SIMPLE KINEMATIC BI-AXIAL TRANSLATION STAGE

B. S. RAMPRASAD, M. K. TIWARI* AND S. G DIWAN*

(*Central Instruments and Services Laboratory, Indian Institute of Science, Bangalore 560012*)

Received on May 16, 1975 and in revised form on January 9, 1976

ABSTRACT

The principles of kinematical design are applied to the design and fabrication of a bi-axial translation stage, resulting in a low-profile stage. Three designs are shown. The motion of the stages has been checked using autocollimators. The undesirable degrees of freedom are largely rotations about the three coordinate axes. For the best design it seldom exceeds one minute of arc. The performance of the stages is analysed by drawing the hysteresis loops for the motion of the stages. The experimental techniques effectively point out the errors in design and manufacture. It is shown how it is possible to remedy some of the common errors.

Key words: Kinematical design, Bi-axial translation stage.

1. INTRODUCTION

Most optical instruments used for measurement need precise and accurate positioning of optical components. This is particularly true of interferometers where linear motion should be controlled to a fraction of a wavelength of light. In real-time holographic inteferometry, a combination of translation and rotary stages providing many degrees of freedom is an advantage.

The importance of the use of kinematical design in instrument mechanisms has been stressed in many books [1, 2, 3]. A well known fact in kinematics states that a rigid body has six degrees of freedom. By eliminating five degrees of freedom using suitable constraints it is possible to provide for one degree of freedom relative to two parts. Proper choice of constraints will give either pure translation or pure rotation for the remaining degrees of freedom. The advantage of kinematic design lies in the fact that very high accuracy in machining and assembly is not called for. The device behaves in a predictable manner, has a high repeatability and stays stable over long periods of time.

* Department of Physics, Indian Institute of Science, Bangalore

In normal practice two or more translation stages are stacked on one another to provide freedom of translation in more than one direction. This results usually in a bulky and unwieldy device. This paper presents three designs for what is popularly called an X-Y translation stage, using kinematic principles.

These have a low profile and have the advantage of having screws actuating movement on the same plane. The comparative performance of these stages in terms of their hysteresis is presented. These can be fabricated in any small laboratory having limited workshop facilities.

2. Construction Details

Well known principles of kinematical design have been applied to evolve three configurations of a bi-axial translation stage, and their construction details are described here. Figure 1 shows the exploded view of the first design of the X–Y stage called here as S1. It consists of a top plate which is the movable table (1) on which optical components can be mounted. It has a 90° vee groove cut on its underside (2). A bottom plate (3) which is the base, has a 90° vee groove (4) cut in a direction orthogonal to the one in the table (i). A middle plate (5) has two balls (6, 7) embedded in a row on the top face to mate with the vee groove (2). Another ball (8) provides the fifth constraint. Similarly the balls (9, 10, 11) fitted on the underside of (5) when in contact with base (3) provide for the assembly of middle plate and the table to move along the vee groove (4). A screw (12) made in stainless steel with 40 tpi cut on it is used to move the table along x axis. A similar screw (13) moves the table along the y axis. Teflon nuts (14) are used to reduce backlash. These are cemented into the brackets (15, 16) using araldite. Telescopic compression spring systems (17, 18) are used to (*a*) maintain positive pressure between the screws and the middle plate while moving forward and (*b*) to restore previous positions of the table when the screw is rotated in the opposite direction, so that well defined point contacts are available. The screw and the spring systems have ball ends. The weight of the top table is sufficient to maintain positive contact of the constraints. The stage is meant to be used on a horizontal plane. However it can be used vertically provided a tension spring is used to hold the three plates together. It is to be recognised that when the x-axis screw is turned clockwise the middle plate and table move forward (using right-handed screw) and that when the y-axis screw is turned clockwise the middle plate is stationary and the table moves backward. If necessary, the y-axis

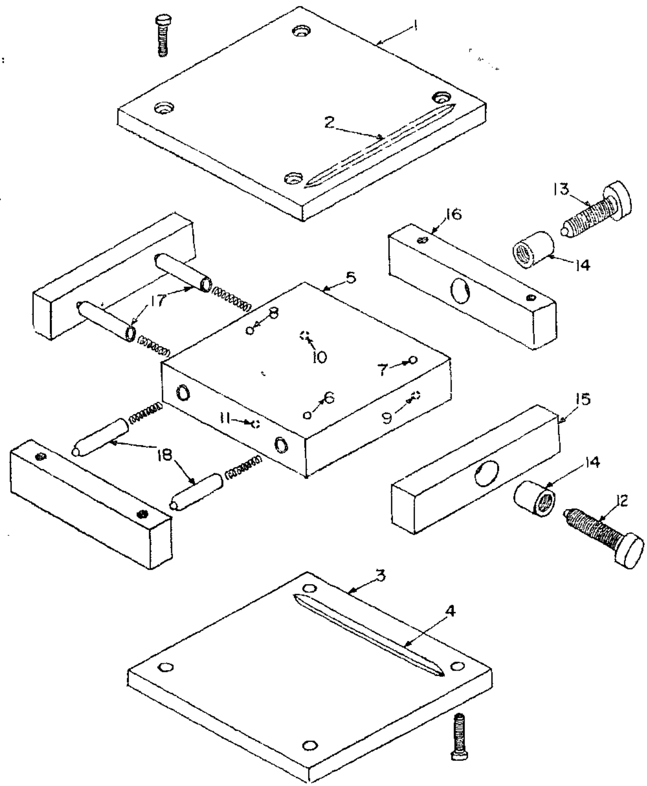

FIG. 1. Exploded view of stage S1.

screw can be cut left-handed so that the motion in the two axes is similar. The axes of the two screws lie on the same plane parallel to the base. The middle plate and top plate are of aluminium. The base is made of mild steel so that it can be fixed on a magnetic chuck for making measurements. However, the bottom plate also can be of aluminium making the stage light in weight. The dimensions of the stage are $5'' \times 5'' \times 1\frac{3}{16}''$. The total amount of linear movement in either axis is 3/8″. Standard holes tapped in the top plate can be used to mount mirror mounts and other components.

Figure 2 shows the exploded view of stage S2. Only some of the salient points are explained here. The middle plate consists of rods (1)

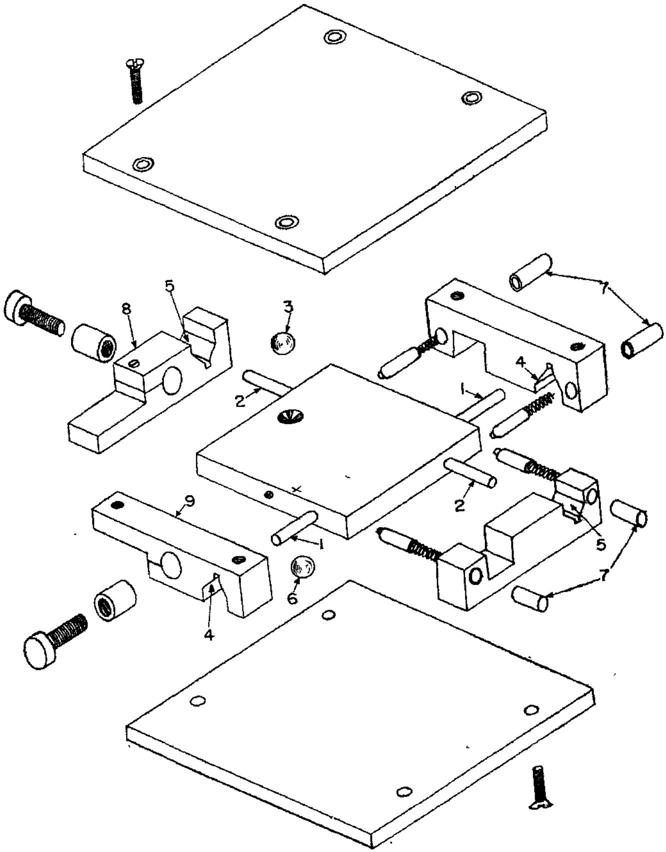

FIG. 2. Exploded view of stage S2.

and (2) fixed along orthogonal axes. These rest in vee grooves. Since the rods make line contact insead of point contacts this design is not strictly kinematic. The rods (1) moving in the vee gooves (4) and the ball (3) fixed on the top of the middle plate allow linear motion of the top table alone. The rods (2) moving in vee grooves (5) and ball (6) fixed on the underside of the middle plate allows for linear motion of both the middle plate and the top plate, which now acts as a unit. A set of bushes (7) for the telescopic spring systems is shown. The set of brackets (8) and (9) are split in the middle so that the teflon bushes can be tightened in position. This eliminates any residual backlash between screw and nut. The holes in the brackets have been made so that a standard micrometer head can be used in place of screw and nut. The size of stage is $5\frac{1}{2}'' \times 5\frac{1}{2}'' \times 1\frac{3}{4}''$ and total movement in either axis is $\frac{1}{2}''$.

Figure 3 shows the exploded view of stage S3. It consists of a plate (1) which acts as the table for fixing components. On its underside

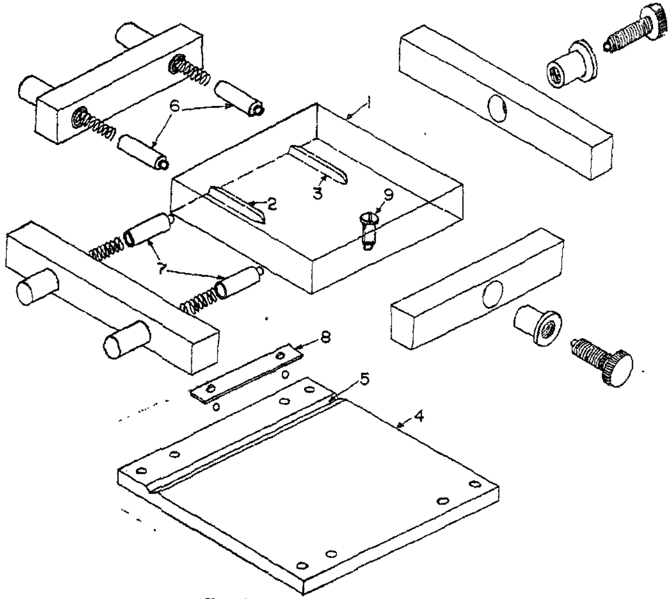

FIG. 3. Exploded view of stage S3.

two vee grooves (2, 3) are made. The base (4) has a vee groove (5) cut orthogonal to the direction of the vee grooves (2, 3). Two balls retained freely in a thin phosphor bronze strip (8) rest in the vee groove (5). This is to ensure that the balls are well separated in the vee groove for proper balance. When the plate (1) is placed on the base the distance between the two balls is such that the two balls will also be in contact with the sides of the vee grooves (2, 3). A ball ended screw (9) is fixed in the plate (1) so that the ball touches the base (4). Initially the height of the screw is adjusted so that the plate (1) becomes parallel to the base. In any one direction the positive constraints are always five because the balls behave rigid in the orthogonal vee groove. Again telescopic spring systems (6, 7) are used for maintaining the positive pressure on the constraints. This has one plate less than the other two stages. The size of the stage S3 is $5'' \times 5'' \times 1''$ and the total movement in either axis is $3/8''$.

3. Theoretical analysis of possible degrees of freedom

It is desirable that any translation stage fabricated should have only the degree of freedom designed into it, which means that no other motion, linear or angular, should be present. Due to shortcomings in manufacture, this condition can be seldom met with. However, using kinematic principles of design the amount of undesirable motions can be reduced to tolerable limits.

The possible degrees of freedom can be analysed by choosing the frame of reference as a rectangular coordinate axes as shown in Fig 4. *a*. When the x-axis screw is operated the stage does not show any linear motion along either y or z-axis, because in the former case there is no component of force in the y direction capable of upsetting the balance of forces between the springs and the y screw. No linear motion is possible in the z direction because the heavy table maintains positive pressure on the constraints. Only degrees of motion possible are the three rotations along the three axes. These are possible due to a variety of reasons. Some of them are (*a*) unequal spring pressures (*b*)ball mounted eccentrically with respect to the screw axis, (*c*) waviness of the vee groove, etc. The experimental set up used to analyse these motions, is described in the following section.

4. Experimental Technique

One of the standard methods of testing the performance of any instrument is to find out its hysteresis [3]. The experimental set up is shown

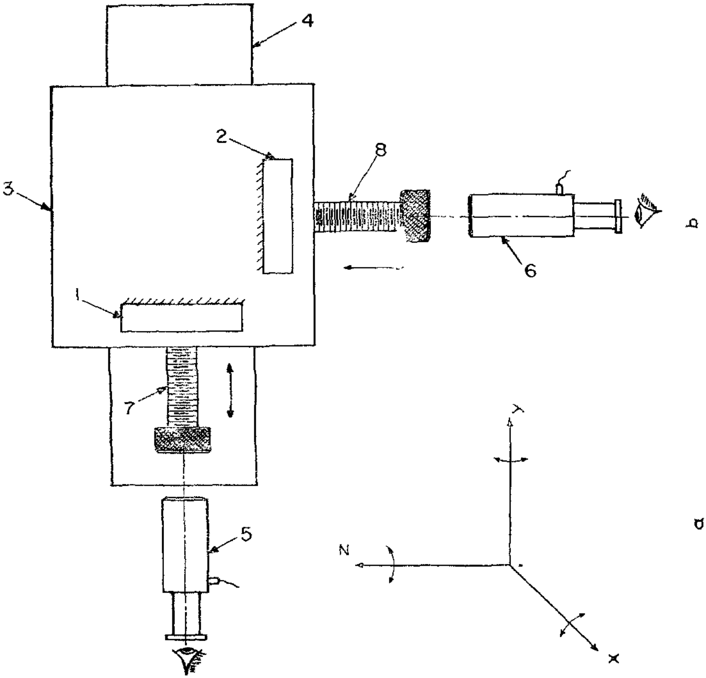

FIG. 4 (*a*) Possible degrees of freedom with respect to a rectangular coordinate axes. (*b*) Schematic of experimental set up for testing the stages.

in Fig. 4 *b*. The angular motions can be found out using autocollimators. The stage (3) to be tested is mounted and fixed on a magnetic chuck (4). Two front surface mirrors (1, 2) of good quality are mounted normal to the moving table of the stage as shown. For stable fixing, optician's cement is used. Autocollimators (5) and (6) are placed orthogonally so that the reflected image of the graticule from the mirror falls on the measuring graticule. Both the autocollimators are adjusted for some arbitrary zero reading. The following convention is adopted for all the stages. Screw (7) is called the *x* screw and screw (8) the *y* screw. Operating any one screw the change in the zero setting of the autocollimators, indicate the rotations along the different axes. When x screw is rotated the autocollimator (5) indicates a change in the position of the horizontal and vertical cross wires which can be read off the scales in terms of minutes. A change in the position of the horizontal cross wire indicates a rotation along the y axis. A change in the position of the vertical cross wire indicates a rotation about the z axis. A change in the position of the horizontal cross wire of the autocollimator (6) indicates a rotation about the x axis. Autocollimator (5) can read upto half a minute of arc in the two perpendicular scales. Autocollimator (6) reads upto half a second of arc being a microptic autocollimator. It is preferable to use both autocollimators with half a minute accuracy, because they have the advantage of two orthogonal scales, whereas the microptic autocollimator can be used to measure in on direction only at a time. A combination has been used here, because only one of each type was available. Both are made by Hilger and Watts, England.

The hysteresis of the stages is measured as follows. Starting from an arbitrarily chosen position of the screw under study the readings of the horizontal and vertical cross wires in both the autocollimators are noted for every full rotation of the screw. Readings are taken for both forward and backward motions of the table. Care is taken to see that the screw is gently rotated without jerks and backlash error is allowed to accumulate till the end of the traverse of the screw. The hysteresis data is taken for both x and y screws for each stage. The data is repeatedly taken. Hysteresis loops for each stage are drawn separately for the x and y motion.

5. Experimental Results

Figure 5 and 6 show the hysteresis loops for x and y motions respectively, of stage S1. The loops for the rotations about the x, y and z axes are drawn separately in both the cases. Figure 5 shows the hysteresis loops when x screw is operated upon. It is to be remembered here that x screw moves the middle plate and the top plate together, consequently having greater load than for the y screw. About the z axis the rotation is reasonably small. Rotation about the y and z axes show variations of a large order. Optimum design of spring will reduce the errors about the y and z axes. Sometimes it is found that the loops overlap on each other. In order to avoid this and make the representation clear the positions of the loops have been shifted. This does not in any way affect the variance of the loops.

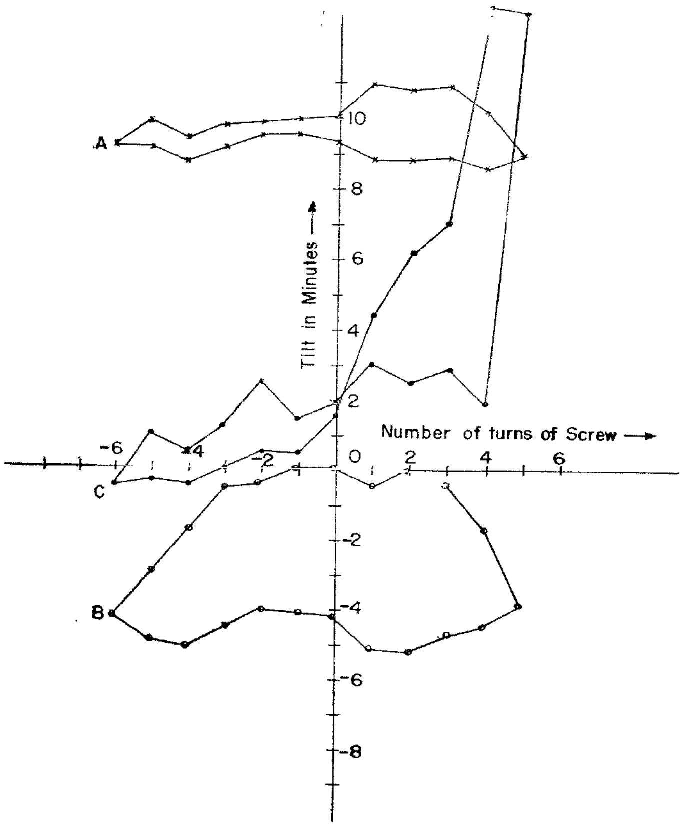

FIG. 5 _ Stage SI—Hysteresis loops for rotations about the x, y and z axes when x screw is moved. (A) rotation about x axis, (B) rotation about y axis, (C) rotation about z axis.

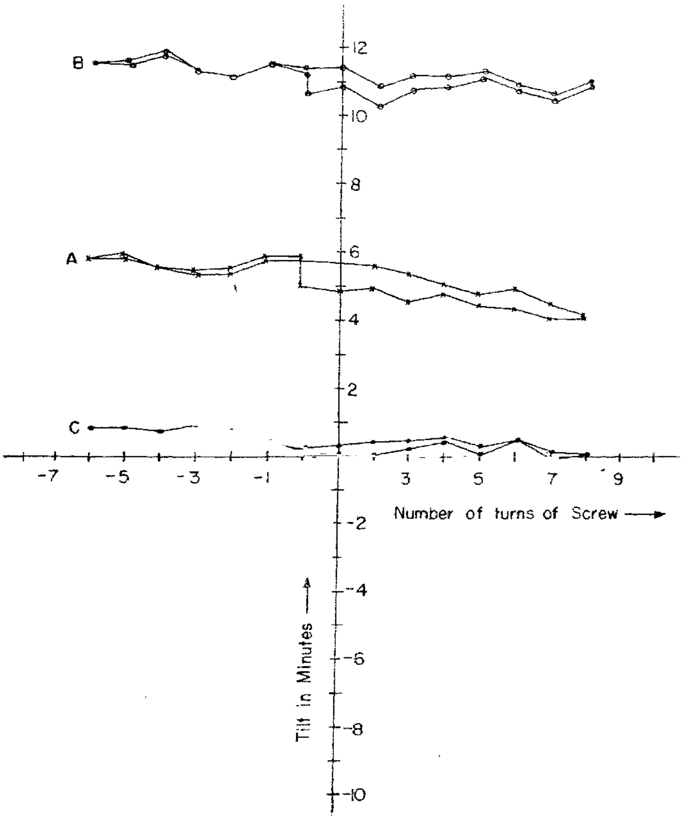

FIG. 6. Stage S1—Hysteresis loops for rotations about the x, y and z axes when y screw is moved. (A) rotation about x axis, (B) rotation about y axis, (C) rotation about z axis.

In Fig 6, the rotation about the z axis is found to be very small, less than $\frac{1}{2}$ minute of arc throughout its travel. The rotation about the x axis shows that the loop does not return to the point of starting. However, the rotation is still less than a minute of arc. The rotation about the z axis is also small.

Figure 7 shows the hysteresis loop for x screw motion for the stage S2. The errors in motion are quite small. Care should be taken not to operate the stage very near the end of traverse on either side, because too much compression of spring is liable to change the axis of application of pressure and when the spring is too loose positive contact may not be there on the middle plate. Hysteresis data for y screw motion (figure not shown) also points out the necessity of proper choice of springs. Figure 8 shows one set of hysteresis loops for stage S3. Hysteresis loops for y motion have been determined but not shown here. The rotation in the three axes ranges from a minimum of 1 minute of arc to a maximum of 4 minutes of arc, in both cases.

It is to be recognised here that the table of this mount is resting on the balls on the base and is held in position by the screws and the springs. If all the constraining and restorring forces do not act in the same plane large tilts are liable to occur. However, when a component of sufficient weight is fixed on the table of this mount the errors will be less pronounced. Better workmanship in fixing the axes of springs and screws, is essential.

Some of the reasons why this particular mount behaves less accurately can be explained as follows. (1) The two vee grooves are not quite parallel. (2) The 90° vee grooves in the table have been cut using a milling cutter with the straight portion less then the required traverse. (3) The balls in the strip are not free to rotate in it. This causes sliding friction which is large. It is suspected that the strip touches the two plates sometimes. (4) It is found that the x screw is inclined to the table by about 2°.

In all cases the end readings were eliminated whenever the motion exceeded the permitted traverse. To make sure that this does not happen often, stops can be fitted into the mount.

Despite the fact that stage S3 shows larger errors, because of its simplicity it can find use in optical systems where only positioning is called for. Stage S3 is very simple to fabricate, though proper care should be taken to avoid obvious mechanical defects. It is lighter in weight than the other two and hence economical. Stages S1 and S2 are more rugged and as such behave better.

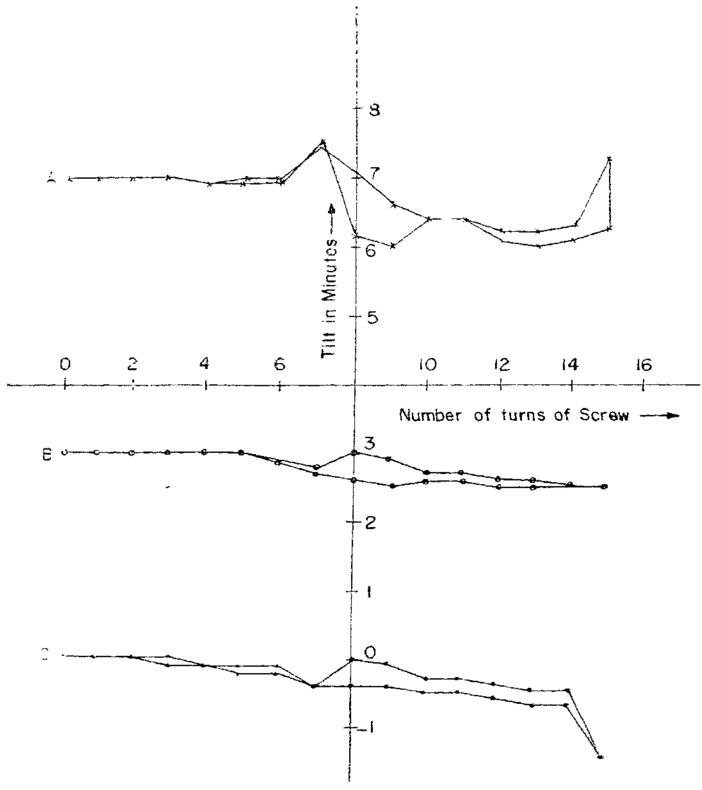

Fig. 7. Stage S2—Hysteresis loops for rotations about the x, y and z axes when x screw is moved. (A) rotation about x axis, (B) rotation about y axis, (C) rotation about z axis.

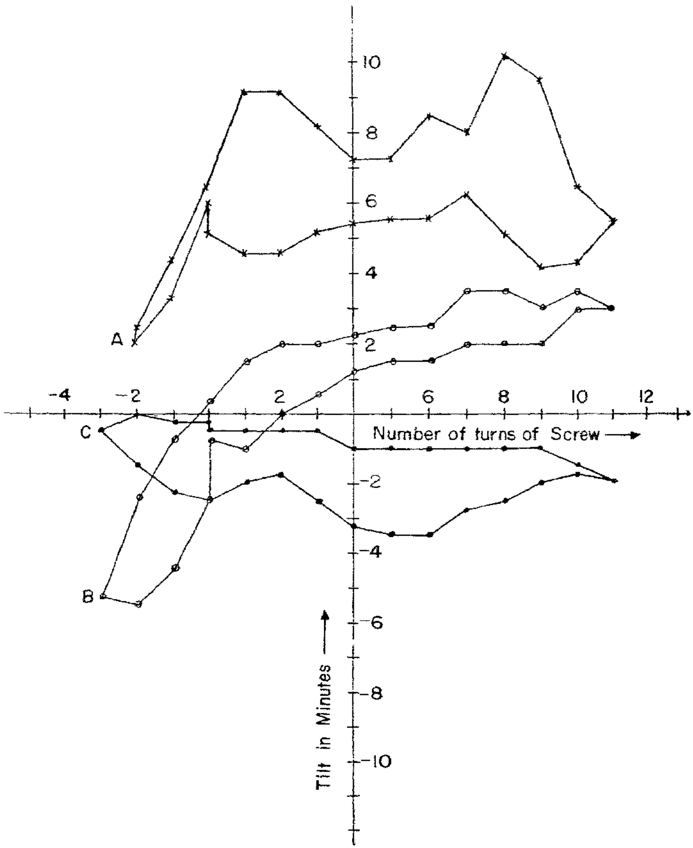

FIG. 8. Stage S3—Hysteresis loops for rotations about the x, y and z axes when x screw is moved (A) rotation about x axis, (B) rotation about y axis, (C) rotation about z axis.

Referring to the hysteresis loops of these stages the extreme variations of tilt measured at any one value of the position of the screw indicates the variance of the stages. That is, it indicates the uncertainty of position of the stage. Though it appears to be large in some cases (of the order of a few minutes) it is not really detrimental to the performance of these stages. Normally when these stages are used for interferometry, one does not move the stage over such large distances as 3/8″. Movements of the order of a few fringes only are required. It can be seen from the graphs that all the mounts behave quite well in the sense that in the neighbourhood of any point along the abcissa the tilt along the different axes is extremely small. The application of the basic principles of kinematic design has yielded three stages of comparative merit and high precision. In order of merit, the three stages can be classified as follows: S2, S1, S3.

6. Conclusion

Basic principles of kinematic design are applied and extended to obtain three configurations of a bi-axial translation stage. The stages are low in profile and are better to use, compared to the conventional way of stacking more than one unidirectional translation stage. The testing of the mounts using autocollimators to determine hysteresis is found to be of immense value in analysing the defects. These defects can be rectified by applying well known mechanical principles. It is suggested here that to overcome the difficulties caused by improper choice of springs magnetic couplings can be used. This would improve the performance of the stages by reducing the variance.

References

[1] Elliott, A. and Dickson, H. *Laboratory Instruments—Their Design and Application*, Chapman and Hall, 1959.

[2] Whitehead, T. N. .. *The Design and Use of Instruments and Accurate Mechanism* Underlying Principles, Dover, 1954.

[3] Pollard, A. F. C. .. *The Kinematical Design of Couplings in Instrument Mechanisms*, Adam Hilger, 1929.