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GENERATION AND REGISTRATION OF DISTURBANCES IN A GAS FLOW.
2. EXPERIMENTS WITH ARRAYS OF TUBULAR MICROHEATERS AND MICROSENSORS

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Aerodynamic experiments with arrays of conducting microtubes are performed, and their electric properties are determined. Sensitivity of microtubes located on the model surface to disturbances of the gas flow is revealed. It is demonstrated that such microtubes can be used both for registration of disturbances being introduced and as disturbance generators.

Key words: *boundary layer, arrays of microtubes, flow control, methods of insertion and registration of disturbances, microtechnologies.*

Pioneering experiments with an individual microtube used as a tubular sensor of a hot-wire anemometer for registration of disturbances were described in [1]. The microtube was located on the leading edge of a thin substrate. Fluctuations of flow velocity in a subsonic boundary layer on a flat plate were measured. Fast operation of the tubular sensor owing to its small thermal inertia was demonstrated. Tubular sensors with a fast response to heating and cooling can be used not only as sensors proper, but also as heaters generating disturbances in the gas flow. If a fast-response control system is used, ordered arrays of microtubes can act as "smart" surfaces preventing the emergence of instability in the boundary layer. Such "smart" surfaces have no moving elements, which offers a significant advantage over mechanical systems of flow control [2].

A technology for creating chips with distributed arrays of tubular microsensors and microheaters (microactuators) was developed in [3], and corresponding chip s were fabricated.

The goal of the present activities, which continue the research described in [3], was to test the fabricated tubular microsensors and microactuators from the viewpoint of generation and registration of disturbances in a subsonic gas flow on a flat plate model.

Experimental Equipment and Measurement Methods. The layout of a chip with an array of distributed microtubes is illustrated in Fig. 1.

To ensure correct measurements, we determined the following important characteristics of tubular elements: 1) time-dependent stability of resistance with power input; 2) scatter of the values of resistance and temperature coefficient between the tubes; 3) operating range of power input.

The temperature coefficients of resistance of microtubes were determined by placing the chip with an array of distributed microtubes into a thermostated cabinet. The microtubes were heated to a temperature $T = 163°\text{C}$. The change in resistance of input conductors was taken into account with the use of results measured by an additional chip with the place allocated for the tube being soldered by tin solder.

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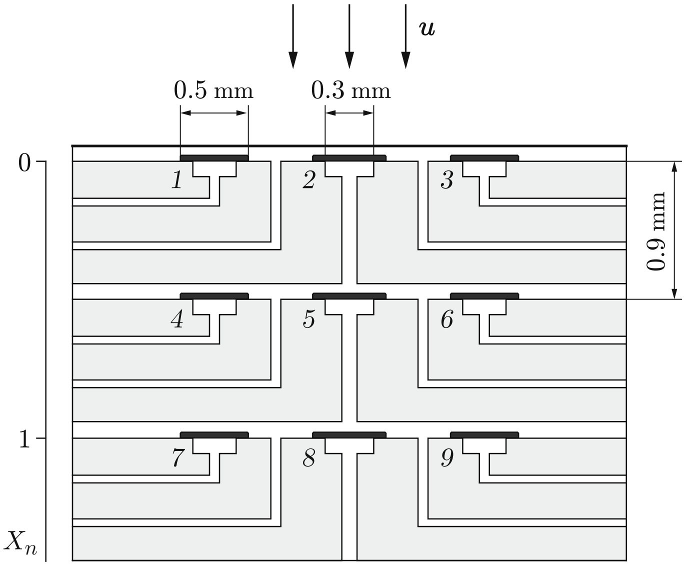


Fig. 1. Chip with an array of distributed microtubes.

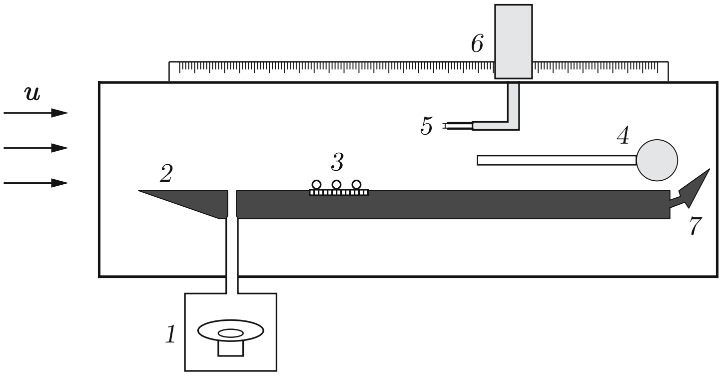


Fig. 2. Arrangement of the experiment: 1) loudspeaker initiating disturbances in the flow; 2) flat plate; 3) array of distributed microtubes; 4) Pitot tube; 5) wire sensor; 6) traversing gear; 7) flap.

The aerodynamic experiments with arrays of conducting microtubes were performed in a T-324 M small subsonic wind tunnel of the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences. The experiments were performed on a flat plate model with a free-stream velocity of the air flow $u = 10$ m/sec. The wind tunnel has a closed test section 200 × 200 × 400 mm. The experiment arrangement is shown in Fig. 2. The flat plate had a slot 0.5 × 50.0 mm. Periodic blowing–suction through this slot was initiated by a loudspeaker located outside the test section. The chip with nine microtubes was flush-mounted with the model surface. The conducting lines to the chip were also built into the model surface to minimize roughness-induced disturbances. The chip attachment is schematically shown in Fig. 3.

The first stage included experiments aimed at determining the possibility of disturbance registration by the microtubes. For this purpose, disturbances were introduced into the flow through the slot by means of periodic blowing–suction at a frequency of 267 Hz. The distance between the slot and the chip located further downstream was 123 mm. The disturbances generated by the loudspeaker were registered by a standard wire sensor of an AN-1003 constant-temperature hot-wire anemometer. The signals from the tubular sensors were measured by a constant-voltage hot-wire anemometer.

For convenience, the first row of microtubes on the chip was chosen as the origin X of the coordinate system. The X coordinate was normalized as $X_n = X/X_{1,3}$, where $X_{1,3}$ is the distance between the first and last rows of microtubes equal to 1.8 mm.

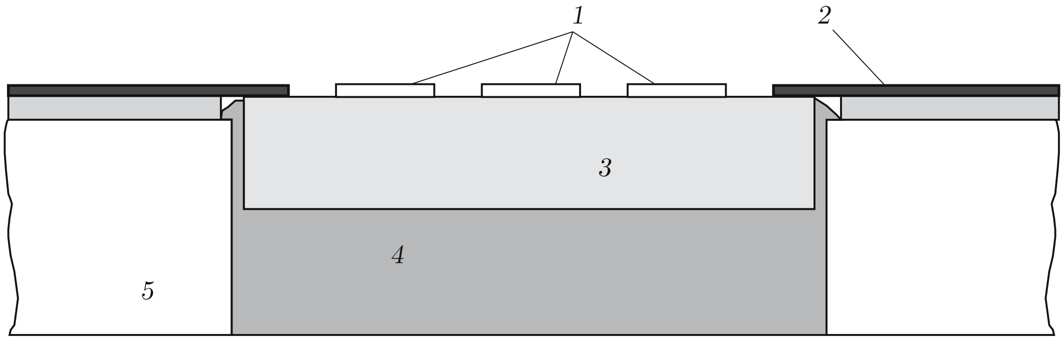


Fig. 3. Chip attachment to the model: 1) microtubes; 2) conducting contacts; 3) silicon substrate; 4) epoxy resin; 5) Plexiglas.

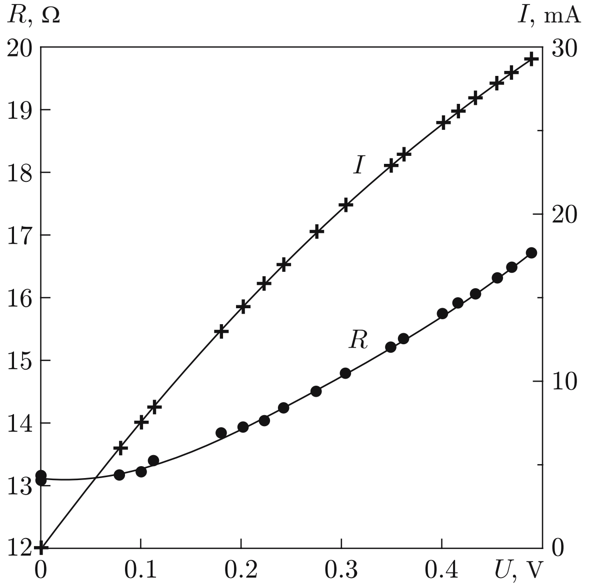


Fig. 4

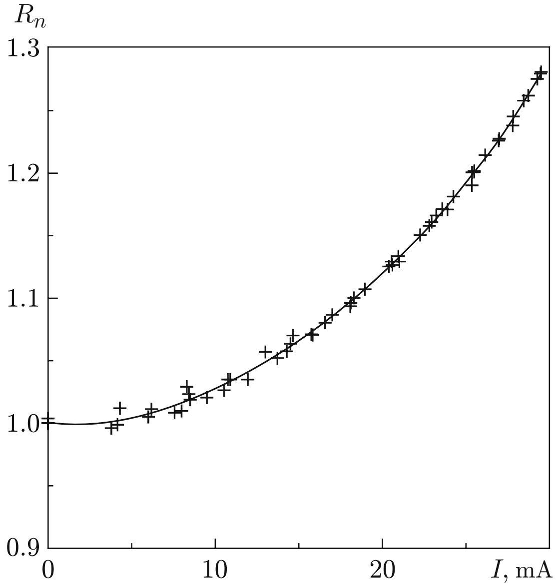


Fig. 5

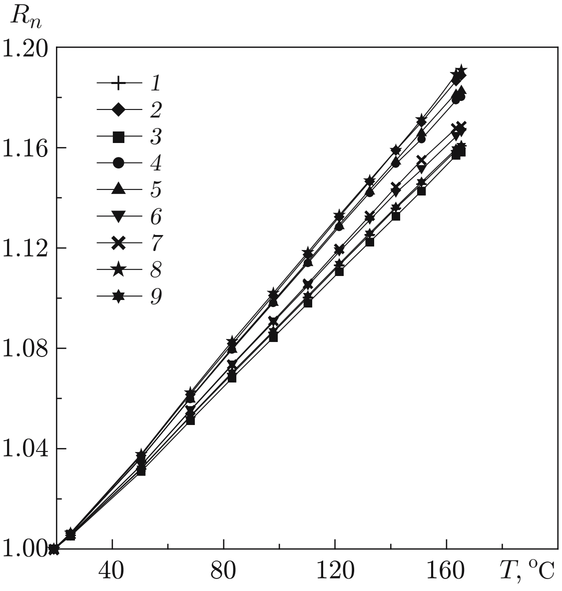
Fig. 4. Current–voltage curve of the microtube.

Fig. 5. Generalizing dependence of the overheat ratio of the microtube on current intensity.

The wire sensor was located above the surface at a height of 0.5 mm. The measurements were performed at a position downstream of the array of distributed tubular microsensors at $X_n = 1.5$–4.5.

The second stage included experiments aimed at determining the possibility of inserting periodic disturbances into the flow by means of pulsed periodic heating of the microtube. For this purpose, a periodic rectangular pulse with an amplitude of 0.45 V and a frequency of 267 Hz was fed from the generator to microtube No. 1 (see Fig. 1). Microtube Nos. 4 and 7 registered the disturbances being inserted.

Results of Experiments. For the power of the signal fed to the microtube equal to 5 mW, the tube resistance was found to decrease by 30% during 24 hours. This phenomenon is caused by stress relaxation in the metal film (slow annealing) [4]. The resistance of the microtubes could be stabilized after their annealing in a thermostated cabinet at a temperature of 240°C during 2 hours. Figure 4 shows a typical current–voltage curve of the microtube. Normalization of resistance of each current-heated microtube to its initial resistance in the absence of current R_n allowed us to construct the generalizing dependence of the overheat ratio R_n on current intensity (Fig. 5). After annealing, the initial resistance of the microtubes remained stable up to the overheat ratio $R_n = 1.3$.



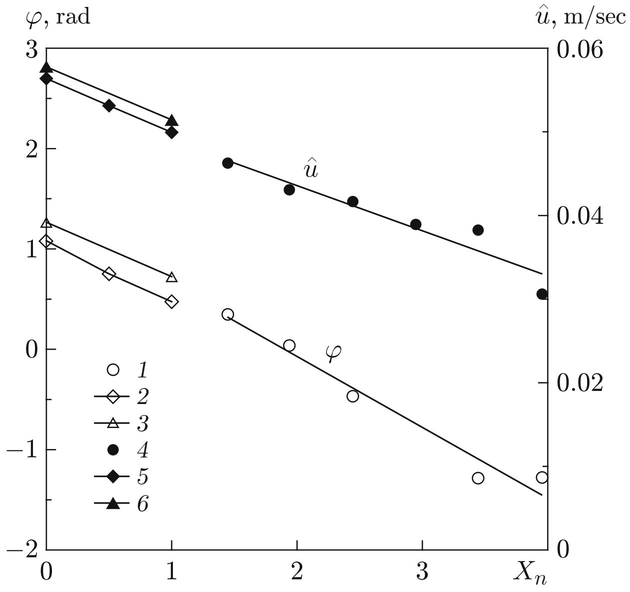


Fig. 6

Fig. 7

Fig. 6. Normalized resistance versus temperature: the points 1–9 refer to the numbers of the sensors (microtubes) (see Fig. 1).

Fig. 7. Streamwise distributions of the phase (points 1–3) and amplitude (points 4–6) of disturbances: points 1 and 4 are the results obtained by the wire sensor; points 2 and 5 are the results obtained by the row of the tubular sensors 1, 4, and 7; points 3 and 6 are the results obtained by the row of the tubular sensors 2 and 8 (see Fig. 1).

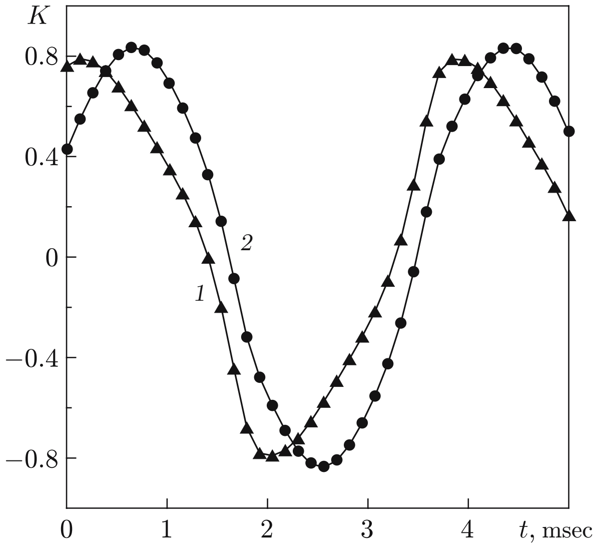


Fig. 8. Correlation coefficient versus time: curves 1 and 2 show the signals measured by microtube Nos. 4 and 7, respectively (see Fig. 1).

The measured temperature coefficient of resistance of the microtubes is plotted in Fig. 6. It is seen that the microtubes have different temperature coefficients of resistance with their values ranging between $1.1 \cdot 10^{-3}$ and $1.3 \cdot 10^{-3}$ deg^{-1}.

The microtubes are found to fail if the power of the input signal reaches 20 mW. The failure is caused by the influence of thermal stresses arising because of nonuniform heating of the microtubes by the current. The electric current passing through the microtube leads to substantial heating of the central part, whereas the zones of microtube attachment to the metal lines remain cold [1].

The measured characteristics of disturbances generated by the loudspeaker and registered by a standard hot-wire sensor and by tubular microsensors are presented below.

Figure 7 shows the streamwise distributions of the phase φ and amplitude $\hat{u}$ of the generated periodic disturbances.

An analysis of the results obtained shows that the X distributions of the disturbance phase are close to linear. In the case considered, the phase velocity of disturbance propagation is 4.6 m/sec. It is seen from Fig. 7 that the results measured by the hot-wire and tubular sensors correspond to one functional dependence. Thus, distributed arrays of tubular sensors can be used to measure flow disturbances and their phase velocities.

When a rectangular electric pulse was fed from the generator to microtube No. 1 (see Fig. 1), the latter was periodically heated with a frequency of 267 Hz defined by the generator. Periodic disturbances were also inserted into the flow, and the microtube operated in the disturbance generator mode. Figure 8 shows the coefficients of correlation between the signal fed to microtube No. 1 (see Fig. 1) and the signals registered by microtube Nos. 4 (curve 1) and 7 (curve 2) versus time. It should be noted that no correlation was observed between the input signal and the signals registered by microtubes in other rows.

It follows from Fig. 8 that the period of the correlation functions is equal to the period of disturbances inserted into the flow (in our case, 3.75 msec). The interval between the peaks on curves 1 and 2 corresponds to the time needed for disturbances to pass from one tubular microsensor to the other. The experimental results show good agreement between the signal generating disturbances inserted into the flow and the measured signal. This fact confirms that semiconductor microtubes can be used as a source of flow disturbances.

Thus, we demonstrated that microtubes located on the surface can be used both for registration of disturbances inserted into the flow and as disturbance generators.

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