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# DESIGN AND CONSTRUCTION OF A FORCE PLATFORM WITH TORQUE MEASUREMENT CAPABILITY

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by

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A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

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## ACKNOWLEDGMENTS

The author would like to express his sincere appreciation to Dr. Stephan Konz without whose contribution of time and effort this thesis could not have been completed.

A special debt of gratitude is also felt for the other members of my thesis committee, Dr. A. E. Hostetter, Dr. George F. Schrader and Dr. Stanley Wearden.

Sincere thanks also go to a great many other professors and fellow students for their contributions of time and ideas in the design and developmental work described in this paper.

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# INTRODUCTION

Industrial engineers have, for years, been concerned with the motions an individual makes in performing a task as well as the forces exerted during the motions. Various techniques have been used to study the motions, including unique film methods such as cyclegraphic and chronocyclegraphic analysis.

Until about 1949, however, very little had been done toward making an analysis of the forces exerted by an individual in the performance of a task. One of the earliest devices for studying these forces was the "Effort Detector" developed by a Frenchman, Lucein Lauru (1953) (1957).

The original design of the Effort Detector was improved by Lauru after he joined the research team of Professor Soula. They have since published the results of their works in several periodicals as well as presenting their findings at the French Academy of Science (Greene, 1957).

Lauru made use of the piezoelectric properties of quartz as a force detector. The variations in force applied to the quartz produced variations in electric currents in an external circuit connected to the quartz crystal. This variation was then recorded on an oscillograph (oscilloscope with camera attachment) and a permanent record made with the camera.

This force detection method was not altogether satisfactory because of the decay rate of the signal generated by the piezoelectric crystals (Greene and Morris, 1959).

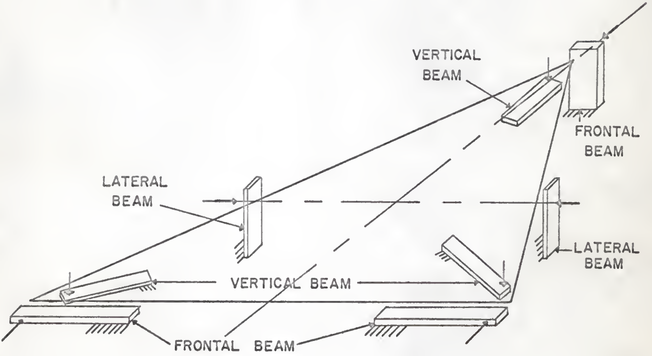
At least four other devices for measuring the forces exerted by a person while performing a task were developed in Europe between the time of Lauru's initial research and the design and construction of the first "force platform" in the United States (Greene, 1957). However, due to the small amount of information available concerning these other European versions of the force platform, no further mention shall be made of them.

Greene (1957) was the first to develop a force platform in this country and to take a sophisticated approach to the problem of interpretation of the force traces obtained from a device of this type.

His innovation consisted basically of two sub-platforms, an upper and a lower. The upper sub-platform was supported in an equilibrium position above the lower sub-platform by cantilever beams acting in three mutually perpendicular directions; three beams in the vertical direction, two beams in the lateral (left-right) direction and three beams in the frontal direction. This support system is shown schematically in Plate I. The lower sub-platform acted mainly as a supporting device for the stationary ends of the cantilever beams and measuring equipment. The linkage between the moving ends of the cantilever beams and the upper sub-platform consisted of ball-bearing balls sandwiched between two smooth steel surfaces. The bearing surfaces that were attached to the upper sub-platform were small triangular steel plates. The other bearing surfaces were attached to the beams. These consisted of the cold upset heads of steel cap screws threaded through the free ends of the beams. These steel cap screws provided a convenient means for adjustment of the

EXPLANATION OF PLATE I

A schematic drawing showing placement of cantilever beams and the direction of forces applied to them in Greene's design of the force platform.


VERTICAL BEAM
FRONTAL BEAM
LATERAL BEAM
LATERAL BEAM
VERTICAL BEAM
FRONTAL BEAM

distance between the horizontal beams and the upper sub-platform as well as a means of preloading the vertical beams.

Greene used three cantilever beams acting in the vertical direction to support the upper sub-platform in his design. The vertical support points were placed at the vertices of an equilateral triangle. With this configuration of support points, as shown mathematically by Greene (1957), the vertical displacement of the centroid of the triangle will be the same regardless of the locus of a force applied vertically downward on the upper sub-platform surface (i.e., within the perimeter of the equilateral triangle).

Lauru (1957) assumed that there was a one-to-one correspondence between the amplitude of the forces exerted by a person and the amount of energy expended (Barany, 1961). Greene and Morris (1958), however, disputed this assumption and, by means of a dimensional analysis, concluded that the force platform measures force and force alone. At any given instant the output from the force platform displacement measuring devices yields a quantity that is proportional to the applied force but the relationship between the force-time integral obtained and the energy remains to be evaluated.

One of the most recent force platform designs was by James W. Barany and Roger G. Whetsel (1962) who varied Greene's design. They installed another set of three cantilever beams which apply forces vertically downward. This set of beams can be used to preload the beams acting vertically upward. By adjustment of the two sets of beams the hexagonal upper platform plate can be placed in a state of equilibrium. With this arrangement a force acting vertically, either up or down, will cause the same movement of the upper platform plate. Like Greene's platform, the pressure points of this additional set of three cantilever beams also lie at the vertices of a second equilateral triangle which is coplanar with the first. The centroid of both equilateral triangles are coincident but the second triangle is rotated in its plane by 60 degrees with respect to the first triangle.

Since the beam displacement of a cantilever beam is proportional to the applied force, displacement of the beams can be used to measure the forces applied to the platform surface which is supported on the cantilever beams.

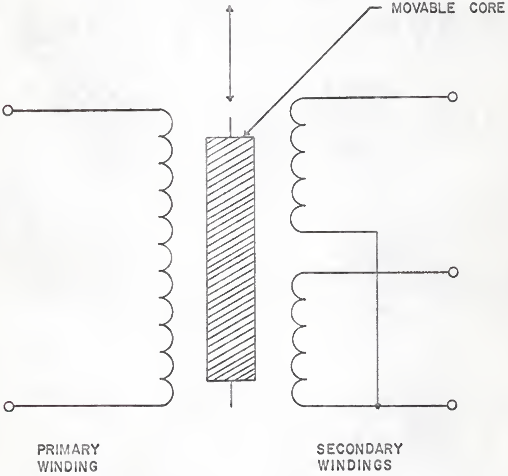
To make these measurements, Greene, as well as Barany and Whetsel, used three Linear Variable Differential Transformers (LVDT) to determine the three orthogonal components of any given force.

The differential transformer is an inductive device consisting of three coils of wire wound coaxially on an insulating spool. It has a ferromagnetic core which develops a variable magnetic coupling between the primary and the two secondary windings. A schematic diagram of a LVDT is shown in Plate II.

The primary winding of the transformer is excited by an alternating current and a voltage is induced in the secondary windings. The ferromagnetic core is positioned inside the coils in such a position that the desired output voltage is obtained from the two coils. The movement of the core changes the number of turns of wire encircled by the magnetic flux, which increases

EXPLANATION OF PLATE II

Schematic diagram of a linear variable differential transformer.


MOVABLE CORE
PRIMARY
WINDING
SECONDARY
WINDINGS

the output from one secondary winding and decreases the output from the other secondary winding.

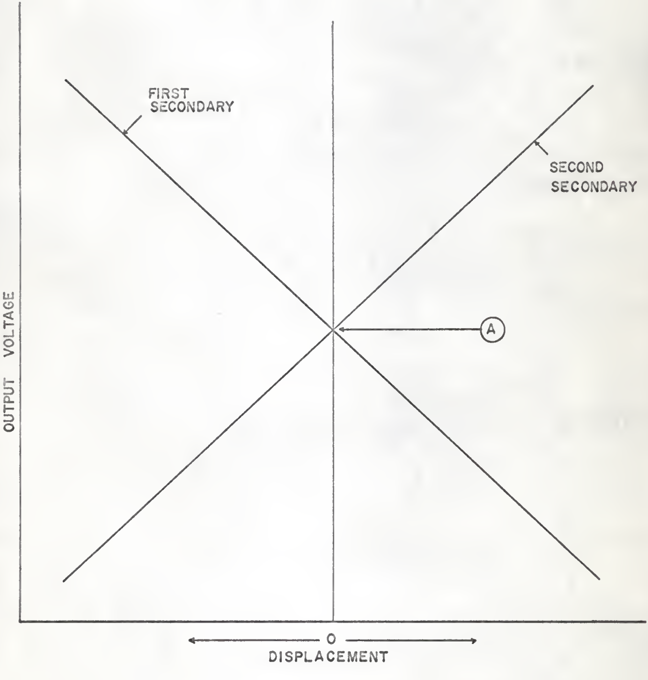
Plate III shows a plot of the output voltage for each secondary winding as a function of core position. Point A in this figure is the point at which the outputs from the two secondaries is the same for a given core position. When the secondary windings are connected in series opposition so that their outputs are 180 degrees out of phase, the resulting output voltage will be as shown in Plate IV. The residual voltage which exists at the null position consists mostly of the third harmonic of the primary input voltage.

From examination of Plate IV it appears that the linear voltage versus core displacement lines on either side of the null or zero core displacement position intersect at a point. When the region very near the null position is examined quite closely, however, it is found that the intersection appears more nearly as shown in Plate V. This results because the small residual voltage components present in each secondary coil do not cancel.

Because of this characteristic of the LVDT's it is desirable to operate the transformers with the core operating range displaced from the null position on one side or the other. A typical position range would be between $x_1$ and $x_2$ as shown in Plate V.

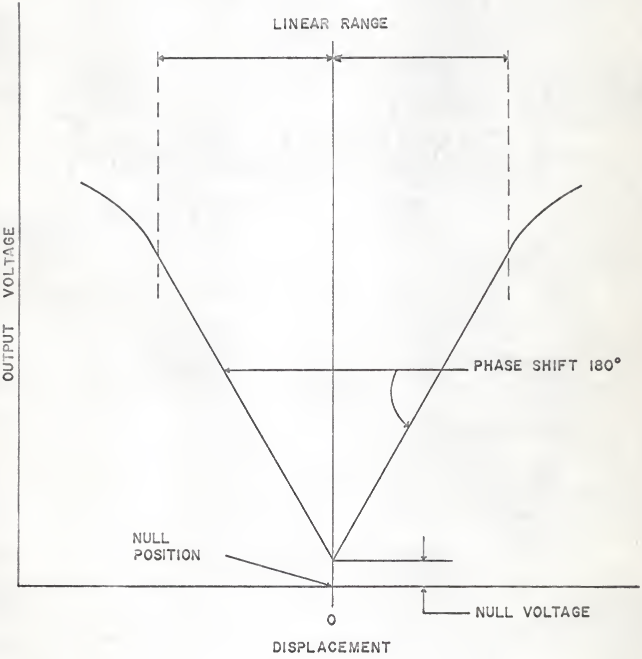
EXPLANATION OF PLATE III

Output voltage from secondary windings of linear variable differential transformer versus core position.


FIRST SECONDARY
SECOND SECONDARY
OUTPUT VOLTAGE
A
0
DISPLACEMENT

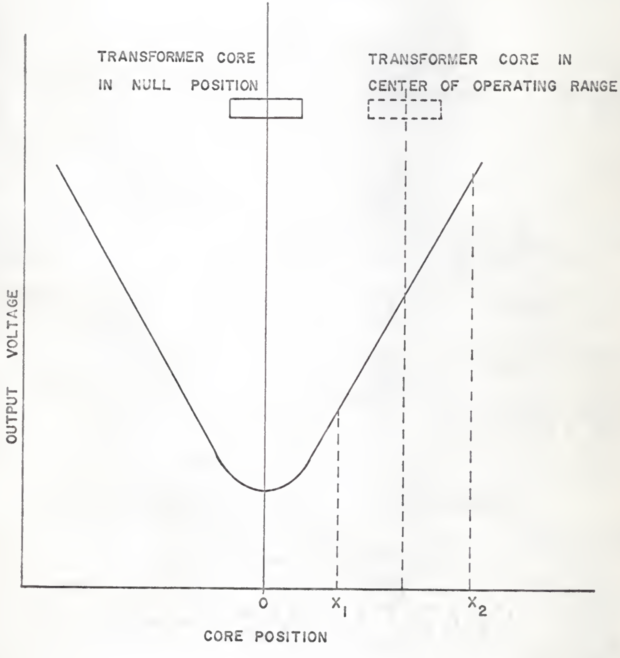
EXPLANATION OF PLATE IV

Output from a linear variable differential transformer versus core displacement when secondaries are connected in series.


LINEAR RANGE
OUTPUT VOLTAGE
PHASE SHIFT 180°
NULL
POSITION
0
NULL VOLTAGE
DISPLACEMENT

EXPLANATION OF PLATE V

Output voltage from a linear variable differential transformer versus core position when the core is very near the null position.


TRANSFORMER CORE
IN NULL POSITION
TRANSFORMER CORE IN
CENTER OF OPERATING RANGE
OUTPUT VOLTAGE
0
$X_1$
$X_2$
CORE POSITION

# METHOD

## Design

The basic design of the platform of Barany and Whetsel has been utilized in the new design. Certain problems, however, were encountered with their design both here at Kansas State University and at other institutions. Primarily, changes incorporated in the new platform were in the following areas:

1. Transformer positioning and adjusting method
2. Transformer core shaft to platform plate linking device
3. Position of the line of action of the horizontal displacement measuring transformers
4. Upper and lower platform plate construction and size
5. Torque measurement.

In addition to the re-design of certain aspects of the platform of Barany and Whetsel, one major original innovation, torque measurement about each of the three orthogonal axes, has been added. This idea arose from a desire to eliminate the torque measurement found to be coupled with the linear translational force measurements obtained with Barany and Whetsel's platform design. The desirability of measuring torque and also linear translational forces independently followed directly and was subsequently incorporated as a new feature in the platform design.

Each of the modifications and the reasons for them shall be discussed separately, in more detail, in the following sections.

1. Transformer Positioning and Adjusting Method. Barany and Whetsel did not incorporate into their design a satisfactory method for making small adjustments of the LVDT's. Their design allowed for movement of each transformer and its associated plastic housing as a single unit only by loosening two screws and sliding the housings to the desired position by hand. The transformer cores were also found to be difficult to adjust because of the instability of the core mounting arrangement after loosening some locking nuts that secured the core shafts to thin brass cantilever beams. This core adjustment problem was a consequence of the great sensitivity of the LVDT's.

In the new design this transformer adjustment problem has been eliminated.

There are nine transformers in the entire new version of the force platform; one transformer for measuring linear translational forces along each of three orthogonal axes and two additional transformers for measuring the rotation about each of the same three orthogonal axes.

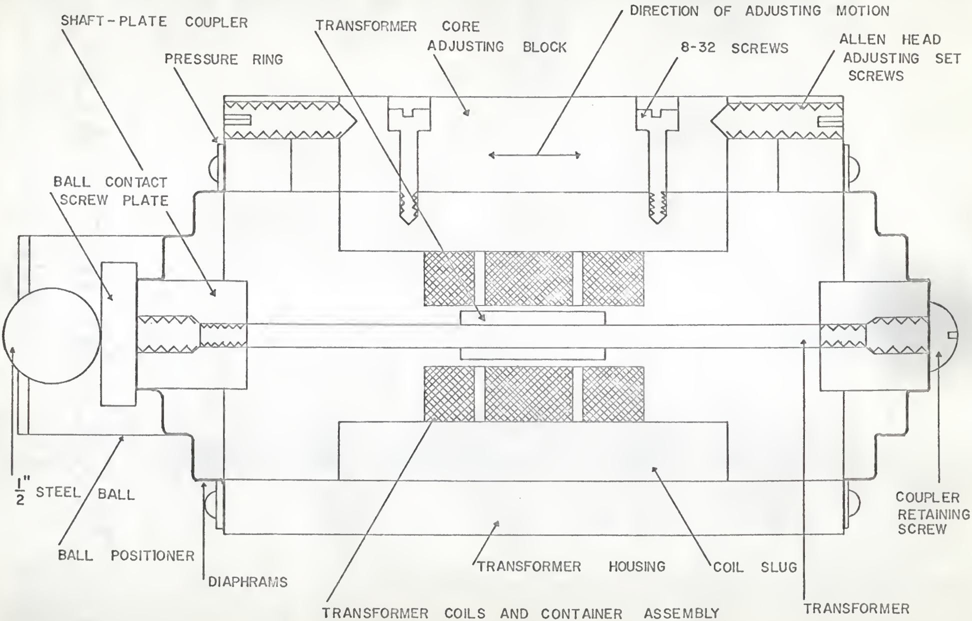
Each transformer is mounted in a sub-assembly so that the core position adjustment within the coil can be made prior to installation of the sub-assembly in the platform. A cross sectional drawing of this sub-assembly is shown in Plate VI.

Each transformer sub-assembly is mounted in the platform on a separate, precision, screw adjustable, dovetail slide mechanism for final positioning after installation.

By this means the desired measuring range of the LVDT's can be selected with confidence.

EXPLANATION OF PLATE VI

Cross sectional drawing of the transformer sub-assembly.



SHAFT-PLATE COUPLER
PRESSURE RING
TRANSFORMER CORE
ADJUSTING BLOCK
DIRECTION OF ADJUSTING MOTION
8-32 SCREWS
ALLEN HEAD
ADJUSTING SET
SCREWS
BALL CONTACT
SCREW PLATE
$\frac{1}{2}$" STEEL BALL
BALL POSITIONER
DIAPHRAMS
TRANSFORMER COILS AND CONTAINER ASSEMBLY
TRANSFORMER HOUSING
COIL SLUG
TRANSFORMER
CORE SHAFT
COUPLER
RETAINING
SCREW

2. Transformer Core Shaft to Platform Plate Linking Device. The linkage between the transformer core shaft and the upper platform plate has been re-designed to minimize friction. The design of Barany and Whetsel employed a "nose cone" shaped part which was fastened to the end of the transformer core shaft. This nose cone pressed against a pressure plate that was fastened to the upper plate of the platform. Any movement of the pressure plate perpendicular to the transformer shaft required that the nose cone slide on the pressure plate. Although no difficulties were directly attributable to this design, it was recognized as a possible trouble point and, consequently, a revision was made.

The revised design consists of a ball-bearing ball supported between two parallel hardened steel plates. This will allow rolling action of the ball in all directions while transmitting translational motion directly along a line perpendicular to the faces of the hardened steel plates. A system is incorporated to re-center the ball should slippage occur between the ball and either of the plates. The ball retaining mechanism and re-centering arrangement is shown in cross section in Plate VI.

The 1/2 inch steel ball is held with very light pressure against the ball contact screw plate by the ball positioner. This pressure is maintained until the transformer assemblies are, by means of the precision slide mechanisms, moved so that the ball comes in contact with a hardened steel plate located on the lower side of the platform upper plate. If the slide mechanisms are now moved so as to apply a little more pressure to the ball and, consequently, the diaphragm, the diaphragm will flex, leaving the ball stationary while the ball positioner moves away from the ball. This leaves the ball in contact only with the ball contact screw plate and the hardened steel plate on the upper platform plate.

Should the ball slip on the hardened steel surfaces for any reason it can be re-aligned by merely moving the slide, with the transformer assembly attached, away from the hardened steel plate. This re-centers the ball in the hole in the ball positioner. Returning the slide mechanism and transformer assembly to its previous position, with the ball against the hardened steel plate, places it in a measuring location once again.

Another feature of this system can be seen from geometric considerations. A rotation of the upper platform plate about one of its axes will cause angular movement of the associated hardened steel plates mounted on the lower side of the upper platform plate. Rolling of the steel balls between these hardened steel plates and the ball contact screw plates results as shown in Plate VII. The angular movement in Plate VII is greatly exaggerated for clarity. If this angular motion is small (i.e., less than about 3 degrees), the position of the ball contact screw plate which is attached to the transformer core shaft does not change. The cantilever beams, because of their material and dimensions, normally yield only very small movements at the free ends of the beams, consequently, the angular motions are very small.

<u>3. Position of the Line of Action of the Horizontal Displacement Measuring Transformers.</u> In the design of Barany and

## EXPLANATION OF PLATE VII

Linking mechanism between linear variable differential transformer core shaft and the platform upper plate.

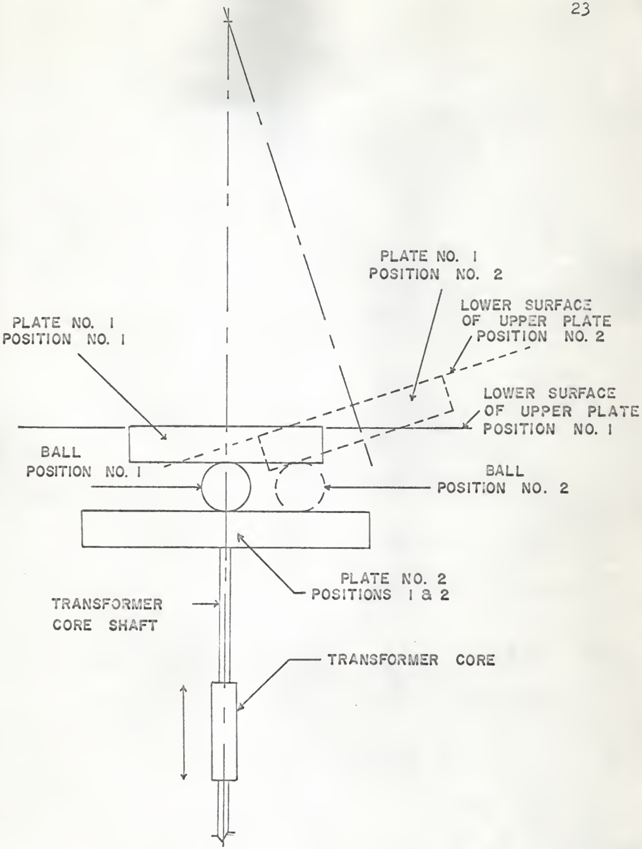


PLATE NO. 1
POSITION NO. 2
LOWER SURFACE
OF UPPER PLATE
POSITION NO. 2
PLATE NO. 1
POSITION NO. 1
LOWER SURFACE
OF UPPER PLATE
POSITION NO. 1
BALL
POSITION NO. 1
BALL
POSITION NO. 2
PLATE NO. 2
POSITIONS 1 & 2
TRANSFORMER
CORE SHAFT
TRANSFORMER CORE

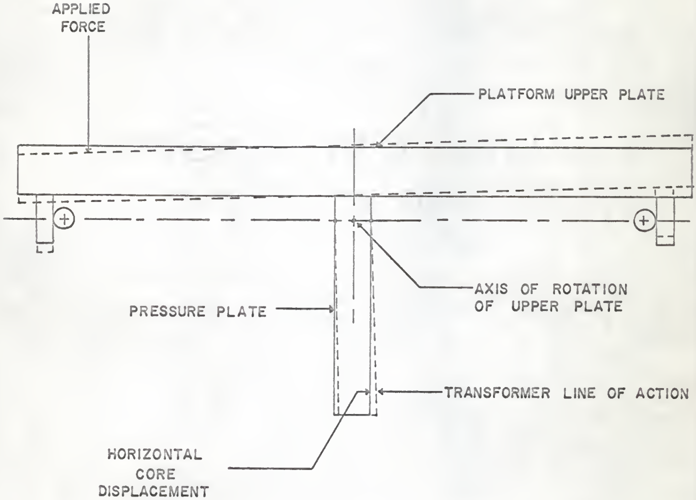
Whetsel, the location of the lines of action of the two horizontal displacement measuring transformers was well below the axes of rotation of the upper plate of the platform. The location of one of the lines of action relative to an associated axis of rotation is shown in an exaggerated position, for the sake of clarity, in Plate VIII. A vertical force acting at the indicated point on the upper platform plate will cause rotation of the platform as shown in dotted lines in Plate VIII. This would result in a linear motion of the horizontal transformer core even though no actual horizontal force was applied to the platform plate.

In the new platform design the lines of action of the horizontal transformer cores are moved so that they pass through the center of rotation of the upper platform plate as shown in Plate IX. With the line of action of the transformer cores in this location no translational movement of the cores will result when rotation of the upper platform plate occurs as shown in dotted lines in Plate IX. This will insure that translational measurements will not be confounded by rotational motions.

4. Upper and Lower Platform Plate Construction and Size. The upper platform plate of Barany and Whetsel's design was a hexagonal shaped 3/4 inch thick aluminum plate. It was 12 inches along a side and had a removable 12 inch square section in the center of the plate to allow access to the transformers for adjusting purposes. This square section was held in place by allen head cap screws that were inserted and tightened after adjustments were made. The lower plate was an identical hex-

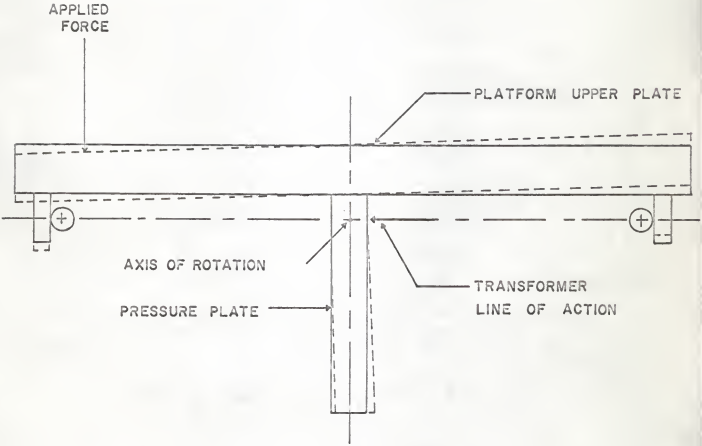
## EXPLANATION OF PLATE VIII

Schematic drawing showing the relationship between the line of action of a horizontal transformer and its associated axis of rotation in Barany and Whetsel's design of the force platform.


APPLIED FORCE
PLATFORM UPPER PLATE
AXIS OF ROTATION OF UPPER PLATE
PRESSURE PLATE
TRANSFORMER LINE OF ACTION
HORIZONTAL CORE DISPLACEMENT

EXPLANATION OF PLATE IX

Schematic drawing showing the relationship between the line of action of a horizontal transformer and its associated axis of rotation in the new design of the force platform.


APPLIED FORCE
PLATFORM UPPER PLATE
AXIS OF ROTATION
TRANSFORMER LINE OF ACTION
PRESSURE PLATE

agonal 3/4 inch thick aluminum plate but without a removable center section.

In the model of this design of the force platform in use here at Kansas State University, replacement of the square section after adjustment of the transformers and tightening of the eight screws resulted in a chenge in the stress characteristics in the upper plate and associated frame work which was bolted to the under side of the hexagonal upper plate. This stress change caused a shift in the position of the transformer cores and a subsequent loss of calibration. Thus, there was no way to calibrate an assembled unit.

In verbal discussion between a member of the faculty of the Department of Industrial Engineering at Kansas State and a member of the faculty at Texas Tech, it was learned that they had also experienced difficulties resulting from the upper plate construction. In addition to calibration difficulties, they found that there was excessive flexure of the upper plate resulting in erroneous data. Their solution was to bolt a solid plate on top of the original upper plate.

In the new design the upper and lower platform plates have been placed far enough apart to allow for transformer adjustment from the side without removal of a section of the upper plate. In addition, the plates are aluminum castings. Each plate was increased in size to 15 inches on a side. The increase in size was found desirable because chairs and stools were difficult to place on the 12 inch model.

The upper plate is one inch thick with 3/4 inch wide ribbing extending down approximately 7/8 inch from the under side of the plate to decrease the possibility of flexure under load. The plate and ribbing are cast as a single unit. The additional thickness plus the elimination of the bolted center section makes the structure more rigid.

The lower plate casting incorporates several parts that were machined separately and bolted together in Barany and Whetsel's design. By casting as a unit the possibility of play in some bolted joints is eliminated. This plate is only 3/4 inch thick after machining the casting but it is to be bolted to a large surface plate so difficulties due to flexure should not arise.

5. Torque Measurement. The measurement of torques about the three orthogonal axes is probably the principal point of interest in this research. Interest was stimulated in this new idea by a study of the following hypothetical situation.

"Place an individual of arbitrary size and stature upon a force platform. Next, place a mechanism outside the force platform world which has a handle to be pulled that offers constant resistive force to the pulling action along the frontal axis and no resistance along the vertical or lateral axes. Let the individual exert a steady pull on the handle for a given distance of movement and at a given handle speed."

A situation of this type can be visualized as an individual standing on the platform and pulling on a handle that is attached to a very long weightless string that passes over a pulley near the other end which is fastened to a hanging weight. A study of a situation similar to this was conducted by Day (1965). The handle he used, however, reacted both to push and pull and did not offer zero resistance to vertical and lateral motions.

Referring to the hypothetical situation described above, it seems obvious that the force exerted in the frontal direction to overcome the resistive force by any individual would be the same and the vertical and lateral forces exerted should be zero within statistical error. Yet, if the individual is small, he may, of necessity, have to lean back in order to apply the required force to move the handle while a large individual may be able to perform the act while in an upright position or, possibly, even leaning forward somewhat.

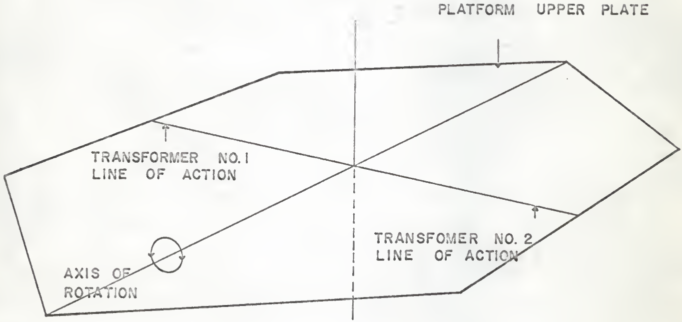
Recognition of these facts stimulated the idea that the shift of one's weight, or center of gravity, about the original rest position may be worthy of investigation. This weight shift can be detected by measuring the torques exerted about the various axes of rotation of the upper plate of the force platform.

The method selected to measure the torques about the three axes is quite simple. It involves the incorporation of two additional LVDT's for each axis of rotation. The two transformers for torque measurement about an axis are placed on the lower platform plate with their lines of action located an equal distance on either side of the axis. These transformer core lines of action also lie in a plane which is perpendicular to the associated axis. A diagram of this arrangement is shown in Plate X.

The electrical connection of the transformers is shown in

EXPLANATION OF PLATE X

Schematic drawing showing the relationship between an axis of rotation of the upper platform plate and the lines of action of the two associated torque measuring transformers.


PLATFORM UPPER PLATE
TRANSFORMER NO. I
LINE OF ACTION
TRANSFOMER NO. 2
LINE OF ACTION
AXIS OF
ROTATION

EXPLANATION OF PLATE XI

Electrical schematic showing the connection of two linear variable differential transformers for torque measurement.

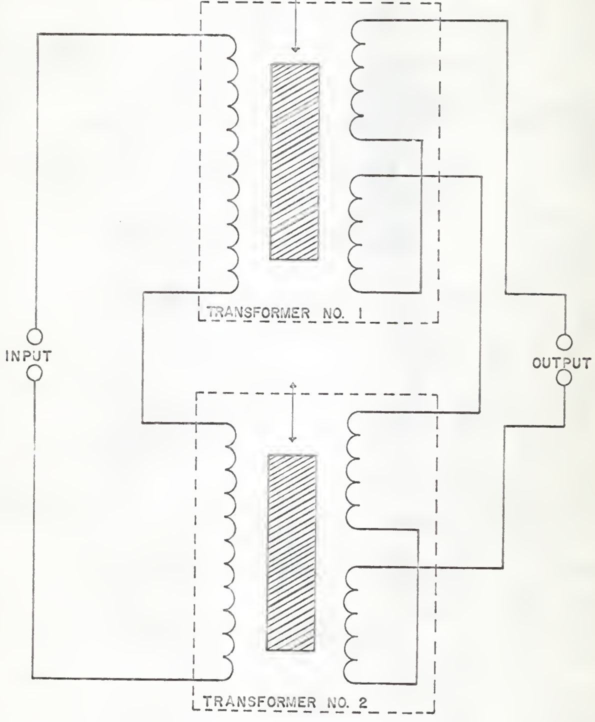

INPUT
OUTPUT
TRANSFORMER NO. 1
TRANSFORMER NO. 2

Plate XI. With this circuit connection the outputs from the transformers can be balanced at a zero torque position by use of the precision adjustable dovetail slides mentioned in the section on the Transformer Positioning and Adjusting Method. Any variation of the position of one transformer core relative to that of the other will give a resulting output. At the same time, the cores may both move along their lines of action by the same amount and remain in balance.

## Fabrication

Both surfaces of the upper plate were machined on a 36 inch Bullard vertical turret lathe to obtain surfaces which were flat and parallel within one to two thousandths of an inch. The bottom surface of the lower plate was also machined on the Bullard vertical turret lathe while the top surface of the lower plate was finished on a No. 3, Model K, Milwaukee vertical milling machine. Here again the surfaces were maintained as flat and parallel as possible. Attempts were made to maintain tolerances on other machined areas on the upper and lower plates of not more than plus and minus two thousandths of an inch.

Machining tolerances on all other parts were maintained better than plus and minus ten thousandths of an inch on all non-critical dimensions. The critical dimensions (i.e., mating surfaces) were held to plus and minus two thousandths of an inch or better.

## Assembly

Machine drawings of each part in the new design of the force platform are included in the appendix. The assembly of these components shall be described here in two sections. The first section, "Assembly of Sub-assemblies", deals with the assembly of the individual sub-assemblies while the second section, "Platform Assembly", is concerned with the sequence of mounting the sub-assemblies and other parts onto the platform upper and lower plates and the assembly of the upper and lower plates.

Assembly of Sub-assemblies. The initial step in the assembly of the force platform was the assembly of the sub-assemblies. These sub-assemblies are as follows: Transformer; Horizontal precision slide; Vertical precision slide; Frontal vertical ball holder; Lateral vertical ball holder; and Horizontal ball holder. The steps in putting the parts together to make each sub-assembly shall be discussed separately.

Transformer Sub-assembly. There are nine identical transformer sub-assemblies in all. For assembly of a transformer sub-assembly, reference should be made to the cross sectional view in Plate VI.

The assembly procedure of a transformer sub-assembly began with the mounting of a Transformer Core on a Transformer Core Shaft. Special care was exercised here since cold working of the core could greatly change the characteristics of the transformer. The core was checked to be certain it would slide onto the Transformer Core Shaft with ease. The core was secured in place against a shoulder on the shaft by a short length of plastic tubing that fit snuggly on the shaft. Only light pressure was applied to the core by the plastic tubing when a Shaft Coupler was screwed onto the end of the shaft.

The Transformer Winding Container was now installed in the plastic Coil Slug. This Coil Slug was then placed in the large center hole in the Transformer Housing and the Slug Adjusting Block inserted in the slot in the top of the Transformer Housing. The Slug Adjusting Block was fastened to the Coil Slug by two fillister head 6-32 screws. The two allen head adjusting set screws were next screwed into the adjusting screw holes in the Transformer Housing until they came in contact with the Slug Adjusting Block. Now, using the adjusting set screws, the Coil Slug was positioned at the approximate center of its adjustment range. The Diaphragms for each end of the Transformer Housing were next fitted with Shaft Couplers. A hardened Ball Contact Screw Plate was used to secure a coupler to one Diaphragm and a standard 10-24 cap screw was used for the other Diaphragm. The Diaphragm with the Ball Contact Screw Plate was then fastened to the end of the Transformer Housing that was drilled and tapped to receive the Ball Positioner. A Pressure Ring was installed on top of the edge of the Diaphragm to apply uniform pressure to the edge of the Diaphragm. This helps to give uniform flexure of the Diaphragm by preventing motion of the edge of the Diaphragm.

The Transformer Core Shaft, with the core mounted on it, was now inserted through the center of the transformer coil and screwed into the coupler on the Diaphragm which was previously installed. This shaft was screwed in firmly with the fingers only in order to prevent damage to the Transformer Core and the Transformer Core Shaft. This step was followed by screwing the other Diaphragm onto the extended end of the Transformer Core Shaft until there was some inward pressure on the Diaphragms (preloaded inward approximately 1/32 inch). The second Diaphragm was now secured to the Transformer Housing after installing a Pressure Ring. The final step in assembling the transformer sub-assembly was placing the steel ball in position on top of the Ball Contact Screw Plate and securing it in position with a Ball Positioner. The ball is held firmly in position by the Ball Positioner but little or no further flexure of the Diaphragm was allowed as a result of the holding pressure.

Adjustment of the nine transformer sub-assemblies was required prior to their installation in the platform. This was accomplished with each individual transformer connected separately to a carrier amplifier and strip chart recorder. The position of the transformer coil was adjusted with the adjusting set screws which provide longitudinal movement of the coil about the core. The coil was moved while observing the output until a null or minimum output was obtained as described in the introduction of this paper.

Horizontal Precision Slide Sub-assembly and Vertical Precision Slide Sub-assembly. The horizontal and vertical precision slides differ only in mounting hole configuration in the Dovetail Slide Base Plates. The horizontal slides are attached to the lower platform plate with allen head cap screws that thread into one face of the Dovetail Slide Base Plate while the vertical slides are fastened to the lower platform plate with allen head cap screws threaded into one end of the plate. There are five vertical precision slide sub-assemblies and four horizontal precision slide sub-assemblies in the platform.

The first step in the assembly of this sub-assembly was to attach a Dovetail Slide Guide to the Dovetail Slide Base Plate. This guide is attached to the surface of the base plate on the side which has the five guide mounting holes nearest the edge of the base plate. This guide was fastened securely with five 6-32 fillister head machine screws that are 1/2 inch in length.

Next a Slide Adjusting Plate was placed on the opposite edge of the base plate so that the 4-40 tapped holes extend above the surface of the base plate. The adjusting plate was secured with five 6-32 flat head screws that are 1/4 inch in length. Five 5/16 inch long 4-40 fillister head machine screws were then threaded through the tapped holes in the adjusting with the screw heads on the same side of the plate as the five flat head screws which were used to secure the adjusting plate to the base plate. Locking nuts were threaded onto the protruding end of each of these screws.

Another Dovetail Slide Guide was then placed in the remaining guide position on the base plate and fastened in place with five 1/2 inch long 6-32 fillister head machine screws. These screws were not tightened at this time as the Dovetail Slide first had to be inserted between the guides.

A Lead Screw was then fitted into a Lead Screw Nut. This was done by threading a Lead Screw into a Lead Screw Nut and inserting a 13/32 inch long 4-40 fillister head machine screw into the clamping hole to apply a slight pressure to the Lead Screw. Only the minimum necessary pressure was applied to remove any play that might exist between the threads.

The Lead Screw was then extracted from the Lead Screw Nut (without loosening the 4-40 clamping screw) and inserted into the hole provided for it at the end of the milled slot in the base plate. The Lead Screw Nut was placed in the milled slot and the Lead Screw re-threaded into the nut.

Next the Dovetail Slide was inserted between the guides and four 11/32 inch long 4-40 fillister head machine screws inserted through the slide and into the threaded holes provided in the Lead Screw Nut. As these screws were tightened, it was made certain that the Lead Screw did not bind in the hole in the base plate.

By tightening the five 4-40 machine screws in the adjusting plate, the play between the slide and the guides was reduced to as small an amount as possible without undue pressure on the slide. The 6-32 screws in the guide which had not previously been tightened were then tightened and the locking nuts on the 4-40 screws in the adjusting plate were tightened.

The Dovetail Slide Adjusting Knob was next placed on the end of the Lead Screw so that the end of the Lead Screw was just even with the face of the adjusting knob. The knob was secured to the Lead Screw by means of a 6-32 allen head set screw.

The final step in assembly of a horizontal precision slide sub-assembly was to install the Dovetail Slide Base End Plate. The end plate is held in place by two 3/4 inch long 3/8"-24 round head machine screws. In the case of the vertical precision slide sub-assemblies, however, the end plate is held in position by the sub-assembly mounting screws.

Ball Holder Sub-assemblies. The two lateral units differ from the four frontal units only in the shape of the Ball Holders. The assembly procedure is identical for both types of units.

The first step in assembly of one of these six sub-assemblies was to install three 1/8 inch diameter steel balls into the three 3/16 inch diameter milled holes in the ball holder. This was followed by the installation of a 1/2 inch steel ball which sets on top of the three 1/8 inch balls. A Vertical Beam Ball Retainer was installed around the 1/2 inch steel ball and secured in place by four 6-32 flat head machine screws 1/2 inch in length.

Assembly of one of the six horizontal ball holder sub-assemblies began with the installation of three 1/8 inch diameter steel balls in the three 3/16 inch diameter milled holes in the ball holder. A 1/2 inch steel ball rests on top of the 1/8 inch diameter steel balls and is held in place with a Horizontal Beam Ball Retainer which is placed around the ball and secured in place with four 4-40 flat head machine screws 1/2 inch in length.

Horizontal ball holder supports were then threaded into the six horizontal ball holders. Three ball holders were each fitted with two Short Horizontal Ball Holder Supports while the other three were each fitted with two Long Horizontal Ball Holder Supports.

Platform Assembly. The initial step in assembly of the platform was to install the components and sub-assemblies on the upper and lower platform plates. The plates were then connected together to form the finished force platform.

The first step in the assembly of the lower platform plate was to install the Vertical Beam Blocks in the appropriate positions on the lower platform plate. Each block is held in place by two $1\frac{1}{2}$ inch long 3/8"-16 allen head cap screws which are inserted from the bottom of the lower platform plate. Next the four 3/16 inch thick frontal vertical beams and the two 1/4 inch thick lateral vertical beams were clamped against the outer surfaces of the Vertical Beam Blocks.

A Vertical Beam Adjuster was installed between each Vertical Beam Block and the vertical beams. The vertical beam and the beam adjuster were clamped against the surface of the Vertical Beam Block with a Vertical Beam Holder that was screwed to the block with two $1\frac{1}{2}$ inch long 3/8"-16 allen head cap screws.

The Horizontal Beams were then secured to the lower platform plate. A Horizontal Beam Adjuster was placed between the beam and the short projections on the lower platform plate. The beams that mount on the tall projections on the lower platform plate have a Horizontal Beam Adjuster placed between the beam and the Horizontal Beam Holder. A Horizontal Beam Holder was used to clamp each of the six Horizontal Beams and its adjuster to its respective projections on the lower platform plate. Each Horizontal Beam Holder is screwed to the lower platform plate with four 2 inch long 5/16"-18 allen head cap screws.

After mounting the vertical and horizontal beams, a ball contact screw is installed in the threaded hole in the end of each beam. A 3/8"-24 Vertical Beam Ball Contact Screw was used for the vertical beams and a 1/2"-20 Horizontal Beam Ball Contact Screw for the horizontal beams. These screws were screwed into the beams until the ball contact end protruded through the beam about 1/16 inch. This prevented the screws from interferring with the placement of the upper platform plate above the lower platform plate.

The precision slide sub-assemblies were then mounted on the lower platform plate. Each of the four horizontal precision slide sub-assemblies were mounted above the surface of the lower platform plate on Dovetail Slide Mounting Blocks. These blocks act as spacers to raise the lines of action of the horizontal transformers. In this raised position, the lines of action of the horizontal transformers are coplanar with the lateral and frontal axes of rotation. These blocks are drilled so that the four mounting screws will pass through the lower platform plate and also the slide mounting blocks before threading into the lower side of a precision slide sub-assembly. The four mounting screws are 3 inch long 5/16"-18 allen head cap screws.

The five vertical precision slide sub-assemblies were mounted in a vertical position on the lower platform plate. The two $1\frac{1}{4}$ inch long 3/8"-24 allen head cap screws for mounting the vertical slides were inserted through the appropriate mounting holes in the lower platform plate from the bottom and a Dovetail Slide Base End Plate was placed over the screws before they were threaded into the Dovetail Slide Base Plate. The end plate is then held in position by the mounting screws.

The last items to be mounted on the lower platform plate were the transformer sub-assemblies. These were attached to the slides of the precision slide sub-assemblies by four 1 inch long 6-32 fillister head machine screws.

Each individual transformer for measuring translational forces is equipped with a shielded cable for connection to external circuitry. Each pair of transformers for measuring torques was connected as shown in Plate XI and also was provided with a shielded cable for connection to external circuitry.

After installation of the transformers into the platform, the transformer sub-assemblies were checked to be sure that each could be moved as a unit with its precision screw adjustable slide mechanism. The transformer sub-assemblies were then moved back (i.e., in the direction of the slide adjusting knob) as far as possible and left in this position until the assembly was completed. In this position the plastic Transformer Housings are less apt to be damaged when placing the upper platform plate in position above the lower platform plate.

The first step in assembly of the upper platform plate was to install the four frontal vertical ball holder sub-assemblies and the two lateral vertical ball holder sub-assemblies. These sub-assemblies are each held in place by four 3/8"-18 allen head cap screws. However, the four screws for each lateral vertical ball holder sub-assembly are all 2 3/4 inches long while the four frontal vertical ball holder sub-assemblies are each held by two 1 3/4 inch screws and two 2 3/4 inch screws.

Next the three horizontal ball holder sub-assemblies with the Short Horizontal Ball Holder Supports threaded into them were fastened to the upper platform plate. Each of these sub-assemblies was secured in place by two 1 inch long 3/8"-16 allen head cap screws. These three sub-assemblies are installed at the appropriate corners of the upper plate so that the balls in the holders will rest on the ball contact screws in the ends of the lower set of horizontal beams when the front point of the upper and lower platform plates are aligned.

The three ball contact plates were next mounted on the area provided for them in the center of the upper platform plate. The Vertical Ball Contact Plate was mounted first since it mounts flat against the lower surface of the upper platform plate with four 1 inch long 1/4"-20 allen head cap screws. Then the Lateral Ball Contact Plate was mounted against the side of the Vertical Ball Contact Plate with two 3/4 inch long 8-32 allen head cap screws. The Frontal Ball Contact Plate was mounted next. This plate was secured to the side of the Vertical Ball Contact Plate with two 3/4 inch long 8-32 allen head cap screws and also to the edge of the Lateral Ball Contact Plate with two 3/4 inch long 8-32 allen head cap screws.

The two Vertical Torque Contact Plates were next mounted on the lower side of the upper platform plate with two 1 inch long

1/4"-20 allen head cap screws.

The last items to be mounted on the upper platform plate before placing it on top of the lower platform plate were the four Horizontal Torque Contact Plates. These plates are threaded on one end and were screwed into the upper platform plate in the four tapped holes.

The upper platform plate was then placed on top of the lower platform plate. Special care was exercised to ensure that the plexiglass transformer housings were not damaged upon installation of the upper platform plate. The upper plate rested on the balls of the three horizontal ball holder sub-assemblies at this point. The next step was to install the three remaining horizontal ball holder sub-assemblies with the Long Horizontal Ball Holder Supports threaded into them. These ball holders are placed beneath the horizontal beams that are mounted on the tall projections of the lower platform plate.

The vertical and horizontal beam ball contact screws were then adjusted to provide some loading of the respective beams. Adjustments of these screws were made so as to maintain the upper platform plate in a centered position above the lower platform plate and also keep the two plates as nearly parallel as possible.

After the beams were adjusted the transformer units were connected to the carrier amplifiers and strip chart recorders. The transformer units were then moved, using the precision screw adjustable slide mechanisms, until the ball on the transformers came in contact with their individual contact surface that was attached to the upper platform plate. Final adjustments of the three linear translation measuring transformers were made to place the measuring range slightly to one side of the null position in a linear range. The torque measuring transformer pairs, however, were adjusted somewhat differently. The first step was to move one of the transformers with its precision adjustable slide mechanism so that its core was slightly off to one side of the null position. Next the other transformer was adjusted so that the output from the pair, which were connected in series opposition, reached a minimum. This is a balance condition whereby displacement of either core with respect to the other will result in an output to the recording equipment.

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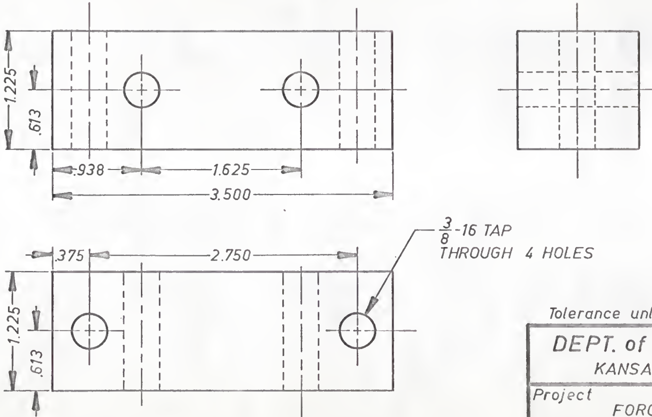
# APPENDIX




Tolerance unless specified 0.010"

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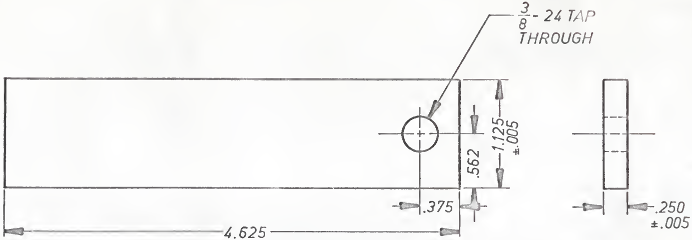


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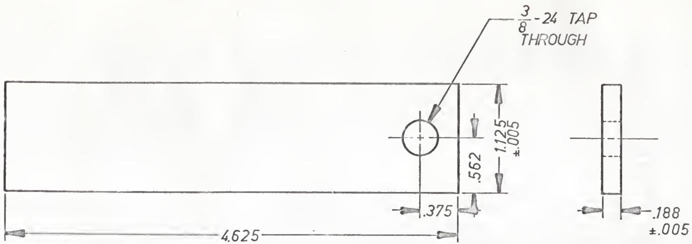


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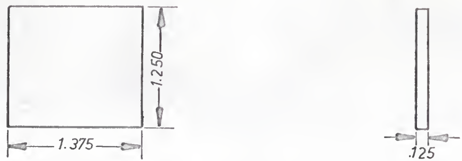


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| No. Req'd 6 | Drawn By V. R. CHITTURI | App'd |
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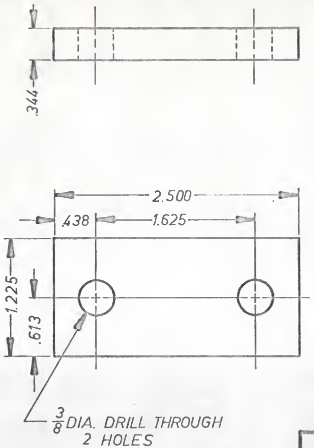


Tolerance unless specified 0.010"

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| DEPT. of INDUSTRIAL ENGG. KANSAS STATE UNIVERSITY | | |
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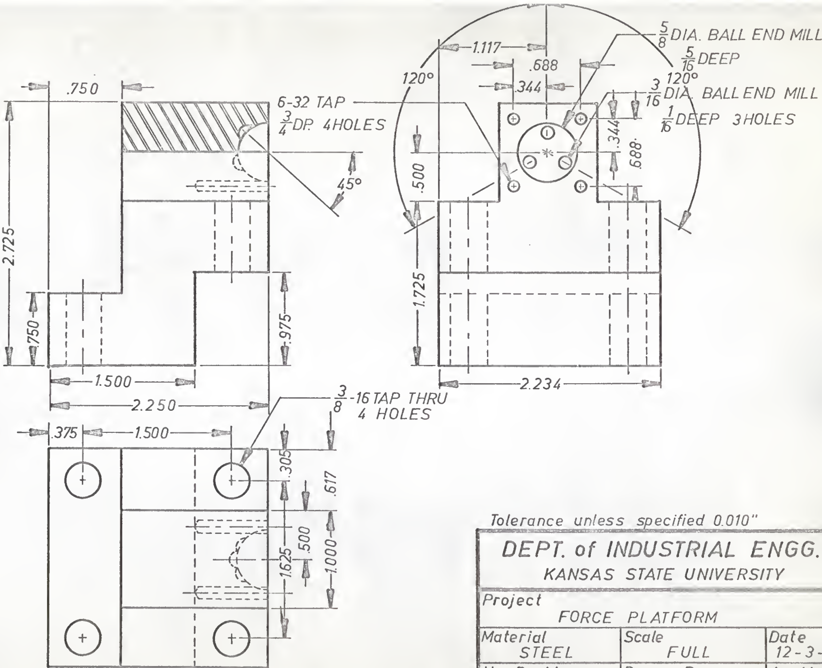
| No. Req'd 6 | Drawn By J.D. HEATH | App'd |
| Part Name VERTICAL BEAM HOLDER | | Part No. |




Tolerance unless specified 0.010"

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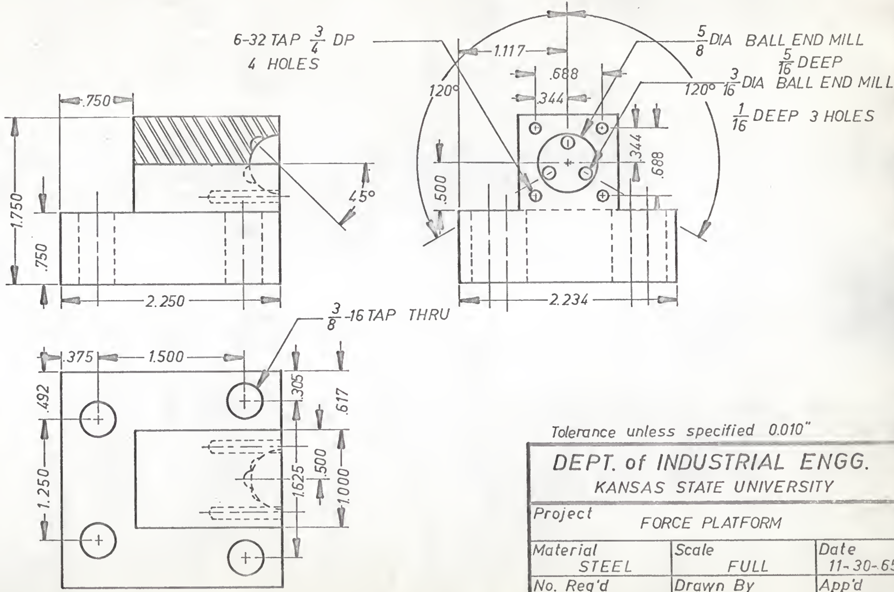


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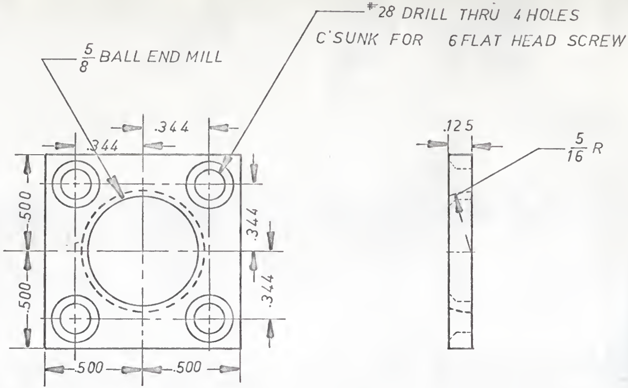


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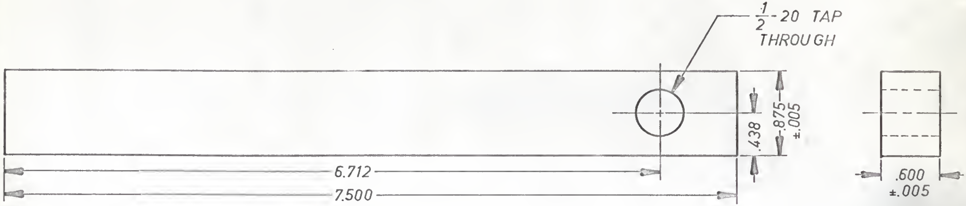


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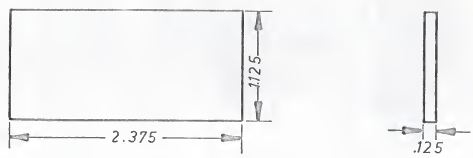


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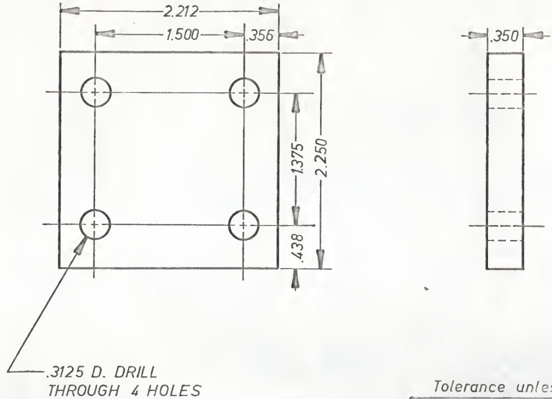


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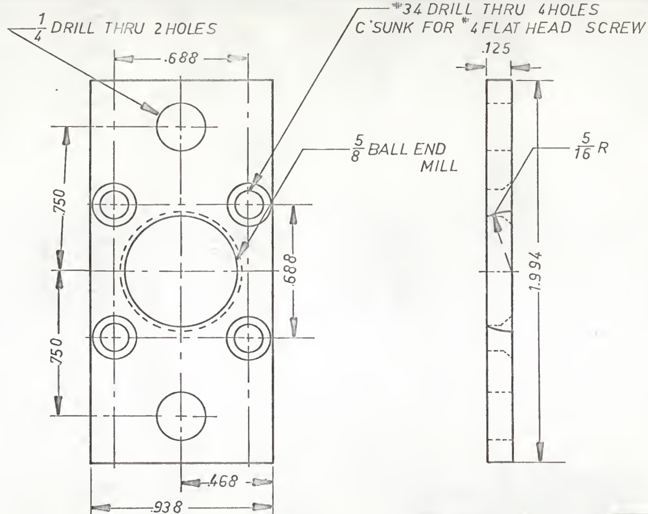


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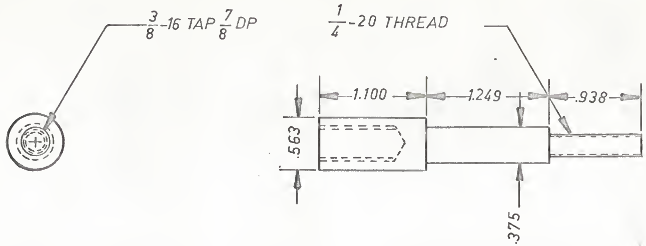


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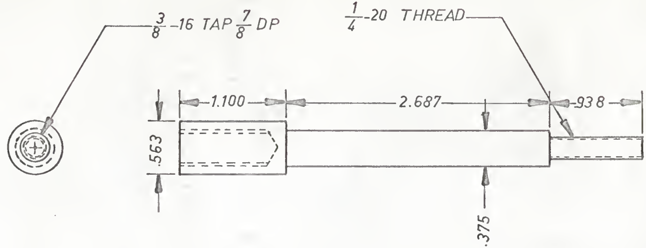


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| Material BRASS | Scale FULL | Date 12-4-65 |
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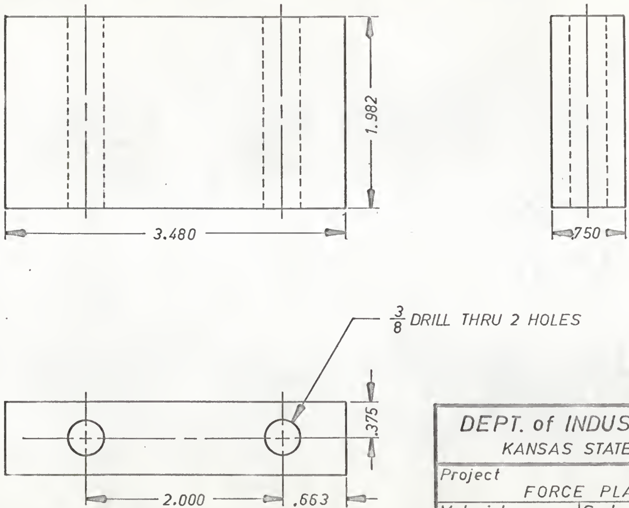


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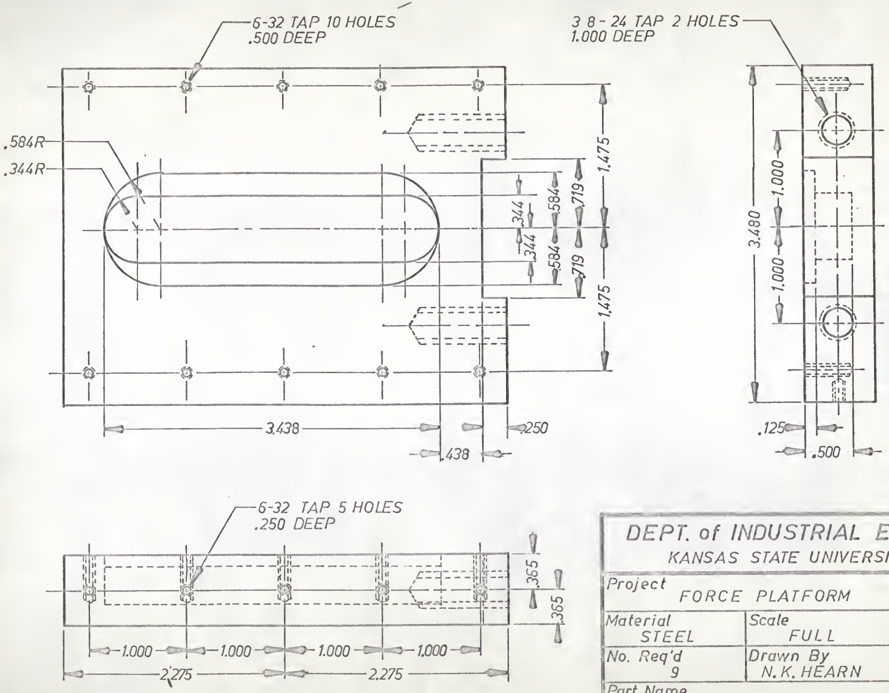


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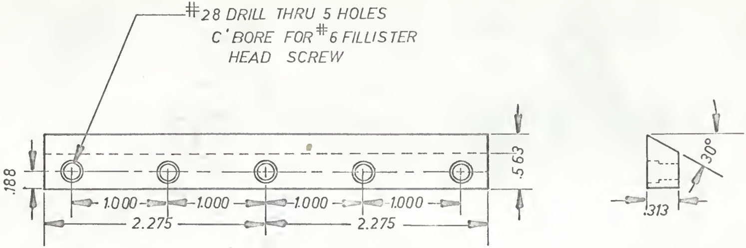


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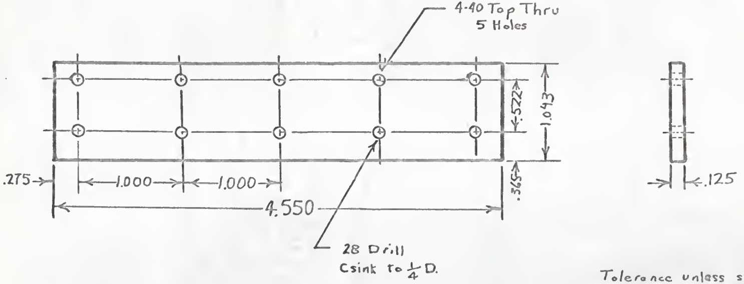


Tolerance unless specified 0.010"

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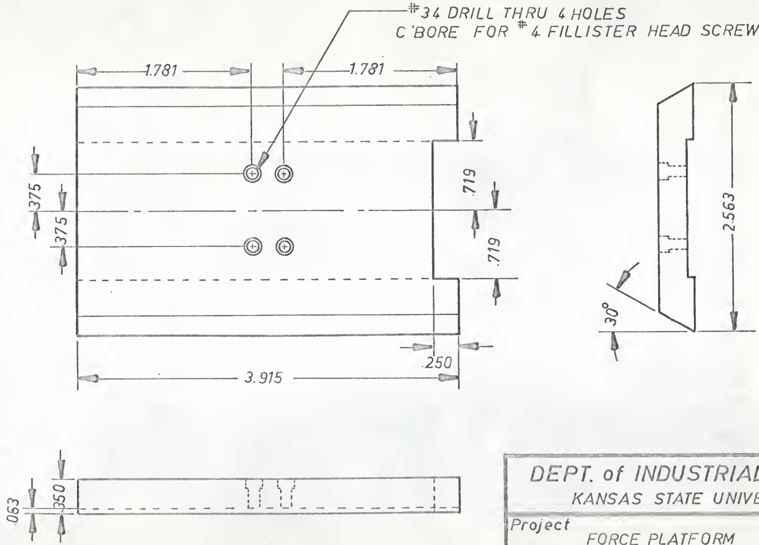


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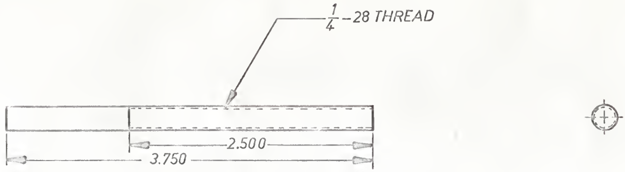


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| Project FORCE PLATFORM | | |
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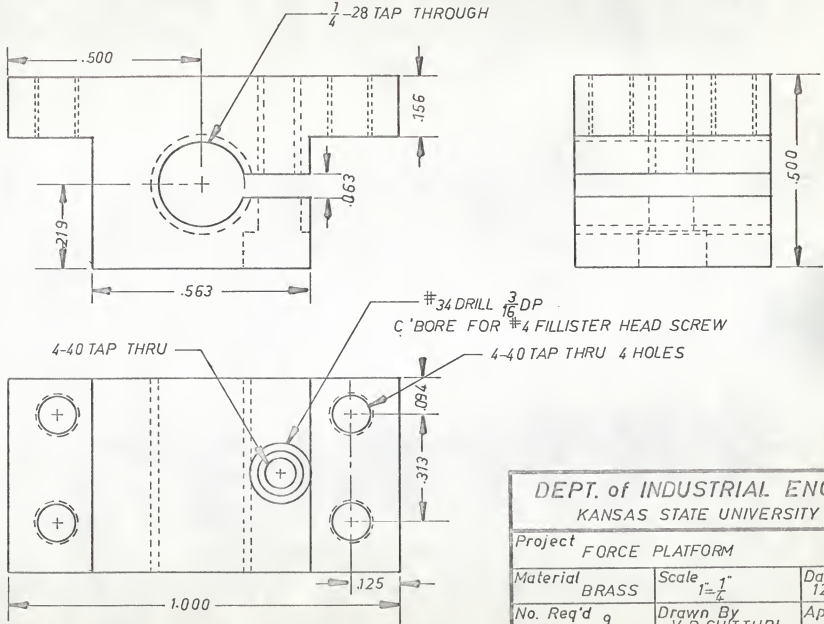


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| Project FORCE PLATFORM | | |
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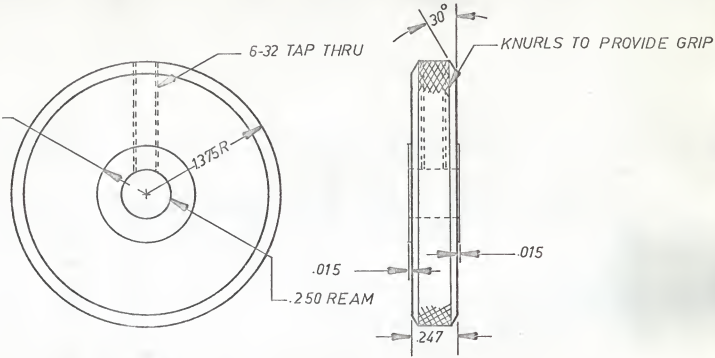


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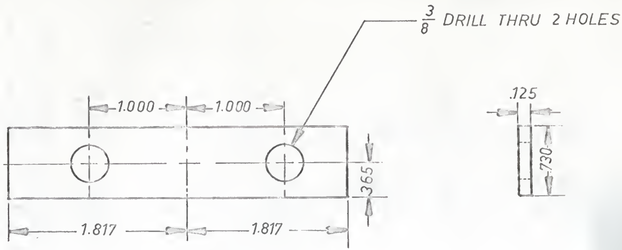


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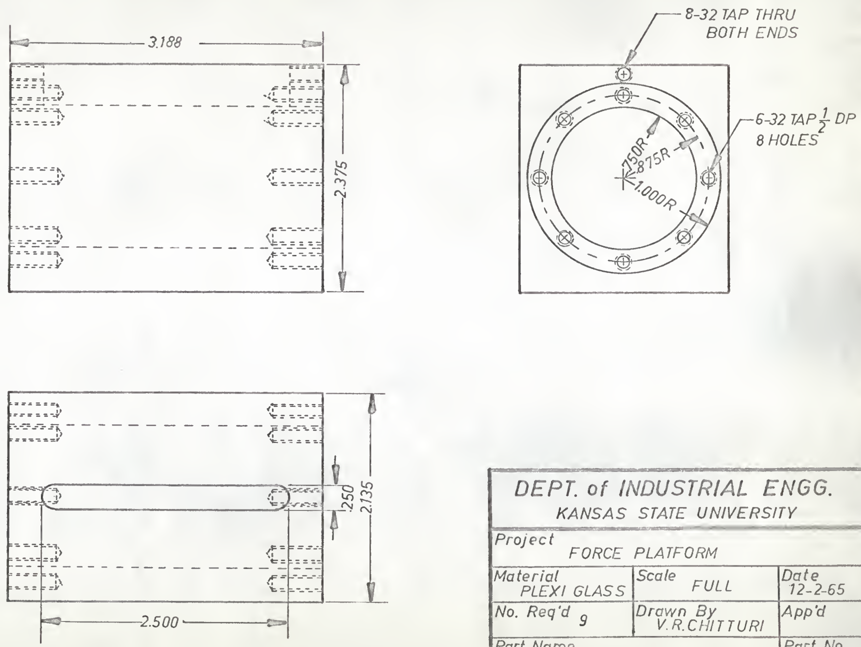
| DEPT. of INDUSTRIAL ENGG.<br>KANSAS STATE UNIVERSITY | | |
| Project FORCE PLATFORM | | |
| Material STEEL | Scale FULL | Date 12-5-65 |
| No. Req'd 9 | Drawn By V R CHITTURI | App'd |
| Part Name DOVETAIL SLIDE BASE END PLATE | | Part No. |

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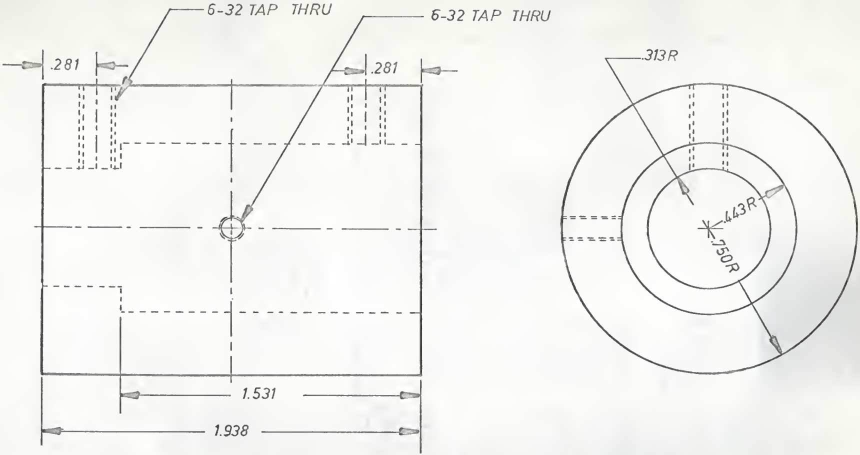
| | | |
|---|---|---|
| Project FORCE PLATFORM | | |
| Material PLEXI GLASS | Scale FULL | Date 12-2-65 |
| No. Req'd 9 | Drawn By V.R.CHITTURI | App'd |
| Part Name TRANSFORMER HOUSING | | Part No. |

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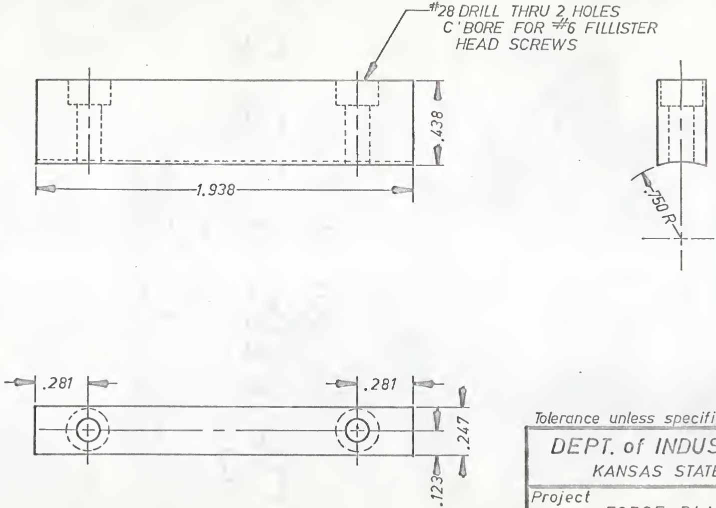
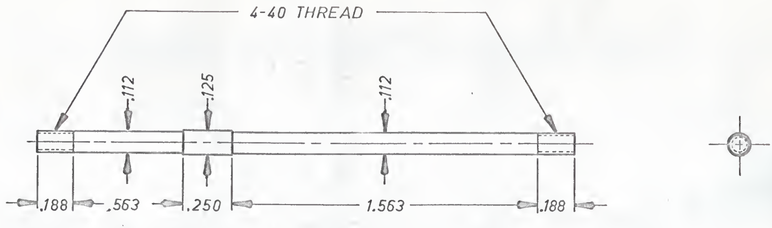
|---|---|---|
| Project FORCE PLATFORM | | |
| Material PLEXIGLASS | Scale DOUBLE | Date 12-4-65 |
| No. Req'd 9 | Drawn By V. R. CHITTURI | App'd |
| Part Name COIL SLUG | | Part No. |




Tolerance unless specified ±0.002

| | | |
|---|---|---|
| DEPT. of INDUSTRIAL ENGG.<br>KANSAS STATE UNIVERSITY | | |
| Project<br>FORCE PLATFORM | | |
| Material<br>PLEXIGLASS | Scale<br>1" = 1/2" | Date<br>12-1-65 |
| No. Req'd<br>9 | Drawn By<br>N. K. HEARN | App'd |
| Part Name<br>SLUG ADJUSTING BLOCK | | Part No. |

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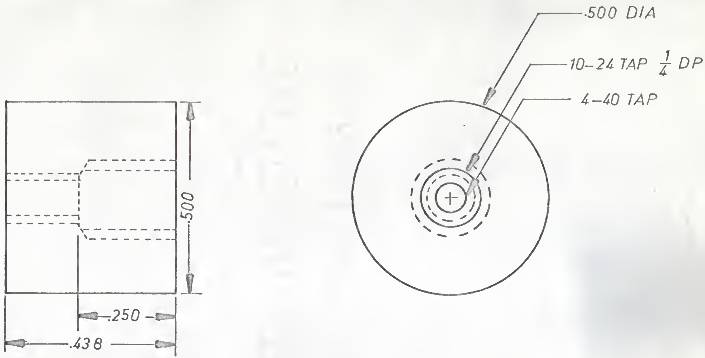
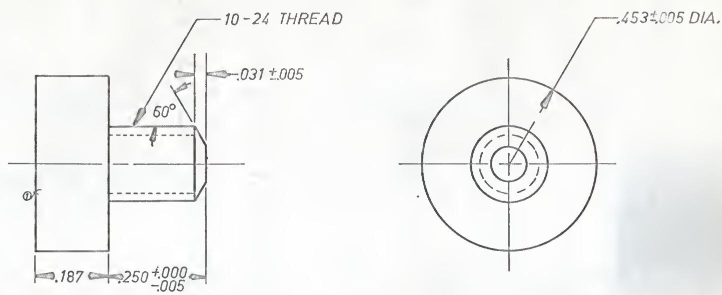
|---|---|---|
| DEPT. of INDUSTRIAL ENGG.<br>KANSAS STATE UNIVERSITY | | |
| Project<br>FORCE PLATEFORM | | |
| Material<br>BRASS | Scale<br>1" = 1/2" | Date<br>12-2-65 |
| No. Req'd<br>9 | Drawn By<br>N. K. HEARN | App'd |
| Part Name<br>TRANSFORMER CORE SHAFT | | Part No. |




| DEPT. of INDUSTRIAL ENGG. KANSAS STATE UNIVERSITY | | |
|---|---|---|
| Project FORCE PLATFORM | | |
| Material BRASS | Scale $1'' = \frac{1}{4}''$ | Date 12-1-65 |
| No. Req'd 18 | Drawn By V. R. CHITTURI | App'd |
| Part Name SHAFT COUPLER | | Part No. |




① Surface finished on 1 micron lapping wheel

Tolerance unless specified ±0.002

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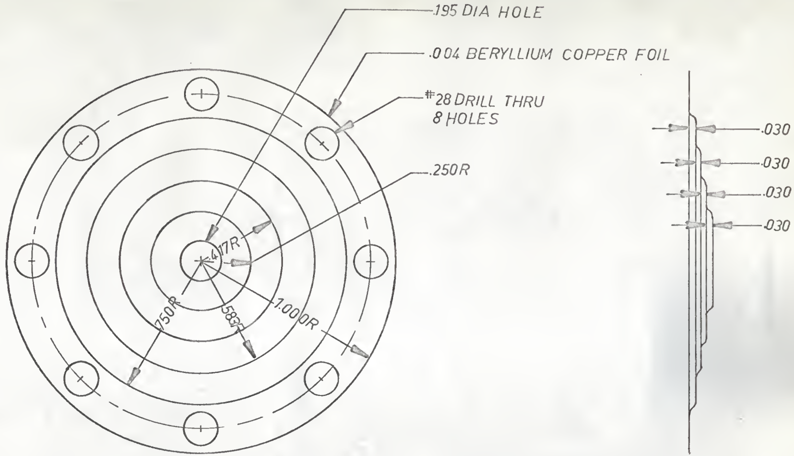
|---|---|---|
| Project FORCE PLATFORM | | |
| Material - STEEL DRILL ROD | Scale 1" = 1/4" | Date 12-1-65 |
| No. Req'd 9 | Drawn By N. K. HEARN | App'd |
| Part Name BALL CONTACT SCREW PLATE | | Part No. |

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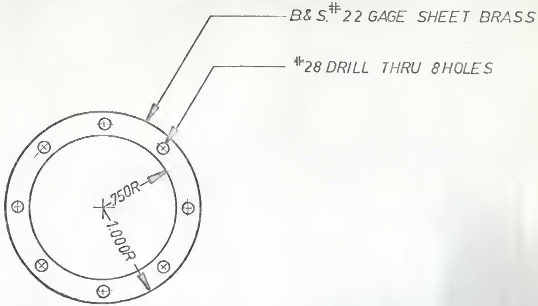
|---|---|---|
| DEPT. of INDUSTRIAL ENGG. KANSAS STATE UNIVERSITY | | |
| Project FORCE PLATFORM | | |
| Material-BERYLLIUM COPPER | Scale DOUBLE | Date 12-1-65 |
| No. Req'd 18 | Drawn By V.R.CHITTURI | App'd |
| Part Name DIAPHRAGM | | Part No. |

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| DEPT. of INDUSTRIAL ENGG. KANSAS STATE UNIVERSITY | | |
| Project FORCE PLATFORM | | |
| Material SHEET BRASS | Scale FULL | Date 12-4-65 |
| No. Req'd 18 | Drawn By V.R. CHITTURI | App'd |
| Part Name DIAPHRAGM PRESSURE RING | | Part No. |

DESIGN AND CONSTRUCTION OF A FORCE PLATFORM
WITH TORQUE MEASUREMENT CAPABILITY

by

NORVAL KELLY NEAL HEARN, JR.
B. A. Emporia State Teachers College, 1957

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

## ABSTRACT

The principal objective of this thesis was to design and construct an improved model of a force platform with torque measuring capabilities. This force platform is similar to one that was designed by James W. Barany and Roger G. Whetsel for measuring on three orthogonal axes the forces a person exerts in performing a task. Torque measurement about the three orthogonal axes is an original idea of the author which is discussed in this thesis.

Primarily, changes were made in Barany and Whetsel's design of the force platform to alleviate problems which have been recognized from practical experience. Discussion of the revisions are included to clarify the reasons for them.

Machine drawings of each of the parts of the platform are also included.