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Theodolite Axis Systems—Their Design, Manufacture, and Precision

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THE AXES are among the most important structural elements of an angle-measuring instrument. Their function is to support the movable parts of the instrument and keep their motion in the desired path. A distinction must be made between the vertical and the horizontal axes of a theodolite. Their precision is determined directly by the precision demanded of the instrument itself.

The production of very precise axes is a continuing concern of designers and workshops alike. Their design depends largely upon the manufacturing methods used and upon the possibilities for checking and control. This will be discussed herein.

VERTICAL AXES

The vertical axis connects the instrument base with the rotating, upper part, or alidade, thereby supporting the alidade and permitting it to rotate about the vertical.

Until a few decades ago, the conical, vertical axis was used almost exclusively. Even today it is far from being extinct. Its wide use was due to the fact that it can be produced with relative ease, using simple handicraft methods. This is the reason why on older theodolites not only the vertical axis, but practically all the seats of circle centers, micrometer arms, etc., were conical in shape.

A taper fit can be produced on any good lathe without special measuring tools, because, in the course of production, the bushing of the pivot or the pivot can be made to conform. If, for example, the bushing is completed first, the pivot can be produced to the desired taper and adjusted to the bushing before the pivot reaches its final dimensions. When the tapers agree, the amount of the overlap of bushing and pivot provides a clue to determine the amount by which the diameter is still too large. Thus a continued control is possible, without the need for any measuring tools. Finally, by lapping, the fit can be further improved. If the grinding is excessive, the situation can be corrected by re-turning the face (Figure 1).

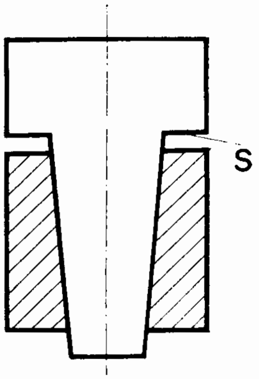

FIGURE 1.

None of this applies for a cylindrical fit. By means of precise machines and measuring tools, bushing and pivot must be shaped to exact cylindrical form. Also the diameter

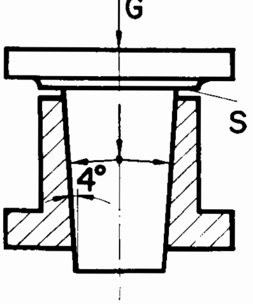

FIGURE 2.

Original appeared in "Vermessungstechnische Rundschau," No. 4/1959. Re-publication authorized by Hanseatische Verlagsanstalt G.m.b.H., Hamburg, Germany.

must be accurately measured, because the fit can only be tested when one part can be slid into the other. If the fit is loose, nothing can be done about it.

This may be the reason why the conical fit and, in particular, the conical, vertical axes were used so widely in spite of serious disadvantages which went along with the bargain (Figure 2).

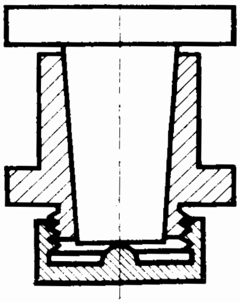

FIGURE 3.

If the weight *G* of the turning, upper part be transmitted directly through the pivot, a considerable contact pressure results. In the case of a 4° cone, the pressure is fourteen times *G*, and there is a correspondingly large, friction force. This friction cannot be permitted because the axis will not move smoothly and will sooner or later corrode. Consequently, the pivot must be so fitted that the face *S* carries most of the weight *G*. The pivot then carries only a small portion of the weight, enough to provide the desired stability for the guidance of the alidade. This is manifestly the weak point of the conical axis. If the pivot carries too little weight, the axis wobbles; if too much, the axis "binds". To overcome this difficulty, all precise and heavy instruments were provided with a means of unloading the axis from below. Moreover, the means was made adjustable so that the operation of the axis could always be regulated (Figure 3).

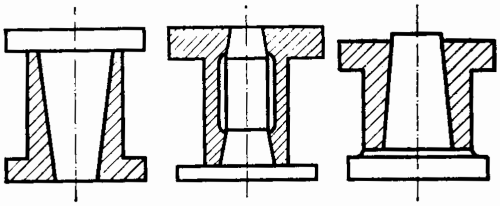

FIGURE 4.

But, even this looks simpler in theory than it is in practice, because the degree of roundness of pivot and bushing, the material used, the surface finish, the cleanness of the surfaces, and the lubricant also play a part.

Dr. Wild[1] describes the difficulties encountered, especially when a repetition instrument is involved on which two conical fits require adjustment:

"At the beginning of the century, I did the triangulation of the Unterwallis with such an instrument. On September 1, 1902, in wonderful weather, I was on the summit of the Dent du Midi (10,700 ft.). I had arrived early and hoped to dispose of the measurement by noon. Instead, I spent two or three hours 'regulating' the instrument, and when it was finally ready there came the first signs of an approaching thunderstorm. In the afternoon we cached the instrument in a protected place on the summit, covering it carefully with flat stones. Then we made a hasty descent. (Today probably no one would leave his light instrument on a peak.) Since a large amount of snow fell, it was not possible to continue the work for several days."

But, even with optimum adjustment, the axis floats on an oil film which causes an uncontrollable, wavering motion when the alidade is rotated.

The particular design of a conical axis is immaterial, since it is influenced by other factors. The following designs of conical axes are essentially the ones usually encountered (Figure 4).

The unpleasant experience mentioned above led H. Wild to look for a new form of axis, that would not require adjustment, when, in 1908, he began work on new designs for geodetic instruments for Zeiss at Jena. The cylindical axis was the result, first for leveling instruments and later for theodolites. Prerequisites for the success of this type of axis were good, distortion-free,

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[1] "The Recent Evolution of some Geodetic Instruments" in "Vermessung-Grundbuch-Karte", publication on occasion of the Swiss National Exposition, 1939.

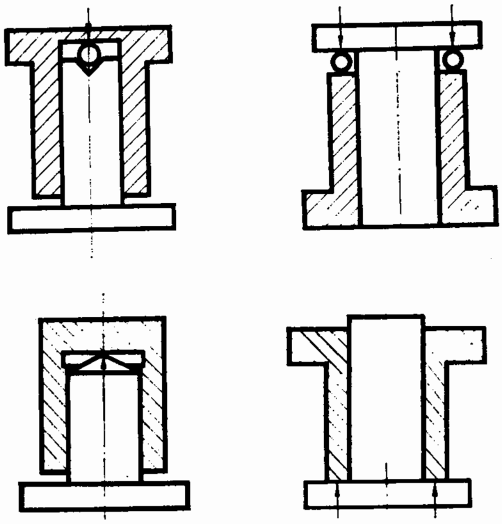

FIGURE 5.

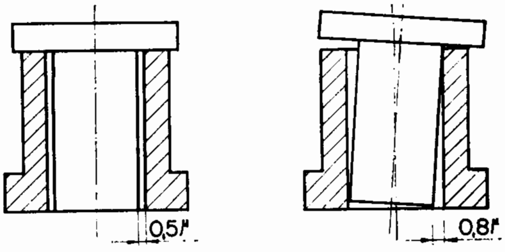

FIGURE 6.

temperable steel and good grinding machines.

With the cylindrical axis, the entire weight of the alidade is supported directly by a face of the bushing, by the pivot end, or by a ball bearing. Figure 5 shows some design forms.

Inasmuch as the alidade is counterbalanced with respect to the vertical axis and the axis itself is vertical, the cylinder generally carries no load. It only has to provide guidance for the alidade. Experience has demonstrated that such an axis, without maintenance, can function satisfactorily for years. Moreover, such an axis does not require any adjustment prior to measuring. The cylindrical axis is, therefore, superior to the old conical axis in regard to mass production and maintenance. With regard to the precision of guidance, however, the conditions are as unfavorable as for the conical axis.

Accuracy of guidance is determined first of all by the cross-section of pivot and bushing. Both regularly depart but little from the desired circle. Although it is disadvantageous to the guidance, it is necessary that an oil film of a certain thickness always exist between pivot and bushing to provide the free motion that is required for accurate pointing of the line of sight. Thus, the cylindrical axis also floats on an oil film and does not occupy a fixed position. The thickness of the oil film must be assumed to be about 0.5 μ, so that in the worst case, each pivot end is unstable by about ± 0.5 μ (Figure 6).

Actually the variations are not this large, since the oil film is not compressed to zero. However, combined with defects of bushing and pivot, the resultant deviations may be between ± 0.3 and 0.4 μ.

For an axis 100 mm. long, the resultant angular deviation varies from ± 1.2″ to 1.6″. Increasing the length of the axis, to the extent that this is feasible, does not reduce the angular deviation materially, because the longer axis must have a larger diameter and this, in turn, due to the larger contact surface, requires a thicker oil film. H. Wild states, in the reference quoted above, that the deviation of a cylindical axis cannot be reduced below three seconds.

The desire to increase the rotational stability of the vertical axis resulted in the design by Wild of a completely new axis system for Kern DK theodolites (Figure 7).

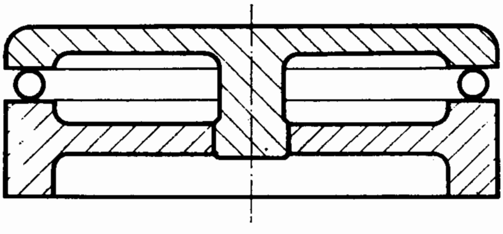

FIGURE 7.

The principal elements of this axis are two flanges of relatively large diameter, each with a precise plane surface. These flanges, together with a number of accurately-sized balls, form a ball bearing. This ball bearing supports the entire upper part of the instrument and simultaneously provides guidance in a plane.

For centering, only a short center pin of relatively small diameter is required. This pin produces very little friction and it need not be very precisely made, since circle readings are taken on diametrically opposed points of the circle. Moreover, this form of axis provides a low, stable, instrument base.

The rotational stability of this axis is dependent upon the two plane surfaces and the balls. The balls alone produce no significant inaccuracy. They differ in diameter by no more than ± 0.2 μ. So far as the axis is concerned, the resultant deviation is much smaller, since numerous balls are carrying the load at all times. The Kern DKM3 triangulation theodolite, which has such an axis, uses sixty 4 mm. balls. Each ball carries about 150 g. (A ball can be loaded to 10 kg. without damage). This small loading of 0.15 kg. results, according to Hertz, in a decrease of the distance between the two plane surfaces, due to flattening of the balls and elastic indentation of the surfaces, of about 0.7 μ (Figure 8), a distance which is substantially more than the variation in the diameters of the balls. Thus, all balls are effective in carrying the weight of the alidade. Moreover, in all probability, there is a random distribution of larger and smaller balls around the periphery, so that the variation of the direction of the axis due to the variation in the diameter of the balls is actually not measurable. Therefore, the planeness of the bearing surfaces alone is the determining factor of the quality of the axis. These surfaces can, without undue effort, be ground to within 0.2 μ of an exact plane, using methods customarily utilized in optical work to produce plane surfaces. Moreover, the fact that these surfaces can be tested very simply with an optical flat, is of great importance. This testing makes it readily possible to bring the surfaces to the desired precision by repolishing.

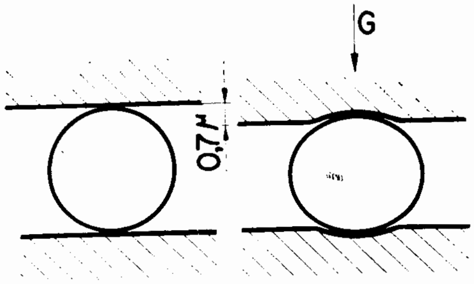

FIGURE 8.

A surface variation of 0.2 μ in each bearing surface would result, for a ball race 124 mm. in diameter, in an axis variation of at most ± 0.35″, depending upon the shape of the surface errors.

The production of an axis system of this type with a variation not larger than ± 0.5″ is, therefore, possible with relative ease. To be sure, this type of construction results in other difficulties. First, the rings with the bearing surfaces must be joined very solidly with the instrument base and the alidade, respectively. To produce this connection without deforming the rings requires the utmost care of both designer and mechanic. The second difficulty is caused by deflection. For a plane, deformation-free assembly of ring and bearing surface, the ring must be supported at three points. Therefore, a ring segment of 120° supported at its ends only is subject to elastic deflection caused by the weight of the alidade. The elastic deflection curve of the loaded ring is a sine curve. As such, rotation of the alidade would produce no variation in the direction of the axis, but only limited vertical motions. However, should the form of only one of the two rings deviate from the normal sine curve, and such deviation can easily result from improper fastening, the direction of the axis would have a variation with a period of 120°. It is self-evident that these deformations are dependent upon the structural strength, i.e., primarily the cross-sectional shape of the rings.

The following results were obtained experimentally:

Figure 9 shows two measurements of a test axis for the DKM2 theodolite. The ball race employed was deliberately taken just as it came from the grinding machine with only a short repolishing. In this condition, the maximum variation in the axis was ± 1.2″ (lower curve). Afterwards, the

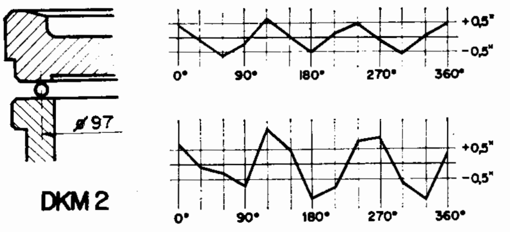

FIGURE 9.

ball races were more carefully polished and the maximum variation was reduced to ± 0.65″ (upper curve).

Figure 10 shows the curves of axis variation of four DKM3 triangulation theodolites taken from current production.

The design of both axis systems is such that it is possible to use the test glass on the surface of the ball race in its built-in state and to repolish this surface if necessary.

In part, the curves show the period of 120° very distinctly. They represent the mean of two successive measurements made with a level having a sensitivity of 2 seconds.

It is evident from the measurements, and confirmed by tests, that a greater increase in precision is possible by improving the ring cross-section, especially the depth. It is sufficient to strengthen only one ring, because on an absolutely flat supporting ring, even an inaccurate upper ring will run without variation if the balls are placed at very short intervals.

The ball-bearing axis in the described form satisfies all demands placed on the vertical axes of triangulation theodolites. With a reasonable increase of dimensions and weight, the limit of ± 0.5″ can be further reduced considerably. Moreover, the guidance is dependent upon the form of the bearing surfaces and the elastic deflection can be determined unmistakably. The effect of the deflection is repeated regularly with each turn so axis variation can be measured exactly and taken into consideration.

Nitriding steel used for these ball rings has passed every test excellently. Damage to the ball race results only occasionally from severe falls.

In special cases where a non-magnetic instrument is required, the nitralloy steel is

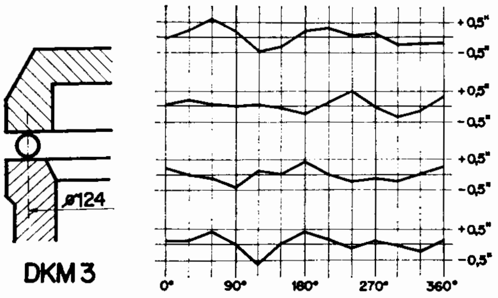

FIGURE 10.

replaced with beryllium bronze. When bronze is used, a hard chrome layer at least 0.15 mm. thick forms the surface of the ball race.

HORIZONTAL AXES

Horizontal axes have changed very little in several decades. The aim of designers has always been to equip the horizontal axes with two cylindrical bearing surfaces with as small a diameter as possible and as far apart as possible. Both trunnions should have the same diameter. This is plainly seen in the old dismountable instruments. These instruments have so-called Y-bearings throughout, in which the position of the axis is well defined by the four points of support.

The responsibility of the manufacturer remains unchanged: to produce trunnions which have an exact circular form or as close thereto as possible. With modern instruments the problem is aggravated because the optical reading system requires an optical path through the axis and, consequently, a larger axis diameter. However, improved grinding machines now available permit the manufacture of axis trunnions without difficulty, except those for special astronomical instruments.

The oil film of the horizontal axis, unlike that of the vertical axis, produces little variation because it is subjected to an always constant pressure. With heavy telescopes, it is necessary to carry a part of the weight on relief bearings if the required ease of motion is to be retained.

The horizontal axis is adjustable on instruments of older design, so that the observer can adjust the tilt of the axis every time he uses the instrument (Figure 11).

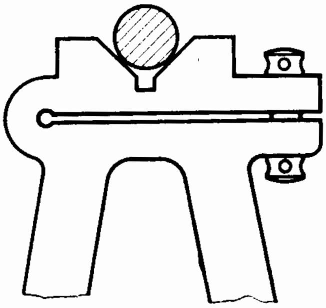

FIGURE 11.

In contrast to this, one of the most important objectives of H. Wild in his new instrument designs was to make the instruments so stable that the relative relationship of the axes would not vary over long periods of time and, therefore, the instrument would always be ready for use.

Hence, no provision for adjusting the horizontal axis is found on modern theodolites. The connection between vertical and horizontal axis is, therefore, much more solid and, consequently, the relationship between the axes is more stable. In order to provide as stable a bearing as possible for the horizontal axis, the Y-bearing is also used on the DKM3, in a slightly modified form, so as to provide a definite, fixed position of the axis (Figure 12).

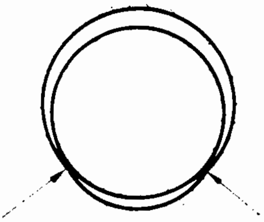

FIGURE 12.

The striding level is used in connection with the horizontal axis. Its employment had meaning so long as the connection between the vertical axis and the trunnion bearings, the so-called standards, were built very lightly, and the trunnion axis was reversible. With the modern, solidly built instruments, it is inconceivable that a spindly-legged, loosely installed striding level can indicate the tilt of the horizontal axis more reliably than a level which is firmly and permanently installed in the alidade. Unfortunately, not all users are convinced of this. Striding levels are still demanded and instruments must be designed to permit their use.

In conclusion, the following production tolerances of the DKM3 are given (Figure 13):

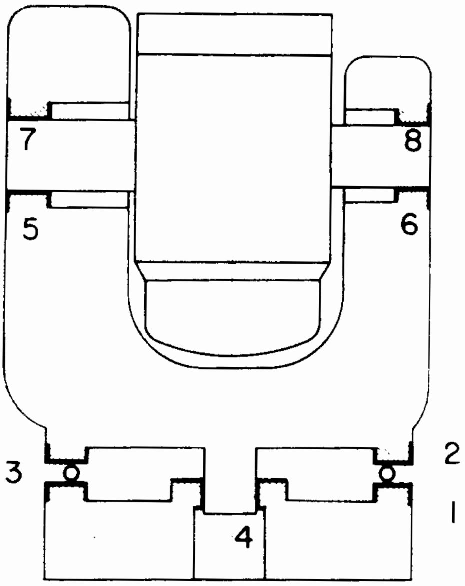

FIGURE 13.

Planeness of the ball race surfaces 1 and 2: within 1 fringe color ~ 0.1 μ
Variation of ball diameter 3: ± 0.1 μ
Play between centering pin and bushing 4 (not lubricated): ~ 0.5 μ
Parallelism between surface 2 and horizontal axis bearings 5 and 6: ± 3″
Variation from true roundness of horizontal axis 7 and 8: max. 0.2 μ

The following may also be of interest on this subject:

A large, circle-dividing machine of Heyde's, which is 50 years old, is still in use at our factory. Its axis corresponds to that of an old theodolite, except that the dimensions are larger—the diameter is 80 mm. and the length 500 mm. (Figure 14). It has a very fine, adjustable, load-relief mechanism. The action of the axis is tested daily and the consequent adjustment is almost a game of chance.

Placed right near the old machine is a dividing engine of our own design. It is equipped with a horizontal axis which is supported by two, bronze Y-bearings and has a load-relief mechanism as sketched in Figure 15. The axis requires practically no attention and no looseness can be detected.

This illustrates the difference between the unstable state in which the conical vertical axis floats, and the stable seating of the horizontal axis which exerts an unvarying pressure on the trunnion bearings.

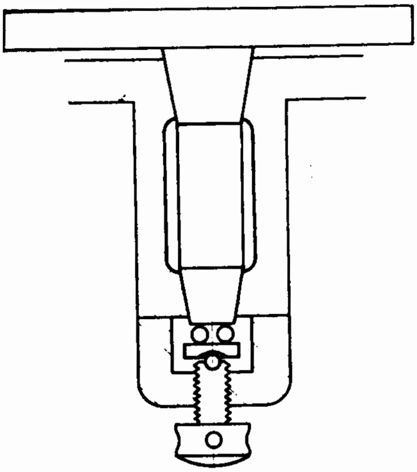

FIGURE 14.

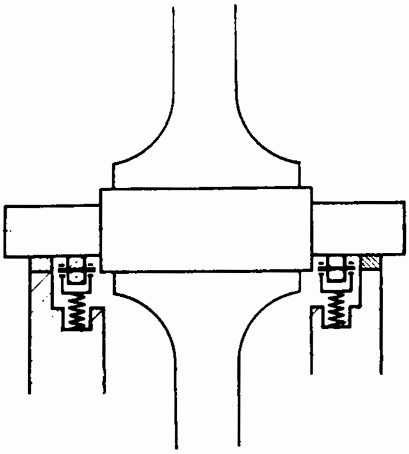

FIGURE 15.