnetic field diffusion presented in section 1 (one of the simple examples is considered in [25]).

However, the limited framework of the survey did not permit us to dwell on the problem of the stability of suspension. As is known, suspension based on discrete track structures is unstable at high speed with respect to vertical oscillations [3]. Similar instability also occurs for continuous track structures, but the use of mechanical dampers permits one to suppress this instability. The corresponding problems are considered in detail in [26].

Further development of electrodynamic levitation theory should proceed in the direction of an ever greater number of factors which were not taken into account during the initial period of the investigation: the total interaction of components of the track structure which provide levitation, stabilization and thrust, the effect of unevenness of laying track components and the effect of external perturbing factors and the dynamics of motion.

Problems of optimization in different postulations are of great interest at the present stage of development of the theory and technology of electrodynamic suspension. Since the real picture of the motion of a magnetic vehicle is very complicated (with regard to the dynamics of motion, unevenness of the bed and so on), it is difficult to formulate the criteria for optimization themselves. Only possible approaches to solution of the indicated problem have as yet been determined.

The problems noted above are complicated and they should be solved with simultaneous full-scale and model experiments. We note in this regard the feasibility of using the impedance method of measuring levitation forces [27], which, being simple and inexpensive, as shown by practice, permits one to achieve rather reliable results, and also the use of the method of simulation based on the use of rotating drums [28] with regard to its capabilities analyzed in [29].

Investigation of the problems enumerated above is a necessary step in developing an efficient system of high-speed surface transport.

BIBLIOGRAPHY

1. "Nazemnyy transport 80-kh godov" [Surface Transport of the 1980s], edited by R. M. Thornton, Mir, 1974.

2. Avatkov, Ye. S., "High-Speed Transport" "Seriya Elektrooborudovaniye transporta (Itogi nauki i tekhniki)" [Series Electrical Equipment of Transport (Results of Science and Technology)], Vol 3, Moscow, Izd-vo VINITI AN SSSR, 1975.

3. "The Current State of Research and Developments of Rolling Stock With Magnetic Levitation," GORODSKOY TRANSPORT: EKSPRESS-INFORMATSIYA, VINITI, No 37, 1976.

4. "The Current State of Research in the United States in the Field of Magnetic Levitation Systems Which Utilizes the Mutual Repulsive Force," GORODSKOY TRANSPORT: EKSPRESS-INFORMATSIYA, VINITI, No 30, 1976.

5. Lee S.-W. and R. Menendez, "Force on Current Coils Moving over a Conducting Sheet With Applications to Magnetic Levitation," PROCEEDINGS OF IEEE, Vol 62, No 5, 1974.

6. Kochetkov, V. M., "Calculating the Levitation Characteristics During Electrodynamic Suspension of High-Speed Vehicles," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 6, 1977.

7. Reitz, J. R. and L. C. Davis, "Force on a Rectangular Coil Moving Above a Conducting Slab," JOURNAL OF APPLIED PHYSICS, Vol 43, No 4, 1972.

8. Kochetkov, V. M., "Calculating the Forces Acting on an Electrodynamic Suspension of Arbitrary Configuration," ELEKTRICHESTVO, No 9, 1978.

9. Treshchev, I. I., V. M. Kochetkov and Yu. V. Yudakov, "Some Problems of the Theory of Electrodynamic Suspension of High-Speed Surface Transport Vehicles," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 8, 1977.

10. Urankar, L. and J. Mierecke, "Theory of Electrodynamic Levitation With a Continuous Sheet Track," Part 1, APPLIED PHYSICS, No 2, 1973.

11. Kim, K. I. and A. A. Mikirtichev, "A Magnetic Field in a Hybrid Type Levitation System," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 8, 1977.

12. Kochetkov, V. M., "Maximum Achievable Levitation Quality for Electrodynamic Suspension," in "Itogi i perspektivy sozdaniya vysokoskorostnogo nazemnogo transporta (VSNT)" [The Results and Prospects for Development of High-Speed Ground Transport], Report Topics of Second All-Union Scientific and Technical Conference, Novocherkassk, Moscow, Informelektro, 1980.

13. Tozoni, O. V., "Analytical Calculation of the Electromagnetic Process in a Linear Motor," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 5, 1977.

14. Tozoni, O. V. and N. S. Nikolayeva, "Calculation of Suspension Systems With Magnetic Levitation," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 5, 1978.

15. Astakhov, V. I., "The Motion of a Conducting Strip in a Magnetic Field," IZVESTIYA VUZOV, ELEKTROMEKHANIKA,NNo 8, 1977.

16. Astakhov, V. I., T. M. Vyal'tseva, G. A. Kirsanova, A. I. Komarets and N. M. Novogrenko, "Analysis of Electrodynamic Suspension (EDP) With Complex Track Structures," in "Vysokoskorostnoy nazemnyy transport," [High-Speed Ground Transport], Novocherkassk, 1979.

17. Astakhov, V. I., Yu. A. Bakhvalov, T. M. Vyal'tseva and G. A. Kirsanova, "Methods of Accelerating Calculation of the Problem on the Motion of a Conducting Strip in a Magnetic Field," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 3, 1979.

18. Ooi, B.-T., "Transverse Force in Magnetic Levitation With Finite Width Sheet Guideways," IEEE TRANSACTIONS ON PAS, Vol 94, No 3, 1975.

19. Ono, Y., M. Ivamoto and T. Yamada, "Characteristics of a Magnetic Suspension System and Thrust Using Superconducting Magnets for High-Speed Trains," in "Nazemnyy transport 80-kh godov," edited by R. M. Thornton, 1974.

20. Hoppie, L. O., "Electromagnetic Lift and Drag Forces on a Superconducting Magnet Propelled Along a Guideway Composed of Metallic Loops," Proceedings of Applied Superconductivity Conference, Annapolis, Maryland, 1972.

21. Omel'yanenko, E. I., V. I. Bocharov, E. I. Dolgosheyev, V. G. Naboka and A. A. Sergiyenko, "Method of Calculating the Lift and Decelerating Force of Electrodynamic Suspension With Discrete Track Structure," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 8, 1977.

22. Bakhvalov, Yu. A. and V. A. Burtsev, "Calculating the Force Interactions in an Electrodynamic Suspension System and the Trends of High-Speed Ground Transport With Discrete Track Structure," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 11, 1979.

23. Bayko, A. V., V. V. Baykov, K. E. Voyevodskiy and V. M. Kochetkov, "Optimizatsiya parametrov sistemy podveshivaniya VSNT c diskretnymi putevymi strukturami" [Optimizing the Parameters of a VSNT Suspension System With Discrete

Track Structures], Moscow, deposited at TsNIITEI of MPS on 30 June 1980, No 1047.

24. Voyevodskiy, K. E., "Effect of Eddy Currents in the Track Structure on the Levitation Characteristics of Discrete Type Zero-Flow Systems," in "Itogi i perspektivy sozdaniya vysokoskorostnogo nazemnogo transporta (VSNT)": Report Topics of Second All-Union Scientific and Technical Conference, Novocherkassk, Moscow, Inform-elektro, 1980.

25. Kochetkov, V. M., "The Vertical Instability of Electrodynamic Suspension," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 5, 1979.

26. Bayko, A. V., K. Ye. Voyevodskiy and V. M. Kochetkov, "Vertical Unstable Stability of Electrodynamic Suspension of High-Speed Ground Transport," CRYOGENICS, No 5, 1980.

27. Iwasa, Y., "Electromagnetic Flight Stability by Model Impedance Simulation," JOURNAL OF APPLIED PHYSICS, Vol 44, No 2, 1973.

28. Vasil'yev, S. V., A. I. Kiyenko, A. V. Kurakin and I. D. Lupkin, "Laboratory Model for Investigation of Electrodynamic Suspension of High-Speed Ground Transport," in "Vysokoskorostnoy nazemnyy transport" [High-Speed Ground Transport], Novocherkassk Polytechnical Institute, Novocherkassk, 1979.

29. Kochetkov, V. M., Ye. F. Makarov, A. V. Cherevatyy and V. V. Baykov, "Analysis of the Conformity of Levitation Parameters of Rotary and Linear Models of Electrodynamic Suspension," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 11, 1971.

FOOTNOTES

1. Here and further values in Fourier representation are written in Gothic script if there are no special stipulations.

2. The indicated dependence is valid if the depth of the skin layer becomes less than the thickness of the conducting bed. The law of a decrease of a decelerating force with an increase of v is found from (1.19) or (1.20) if δ is expanded with accuracy to first power $k^2/(\mu_0\sigma v k_x)$. However, under ordinary conditions $\delta \gtrsim T$ and in this case the levitation quality depends on speed as v^{-1} (theory of a thin bed [7]).

3. Here A is an arbitrary constant. Upon numerical integration, the result is more accurate if one selects $A \approx 1/L_x$, where L_x is the arbitrary dimension of the source (solenoid).

4. The coordinate system of a quiescent bed is used in this paper and the Fourier transform is determined by an equality of type (1.9). The values of k and v in subsequent formulas are different in this regard from those used in [15].

5. Numerical estimates of the value of $\gamma = k/\sigma v \mu_0$ may serve as partial justification of the assumption made. The calculation yields $|\gamma| \ll 1$ for k that a significant contribution to quadratures of type (2.5) and thus the first

term of the left side in (2.12) is negligible compared to the term of the right side. Since coordinates x and y in the problem under consideration are approximately equivalent, there is the basis to assume that the term $\partial^2 B_z/\partial y^2$ is also small.

6. We note that, besides version b, a zero-flow system can have a coil track structure a, but in this case the conducting circuit of the electromagnet should have the shape of one of the circuits of type b and should encompass the turns of the track structure upon motion. Subsequently, both modifications of a zero-flow system are naturally described in the framework of a single theory.

7. Equation (3.15), being transcendent, has an infinite number of roots, but as shown by analysis, consideration of the root of (3.16) is sufficient in many cases since the remainders in the remaining poles are small in value. Even so, the use of the described approximate method requires caution and it is always desirable to check the permissibility of considering only a single root for a specific set of parameters which control a suspension system.

8. Reference [20], from which the given functions were borrowed, contains an inaccuracy related to the rule of calculation of the force acting on the conducting circuit (the requirement that current be maintained upon differentiation of the mutual inductance was not taken into account). Consideration of this inaccuracy somewhat alters the values of the forces, but the qualitative form of the curves is maintained.

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OPTIMIZATION OF MAGNETIC SUSPENSION AND ANALYSIS OF VEHICLE DYNAMICS

Moscow IZVESTIYA AKADEMII NAUK SSSR: ENERGETIKA I TRANSPORT in Russian No 1, Jan-Feb 81 pp 113-120

[Article by L. P. Poberezhskiy, G. I. Renzhin and Yu. V. Tyurin, Moscow]

[Text] Development of transport on magnetic suspension requires optimization of vehicle, track, suspension equipment, stabilization and drive indicators [1].

It is difficult to formulate and solve very complicated, multiparametric problems of optimization related to a number of restrictions dictated by technology as variational problems. It is also difficult to develop machine design algorithms in which the set of input data would figure, while the design solution would be the output.

The use of digital computers for optimum design may be faster in the dialogue mode when the developer may extract the parameters of the system and consider the effect of these variations on the selected quality indicators. This should stimulate development of adequate mathematical models which would permit one to cover the path to more important indicators, which are final indicators at the considered stage of development. Such indicators at the given stage may apparently be regarded as some quantitative characteristics of motion stability at a given level of external disturbances and required conditions of comfort [1].

No less difficult than optimization is analysis of the effectiveness of results achieved. The capability of visualizing vehicle motion by using external devices of modern digital computers of the graphic display type open up specific prospects in this regard. This tool specifically permits one to see the possible points of contact of the vehicle and track components upon analysis of motion stability.

The enumerated problems are considered below on the examples of optimizing a suspension system based on permanent repulsion magnets (SPMO) and graphic visualization of the disturbed vehicle motion, equipped with this type of system, is used.

Greater attention is now being devoted to the electromagnetic [1] and electrodynamic [2] methods of suspension. However, there are also prospects for using systems with permanent magnets, at least in special transport devices or beds. Systems with permanent magnets were developed both in the USSR and abroad [3, 4]. Many structural components ("magnetic skis" [1]) and means of mathematical description of disturbed motion are sufficiently general for all methods of suspension.

The system of indicators. The ratio $\bar{F}_y$ of the developed lift F_y to the weight of the magnet G_m was considered until now as the main indicator of SPMO. However, consideration of a wider range of indicators is required to provide the necessary indicators of vehicle motion such as comfort and reliability, deformation of the track structure and the supporting frame and so on. Specifically, one may consider the magnetic stiffness tensor (derivatives of forces and moments due to possible displacements) and especially the individual components of this tensor: vertical and lateral gradients of lift $\partial F_y/\partial y$ and $\partial F_y/\partial z$, the gradient of the destabilizing horizontal (lateral) force $\partial F_z/\partial z$, the lateral force F_z for some values of vehicle or track displacement in the horizontal plane (specifically, upon displacement of tolerance by an order of magnitude on the accuracy of laying track) and lateral displacement at which lift changes sign ("adhesion" of the vehicle) and lift per unit area of suspension system and per unit length or width of the system.

One may also consider the indicators which characterize the engineering realizability of the magnetic system, specifically, the possibility of manufacturing it from standard components, the sensitivity of the indicators named above to inaccuracies of executing the system and the possibility of regulation and adjustment of the system parameters. Let us point out that systems made up of rectangular components with direction of the magnetization vector along the narrowest side of a block are preferable according to concepts of technology.

Mathematical models of the suspension system. The complete model of interaction of permanent magnets should take into account variation of the orientation of the magnetization vector p due to the effect of the total magnetic field. However, numerical analyses show [5] that although reorientation of p in some parts of the magnetic system can be very appreciable, this has little effect on the total forces.

Therefore, to calculate the forces let us use the hypothesis on the constant orientation p and let us use the known expression [6]:

$$d\mathbf{F}_{12}=(d\mathbf{p}_1\nabla)\mathbf{B}_2, \tag{1}$$

where p_1 and B_2 are the magnetization vector of the magnet 1 and the field induction created by magnet 2.

The expression for the forces of interaction of two long rectangular strips can be found by integration of expression (1):

$$\mathbf{F}=\mu_0\mathbf{J}^2 b h_1 \mathbf{f}, \tag{2}$$

$$f_y=\sum_{i=1}^{4}\sum_{j=1}^{4}(-1)^{i+j}\left[\frac{y_i}{2h_1}\ln\left(\frac{y_i^2+z_j^2}{h_1}\right)-\frac{z_j}{h_1}\operatorname{arc\,tg}\frac{z_j}{y_i}\right], \tag{3}$$

$$f_z=\sum_{i=1}^{4}\sum_{j=1}^{4}(-1)^{i+j}\left[\frac{z_j}{2h_1}\ln\left(\frac{y_i^2+z_j^2}{h_1}\right)-\frac{y_i}{h_1}\operatorname{arc\,tg}\frac{y_i}{z_j}\right], \tag{4}$$

$$y_1=h_2+\delta,\ y_2=h_1+h_2+\delta,\ y_3=h_1+\delta,\ y_4=\delta, \tag{5}$$

$$z_1 = -\frac{a_1-a_2}{2}+\varepsilon, \quad z_2 = \frac{a_1+a_2}{2}+\varepsilon, \quad z_3 = \frac{a_1-a_2}{2}+\varepsilon, \quad z_4 = -\frac{a_1+a_2}{2}+\varepsilon, \qquad (6)$$

where J is the magnetic moment of unit volume and b is the length along the direction of motion (the remaining notations are given in Figure 1).

The results of calculating the components of the forces of interaction with different arrangement of the magnets and also the results of experiments[1] are shown in Figure 1. The results of calculating the forces when the magnetic strips are replaced by dipole filaments arranged in the geometric centers of the strips are shown in the same figure. It is obvious that the difference is small.

Relation (1) can also be integrated for magnets in the form of bars of finite length [3]. However, in view of the cumbersomeness of the expressions for the first estimates of the properties of systems, one can use the model of a local dipole for which

$$F=\mu_0 J_1 J_2 S_1 S_2 b_1 f/2\delta^3, \qquad (7)$$

$$f_y=2\bar{y}(3\bar{z}^2-\bar{y}^2)/(\bar{y}^2+\bar{z}^2)^3, \qquad (8)$$

$$f_z=2\bar{z}^2(\bar{z}^2-3\bar{y}^2)/(\bar{y}^2+\bar{z}^2)^3, \qquad (9)$$

$$\bar{y}=y/\delta, \quad \bar{z}=z/\delta, \qquad (10)$$

where S_1, S_2, y and z are the cross-sectional areas of the bars and the vertical and horizontal dimensions, b_1 is the length of the bar along the direction of motion and δ is the clearance.

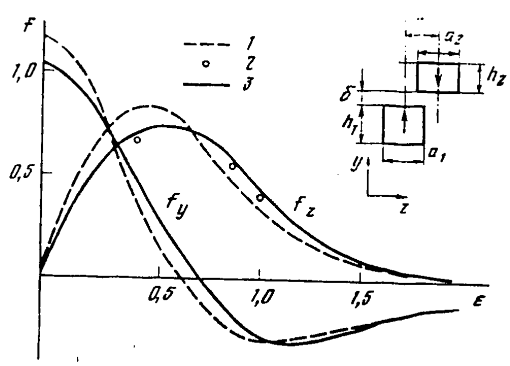

Figure 1. Calculation of Components of Forces for the Case $a_1 = a_2 = h_1 = h_2$ and $\delta/a = 0.2$: 1--calculation for magnetic dipoles; 2--experiment; 3--calculation for magnetic strips

The relations can be refined by modelling the fields [7] or by other methods if there are ferromagnetic components near the permanent magnets [7]. Some general properties of the force field can be found from consideration of the expression for force. Consideration of these properties permits one to constrict the area of searching for the optimum.

Thus, not only the impossibility of providing stability, which follows from Brownbeck's theorem but also the nondivergence of the force field created by the permanent magnets ensue from relation (1):

$$\nabla F=\nabla[(p\nabla)B]=(\nabla p)(\nabla B)+p(\nabla\nabla)B+(p\nabla)(\nabla B)=0, \quad (11)$$

i.e., for elongated systems--the equality to zero of the sum of the diagonal components of the magnetic stiffness tensor:

$$\partial F_y/\partial y=-\partial F_z/\partial z. \quad (12)$$

Thus, an increase of magnetic stiffness in the vertical direction results in an increase of the gradient of the horizontal destabilizing force.

It is obvious from expressions (1)-(3) that the values of lift and lateral forces change places when one of the magnetization vectors is rotated by 90°.

It is obvious from the dependence of forces on lateral displacement (Figure 1) that the lift decreases rapidly with an increase of the shift of the magnets with respect to each other. The same is true of the lateral force after it passes through a maximum. Each magnetic strip thus interacts with practically only two adjacent strips and only this interaction can be taken into account for the first estimates.

Finding the optimum configuration. There is a large number of possible configurations of a magnetic system. To reduce the area of search, one may take into account the preferable execution of the block system mentioned above and use a model of dipole filaments during the initial calculations and one may also compare some main configurations, for example, with vertical sign-constant orientation of the magnetization vectors (canonical), vertical sign-variable (sign-variable orientation), vertical sign-variable in the track and horizontal sign-variable in the vehicle (checkerboard configuration). Checkerboard configuration of a magnetic system is shown in Figure 2.

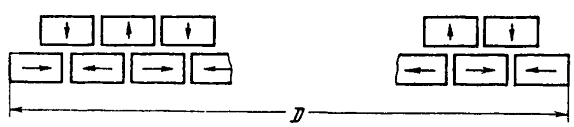

Figure 2

Comparison of the systems (Table 1) shows that the maximum possible values of lift with sign-variable and checkerboard systems almost coincide upon variation of the parameters named above, while those of a canonical system are less by a factor of 1.5. The value of the lateral force gradient during maximum lift is 33 percent higher in a sign-variable system than in a checkerboard system. If the value of the lateral force gradient must be limited, the checkerboard system permits one to do this with far fewer losses of lift than the remaining systems. The checkerboard system also has shorter distance between strips, corresponding to maximum lift, and thus lift is higher per unit width of the strip.

Further detailed optimization can also be carried out for this system. The variable parameters here may be the characteristics of system configuration: the width of one group of strips $q_1 = D$, the ratio of the width of a magnetic strip to its height q_2, the number of strips of track q_3 and of the vehicle q_4 and so on.

Table 1. Comparison of Suspension Systems

(1) Показатель	Вид системы (2)		
	каноническая (3)	знакопеременная (4)	шахматная (5)
Максимальные значения f_y (6)	1,04	1,64	1,52
Расстояние между полосами пути и экипажа при максимальной подъемной силе, отнесенное к h_1 (7)	3,0	1,2	0,65
Градиент отношения боковой силы к максимальной подъемной $\partial(f_z/f_{y\ макс})/\partial z$ при подъемной силе, равной максимальной (8)	2,2	4,0	3,0
Значение f_y, при котором может быть обеспечено $\partial f_z/\partial z \leqslant 1$ (9)	0,47	0,30	0,90
Процентное снижение подъемной силы при боковом смещении, равном 20% зазора (10)	0,24	0,25	0,06

Key:
1. Indicator
2. Type of system
3. Canonical
4. Sign-variable
5. Checkerboard
6. Maximum values of f_y
7. Distance between strips of track and vehicle at maximum lift, related to h_1
8. Gradient of ratio of lateral force to maximum lift $\partial(f_z/f_{y\ maks})/\partial z$ with lift equal to maximum
9. Value of f_y at which $\partial f_z/\partial z \leq 1$ can be provided
10. Percentage reduction of lift during lateral displacement equal to 20 percent of clearance

A number of indicators may be limited, having selected for example, the maximum variations of the gradients:

$$m \leqslant (-\partial F_y/\partial_y) \leqslant M. \tag{13}$$

One may also be given the total cross-sectional area of the vehicle magnets $q_5 = S_m$.

Table 2 illustrates the procedure for finding the optimum indicators. The program developed at IPM [Institute of the Problems of Mechanics] of the USSR Academy of Sciences [8] was used here to optimize the value of $\bar{F}_y$ at given values of q_1, q_3, q_4 and q_5.

Comparison of the indicators of an optimized system and of previously known canonical and sign-variable systems shows that the value of indicator $\bar{F}_y$ is almost comparable in total optimization to a similar value for a sign-variable system which creates the greatest repulsive force. At the same time the remaining indicators,

Table 2. Results of Precise Numerical Optimization of Checkerboard System (vehicle length of 7 meters)

(1) Показатель	Номер варианта (2)		
	1	2	3
Число полос одной системы пути (3)	10	11	12
Число полос одной системы экипажа (4)	9	10	11
Ширина и высота полосы экипажа, мм (5)	68×57	75×48	80,2×40,8
Ширина системы полос, мм (6)	955	1020	1180
Ширина и высота полосы пути, мм (7)	70×57	87,4×45	64×46,4
Градиент вертикальной силы, кгс/мм (8)	−300	−300	−300
Подъемная сила, кгс (9)	10057	10835	9876

Key:
1. Indicator
2. Number of variant
3. Number of strips of single track system
4. Number of strips of single vehicle system
5. Width and height of vehicle strip, mm
6. Width of system of strips, mm
7. Width and height of track strip, mm
8. Gradient of vertical force, kgf/mm
9. Lift, kgf

specifically, the lateral force gradient, and a reduction of lift during lateral displacement are considerably better. Thus, an optimized system is far more preferable in engineering realization.

Selection of the optimum configuration continuous in the direction of motion of the system of course does not exhaust all the possible methods of optimization. For example, let us consider the possibility of achieving an advantage in weight by sectioning the magnets along the direction of motion. The first estimates using the model of local dipoles yield an approximately 10 percent advantage of magnet weight. The value of the advantage estimated by means of numerical integration of expression (1) for this case is also of the same order. Thus, this method of optimization may also yield some, although low, advantage in the value of indicator $\bar{F}_y$.

Let us consider the possibility of increasing stability due to control of the magnetization vector of the vehicle magnets (due to, for example, a winding with current) or by positioning them with respect to the vehicle in finding possible resources of control. The impossibility of changing the ratio of the main components of the stiffness tensor $\partial F_y/\partial y$ and $\partial F_z/\partial z$ follows from expression (11) in this case. Actually, in view of $\nabla B = 0$, variation of p ($\nabla p \neq 0$) does not change the mentioned relation and the values of the derivatives of p through the coordinates generally are not contained in the expression for ∇F.

Visualization of disturbed motion. The value of the magnetic stiffness tensor permits one to close the system of equations of disturbed motion and to find the mathematical model of this motion in the vertical plane.

The equations of the mathematical model of vehicle motion and of all the components of the suspension system in the form of a "magnetic ski" are presented in [1]. Numerical integration of these equations with subsequent input of data from the storage device to the graphic display permits one to observe the motion in real time and to actively control it.

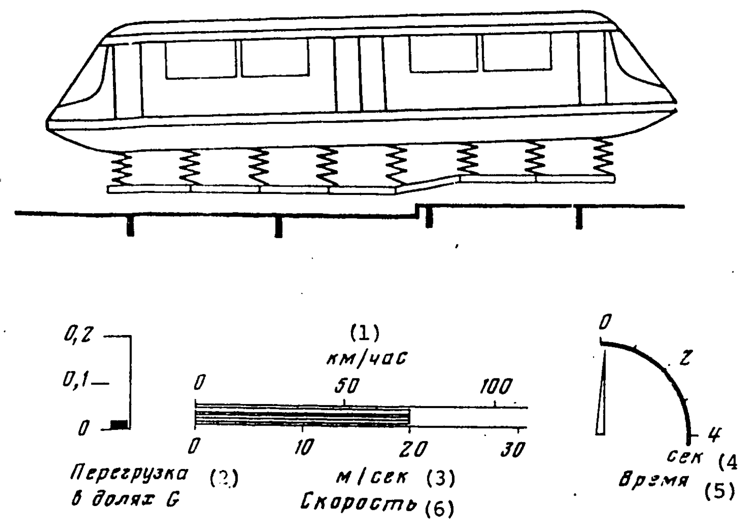

Figure 3

Key:

1. km/hour
2. Load in fractions of G
3. Meters per second
4. Seconds
5. Time
6. Velocity

Models of display frames are shown in Figures 3-5. Subprograms for generation of the image of the graph components, developed at IPM of the USSR Academy of Sciences [9, 10], were used in constructing these displays. The capabilities of the display permit one to visualize a number of motion indicators in addition to the configuration of the system, having done this in ordinary and visual form. Thus, the values of current time, travel speed of the object and the vertical load at the lower point of the body over the first of the elastic couplings to the ski component are presented in the frames of Figures 3-5. The scale of the clearance with respect to the vehicle dimensions is also increased for greater clarity.

For example, let us name selection of the minimum magnetic stiffness $\partial F_y/\partial y$ at which stable motion can still be provided with the given composition of track disturbances, as problems which can be solved by visualization. Both the form of the unevennesses and the value of magnetic stiffness as well as the flexibility of the couplings of the ski and body components, the degree of damping of oscillations, the mass and dimensions of the ski components, velocity and so on may vary during solution of this problem by observing the pattern of passage over track unevennesses.

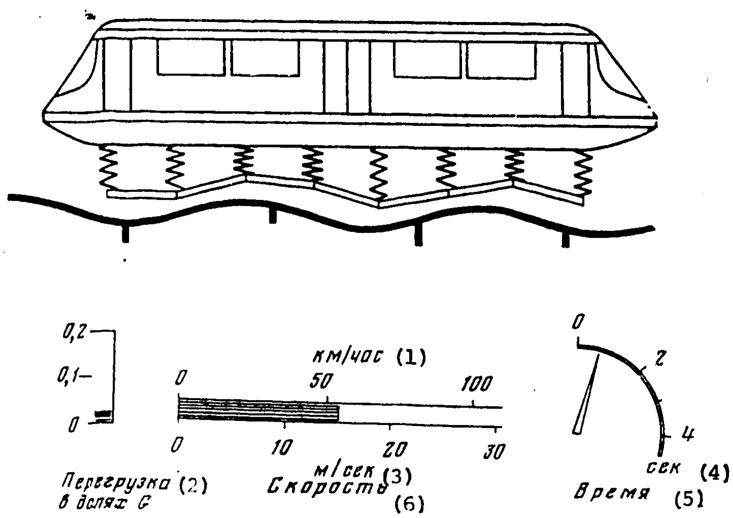

Figure 4

Key:

1. Km/hour
2. Load in fractions of G
3. Meters per second
4. Seconds
5. Time
6. Velocity

Stepped and sinusoidal waves with different length are shown in Figures 3-5 as two typical disturbances.

Consideration of the patterns of motion shows that fulfillment or nonfulfillment of a finite criterion of stability (contact of the ski and track) occurs at different points since it is very difficult to predict beforehand the point of contact or the part of the ski which approaches the track more than the remaining parts. Observation of the vehicle as a whole permits one to accumulate known experience of dangerous situations or of an unfavorable combination of parameters from these positions.

Thus, it was specifically established that consideration of the response to stepped disturbance is rather effective for preliminary comparison of different variants, but consideration of one of the most unfavorable cases, for example, of sinusoidal disturbance of the route with wavelength coinciding with half the length or the length of the ski, is required for final selection.

There is no doubt that more complete modelling of motion and, which is especially important, experimental investigations are required for final adoption of engineering decisions. However, it is felt that the procedures of optimization and visualization described above are an effective auxiliary tool in the hands of developers of specific systems.

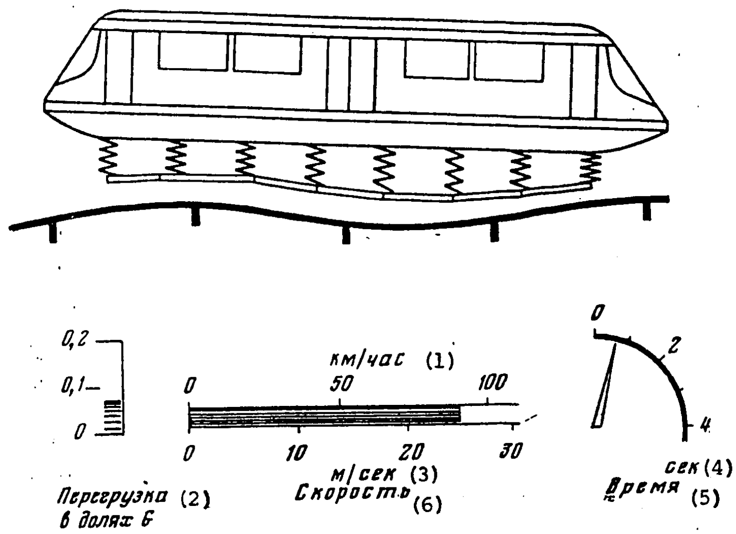

Figure 5

Key:

1. Km/hour
2. Load in fractions of G
3. Meters per second
4. Seconds
5. Time
6. Velocity

Conclusions. 1. The force field acting on a system of permanent repulsion magnets has the property of nondivergence which determines the equality of the stabilizing system of the vertical force gradient and the destabilizing lateral force gradient.

2. The configuration of a system optimized by a set of indicators selected on the basis of analyzing vehicle dynamics differs considerably from that of a system optimized by the usually considered unit indicator--the ratio of lift to the weight of the system.

3. The proposed configuration permits one to achieve rather high values of lift per unit weight of the system with a moderate value of the destabilizing lateral force gradient.

4. The considered system is most critical to sinusoidal disturbances of the route with wavelength, coinciding with half the length or with the length of the ski. These disturbances may also be used as calculating values.

BIBLIOGRAPHY

1. Baybakov, S. N., B. I. Rabinovich and Yu. D. Sokolov, "Dynamics of Transport Rolling Stock on Magnetic Suspension," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 1, 1981.

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000400010036-7

2. "Nazemnyy transport 80-kh godov" [Ground Transport of the 1980s], edited by D. M. Thornton, Mir, 1975.

3. Baran, W., "Berechnung von Anzeehungs und Maftcraften fuer Magnetik Koerper," TECHNISCHE MITTELUNGER KRUPP, Vol 19, No 4, 1961.

4. Frishman, Ye. M., "Investigating the Suspension of Rolling Stock by Using Permanent Repulsion Magnets," candidate dissertation, Leningrad, 1975.

5. Tozoni, O. V. and S. S. Romanovich, "Calculating Permanent Magnets on Digital Computers," IZVESTIYA VUZOV, ELEKTROMEKHANIKA, No 8, 1975.

6. Smythe, D., "Elektrostatika i elektrodinamika" [Electrostatics and Electrodynamics], Moscow, Izd-vo Inostrannoy literatury, 1954.

7. Demirchyan, K. S., "Modelirovaniye magnitnykh poley" [Simulation of Magnetic Fields], Moscow, Energiya, 1974.

8. Mitrofanov, V. B., "An Algorithm for Multidimensional Random Search," Moscow, Preprint No 118 of IPM AN SSSR, 1974.

9. Bayakovskiy, Yu. M., T. N. Mikhaylova and S. T. Mishakova, "GRAFOR: A Complex of Graphical Programs in FORTRAN," Moscow, IPM Preprint, No 41, 1972.

10. Lazutin, Yu. M., "Organizing Work with a Light Pen in FORTRAN IV Language on the SDS-910 Computer," Moscow, IPM Preprint No 64, 1972.

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ELECTROMAGNET CONTROL IN THE SUSPENSION SYSTEMS OF HIGH-SPEED TRANSPORT

Moscow IZVESTIYA AKADEMII NAUK SSSR: ENERGETIKA I TRANSPORT in Russian No 1, Jan-Feb 81 pp 108-112

[Article by T. I. Katsan, V. G. Lebedev and A. I. Mytarev, Moscow]

[Text] Let us consider a simplified mechanical model--a heavy electromagnet with elastically suspended mass whose characteristics correspond to an individual electromagnetic module with vehicle mass on it to synthesize the stabilization algorithm of a rail car with electromagnetic ski [1, 2]. The dynamics of this model are described by the following system of linearized differential equations, which can be found from those presented in [1, 2]:

$$\begin{gathered}\ddot{y}_1+\varepsilon_1\dot{y}_1+\omega_1^2 y_1=\varepsilon_1\dot{y}_2+\omega_1^2 y_2,\\ \ddot{y}_2+\varepsilon_{12}\dot{y}_2+\omega_{12}^2 y_2=\varepsilon_{12}\dot{y}_1+\omega_{12}^2 y_1+a_{yy}S-a_{y\delta}I^*,\\ \tau\dot{I}^*+I^*=I,\\ T\dot{I}+I=U/R+a_{yy}'S,\\ U(p)/R=L_S(p)\tilde{S}(p)+L_I(p)\tilde{I}(p),\\ S=y_2-h.\end{gathered} \qquad (1)$$

Here y_1 and y_2 are variations of the vehicle coordinates and of the electromagnet with respect to the nominal value, S is variation of the gap between the electromagnet and the ferromagnetic rail, U and I are variations of the control voltage and current of the electromagnet, I* is variation of the variable which takes into account the dynamics of establishing the electromagnetic field (the force of the electromagnet) in a ferromagnetic rail during variation of current I; $\tilde{S}$ and $\tilde{I}$ are the readings of the gap and current sensors, respectively, h is disturbance of the track structure, T and R are the time constant and ohmic resistance of the electromagnet, τ is the time constant of penetration of the electromagnetic field into the metal upon variation of the control current* I, ε_1 and ω_1 are the partial damping coefficient and oscillation frequency of the vehicle with a fixed electromagnet, ε_{12} and ω_{12} are the partial damping coefficient and oscillation frequency of the electromagnet with respect to the body, $L_S(p)$ and $L_I(p)$ are the integrodifferential control operators which utilize the readings of the gap and current sensors and a_{yy}, a_y and a'_{yy} are the linearization coefficients of the attractive force of the electromagnet.

*The matter of developing the standard documentation for the dispatcher services will be accelerated significantly.

We note that the time constant τ is actually a function of the frequency of electromagnetic field variation. However, τ varies slightly in the range of the (working) frequencies being investigated, which provides the basis to assume it is equal to a constant value. It should be noted that the dynamic delay of the electromagnet force is not taken into account in equations (1) with respect to variation of the gap. This assumption was made so as to synthesize the stabilization algorithm for an object with worse dynamic properties than in reality and to carry out a "reserve" calculation since a delay in the component of force through the gap $a_{yy}S$ attenuates its destabilizing effect and simplifies the problem of stabilization.

The following tasks are faced by the stabilization system of the object under consideration [1]: provision of stable tracking of the object over guide rails with possible deviations of the parameters of the object and the stabilization automaton from nominal values, maintenance of the gaps between the electromagnets and rails in the range of $\pm$(2-4) mm from nominal values in all operating modes, provision of the comfort conditions for passengers in the sense of the oscillating components of loads and provision of noise protection of the system.

The problem of comfort provision is solved by spring-loading the body with partial oscillation frequency ω_1, which, moreover, permits control of essentially only the mass of the electromagnet at high frequencies $\omega > \omega_1$, which in turn considerably simplifies the problem of stabilization. Based on solution of the remaining problems, one can formulate the freuirements on the frequency characteristic $W_{y2h}(p) = y_2(p)/h(p)$, where $p = i\omega$, which characterizes the quality of tracking on the track structure. The condition $W_{y2h}(i\omega) \approx 1$ should be fulfilled up to frequencies of approximately 10 Hz and the condition $|W_{y2h}(i\omega)| \simeq 0.2$ should be fulfilled at frequencies near 50 Hz, where settings of the power supply system are possible. Moreover, the system should have 30 to 40 percent stability reserves according to the coefficients of the object.

Due to the fact that the stabilization system should have high speed, the hypothesis of dynamic uncoupling ($y_1 \ll y_2$) of vehicle and electromagnet motions at working tracking frequencies $\omega \gg \omega_1$ is rather strict. The degree of freedon corresponding to motion of the vehicle should have characteristics close to partial.

To synthesize the stabilization algorithm which solves the problems named above, let us write the characteristic equation of system (1) at $y_1 \equiv 0$:

$$p^4 + \left[\frac{1}{T} + \frac{1}{\tau} + \varepsilon_{12}\right] p^3 + \frac{1+\varepsilon_{12}(T+\tau) - a_{yy}T\tau}{T\tau} p^2 + \frac{\varepsilon_{12} + \omega_{12}^2 (T+\tau) + a_{yy}' a_{y\delta} - a_{yy}T}{T\tau} p - \frac{a_{yy}}{T\tau} + \frac{L_B(p) a_{y\delta} - (p^2 + \varepsilon_{12}p + \omega_{12}^2 - a_{yy})(\tau p + 1) L_I(p)}{T\tau} = 0. \quad (2)$$

This equation is a fourth-order polynomial. The coefficient of p^3 is equal to the sum of the real parts of roots with the minus sign. Based on the provision of stability and the required speed of system (1), each of the four roots should have a negative real part modulo no less than the given value. The value $\alpha = 1/T + 1/\tau + \varepsilon_{12}$ is insufficient. Therefore, triple differentiation of the readings of the gap sensor is required as a minimum in the simplest case. The stabilization algorithm is written in this case in the following manner:

$$L_\delta(p)=a_0+a_1p+a_2p^2+a_3p^3, \quad (3)$$
$$L_I(p)=0.$$

However, it has at least two disadvantages: the complexity of a triply differentiating circuit (the result is an easily stimulated tank circuit) and the fact that the transfer function $W_{y2h}(p)$ has the order of the polynomial of the numerator a unit below the denominator and variation of the amplitude-frequency characteristic in the high-frequency range has the order of $1/\omega$, which is insufficient for satisfactory filtration of high-frequency noise.

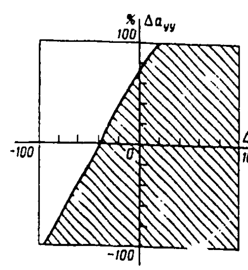

Figure 1. Stability Range

Therefore, let us consider an algorithm with continuous feedback with respect to current and double differentiation of the gap:

$$L_\delta(p)=a_0+a_1p+a_2p^2,$$
$$L_I(p)=-k_I \ (k_I>0). \quad (4)$$

In this algorithm, the frequency characteristic $W_{y2h}(i\omega)$ in the high-frequency range varies as $1/\omega^2$, which is quite adequate for satisfactory filtration of the high-frequency noise on the track. However, the stability reserves according to the parameters of the object a_{yy} and $a_{y\delta}$ are impermissibly low in this algorithm, while coefficients a_0, a_1 and a_2 are impermissibly high.

To explain the foregoing, let us write the expression for the free term b_0 of equation (2) with regard to (4), equal in turn to the product of the roots p_i (i = 1, 2, 3, 4):

$$b_0=\frac{a_0a_{y\delta}-(1+k_I)\,(a_{yy}-\omega_{12}^2)}{T\tau}=\prod_{i=1}^{4}p_i.$$

Due to the fact that quite specific frequency properties must be assigned to the system, the value $\prod_{i=1}^{4} p_i = \text{const}$.

Let us write the equation for the coefficient of the algorithm a_0:

$$a_0 = \frac{(1+k_I)(a_{yy} - \omega_{12}^2) + T\tau \prod_{i=1}^{4} p_i}{a_{y\delta}}.$$

Let us introduce the relative deviation of Δa_{yy} of coefficient a_{yy} from the nominal a_{yy}^0, i.e., $a_{yy} = a_{yy}^0(1 + \Delta a_{yy})$, and let us express the required condition of stability of the system $b_0 > 0$ by Δa_{yy}:

$$\Delta a_{yy} < \frac{T\tau \prod_{i=1}^{4} p_i}{(1+k_I)(a_{yy}^0 - \omega_{12}^2)}.$$

We note that the value of $k_I \approx 50$; therefore, the coefficients of the algorithm increased 50-fold, which is impermissible from the viewpoint of the noise stability of the system, while the stability reserves decrease by a factor of 50 compared to an algorithm without continuous current feedback.

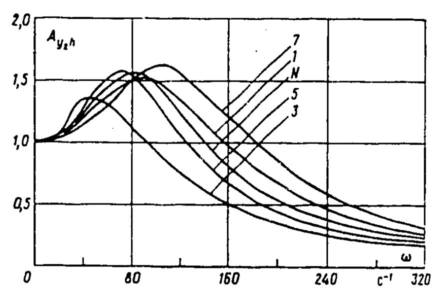

Figure 2. Amplitude-Frequency Characteristics

An algorithm of the following type is free of the indicated deficiencies:

$$L_\delta(p) = a_0 + a_1 p + a_2 p^2,$$
$$L_I(p) = -k_I \tau_M p / (\tau_M p + 1). \quad (5)$$

Introduction of feedback with respect to I*, i.e., with respect to the derivative of the control force, is actually the basis of algorithm (5) at $\tau_M = \tau I(p)/(\tau_M p + 1) = I^*(p)$.

The stability zones and the amplitude-frequency characteristics were calculated for system (1) with algorithm (5).

The stability zone in the plane of deviation of the parameters of the object a_{yy} and $a_{y\delta}$ from their nominal (calculated) values is presented in Figure 1. The set of amplitude-frequency characteristics corresponding to $W_{y2h}(i\omega)$ for five versions of a_{yy} and $a_{y\delta}$: $\Delta a_{yy} = 0$ (nominal), $\Delta a_{y\delta} = 0$; $\Delta a_{yy} = 15$ percent, $\Delta a_{y\delta} = 15$ percent; $\Delta a_{yy} = 15$ percent, $\Delta a_{y\delta} = -15$ percent; $a_{yy} = -15$ percent, $\Delta a_{y\delta} = -15$ percent; and $\Delta a_{yy} = -15$ percent, $\Delta a_{y\delta} = 15$ percent, is presented in Figure 2.

The notations in Figure 2 are explained below. Analysis of the results shows that algorithm (5) satisfies all the requirements formulated above in the range of variation of the object parameters. We note that the given calculations were made by the complete dynamic scheme with regard to the effect of the vehicle mass. As can be seen, resonance phenomena at frequencies close to partial suspension frequencies of the vehicle $\omega \approx \omega_1$ are considered with the selected structure and at the parameters of the algorithm with respect to the electromagnet coordinate y_2.

The roots of the characteristic equation of a rail car with electromagnetic ski stabilized by a proposed algorithm were calculated to justify the permissibility of synthesizing the algorithm on the basis of a simplified mechanical model. In view of the large dimensionality of the system and the dense frequency spectrum, the program described in [3], which is specially oriented toward calculation of systems of this class, was used in calculating the roots of the characteristic equation.

(1) Номер подсистемы S	Значение корней p_s^k (c^{-1}), соответствующих номеру корня k (2)				
	1; 2	3	4	5	6; 7
1	−1,055±i7,782	−40	−9,834	−161,3	−54,92±i77,03
2	−1,139±i8,002	−40	−9,660	−164,6	−53,35±i77,25
3	–	−40	−9,155	−163,8	−53,92±i81,52
4	–	−40	−8,370	−167,1	−52,64±i87,78
5	–	−40	−7,445	−171,5	−50,87±i96,38
6	–	−40	−6,980	−174,0	−49,86±i101,40

Key:

1. Number of subsystem S
2. Value of roots $p_S^k(s^{-1})$ corresponding to number of root k

Roots p_S^k (s^{-1}) are presented in the table. The subscript S = 1 corresponds to a subsystem with degrees of freedom corresponding to (η, p_0, δ_0) [2]; S = 2 – – (η, p_0, Δ_0), S = 3 – (p_1, δ_1), S = 4 – (p_1, Δ_1), S = 5 – (p_2, δ_2) and S = 6 – – (p_2, Δ_2). The notations correspond to those used in the indicated paper.

The roots of a two-mass system with algorithm (5) were calculated in the same manner upon variation of parameters a_{yy}, $a_{y\delta}$ on the scattering plane around a circle with radius of 20 percent, inside which the system retains satisfactory frequency properties (see Figure 2). The results of calculation are represented in the form of "root locus" curves in the upper half-plane of the complex variable in Figure 3, where the "root locus" are also shown according to the table upon transition from one degree of freedom to another (there is complete agreement in number of the versions in Figures 2 and 3). The following notations were used here: I is the variant of variation by parameters α_{yy} and $\alpha_{y\delta}$ and II is the variant of taking into account the multidimensionality of the system. The numbers of the roots are presented in parentheses. The root which remains constant from variant to variant, as roots $p_{1,2}^{(1,2)}$, corresponding to forward and angular displacements of the rail car with respect to the ski, is denoted by $p_i^{(3)} = -1/T_M = -40\ s^{-1}$. The roots $p_{6,7}^*$ and p_5^* correspond to the nominal values of the parameter (point N in Figures 2 and 3). The height of the columns for real roots is arbitrary in nature.

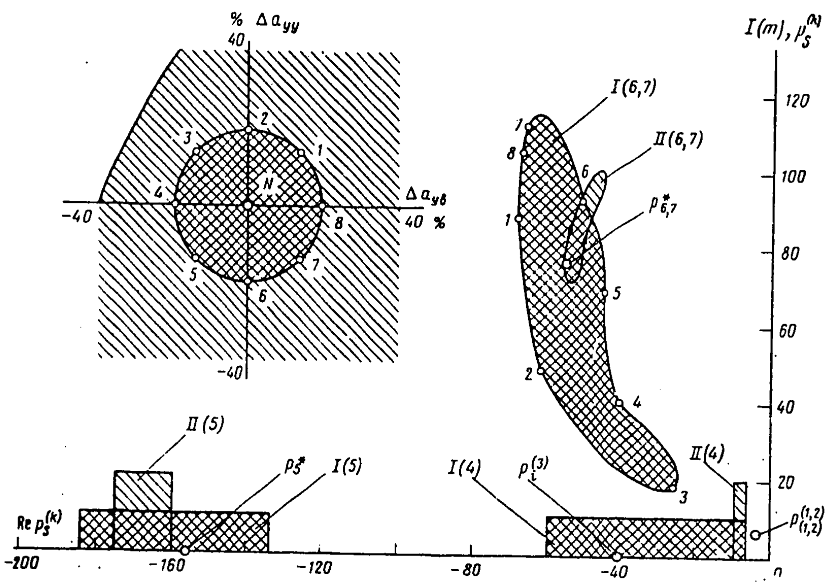

Figure 3. "Root Locus" Curves

Based on the fact that the roots of a multimass car-ski system are close to the roots of a two-mass system, one can state that algorithm (5) should satisfactorily solve the problem of stabilization for the entire system as a whole and selection of the algorithm based on the simplified mechanical model is sufficiently justified.

Conclusions. 1. The law of control which provides satisfactory solution of the stabilization problem for the car-ski system can be synthesized as a whole on the basis of a simplified two-mass model of the control object.

2. The stabilization algorithm is synthesized on the basis of signals proportional to variations of the gap and current and their derivatives up to second order.

BIBLIOGRAPHY

1. Baybakov, S. N., B. I. Rabinovich and Yu. D. Sokolov, "The Dynamics of Transport Rolling Stock on Magnetic Suspension," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 1, 1981.

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000400010036-7

2. Bagryantsev, V. I., V. S. Nevarko and B. I. Rabinovich, "The Mathematical Model of a Rail Car With Electromagnetic Suspension," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 1, 1981.

3. Kalinina, A. V., V. G. Lebedev and B. I. Rabinovich, "Recursion Iteration Algorithm for Solving the Characteristic Equation in Problems of the Dynamics of Structures and its Realization on the BESM-6 and YeS-1040 Computers," in "Issledovaniya po teorii sooruzheniy" [Investigations on the Theory of Structures], Moscow, Stroyizdat, 1979.

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CSO: 1861

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MATHEMATICAL MODEL OF A RAIL CAR WITH ELECTROMAGNETIC SUSPENSION

Moscow IZVESTIYA AKADEMII NAUK SSSR: ENERGETIKA I TRANSPORT in Russian No 1, Jan-Feb 81 pp 101-107

[Article by V. I. Bagryantsev, V. S. Nevarko and B. I. Rabinovich, Moscow]

[Text] Investigating the dynamics and stability of the rolling stock of high-speed transport on magnetic suspension is a very complex problem [1-3]. The success of solving it at the design stage is determined largely by the adequacy of mathematical models of the "object-regulator" system used. A mathematical model of a rail car with suspension in the form of two multilink jointed kinematic chains with rigid modules carrying two electromagnets each with independent control systems suspended to the body by viscoelastic couplings is synthesized below [1]. In this case the disturbed motion of the rail car in the vertical plane is considered at which one equivalent "electromagnetic ski" with two double electromagnets in each module can be considered. Horizontal motion with constant velocity v and constant gap s° is taken as undisturbed motion.

Let us use the linearized mathematical model of an electromagnet [1-3]. For an example let us consider a simplified stabilization algorithm in which only the gap is used as the observable coordinate. Let us introduce the following coordinate systems.

1. The starting system $\tilde{O}\tilde{x}\tilde{y}\tilde{z}$ connected to an ideal track structure.

2. An absolute system G*x*y*z* connected to the "car-ski" system hardened in undisturbed motion (G* is the center of mass of the system).

3. A correlated system Gxyz rigidly attached to the hardened "car-ski" system during disturbed motion with respect to G*x*y*z*.

The position of coordinate system Gxyz with respect to G*x*y*z* in the vertical plane is determined by generalized coordinates η and ϑ (Figure 1), which are assumed to be small in the sense that linearization by these coordinates is permissible. The position of the ski in coordinate system Gxyz is determined by the deflection function f(x, t). Deflection of the ferromagnetic rail surface from the horizontal plane is characterized by the function $\tilde{f}(\tilde{x})$. The gap $\hat{s}$ (x, t) during disturbed motion is related to the nominal gap s° by the relations

$$s(x,\ t)=s^{\circ}+s(x,\ t),\quad s(x,\ t)=\tilde{f}(\tilde{x})-[\eta+\vartheta x+f(x,\ t)]. \qquad (1)$$

Let us introduce the following local coordinate systems to describe the motion of an individual electromagnet (Figure 2): O*x*y*z* and Oxyz whose axes are directed the same as the axes of coordinate systems G*x*y*z* and Gxyz. The origins O* and O lie in the plane of the pole shoes of the electromagnets.

Let us consider an electromagnet of unit length in the direction of the Ox axis. The linearized system of equations of the dynamics of a controlled electromagnet with the simplest law of control (stabilization algorithm) with respect to the gap and its first two derivatives has the form [1-3]

$$F=c_I I-c_s s,$$
$$c_I'\dot{I}+RI-c_s'\dot{s}=U, \qquad (2)$$
$$U=a_0 s+a_1\dot{s}+a_2\ddot{s},$$

where U, I and F are the voltage, current and vertical force developed by the electromagnet, c_I, c_I', c_s and c_s' are coefficients dependent on the parameters of the electromagnet and the undisturbed value of the gap s°, where $c_I' c_s = c_I c_s'$ and $c_s' = c_I$ and R is effective resistance. The dot indicates the time derivative. After elimination of variable I and some transformations [1], one can impart the following form to system (2):

$$F=c_i s+\delta,$$
$$\beta_\delta\dot{\delta}+\delta+c_{\delta s}''\ddot{s}+c_{\delta s}'\dot{s}=0, \qquad (3)$$

where

$$c_i=\frac{a_0 c_I}{R}-c_s,\quad \beta_\delta=\frac{c_I'}{R},$$
$$c_{\delta s}''=-\frac{a_2 c_I}{c_F' c_I'},\quad c_{\delta s}'=\beta_\delta c_i-\frac{a_1 c_I}{c_I' c_F}. \qquad (4)$$

The first term in the expression of variation of force (3) corresponds to quasi-static control in which variation of current is proportional to variation of the gap and consequently the total variation of the electromagnetic force is proportional to variation of the gap s.

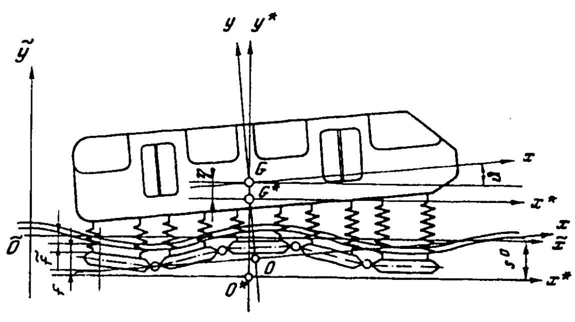

Figure 1. Rail Car With Suspension in the Form of an Electric Ski with Discrete Modules.

The equivalent electromagnetic ski under consideration consists of identical hinge-coupled modules which carry two double electromagnets each and two gap sensors each.

Each n-th module considered separately from the remaining ones is a rigid body with two degrees of freedom (excluding longitudinal displacement), to which the generalized coordinates ξ_n and ξ_{n+1} presented in Figure 3 can be set into agreement (the following notations are also presented in Figure 3: a/2 is the distance from the center to the end of the module, b/2 is the distance to the line of action of the elastic components which couple the module to the body, d/2 is the distance to the line of action of the equivalent electromagnetic forces during quasi-static control and e/2 is the distance to the axis of sensitivity of the gap sensor). Having compiled a Lagrangian equation of second kind, we find the following equations of disturbed motion of the ski with quasi-static control of each of the electromagnets $(\zeta \equiv 0)$:

$$
\begin{gathered}
2(\gamma^*\ddot{\xi}_1+\alpha^*\Omega^2\xi_1)+\delta^*\ddot{\xi}_2+\beta^*\Omega^2\xi_2=0,\\
\cdots\cdots\cdots\cdots\cdots\cdots\\
4(\gamma^*\ddot{\xi}_n+\alpha^*\Omega^2\xi_n)+\delta^*(\ddot{\xi}_{n+1}+\ddot{\xi}_{n-1})+\beta^*\Omega^2(\xi_{n+1}+\xi_{n-1})=0,\\
\cdots\cdots\cdots\cdots\cdots\cdots\\
2(\gamma^*\ddot{\xi}_{N+1}+\alpha^*\Omega^2\xi_{N+1})+\delta^*\ddot{\xi}_N+\beta^*\Omega^2\xi_N=0,
\end{gathered}
\tag{5}
$$

where

$$
\begin{gathered}
\Omega^2=\frac{C}{M}\gamma,\quad \gamma=-1+\delta_0^*+\delta_1^*,\quad \delta_0^*=\frac{K_0}{C},\\
\delta_1^*=\frac{K_1}{C},\\
\alpha^*=\left[-1+\frac{3}{4}\delta_0^*(1+\bar{b}^2)+\frac{3}{4}\delta_1^*(1+\bar{d}\bar{e})\right]\frac{1}{\gamma},\\
\beta^*=\left[-1+\frac{3}{2}\delta_0^*(1-\bar{b}^2)+\frac{3}{2}\delta_1^*(1-\bar{d}\bar{e})\right]\frac{1}{\gamma},\\
\gamma^*=1+\varepsilon/4,\ \delta^*=1-\varepsilon/2,\ \varepsilon=12\bar{\rho}^2-1,\\
\bar{b}=b/a,\ \bar{d}=d/a,\ \bar{e}=e/a,\ \bar{\rho}=\rho/a,
\end{gathered}
\tag{6}
$$

N is the number of modules, M is the total mass of the ski, K_0 is the total stiffness of the springs which link the ski to the body, G is the modulus of the total gradient of forces of uncontrolled electromagnets through the gap, K_1 is the total gradient of control forces of electromagnets through the gap during quasi-static control and ρ is the radius of inertia of the module with respect to its main central axis.

Having set $\xi_n = \bar{\xi}_n e^{i\omega t}$, let us reduce system (5) to an ordinary boundary-value problem for eigen-values whose solutions are essentially eigen-vectors $\xi^{(j)}$ with components $\bar{\xi}_1^{(j)}, \bar{\xi}_2^{(j)}, \ldots, \bar{\xi}_{N+1}^{(j)}$ and eigenvalues ξ_j^2 (j = 1, 2, ..., N + 1).

Since the gap sensor measures linear displacements, the amplification factor of the sensor with respect to angular displacement of the module varies upon variation of its distance e/2 from the center of the module (Figure 3). This leads to the dependence of the natural frequencies of angular oscillations of the module from the position of the gap sensor. The amplification factor of the sensor remains constant during forward motion of the module regardless of the coordinate of e/2. The position of the sensor does not affect the frequency of the corresponding oscillations of the module. Thus, the range of natural frequencies of the ski is totally dependent on parameter $\bar{e}$. Specifically, at a "critical" value of the coordinate of the sensor ($\bar{e} = \bar{e}^\circ$)

$$\bar{e}^\circ = \frac{1}{3\bar{d}}\left[1+\frac{\gamma\varepsilon}{\delta_1^\cdot}+\frac{\delta_0^\cdot}{\delta_1^\cdot}(1-3\bar{b}^2)\right] \quad (7)$$

some "maximum ski" is realized in which a single natural frequency $\omega = \Omega$ corresponds to all the harmonics of natural oscillations. The ski makes forward and angular oscillations like a rigid body at this same frequency. Let us assume for further analysis that

$$\varepsilon \ll 1,\ \delta_0^\cdot/\delta_1^\cdot \ll 1,\ \bar{e} \approx \bar{e}^\circ. \quad (8)$$

From (7) we find $\bar{e}^\circ\bar{d} \approx 1/3$ and at $\bar{d} = 1/2$ we have $\bar{e}^\circ = 2/3$. This value, corresponding to the coincidence of the frequencies of forward and angular oscillations of a single module, is an analog of a body with two elastic supports known in oscillation theory [4].

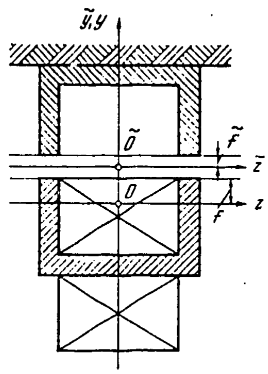

Figure 2. Cross-Sections of Electromagnet and of Ferromagnetic Rail

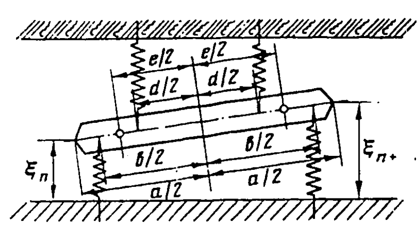

Figure 3. Diagram of Electromagnetic Ski Module

Using the components of eigen vectors $\xi_1^{(j)}, \xi_2^{(j)}, \ldots, \xi_{N+1}^{(j)}$, we find the harmonics of the natural oscillations of the ski in the form of piecewise linear functions

$\zeta_j(x)$ $(j = 1, 2, \ldots, N + 1)$ corresponding to natural frequencies ω_j. The latter form a dense spectrum which approaches point $\omega_j = \Omega$ at $\bar{e} \to \bar{e}^\circ$ in view of the last of conditions (8).

The mathematical model of an electromagnetic ski with complete law of control (3), i.e., at $\delta \neq 0$, is constructed by the Bubnov-Galerkin method. Following the ordinary procedure of this method and utilizing functions $\zeta_j(x)$, let us represent the functions $f(x, t)$, $\delta(x, t)$, $u(x, t)$ and $i(x, t)$, orthogonal on segment $(-l/2, l/2)$, as coordinate functions, in the form of the following series:

$$f(x,t)=\sum_{j=1}^{N+1} f_j(t)\zeta_j(x), \quad \delta(x,t)=\sum_{j=1}^{N+1}\delta_j(t)\zeta_j(x),$$
$$u(x,t)=\sum_{j=1}^{N+1} U_j(t)\zeta_j(x), \quad i(x,t)=\sum_{j=1}^{N+1} I_j(t)\zeta_j(x). \qquad (9)$$

The mathematical model of the ski acquires the following form upon consideration of (3), (5), (8) and (9):

$$\mu_j(\ddot{f}_j+\beta_j\dot{f}_j+\omega_j^2 f_j)=\delta_j+F_j(t),$$
$$\beta_\delta\dot{\delta}_j+\delta_j-\frac{2}{a}d_j(c_{\delta e}''\ddot{f}_j+c_{\delta e}'f_j)=\Phi_j(t) \qquad (10)$$
$$(j=1, 2, \ldots, N+1).$$

Here

$$\mu_j=MN_j^2/2lN, \quad \beta_j=b_j/\mu_j,$$
$$N_j^2=\frac{l}{3}\sum_{n=1}^{N}[\gamma^*(\bar{\xi}_{n+1}^{(j)2}+\bar{\xi}_n^{(j)2})+\delta^*\bar{\xi}_{n+1}^{(j)}\bar{\xi}_n^{(j)}].$$
$$b_j=\beta\sum_{i=1}^{N}\Big[(\bar{\xi}_{n+1}^{(j)2}+\bar{\xi}_n^{(j)2})(1+b^2)+2\bar{\xi}_{n+1}^{(j)}\bar{\xi}_n^{(j)}(1-\bar{b}^2)\Big]. \qquad (11)$$
$$d_j=\frac{l}{3N}\sum_{n=1}^{N}(\bar{\xi}_{n+1}^{(j)2}+\bar{\xi}_n^{(j)2}+\bar{\xi}_{n+1}^{(j)}\bar{\xi}_n^{(j)}),$$
$$F_j(t)=\int_{-l/2}^{l/2}\bar{c}_1\bar{f}(\tilde{x})\zeta_j(x)\,dx;$$
$$\bar{c}_1=\frac{1}{l}(K_1-C),$$

$$\Phi_j(t) = -\frac{2}{a} c_{\delta_0}'' v^2 \int_{-l/2}^{l/2} \tilde{f}''(\tilde{x}) \zeta_j(x)\,dx -$$

$$-\frac{2}{a} c_{\delta_0}' v \int_{-l/2}^{l/2} \tilde{f}'(\tilde{x}) \zeta_j(x)\,dx,$$

M is the mass of the ski and β is the coefficient of natural damping of visco-elastic couplings of the ski to the body.

The equations for generalized coordinates $U_j(t)$ and $I_j(t)$, which follow from (2), are independent and will not be given here.

Due to the symmetry of the ski and the boundary-value conditions with respect to point x = 0, the set of functions $\zeta_j(x)$ reduces to two subsets: functions $\xi_j(x)$ symmetrical with respect to the point x = 0 and $\eta_j(x)$ antisymmetrical with respect to this point. Functions $\xi_j(x)$ and $\eta_j(x)$ are mutually orthogonal on segment (-1/2, 1/2). Let us ascribe the index j = 0 to functions $\xi_0(x) = 1$ and $\eta_0(x) = x$ and let us establish independent indexing and the following normalization for the remaining functions:

$$\xi_j(-l/2) = 1; \quad \eta_j(-l/2) = 1.$$

Let N be an odd number, then j = 1, 2, ..., (N - 1)/2. Let us denote the generalized coordinates corresponding to eigen functions $\xi_j(x)$ and $\eta_j(x)$ by $p_j(t)$ and $q_j(t)$ and let us denote the natural frequencies and damping coefficients ω_{pj}, ω_{qj} and β_{pj}, β_{qj}, respectively. Let us retain the notations of δ_j for the expansion coefficients of function $\delta(x, t)$ (9), corresponding to the symmetrical harmonics of oscillations and let us denote the same coefficients for antisymmetrical harmonics by Δ_j. Let us ascribe subscripts s and a, respectively, to the disturbing functions.

Returning to coordinate systems G*x*y*z* and Gxyz and using theorems of the momentum and kinetic moment, we find the following mathematical model of the rail car as a whole.

1. Forward motion in the direction of the G*y* axis

$$\begin{gathered}
(M^\circ + M)(\ddot{\eta} + \omega_\eta^2 \eta) + M\ddot{p}_0 + e_\eta p_0 = \delta_0 + P_v(t), \\
M(\ddot{p}_0 + \beta_{p0}\dot{p} + \omega_{p0}^2 p_0) + M\ddot{\eta} + e_\eta \eta = \delta_0 + P_0(t), \\
\beta_\delta \dot{\delta}_0 + \delta_0 - \frac{2}{a} e_{\eta 0}[c_{\delta_0}''(\ddot{\eta} + p_0) + c_{\delta_0}'(\dot{\eta} + \dot{p}_0)] = \Phi_{s0}(t), \\
a_j(\ddot{p}_j + \beta_{pj}\dot{p}_j + \omega_{pj}^2 p_j) = \delta_j + P_j(t); \\
\beta_\delta \dot{\delta}_j + \delta_j - \frac{2}{a} e_{\delta_s}(c_{\delta_0}''\ddot{p}_j + c_{\delta_0}'\dot{p}_j) = \Phi_{sj}(t) \\
(j = 1, 2, \ldots, (N-1)/2).
\end{gathered} \quad (13)$$

Here

$$\omega_\eta^2=\frac{e_\eta}{M^\circ+M};\quad e_\eta=K_1-C;\quad e_{\eta 0}=l,$$

$$P_v(t)=\bar{c}_j\int_{-l/2}^{l/2}\bar{f}(\bar{x})\,dx+P_v^\circ(t),$$

$$P_j(t)=\bar{c}_i\int_{-l/2}^{l/2}\bar{f}(\bar{x})\,\xi_j(x)\,dx;\quad e_{\eta j}=\int_{-l/2}^{l/2}\xi_j^2(x)\,dx=d_j,\tag{14}$$

$$\Phi_{sj}(t)=-\frac{2}{a}\Big[c_{0s}''v^2\int_{-l/2}^{l/2}\bar{f}''(\bar{x})\,\xi_j(x)\,dx+$$

$$+c_{0s}'v\int_{-l/2}^{l/2}\bar{f}'(\bar{x})\,\xi_j(x)\,dx\Big]$$

$$(j=0,1,\ldots,(N-1)/2),$$

M° is the mass of the body and M is the mass of ski; the appearance of multiplier 2/a in equations (13) and subsequently in equations (15) is related to the fact that two electromagnets are located on a single module.

2. Rotary motion around the Gz axis

$$\begin{gathered}(J_z+J_z^\circ)(\ddot{\vartheta}+\omega_\vartheta^2\vartheta)+J_z\ddot{q}_0+e_\vartheta q_0=\Delta_0+M_{Gz}(t),\\ J_z(\ddot{q}_0+\beta_{q0}\dot{q}_0+\omega_{q0}^2q_0)+J_z\ddot{\vartheta}+e_\vartheta\vartheta=\Delta_0+Q_0(t),\\ \beta_0\dot{\Delta}_0+\Delta_0-\frac{2}{a}e_{\vartheta 0}[c_{0s}''(\ddot{\vartheta}+\ddot{q}_0)+c_{0s}'(\dot{\vartheta}+\dot{q}_0)]=\Phi_{a0}(t),\\ b_j(\ddot{q}_j+\beta_{qj}\dot{q}_j+\omega_{qj}^2q_j)=\Delta_j+Q_j(t),\\ \beta_0\dot{\Delta}_j+\Delta_j-\frac{2}{a}e_{\vartheta j}(c_{0s}''\ddot{q}_j-c_{0s}\dot{q}_j)=\Phi_{aj}(t)\\ (j=1,2,\ldots,(N-1)/2).\end{gathered}\tag{15}$$

Here

$$\omega_\vartheta^2=\frac{e_\vartheta}{J_z^\circ+J_z^\circ},\quad e_\vartheta=4k_sa^2\Big[\frac{\bar{e}\bar{d}}{4}+2\sum_{n=1}^{(N-1)/2}\Big(n^2+\frac{\bar{e}\bar{d}}{4}\Big)\Big]-G\frac{l^2}{12},$$

$$k_s=\frac{a_0c_I}{R},\quad e_{\vartheta 0}=\frac{l^2}{12},\quad e_{\vartheta j}=\int_{-l/2}^{l/2}\eta_j^2(x)\,dx=d_j,\tag{16}$$

$$M_{Gz}=\bar{c}_i\int_{-l/2}^{l/2}\tilde{f}(\tilde{x})\,x\,dx+M_{Gz}{}^0,\quad Q_j(t)=\bar{c}_i\int_{-l/2}^{l/2}\tilde{f}(\tilde{x})\,\eta_j(x)\,dx,$$

$$\Phi_{aj}(t)=-\frac{2}{a}\left[c_{\delta s}{}''v^2\int_{-l/2}^{l/2}\tilde{f}''(\tilde{x})\,\eta_j(x)\,dx+c_{\delta s}{}'v\int_{-l/2}^{l/2}\tilde{f}'(x)\,\eta_j(x)\,dx\right]$$

$$(j=0,1,\ldots,(N-1)/2),$$

J_z^0 is the moment of inertia of the body without a ski with respect to the Gz axis, J_z^* is the moment of inertia of the ski with respect to the Gz axis, J_z is the moment of inertia of the ski with respect to the main central axis parallel to Gz and M_{Gz} is the projection of the main moment of the system of external forces applied to the car with respect to point G onto the Gz axis.

Knowing the solutions of equations (13) and (15) one can find the variation of the gap at each point of the ski and the variation of current and voltage for each of the electromagnets by using equations (2) and expressions (1) and (9). In the special case of $\delta_0 \equiv 0$, $\delta_j \equiv 0$, $\Delta_0 \equiv 0$ and $\Delta_j \equiv 0$, equations (13) and (15) change to a mathematical model of a rail car with permanent repulsion magnets [5] with linear gradient c_i (the absolute value) per unit length of the ski.

Conclusions. Plane disturbed motion of a rail car with an "electromagnetic ski" can be described by two independent systems of ordinary differential equations of order 2(N + 2) each, where N is the number of ski modules, with the simplest law of control with the two first derivatives of the gap.

BIBLIOGRAPHY

1. Baybakov, S. N., B. I. Rabinovich and Yu. D. Sokolov, "The Dynamics of Transport Rolling Stock on Magnetic Suspension," IZVESTIYA AN SSSR, ENERGETIKA I TRANSPORT, No 1, 1981.

2. Brock, K. H., E. Gottzein, E. Mannlein and J. Pfefferl, "Control Aspects of Tracked Magnetic Levitation High-Speed Vehicles," Sixth IFAC Symposium on Automatic Control in Space, Boston/Cambridge, Massachusetts, August 1975.

3. Gottzein, E. and B. Lange, "Magnetic Suspension Control Systems for the MBB High-Speed Train," AUTOMATIKA, Vol 11, 1975.

4. Panovko, Ya. G. and I. I. Gubanova, "Ustoychivost' i kolebaniya uprugikh sistem" [The Stability and Oscillations of Elastic Systems], Moscow, Nauka, 1967.

5. Rabinovich, B. I., "Prikladnyye zadachi ustoychivosti stabilizirovannykh ob"yektov" [Applied Problems of the Stability of Stabilized Objects], Moscow, Mashinostroyeniye, 1978.

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DYNAMICS OF TRANSPORT ROLLING STOCK ON MAGNETIC SUSPENSION

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[Article by S. N. Baybakov, B. I. Rabinovich and Yu. D. Sokolov, Moscow]

[Text] Introduction. High-speed passenger transport on magnetic suspension has won ever greater recognition during the past few years. There are a number of test benches on which the speed of experimental vehicles to 400 km/hr has been achieved [1, 2]. We shall dwell here on low-clearance suspension systems, on the order of 10-15 mm, realized on the basis of controlled attraction electromagnets. One of the central problems related to development of this class of systems is that of providing stability of motion with retention of the clearance close to nominal, with simultaneous provision of a high level of filtration of disturbances related to unevennesses of the track to ensure the necessary conditions of comfort for passengers and also to protect the system against interference. One must encounter some of the problems arising here when considering suspension systems on permanent magnets constructed on the repulsion principle and also electrodynamic suspension systems. A number of aspects of these problems are discussed in [1-8].

Some shift of emphasis in determination of rational areas of the applicability of passenger transport systems on electromagnetic suspension has recently been observed on the trend from mainline to "city-airport" and "city-satellite city" systems. Accordingly, the optimum range of speeds subject to consideration is reduced to 100-250 km/hr, where the lower values correspond to intracity transport and the larger values correspond to "city-airport" and "city-satellite city" transport, compared to mainline systems.

When developing a suspension with favorable dynamic characteristics, it is rational to strive for systems having the highest functional reliability with simple compilation of measurements and the absence of high-precision sensors having movable components (gyroscopic attitude and angular-rate sensors, integrating accelerometers with movable mass and so on). In this case the on-board control system should include a central processor for overall program control of the electromagnets, processing information about the status of all systems and diagnosis of malfunctions and failures and microprocessors or analog subsystems at a lower hierarchical level --in the self-contained electromagnet control circuits.

A suspension system should undoubtedly have adaptability to track unevennesses so as not to place special requirements on the precision of forming the track structure compared to existing transport systems. At the same time, it should provide minimum energy expenditures to correct the corresponding disturbances and should have a high level of comfort in the passenger section.

Solution of all these problems requires complex consideration of the mechanical suspension system and the electromagnet control system.

Adaptation to track unevenness and filtration of disturbances. Let us consider a system based on attraction electromagnets distributed along the length of the body, naturally stable in the lateral direction due to the U-shaped cross-section of the pole shoes and ferromagnetic rails with automatic control of each of the electromagnets, which ensures its stability in the vertical direction, as a specific variant of the suspension system.

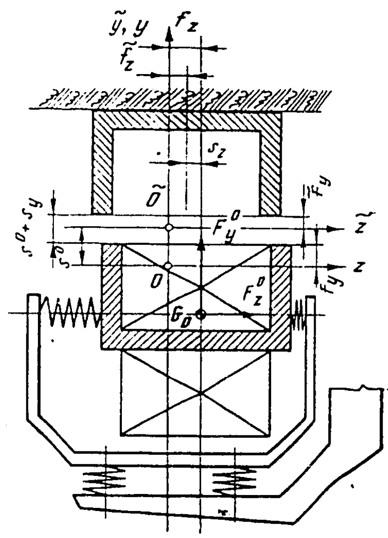

Figure 1. Diagram of Electromagnet With Two Degrees of Freedom

Let the suspension system be realized in the shape of two parallel elastic "magnetic skis," along which are arranged attraction electromagnets (electromagnetic skis). These skis have transverse elasticity in two mutually perpendicular planes and are connected to the body by viscoelastic couplings oriented in the vertical and lateral directions (Figures 1 and 2). The same design can also be used for a system with permanent repulsion magnets interacting with the permanent magnets of the track structure. The specific block diagram of the ski may be different; specifically, this may be a multilink kinematic chain with rigid links--modules which carry two electromagnets each, and elastic spherical joints which connect the modules to each other. The elastic couplings of the skis with the body, which create viscous damping, play the role of a secondary suspension. This suspension scheme has a number of advantages which make it possible to find principal solution of the problems formulated above:

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1. The presence of two levels of dynamic couplings (rail-skis and skis-body) permits firm tracking of the skis over track unevennesses with slight deviations of the clearance from the nominal and soft suspension of the body to the skis when selecting rational values of stiffness and the degree of damping of the mechanical part of the suspension system and the dynamic amplification factor of the electromagnet control circuit.

2. Elastic suspension of electromagnets to the body leads to the fact that the control system should stabilize the mass which comprises 10-20 percent of the total mass of the car and essentially completely suppresses the excitation of the high-frequency harmonics of elastic oscillations of the body itself by the control system. The result is expansion of the zones of stability and a sharp reduction of energy expenditures to correct track disturbances.

3. The elasticity of the skis in the lateral direction permits easy tracking of unevennesses and deviations of the track structure and of each individual rail in the lateral direction and also makes it possible to enter the curvilinear sections of the route.

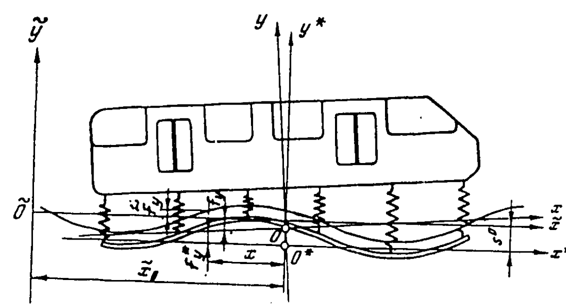

Figure 2. Diagram of Suspension With Electromagnetic Skis

4. Continuous distribution of the electromagnets along the body permits a reduction of their cross-section and accordingly of the cross-section of the ferromagnetic rails, a reduction of linear loads on the supporting frame of the car and the track structure, a reduction of losses to magnetic resistance during motion, i.e., in the final analysis a reduction of the mass of the car and track structure.

5. The operating reliability of the suspension system structure is increased sharply due to significant functional redundancy: the capability of operation upon failure of any single electromagnet is retained and an emergency situation with simultaneous failure of several electromagnets is prevented since adjacent electromagnets take on their functions.

6. The system under consideration of course is not devoid of specific deficiencies, namely: the lower absolute lift of the electromagnet reduces its specific mass characteristics, while the presence of an individual stabilization system for each electromagnet complicates the control system as a whole. However, the advantages of the described configuration scheme undoubtedly exceed the disadvantages.

There are specific problems which require careful consideration in analyzing the disturbed motion of the skis and of the entire "car-ski-track structure" closed system, which will be discussed below.

Mathematical model of a single electromagnet with clearance and current control. Let us consider an electromagnet extended in the direction of the longitudinal axis of the car having U-shaped cross-section in the plane perpendicular to this axis. Let us assume that it is attached to the car by viscoelastic couplings which provide two degrees of freedom to it with respect to the car: motions in the vertical and lateral directions (Figure 1). Let us assume that the car having significantly greater mass than the electromagnet is immobile or movable at constant velocity v. Let us take the state in which there is a small permanent gap $\overset{\circ}{s}$ between the electromagnet poles and the ferromagnetic rail of the U-shaped cross-section and in which there is no deflection of the electromagnet in the lateral direction (its plane of symmetry coincides with that of the rail), as steady undisturbed motion (or equilibrium) of the system. With regard to the plane of symmetry of the rail, let us also assume that in this state the rail has no deviations from the nominal position either in the vertical or lateral directions. Let us introduce right-handed coordinate systems: $\tilde{O}\tilde{x}\tilde{y}\tilde{z}$ bound to an ideal system (having no adjustment errors and undeformed by the track structure) and Oxyz, rigidly connected to the car. The $\tilde{O}\tilde{x}$ and Ox axes of these coordinate systems are directed along the longitudinal axis of the electromagnet in the direction of motion. The origin $\tilde{O}$ is located at an arbitrary point, as which the end of acceleration to velocity v may be taken, so that $x = x_0 + x = vt + x$. Point O lies on the plane of the electromagnet poles. Assuming that deviations of all the generalized coordinates and of their first derivatives during disturbed motion are small compared to the corresponding unperturbed values, let us make use of the general equations of disturbed motion of an electromechanical system with m independent electromagnets having n degrees of freedom [9]:

$$\sum_{i=1}^{n}[a_{ji}\ddot{q}_i+b_{ji}\dot{q}_i+(c_{ji}-d_{ji})q_i]-\sum_{k=1}^{m}e_{jk}I_k'=Q_j,$$
$$\sum_{r=1}^{m}(L_{kr}{}^{\circ}\dot{I}_r+R_{kr}\delta_{kr}I_r)+\sum_{j=1}^{n}e_{jk}\dot{q}_j=U_k \qquad (1)$$
$$(j=1,\ 2,\dots,n;\ k=1,2,\dots,m),$$

where

$$d_{ij}=d_{ji}=\frac{1}{2}\sum_{r,s=1}^{m}\left(\frac{\partial^2 L_{rs}}{\partial q_i\partial q_j}\right)^{\circ}I_r{}^{\circ}I_s{}^{\circ},$$
$$e_{jk}=\sum_{r=1}^{m}\left(\frac{\partial L_{kr}}{\partial q_j}\right)^{\circ}I_r{}^{\circ}=\sum_{r=1}^{m}\left(\frac{\partial L_{rk}}{\partial q_j}\right)^{\circ}I_r{}^{\circ}, \qquad (2)$$
$$\delta_{kr}=\begin{matrix}0 & \text{at} & k\neq r\\ 1 & \text{at} & k=r;\end{matrix}$$

Q_j is the generalized force corresponding to the j-th coordinate, U_k is the voltage applied to the k-th winding, I_r is the current in the r-th electromagnet, q_j is the j-th generalized coordinate, L_{kr} $(r \neq k)$ is the mutual inductance coefficient, L_{kk} and R_{kk} are the self-induction and effective resistance coefficient of the winding of the k-th electromagnet and a_{ji}, c_{ji} and b_{ji} are the matrix components of the generalized mass and stiffness and of the coefficients of the mechanical dissipative function. The superscript ° corresponds to the parameters of unperturbed motion.

Let us apply equations (1) to the case of a single electromagnet with two degrees of freedom and let us reduce the equation of current and clearance control to it:

$$U=\mathscr{A}(s_y)+\mathscr{B}(I), \tag{3}$$

where $\mathscr{A}$ and $\mathscr{B}$ are linear differential operators which we shall subsequently take as second and first order, respectively. Using the more meaningful notations, we find as a result the following equations of perturbed motion:

$$\begin{gathered}
m(\ddot{f}_y+\beta_y\dot{f}_y+\sigma_y^2 f_y)=F_y+F_y^\circ(t);\\
m(\ddot{f}_z+\beta_z\dot{f}_z+\sigma_z^2 f_z)=F_z+F_z^\circ(t);\\
c_I'\dot{I}+RI-c_s'\dot{s}_y=U;\\
U=a_0 s_y+a_1\dot{s}_y+a_2\ddot{s}_y+b_0 I+b_1\dot{I};\\
F_y=c_I I-c_{sy}s_y; \quad F_z=-c_{sz}s_z;\\
s_y=-f_y+\tilde{f}_y(\tilde{x}); \quad s_z=f_z-\tilde{f}_z(\tilde{x}),
\end{gathered} \tag{4}$$

where

$$L_{11}\approx\frac{\bar{L}_{11}(s_z)}{s^\circ+s_y}, \quad c_I'=L_{11}^\circ=\frac{\bar{L}_{11}(0)}{s^\circ},$$

$$\begin{gathered}
c_{sz}=-d_{22}=-\frac{1}{2}\left(\frac{\partial^2\bar{L}_{11}}{\partial s_z^2}\right)\frac{I^{\circ 2}}{s^\circ}>0,\\
c_I=c_s'=e_{11}=L_{11}^\circ(I^\circ/s^\circ), \quad c_{sy}=d_{11}=L_{11}^\circ(I_0/s^\circ)^2>0,\\
d_{12}=d_{21}\equiv 0, \quad e_{12}=e_{21}\equiv 0,\\
\sigma_y^2=c_{ey}/m, \quad \sigma_z^2=c_{ez}/m;
\end{gathered} \tag{5}$$

m is the mass of the electromagnet, β_y, β_z, c_{ey} and c_{ez} are the damping and stiffness coefficients of the viscoelastic couplings, F and U are the ponderomotive force and voltage, s_y and s_z is variation of the vertical and lateral clearance, respectively, f_y, f_z and $\tilde{f}_y(\tilde{x})$, $\tilde{f}_z(\tilde{x})$ are the generalized coordinates which characterize the position of the electromagnet and the rail, $F_y^\circ(t)$ and $F_z^\circ(t)$ are the external perturbing forces reduced to the center of mass of the electromagnet G_0 (Figure 1); coefficients d_{jj} (j = 1, 2), $\bar{L}_{11}$ and e_{11} depend on the configuration of the system and can be determined by means of known methods of simulation of electromagnetic fields [10].

Let us introduce a new variable δ, related to F_y by the relations:

$$F_y = c_{iy} s_y + \delta,$$
$$c_{iy} = k_s - c_{sy}; \quad k_s = \frac{c_I a_0}{R} > c_{sy}. \qquad (6)$$

At $\delta \equiv 0$ we find the quasi-static electromagnet control by the law

$$U = a_0 s_y, \quad I = a_0 s_y / R. \qquad (7)$$

Therefore, δ has the meaning of "control" with respect to a variable control object in which an electromagnet with quasi-static control is transformed, making it statically stable in the vertical direction ($c_{iy} > 0$). Static stability is provided in the lateral direction by the edge effect intensified by the U-shaped cross-section of the poles and rails ($c_{sz} > 0$).

After expressions (6) are substituted into equations (4) and after I is eliminated from the third equation, one can find

$$
\begin{aligned}
& m(\ddot{f}_y + \beta_y \dot{f}_y + \omega_y^2 f_y) = \delta + F_y^{*}(t), \\
& m(\ddot{f}_z + \beta_z \dot{f}_z + \omega_z^2 f_z) = F_z^{*}(t), \\
& \beta_0 \dot{\delta} + \delta + a_{\delta s}' \dot{s}_y + a_{\delta s} s_y = a_{\delta u} U, \\
& U = a_0 s_y + a_1 \dot{s}_y + a_2 \ddot{s}_y + b_0 I + b_1 \dot{I}, \\
& I = a_{I\delta} \delta + a_{Is} s_y, \\
& s_y = -f_y + \tilde{f}_y(\tilde{x}).
\end{aligned} \qquad (8)
$$

Here

$$
\begin{aligned}
& \omega_y^2 = \frac{1}{m}(c_{ey} + c_{iy}) = \frac{1}{m}(c_{ey} - c_{sy} + k_s), \quad \omega_z^2 = \frac{1}{m}(c_{ez} + c_{sz}), \\
& \beta_\delta = c_I'/R, \quad a_{\delta u} = c_I/\dot{R}, \quad a_{I\delta} = 1/c_I, \\
& a_{\delta s}' = c_{iy} \frac{c_I'}{R}, \quad a_{\delta s} = k_s, \quad a_{Is} = \frac{a_0}{R}, \\
& F_y^{*}(t) = F_y^{\circ}(t) + c_{iy} \tilde{f}_y(\tilde{x}), \quad F_z^{*}(t) = F_z^{\circ}(t) + c_{sz} \tilde{f}_z(\tilde{x}).
\end{aligned} \qquad (9)
$$

The system of equations (7) is a variant of the mathematical model of an electromagnet convenient for investigation of the dynamics of an electromagnetic ski.

Mathematical model of an automatically stabilized electromagnetic ski. Let us consider an elastic beam on a linear viscoelastic base (mechanical suspension) with electromagnets continuously distributed along its length that do not interact with each other as an idealized model of an electromagnetic ski. Let us describe the latter by mathematical model (8), assuming that all its characteristics (4) and (9) are related to the unit of length in the direction of the longitudinal axis of the electromagnet.

Let us now take into account the perturbed motion of the car. Let us use the coordinate systems $\tilde{O}\tilde{x}\tilde{y}\tilde{z}$ and Oxyz introduced above, to which we add the intermediate coordinate system O*x*y*z* connected to the car during undisturbed motion. Let us place the origin O on the line of intersection of the plane passing through the center of mass of the "car-ski" system and the end plane of the pole shoes (Figures 1 and 2).

The disturbed motion of the ski consists of its transient motion together with coordinate system Oxyz (the disturbed motion of the car) and relative motion with respect to coordinate system Oxyz (Figure 2).

Let us ascribe the same properties to the disturbed motion of the car as a rigid solid as to the disturbed motion of each electromagnet and of the entire ski. Linear functions f_y^* (x, t) and f_z^* (x, t) of the displacements of the ski points with respect to x correspond to this transient motion.

All the values which characterize the mathematical model of the electromagnet introduced in the previous section now become functions of two independent variables x and t and they may be dependent on time both explicitly and by means of $\tilde{x}(t)$ as, for example, $\tilde{f}_y(\tilde{x})$ and $\tilde{f}_z(\tilde{x})$.

Let us assume that the track structure and the trestle at a given stage of investigation are absolutely rigid. Taking kinematic relations into account

$$s_y(x,t)=-f_y^*(x,t)-f_y(x,t)+\tilde{f}_y(\tilde{x}),$$
$$s_z(x,t)=f_z^*(x,t)+f_z(x,t)-\tilde{f}_z(\tilde{x}) \qquad (10)$$

and using equations (8) and also the boundary-value conditions for a beam with free ends, we find the following systems of equations in partial derivatives and boundary-value conditions:

$$\frac{\partial^2}{\partial x^2}\left(EJ_z\frac{\partial^2 f_y}{\partial x^2}\right)+m\frac{\partial^2 f_y}{\partial t^2}+\beta_y\frac{\partial f_y}{\partial t}+\alpha_y f_y=\delta+F_y^*(x,t),$$
$$\beta_\delta\frac{\partial\delta}{\partial t}+\delta+a_{\delta s}'\frac{\partial s_y}{\partial t}+a_{\delta s}s_y=a_{\delta u}u,$$
$$u(x,t)=a_0 s_y+a_1\frac{\partial s_y}{\partial t}+a_2\frac{\partial^2 s_y}{\partial t^2}+b_0 i+b_1\frac{\partial i}{\partial t}, \qquad (11)$$

$$i(x,t)=a_{I\delta}\delta+a_{Is}s_y,$$
$$s_y(x,t)=-f_y+\tilde{f}_y(\tilde{x})-f_y^*(x,t);$$
$$\frac{\partial}{\partial x}\left(EJ_z\frac{\partial^2 f_y}{\partial x^2}\right)=0;\quad EJ_z\frac{\partial^2 f_y}{\partial x^2}=0 \quad \text{at} \quad x=\pm\frac{l}{2};$$
$$\frac{\partial^2}{\partial x^2}\left(EJ_y\frac{\partial^2 f_z}{\partial x^2}\right)+m\frac{\partial^2 f_z}{\partial t^2}+\beta_z\frac{\partial f_z}{\partial t}+\alpha_z f_z=E_z^*(x,t), \qquad (12)$$
$$\frac{\partial}{\partial x}\left(EJ_y\frac{\partial^2 f_z}{\partial x^2}\right)=0,\quad EJ_y\frac{\partial^2 f_z}{\partial x^2}=0 \quad \text{at} \quad x=\pm\frac{l}{2};$$

Here

$$F_y^*(x,t)=f_y^\circ(x,t)-m\frac{\partial^2 f_y^*(x,t)}{\partial t^2}+c_{iy}s_y^*(x,t),$$
$$F_z^*(x,t)=f_z^\circ(x,t)-m\frac{\partial^2 f_z^*(x,t)}{\partial t^2}-c_{sz}s_z^*(x,t),$$
$$s_y^*(x,t)=\tilde{f}_y(\tilde{x})-f_y^*(x,t),$$
$$s_z^*(x,t)=-\tilde{f}_z(\tilde{x})+f_z^*(x,t),$$
$$\alpha_y=c_{iy}+c_{ey},\quad \alpha_z=c_{sz}+c_{ez}; \tag{13}$$

l is the length of the ski, EJ_y and EJ_z are the bending stiffness in two planes of the ski as an elastic beam and u(x, t), i(x, t), $f_y^\circ(x, t)$ and $f_z^\circ(x, t)$ correspond to U, I, F_y° and F_z° contained in (8) and (9).

We found two independent boundary-value problems (11) and (12) which together with additional relations (13) form a closed mathematical model of an automatically stabilized electromagnetic ski. If one assumes that $c_{sz} = -c_{sz}'$, where $c_{sz}' > 0$ and $\delta \equiv 0$, then this model will describe a ski with permanent repulstion magnets (without a control system).

The equations in partial derivatives (10) and (11) can be reduced by the Bubnov-Galerkin method to an infinite system of ordinary differential equations which is reduced upon transition to one or another discrete model to a finite system of linear equations. It is convenient to select the harmonics of the natural oscillations of the ski at $\delta \equiv 0$, $\beta_y \equiv 0$ and $\beta_z \equiv 0$ as the coordinate functions.

Some problems of the dynamics of the "car-ski" system. Let us consider the disturbed motion of a ski in the vertical plane, taking as undisturbed motion the motion of the ski with constant velocity v in the direction of the $O\tilde{x}$ axis and with permanent gap s°. Let us disregard damping in the elastic couplings and let us approximate by sine waves the harmonics of natural oscillations of the ski in the first approximation. Let the track structure have sinusoidal disturbances $\tilde{f}_y(\tilde{x})$ with period λ with respect to $\tilde{x}$ (wavelength). Introducing into consideration the speed of propagation of the j-th travelling wave $v_j = \lambda_j\sigma_j/2$, where λ_j and σ_j are the length of the standing wave which approximates the j-th harmonic of natural oscillations of the ski and the natural frequency corresponding to it, we find the critical travelling speed of the ski at which resonance corresponding to excitation of the j-th harmonic of its natural oscillations begins at $\lambda = \lambda_j$. The following inequality must be fulfilled for normal functioning of the ski

$$v<\{v_j\}_{\min}\ (j=1,\,2,\ldots,N), \tag{14}$$

where N is a finite number which determines the higher harmonic of ski oscillations which can be excited in a real design.

If the ski is made by the scheme of a multilink kinematic chain with negligible bending stiffness ($EJ_z \to 0$), then as follows from the first equation of (11), all the frequencies of natural oscillations are identical and equal to

$$\Omega\sqrt{\alpha_y/m}=\sqrt{(c_{iy}+c_{ey})/m}. \quad (15)$$

In this case

$$\{v_j\}_{min}=\Omega\lambda_{min}/2\pi. \quad (16)$$

If the critical velocity is exceeded, the ski is in counterphase to the corresponding harmonic of disturbances of the track structure, i.e., it loses the property of adaptivity to this harmonic. Hence, the need to maximize the value of $\alpha_y = c_{iy} + c_{ey}$ is clear, which permits an increase of critical velocity.

However, the suspension should be sufficiently soft to improve the mechanical filtration of disturbances, which places restrictions from the top on the stiffness of the elastic couplings c_{ey}. Consequently, the static amplification factor a_0 in the electromagnet control circuit, which directly affects parameter c_{iy}, must be increased if possible.

The situation is analogous in the horizontal plane where parameter c_{sz} must be maximized. Besides the presence of the correct range of natural frequencies, practically total damping of its free oscillations during time $T = v/\lambda$ is required for normal functioning of the ski in the sense of its dynamics, which places rigid restrictions on the minimum value of the damping coefficient of elastic couplings of the ski with the body. Correct consideration of the dynamic interaction of the ski and body plays an important role in selection of the suspension parameters during controlled motion under conditions of stochastic disturbances. All this gives rise to the problem of developing a more complete mathematical model for describing the disturbed motion of the "body-electromagnetic skis" system and optimization of its parameters.

Synthesis of rational laws of control (of stabilization algorithms) oriented toward sufficiently simple compilation of measurements (1) and at the same time which satisfy the requirements which were formulated above within the framework of the more adequate mathematical models of the control object is also one of the most important problems related to development of an electromagnetic suspension system.

Since each electromagnet in the adapted concept of the control system is self-contained, any sufficiently complete mathematical model should include a mathematical description of a large number of partial "object-regulator" systems, which sharply increases the order of the corresponding differential equations even with simple stabilization algorithms. The problem of developing special methods, algorithms and programs for investigating the stability of their solutions, specially adjusted to the structure and dynamic characteristics of these systems, is very acute (see [11]). The problem of mathematical modelling of disturbed motion is no less acute, including construction of the corresponding a priori statistical portraits, which suggests the necessity of processing large information flows. Modern finite digital computer devices of the graph-plotter and graphical display type, which permit efficient visualization of the disturbed motion of a system during mathematical modelling, may be of inestimable value in this case.

Thus, one of the main trends of investigations to develop these suspension systems is synthesis of the laws of electromagnet control (stabilization algorithms) simultaneously with selection of the dynamic characteristics of their viscoelastic couplings to the body to optimize the dynamic characteristics of the suspension system as a whole. An important element of quantitative analysis and synthesis of these systems is development of adequate mathematical models and methods of investigating them which take into account the specifics of a large number of degrees of freedom, a developed control system and complex dynamic couplings between subsystems.

Conclusions. The problem of synthesis of electromagnetic suspension systems with optimum dynamic characteristics may essentially be solved on the basis of the "electromagnetic ski" concept, which includes viscoelastic mechanical suspension and autonomous control systems for each of the electromagnets distributed along the length of the "ski."

BIBLIOGRAPHY

1. Brock, K. H., E. Gottzein, E. Mannlein and J. Pfeffert, "Control Aspects of Tracked Magnetic Levitation High-Speed Vehicles," Sixth IFAC Symposium on Automatic Control in Space, Boston/Cambridge, Massachusetts, August 1975.

2. Gottzein, E. and B. Lange, "Magnetic Suspension Control Systems for the MBB High-Speed Train," AUTOMATIKA, Vol 11, 1975.

3. Gottzein, E., L. Miller and R. Meisinger, "Magnetic Suspension Control System for High-Speed Ground Transportation Vehicles," World Electrotechnical Congress, June 21-25, 1977.

4. Thornton, R. D., "Magnetic Levitation and Propulsion," IEEE TRANSACTIONS ON MAGNETICS, Vol Mag-11, No 4, July 1975.

5. Laithwaite, E. R., "Transport Without Wheels," London, ELECTRONICS SCIENCE, 1977.

6. Tozoni, O. V., "Calculation of an Electromagnet Field Moving Along a Ferromagnetic Plate," IZVESTIYA AN SSSR. ENERGETIKA I TRANSPORT, No 6, 1977.

7. Kochetkov, V. I., "Calculation of Levitation Characteristics with Electrodynamic Suspension of High-Speed Vehicles," IZVESTIYA AN SSSR. ENERGETIKA I TRANSPORT, No 6, 1977.

8. Mikirtichev, A. A., K. I. Kim and S. V. Vasil'yev, "The Electromagnetic Properties of a Repulsive Levitation System with Three-Dimensional Oscillations of the Field Sources," IZVESTIYA AN SSSR. ENERGETIKA I TRANSPORT, No 4, 1978.

9. "Vibratsiya v tekhnike" [Vibration in Equipment], Vol 2, Moscow, Mashinostroyeniye, 1979.

10. Demirchyan, K. S., "Modelirovaniye magnitnykh poley" [Simulation of Magnetic Fields], Moscow, Energiya, 1974.

11. Kalinina, A. V., V. G. Lebedev and B. I. Rabinovich, "A Recursion-Iteration Algorithm for Solving the Characteristic Equation in Problems of the Dynamics

of Structures and Its Realization on the BESM-6 and YeS-1040 Computers," in "Issledovaniya po teorii sooruzheniy" [Investigations on the Theory of Structures], Moscow, Stroyizdat, 1980.

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MARINE AND SHIPBUILDING

VIBRATION ABSORPTION ON SHIPS

Leningrad VIBROPOGLOSHCHENIYE NA SUDAKH in Russian 1979 (signed to press 21 Dec 78) pp 4, 183-184

[Annotation and table of contents from book "Vibration Absorption on Ships" by Aleksey Sergeyevich Nikiforov, Izdatel'stvo "Sudostroyeniye", 2,700 copies, 184 pages]

[Text] The different aspects of the problem of reducing acoustic vibration occurring in ship structures during operation of machinery and which is the cause of an increase of airborne noise in ship compartments, are considered. The operating principle of vibration-absorbing devices and their designs are described. Recommendations are presented on efficient use of means of vibration absorption and methods of estimating their acoustic efficiency on ships. The technology of manufacturing some vibration absorbing materials is outlined.

The book is intended for engineering and technical and scientific personnel involved in problems of reducing acoustic vibrations and airborne noise on ships. It may be of interest to specialists working on problems of reducing acoustic vibrations and noise in motor, rail and air transport. The book will be useful to students and graduate students specializing in the indicated field of acoustics.

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AUTOMATED SHIP POWER PLANTS

Moscow SUDOVYYE AVTOMATIZIROVANNYYE ENERGETICHESKIYE USTANOVKI in Russian 1980 (signed to press 31 Mar 80) pp 2, 350-352

[Annotation and table of contents from book "Automated Ship Power Plants", by Pavel Petrovich Akimov, Izdatel'stvo "Transport", 7,000 copies, 352 pages]

[Text] The book is a textbook on the course "Automated Ship Power Plants" for electromechanical, navigation and operational faculties of higher educational institutions of the Ministry of the Maritime Fleet.

The designs of the main and auxiliary ship engines, ship steam boilers and auxiliary machinery, their operating principle, automatic control and some problems of technical operation are considered in the textbook.

Most attention is devoted in the book to description of the power plants of the latest serial ships. However, future plants--gas turbine and nuclear (atomic) are also considered in it. Some problems of engineering thermodynamics are outlined in Section 1 of the textbook for conscious understanding of the working processes occurring in engines and machinery.

All the composite parts of ship power plants are essentially considered in the textbook and special attention is devoted to automation of servicing them. The operational and technical and economic indicators of modern ship power plants of various types are also considered.

Examples with detailed solutions are presented in the textbook for correspondence students.

The book may be of interest to navigators, electrical engineers and engineering and technical personnel of ship handling services of marine shipping companies.

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NON-NUCLEAR ENERGY

MODERNIZATION OF TURBOGENERATORS

Moscow MODERNIZATSIYA TURBOGENERATOROV in Russian 1980 (signed to press 7 May 80) pp 2-4, 230-231

[Annotation, foreword and table of contents from book "Modernization of Turbogenerators" by Yuriy Ivanovich Azbukin and Vladimir Yur'yevich Avrukh, Izdatel'stvo "Energiya", 3,000 copies, 232 pages]

[Text] The technical and economic bases for modernization of the power engineering equipment of electric power plants are given. The main directions in modernization of turbogenerators and of improving their operating modes and methods of improving cooling and ventilation systems are presented. Problems of increasing the output and reliability of turbogenerators are outlined.

The book is intended for engineering and technical personnel, foremen and brigade leaders involved in design, maintenance and repair of the electrical equipment of electric power plants.

Foreword

The basic stock of power engineering equipment of thermoelectric power plants is being supplemented continuously by new units made with regard to the latest advances of energy machine-building technology. At the same time, machines with the technical level of many years, but with a degree of actual depreciation that do not justify disassembly and replacement by new equipment continue to be operated in all energy systems.

The gap between the technical levels of old and new equipment is increasing constantly. This is especially discernible in turbogenerators, the main design principles of which have undergone great changes during the past 20-25 years. Moreover, the operating conditions have changed and new requirements have appeared which previously produced equipment do not meet.

Many years of experience in operation of old-model turbogenerators made it possible to determine weak spots in the design and to evaluate their latent reserves that remain unutilized.

The experience of manufacture and operation of new turbogenerators also made it possible to critically reevaluate a number of principle design propositions included in previously produced machines.

Modernization of equipment, during which assemblies inadequately resolved with success are reconstructed, increases the strength and thermal reserves of the active parts of the turbogenerator and permits an increase of the output, economy and operating reliability of the equipment. Besides the direct economic effectiveness, modernization permits operational testing of the original engineering solutions and makes it possible to bring the finishing of individual assemblies of a machine to a high degree of perfection. The results of this work, along with investigations of plant laboratories and observations of operational personnel, contribute to the appearance of new technical ideas which have been realized by domestic turbogenerator building plants in development of new machines.

The turbogenerator building plants which systematically inspect all their products, themselves conduct extensive work on modernization of existing machines.

The development of typical plans for modernization of turbogenerators at the USSR Ministry of Power and Electrification is concentrated in the Central Design Office (TsKB) of Glavenergoremont [Main Administration for the Repair of Electric Power Plant Equipment].

The leading production repair enterprises of Glavenergoremont: Rostovenergoremont [Rostov Administration for Repair of Electric Power Plant Equipment], Uralenergoremont [Urals Administration for Repair of Electric Power Plant Equipment], Mosenergoremont [Moscow Administration for Repair of Electric Power Plant Equipment], Lenenergoremont [Leningrad Administration for Repair of Electric Power Plant Equipment], L'vovenergoremont [L'vov Administration for Repair of Electric Power Plant Equipment] and others, whose personnel took on themselves the responsibility of introduction and debugging of pilot prototypes and also participated creatively in development of a number of modernization plans, made an important contribution to modernization of power engineering equipment.

Modernization of turbogenerators carried out according to plans developed by the collective of the Department of Turbogenerators of TsKB under the supervision of the authors, is mainly considered in the book. The leading specialists of the department comrades A. G. Voinov, L. A. Duginov, N. M. Portnov and V. A. Shelepov are developers of most plans for modernization and coinventors of inventions on the basis of which the modernization plans were developed. Since one of the problems of modernization is to ensure reliable operation and optimum operating parameters of turbogenerators under normal and special operating modes, some operating mode problems are reflected in the book.

Chapters 1 and 2 were written by V. Yu. Avrukh, Chapters 3 and 5 were written by Yu. I. Azbukin and Chapters 4 and 6 were written jointly.

The authors will be grateful for comments and suggestions with respect to the book and request that they be sent to the address of Izdatel'stvo "Energiya": 113114, Moscow, M-114, Shlyuzovaya naberezhnaya, 10.

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NAVIGATION AND GUIDANCE SYSTEMS

GYRO STABILIZERS OF INERTIAL CONTROL SYSTEMS

Leningrad GIROSTABILIZATORY INERTSIAL'NYKH SISTEM UPRAVLENIYA in Russian 1979 (signed to press 19 Feb 79) pp 2-4, 143-150

[Annotation, foreword, table of contents and bibliography from book "Gyro Stabilizers of Inertial Control Systems" by Leonid Anatol'yevich Severov, Izdatel'stvo Leningradskogo universiteta, 924 copies, 152 pages]

[Text] Gyro stabilizers of noncorrectable inertial control systems of unmanned flight vehicles are considered in the book. Main attention is devoted to problems of analysis and synthesis of the platform stabilization circuit. A kinematic and dynamic description of gyro stabilizers with different layouts of the gimbal suspensions of the platform and with different methods of arrangement of gyroscopes and stabilizing motors is presented. The problem of analytical design of practically realizable optimum gyro stabilizer regulators is posed and solved. The possibility of achieving high amplification factors in the stabilization circuit is analyzed both from viewpoints of structural conditions of the stability of a multidimensional linear system and from the condition of the absolute stability of a system with standard nonlinear components.

The book is intended for specialists involved in design of gyro stabilizers and may also be useful to students and graduate students of the corresponding specialties.

Foreword

The modern self-contained inertial control systems (ISU) of flight vehicles are constructed with gyro stabilization of the inertial sensing elements, which is most frequently realized by using a three-axis gyro stabilizer (TGS) [1-5].

Inertial orientation of the TGS platform is usually employed in the ISU. The short operating time of the system permits one to construct closed type ISU [6]. Variation of the acceleration of gravity during flight is taken into account with more precise solution of the control problem [1]. It follows from the foregoing that the ISU error will include the errors introduced by the TGS. Therefore, special attention is devoted in design of TGS to solution of two main problems: 1) highly accurate initial deployment of the platform with inertial sensing elements and 2) provision of precise inertial orientation of the platform during flight.

It must be noted that TGS of the type under consideration operate during flight under intensive vibrations and g-loads. This significantly complicates solution of the second main problem and requires construction of a platform stabilization circuit with high amplification factors and adoption of special measures to reduce the instrument drift of the platform [4].

Problems of analysis and design of a platform stabilization system are mainly outlined in the given monograph. A mathematical model of a multidimensional stabilization system which takes into account elastic deformations of components, standard nonlinearities and different arrangements of gyroscopes and stabilizing motors is developed. The composition of the perturbing effects is analyzed and the problem of analytical design of practically realizable optimum TGS regulators of inertial control systems is posed and solved. The possibility of achieving high amplification factors in the stabilization system is analyzed both from the viewpoint of structural conditions of the stability of TGS constructed on the basis of one-axis gyroscopes and from conditions of the absolute stability of a multidimensional nonlinear system containing typical nonlinearities of components.

The author hopes that the proposed book is useful in solving problems of design of TGS of inertial control systems.

Contents

BIBLIOGRAPHY

1. Ishlinskiy, A. Yu., "Inertsial'noye upravleniye ballisticheskimi raketami" [Inertial Control of Ballistic Missiles], Moscow, Nauka, 1968.

2. Nazarov, B. I., "Power Gyro Stabiliziers," in "Razvitiye mekhaniki giroskopicheskikh i inertsial'nykh sistem" [Developing the Mechanics of Gyroscopic and Inertial Systems], Moscow, 1973.

3. "Giroskopicheskiye sistemy. Proyektirovaniye giroskopicheskikh sistem" [Gyroscopic Systems. Design of Gyroscopic Systems], edited by D. S. Pel'por, Parts 1 and 2, Moscow, 1977.

4. "Inertsial'nyye sistemy upravleniya" [Inertial Control Systems], edited by J. Pittman, Moscow, 1964.

5. "Inertsial'naya navigatsiya" [Inertial Navigation], edited by K. F. O'Donnell, Moscow, 1969.

6. Fridlender, G. O., "Inertsial'nyye sistemy navigatsii" [Inertial Navigation Systems], Moscow, 1961.

7. Pel'por, D. S., "Giroskopicheskiye sistemy" [Gyroscopic Systems], Moscow, 1971.

8. "Giroskopicheskiye sistemy" [Gyroscopic Systems], edited by L. A. Severov, Leningrad, 1975.

9. Ishlinskiy, A. Yu., "Orientatsiya, giroskopy i inertsial'naya navigatsiya" [Orientation, Gyroscopes and Inertial Navigation], Moscow, 1976.

10. Maunder, L., "Problems of the Dynamics of the Gimbal Suspension of Gyroscopes," in "Problemy giroskopii" [Problems of Gyroscopy], Moscow, 1967.

11. Ponyrko, S. A. and L. A. Severov, "Engineering Methods of Compiling the Equations of Motion of a Three-Axis Gyro Stabilizer," TRUDY LIAP.

12. Besekerskiy, V. A. and Ye. A. Fabrikant, "Dinamicheskiy sintez sistem giroskopicheskoy stabilizatsii" [Dynamic Synthesis of Gyro Stabilization Systems], Leningrad, 1968.

13. Brokmeyster, I. F., "Sistemy inertsial'noy navigatsii" [Inertial Navigation Systems], Leningrad, 1967.

14. Rivkin, S. S., "Applying the Method of Matrix Theory to Analysis of the Configuration of Gyroscopic Devices," in "Voprosy prikladnoy giroskopii" [Problems of Applied Gyroscopy], No 2, Leningrad, 1960.

15. Roytenberg, Ya. N., "Giroskopy" [Gyroscopes], Moscow, 1966.

16. Lur'ye, L. I., "Analiticheskaya mekhanika" [Analytical Mechanics], Moscow, 1961.

17. Butenin, N. V., "Vvedeniye v analiticheskuyu mekhaniku" [Introduction to Analytical Mechanics], Moscow, 1971.

18. Arnol'd, R. N. and L. Monder, "Girodinamika i yeye tekhnicheskoye primeneniye" [Gyro Dynamics and Its Engineering Application], Moscow, 1964.

19. Savant, S. J. et al, "Printsipy inertsial'noy navigatsii" [Principles of Inertial Navigation], Moscow, 1965.

20. Safarov, R. G., "Analyzing the Stability of a Three-Axis Gyro Stabilizer With Additional Frame," in SBORNIK NAUCHNYKH TRUDOV PLI, No 47, Perm', 1968.

21. McClure, K. L., "Teoriya inertsial'noy navigatsii" [Inertial Navigation Theory], Moscow, 1964.

22. El'sgol'ts, L. E., "Differentsial'nyye uravneniya i variatsionnoye ischisleniye" [Differential Equations and Variational Calculus], Moscow, 1969.

23. Siu, D. and A. Meyyer, "Sovremennaya teoriya avtomaticheskogo upravleniya i yeye primeneniye" [Modern Theory of Automatic Control and Application of It], Moscow, 1972.

24. Pukhov, R. Ye., G. I. Grezdov and A. F. Verlan', "Metody resheniya krayevykh zadach na elektronnykh modelyakh" [Methods of Solving Boundary-Value Problems on Electron Models], Kiev, 1965.

25. Berezin, I. S. and N. G. Zhidkov, "Metody vychisleniya" [Methods of Calculation], Moscow, 1966.

26. Severov, L. A. and G. M. Bykova, "Optimum Control of the Supplementary Ring Motor in a Three-Axis Gyro Stabilizer With Arbitrary Motion of the Object," in "Prikladnaya giroskopiya" [Applied Gyroscopy], Izd-vo Leningradskogo universiteta, 1974.

27. Bykova, G. M. and L. A. Severov, "Optimization of the Kinematic Characteristics of the Gimbal Suspensions of Three-Axis Gyro Stabilizers With Additional Degrees of Freedom," IZVESTIYA VYSSHIKH UCHEBNIKH ZAVEDENIY. PRIBOROSTROYENIYE, Vol 20, No 6, 1977.

28. Nazarov, B. I., "Gyro Stabilizer Errors," IZVESTIYA AN SSSR, OTN. TEKHNICHESKAYA KIBERNETIKA, No 2, 1963.

29. Rivkin, S. S., "Investigating Ship Gyro Devices With Irregular Rolling of the Ship," in "Pervaya mezhvuzovskaya nauchno-tekhnicheskaya konferentsiya po problemam sovremennoy giroskopii" [The First Intervuz Scientific and Technical Conference on Problems of Modern Gyroscopy], Leningrad, 1960.

30. Kuzovkov, N. T., "The Stability of Power Gyro Stabilizers With Large Deflection Angles," IZVESTIYA AN SSSR, OTN, No 1, 1958.

31. Pel'por, S. D., Yu. A. Kolosov and Ye. R. Rakhteyenko, "Raschet i proyektirovaniye giroskopicheskikh stabilizatorov" [Calculation and Design of Gyro-Stabilizers], Moscow, 1972.

32. Severov, L. A., "Problems of the Dynamics of a Three-Axis Gyro Stabilizer, in "Problemy povysheniya tochnosti i nadezhnosti giroskopicheskikh sistem" [Problems of Increasing the Accuracy and Reliability of Gyroscopic Systems], Leningrad, 1967.

33. Severov, L. A. and P. B. Dergachev, "Orientation of Gyroscopes on a Three-Axis Gyro Stabilizer Platform," TRUDY LIAP, No 60, 1969.

34. Astrom, K. J., "Analysis and Synthesis of Inertial Platforms With Single-Axis Gyroscopes," Goteborg, 1919.

35. Nazarov, B. I., "The Dynamic Drift of Gyroscopic Devices During Random Perturbations," in "Problemy povysheniya tochnosti i nadezhnosti giroskopicheskikh sistem," Leningrad, 1967.

36. Novozhilov, I. V., "The Working Principle of a Three-Axis Gyro Stabilizer," IZVESTIYA AN SSSR. MEKHANIKA, No 5, 1965.

37. Shilinskiy, A. Yu., "Mekhanika giroskopicheskikh sistem," [The Mechanics of Gyroscopic Systems], Moscow, 1963.

38. Shilinskiy, A. Yu., "One Mechanical Analogy of a Gyro Stabilizer in the Presence of the Elastic Pliability of Its Components," DOKLADY AN SSSR, Vol 161, No 6, 1965.

39. Severov, L. A., "Calculating the Stability of Gyroscope Frames With Regard to the Flexible Pliancy of Some Components of the Gyroscope Suspension," IZVESTIYA VYSSHYKH UCHEBNIKH ZAVEDENIY. PRIBOROSTROYENIYE, No 6, 1963.

40. Morozovskiy, V. T., "Mnogosvyazannyye sistemy avtomaticheskogo regulirovaniya" [Multiconnected automatic control systems], Moscow, 1970.

41. Letov, A. M., "Analytical Design of Regulators," AVTOMATIKA I TELEMEKHANIKA, Vol 21, No 4-6, 1960; Vol 22, No 4, 1961.

42. Aleksandrov, A. G., "Analytical Design of an Optimum Gyroscopic Frame Regulator Installed on a Fixed Base," AVTOMATIKA I TELEMEKHANIKA, No 12, 1967.

43. Abramov, A. T. and I. B. Berlin, "Synthesis of the Optimum Control Part of a Power Gyro Stabilizer," AVTOMATIKA I TELEMEKHANIKA, No 8, 1970.

44. Shandon, S. L. and Chang, "Sintez optimal'nykh sistem avtomaticheskogo upravleniya" [Synthesis of Optimum Automatic Control Systems], Moscow, 1964.

45. Larin, V. B., K. I. Naumenko and V. N. Suntsev, "Sintez optimal'nykh lineynykh sistem s obratnoy svyaz'yu" [Synthesis of Optimum Linear Feedback Systems], Kiev, 1973.

46. Yanushevskiy, R. T., "Teoriya lineynykh optimal'nykh mnogosvyazannykh sistem upravleniya" [The Theory of Linear Optimum Multiconnected Control Systems], Moscow, 1973.

47. Nazarov, B. I. and G. A. Khlebnikov, "Girostabilizatory raket" [The Gyro Stabilizers of Missiles], Moscow, 1975.

48. "Navigatsiya, navedeniye i stabilizatsiya v kosmose" [Navigation, Guidance and Stabilization in Space], edited by D. E. Miller, Moscow, 1970.

49. Sinitsin, I. N. and L. N. Slezkin, "Gyro Stabilizers of Linear Accelerations," in "Razvitiye mekhaniki giroskopicheskikh i inertsial'nykh sistem" [Developing the Mechanics of Gyroscopic and Inertial Systems], Moscow, 1973.

50. Livshits, N. A. and V. N. Pugachev, "Veroyatnostnyy analiz sistem avtomaticheskogo upravleniya" [Probability Analysis of Automatic Control Systems], Parts 1 and 2, Moscow, 1963.

51. Reising, H. and T. Angelitse, "Measuring Apparatus for Investigating the Unstable Combustion Phenomenon," in "Issledovaniye raketnykh dvigateley na zhidkom toplive" [Investigation of Liquid-Fuel Rocket Engines], Moscow, 1964.

52. Pittman, J. and E. Goodson, "The Behavior of Gyroscopic Devices Exposed to Random Vibrations," in "Problemy giroskopii" [Problems of Gyroscopy], Moscow, 1967.

53. Roytenberg, Ya. N., "Avtomaticheskoye upravleniye" [Automatic Control], Moscow, 1971.

54. Solodovnikov, V. V. and V. L. Lenskiy, "Synthesis of Control Systems of Minimum Complexity," IZVESTIYA AN SSSR. TEKHNICHESKAYA KIBERNETIKA, No 2, 1966.

55. Solodovnikov, V. V., "The Principle of Minimum Complexity and Its Application to Regularization of Problems of Optimum Stochastic Control," IZVESTIYA VYSSHIKH UCHEBNIKH ZAVEDENIY. PRIBOROSTROYENIYE, Vol 13, No 3, 1970.

56. Kalman, R. E., "When is a Linear Central System Optimal?" in Joint Automatic Control Conference, Minnesota, 1963.

57. Doetsch, G., "Rukovodstvo k prakticheskomu primeneniyu preobrazovaniya Laplasa" [Handbook on Practical Application of the Laplace Transform], Moscow, 1965.

58. Gantmakher, F. R., "Teoriya matrits" [Matrix Theory], Moscow, 1967.

59. Sveshnikov, A. G. and A. N. Tikhonov, "Teoriya funktsiy kompleksnoy peremennoy" [The Theory of Complex Variable Functions], Moscow, 1970.

60. Sveshnikov, A. A., "Prikladnyye metody teorii sluchaynykh funktsiy" [Applied Methods of Random Function Theory], Moscow, 1968.

61. Davis, M. C., "On Factoring the Spectral Matrix," in Joint Automatic Control Conference, Minnesota, 1963.

62. "Sovremennaya teoriya sistem upravleniya" [Modern Theory of Control Systems] edited by K. T. Leondes, Moscow, 1970.

63. Lunts, Ya. L., "Oshibki giroskopicheskikh priborov" [Errors of Gyroscopic Devices], Leningrad, 1968.

64. Severov, L. A. and Yu. A. Taran, "The Drift of a Static Three-Axis Gyro Stabilizer Exposed to Random External Perturbation Through One Stabilization Axis," IZVESTIYA VYSSHIKH UCHEBNIKH ZAVEDENIY. PRIBOROSTROYENIYE, Vol 12, No 4, 1969.

65. Ishlinskiy, A. Yu., "The Lower Stability of a Two-Axis Gyro Stabilizer Compared to a Single-Axis Stabilizer," DOKLADY AN SSSR, No 6, 1965.

66. Karpov, V. N., "The Dynamics of a Three-Axis Gyro Stabilizer," IZVESTIYA VYSSHIKH UCHEBNIKH ZAVEDENIY. PRIBOROSTROYENIYE, No 5, 1964.

67. Slezkin, L. N. and Dang-Zhi Wang, "The Effect of Relationships Between Heat of a Gyro Platform," IZVESTIYA VYSSHIKH UCHEBNIKH ZAVEDENIY. PRIBOROSTROYENIYE, No 4, 1965.

68. Severov, L. A., "The Effect of the Inertia of a Gimbal Suspension on the Stability of a Three-Dimensional Gyroscope Frame on Floated Integrating Gyroscopes," TRUDY LIAP, No 40, 1963.

69. Sobolev, O. S., "Odnotipnyye svyazannyye sistemy regulirovaniya" [Single-Type Connected Control Systems], Moscow, 1973.

70. Besekerskiy, V. A. and Ye. P. Popov, "Teoriya sistem avtomaticheskogo regulirovaniya" [The Theory of Automatic Control Systems], Moscow, 1966.

71. Severov, L. A., "Synthesizing the Parameters of a Single-Axis Gyro Stabilizer on an Integrating Gyroscope With Typical Intermittent Perturbation," TRUDY LIAP, No 49, 1966.

72. Formal'skiy, A. M., "Upravlyayemost' i ustoychivost' sistem s ogranichennymi resursami" [The Controllability and Stability of Systems With Limited Resources], Moscow, 1974.

73. Popov, Y. M., "New Criterion of the Stability of Automatic Nonlinear Systems," REV. D'ELECTR. ET D'ENERG., No 1, 1960.

74. Dzhuri, E. and B. Lee, "The Absolute Stability of Systems With Many Nonlinearities," AVTOMATIKA I TELEMEKHANIKA, No 6, 1965.

75. Dzhuri, E. and B. Lee, "Theory of the Stability of Automatic Systems With Many Nonlinearities," in "Trudy 3-go mezhdunarodnogo kongressa IFAK" [Proceedings of the Third International Congress of IFAC], Moscow, 1971.

76. Yakubovich, V. A., "Frequency Conditions of the Absolute Stability of Control Systems With Several Nonlinear or Linear Unfixed Units," AVTOMATIKA I TELEMEKHANIKA, No 6, 1967.

77. "Metody issledovaniya nelineynykh sistem avtomaticheskogo upravleniya" [Methods of Investigating Nonlinear Automatic Control Systems] edited by R. A. Nelepik, Moscow, 1975.

78. Popov, V. M., "The Absolute Stability of Nonlinear Automatic Control Systems," AVTOMATIKA I TELEMEKHANIKA, No 8, 1961.

79. Ayzerman, M. A. and F. R. Gantmakher, "Absolyutnaya ustoychivost' reguliruyemykh sistem" [The Absolute Stability of Regulated Systems], Moscow, 1963.

80. Naumov, B. N., "Teoriya nelineynykh avtomaticheskikh sistem" [The Theory of Nonlinear Automatic Systems], Moscow, 1972.

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ASTROORIENTATION METHODS AND INSTRUMENTATION EXAMINED

Moscow SISTEMY ASTRONOMICHESKOY ORIYENTATSII KOSMICHESKIKH APPARATOV in Russian 1980 (signed to press 24 Mar 80) pp 2-4, 144

[Annotation, foreword and table of contents from book "Space Vehicle Astroorientation Systems", by Valentin Ivanovich Kochetkov, Izdatel'stvo "Mashinostroyeniye", 950 copies, 144 pages]

[Text] This book presents the basic questions of the theory and principle of constructing space vehicle orientation-control systems with the help of star-tracking sensors which sight on single stars in the star field.

Equations are introduced which relate the orientation parameters to astronomical measurements. Laws of reorientation control are synthesized which are optimal with respect to response time and energy expenditure. Considerable attention is devoted to the design and the statistical analysis and optimization of parameters of astrosystems which are subject to random perturbations.

This book is intended for senior technical personnel engaged in the design of space vehicle control systems.

Foreword

A space vehicle flight-control system is designed to control the movement of the vehicle's center of mass and to control its orientation (its movement around the center of the mass). For the majority of space vehicles, orientation control is the basic mode of movement control and is carried out continuously or periodically during the operation of onboard scientific apparatus requiring a specific attitude for the space vehicle.

The accuracy of orientation control can vary and is determined by the vehicle's purpose. For example, an accuracy of 10-20° [28] is sufficient for the orientation of solar batteries and antennas with a wide aperture of directivity. The majority of space vehicles require an accuracy of orientation on the order of a few degrees or a little more. There are, however, a number of missions, such as the study of space and the trajectory correction for interplanetary space vehicles, which require an accuracy of orientation control no worse than a few degrees or even fractions of angular minutes [2, 28].

Various means can be employed for orientation control. Optical means based on the use of solar, planetary and astral sensors are the most widely used. At the present time, the accuracy of solar and planetary sensors is limited to tens of angular minutes [15].

Star sensors (astrosensors) can, in essence, offer very high accuracy (up to a few angular seconds [28]), since stars are point-sources of light and their coordinates in the celestial sphere are known with very great accuracy. This is explained by the fact that experts in recent years have devoted a great deal of attention to the problems of constructing highly accurate astronomical systems for space vehicle orientation control.

At the present time, various types of star sensors have been created which can be successfully employed on space vehicles. A number of books and articles [5, 11, 13, 17, 19, 24, 30, et al.] are devoted to questions of employing star sensors for navigation on aircraft and space vehicles.

This book is an attempt to summarize and systematize certain data. Along with the theoretical aspects (the derivation of the basic equations relating celestial measurements to the parameters of orientation, the synthesis of laws of reorientation control, etc.), data are presented on the selection of functional arrangements for the various types of astroorientation systems. Examples of solutions to problems of statistically optimizing their parameters are also cited.

The book is logically structured in the following manner:

- principles for the construction and classification of astroorientation systems are presented; data for celestial reference points and the characteristics of practicable instruments for their direction finding are cited (chapters 1 and 2);

- basic astroorientation equations are derived and optimal laws for reorientation (turn) control of space vehicles are synthesized (chapters 3 and 4);

- different versions for the construction of functional arrangements realizing the astroorientation equations are proven to be valid; steps are proposed for the statistical optimization of the parameters of the arrangement selected; the criterion of "maximum probability" and the method of "statistical points" are substantiated for this purpose (chapters 5 and 6).

The application of astronomical devices which insure a high degree of accuracy to orient space vehicles is expedient only on those segments of the orbit where high accuracy is necessary, for example, during the operation of the scientific apparatus. This is explained by the fact that highly accurate orientation demands a higher than usual expenditure of energy (propellant). For this reason, when a high degree of orientation is not required, the space vehicle, as a rule, is oriented in an economical mode with reduced accuracy and the use of simpler methods and instruments, without calling upon complicated computer equipment.

A number of the astroorientation equations presented in the book belong to the "accuracy" stage of dual-mode space vehicle angular movement control. With the aid of other equations (when using star sensors that sight on the star field), one can determine the space vehicle's attitude with great accuracy, even when it is grossly disoriented in space; that is, when its prior attitude is not known. After determining the attitude of such a space vehicle, it is necessary to reorient the craft in the required attitude by turning it about its center of mass.

The author expresses gratitude toward his reviewer, Candidate of Physicomathematical Sciences P. A. Barankov, for his valuable advice and notes which contributed to improving the book.

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