Cosmic Research, Vol. 39, No. 2, 2001, pp. 159–166. Translated from Kosmicheskie Issledovaniya, Vol. 39, No. 2, 2001, pp. 170–178.

Mathematical Modeling of Convection in the DACON Sensor under Conditions of Real Space Flight

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Received November 30, 2000

Abstract—A mathematical model of the operation of the sensor of convection under ground and space conditions is described, and the results of modeling are compared to experimental data. A good agreement of the model and experiment is obtained for ground conditions. The sensor operation under conditions of a space flight is simulated using actual microaccelerations that took place onboard the *Mir* station. Good sensitivity of the sensor to the measured components of acceleration is demonstrated. The results of simulation are compared to the results of space experiments carried out with the DACON instrument onboard the *Mir* station.

INTRODUCTION

When executing technological experiments onboard automatic and manned spacecraft (SC), a high sensitivity of working processes to residual microaccelerations (so-called gravitational sensitivity) was discovered. These microaccelerations are most significant in the frequency range 0–0.01 Hz. In this connection, to develop an instrument, which would allow the reaction of working characteristics on microaccelerations to be measured *in situ*, is of considerable interest.

The DACON sensor of convection (Fig. 1) is designed for taking data on temperature variation in a closed volume filled with liquid or gas at strictly controlled boundary conditions and for monitoring a space flight at prompt calculation of this temperature field, based on a three-dimensional nonstationary mathematical model that takes into account the features of space-time variation of both natural and artificial fields of microaccelerations aboard spacecraft.

A detailed substantiation of expediency of such an instrument is given in [1–4] together with a description of the preflight stage of its development. The air-filled cylinder cavity serves as a measuring element of the considered sensor of convection. Two crossed differential thermocouple probes are placed in this cavity in such a way that their lines of sensitivity are perpendicular to the cylinder axis. A constant temperature difference is kept between the cylinder bases.

In this work, we deal with the problems of mathematical modeling of heat convection in the DACON sensor. The mathematical model takes into consideration the cylindrical geometry of the sensor and the forces acting during a space flight, including the gravity gradient, permanent and variable rotation of the station, vibrations and three-dimensional nonstationary flow pattern, and the influence of the Coriolis force. The scheme of numerical calculations based on the method of finite volumes was previously checked by solving a number of problems for isothermal and convective flows in a cube and parallelepiped [3, 5]. In the process of optimization of the cylindrical code, the additional test calculations of three-dimensional stationary and nonstationary problems were performed [6].

In addition to comparing the results of calculations with the data of laboratory measurements, we present in this work some data on the spatial structure of the flow pattern and temperature field that substantially complement the measured characteristics. A prediction for the sensor operation under the real conditions of a space flight is made, in particular, its sensitivity is determined for the case of the use of air as a working substance. This principally allows one to organize prompt analysis of the results of space experiments and to control the convection sensor. The results of modeling are compared to the data of experiments with the sensor aboard the *Mir* station.

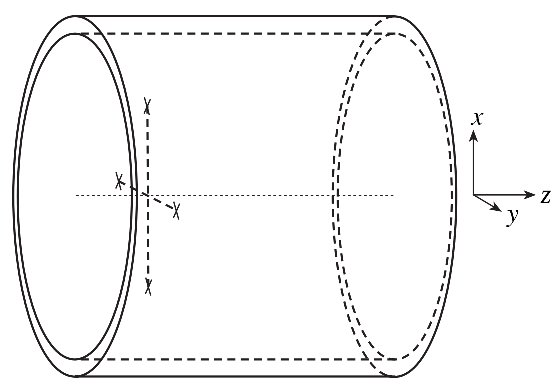

Fig. 1. A scheme of the DACON convection sensor. The thermocouple junctions are shown by crosses.

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MATHEMATICAL MODEL

The numerical simulation of nonstationary convective processes in the DACON cylinder sensor of convection is based on solving the Navier–Stokes equations in the Boussinesq approximation.

For more precise simulation of the real experimental setup, the conjugate problem is solved with taking finite heat conductivity of cavity walls and temperature dependence of physical properties of air into account. The original equations are written in a dimensional form for the variables of velocity **V**, pressure p, and temperature T as

$$\nabla \cdot \mathbf{V} = 0, \tag{1}$$

$$\rho\left[\frac{\partial \mathbf{V}}{\partial t} + \nabla \cdot (\mathbf{V}\mathbf{V}) - 2(\mathbf{V} \times \boldsymbol{\omega})\right] = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{V}) + \rho \mathbf{n}, \tag{2}$$

$$\rho c_p\left[\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{V}T)\right] = \nabla \cdot (k \nabla T), \tag{3}$$

$$\rho_w c_w \frac{\partial T_w}{\partial t} = k_w \nabla^2 T_w. \tag{4}$$

Here, $\mu = \mu(T)$ and $k = k(T)$ are the air dynamical viscosity and heat conduction; ρ and c_p are the air density and specific heat capacity (at constant pressure); while k_w, ρ_w, and c_w are heat conduction, density, and specific heat capacity, respectively, of the material of the cylindrical sensor shell.

The variable microacceleration due to rotation, angular acceleration, and gravity gradient is expressed as

$$\mathbf{n} = \mathbf{n}_a + \boldsymbol{\omega} \times (\mathbf{r} \times \boldsymbol{\omega}) + \mathbf{r} \times \dot{\boldsymbol{\omega}} + \kappa[3(\mathbf{e}_R \cdot \mathbf{r})\mathbf{e}_R - \mathbf{r}],$$

where **r** is the radius vector of a point, $\boldsymbol{\omega}$ is its angular velocity, $\dot{\boldsymbol{\omega}}$ is the angular acceleration, $\mathbf{e}_R$ is the unit vector directed to the Earth, κ is the gravitational parameter, and $\mathbf{n}_a$ is the acceleration due to other causes (for example, the atmosphere drag).

In the Boussinesq approximation, the buoyancy force can be expressed as

$$\rho \mathbf{n} = \rho_0 \mathbf{r} \times \dot{\boldsymbol{\omega}} - \rho\beta(T - T_0)\mathbf{n},$$

where T_0 is the mean temperature of air, ρ_0 is the density at the temperature T_0, β is the coefficient of thermal expansion. The first component of this force determines the action of the angular acceleration, while the second one depends only on the relative temperature.

The temperature dependences of the viscosity μ and heat conduction k are assumed to be linear (in a working range of 20–70°C).

System of equations (1)–(4) is solved in the cylindrical system of coordinates (φ, z, r) in the region

$$0 \le \varphi \le 2\pi, \quad 0 \le z \le L, \quad 0 \le r \le R,$$

and for the shell wall $R \le r \le R_w$.

For the velocity at all boundaries the conditions of adhesion and impenetrability are specified. The isothermic conditions

$$T|_{z=0} = T_h, \quad T|_{z=L} = T_l$$

take place at the end boundaries (cold and hot).

At the inner and outer boundaries of the cylinder shell the conditions of temperature mating and adiabatic conditions

$$T|_{r=R} = T_w|_{r=R},$$

$$k\frac{\partial T}{\partial r}\bigg|_{r=R} = k_w \frac{\partial T_w}{\partial r}\bigg|_{r=R}, \quad \frac{\partial T_w}{\partial r}\bigg|_{r=R_w} = 0$$

are specified.

The necessity of solving the conjugate problem and taking the heat conductivity of the walls into account is caused by poor adequacy of the original model which assumes isothermal boundary conditions with a linear distribution of temperature over the wall along the longitudinal z axis. At relatively small thickness of the wall (2.5 mm) and low heat conductivity of the synthetic material (caprolone), the longitudinal heat flux is insufficient for supporting the original temperature distribution in the presence of a convective flow. Since the junctions of a signal thermocouple are located not far from the cylindrical boundary of the cavity (10 mm at an inner diameter of 45 mm), the use of a simplified model with an isothermic boundary leads to underestimation of the calculated difference of temperatures $\Delta\theta$ by 10–15% in comparison with the complete model and experimental data.

It should be noted that the model developed allows the entire spectrum of boundary conditions to be realized: from isothermic ($k_w = \infty$) to adiabatic ($k_w = 0$) conditions.

METHOD OF SOLVING

In order to solve equations (1)–(4) we use the method of finite volumes. The separated uniform meshes are used. For discretization of convective terms the central differences are used which provide for the second order of accuracy. For modeling of essentially nonaxisymmetric flows a special method of discretization in the vicinity of a cylinder axis ($r = 0$) is developed.

The wall of the cylinder shell is partitioned into computational cells (test volumes) in the axial and azimuthal directions, while in the radial direction the wall is assumed to be thin and consisting of a single cell. Such a simplification is justified, since the heat conductivity of the wall material is high (comparing to air) and, as a consequence, the value of temperature gradient in the radial direction is small.

Equations (1)–(4) are solved separately by using the method of projections. A partially implicit scheme of integration over time is used, with treating implicitly the diffusion terms of equation (2) in the azimuthal direction, completely implicit solving of equations for temperature (3)–(4), and implicit coupling of equations (2) and (3)–(4) through a half time step. For implicit terms the scheme corresponds to the Crank–Nicolson method.

To solve the Poisson equation for pressure, the Fourier method is used which is characterized by high numerical efficiency.

The algorithm scheme of calculations can be presented as a sequence of the following stages:

1. Calculation of the intermediate velocity $\mathbf{V}^*$ from the finite-difference equation for the time instant (n + 1/2)

$$\frac{\mathbf{V}^* - \mathbf{V}^n}{\Delta t} = f\left(\frac{\mathbf{V}^n + \mathbf{V}^*}{2}, p^{n-\frac{1}{2}}, T^{n+\frac{1}{2}}\right).$$

2. Corrections of the pressure and velocity

$$\nabla^2\varphi = \boldsymbol{\nabla} \cdot \mathbf{V}^* \quad \text{for} \quad \varphi = \frac{p^{n+\frac{1}{2}} - p^{n-\frac{1}{2}}}{\Delta t},$$

$$\mathbf{V}^{n+1} = \mathbf{V}^* - \boldsymbol{\nabla}\varphi, \quad p^{n+\frac{1}{2}} = p^{n-\frac{1}{2}} + \frac{\varphi}{\Delta t}.$$

3. Calculation of the temperature $T^{n+3/2}$ from the finite-difference equation for the time instant (n + 1)

$$\frac{T^{n+\frac{3}{2}} - T^{n+\frac{1}{2}}}{\Delta t} = f\left(\frac{T^{n+\frac{1}{2}} + T^{n+\frac{3}{2}}}{\Delta t}, \mathbf{V}^{n+1}\right).$$

The chosen direct method of solution in combination with a selective use of the implicit scheme ensures a high computing efficiency of the algorithm. When using a personal computer of the Pentium Pro class for calculations on the grid 32 × 16 × 8 (in φ, z, and r, respectively), the computing time is equal to 40 min to simulate a nonstationary process with a duration of one hour. This is enough, for example, for a transition to a steady-state convective process (to an accuracy of 10^{-6}) with taking full heating of cavity walls into account. When modeling only air flows, without considering the heat conductivity of walls, the computing time is reduced to 20 s for the grid 32 × 16 × 8 and does not exceed 10 min on the denser grid 64 × 32 × 16.

Further improvements of the algorithm and the use of high-performance computers will allow the speed of calculations to be increased by a factor of 5–10.

MODELING OF THE SENSOR IN GROUND CONDITIONS

In order to refine the computing method and to determine the features of flows inside the cylinder cavity we performed modeling of thermal convection under terrestrial conditions, with gravitation force vector being directed across the cylinder axis.

Some examples of flow patterns (isolines of temperature in the vertical diameter cross section) are presented in Fig. 2 for Rayleigh number values of

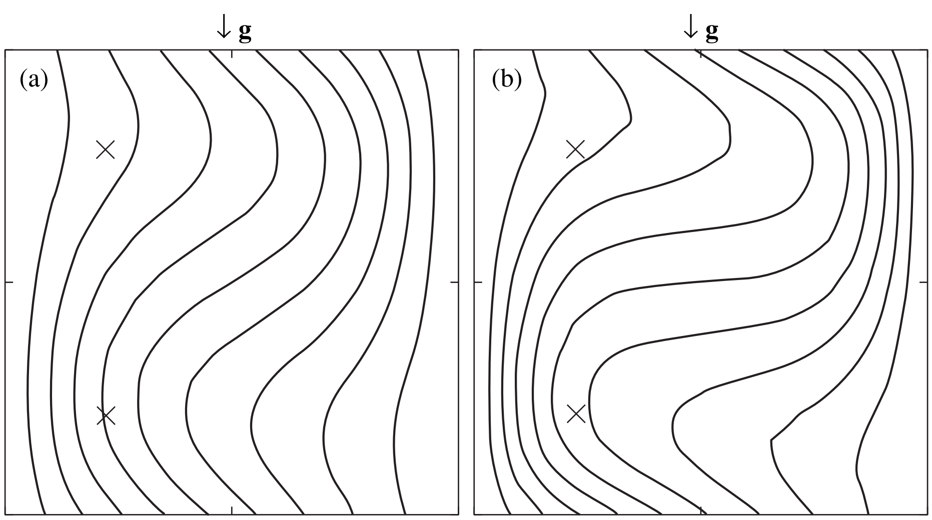

Fig. 2. Isothermal lines in the vertical diameter cross section for (a) Ra = 5000 and (b) Ra = 16000.

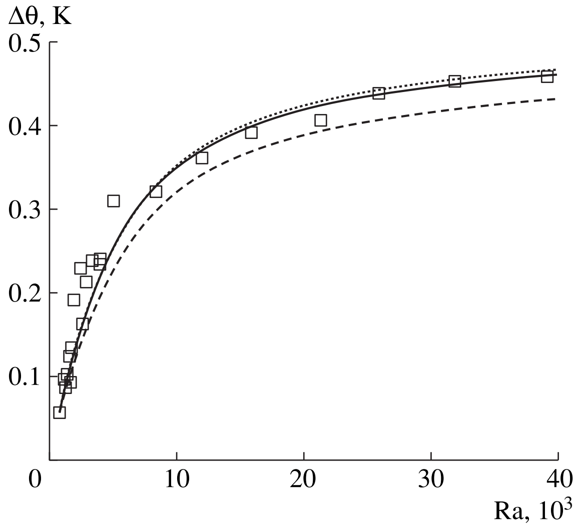

Fig. 3. The recorded temperature difference Δθ versus the Rayleigh number.

5000 and 16 000. One can clearly see in the figures the shifts of temperature isolines near the top (to the right) and bottom (to the left) boundaries, which are due to finite heat conductivity of the material of the cavity walls. The junctions of signal thermocouples for measuring the temperature difference Δθ are marked by crosses.

For the sake of comparison with experimental data we performed a simulation in the range of Rayleigh numbers from 820 to 78 500. In order to investigate the influence of the thermal current through the cylindrical cavity wall we have studied the dependence of the temperature difference Δθ on the heat conductivity coefficient of the wall material (caprolone) k_w. This was necessary to do in view of a wide range of reference values for this quantity: from 0.16 up to 2.3 W/(m K).

Figure 3 presents the results of simulation in comparison to the experimental data for a range of Rayleigh numbers Ra from 0 to 40 000. The lower curve (dashed line) shows the dependence of Δθ on Ra for an isothermal boundary with a linear temperature profile ($k_w = \infty$), while the upper curves (solid and dotted lines) correspond to the heat conductivity coefficient k_w = 0.66 W/(m K). The solid and dotted lines are for the grids 64 × 32 × 16 and 32 × 16 × 8, respectively. It is seen from the plot that for middle and low values of the Rayleigh number (up to 10 000) there is practically no difference between the curves, i.e., the coarser grid 32 × 16 × 8 gives a sufficient accuracy of discretization.

The comparison of calculated data with experimental (small squares on the plot) demonstrates a good agreement over the entire range, excluding five points for Ra between 2000 and 5000, which is, apparently, connected with errors of temperature measurements.

For the lower part of the range, the sensor data have almost linear dependence on the Rayleigh number and, hence, on the acceleration of gravity. The calculation performed for a difference between the heater and cooler temperatures of 50° and low acceleration values confirmed good linearity of this dependence. In this case, the sensitivity of the sensor is 1.1 × 10^2 K s^2/m (1.1 × 10^{-3} degrees per $10^{-6}g_0$, where g_0 is the acceleration of gravity on the ground level).

In addition to modeling the DACON sensor, the numerical method and computing code were tested on the problem of convection in a melt for the Czochralski method. The calculations were performed both for axisymmetric and for nonaxisymmetric and nonstationary (at large Ra) flow patterns. The results obtained are in a good agreement with the data of other authors.

The results of a ground-based experiment at periodically variable side heating are presented in Fig. 4 together with the results of mathematical simulation. The difference of temperatures of the heater and cooler is shown in the upper part of the figure (left scale), while experimental data for two axes are shown by dashed lines and the results of calculations (vertical axis) by solid line in the lower part of the figure (right scale). One can see that the sensor readings are unstable both in vertical axis (the mean signal absolute value increases with time from 0.5° to 0.8°) and in horizontal axis (the increase from zero to 0.2°). Nevertheless, if the sensor readings in vertical axis are considered in asymptotic approximation, a good qualitative and quantitative agreement with the calculation results. One can also see from the data obtained that the time of response (delay) of the sensor to a change of the heater temperature is equal to approximately 1 s.

SIMULATION WITH USING REAL DATA ON MICROACCELERATIONS IN A SPACE FLIGHT

Under conditions of a space flight, the Rayleigh number does not exceed a value of several tens, and the flow pattern attains mostly diffusion character. Figure 5a shows by solid lines the temperature isolines for Ra = 10. The isolines for a model with air characteristics that are independent of temperature are shown by dashed lines. Because of a small intensity of convective motion, the temperature variations at check points are insignificant and cannot be seen in the figure. The isolines of temperature deviation at Ra = 10 from a purely diffusion distribution at Ra = 0 are demonstrated in Fig. 5b. Here, an isoline step comprises 0.0001 of dimensionless temperature (0.005°) which is 1000 times less than in the previous figure. In the upper half of the cavity the displayed quantity (temperature deviation) is positive due to convective heat application from the left (hot) end wall, while in the lower half of the cavity it is negative. A small asymmetry of the pattern is due to the temperature dependence of air properties.

This plot (isolines of temperature deviation) is a good illustration of a microconvection influence on the

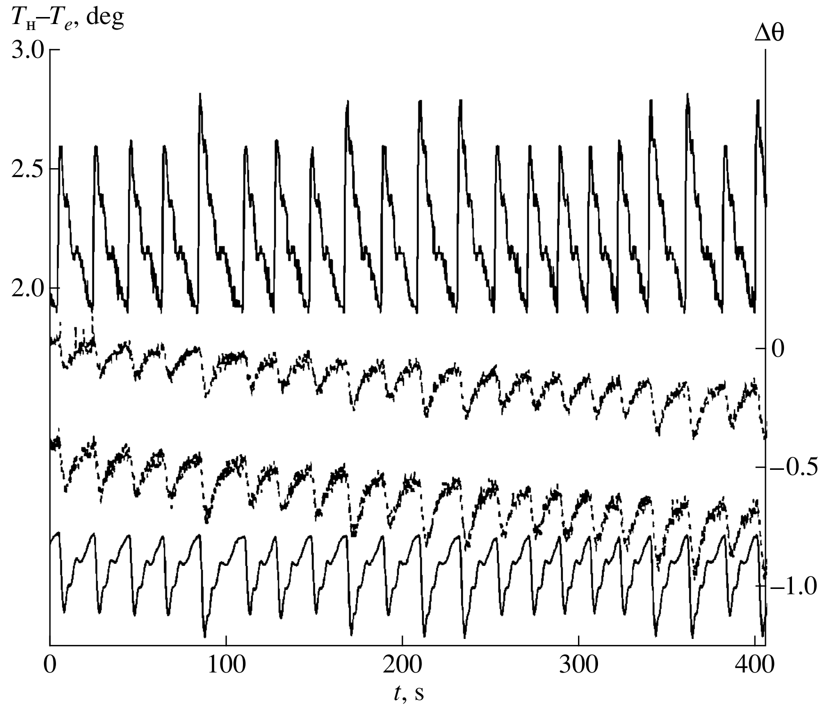

Fig. 4. The sensor signals at periodically variable side heating.

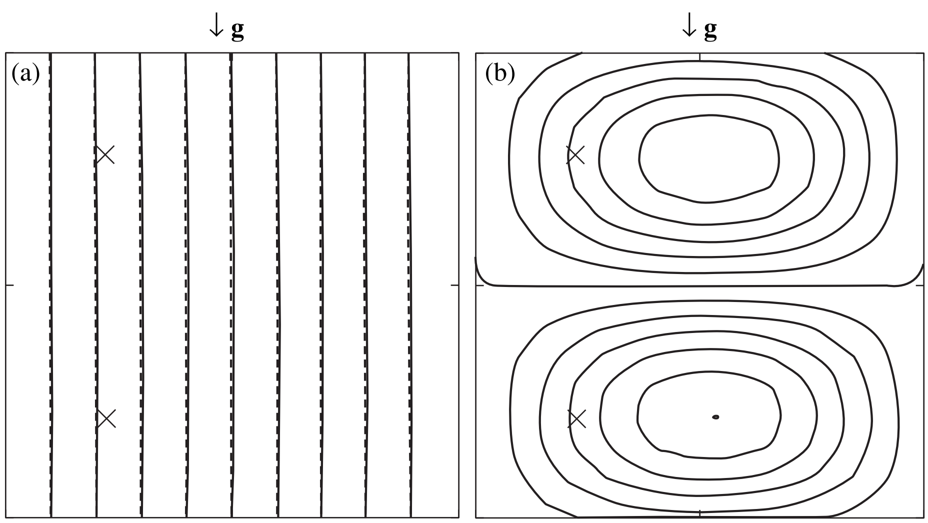

Fig. 5. (a) Temperature isolines (a step of 0.1) in vertical diameter cross section for Ra = 10 and (b) isolines of the temperature deviation (a step of 0.0001) from a purely diffusion distribution.

temperature distribution in the cavity. At a later time, we assume to use similar technique for visualization of nonstationary processes in the DACON sensor during space flights on the basis of prompt simulation of the sensor as the data on microacceleration components become available. Video films about these processes can also be prepared with this technique.

Using previously collected data on quasistatic components of microaccelerations onboard the *Mir* station, we have performed a simulation of the sensor for several sessions with a duration of 1 to 4 h. The data on angular velocity, angular acceleration, gravity gradient, and the residual microacceleration in the center of mass of the station were calculated by V.V. Sazonov

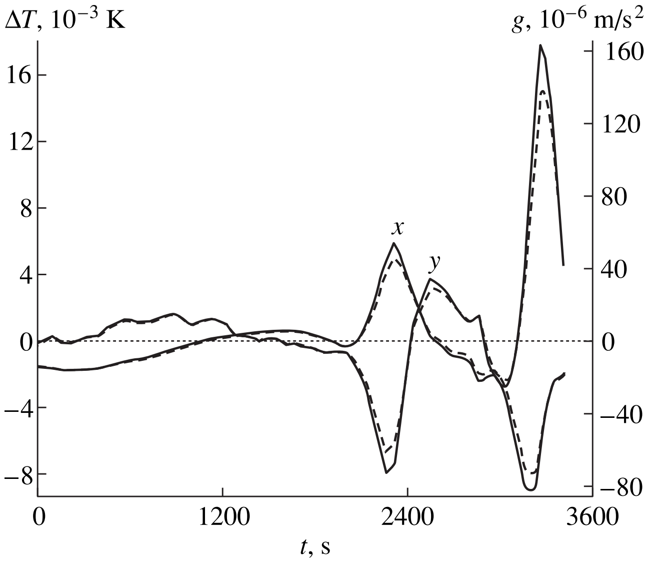

Fig. 6. The components of microacceleration g_x and g_y (solid lines, right scale) and the temperature differences ΔT_x and ΔT_y (dashed lines, left scale) predicted by simulation results.

(Keldysh Institute of Applied Mathematics of RAS) on the basis of telemetry data on the station orientation coming to the mission control center [7]. The data with a time step of 30 s taken during the experiments onboard the *Mir* station in October of 1995 were used in the present calculations.

The point $\mathbf{r}$ = –4.16, 0.86, and –8.07 m (in the construction coordinate system of the station) was chosen as a sensor location onboard the station, which corresponds to the location of the Alice instrument [7]. Since the DACON sensor has a pair of thermocouples with junctions installed in mutual perpendicular direction x and y (across the z axis of the cylinder), we have chosen the sensor orientation that provides for recording the most strongly variable components of acceleration.

Figure 6 shows the results of modeling the most representative flight regime with a duration of 1 h. The acceleration components g_x and g_y (solid lines) are presented and the recorded temperature differences ΔT_x and ΔT_y (dashed lines) corresponding to them. The acceleration unit is 10^{-6} m/s^2 (right scale), and the temperature unit is 10^{-3} degrees (left scale).

One can see from the figure that the sensor sensitivity is equal to approximately 10^{-3} degrees per 10^{-5} m/s^2 ($10^{-6}g_0$).

Owing to the use of air as a working medium, the sensor has a good reactivity. In the regions of a strong variation of acceleration, the time delay of sensor response is as small as a few seconds. The additional numerical simulation of the sensor response to harmonic oscillations of gravity showed the time delay to increase with increasing period of oscillations tending to an asymptotic value of 3 s.

Another important property of the sensor which was discovered in the process of simulation is the absence of significant cross influence of the components g_x and g_y on the recorded quantities $\Delta\theta_y$ and $\Delta\theta_x$, i.e., a good directional selectivity of the sensor. Figure 6 demonstrates the absence of such an influence at the places of strong variation of one of the components of acceleration.

In order to investigate the sensor selectivity, we have performed additional simulation for the stationary gravity acceleration g_x corresponding to the value Ra = 10 and for different values $g_y \geqslant g_x$. It was found that the deviation of recorded value of $\Delta\theta_x$ from its unperturbed value (g_y = 0) equaled 0.03% and 2% for the ratios g_y/g_x = 10 and g_y/g_x = 100, respectively. A good selectivity of the sensor can be the result of choosing a cylindrical form for the working volume.

The influence of the longitudinal component of gravity g_z on $\Delta\theta_x$ was also investigated. Its value turns out to be 1.5% for g_z/g_x =10 and 15% for g_z/g_x = 100, which is the result of distortion of the flow pattern in near-wall regions, where the gradients of temperature across the cylinder axis are high. However, for the g_z values comparable to g_x the influence on $\Delta\theta_x$ is also insignificant.

In general, the mathematical modeling showed the DACON sensor to have good sensitivity, reactivity, and directional selectivity. So, it can be used for prompt recording of microaccelerations at a level of 10^{-4} m/s^2 ($10^{-5}g_0$) and above.

COMPARING THE RESULTS OF MEASUREMENTS ON THE *MIR* STATION WITH NUMERICAL CALCULATIONS

In 1998, the DACON sensor was transported to the *Mir* station, and a number of space experiments were carried out with it [8]. Since the sensitivity of DACON is relatively low, for checking its response to sufficiently strong perturbations in an orbital flight, an experiment was made in which an astronaut swung the sensor in his hands along the axis of thermocouple sensitivity (the x axis) with an amplitude of 20–25 cm and a frequency of 0.18–0.2 Hz.

Figure 7 presents a record of the sensor signal ΔT_x (solid line) for the interval lasting from 170th to 250th seconds of the experiment. For the same interval, the mathematical modeling of harmonic swaying with a frequency of 0.2 Hz and amplitudes of 10 cm (coarse dashed line) and 20 cm (fine dashed line) was performed using the recorded data on the temperatures of hot and cold walls of the sensor.

The results demonstrate a good qualitative agreement with calculated data, but the amplitude of sensor signal is approximately two times lower (for an ampli-

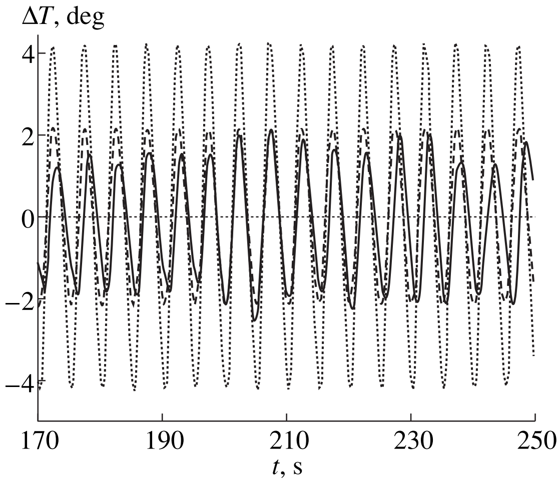

Fig. 7. The sensor signals at swaying.

tude of swaying estimated as 20 cm). This can be, apparently, explained by nonparallel displacements of the sensor and by a presence, in this connection, of lateral oscillations of its longitudinal axis.

For the sake of comparison with the data of the sensor rigidly fixed onboard the station, we have performed numerical simulation with using the data on quasistatic components of microaccelerations in the center of mass of the station at the moment of carrying out the experiment. The data were calculated by V.V. Sazonov (Keldysh Institute of Applied Mathematics of RAS) using the telemetry data on the station orientation. In modeling, the recorded data about temperatures of hot and cold walls of the cavity were used.

Figure 8 presents the sensor data on temperature difference along the y axis (fine dashed line), and the results of calculations for y axis and the x axis perpendicular to it (coarse dashed line). The experiment was carried out on July 23, 1998, the sensor at this moment being placed in the position $\mathbf{r}$ = (3.11 m, 0.27 m, –4.67 m) in the station system of coordinates (x, y, z).

The plots presented demonstrate considerable discrepancy between experimental and computational results. The oscillations of sensor data is caused, apparently, by the noise of electronics. In addition, substantial influence of parasitic microaccelerations onboard the station, which were not taken into account when calculating quasistatic components, is also possible. Nonuniformity of the heat current over the sensor cavity has some effect too.

Thus, space experiments together with numerical simulations confirmed the capabilities of the DACON sensor to measure variable accelerations onboard the station. However, for ensuring sufficiently reliable recording of quasistatic microaccelerations the improved accuracy of temperature measurements at the thermocouples, the reduction of parasitic effects, and the use of special statistical methods of processing experimental data accumulated over long time intervals are required.

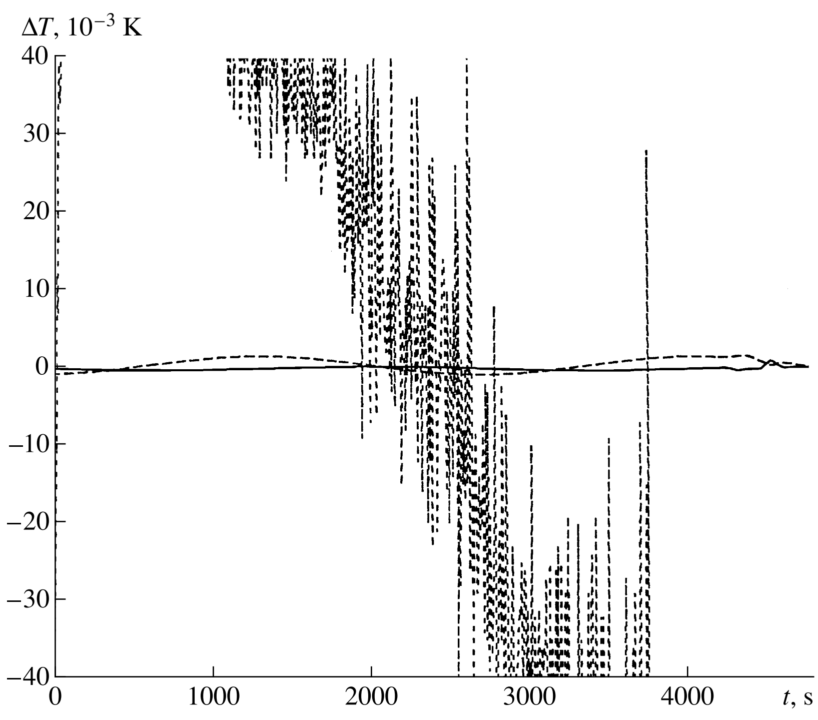

Fig. 8. The sensor signals for the y axis (fine dashed line) during the experiment at the *Mir* station and the results of calculations for the axes y (solid line) and x (coarse dashed line).

CONCLUSIONS

A three-dimensional nonstationary mathematical model of thermal convection in a cylinder sensor is developed, and it is implemented as a computer code. The model takes into account the features of a real space-time variation of the field of microaccelerations onboard an orbital station. The program allows prompt calculations to be made on the basis of experimental data obtained in orbital flight conditions in order to compare with measured temperature differences in the entire range of these orbital conditions. Numerical solutions of various test problems in the axisymmetric and three-dimensional statements are well consistent with the solutions derived by other authors that used finite-difference and spectral-difference methods. The results of calculations are also in a good agreement with the data of ground-based measurements at a horizontal position of the sensor.

The predictions made for operation of an air-filled sensor at standard temperature difference under real conditions of a space flight showed this sensor to have high sensitivity, reactivity, and directional selectivity. The experiments carried out with the DACON sensor onboard the *Mir* station in 1998–1999 confirmed its serviceability and applicability for measuring variable microaccelerations.

On the basis of the above calculation results it seems to be expedient to include a convective sensor with similar characteristics into instrumentation and research programs of future space missions of the *Photon* and *MKS* types. We plan to specify finally the working substance type after the completion of testing the instrument in the experiments onboard the *Mir* station.

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