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A MECHANISM FOR PRECISE LINEAR AND ANGULAR ADJUSTMENT UTILIZING FLEXURES*

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This paper describes the design and development of a mechanism for precise linear and angular adjustment. This work was in support of the development of a mechanical extensometer for biaxial strain measurement. A compact mechanism was required which would allow angular adjustments about perpendicular axes with better than 10^{-3} degree resolution.

The approach adopted was first to develop a means of precise linear adjustment. To this end, a mechanism based on the toggle principle was built with inexpensive and easily manufactured parts. A detailed evaluation showed that the resolution of the mechanism was better than 1 μm and that adjustments made by using the device were repeatable.

In the second stage of this work, the linear adjustment mechanisms were used in conjunction with a simple arrangement of flexural pivots and attachment blocks to provide the required angular adjustments. A series of experiments conducted with an autocollimator showed that the resolution of the mechanisms was better than 10^{-3} degrees. Also, the mechanism met all requirements regarding size, weight, and mechanical simplicity.

Attempts to use the mechanism in conjunction with the biaxial extensometer under development proved unsuccessful. Any form of in situ adjustment was found to cause erratic changes in instrument output. These changes were due to problems with the suspension system. However, the subject mechanism performed well in its own right and appeared to have potential for use in other applications. One important advantage of flexure-based mechanisms is that they can be designed to operate independently of screw threads. This raises the possibility that they can be used for precise linear and angular adjustment in a space environment.

INTRODUCTION

The many difficulties associated with conducting mechanical tests under complex loading conditions have received considerable attention during the

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past 10 years (ref. 1). As a result of this attention, test systems have been developed which allow tubular specimens to be tested under combinations of axial load, torsional load, and internal and external pressure. The mechanical design and electronic control features of such test systems have been fully developed, and they present no difficulty. However, one associated aspect of multiaxial testing, that of precise strain measurement, has received little attention.

This deficiency was recognized at the Oak Ridge National Laboratory, and an effort was directed at developing a mechanical extensometer capable of measuring axial, torsional, and diametral strains at elevated temperatures (ref. 2). The basic approach is illustrated schematically in figure 1. Two sensors incorporating ceramic probes grip the specimen by means of friction. The assumption is that, once installed, the point of contact of each probe remains fixed on the specimen. The probes, therefore, transmit specimen displacements and rotations to the body of the instrument. A further assumption is that a suspension system can be designed to constrain the sensors to planes parallel to the X-Y plane in figure 1(a). Two such planes are the DEFG and HIJK planes shown in the figure.

The method of strain measurement is now described. Under axial loading, the vertical distance between the sensors, BB in figure 1(a), changes and is used as a basis for axial strain measurement. This is achieved by positioning proximity transducers on the top sensor and a target on the bottom sensor. With regard to diametral strain measurement, changes in specimen diameter resulting from radial loadings are transmitted via the hinge to the mounting arms. Relative movement between the mounting arms, AA in figure 1(a), is used for measurement purposes by positioning the core of a linear variable differential transformer (LVDT) on one mounting arm and the coil on the other. Under torsional loading, the sensors rotate different amounts about the Z-axis within their respective reference planes. This difference in angular rotation, θ in figure 1(a), is used for torsional strain measurement. A system of levers and rotary variable differential transformers (RVDT's) is used for this purpose.

One difficulty encountered during the development of the instrument was that very precise angular alignment of the target relative to the HIJK reference plane was needed to avoid crosstalk between the axial and torsional components of straining. A mechanism was required to give angular adjustment about two perpendicular axes with a 10^{-3} degree resolution. Furthermore, since space was limited, the mechanism was to be compact and occupy a cube with sides no greater than 5 cm. Also, the weight of the device was to be kept to a minimum to avoid difficulties in experiments involving rapid loadings.

This paper describes the design and development of a positioning mechanism to meet these requirements. It will be shown that the toggle principle can be used to advantage in this application, with linear and angular accuracies better than 1 μm and 10^{-3} degrees ultimately being achieved. Finally, possible improvements to the mechanism are discussed and some alternative applications are suggested.

MECHANICAL DETAILS

The approach adopted in resolving the alignment problem was first to develop a means of precise linear adjustment using the principle of the toggle (ref. 3). With this method, small displacements are obtained by modifying the curvature of flexural elements. This approach was preferred as it offered the advantages of mechanical simplicity and low weight.

Linear Adjustment Mechanism

In the present design, the initial curvature of four rectangular section flexures is modified by using a tapered adjustment screw (fig. 2(a)). These curvature changes cause the button attached to the free end of the flexures to displace axially. The magnitude of these displacements is governed by the initial curvature of the flexures and by the type of thread and taper on the adjustment screw. A means of coarse linear adjustment is provided by enclosing the toggle mechanisms in an externally threaded sleeve (fig. 2(b)). The screw thread used had 40 threads per inch (TPI), which allowed the usual form of micrometer adjustment.

One difference between this and earlier applications of the toggle principle for precise linear adjustment is that the mechanism was assembled from a number of easily manufactured parts (fig. 3). The flexures consist of straight lengths of spring steel with hardened steel balls located at their midsections. The balls, which were attached by spot welding, provide point contact between the flexures and the tapered adjustment screw.

Curvature of the flexures in the assembled form was obtained by constraining the flexures to follow 10° tapers over 6-mm lengths at each end. The clamping force necessary to achieve this condition was provided by collars held in position by spot-welded straps.

Assembly of the mechanism was not straightforward and involved the use of a number of special purpose fixtures. One such fixture, shown in figure 4, ensured precise alignment of the button and the screw holder while allowing the distance between these components to be varied in a controlled manner. Adjustments of this type were necessary as the flexures were forced to assume the required curvature. In addition, less complicated fixtures were used for attaching the balls to the flexures and for supporting the mechanism during installation of the straps.

Angular Adjustment Mechanism

The mechanism used to convert linear adjustment to the required form of angular adjustment utilizes the cylindrical type of flexural pivot (ref. 4). These pivots consist of two cylindrical elements joined by crossed flexures. This arrangement has the advantage of allowing rotation between mating parts without any associated friction or backlash.

The approach adopted in the present application is shown schematically in figure 5. Pairs of flexural pivots are gripped along two perpendicular axes in an attachment block. One pair of pivots is then attached to the target plate with two clamp blocks while the other pair is attached in a similar manner to the base plate. Inspection of figure 5 shows that this arrangement allows angular adjustment of the target plate about two perpendicular axes.

Operation of the subject mechanism is further illustrated in figures 6(a) and (b). Coarse adjustments are made by rotating the linear adjustment mechanisms relative to the base plate using the knurled drums. When the required coarse setting is achieved, the locking arrangement is used to prevent further rotation. Fine adjustments are then made by rotating the adjustment screw of the toggle mechanism. Again, knurled drums are provided to facilitate these adjustments.

TESTING AND RESULTS

The performance of the device was evaluated in two stages in a dimensional inspection facility. The experiments were conducted under closely controlled environmental conditions on an inspection-grade granite surface table. All experiments were performed using forward rotations of the various adjustment screws, as this was the intended mode of operation during biaxial experiments.

Evaluation of the Linear Adjustment Mechanism

The first series of experiments was conducted with the target plate removed from the assembly, which allowed the characteristics of the toggle mechanisms to be checked independently. This was accomplished by cementing small targets to the buttons of the mechanisms and using proximity transducers to measure the displacements resulting from known rotations of the adjustment screws. Since this measurement system is noncontacting, the performance of the toggle assemblies was unaffected by the measurement method. The instrumentation used for this work, the Hitec Proximic type, was calibrated so that 1 μm (39.4 μin) was equivalent to 39.4 mV. Typical results obtained for two revolutions of the adjustment screw are shown in table I and figure 7. As indicated, the experiments were conducted five times to determine the repeatability of the data.

Evaluation of Angular Adjustment Mechanism

The approach adopted in evaluating the mechanism's capabilities for making precise angular adjustments was to mount an optically flat mirror on the target plate and to use an autocollimator to measure angular changes. The procedure followed was to cover two revolutions of screw adjustment in five division increments and to record the corresponding angular changes.

The autocollimator allowed angular measurements to be made down to 0.1 sec or 3.0×10^{-4} degrees. The results obtained for angular rotations about the X-X axis are shown in table II and figure 8(a). Similar data obtained for rotations about the Y-Y axis are shown in figure 8(b). As in the earlier experiments, five repeat runs were made to gain some insight regarding the repeatability of the data.

A final series of experiments was conducted to determine the angular changes resulting from coarse adjustments over a 0.25-mm range in 0.05-mm steps. As the range of the autocollimator was limited, the procedure followed was to reset the instrument to zero after measuring the angular changes resulting from each 0.05-mm adjustment. Measurements of this type were made for adjustments about both the X-X and Y-Y axes.

DISCUSSION

Consideration is given first to the performance of the linear adjustment mechanism. Table I shows that one complete revolution of the adjustment screw caused the button to displace 9.04 μm (356 μin). By way of comparison, a similar displacement would be obtained by rotating a screw with 3000 TPI through one revolution. Using the various scales provided for fine adjustment, one division of adjustment gave a displacement of 0.29 μm (11.5 μin). In light of this result, the resolution of the toggle mechanism was judged to be about two orders of magnitude better than that of micrometers utilizing 40 TPI screw threads. Another characteristic of the data shown in table I is that the displacements resulting from particular screw settings are repeatable. A detailed analysis showed that the displacements obtained in the five repeat runs fell within ±1 percent of the mean.

The relationship between button displacement and screw setting is illustrated in figure 7. This relationship is nearly linear up to settings of about 40 divisions. At higher values, the relationship becomes progressively more nonlinear. A series of curve fits shows that a second-order polynomial could be used to represent the data over the full range of interest. The rms error for the expression subsequently obtained by least squares is 0.61 (fig. 8).

The performance of the mechanism in making fine angular adjustments was similar to that just described. As indicated in table II, one revolution of the appropriate fine adjustment screw caused the target plate to rotate 21.38×10^{-3} degrees about the X-X axis. The corresponding rotation for one division of screw adjustment is 6.9×10^{-4} degrees. In the case of adjustments about the Y-Y axis, these values are 25.11×10^{-3} and 8.1×10^{-4} degrees, respectively. Again, the data were repeatable, the maximum and minimum percentage deviations falling, for the most part, within ±1 percent of the mean.

Figures 8(a) and (b) illustrate the performance of the mechanism over the full range of interest. The relationships between screw settings and angular rotation are approximately linear up to settings of 40 divisions and nonlinear at higher values. Second-order polynomials were used to fit the data with the result shown in the figures. The rms error for the X-X adjustments was 0.29 while that for the Y-Y adjustments was 0.84. The latter, less than desirable result was caused by systematic errors occurring at particular adjustment screw settings. The source of these errors is unknown at the time of this writing.

The performance of the mechanism in making coarse angular adjustments was similar for both the X-X and the Y-Y axes, the angular change produced by two divisions of coarse setting falling in the range of 133.61×10^{-3} to 156.28×10^{-3} degrees. The average value for all settings was 141.91×10^{-3} degrees, and the deviations of repeat data fell, for the most part, within ± 3 percent of the mean. Thus, the fine and coarse adjustment ranges are complementary provided the target plate is roughed into position within 0.5 coarse setting divisions or 35.0×10^{-3} degrees.

The intent of this work was to develop a compact mechanism providing angular adjustment about two axes with a 10^{-3} degree resolution. The results described showed that the subject mechanism met these design requirements, at least under ideal bench checkout conditions. However, attempting to use this device to minimize crosstalk in multiaxial experiments proved unsuccessful. This was because any form of in situ adjustment caused the relative position of the sensors to change in an uncontrolled manner. It was concluded, however, that the problem lay with the method of extensometer suspension rather than with the subject mechanism. Thus, this approach was discontinued in favor of one ensuring a more positive location of the target relative to the proximity transducer.

However, because the mechanism performed well in its own right, some consideration was given to design improvements and alternative applications. One obvious shortcoming of the device in the form described is that its output was nonlinear. This problem could be overcome without much difficulty by using a predetermined profile on the adjustment screw rather than a straight taper. Also, the resolution of the device could be improved by using a finer thread on the adjustment screw.

An alternative application might be to use the device in its present form for ultrafine adjustments in setting up microscopes or optical systems. An important advantage of the toggle mechanism is that in principle it can be used independent of screw threads. This situation could be achieved by using a linear actuator to drive the tapered pin against the flexures. Thus, the problems usually associated with screw threads would be eliminated, and extreme precision could be achieved. Also, elimination of screw threads might allow the device to be used to advantage for precise linear and angular adjustment in hostile environments.

CONCLUSIONS

The following are the conclusions reached regarding the design, manufacture, and performance of the flexure-based adjustment mechanism:

1. The toggle principle was used to provide linear adjustments with better than 1-μm resolution. The advantages of the approach were viewed as being mechanical simplicity and low weight.

2. The flexure-based mechanism was fabricated successfully from inexpensive and easily manufactured parts. However, the assembly of the device was not straightforward.

3. Linear adjustment mechanisms were used in conjunction with a simple arrangement of flexural pivots to give a two-axis angular adjustment with better than a 10^{-3} degree resolution. The resulting mechanism was both mechanically simple and compact.

4. Attempts to use the mechanism to resolve alignment problems associated with biaxial strain measurement proved unsuccessful. However, the difficulty lay with the extensometer design rather than with the subject mechanism.

5. The toggle mechanism can be made to operate independently of screw threads. This raises the possibility that mechanisms of this type could be used to advantage for precise linear or angular adjustment in space environment.

REFERENCES

1. Brown, M.W.: Low Cycle Fatigue Testing Under Multiaxial Stresses at Elevated Temperatures. Measurement of High Temperautre Mechanical Properties of Materials, M.S. Loveday, M.F. Day, and B.F. Dyson, eds., H.M.S.O., London, 1982, pp. 185-203.

2. Ellis, J.R.: A Multiaxial Extensometer for Measuring Axial, Torsional, and Diametral Strains at Elevated Temperatures. Oak Ridge National Laboratory Report, ORNL/TM-8760, June 1983.

3. King, H.M.; and Weir, J.B.: Adjusting Device Incorporating an Ultrafine Movement. J. Sci. Instrum., vol. 39, no. 1, Jan. 1962, p. 31.

4. Troeger, H.: Considerations in the Application of Flexural Pivots. Automatic Control, vol. 17, no. 4, Nov. 1962, pp. 41-46.

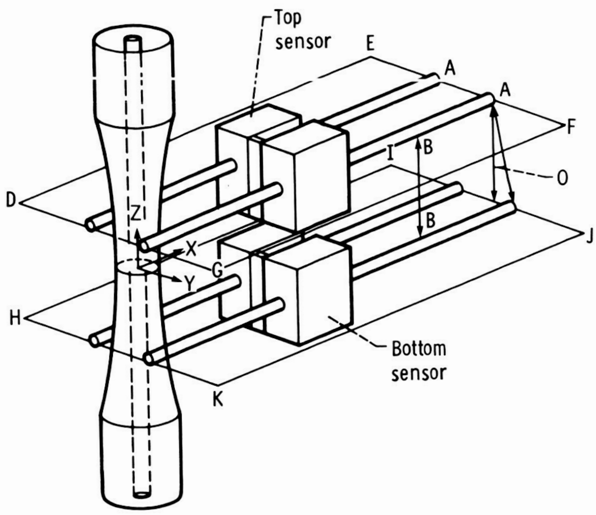
TABLE I. - EVALUATION OF LINEAR ADJUSTMENT MECHANISM

[1 revolution of the adjustment screw corresponds to a setting of 31 divisions; 1 μm = 39.4 μin, equivalent to 39.4 mV.]

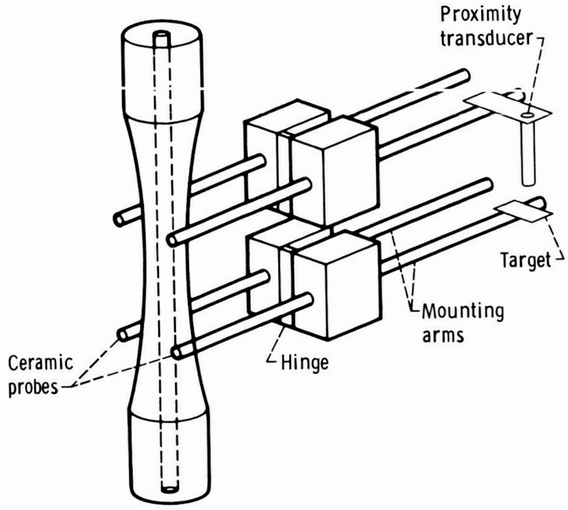
Screw setting, divisions	Button displacement									
	Run 1		Run 2		Run 3		Run 4		Run 5	
	μm	μin	μm	μin	μm	μin	μm	μin	μm	μin
0	0	0	0	0	0	0	0	0	0	0
6	1.80	71	1.91	75	2.21	87	2.13	84	2.16	85
11	3.28	129	3.38	133	3.63	143	3.51	138	3.51	138
16	4.72	186	4.83	190	5.11	201	5.03	198	5.05	199
21	6.12	241	6.10	240	6.30	248	6.20	244	6.25	246
26	7.44	293	7.49	295	7.57	298	7.62	300	7.65	301
31	8.94	352	9.02	335	9.09	358	9.07	357	9.07	357
37	10.77	424	10.95	431	10.87	428	10.85	427	10.80	425
42	12.14	478	12.32	485	12.27	483	12.17	479	12.09	476
47	13.31	524	13.51	532	13.46	530	13.28	523	13.26	522
52	14.43	568	14.58	574	14.45	569	14.40	567	14.30	563
57	15.47	609	15.67	617	15.49	610	15.54	612	15.37	605
62	16.76	660	16.89	665	16.69	657	16.69	657	16.61	654

TABLE II. - EVALUATION OF MECHANISM FOR FINE ADJUSTMENT ABOUT THE X-X AXIS

Fine screw setting, divisions	Rotation about X-X axis									
	Run 1		Run 2		Run 3		Run 4		Run 5	
	min:sec	deg	min:sec	deg	min:sec	deg	min:sec	deg	min:sec	deg
0	0	0	0	0	0	0	0	0	0	0
6	0:15.4	4.28×10^{-3}	0:15.6	4.33×10^{-3}	0:15.6	4.33×10^{-3}	0:15.9	4.42×10^{-3}	0:15.8	4.39×10^{-3}
11	0:28.8	8.00	0:28.6	7.94	0:28.5	7.92	0:28.8	8.00	0:28.7	7.97
16	0:40.8	11.33	0:40.5	11.25	0:40.6	11.28	0:40.7	11.31	0:40.8	11.33
21	0:51.7	14.36	0:52.2	14.50	0:52.0	14.44	0:52.5	14.58	0:52.5	14.58
26	1:4.0	17.78	1:4.4	17.89	1:5.2	18.11	1:5.5	18.19	1:4.7	17.97
31	1:16.7	21.31	1:16.8	21.33	1:17.1	21.42	1:17.2	21.44	1:17.0	21.39
37	1:29.7	24.92	1:29.9	24.97	1:29.5	24.86	1:29.9	24.97	1:30.0	25.00
42	1:40.4	27.89	1:40.0	27.78	1:39.6	27.67	1:40.0	27.78	1:39.9	27.75
47	1:49.8	30.50	1:49.8	30.50	1:50.0	30.56	1:50.3	30.64	1:50.0	30.56
52	1:58.6	32.94	1:59.3	33.14	1:58.8	33.00	1:59.4	33.17	1:59.3	33.14
57	2:9.2	35.89	2:9.3	35.92	2:8.2	35.61	2:9.6	36.00	2:9.4	35.94
62	2:18.2	38.39	2:18.4	38.44	2:18.1	38.36	2:18.5	38.47	2:18.3	38.42

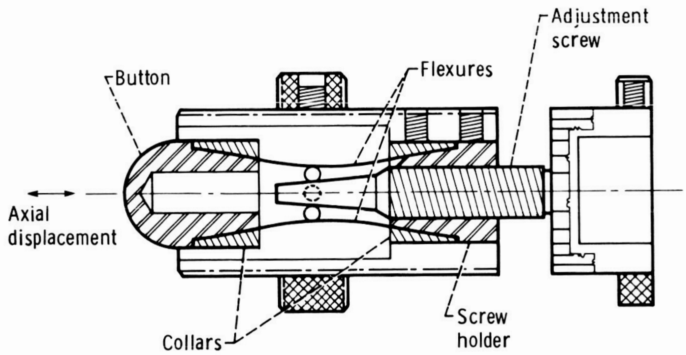


(a) Basic approach.

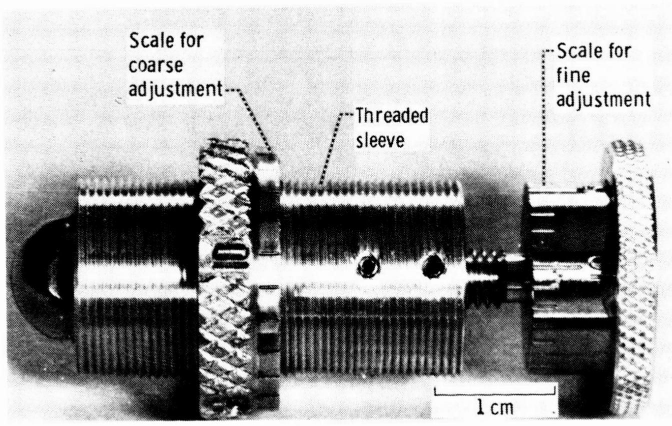


(b) Method of axial strain measurement.

Figure 1. - Multiaxial extensometer for measuring axial, torsional, and diametral strains at elevated temperatures.



(a) Sectional view.



(b) Sleeve details.

Figure 2. - Linear adjustment mechanism.

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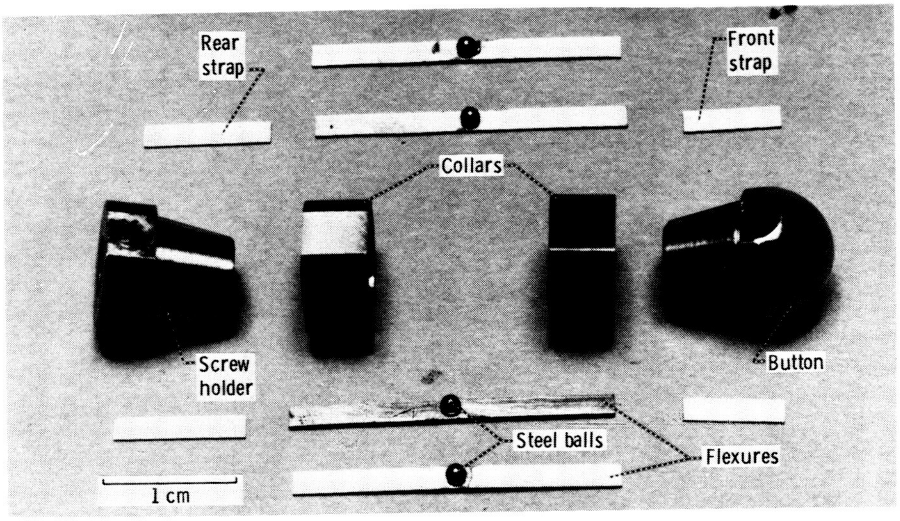

Figure 3. - Parts of toggle mechanism.

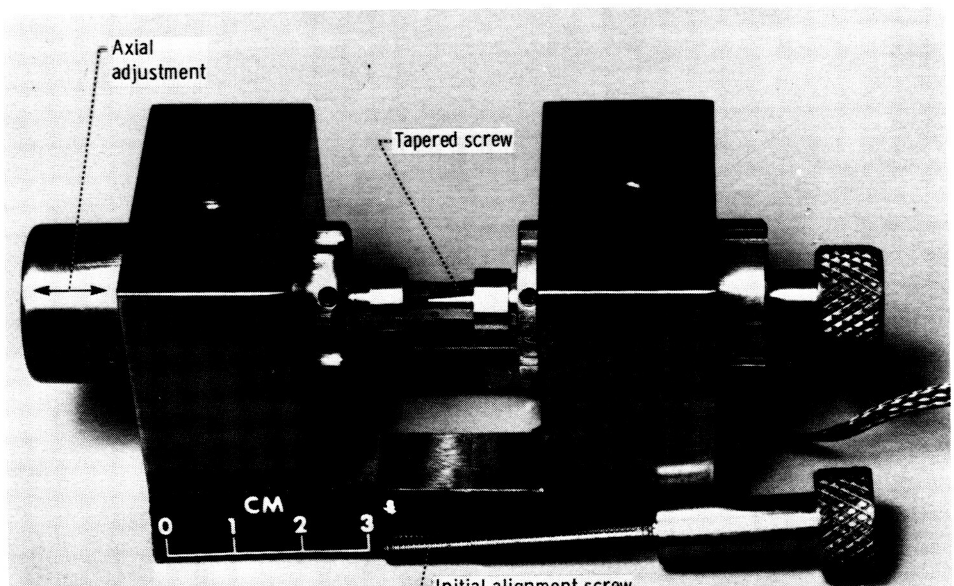

Figure 4. - Fixture used to assemble toggle mechanism.

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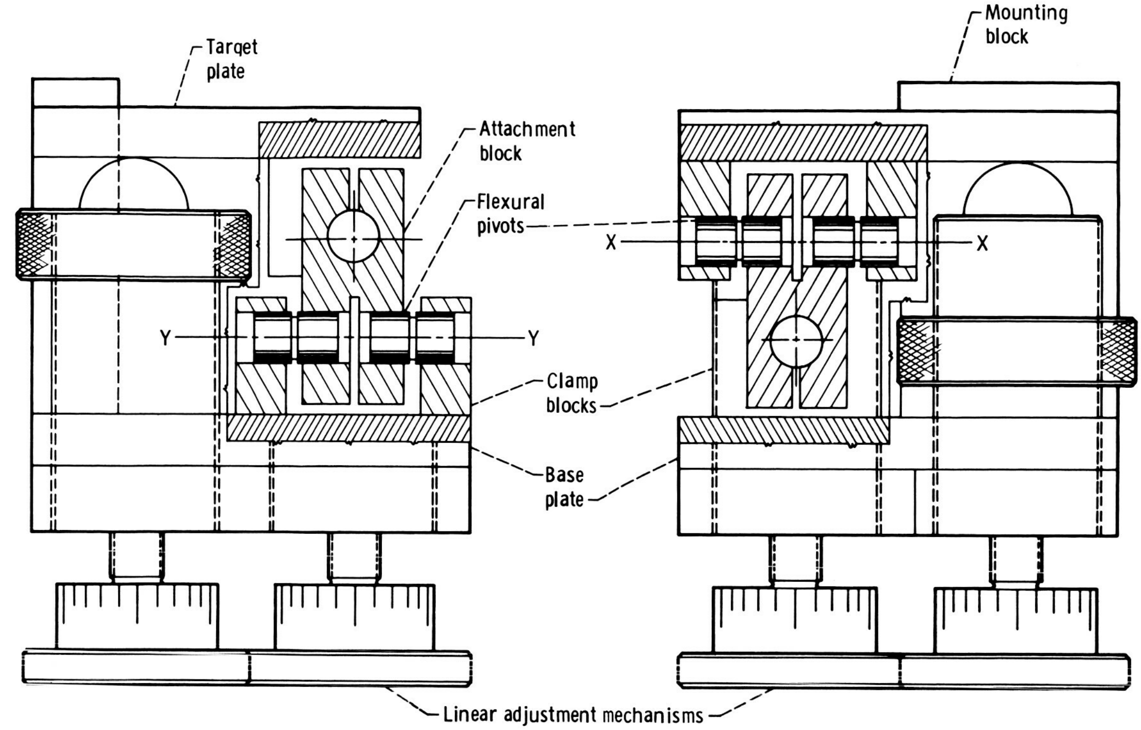
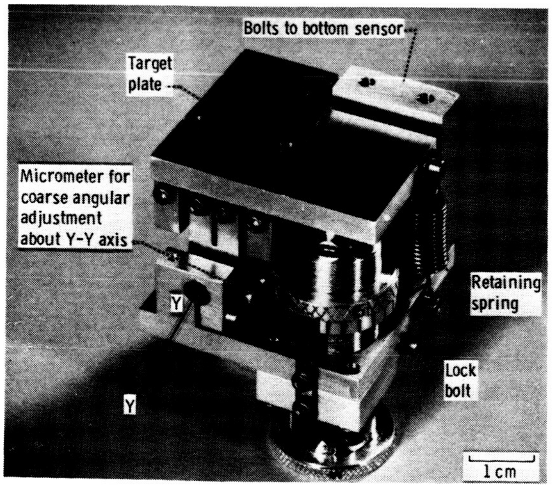
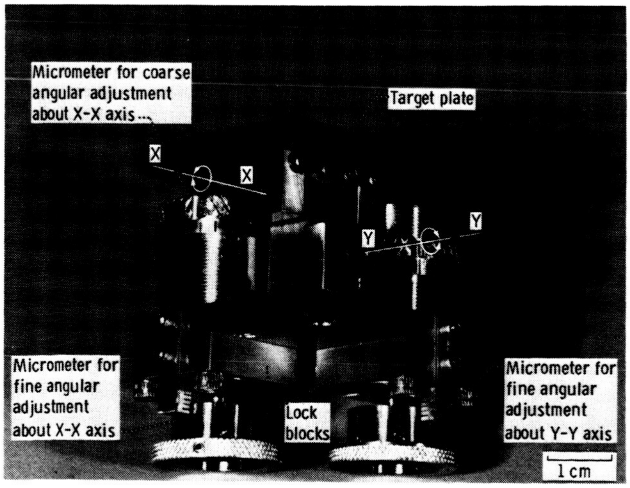


Figure 5. - Schematic of angular adjustment mechanisms.



(a) Viewed from above.



(b) Viewed from below.

Figure 6. - Angular adjustment mechanism.

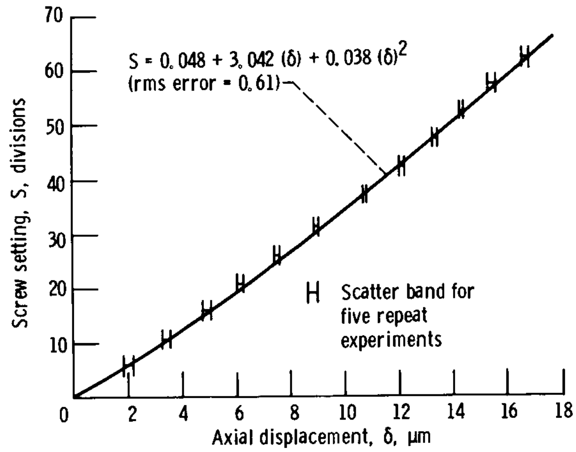


Figure 7. - Evaluation of linear adjustment mechanism.

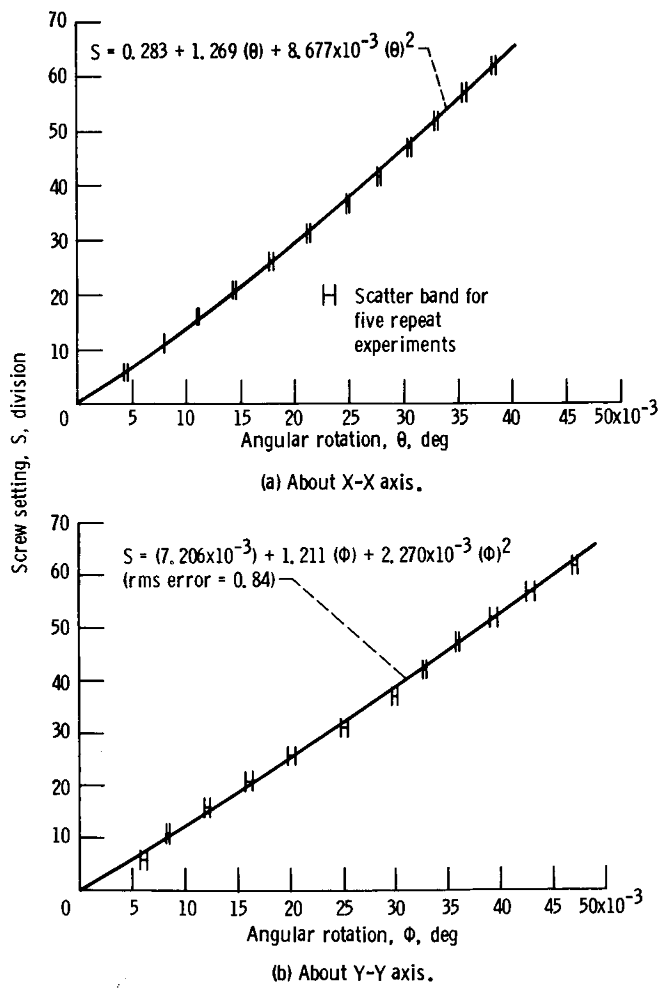


Figure 8. - Evaluation of angular adjustment mechanism for fine adjustments.