

Physics. — *A complete arrangement for the investigation, the measurement and the recording of rapid airspeed fluctuations with very thin and short hot wires.* By M. ZIEGLER. (Mededeeling No. 21 uit het Laboratorium voor Aero- en Hydrodynamica der Technische Hoogeschool te Delft.) (Communicated by Prof. J. M. BURGERS.)

(Communicated at the meeting of May 30, 1931.)

In Mededeeling N^o. 20 from this Laboratory the conditions were indicated which must be satisfied by a hot wire anemometer for the study of the turbulent boundary layer. The theoretical considerations about the lag of hot wires were confirmed by the experimental results, and an arrangement was given, which makes it possible to compensate very easily the difference in sensitivity for slow and rapid fluctuations, so that a constant sensitivity can be obtained up till arbitrary high frequencies.¹⁾

This compensation, however, and the requirement that the wires must be as short as possible (shorter than 1 mm), cause a considerable decrease of the sensitivity of the hot wire and thus make a great amplification necessary. The purpose of the present communication is to give a description of the arrangement which is used now at this laboratory for the investigation mentioned.

The hot wires.

The hot wires are platinum wires of 0,003 or 0,005 mm diameter, and of a maximum length of 1 mm. These wires are obtained in the following way. To the two thin needles of a hot wire holder are soldered the ends of a piece of Wollaston wire bent in *U*-shape.²⁾ Then the middle part of the Wollaston wire is pinched in the form of a little loop, the top of which is immersed in nitric acid. The silver mantle here dissolves and the thin platinum core remains. Through a microscope it is possible to see how far the loop reaches into the acid and to control the progress of the process. Owing to capillary action the acid comes in contact with the wire in such a manner that the silver which remains unattacked ends into two pretty sharp points. When all the silver at the top is dissolved, the platinum wire must be stretched very carefully by means of an adjusting screw provided at the holder for that purpose. The two silver

¹⁾ M. ZIEGLER, These Proceedings, 33, p. 723, 1930. The application of the hot-wire anemometer for the investigation of the turbulence of an airstream.

²⁾ The Wollaston wire used is supplied by HARTMANN and BRAUN A. G. Frankfurt am Main.

threads between which the platinum wire is stretched, although fairly thin themselves (about 0.15 to 0.25 mm) are more than rigid enough as carriers of the platinum wire. The photos of fig. 1 and 2 show such a 0.005 mm platinum wire and its holder. It may be safely assumed that a hot wire anemometer of such a type will cause a minimum of disturbance in the phenomena to be investigated.

It is desirable to have the holders already fixed in the position they will occupy during the experiments, before the silver mantle of the wire is dissolved, as the smallest shock on the holder usually causes the rupture of the wire. The investigation of the turbulent boundary layer happens in the smaller windchannel of the laboratory along a smooth glass plate of 50 cm breadth and 2,30 m length, placed horizontally at 15 cm above the under side of the working section of the tunnel, the dimensions of which are $50 \times 50 \times 260$ cm. The leading edge of the plate is provided with a metallic nose, which ends very sharply and fits quite smoothly to the glass plate, owing to an accurate stopping with paraffine wax. The upper side of the nose is horizontal, while the under side reaches the glass plate under an obtuse angle. Two hot wire holders are fixed to micrometer screws which are mounted above the working section, and by mean of which the wires can be brought very accurately at different distances from the plate. This vertical motion is also very convenient during the preparation of the wire for the judicious adjustment of the depth of immersion into the nitric acid. The micrometer screws themselves can be moved in two horizontal directions so that the wires can be placed at various positions, both in regard to the plate and to themselves. As all electric measurements and records are made in another room, connecting lines are provided from each wire to its respective measuring set.

Wheatstone bridge arrangement.

Though for the observation and recording of airspeed fluctuations it is sufficient to amplify the modifications of the electric tension between the ends of the hot wires, and one could do with a heating battery and a series resistance only, it is customary to connect each wire to a Wheatstone bridge arrangement. (See the wiring diagram, fig. 3). This is very convenient for the determination of the resistance (temperature) of the wire and for adjusting a suitable heating current, and besides is necessary for various tests which will be described in the following pages. Suitable values of the bridge resistances are indicated in the diagram. The resistance of a 0.005 mm hot wire of less than 1 mm in working conditions, can be for example about 20 ohms, the heating current being about 50 mA. The potential differences between the points A_1 and A_2 are led to the grid of the first amplifier tube via the compensating circuit. It is of great importance that the resistance between A_1 and A_2 should be low in view of parasitic disturbances which generally would become

M. ZIEGLER: A COMPLETE ARRANGEMENT FOR THE INVESTIGATION
THE MEASUREMENT AND THE RECORDING OF RAPID AIRSPEED
FLUCTUATIONS WITH VERY THIN AND SHORT HOT WIRES.

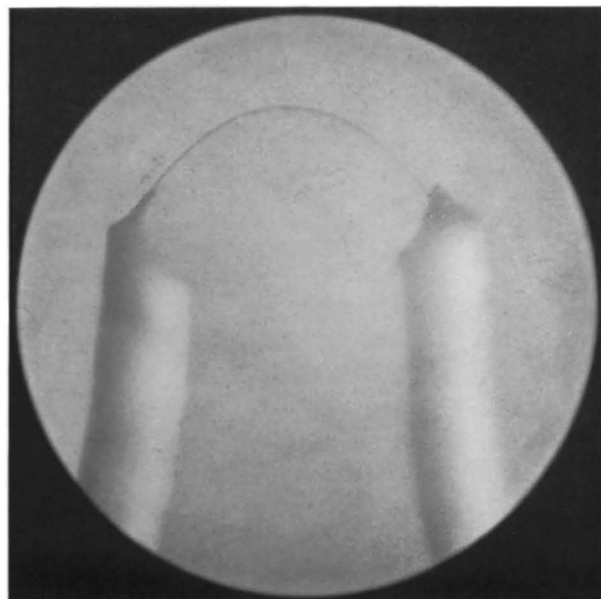


Fig. 1.

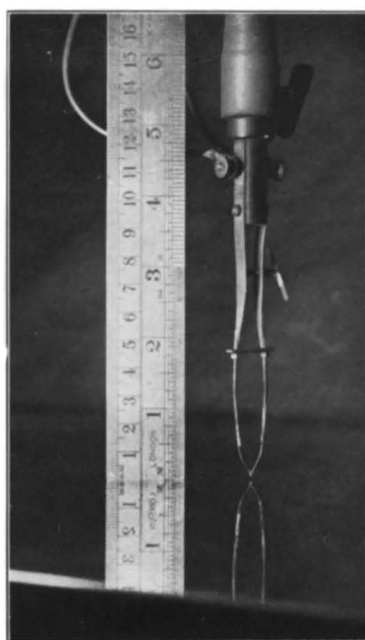


Fig. 2.

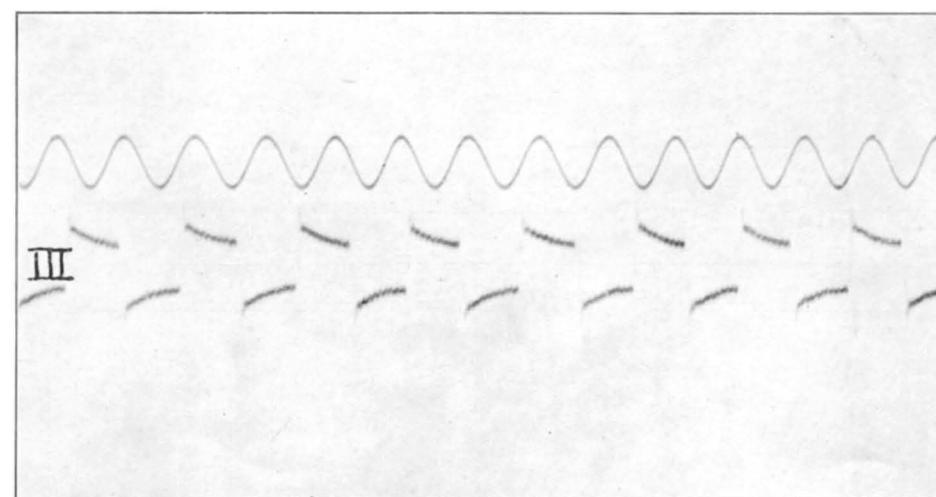
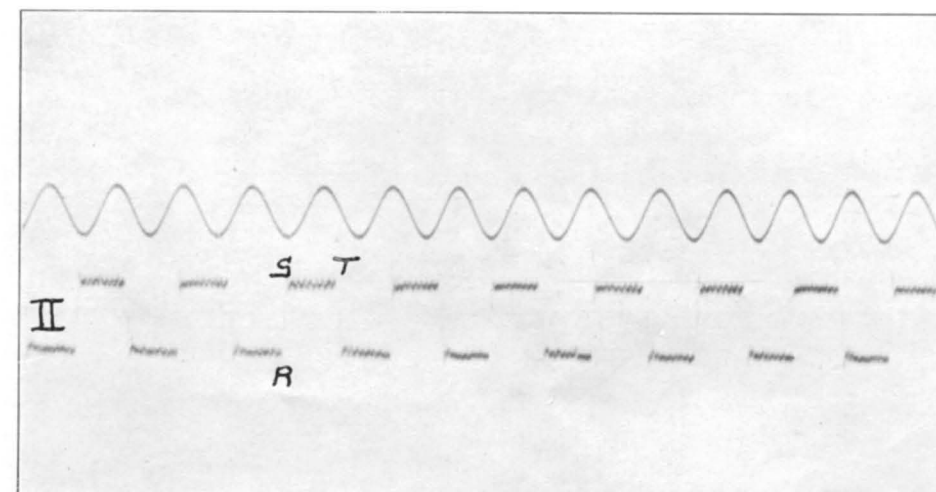
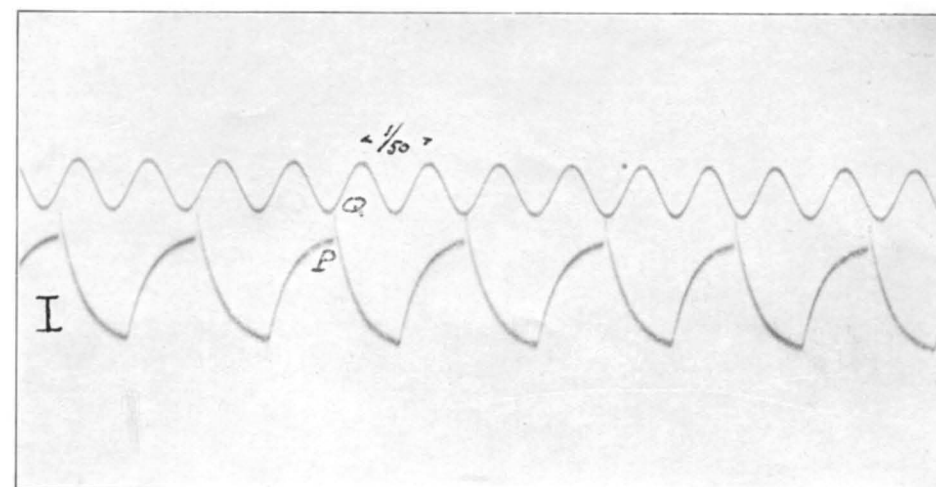


Fig. 4.

much stronger when using a high input resistance, and also with regard to the stability of the amplifier which depends principally on the reaction of the last stage on the input arrangement.

Compensating circuit and amplifier.

Two amplifiers are in use at present. Connected respectively to two hot wires they enable the recording of simultaneous fluctuations at two different points. Every amplifier is mounted in a red copper box which contains also, at the input side, the compensating circuit. The wire wound variable resistances R_1 and R_2 are of the type which is commonly used for radio purposes. By disconnecting the condenser C , which can be done with the interruptor I , the compensating effect of the arrangement can be annihilated.

There are 5 amplifying stages, with resistance coupling, which are shielded mutually by four copper partitions. The last stage is fed quite separately — it has even a separate heating current battery — as otherwise it proved to be very difficult to eliminate reactive effects when using the greatest amplification. The same storage batteries can provide, however, the filament heating current for both amplifiers.

When using PHILIPS A 425 as end tube, the maximum voltage amplification is more than 10^6 times. When using two B 405 tubes connected parallel in the end stage, the greatest current amplification of the whole amplifier is about 30 mA per 0,1 millivolt. The amplification is practically constant for frequencies from 1 up to 10,000 periods per sec. The time constant of the amplifier can be made still greater by using grid leak resistances of a few megohms for example. This, however, has various practical inconveniences, while on the other hand the necessity of amplifying fluctuations of longer periods than $\frac{1}{5}$ sec for example has not presented itself till now. By means of switches and interruptors, one can use 3, 4, or 5 stages as required; besides the total amplification can be controlled by means of the potentiometer P_C in the grid circuit of the fourth stage. In the plate circuit of the last stage an arrangement is indicated by means of which it is possible, without using any separate battery, to balance the direct current, which would flow through the oscillograph system O . This is necessary when working with sensitive oscillograph systems which can stand only a few mA, less than the normal plate current of a triode.

Observing and Recording Apparatus.

The character of the airstream in the first place can be investigated auditively by means of an electro-dynamic loudspeaker. The irregular fluctuations in the boundary layer for example cause a flopping and clapping noise, which reminds somewhat the atmospheric parasites in radio reception. In the second place the progress and the form of the fluctuations can be observed visually by means of the ordinary oscillograph, using a

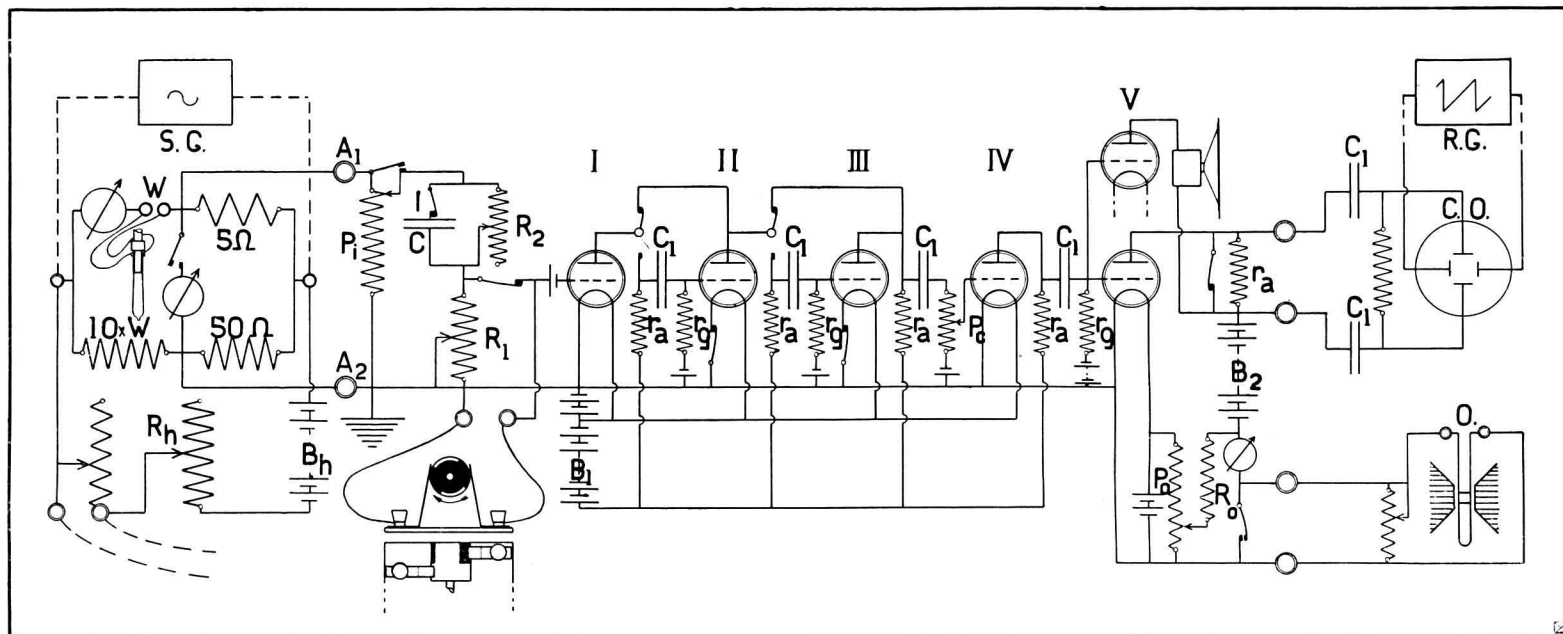


Fig. 3. Wiring diagram of the complete arrangement.

S. G. Generator of sinusoidal tension of variable frequency.

W Hot wire.

R_h Resistance of the heating circuit. The value of it depends on the wire used and on the tension of the heating battery.

B_h Heating battery (100 V. or less)

P_i Input potentiometer of the amplifier.

C. Fixed condenser of 0,05 MF.

R_1 Variable resistance 0—2500 Ohm.

R_2 " " 0—25000 Ohm.

r_a Anode circuit resistance 200.000 Ohm.

r_g Grid leak 0.5 Megohm.

C_1 Coupling condenser 8 MF.

P_c Volume control potentiometer 0—700.000 Ohm.

B_1 Dry cell battery of 200 V.

B_2 Accumulator battery of 200 V.

P_0 Potentiometer 200 Ohm.

R_0 Resistance 100 Ohm.

O. Electro magnetic oscillograph.

C.O. Cathode ray oscillograph.

R.G. Generator of relaxation oscillations of variable frequency.

In the stages I, II, III and IV A 125 tubes are used. In the last stage various types of valves may be used.

For the indicated position of the switches in the plate circuits of I and II (position for 3 stage amplification), the heating current of I and II ought to be interrupted. When 4- or 5 stage amplification is required, the switches mentioned have to be switched on.

rotating mirror or lensbarrel. For this purpose mostly a cathode ray oscillograph is used, which would, eventually, enable also the recording of the observed phenomena ¹⁾. A rotating mirror is made superfluous by an arrangement, commonly used in many laboratories. The cathode ray oscillograph tube has two sets of plates: one set causes the vertical deflection of the spot, the other the horizontal deflection. On the latter set of plates is put a potential difference which increases linearly with time up to a certain maximum value, and then suddenly returns to its original value, from which it increases again. The apparatus which gives this fluctuating tension is composed in principle of a condensor which is shunted by a gas filled tube (a neon tube) and is gradually charged up by a battery through a high resistance. When the ignition potential of the tube is reached, the tube flashes, the condensor suddenly discharges through it and its potential falls to such a value that the discharge ends. At this moment the process starts again repeating itself indefinitely. The frequency is proportional to RC , R being the value of the resistance and C the capacity of the condensor, and the adjustment to an arbitrary value thus is very easy. The electric tension to be investigated is put on the plates which cause the vertical deflection. When this tension is periodic, the curve on the oscillograph will stand still if the frequency of the horizontal deflection is the same as the frequency of the periodic phenomenon or equal to a subharmonic of it.

The arrangement described allows the observation of much higher frequencies than can be done with a rotating mirror. The cathode ray oscillograph can be used in various circumstances; the fact that its use does not present any danger for itself and that the deflections or curves can be observed from a certain distance even at daylight makes it a very useful instrument.

In order to analyze the fine structure of the complicated airspeed fluctuations in the turbulent boundary layer, it proved to be necessary to take records on rapidly moving sensitive paper or film. The optical arrangement and the recording camera which are used here with the normal SIEMENS oscillograph make it possible to take fair records without difficulty on sensitive paper moving with velocities up to 1,50 m per sec.

Calibration of the entire arrangement.

Though the behaviour of the apparatus remains fairly constant for a given adjustment during a rather long time, it is impossible to calibrate the whole arrangement once for all in consequence of the many varying elements present in it. The hot wires themselves are the most important sources of change as they break frequently and then have to be replaced, but battery tensions, vacuum tube characteristics, oscillograph oil qualities etc, also must be mentioned. Hence it is necessary to dispose of a simple

¹⁾ This cathode ray oscillograph, of the ordinary laboratory type, is supplied by MANFRED VON ARDENNE's Research Laboratory, Berlin.

method by means of which it is possible, for each series of records, to determine easily and accurately, which oscillograph deflection corresponds to a velocity variation of given value.

Before performing the calibration, the variation of the sensitivity as a function of the frequency of sinusoidal fluctuations must be investigated in order to make it independent of the frequency, at least within a certain range, by means of the compensating circuit. For this detail the reader is referred to the paper mentioned, which contains a full description of the frequency calibration.

Air flow velocities in the wind channel are measured with Pitot tube and micromanometer, and all hot wire anemometers originally must be calibrated against them. Keeping the heating current constant, it is possible for a series of airspeeds either to measure the resistance of the hot wire (the potential difference between its extremities) or to determine the values of the current which, for a given bridge arrangement, flows through the galvanometer connected in series with a known resistance. The latter method would give the direct tension existing at each airspeed between the points A_1 and A_2 . The amplifier, however, though amplifying still very slow fluctuations, does not reproduce differences of direct current. Hence it would be necessary, each time to calculate the magnitude of the variations of the velocity from the oscillograph deflections, taking account of the adjustment of the compensator, the amplifying factor of the amplifier for the position of the volume control during the experiment, and the sensitivity of the oscillograph. It would be much easier therefore when we could succeed in making airspeed fluctuations of known magnitude and see directly which oscillograph deviations would result. Nevertheless this is not possible in practice; the following method, however, which is very simple may be used.

Each permanent deviation ΔV of the air velocity from the value V for which the bridge has been equilibrated, provokes a potential difference E between the points A_1 and A_2 and thus also one on the resistance R_1

of the compensating circuit equal to $e = \frac{R_1}{R_1 + R_2} E$. This direct tension

e , by which the potential of the grid of the first amplifier tube is changed, is just equal to the sensitivity of the compensated hot wire without amplifier for that constant velocity change V and thus also for fluctuations of the same amplitude. Periodic shortcircuiting of R_1 will provoke input tension variations of magnitude e , and thus, via the amplifier corresponding oscillograph deviations which, on account of their rectangular form, give two light spots on a screen, the distance of which is equal to the sensitivity of the whole arrangement for velocity variations of magnitude ΔV .

The periodic short circuiting of R_1 occurs by means of a rotating ebonite cylinder, mounted on the axis of a small electromotor and fitted with brass contact strips which periodically connect two red copper brushes pressing against the cylinder. The use of carbon brushes must be avoided in our

case, in regard of the contact potential between brass and carbon, which cannot be neglected here.

The calibration of the arrangement now cannot be more simple. The motor of the periodic interruptor is switched in, the hot wire being in a steady flow of the same velocity as that used in the experiments. If the bridge was not balanced correctly this causes a deflection of the oscillograph. Observation of this deflection makes it easy to adjust the exact equilibrium. The bridge galvanometer thus becomes superfluous. *Then it is only necessary to bring the velocity of the airflow in the channel at some other values, to be measured with Pitot tube and micromanometer, and to read the corresponding oscillograph deviations or to record them, if required, on sensitive paper.*

It will occur sometimes that the mean velocity of the turbulent flow which must be investigated will be different from the velocity in the undisturbed region, or that the fluctuations have an assymetric character which makes it practically impossible to determine the zero line on the oscillogram. In this case it would be impossible to read in the oscillogram the absolute value of the velocity at any instant. This inconvenience can be avoided in the following way. The bridge is balanced and the calibration effected when the hot wire is in a steady flow of known velocity; then without changing the adjustment the wire is brought in regions of unknown mean velocity, where the flow may be either steady or turbulent. Periodic shortcircuiting of R_1 will now cause oscillograph deflections which for each case, all will reach the line of the original velocity V , the zero line of the calibration. *The distance between a certain point of the recorded curve and this line, indicates how much, at any instant, at the place of the hot wire, the velocity differs from the known velocity V of the undisturbed airflow.*

All the preceding considerations principally had in view the investigation of velocity fluctuations, which are not too small compared with the mean velocity, and no attention was given to the fluctuations which are still present in the steady airflow of the best wind channel ¹⁾. Compared with the fluctuations in the turbulent boundary layer the latter entirely can be neglected in our case. When on the other hand especially these small airspeed fluctuations of the free stream are to be investigated and measured, the calibration of the arrangement can be performed in quite the same way as is described above, with an amplification which does not yet show the disturbances which must be studied. If then, for the investigation, the amplification must become n times larger, the sensitivity will be n times the value which is given by the tangent at the point of the calibration curve corresponding to the mean velocity in the investigated region.

¹⁾ Comp. f.i. J. M. BURGERS, These Proceedings 29, p. 547, 1926. Experiments on the fluctuations of the velocity in a current of air.

The reproduction of „rectangular” velocity fluctuations.

A good check on the behaviour of the anemometer arrangement would be the reproduction of sharp edged velocity fluctuations of known type, for example of rectangular form. Indeed when an uncompensated hot wire is mounted in an air current which shows rectangular velocity fluctuations of short period, the reproduction will generally depart considerably from the original form, owing to the lag of the hot wire. The temperature T of the wire each time approaches to the equilibrium value corresponding with the new velocity according to the equation:

$$T - T_2 = (T_1 - T_2)e^{-\lambda t},$$

where T_1 and T_2 are resp. the original and the final temperature, and λ is a factor dependent on the dimensions, etc. of the hot wire ¹⁾. Hence T will reach its final value only if the new velocity remains constant long enough. When the period of the fluctuations is not great compared with the time constant $1/\lambda$ of the wire, the temperature will change again in the opposite direction already before the state of equilibrium will have been reached.

If the compensation is efficacious, the influence of the lag must be eliminated, and the reproduction must show a fair approximation of the rectangular form.

It has been mentioned already that the behaviour of a wire with regard to its lag can be estimated by studying the influence of heating current fluctuations in stead of that of airspeed fluctuations ²⁾. This circumstance may be used also in the present case.

By means of the rotating interruptor it is possible periodically to short circuit a resistance in series with the heating current battery and thus to vary periodically the current from the value i to the value $i + \Delta i$. The change of temperature of the wire will then be approximately the same as that caused by rectangular velocity fluctuations and the lag will show it self in the same manner.

A picture of this effect is given by the first oscillogram of fig. 4 obtained with a platina iridium hot wire of 0,015 mm diameter. A rather thick wire has been taken for these records, as in that case the lag is much greater than with the thinner wires used for boundary layer work. The points A_1 and A_2 were connected directly with the first amplifier tube. For an air velocity of about 10 m. per sec the heating current was brought periodically from the value 0,220 A for which the bridge was equilibrated, to 0,195 A. The peculiar sharp peak which is formed at one side is an effect of the second order inherent to the experiment. At the point P of the oscillogram the wire through which then flows a current of 0,195 A, has obtained a certain temperature and thus presents a certain

¹⁾ For the signification of λ , see the publication mentioned at the preceding page.

²⁾ See Mededeeling 20.

resistance for which the bridge is no more balanced. When now suddenly the current increases, the resistance of the wire first remains the same, and the tension between A_1 and A_2 , which, for given values of the bridge resistances is proportional to the current, increases also suddenly. From the point Q the ordinary curve of temperature variation of the wire begins again.

The next oscillogram is taken in the same circumstances but after insertion of the compensating circuit which made necessary a much greater amplification as the loss of sensitivity by compensation is greater of course for thick wires than for the thin wires generally used when the same frequency characteristic is required. Some parasites are the cause of the small deviations from the smooth line.

By observing these curves with the aid of the oscillograph it is possible to find the adjustment of the compensating circuit which gives quite the same sensitivity for the slowest and for the most rapid fluctuations¹⁾. Taking provisionally R_2 very great it is seen that upon diminishing the value of R_1 , the line RS becomes more and more steep, hence the arrangement less and less slow, but the larger must be the total amplification. This gives a practical limit for compensation. Then R_2 must be given such a value that the line ST is horizontal (oscillogram II). If its value is too high the picture of oscillogram III is obtained. The wire then is "over compensated". On the other hand when it is too low the picture obtained is more and more like oscillogram I. By pushing out the interruptor I, the compensation is eliminated but the sensitivity for the lower frequencies remains the same. If the period of the heating current fluctuations is long enough in order that the resistance of the wire each time reaches a constant value, the curve which we observe has a horizontal part (the time constant of the amplifier is still much longer and does not cause any declination of the line). Connecting again the condensor has the effect that the first part of the curve becomes much steeper and thus much sooner reaches the horizontal line. The inclination of this part of the curve gives an idea of the remaining lag of the arrangement.

It is thus possible, without using a generator as described in Mededeeling 20, to make a hot wire anemometer suitable, with a fairly great accuracy, to the exact reproduction of air velocity fluctuations with components of very different frequencies.

Moreover, if one has ascertained that an air velocity variation of value ΔV causes the same resistance change of the wire as the current variation Δi which was used in the experiments, the deviation of the oscillograph — here again, owing to the compensation, visible in the form of two light spots on a screen — at the same time gives the sensitivity of the whole arrangement for that airspeed variation ΔV . This method

¹⁾ It is advisable to observe the curves on the oscillograph used for recording, as then the frequency characteristic of the oscillograph itself automatically is taken in consideration when adjusting the compensating circuit.

of calibration is almost as simple as that which is described above; now, however, for each variation of velocity, it is necessary to determine *each time again* the value of the resistance in the heating current circuit which has to be short circuited.

Phase.

The fact that, by using the compensating circuit, the rectangular form reappears in the experiment described proves in it self that the relative phases of the different components have got the original values again. This fact was confirmed by a separate investigation executed with a 0,015 mm wire by means of the cathode ray oscillograph.

For this experiment the horizontal deflections of the cathode ray were derived from the sinusoidal voltage given by the generator described in the preceding communication. The plates of the oscillograph which cause the vertical deflection of the spot were connected to the output of the amplifier while through the bridge an alternating current was sent, given by the same generator and in phase with the tension which caused the horizontal deflections. It appeared that when the compensator was put out of circuit, the vertical deviations, which correspond to the temperature fluctuations of the wire, show an appreciable retardation in phase compared with the tension taken directly from the generator, i.e. compared with the current by which these temperature variations are caused. When the frequency of the generated sinusoidal tension is increased e.g. from 20 periods per sec upwards, and the output amplitude of the amplifier is kept constant at the proper value by means of the volume control, the narrow ellips which is already to be seen at the lowest frequencies, changes gradually in width and becomes a circle at about 200—300 periods which indicates a phase retardation of 90° . The phase difference caused by the amplifier itself can be neglected for these frequencies.

Insertion of the compensating circuit not only had as result that *the output amplitude was automatically constant up till a certain frequency*, but also that over the greatest part of the frequency range of constant amplitude, *the cathode ray oscillograph showed a straight line sloping under 45° , which proved that the phases were equal again.*

EXPLANATION OF THE FIGURES

- Fig. 1. Micro photo of a 0.005 mm wire. The wire is not yet stretched entirely. The distance between the two points is about 0.6 mm.
 - Fig. 2. One of the hot wire holders in its position for the investigation of the boundary layer along the glass plate.
 - Fig. 4. Reproduction of rectangular fluctuations by a 0.015 mm hot wire.
 - I. Without compensation,
 - II. With a correct compensation and greater amplification.
 - III. With "over compensation".
-