DESIGN OF A RATE OF TURN RECORDING INSTRUMENT

by

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Engineering

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May 16, 1940

Professor George W. Swett

Secretary of the Faculty

Massachusetts Institute of Technology

Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Bachelor of Science in Aeronautical Engineering, I hereby submit a thesis entitled "The Design of a Rate of Turn Recording Instrument".

Respectfully submitted,

Paul M. Butman

ACKNOWLEDGEMENT

The author wishes to express his thanks to Professors Charles S. Draper and Arthur C. Hardy for their helpfull suggestions concerning the design of this instrument. In particular he wishes to acknowledge the advice and suggestions of Mr. Harry Ashworth whose guidance in construction greatly facilitated the design.

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DESIGN SPECIFICATIONS

It is desired that an instrument be designed which will give a continuous record of the response of an airplane rate of turn meter to maneuvers of the airplane. This instrument is to be free of the lag and inertia effects evidenced in previously attempted designs. It must be void of any coulomb friction in the recording mechanism, and no moving parts incorporated in the design shall be of such a natural frequency that the airplane engine, or any other source of vibration, shall excite the recording mechanism and give a secondary disturbance in the resulting record.

The fact that this instrument shall be used in an airplane automatically imposes the requirement that it shall be as compact as possible and not unduly heavy.

It is desired that the record may be made either continuously or interrupted, that this record may be removed from the instrument, and that the results may be interpreted to give the period and magnitude of the airplane maneuver.

Purpose of the Instrument

The function of a "Rate of Turn" instrument is to measure the rate of angular displacement of the instrument, or airplane to which it is rigidly fixed, about any axis that is parallel to a symmetrical line extending from the top to the bottom of the dial. Since in general we are most concerned with the angular displacement of airplane about a vertical axis, i.e. change in azimuth, the instrument is customarily mounted with this reference line parallel to the vertical axis of the airplane when in level flight. In this case, however, the recording instrument will be used for test purposes and may be oriented such that it will record rate of roll, rate of pitch, as well as rate of yaw or turn.

In many cases one is not as interested in the rate of angular displacement of an oscillation, which is a second order effect, as one is interested in the period and magnitude of the angular displacement itself, which is of the first order. Since any oscillation, no matter how irregular, is a series of repetitions, and the period of the first order effect on the "nth" order effect are identical. The period may therefore be scaled off the record as the interval between changes in the geometric pattern. The magnitude of the angular displacement about the reference axis at any time is represented by the area under the recorded trace. Using a planimeter the magnitude may be obtained reasonably accurate, and this in turn affords a method for calibrating or adjusting constants of the "Rate of Turn" meter.

General Solution of Design

The required elimination of lag, inertia effects, and coulomb friction immediately suggests that an optical system must be used in place of a stylus. When the question arose as to the photo-sensitive paper to be used, Professor Draper desired that the properties of a commercial positive print, known as Ozalid, be investigated. This paper had two very desirable features:

1. It is dry developed, that is, it is developed in the presence of ammonia vapors which might easily be incorporated into the instrument simplifying the scope and limitations of the design.
2. The paper is inexpensive.

Unfortunately this paper is treated with a commercial dye which is light sensitive but extremely "slow" as a photographic paper. In fact it was not affected when exposed in an artificially lighted room. The problem, therefore, was to obtain the most powerful light source and use the most efficient lighting system obtainable.

The most powerful light proved to be a 50 candle power headlight lamp rated at 6 volts. By increasing the voltage to 8 volts the lamp's life was greatly abbreviated but the output was almost doubled.

For maximum illumination in an optical system the writer is indebted to Professor A. C. Hardy for his article on this subject published in the Journal of the Optical Society of America. In any optical system of spherical lenses some one opening will limit the zone of illumination. This opening is known as the "aperture stop" of the system. Neglecting the loss of light due to reflection, refraction, and dispersion, (which may amount to as much as 50 percent) the maximum illumination on the film expressed in lumens per square centimeter is equal to the product of the brightness of the source in candles per square centimeter and the solid angle subtended by the exit pupil at the film.

$$I = B \times \omega$$

where I = Illumination in lumens/cm^2

B = Brightness in candles/cm^2

ω = Solid angle.

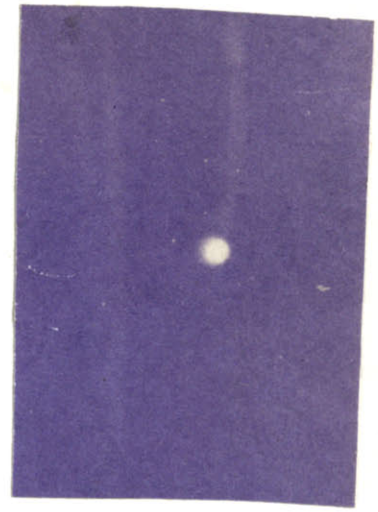
In order to investigate the properties of the commercial "Ozalid" paper, the author obtained the fastest type positive print manufactured and subjected it to optimum conditions. Conditions far better than could ever be approached in an instrument. The optical system consisted of the previously mentioned headlight and a powerful condenser lens loaned by the Department of Physics. The aperture of this lens, which was also the aperture stop of the system, was three inches in diameter and had a six inch focal length. For simplicity, the object and image were at conjugate points, the mirrors were omitted, and no attempt was made to reduce the size of the image by slits which would also cut down illumination. The film speed varied from 1 inch/sec. to 1/5 inch/sec.

Results

The results of this test were very discouraging but conclusive. Sample 1 shows the positive print undeveloped. Sample 2 shows the trace obtained from filament overloaded at eight volts and a film speed of one inch per second. Sample 3 shows the trace obtained at the film speed of 1/5 inch per second. The dot at center represents a 5 second exposure.

Sample 1

Sample 2



Sample 3

The second reason for the elimination of the use of this paper was evidenced in the attempt to develop the exposed print. After holding the paper for ten minutes over boiling concentrated ammonium hydroxide the paper did not develop, but instead required twelve hours of exposure in a closed container with dilute ammonium hydroxide.

Upon the rejection of "Ozalid" paper as a possible recording film, the logical step was to try a photographic paper. The positive print most widely used in industry is bromide paper, which is by far the least expensive recording paper and almost approaches motion picture positive film in speed characteristics. This film is widely used in commercial oscillographs and stetho-cardiograph instruments which measure heart reactions. In the latter case the top film speed is 3 inches per second and the light source is a simple flashlight bulb. The film itself is mounted on course heavy paper 6 cm. wide and rolled in lengths of 175 feet. The roll is 4.6 inches outside diameter and is mounted on a wooden core.

DETAIL DESIGN

THE OPTICAL SYSTEM

The most important mechanism in the instrument is the optical system, and the quality of its performance is dependent upon the simplicity of the design. The function of this system is to convert the angular deflection of a mirror mounted on the turn indicator into a linear motion of a point of light. The limitations imposed upon this design are the finite width of the recording paper (6 cm.) and the maximum turning velocity of the airplane, (one revolution per minute) which, according to the calibration curve on the following page, corresponds to a 10° deflection of the mirror. Since this 10° deflection of the normal to the mirror represents a 20° deflection of the actual light beam (10° on either side of the normal to the mirror), the distance between the mirror and film was required to be 3 inches.

Mirror deflection = 10°

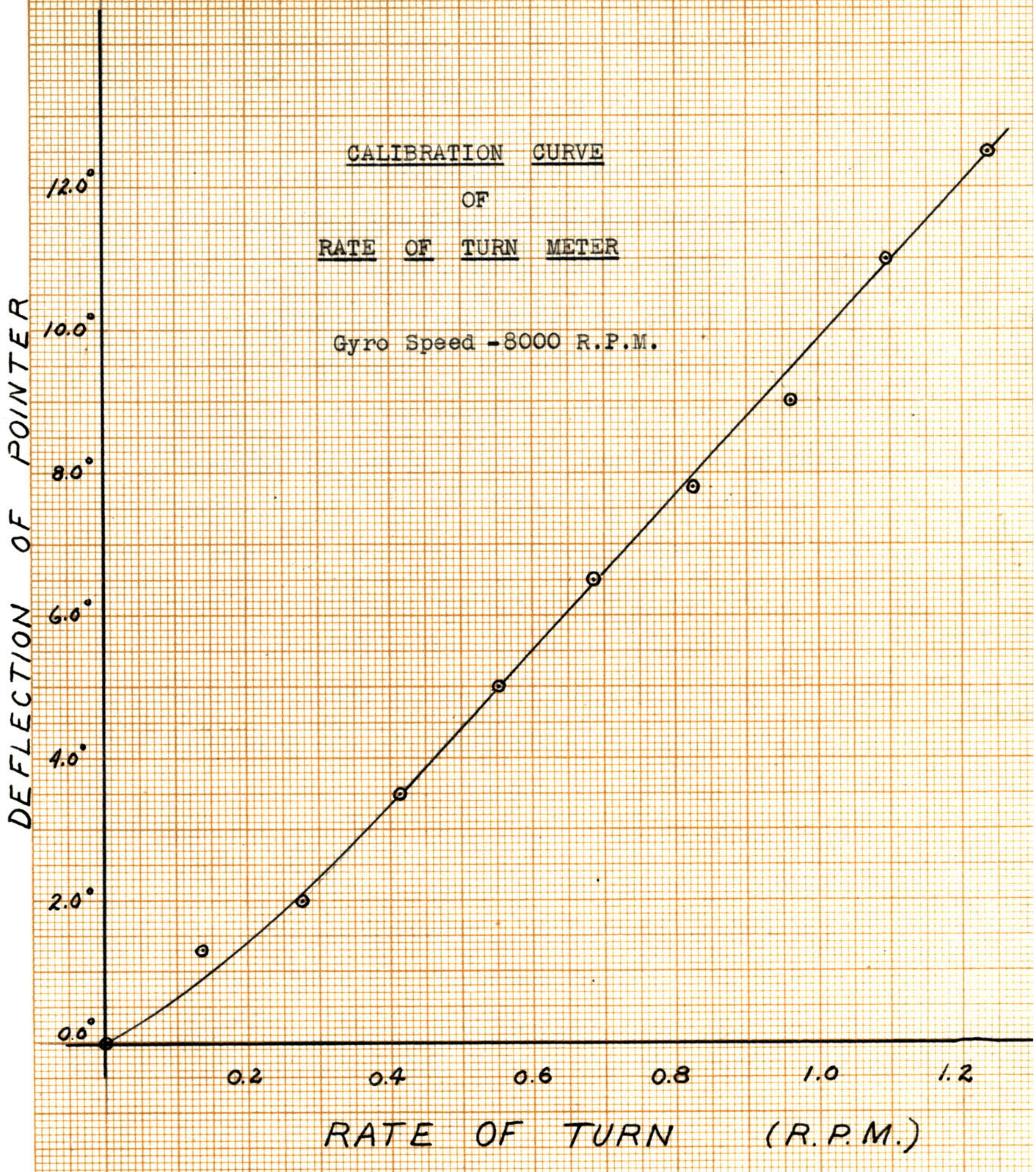
Beam deflection = 20°

Deflection arm = 3 inches

Linear travel of spot either side of center line $= \frac{20}{57.3} \times 3 = 1.05$ in.

Semi-width of film = 3 cm. $= 3 \times \frac{1}{2.54} = 1.18$ in.

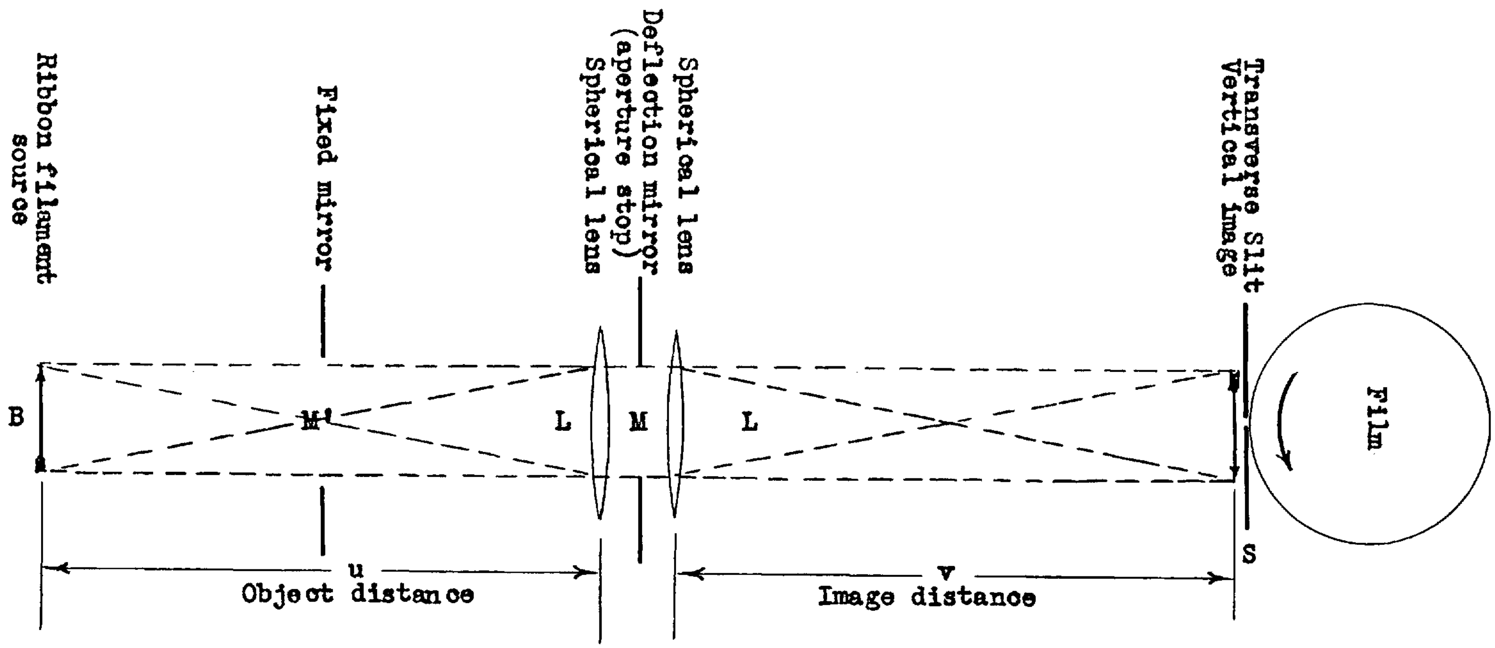
Margin of record = $1.18 - 1.05 = .13$ in.



Calibrated 2/20/40
Paul M. Butman

The above calculations give tentative dimensions to the design but a wide range of alteration is permitted by adjusting the inherent characteristics of the turn indicator.

A diagramatic sketch of the optical system, as shown on the following page, is one commonly employed in recording instruments. In Professor A. C. Hardy's article entitled "The Optical System Recording Instruments" this system is considered because of its virtues in giving the intense illumination. Unlike the oscillograph, however, this instrument is not stressed for light intensity, but the optical system was chosen on the basis of its simplicity. The aperture stop in this system, as in the oscillograph, is the deflection mirror, "M", which is a highly polished flat galvanometer mirror 9/16 of an inch in diameter. Compared to the oscillograph mirror, however, it is tremendous, and immediately removes the accent on obtaining intense illumination by the optical system. The light source, "B", is a special Westinghouse double contact ribbon filament bulb rated at four volts, which supplants the use of an arc and slit combination. When "B" is imaged on the film "F" through the lens "L" a bright image of the ribbon filament is reproduced having a width of approximately .030 of an inch. The lens "L" are actually a single lense through which the



Diagramatic Sketch of the Optical System used in the

Rate of Turn Recording Instrument

light beam travels twice, being reflected by the galvanometer mirror, and the optical equations become:

$$\frac{1}{u} + \frac{1}{v} = \frac{2}{f}$$

$$m = \frac{v}{u}$$

where: u = image distance

v = object distance

f = focal length of the lense

m = magnification ratio.

Since the clearest image and least loss of light occurs when the galvanometer mirror is as close to the lens as the mirror deflection will permit, the deflection arm becomes equal approximately to the image distance. By choosing the spherical lens with a focal length of 2 3/4 inches and making the interval between the galvanometer mirror and lens 1/8 of an inch, the deflection arm becomes the desired 3 inches and both the filament and image automatically lie at corresponding focal points of the compound lens system. The light rays striking the mirror are parallel, (that is, focused at infinity) and there is no magnification of the ribbon filament at the film.

$$v \cong f \cong 3 \text{ inches}$$

$$\frac{1}{v} + \frac{1}{v} \cong \frac{2}{f}$$

$$u \cong v \cong f$$

$$m = \frac{v}{u} \cong 1$$

In order to make the object and image distance equal without having the light bulb lie in the plane of the film, a second mirror "M'" was introduced.

Finally since a point of light was desired instead of a line, the image of the filament is intercepted by a sheet of alluminum containing a slit "S" which is cut .030 inch wide and 6 cm. long. The long dimension of the slit lies at right angles to the long dimension of the filament image, such that as the filament image travels across the slit, only a segment of the image (.030 inches) can pass through the allumimm sheet to the film. It is important that the film be in immediate contact with the metal edges of the slit in order that, according to Huygen's principle, the dispersion of light caused by a straight edge does not set in. Since the image distance of 3 inches remains constant at all deflections of the mirror, both the slit and film must be bent to a 3 inch radius to keep the image in focus.

The spherical lens "S" consists of an ordinary magnifying glass having an aperture of one inch. The advantage of this over-size lens lies in the fact that only the center portion (9/32 inch radius) is used and thereby avoiding the corrections for spherical aberrations required of a smaller lens.

To insure that only the light from the filament image is permitted to strike the film, the bulb "B" and mirror "M'" are enveloped in a light-tight box coated on the inside with black instrument paint, but having a small opening on the side for the desired path of light.

The details of construction of the individual parts of the optical system are shown in Figure 1. The galvanometer mirror "M" is mounted on a shaft 1 1/4 inches long and is firmly held in the instrument by a bearing seat and set screw. Since it rotates about its long axis its moment of inertia is negligible. When the mirror is mounted on the turn indicator, the line of nodes between the plane of the mirror and the horizontal plane should be parallel to the face of the dial. Due to the cantilever construction of the mirror mounting, the adjustment of the line of nodes is very delicate and uncertain, and any variation from perfect adjustment results in a motion of the image toward or away from the face of the dial accompanying the right and left deflection. If the

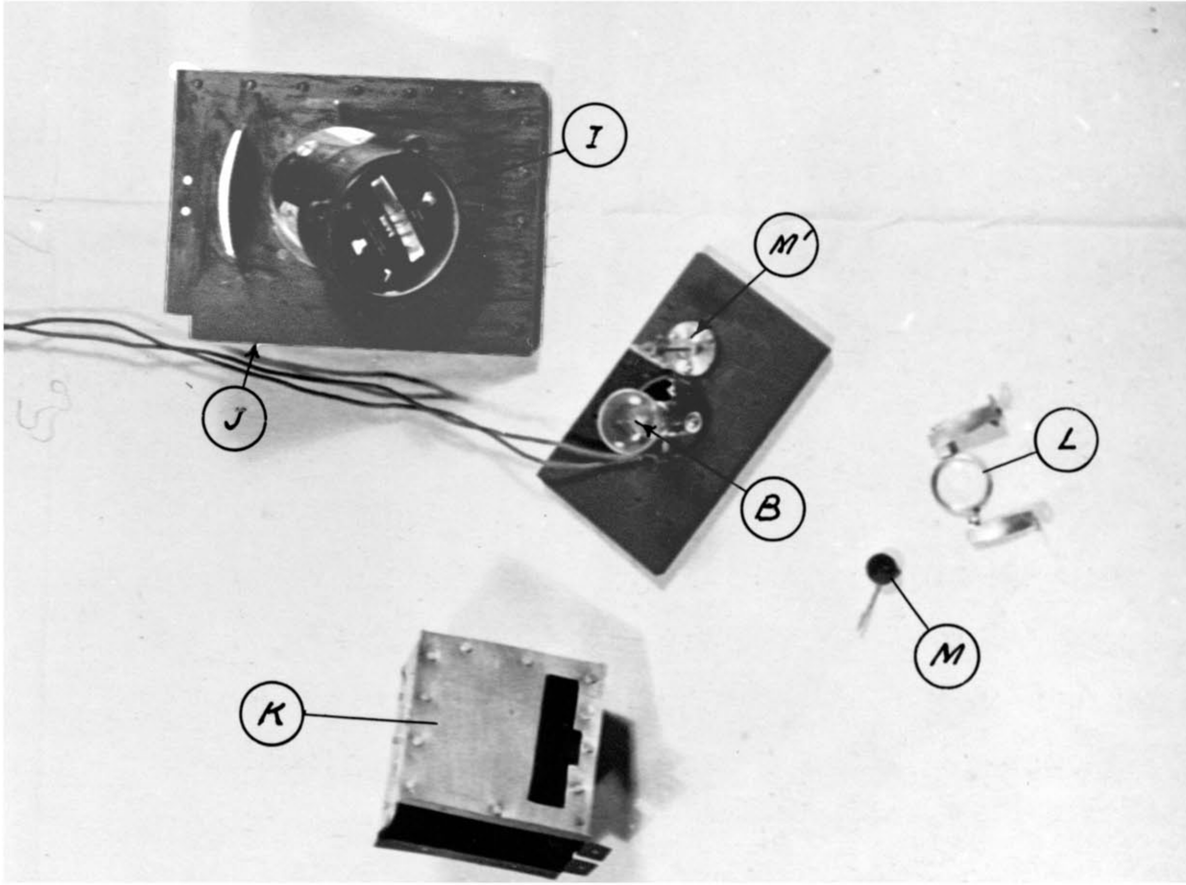


Figure 1

Optical System - Unassembled

<u>Parts List</u>

B = 4 volts Westinghouse ribbon filament lamp.

I = "Rate of Turn" indicator.

J = Mounting panel for Turn Indicator.

K = Light-tight box for optical system.

L = Spherical lens (2 7/8 inch focal length).

M = Galvanometer deflection mirror and mounting.

M' = Fixed mirror and mounting.

image were a point of light, instead of a line, this effect would greatly distort the recording wave, but under the existing optical system this maladjustment may be present to considerable extent without effecting the record. The only requirement is that the slit be made parallel to the face of the dial.

Figure 2 illustrates the complete optical system as it is mounted on the center panel of the instrument. The light-tight box when mounted partially covers the spherical lens, the edge of the shield being 5/8 of an inch above the surface of the lens.

The fixed mirror is mounted on a post with a sleeve and set screw which permits adjustment if necessary. Both the lamp and mirror are mounted as one unit on a wooded base which in turn can be adjusted relative to the lens and mirror by screws into the center panel.

Since the optimum optical conditions require that the galvanometer mirror be placed as close to the lens as possible, there is a danger that in handling the instrument rates of turn in excess of one revolution per minute will jam the mirror against the lens. To eliminate this possibility stops are mounted on the face of the dial.

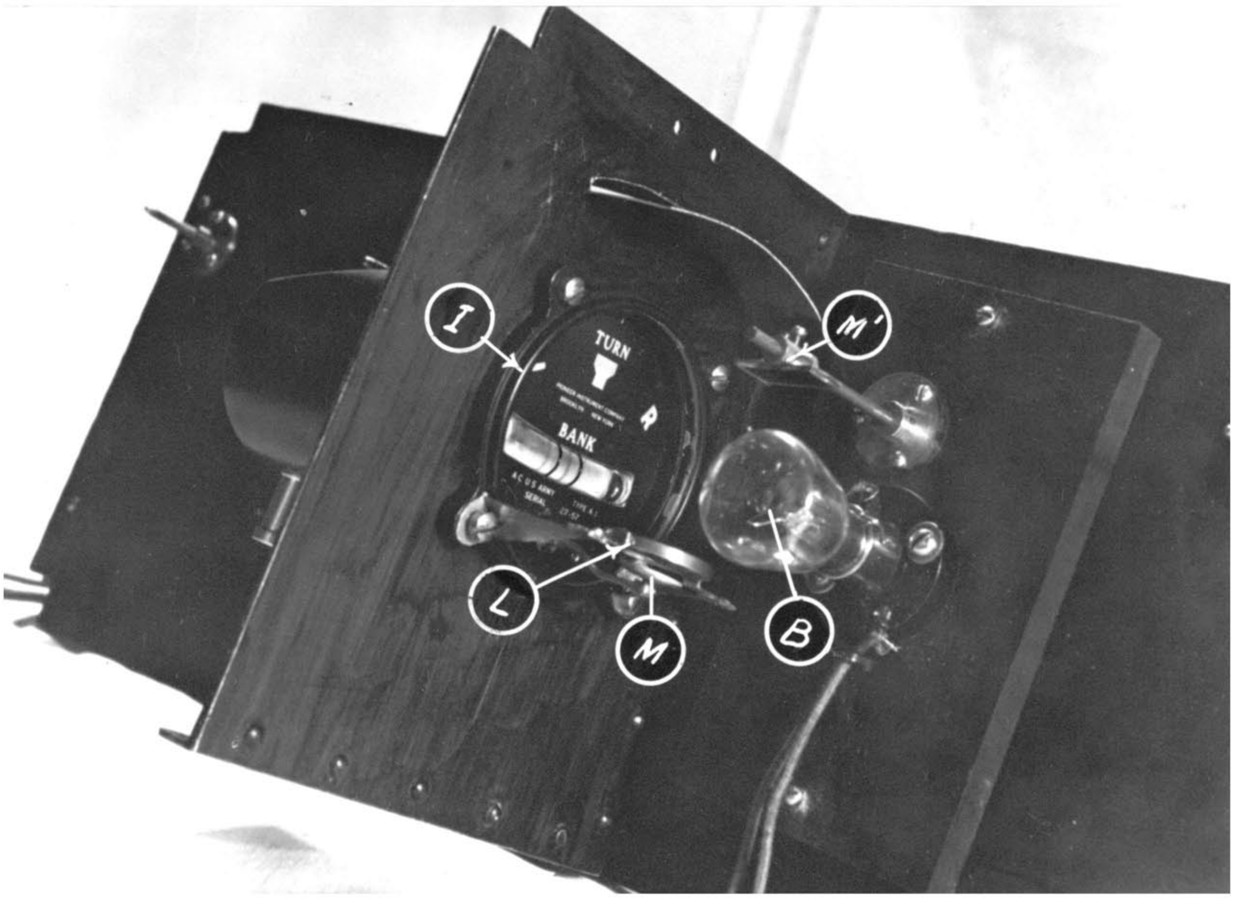


Figure 2.

The Complete Optical System Mounted without Light Shield

Parts List

B = 4 volts Westinghouse ribbon filament lamp.

I = "Rate of Turn" indicator.

L = Spherical lens (2 7/8 inch focal length).

M = Galvanometer deflection mirror and mounting.

M' = Fixed mirror and mounting.

DESIGN OF MECHANICAL SYSTEM

The purpose of any recording instrument is to mechanically draw a plot of some variable as a function of time. The variable in this case is the rate of turn. As previously pointed out in the "Purposes of Design" it is essential to accurately measure the periods of recorded results and to accurately converted planimetered areas into the numerical values they represent. Obviously this accuracy is dependent upon knowing and controlling the speed of the film to a constant value. Fortunately the author was given a 12 volt constant speed motor with a centrifugal governor and a gear reduction unit of ratio 620:1. Calibration tests on this motor never showed more than a 3% variation in speed over a much wider range of torque loads than the motor would ever experience driving a film.

Since the bromide paper used in this apparatus is course and heavy, it requires a slight tension in it to make it conform with the guide surfaces. This tension is established by introducing friction into the unwinding spool. Figure 3 illustrates the spring and sleeve mechanism employed. A plug screwed into the outer sleeve provides the method of adjusting the friction-bearing pressure on the inner sleeve.

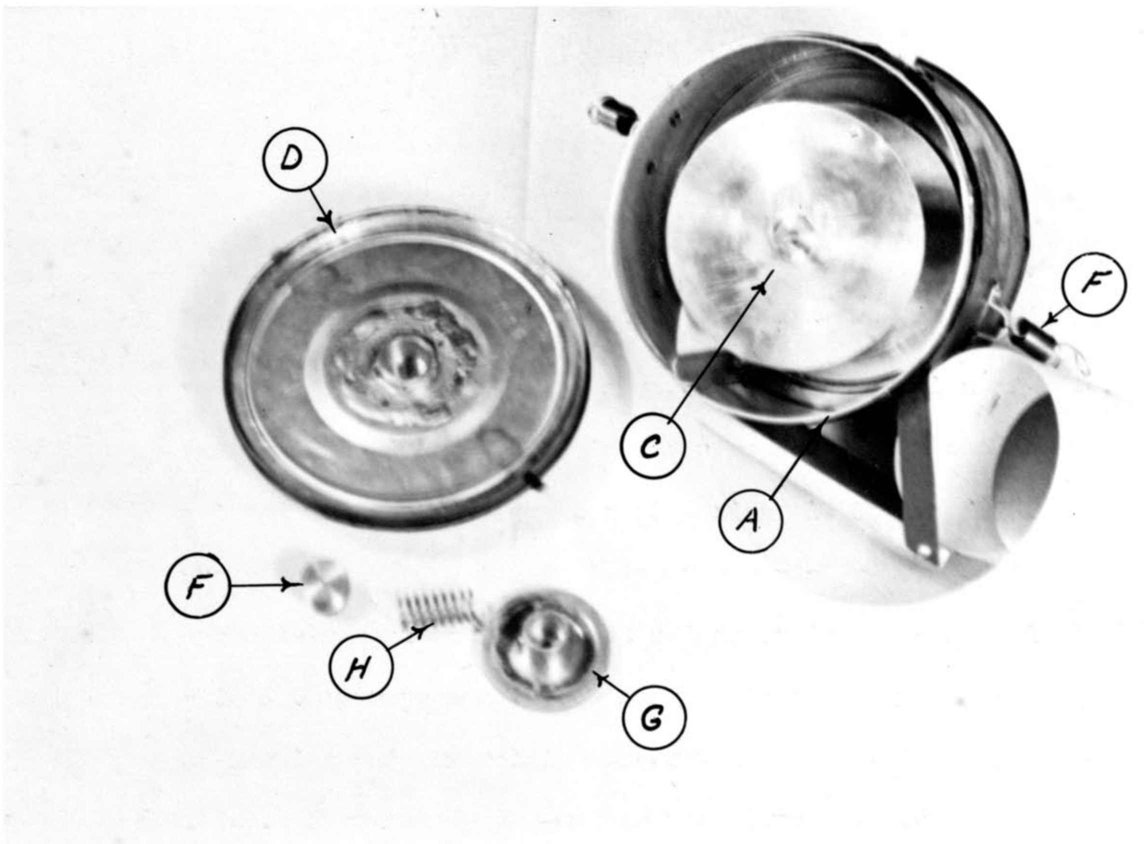


Figure 3.

Friction Assembly in Unwinding Film Container

Parts List

A = Unexposed film container.

C = Spool for unexposed film.

D = Cover for A with threaded friction adjuster bearing.

E = Spring clamp for cover D.

F = Friction bearing spring plug adjuster.

G = Friction bearing shoulder.

H = Friction bearing spring.

During the course of winding up the paper on the take-up spool the diameter of the roll is continually changing. The take-up spool cannot therefore be coordinated with the constant speed of the roller drive, so slip had to be introduced into the drive of the take-up by connecting the drive shaft and the take-up shaft with a spring slip-pulley.

It is desired that after a record is made with the instrument, the exposed film should be removed in the take-up container without taking the entire instrument to the dark room. This problem is solved by breaking the take-up shaft and connecting the two units by a dog clutch as shown in Figure 4.

The final mechanical problem in this design was that of preventing the take-up spool from winding the film faster than it is fed through the constant speed rollers. This difficulty is partially overcome by the slip pulley and also by mounting the upper rollers on a stiff hinge causing sufficient pressure between the film and driving roller to prevent slippage.

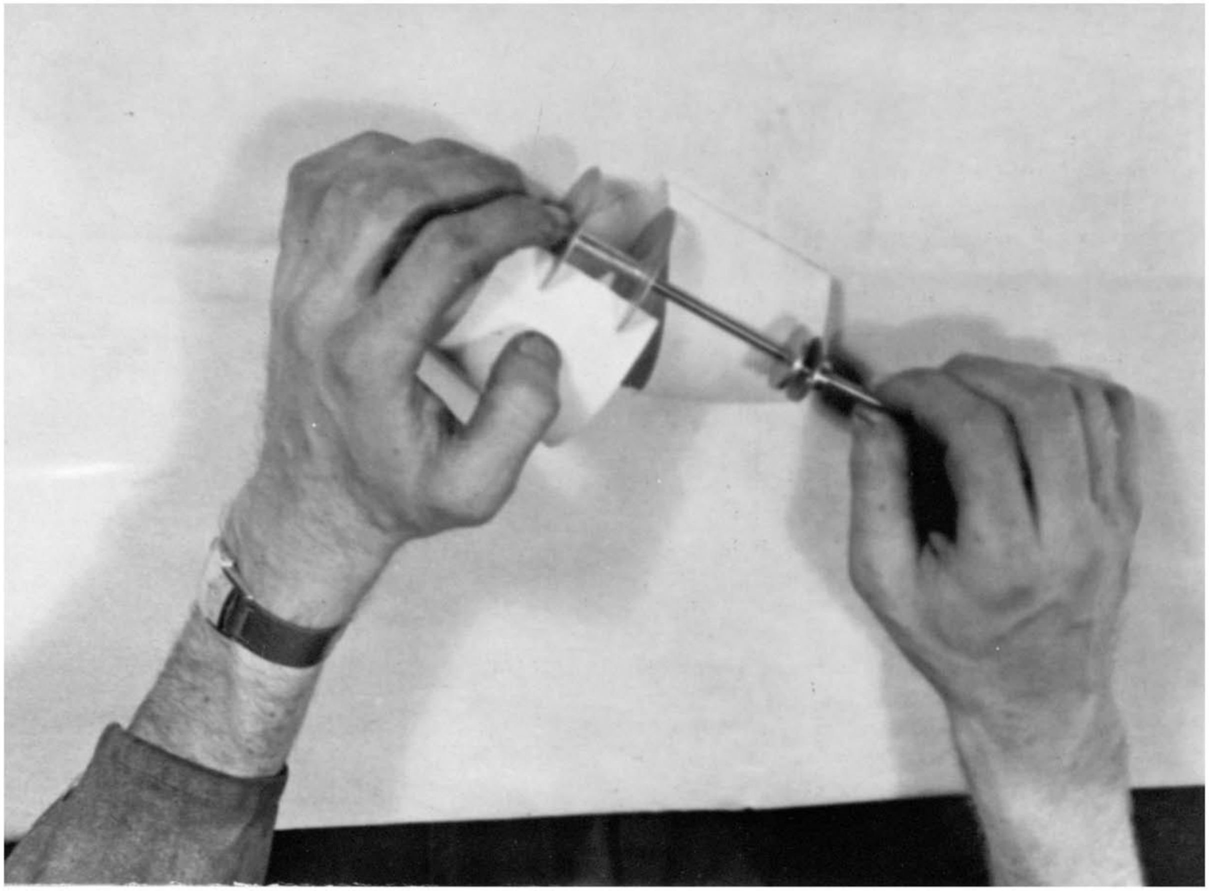


Figure 4

Dog Clutch Mechanism for Removing the Take-up Container from Instrument.

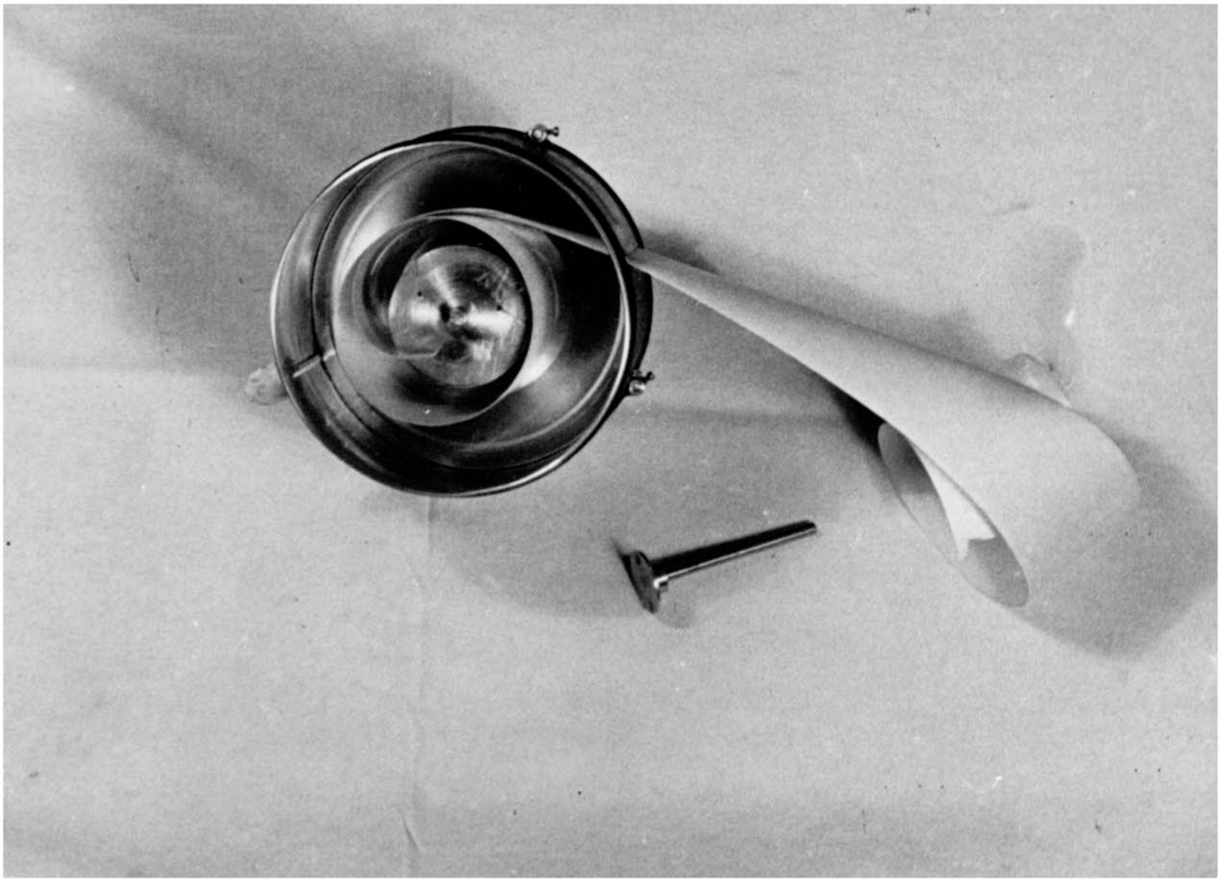


Figure 5

Take-up Film Container Assembly

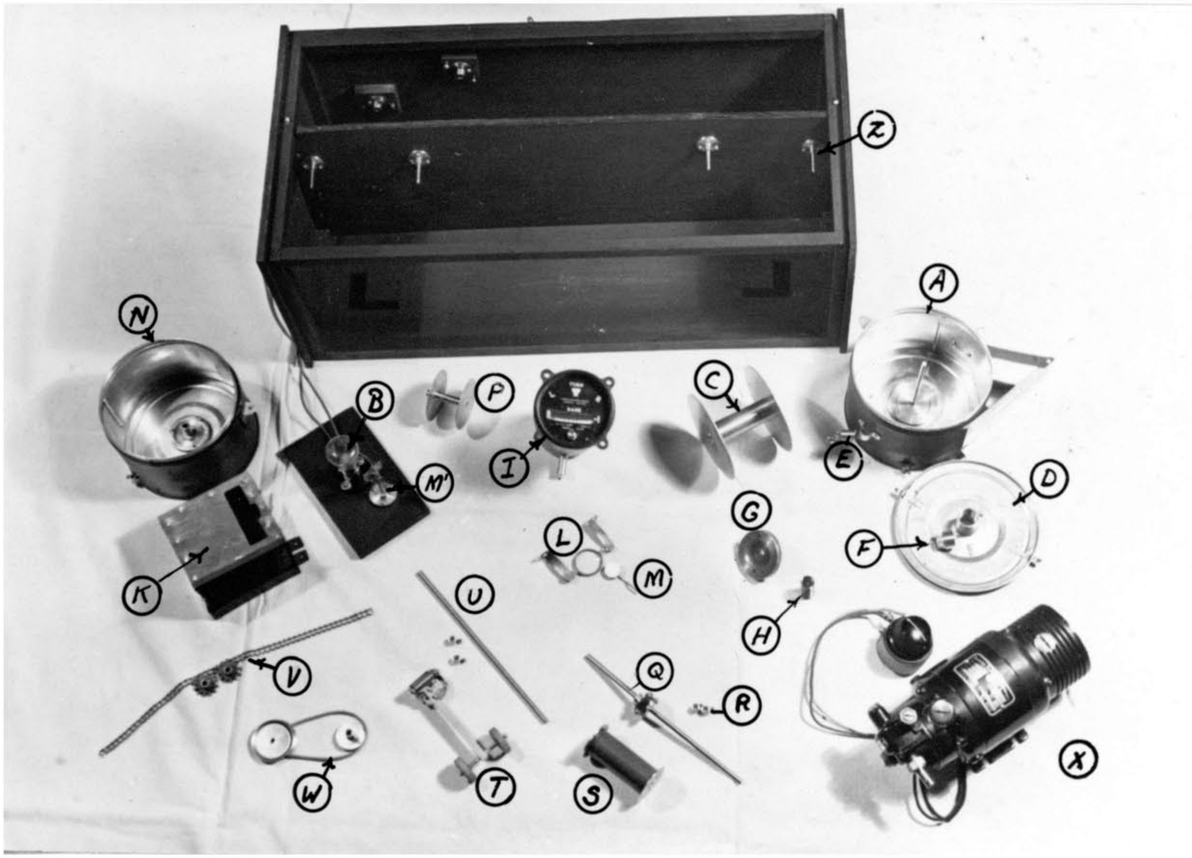


Figure 6

Complete Rate of Turn Recording Instrument Unassembled

A = Unexposed film container.

B = 4 volts Westinghouse ribbon filament lamp.

C = Spool for unexposed film.

D = Cover for A with threaded friction adjuster bearing.

E = Spring clamp for cover D.

F = Friction bearing spring plug adjuster.

G = Friction bearing shoulder.

H = Friction bearing spring.

I = "Rate of Turn" indicator.

J = Mounting panel for Turn Indicator.

K = Light-tight box for optical system.

L = Spherical lens (2 7/8 inch focal length).

M = Galvanometer deflection mirror and mounting.

M' = Fixed mirror and mounting.

N = Take-up film container.

P = Take-up spool.

Q = Take-up spool drive shaft and dog clutch.

R = Take-up spool drive shaft collars.

S = Constant speed drive roller.

T = Constant speed pressure rollers.

U = Constant speed driven shaft.

V = Chain and sprockets connecting constant speed motor and driven shaft.

W = Slip-drive spring belt and pulleys to take-up spool drive shaft.

X = Constant speed motor.

Y = Drive shaft shoulder bearings.

Z = Mounting post for film container.

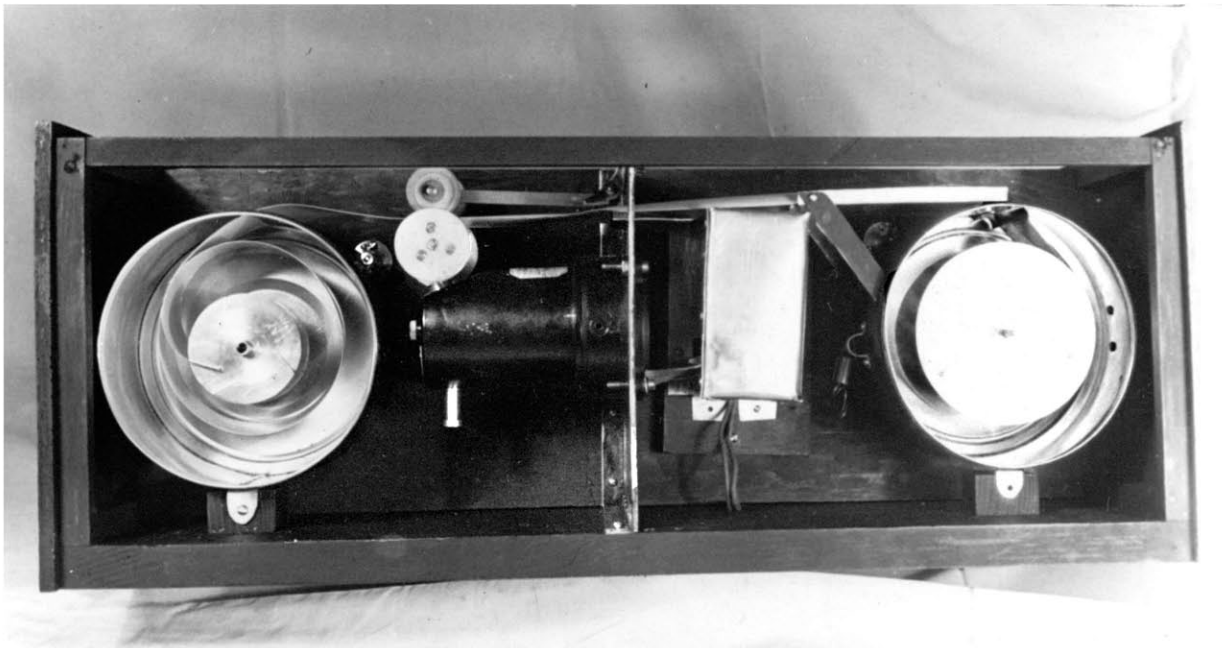


Figure 7

Complete Instrument Mounted in the Box Showing

Film Drive

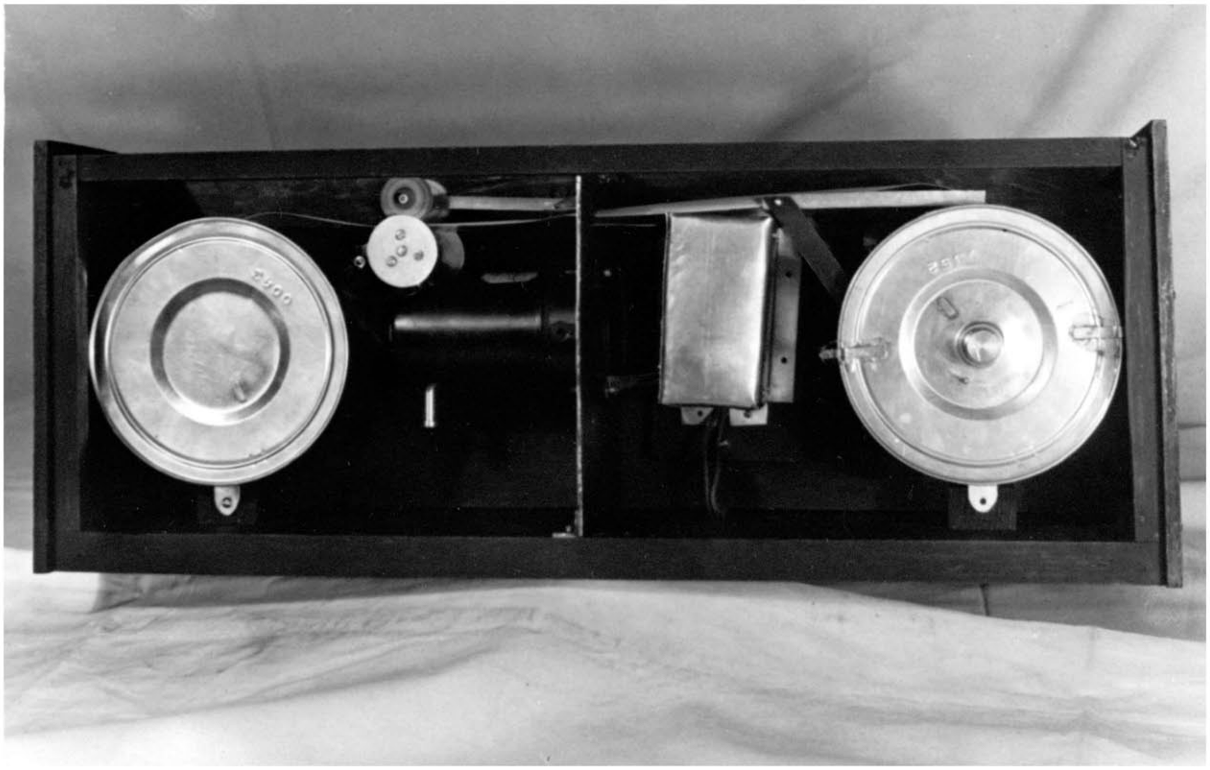


Figure 8

Complete Instrument with Film Containers Sealed.

TESTING RESULTS

Testing Results

The following pictures were taken with the instrument mounted on a turn-table driven by a controllable speed motor. By means of a reduction gear the R.P.M. of the turn-table was lowered to the range of angular velocities of a turning airplane. These records, however, were not intended to simulate the performance of an airplane, but merely to show that principally the instrument records, and secondly under what conditions its operation is most favorable.

The first record, as shown on the following page, was taken with the filament burning under its rated voltage, four volts. Although the lamp is shielded and the image brought to a sharp focus, there was sufficient leakage and diffusion of light to cloud the entire film as it passed over the slit. Furthermore the image was so intense that a very dark and blurred record resulted as shown on the left of Plate 1. However by changing the filament voltage from four volts to two volts, a very clear trace resulted. The contrast is well brought out on the right hand portion of Plate 1. The slight discoloration of the background evidenced after the voltage was changed is due to a leakage of light onto an exposed portion of the film while operating at four volts. This may be discredited because the actual trace when operating at two volts reveals no diffusion of light as shown on the extreme right of Plate 1.

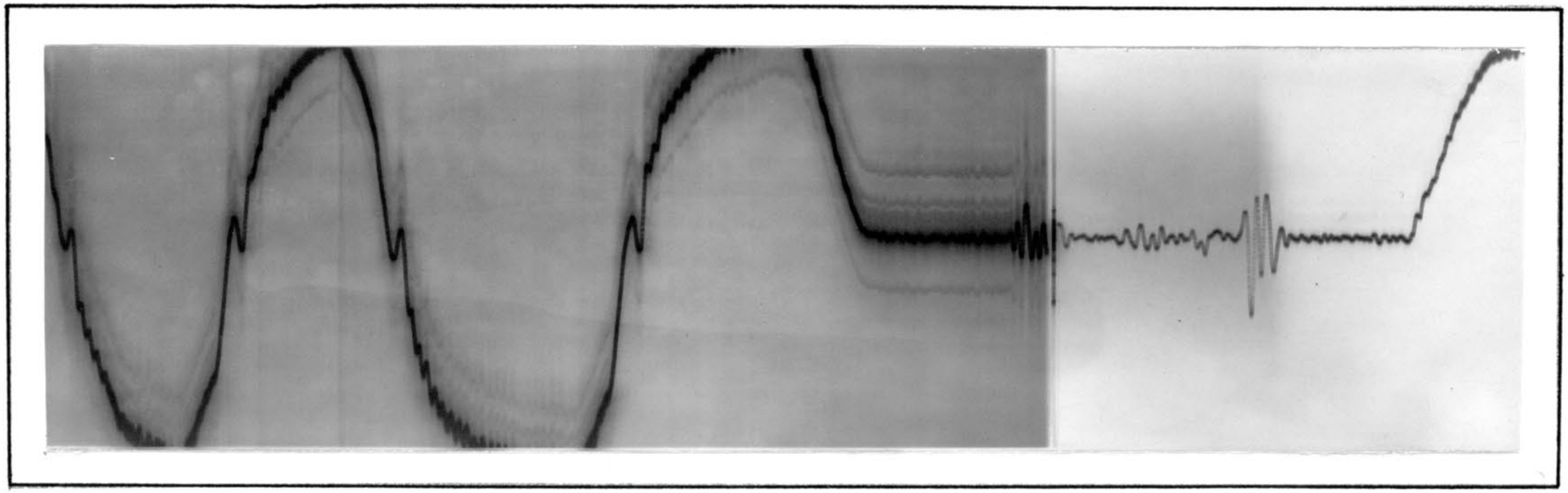


PLATE I

It was anticipated that running the film over the edges of the sheet aluminium guide would cause scratches to be seen on the film. Finishing the edges of the guide with a fine emery cloth eliminated this trouble, and no scratches were observed.

The record shown on Plate 1 represents the result of reversing the direction of rotation of the instrument at approximately five second intervals. The reversal is made possible by a double throw switch. The turn-table was regulated for a double rate turn, that is, one revolution per minute. The record expected would logically resemble that of a series of step functions having the same amplitude in both the positive and negative direction. The actual record, however, shows considerable rounding off of the corners of the forcing function. This effect does not represent the response of the rate of turn indicator, but rather that of the turn-table. Also between each reversal of rotation there is a single small oscillation occuring along the time axis, which likewise is a characteristic of the turn-table. The large moment of inertia of the instrument when mounted on the turn-table permited the drive shaft to behave noticeably as a torque pendulum when subjected to a sudden reversal in direction.

To best illustrate the response of the rate of turn indicator independent of the electric drive, the author forceably shook the platform back and forth. The oscillations proved to have a period of approximately one half second as shown on Plate 2..In this case there is no evidence of an oscillation at the zero axis as is the case when the motor was driving the turn-table.

Throughout the records there is a secondary vibration of very small amplitude which gives the trace a ragged appearance. This oscillation represents a vibration within the turn indicator itself due to sloppy bearings, and may be eliminated by replacing that particular indicator with one having noiseless bearings.

Plate 2 shows the record made when the instrument was stationary. In this undeflected position (center of Plate 2) the secondary vibration is not as noticeable as in the deflected position.

In order to design this instrument such that a double rate turn would represent the maximum recorded deflection, it was first necessary to calibrate the turn indicator. The calibration curve on page 8a, however, was not obtained from the turn indicator used in the recording instrument, but from a duplicate indicator having half the casing cut away such that the R.P.M. of the gyro could be

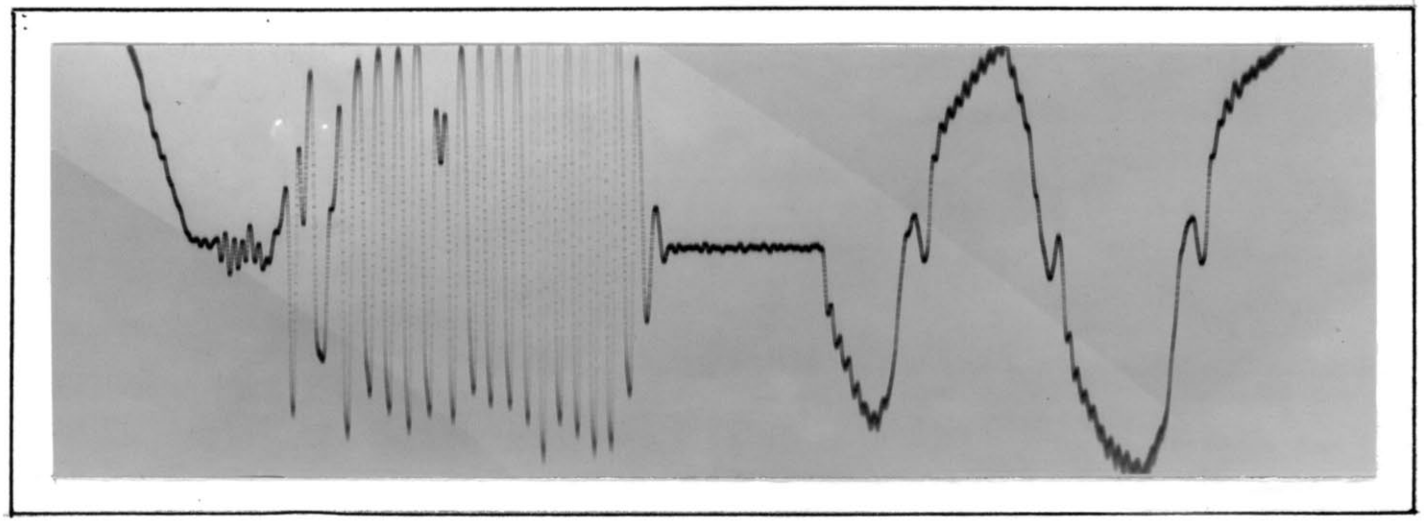


PLATE II

recorded by a stoboscope. In the case of this latter instrument, the restraining spring had a greater initial tension than the one used in the recording instrument. The results, therefore, showed that a double rate turn corresponded to a larger deflection of the mirror than the instrument was designed for, and the beam of light moved off the edge of the film. Plate 3 illustrates the record, or lack of record, made by reversing the turntable while running at a double rate turn (1 rpm.). Since the initial tension in the restraining spring can be controlled by a set screw mounted on the outside casing of the rate of turn indicator, the image deflection of a double rate turn could very easily be adjusted to any desired position within limits. Further if it is desired to obtain records involving other ranges of angular velocities, it is a simple matter to substitute another spring of the desired coefficient to accomodate this new condition.

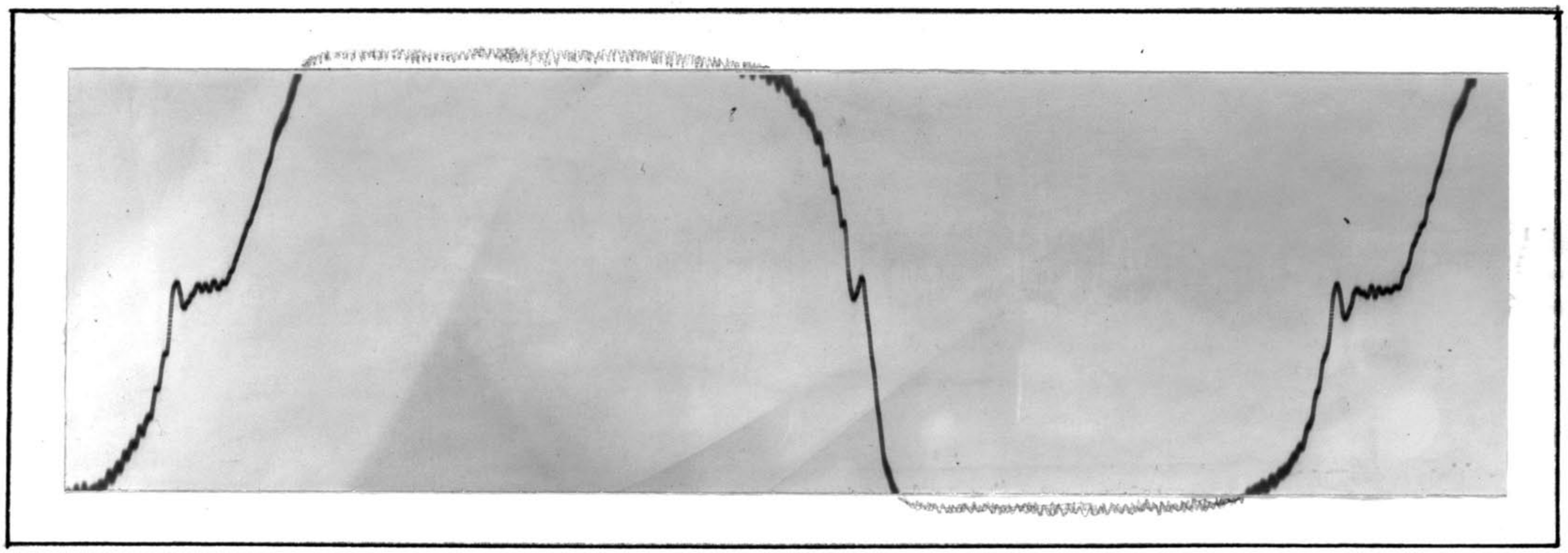


PLATE III