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A WIRE-WINDING AND TENSIONING MACHINE FOR THE CONSTRUCTION OF PROPORTIONAL WIRE PLANES AND WIRE SPARK CHAMBERS

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I. Introduction:

The construction of proportional wire planes (pwp) and wire spark chambers requires the laying of wires at equal spacing and tension to form wire planes. This can be accomplished by manually placing wires in machined grooves and stretching them to a specified tension with weights. This procedure is quite time consuming but it can be automated by using a type of weaving machine [(1)] or a wire-winding machine such as is described in this note.

The characteristics that have been obtained with the current design of the winding machine are:

a) uniform spacing of wires at .100", .050", and .025". The root mean square deviation about the mean for the .100" spacing is ±0.001" with a maximum deviation of .006" over a distance of 10".

b) continuously variable wire tensions from 20 g. to 300 g. with an estimated variation at any one setting of ∿5 g.

c) continuously variable winding speed from .33 to 19 rpm. (n.b. the speed is not always an independent variable but must sometimes be set to minimize the uncertainty in wire tension.)

d) chamber frame sizes up to 5 ft. by ∿10 ft. may be wound. Even larger sizes may be accomodated in the 5 ft. direction either by increasing the length of the lead screw or by moving the wire-spooling carriage laterally a fixed distance (see Fig. 2.).

e) the possibility of the pre-tensioning of frames being wound in place, so as to offset the force due to wire tension which would otherwise deform the frames and thereby change the tension, and the possibility of winding "transfer" frames which can be used for chamber construction away from the winding machine.

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(1) Private communication, Mr. G. Muratori (CERN, Geneva, Switzerland).

f) the possibility of mounting an existing 26 in. diameter cylinder 5 ft. in length in place of the winding frame. On this cylinder thin mylar sheets may be extended and wires epoxied to it at a fixed spacing. Such sheets can then be used as wire-planes. This method of constructing wire planes is in current use for wire spark chambers at Argonne National Laboratory[2] and has been used here to construct thin streamer-chamber plates[3].

II. Design Considerations for a Wire-Winding Machine:

In Fig. 1 the principle of the wire-winding machine is summarized. In this description the thickness of the winding and chamber frames are ignored. Expressions for the wire speed, $d\ell/dt$, for the wire acceleration, $d^2\ell/dt^2$, and for the transverse speed, $\dot{x}$, of the spooling pulley are given.

In general, the maximum wire speed occurs when $\theta \sim \pi/2$ and the maximum wire acceleration when $\theta \sim 0$[4]. This is immediately clear when one assumes $D >> B(D \sim \ell)$. This assumed condition, however, is not always convenient, particularly when B is large. It turns out that even if $D = 2B$, the maximum value acceleration is not increased by more than a factor of 2 over that for $D >> B$. It would seem, therefore, that $D = 2B$ might be a reasonable compromise with $D < 2B$ requiring a more critical analysis.

The wire tensions is maintained by a hystersis brake to which the spooling pulley is attached. The hystersis brake gives a constant torque at any speed of rotation if inertial forces are ignored, and the value of the torque may be continuously varied over a limited range, i.e., 0.4 to 14.0 in. oz. with the two hystersis brakes that have been purchased. Ignoring (for the moment) the tension of the wire coming to the pulley and assuming that the wire does not slip in the pulley[5], the tension is simply the torque divided by the pulley radius. The tension exerted on the incoming wire and on the outgoing wire by the wire guide, must be added to tension introduced by the hystersis brake to obtain the total tension.

The above analysis was made under the assumption of a constant wire-spooling speed or a constant speed of rotation for the pulley. However, in our case, the angular velocity of winding frame, W, is constant and the wire velocity varies during each revolution. The value for the instantaneous wire acceleration, $d^2\ell/dt^2$, may be calculated from the equation given in Fig. 1. The effect of this acceleration is to

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(2) P. Steinberg private communication.
(3) W. Risk, private communication.
(4) For finite frame thicknesses, $\theta = 0$, is never reached and a lesser value for acceleration results.
(5) It turns out that two turns of wire about the pulley is necessary in some cases to assure no slip.

add an inertial torque to the system which is simply $T = \ddot{\ell}I$, where I is the moment of inertia of the hysteresis brake, the spooling pulley, and the wire guide. It is now clear why it is advisable to minimize $d^2\ell/dt^2$ by making $D \geq 2B$ and, by careful design of the spooling pulley and wire guide, to reduce its moment of inertia. In addition the small frictional force due to the wire guide varies during a revolution.

The conditions required to give a uniform tension to the wire, however, are actually less severe than those discussed above, provided a repetitive regime of operation for each revolution of the frame is established. In this case the value of the wire tension must be calculated to include forces due to wire acceleration and friction, but it can still be quite repeatable from wire to wire. This calculation requires a knowledge of the effective moment of inertia of each hysteresis brake as well as the spooling pulleys and an estimate of the frictional forces. The moment of inertia of the two hysteresis brakes have been measured to be $\sim$260 gcm^2 for the brake having 1-14 in. oz. torque and $\sim$170 gcm^2 for the brake with .4-4 in. oz. torque. The existing fiberglass spooling pullies of 2 and 4 in. in diameter have moments of inertia of 38 and 588 gcm^2, respectively. The wire guide has a moment of inertia of 1.2 gcm^2.

III. Description:

A schematic drawing of the wire-winding machine is shown in Fig. 2. Its construction takes advantage of the Physics Department building structure in that the drive mechanism is attached to an exposed building column and the steel column supporting the other side of the winding frame, T, is secured by vertical pressure on floor and ceiling. This assures a solid structure even for winding 10 ft. by 10 ft. frames. A list of commercial components and suppliers is given in Appendix A.

The drive mechanisms for the winding frame and the wire-spooling stage was mounted on a steel plate 3/8" thick which was then bolted to the building column. It can be placed in two positions with the frame axis 49.5" and 59.5" from the floor level. The higher position permits a larger size frame to be wound, e.g., 5 ft. x 10 ft.

The frame drive was designed to reduce the speed of the variable-speed motor, A, (500 R.P.M. to 5000 R.P.M.) to a useful speed range of .33 to 19 R.P.M. The motor drives a double-V-belt speed reducer, B, which by changing pulleys and belts, gives useful speed reductions of 26:1 and, 7.6:1[6]. This drives a fixed-

(6) A ratio of 1:1 is possible but, due to motor overload, it is not used.

ratio gear reducer of 48:1, C, which is then coupled directly to the winding frame shaft. The above reduction ratios give frame-rotation-speed ranges from 0.33 R.P.M. to 5 R.P.M. and 1.33 R.P.M. to 19 R.P.M.

There are two flexible couplings, E, in Fig. 2, which drive the winding frame. It is possible to reduce the effects of backlash in this drive system by a flat-belt pulley and brake, F. The brake is anchored to the mounting plate and acts as a friction load to the drive system.

The speed reduction drive, indicated as, D, in Fig. 2 turns the lead screw for the wire-spooling stage. By varying the size of existing ladder-chain sprockets the stage speed may be varied to give 10, 20, and 40 wires per inch. A gear reduction of 4 to 1 is realized with the two spur gears with 96 and 24 teeth, respectively. The lead screw has 5 threads per inch, so, for example, equal size ladder-chain sprockets would give 20 wires per inch.

The movement of the wire-spooling stage is determined by two ball bushings, N, moving along a straight steel cylinder 1.5" in diameter and adjusted to have no lateral play. The other side of the stage is supported by a single ball bearing moving along a flat surface. The cylinder and flat surface were adjusted to be parallel to the lead screw which is only 0.5 in. in diameter. The stage was then rigidly attached with a 2" x 2" Al. bar to a ball nut, M, riding on the lead screw. Any backlash in the ball nut is reduced through a pulley system and weight which applies a constant force to the stage in the direction of the lead screw. During wire winding, the lead screw drives the stage through a mechanical coupling, L. The stage may also be manually positioned by disconnecting the synchronized drive at L, and by turning the lead screw manually using the handle at the opposite end.

Mounted on the wire-spooling stage is the wire spool, O, whose rotational motion although otherwise free, is damped by a thin paddle wheel operating in a glycerin bath, P. This arrangement gives a velocity dependent force for spooling. The level of the glycerin is adjusted to give the desired average wire-spooling speed with a given weight for Q. Q is required in order to buffer accelerating forces acting on the wire spool due to the sinusoidal wire velocity and must be suspended by the wire during operation so that effects upon the wire tension due to wire acceleration are minimized. The wire tension is selected by the adjustment of the velocity-independent hystersis brake, R. See Appendix A for technical data on the two hystersis brakes which are used. For a particular setting, the hystersis brake requires a fixed torque (except for the effect of its small inertial moment) in order to be turned. Thus for a particular pulley, S, over which the wire is looped, the wire tension is determined essentially by the torque setting of R and by the wire tension produced by Q. As the tension produced by Q varies during a frame rotation, it is advisable to keep the weight of Q small; its present value is 17.5 g. The wire guide, U, is a bronze cylinder with a very sharp V engraved in it which is mounted on axially-loaded precision ball bearings. It is placed so that the wire always contacts the guide but with a minimum force. The tensions are continuously variable by adjusting the hysteresis brakes. The small brake is adjustable to produce a tension varying from 6 to 140 gms using both a 2 in. and a 4 in. pulley and for the large brake 25-280 gms using both a 2 in. and a 4 in. pulley. Another ~15 gms is added to the pulley tension and is produced by Q which is required for unspooling wire from the viscously-damped wire spool. The wire guide, U, introduces an average tension which has been estimated to be less than 0.5 g.

Chamber frames, H, that are to be wound are usually mounted on the winding frame as shown in Fig. 2. (An additional frame may be mounted on the other side of the winding frames as well.) The cross members of the present winding frame may be adjusted to accomodate chamber frames 8" x 8" up to 26" x 26" in size at present. Once the arms, G, are clamped to the 1.25 in. diameter shaft by the pulleys, J, the level of the cross members may be adjusted to be flat by adjusting screws, I. These operations should be performed with the frame and shaft disconnected from the winding machine (at E) and placed on a flat surface plate.

The chamber frame may be pre-tensioned with a force equal to the sum of the tension of all wires attached to the frame. This is done by a series of set screws along cross bars on both sides of the frame (not shown in Fig. 2.)

Based on the above methods, larger wire winding frames may be constructed and chamber frames up to 10 ft. x 10 ft. may be wound with the present drive and wire-spooling system. Wires having diameters up to ~10 mils can be wound with the present system.

IV. Procedure for Frame Winding:

1) Remove the winding frame and shaft from the winding machine and adjust the position of the cross arms of the winding frame so as to accomodate the frame(s) to be wound.

2) Using precision spacer blocks on a surface plate and adjusting screws (I of Fig. 2.), adjust the surfaces of the cross arms of the winding frame so that they form a plane. Clamp them in place with lateral screws (not shown in Fig. 2).

3) (Optional) From a knowledge of the wire tension and the number of wires per inch, calculate the deflection expected in the sides of the frames on which the wires are to be attached. The possibility of pretensioning of these frames should be tested with the winding frame in this position. For example: a 43 cm x 3 cm fiberglas

chamber side, acquires a central deflection of .0381 cm = .015 in. when 40 wires per inch (diameter = 50 microns) are tensioned to 90 g and attached to it.

4) Mount the winding frame in the winding machine (without chamber frames) and prepare the winding machine for your particular requirements:

a) Adjust hysteresis brake for the torque to give the desired tension.

b) Choose the combination of ladder-chain sprockets to give the desired wire spacing. Sprocket teeth ratios 1:2, 1:1, 2:1, result in 10, 20, and 40 wires per inch, respectively.

c) Select the pulley combination for B to give the desired range in angular speed of rotation for winding.

5) Mount the appropriate wire spool, O, and thread the wire through to the spooling pulley as indicated in Fig. 2. Make 1 or 2 loops around this pulley and the wire guide should be adjusted so that the wireis always in contact with the wire. Now attach the wire to the winding frame and prepare for a dry run of the system. This dry run serves to determine the glycerin level in P, for the particular rotational speed desired. The criterion is to keep Q suspended during winding with a median position as low as possible. (In this procedure, as not all parameters are independent, the requirement of stability in operation usually sets the speed of rotation.) Using the wire position in this dry run, scribe a reference line parallel to the wires being wound on the winding frame.

6) The chamber frame(s) to be wound may now be mounted on one side or both sides of the winding frame. The frames are then aligned, using the reference line(s) made in 5), so that the wires will be wound in the direction at the position desired on the chamber frame(s). When using the set screws to fix the frame psoitions, the frames may also be pre-tensioned as was tried in 3). Frames are pre-tensioned to obtain a calculated deflection which would be produced by the wires when attached.

7) After the frame(s) have been wound, the usual procedure is to epoxy the wires on the frame allowing ~12-24 hours for the epoxy to harden. If there is a frame on the opposite side of the winding frame then this procedure would be repeated.

To date, chamber frames of the following dimensions and wire diameter and spacing have been wound:

1) 43 cm x 32 cm outside dimensions with a 3 cm frame width have been used. 50μ BeCu wire at 40 wires per in. were used on the outside and 40 and 20μ Mo wire at 10 wires per inch on inside counter planes.

Acknowledgements

We would like to express our appreciation to Messrs. F. Desrosier, J. B. McClure and S. L. Horn of the Mechanical Engineering Group of the Physics Department for their active collaboration and interest in the design and construction of this wire-winding machine.

NOTE ADDED IN PROOF: Measurements were made recently at Princeton (O'Neill's group) of the tensions of 90 twenty-micron wires of a pwp wound with this winding machine. The result was 37.5 ± 1.2g. where the error is the root-mean-square deviation about the mean value. The value of 1.2g. is in part due to measurement error, which when subtracted gives standard deviation in the wire tension of $\sim$0.6g.

APPENDIX A

A list of commercial components used in the construction of the wire-winding machine follows:

ITEM				Location in Fig. 2.	Manufacturer & Local Representative
Pillow Blocks					
Number Required	Bore Diam.	Type			
1	1.500"	SC		Supporting main shaft and mounted on steel plate.	Dodge Manufacturing Co.
2	1.250"	SC			
2	0.625"	SC		In D.	Local Representative
6	0.500"	SC		In B and supporting ball threaded shaft.	Bearings Inc. 2522 Greenmount Ave. Balto., Md. 21218
Flange Bearing					
1	1.500"	SC-4		On steel pillar supporting main shaft.	
V-Belt Pulleys					
Number Required	Shaft Diam.	Pitch Diam.	Stock Number		
2	0.500	10-1/4"	1FA103	B	
2	0.500	5-1/2"	1FA55	B	
4	0.500	2"	1AX25	B	
2	1.250	4"	1FA45	J	
Spur Gears					
1" Face	14.50	Pressure angle			
Number Needed	Number Teeth	Catalogue Number			
1	24	GF24		D	Boston Gear Co.
1	96	GF96		D	
Steel Sprockets for #2 ladder chain					Local Representative:
Number Required	No. of Teeth	Catalogue Number			Carey Machinery & Supply 3501 Brehms Lane Balto., Md. 21203
2	24	C324		D and on ball threaded shaft.	
2	48	C348		D and on ball threaded shaft.	
Ladder Chain #2 high tensile ladder				K	

ITEM	Location in Fig. 2.	Manufacturer & Local Representative
1" dia. nylon pullies No. P1250-2	Q	Boston Gear Co.
6" dia. flat-belt pulley for 1" belt, No. PCA6	F	
Steel Shafts Length / O.D. / Tolerance 10' / 1.500" / +0.000-0.001 10' / 1.250" / +0.000-0.001 Turned, ground, & polished #1045 steel.		U. S. Steel Local Representative: U.S. Steel Supply P.O. Box 2036 Baltimore, Md.
48:1 Right Angle Speed Reducer #22422	C	Dayton Electric Mfg. Co. Chicago, Ill. 60648
Variable speed motor 1/2 hp 500-5000 R.P.M. #6K011	A	Local Representative: W.W. Granger 945 V Street, N.E. Washington, D. C. 20018
Flexible Couplings Number Required / Bore Diam. / Catalogue Number 2 / 1.250" / 4x196	E	W.W. Granger 945 V Street, N.E. Washington, D. C. 20018
Hysteresis Brakes Torque Range (in.oz.) / Moment of Inertia / Catalogue Number 0.4-4.0 / ~170 gcm^2 / CR540AA302AA 2.0-14.0 / ~260 gcm^2 / CR540AA401AA	R R	General Electric Co. Bloomington, Illinois
G-10 Glass fiber epoxy composite in sanded flat sheets, thickness tolerance is ±5 mils (usually it is better). Cost ~$100/sheet 1/4"x3'x4'. Delivery in ~3 wks.	H	General Electric Co. Construction Materials Div. Laminated Products Dept. Coshocton, Ohio 43812
Ball Thread Components dimension 1/2" x 6' 5 threads/in screw #0631-0200-SKT-5707540 nut #5707504 flange #5707570 accuracy 0.0015"/ft.		Saganaw Mfg. Local Representative: Bearings, Inc. 2522 Graymount Ave. Balto., Md.
2-Split ball bushing for 1.500" shaft diam.	N	

ITEM	Location in Fig. 2.	Manufacturer & Local Representative
2-Precision ball bearings with flange. 0.125" bore, 0.250" O.D., No. E4-6.	U	Precision Instrument Components Design Corp. Benrus Center, P.O. Box 335 Ridgefield, Conn. 06877
Copper-Berillium (used by BNL group) (CuBe) wire Available in sized .002 in. to .072" in diameter. Can have silver-flashed coating. .002" wire - $21/lb + $25 set up charge, 85,000/lb. Min order $40. .004" wire-$7.50/lb. + #15 set up charge, 21,000'/lb., min. order $25. 15-24 lbs. - $.20/lb. plus set up charge. 25 lbx. - $.40/lb., no set up charge Wire is available from dead soft to spring tempered.	O	Little Falls Alloys, Inc. 189 Caldwell Ave. Paterson, N.J.
Gold Plated Molydum (Mo) and Tungeston (W) wire Type / Diam. / Cost W / .0004" / $20/1000M W / .0008" / $15/1000M Mo / .0008" / $50/1000M Mo / .0016" / $14/1000M these costs are for quantities of 10^3 - 10^4 M., min. order $75.	O	Thermoionic Products Co. Futerhaven and Grove Street Plainfield, N.J.
Stainless Steel Wire (used by LRL group) 20 micron in diameter 2000' $65/1000' 5000' 53.30/1000' 10,000' 51.10/1000' 2 drawing dies can be purchased for $35 each. Having own dies will allow one to obtain much more uniform wire.	O	California Fine Wire P.O. Box 446 Gruver City, California 93433
Tungeston (w) wire (gold plated, 5%) .0004 dia. 52.74/1000M .0008 dia. 20.21/1000M set up charge of $20/item is charged for quantities less than 10^4 M.	O	Philips Element Co. Libson Rd., P.O. Box 1041 Lewiston, Maine 04240

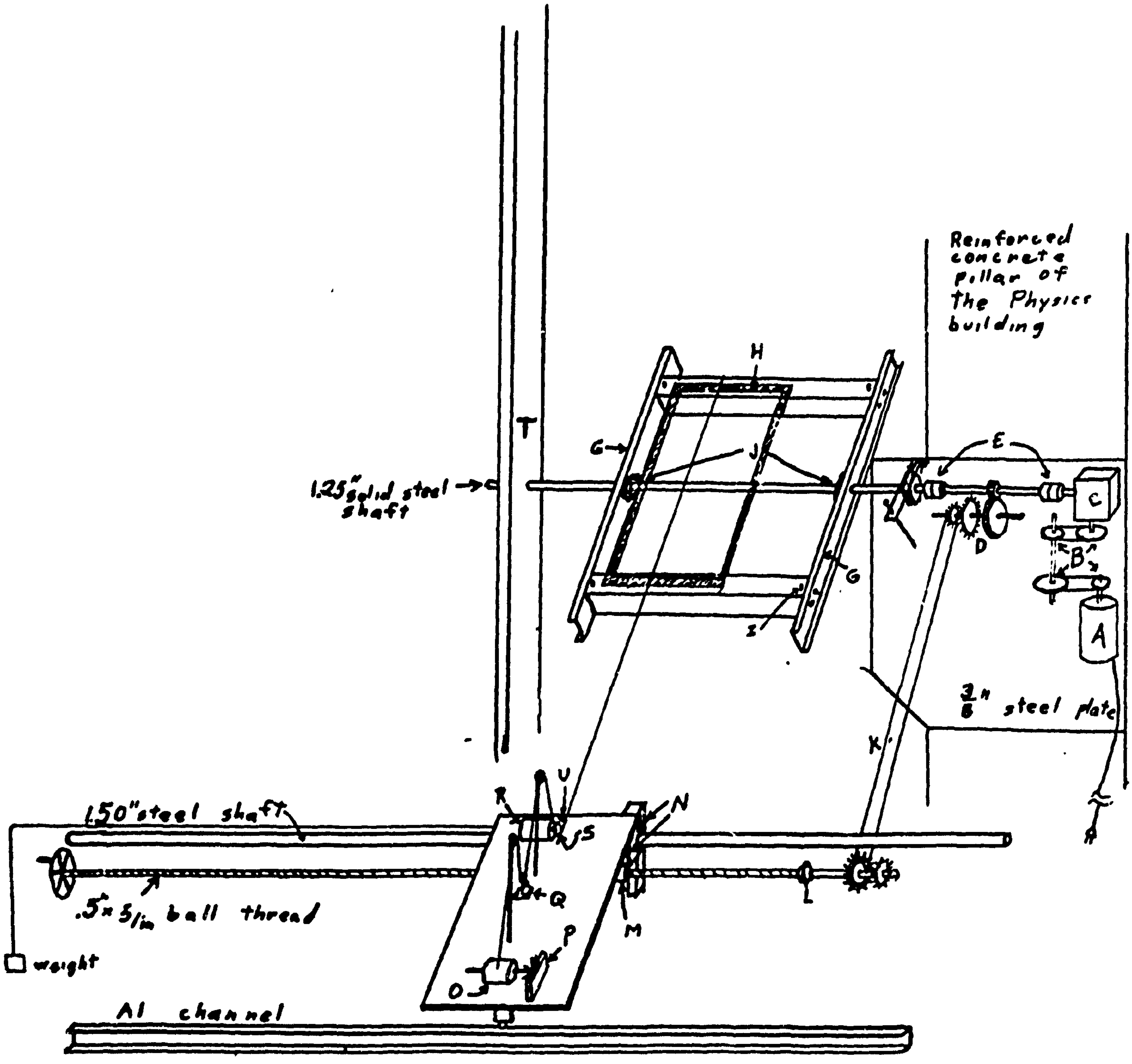
Reinforced concrete pillar of the Physics building
H
T
G
J
E
C
1.25" solid steel shaft
D
B
G
I
A
3/8" steel plate
K
1.50" steel shaft
R
U
N
S
.5" x 5/in ball thread
Q
M
L
P
weight
O
Al channel

FIGURE 2