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ELECTRONIC EQUIPMENT FOR WIRE-STRETCHING MACHINES

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GENEVA
1976
ABSTRACT

The construction of wire chambers for the detection of elementary particles involves the stretching of very fine wires with diameters of the order of 10 μm. The report describes the design of electronic equipment for the automatic control of wire tensions in the range of 0.01-1 newton. The equipment consists of two separate motor/transducer units, one for stretching very fine wires and tensions up to 0.1 N, the other for thicker wires and tensions up to 2 N. The design and performance of the control circuits are presented in detail.
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LIST OF SYMBOLS

a  radius of bobbin
Ea  armature voltage
Eb  counter EMF of the motor
G(s)  transfer function of current control amplifier
GF  gauge factor of strain gauges
H(s)  transfer function of wire tension transducer
I  inertia of bobbin and armature together
ja  armature current
ka  torque per unit armature current ("specific torque")
k_b  EMF per unit angular speed ("specific EMF")
ke  elasticity coefficient of wire and transducer arm combined
kf  friction coefficient \( T_f = k_f \Omega \)
k_i  feedback factor of the armature current
Ra  resistance of the armature plus shunt
Ta  torque developed by the armature (motor)
Tf  torque due to friction
Tw  wire tension
TCR  temperature coefficient of the resistance of a strain gauge
UB  supply voltage of the strain gauge bridge
Vw  wire speed
Za  impedance of the armature circuit
\( \alpha \)  expansion coefficient
\( \zeta \)  damping factor
\( \theta \)  angular displacement of bobbin
\( \tau_e \)  time constant of the armature circuit
\( \tau_1, \tau_2, \tau_3, \tau_4 \)  time constants of the frequency correction networks
\( \Omega \)  angular speed of the bobbin
\( \omega_b, \omega_s, \omega_1, \omega_2, \omega_3, \omega_4 \)  "corner frequencies"
\( \omega_n \)  resonance frequency of the transducer arm
1. INTRODUCTION

The construction of wire chambers for use in nuclear physics experiments implies the stretching of thin metal (tungsten) wires. The development in this particular field of instrumentation has led to the use of wires which are extremely fine and fragile, thus making the task of stretching them more and more delicate. The wire-stretching machines\(^1\) which were developed by the Technical Assistance group of the Nuclear Physics Division at CERN some 10 years ago were designed to stretch wires of diameters down to approximately 100 \(\mu\text{m}\), but have performed well down to diameters of 20 \(\mu\text{m}\). In order to use these machines for still finer wires, a new electronic control system has been developed to replace the existing one.

2. DESCRIPTION

2.1 General

The functional block diagram in Fig. 1 shows the control system with its various components. On the left is shown the reference potentiometer by which the desired wire tension is set. Then follows the summing point, where the deviation signal is created by subtracting the analogue wire tension signal from the reference signal. The deviation is amplified in the "tension control amplifier" -- including frequency-correcting networks -- and fed into a loop controlling the armature current of the motor, which in turn is supplying a torque to the bobbin containing the wire. Hence, the last-mentioned loop acts as a constant torque source, controlled by the amplified tension error signal. The torque of the motor is counteracted by the wire tension -- the controlled condition -- which is measured by the wire tension transducer.

![Block diagram of the wire tension control loop](image)

Fig. 1 Descriptive block diagram of the wire tension control loop

In practice, it is convenient to have two motors and two wire tension transducers: a little motor and a sensitive transducer for the fine wires [tensions up to 0.1 N\(^*\)], a more powerful motor and a more robust transducer for the stronger wires (tensions up to 2 N). By means of a manual switch, either the fine wire or the stronger wire equipment is connected. In the following, a description of the essential mechanical parts of the block diagram in Fig. 1 is given.

\(^*)\) 1 newton = 101.9716 pond (gramme-force); 1 p = 0.0098067 N.
2.2 Wire tension transducer

The wire of which the tension has to be measured passes over a pulley mounted at the end of an arm (see Fig. 2) such that the incoming wire is parallel to the outgoing one. Hence, the force exerted at the end of the bar is twice the wire tension. The resulting elastic deformation of the arm is sensed by two piezoresistive strain gauges mounted on opposite sides of the arm. The arm is made of aluminium alloy ("Anticorrodial") and is shaped so as to combine a high resonant frequency with a sufficient sensitivity. In order to increase the damping at the resonance frequency of the system armature-bobbin-transducer, the arm is mounted in a flexible support (made of rubber). The construction shown in Fig. 2 has a resonant frequency of approximately 1200 Hz. When mechanically coupled to the inertia of the spool plus armature by the wire being stretched, the resonance frequency is lower (see later). The assembly of Fig. 3 was used for testing and measuring.

2.3 Motors

The bobbin containing the wire to be stretched is mounted on the shaft of a low inertia d.c. motor. For thin wires (tensions below 0.1 N) a small motor of 1.6 W mechanical power, with metal brushes and a rotor with self-supporting windings without iron, is employed. For the heavier wires (tensions of 0.2 N and upwards) a motor of 90 W mechanical power, with carbon brushes and self-supporting windings of the rotor, is used. In Table 1 are given the essential data of the two motors.
3. THEORY

As mentioned before, the system is composed of two loops -- one controlling the armature current (torque) of the motor and one controlling the wire tension. They will be described in the following.

3.1 Armature current control loop

The functional block diagram employed for this loop is shown in Fig. 4. It can be shown that if \( k_1 \dot{I}_a \gg k_b k_a I_a \), then the gain of the feedback loop which is created by the

![Functional block diagram](image)

**Fig. 4** Functional block diagram of the current control loop. \( G_i \) is the transfer function of the control amplifier and correction networks: \( G_i = \frac{(1 + s\tau_1)}{(s\tau_2)} \).

counter EMF is very small and one may neglect its influence. The above-mentioned inequality holds in the present case and hence the current feedback loop reduces to the diagram shown in Fig. 5.
The simplified current control. It is assumed that $F_b$ may be neglected.

The impedance $Z_a$ of the armature circuit can be written as

$$Z_a = R_a (1 + s \tau_e) ,$$  \hspace{1cm} (1)$$

where $R_a$ is the resistance and $\tau_e$ is the electrical time constant of the armature circuit. Choosing $\tau_a = \tau_e$ results in a continuous roll-off of 20 dB/decade of the open-loop frequency characteristic. The closed-loop function is then as shown in Fig. 6. The values of $k_i$ and $\tau_a$ are chosen such that the response is much faster than that which can be expected of the wire tension control loop.

Fig. 6 The closed-loop transfer function of the current control circuit.

3.2 Wire tension control loop

In this loop, resonance phenomena of the mechanical parts have to be considered. The inertia ($I$) of the armature plus bobbin in connection with the elasticity of the wire and transducer arm represents a mechanical resonant system (see Fig. 7). The wire tension may be expressed by $t_w = k_e a \dot{\theta}$, where $k_e$ is the combined elasticity coefficient of the wire and the transducer arm, $a$ is the radius of the bobbin, and $\dot{\theta}$ the angular displacement of the bobbin. The system is described by the following two equations:

$$T_a - t_w a - T_f = I \frac{d\dot{\theta}}{dt}$$  \hspace{1cm} (2)$$

$$t_w = k_e a \dot{\theta} = k_e a \int \ddot{\theta} \, dt .$$  \hspace{1cm} (3)$$

Here $\dot{\theta}$ is the angular speed of the bobbin and $T_f$ is the torque due to friction.

Fig. 7 Spring-restrained inertia composed of the wire elasticity and the bobbin plus armature inertia.
A part of \( T_f \) is proportional to \( \Omega \) (viscous friction) and a more important part is constant independent of the speed. So, a graphic representation of \( T_f \) versus \( \Omega \) is essentially that shown in Fig. 8. The non-linear characteristic of \( T_f(\Omega) \) gives rise to a phase lag

![Fig. 8 Graph showing the nature of the friction (torque)-velocity relationship](image)

which is amplitude- and frequency-dependent. The system can, however, still be treated as a linear system, keeping in mind the particular effects of the friction. The block diagram of the spring-restrained inertia (bobbin plus armature) would then be that shown in Fig. 9. There the dry friction is neglected. After some calculations one gets for the transfer function:

\[
\frac{t_w}{T_a} = \frac{1}{a} \frac{1}{\frac{2\zeta}{\omega_n} s + 1},
\]

(4)

where

\[
\omega_n^2 = \frac{k_e a^2}{I} \quad \text{and} \quad \zeta = \frac{1}{2} \frac{\omega_n}{k_f} = \frac{1}{2} \frac{k_f}{avT_e}.
\]

Measurement of the amplitude characteristic has shown that the system is heavily damped (\( \zeta \gg 1 \)) and consequently the denominator polynomial has real roots. One can therefore write:

\[
\frac{t_w}{T_a} = \frac{\omega_a \omega_b}{a} \frac{1}{(s + \omega_a)(s + \omega_b)},
\]

(5)

where \( \omega_a \) and \( \omega_b \) are the (real) roots.

![Fig. 9 Functional block diagram of the mechanical part of the system](image)
The entire wire tension control loop including an external perturbation acting on the wire speed:

\[ A(s) = \frac{\omega_5}{\omega_4} \frac{s + \omega_5}{s + \omega_4}, \quad \omega_5 > \omega_4 \]

\[ B(s) = \frac{1}{s + \omega_i}, \quad \frac{1}{R_a + 1} = \frac{\omega_i}{k_i} \]

\[ C(s) = \frac{1}{s^2(1/\omega_n^2) + (2\zeta/\omega_n) + 1} \]

The frequency characteristic of the transducer arm exhibits a resonance frequency, the value of which depends on the material and the method of construction employed. However, when the wire-stretching machine is in use, the transducer arm is coupled with the inertia of the bobbin plus armature by the wire to be stretched. This lowers the resonant frequency to about half that of the arm alone (this is for the system for low tensions, 0-0.1 N). The block diagram of the entire system is then as shown in Fig. 10. H(s) is the transfer function of the transducer. It constitutes part of the mechanical system of which the transfer function was measured and is plotted in Fig. 11. Its resonance frequency falls outside the frequency range of the system but, as the resonance peak is high, the closed-loop transfer function exhibits a tendency to oscillate at this frequency. For this reason, a band-stop filter ("twin tee") is inserted in the loop in front of the power amplifier which supplies the armature current. This circuit is not shown in the block diagram.

The function in the block after the summing point belongs to the tension control amplifier. For frequencies in the interval \( \omega_n < \omega < \omega_5 \) it has derivative action. The Bode plot is shown in Fig. 12. \( t_w \) stands for the variations of wire tension which eventually are to be minimized by the feedback loop. The variations arise mainly from variations of the speed (\( v_w \)) at which the wire is delivered from the bobbin. One has for the relation between wire tension and speed:

\[ I_0^a + k_f \Omega = t_w a \quad (6) \]

or

\[ a^{-1} I_0 \dot{v}_w + a^{-1} k_f v_w = t_w a \quad (7) \]

\[ a^{-2} (I_0^w + k_f v_w) = t_w \quad (8) \]

This relation is included in the block diagram of Fig. 10.
4. CIRCUIT DIAGRAM

In the circuit diagram of Fig. 13 only the most essential components are shown in detail.

The components marked (1) and (2) to the right are the strain gauges of the transducers for measurement of wire tension. Transducer (1) is for 0-0.1 N and (2) is for up to 2 N wire tension.

The offsets of the two Wheatstone bridges of which the strain gauges are a part are adjusted by the potentiometers R7 and R14. The gains of the amplifiers A2 and A4 are adjusted to give 10 V output at maximum wire tension. By the control amplifier A5, the desired gain-phase corrections are established for best stability and speed performance of the wire tension control loop.

After amplification in A5, the analogue wire tension deviation goes to the input of the armature current control loop which includes a control amplifier A8, performing derivative and integral action.

Via a band-stop filter (600 Hz), the output of A8 is fed to a power amplifier (A9) capable of delivering sufficient current for the maximum desired torque. The armature current is measured by means of shunts (R44 and R45). The output of A9 can be connected to one or the other of the two motors (and shunts) by means of a manual switch, according to the desired range of wire tension. The current buffer A6 performs the required scaling of the shunt outputs.

5. BODE PLOTS

5.1 Mechanical parts

In order to be able to establish the transfer function of the entire open loop, the transfer function of the mechanical part of the system is measured. That is, a Bode plot is made of the output of the strain gauge Wheatstone bridge relative to the armature current or, in other words, of the wire tension relative to torque.

Because of the non-linear effect of the dry friction (see Fig. 8), the phase lag increases with increasing amplitude. Therefore, in order to obtain the safest values, to serve as a basis for design, the measurement was made at a signal level such that either the armature current, or the analogue wire tension signal (whichever was first affected), was just below the level which would result in a distorted output. By this means the closed loop is prevented from being unstable at high amplitude, although being stable at low signal levels. The plot for the range of 0-0.1 N wire tension is shown in Fig. 11.
Fig. 13 Circuit diagram of the wire tension control system

Notes:
1) 1-10 range
2) 20-200 range
At about 10 Hz the attenuation starts, corresponding to the cut-off frequency \( f_a = \omega_a / 2\pi \) mentioned in Section 3.2, Eq. (5). The frequency \( f_b \) is situated somewhere outside the diagram to the right.

According to Eq. (5), the Bode plot should correspond to a system with one time constant (one single pole) for \( f \ll f_b \). However, it rather corresponds to a second-order system (for \( f < 100 \) Hz). This discrepancy is imputed to be due to the dry friction and, effectively, the smaller the signal level, the more the measured transfer function approaches that of a first-order system.

A measurement at low signal levels is in the best case very inaccurate because of friction in bearings and brushes of the motor. For this reason, and because of little practical interest (in the present case), the corresponding Bode plot has not been made. The resonance peak situated at about 550 Hz is due to the mechanical resonance of the transducer arm coupled with the inertia of the bobbin plus armature. The plot also shows that for \( f > 10 \) Hz the phase lag quickly approaches 180° so, in order to obtain stability at a reasonable speed of resonance, a circuit with a derivative action must be included in the loop.

5.2 Armature current control loop

This loop has to be treated before the entire open-loop characteristic can be fixed. It indirectly controls the torque of the motor so that the wire tension loop essentially has to cope with the perturbations due to interactions between delivery speed and inertia and friction. In Fig. 14 the Bode diagrams for the current loops (1) and (2) are shown. In order not to create confusion with units, the loop is transformed into an equivalent unity gain system and the quantity \( k_i J_a \) is plotted instead of \( J_a \). The two loops (1) and (2) do not have the same speed of response but, as the speed of response of the slowest is sufficient, this is not of any importance. In Table 2 the numerical values of the constants and parameters of the control loop are listed.

![Bode plots for the current control loop](image-url)
Table 2

Values of the armature current control loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Range 1</th>
<th>Range 2</th>
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<tbody>
<tr>
<td>Maximum wire tension</td>
<td>$t_{w\max}$</td>
<td>N</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Maximum bobbin radius</td>
<td>$a$</td>
<td>cm</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Maximum steady state torque</td>
<td>$T_{as}$</td>
<td>Nm</td>
<td>$10^{-3}$</td>
<td>$100 \times 10^{-3}$</td>
</tr>
<tr>
<td>Maximum intermittent torque</td>
<td>$T_{ai}$</td>
<td>Nm</td>
<td>$6 \times 10^{-3}$</td>
<td>$160 \times 10^{-3}$</td>
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<tr>
<td>Maximum steady state armature current</td>
<td>$i_{as} = k_{a}T_{as}$</td>
<td>A</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Maximum intermittent armature current</td>
<td>$i_{ai} = k_{a}T_{ai}$</td>
<td>A</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Integration constant</td>
<td>$\tau_{i} = R_{i}C_{i}$</td>
<td>sec</td>
<td>$12 \times 10^{-4}$</td>
<td>$12 \times 10^{-6}$</td>
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<td>Cut-off frequency of armature current control</td>
<td>$\omega_{i}$</td>
<td>sec$^{-1}$</td>
<td>$12 \times 10^{3}$</td>
<td>$6.7 \times 10^{3}$</td>
</tr>
<tr>
<td>$f_{1}$</td>
<td>Hz</td>
<td></td>
<td>$2 \times 10^{3}$</td>
<td>$10^{3}$</td>
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<tr>
<td>Electrical time constant of armature circuit</td>
<td>$\tau_{e}$</td>
<td>sec</td>
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<td>Feedback constant of current loop</td>
<td>$k_{i}$</td>
<td>V/A</td>
<td>18</td>
<td>5.6</td>
</tr>
</tbody>
</table>

5.3 Wire tension control loop

The complete wire tension loop is composed of the components mentioned in the preceding sections, i.e. wire tension control amplifier, armature current control loop, mechanical system, and wire tension transducer. The Bode diagram is now approximated by a second-order system with its cut-off frequency at 10 Hz. The plot for the entire loop is then as shown in Fig. 15. It is seen that the cut-off frequency for the closed loop is approximately 30 Hz. At low signal levels this frequency will be higher as the slope of the curve gets smaller, because of the effect of dry friction, as mentioned earlier.

6. RESPONSE

The response to a perturbation was measured by feeding a current step into one branch of the bridge circuit of the wire tension transducer. This is equivalent to an abrupt change of the wire tension (the speed of response of the transducer is so high, compared to the response of the loop, that one can disregard the time constant of the transducer response). The oscillogram of Fig. 16 shows how the system responds. The perturbation corresponds to a step of 0.01 N (i.e. 10% of full range). In the first instant the error of the tension signal is equally 0.01 N, but it rapidly decreases to an insignificant value after about 5 msec.
Fig. 16 Response to a perturbation of the wire tension. The perturbation was created by feeding a current step into the input of the buffer amplifier A2 of Fig. 13. The low-amplitude oscillation is due to the mechanical resonance of the arm.

Upper trace: wire tension = 0.01 N per division;
Lower trace: perturbation = 0.01 N per division;
Time base: 10 msec per division.

7. TEMPERATURE DRIFT

Of the possible sources of error, the temperature drift of the strain gauge elements is the most important.

Three effects have an influence on the temperature drift of the output voltage from the strain gauge bridge:

i) Different temperature coefficients of the resistances of the two strain gauges give rise to an imbalance.

ii) The above-mentioned temperature coefficients also give rise to an increase in bridge voltage, thus increasing the scale factor of the bridge with temperature.

iii) The temperature coefficient of the gauge factor (TCGF) influences the scale factor of the bridge.

(Also, Young's modulus of elasticity changes with temperature but, as the change is very small for the temperatures in question, the effect is neglected.)

The first-mentioned source of error is independent of the bridge output and therefore gives rise to an error which is the more disturbing the lower the signal.

The two other sources influence the gain of the bridge and the error is, therefore, a constant proportion of the actual output. The two errors counteract each other, so that the resulting error is smaller than each taken separately. In the following, a brief quantitative treatment of the errors will be given.

The temperature coefficient of the resistance of one strain gauge element (TCR) is given by the manufacturer to be

\[ TCR = \frac{dR}{R} |_t = 0.18/100^\circ F = 10^{-3}/^\circ C. \]
The bridge is shown in Fig. 17. The two resistances of the strain gauges are expected to be balanced to better than 2% (they are received in sets of four, matched). Consequently, the maximum error, due to an imbalance of these two resistances, is

$$\frac{\Delta_1 U}{U_b} = \frac{1}{4} \frac{\Delta R}{R} t = \frac{1}{4} \text{TCR} 0.02 \Delta t = 5 \times 10^{-6} \Delta t.$$  

Fig. 17  The Wheatstone bridge for the measurement of wire tensions

$U_b$ is approximately 10 V, so $\Delta_1 U = 50 \times 10^{-6} \Delta t$. The full scale (FS) output from the bridge is approximately 0.1 V, so the error relative to maximum output is $\leq 500 \times 10^{-6}/°C$. For a temperature change of $\Delta t = 10°C$ one obtains the error due to an imbalance of the TC's of the gauge resistances to be a maximum of 0.5% FS. It may be positive or negative.

As regards the sources of error mentioned under (ii) and (iii), after some calculations, one finds

$$\Delta_2 U = \Delta U \left(1 + \frac{R_1}{R + 2R_1} \left[\text{TCR} + \alpha GF\right] \Delta t\right).$$  \hspace{1cm} (9)

Here $\Delta_2 U$ is the bridge output voltage including these two sources of error and $\Delta U$ is the correct output voltage due to a certain wire tension $[\Delta U = 1/2 \text{ GF (Δt/°C)} U_b]$. $\alpha$ is the expansion coefficient of the support material (aluminium: $\alpha = 23.7 \times 10^{-6}/°C$). GF is the gauge factor (GF = 155). With $R = R_1$ one obtains for the relative error

$$\frac{\Delta_2 U - \Delta U}{\Delta U} = +0.0008/°C \text{ or } +0.08%/°C \text{ max}.$$  

For $\Delta t = +10°C$ one has +0.8% max.

The error arising from source (i) may in the worst case add to this value, so the most pessimistic forecast indicates an error of +1.3% for a temperature change of +10°C or $\pm 0.75%$ for a temperature change of $\pm 5°C$, the error due to input offset drifts of the associated amplifiers being negligible.
8. AUXILIARY CONTROLS

In addition to the control of the wire tension, a control of the feeding speed of the wire ("chariot control"), and of the advance ("step control") is provided for, as well as an end stop for a predetermined length of the wire plane. Thus the machine, once started, can be left on its own and stops when the desired number of wires is stretched. When the wire breaks an alarm is activated and the machine stops.

9. CONCLUSION

The need for controlling wire tensions down to very small values makes a rather thorough study of the stability criteria necessary. It should be noted that the frequency- and amplitude-dependent effect of the friction of the moving mechanical parts is very important and requires special consideration.

Acknowledgements

The author wishes to acknowledge the valuable support he received from the members of the EP/TA group at CERN.

* * *

REFERENCE