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Cylinders in Vs

An optomechanical methodology

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Abstract
The mounting of rotationally symmetric optical elements in cylinders, which are then located in a V-shaped trough, is often a convenient optomechanical approach. This is a near ideal geometry, since lens alignment normal to the axis is typically most critical, axial position is less so, and azimuth is irrelevant The mechanical constraints correspond to the optical requirements, so the arrangement is as simple as possible and no simpler. Location is kinematic or semi-kinematic, and hence repeatable, allowing for quick, accurate swapping between setups, with critical adjustments made once. Axial position can be without influencing lateral position and tilt. Likewise, rotation alone can be done. Self checking alignment methods can be used. The approach is compatible with other means of mounting. Practical considerations of this surprisingly flexible approach are discussed, including various ways to make Vs; methods of testing Vs; errors in cylindricity and the testing of cylinders; methods of centering optics in cylinders; the systematic establishment of masters and working fixtures; the measurement and control of axial separations; clamping; lens systems

Key Words
optomechanics, cylinder, V, lens mounting, kinematic location

Preface
The methodology discussed here is not new or difficult, but it is underutilized. This paper is both a testimonial for this approach and a compendium of many of the considerations encountered in exercising it. Our own experience began with a general belief in modularity and a specific requirement for field replaceable—hence interchangeable—units for a particular product. As we exercised this method, it spread easily through our fixturing and then into other projects, and we increasingly recognized and appreciated its simplicity and flexibility. Finally, it became to us a system with a wide range of applications.

There are many embodiments of the cylinder-in-V methodology, with variations in size, materials, accuracy, and so forth. This paper discusses many of the factors that go into selecting an appropriate embodiment, and provides some particular ideas for solutions. Some of these comments apply only to very high accuracy work.

Laboratory apparatus for mounting optics used to be dominated by the optical bench With the development of holography, non-rotationally symmetric arrangements came into common use, particularly in research, and breadboard tables largely displaced optical benches. But rotationally symmetric applications remain, and it is now common to find people struggling to align such systems on a table, using expensive apparatus with too many degrees of freedom for the task Such alignment efforts can be painful and time consuming, and the result can be inferior to what can be obtained with appropriate hardware, which can also be less expensive.

Since a general system is described here, some standard terminology is useful. Italics are used when terms are defined or first used.

Standard mechanical measurement and testing methods are alluded to here, and a general bibliography of mechanical metrology and standards is provided

The basic idea

For rotationally symmetric optics, the critical adjustments for positioning elements are displacements orthogonal to the axis and tilts orthogonal to the axis, Fig.1. Rotation about the axis is irrelevant, but it is useful as a check of correct mounting. Axial position is less critical than lateral position. Adjustable axial position is sometimes required, for instance to change magnification, image position, or beam properties. In cases where it is eventually fixed, axial position is sometimes fine tuned after fabricating the elements to compensate for deviations of lens geometry from the nominal or to allow freedom from too tightly specifying focal lengths or other parameters.

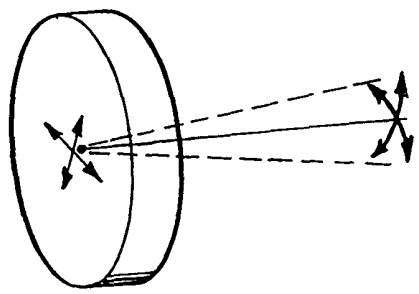

Fig.1 Critical degrees of freedom of rotationally symmetric optical elements

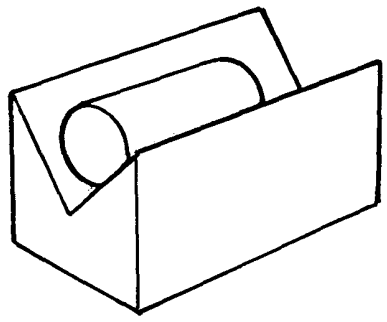

Fig.2 Basic cylinder in V

In the cylinder-in-V system, rotationally symmetric optical elements are mounted in rotationally symmetric mechanical objects of identical diameters, referred to here as cylinders, with the optical element axes collinear with the cylinder axes. The cylinders are constrained on two parallel lines by a structure, typically a trough, referred to here as a V, Fig.2. The mechanical constraints of a cylinder in a V match the optical requirements. The four critical degrees of freedom are constrained, rotation about the axis is permitted, and motion along the axis is permitted.

General cylinders and general Vs

For the mounting of optics, a variety of shapes has the properties of the basic cylinder in the basic V of Fig.2. Some of this paper applies to all such shapes, and some to particular embodiments, so terminology is needed for the distinctions. It is difficult to devise general and concise mathematical definitions of the cylinder and V, since the basic concept is so intuitive and since there are so many possible embodiments—many with limited practical interest. The key is straightness and tangential contact to certain round shapes. A cylinder constrained by a V has two degrees of freedom, rotation about its axis and translation along a straight line in the direction of its axis.

The term *simple cylinder* refers to a "plain cylinder," defined[1] as "the surface traced by one side of a rectangle rotated round the parallel side as axis." The term *general cylinder*, or simply *cylinder*, refers to any shape that behaves like a simple cylinder with respect to a V. This includes various barbell-like and bone-like shapes, Fig.12. The *diameter* of a general cylinder is that of a simple cylinder just enclosing it There is usually the implication that a cylinder contains, or will contain, a centered optical element.

The *planar V* is a trough defined by two non-parallel planes, a section of which makes the shape of a letter "V". The *general V*, for which simply *V* is usually used, refers to any shape that behaves with respect to a simple cylinder as a planar V does. Some possible definitions of the general V, all equivalent in the end, are (1) a shape with the property that the center of a sphere rolling in it describes a straight line; (2) a projection perpendicular to a plane of a figure in the plane that is tangent to a circle at two points not diametrically opposed; (3) a shape that contacts a simple cylinder tangentially on two parallel lines. (Interestingly, another[2] definition of a cylinder is "the surface traced by any straight line moving parallel to a fixed straight line and intersecting a fixed curve." According to this definition, what is called a V here is also cylinder.)

It is understood that the cylinder and V form a pair, since what is a V to a cylinder of one diameter may not be a V to a cylinder of other diameters, and likewise for cylinders.

The terms *ideal cylinder* and *ideal V* are used to discuss shapes that are free from real world imperfections, e.g. planar Vs with perfectly flat surfaces and exactly round cylinders.

The *straightness of a V* has to do with how the axis of an ideal cylinder sliding in the V changes position and direction. This property depends jointly on the V and on the way the cylinder contacts the V, including, the lengths and separations of the contact regions. An unambiguous descriptor of V straightness is given by the path made by the center of an ideal sphere of the same diameter as the cylinder as the sphere moves along the V.

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[1] *Webster New International Dictionary*, second edition (G.& C .Merriam, Springfield, MA, 1936)

[2] *Webster's Third New International Dictionary* (G.& C. Merriam, Springfield, MA, 1976)

THE V

Terminology and definitions

Fundamental geometric characteristics of the ideal general V are shown in Fig.3. The V contacts a cylinder tangentially on two parallel *contact lines*, around which are two regions, the *contact strips*. The *defining planes* are the planes tangent to the cylinder containing the contact lines. The *vertex* is the intersection of the two defining planes. The *V angle* is the angle between the lines intersected by a plane at right angles to both defining planes. The *bisector* is the plane that makes equal angles with the two defining planes. The *centerline* is the axis of an ideal cylinder of a specific diameter in the V. For a cylinder of diameter d and a V of angle θ, the distance from vertex to centerline is $(d / 2) / \sin (\theta / 2)$.

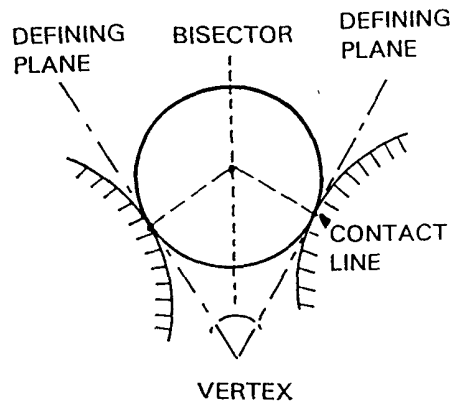

Fig.3 Geometrical definitions for the V

A variety of shapes functions as a V, for example, a pair of parallel cylinders, Fig.9, and a cylinder whose axis is parallel to a flat, Fig.10. Much of this discussion treats the planar V, because this form has unique features that are advantageous in practice. Its construction is simplified by the fact that any two planes define a planar V, so straightness of the V can be obtained regardless of the relative orientation of the two sides. In addition, the two planar strips can easily be independently tested for straightness along the contact lines.

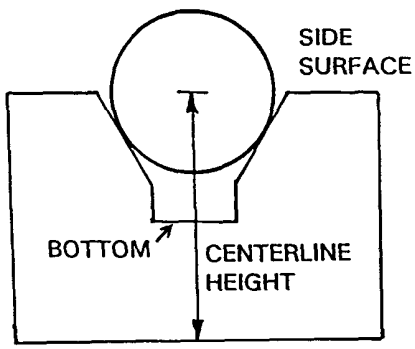

Fig.4 Typical structure of a planar V

The *structure* of the V refers to the complete physical embodiment, Fig.4. The structure need not provide large contact areas. All that is required for a given cylinder diameter is two thin regions, called *contact strips*. The arrangement can be at any overall orientation, but in the laboratory it is most often open at the top and the terminology uses this convention. The *bottom* of the V is a non-contacting portion. The *side surfaces* are the portions of the structure adjacent to the contact surfaces. The *centerline height* is the distance from the centerline to the *base*, the bottom of the structure. The structure also has *outer sides*, and *ends*. Other arrangements are possible and may be preferred for apparatus used out of the laboratory. For example, the V may be made as an L or as a U, with two of the sides used for alignment

The V angle

Planar 90° Vs are usually the easiest to make and are the most convenient in the laboratory They can be used with square objects, for example, square filters and square bars. Other 90° Vs are readily available for measurement and comparison. The centerline-to-vertex distance is $d/2^{1/2}$. The 60° planar V produces symmetrical forces on a cylinder clamped on the bisector, which may be advantageous for hardware used

outside of the laboratory. Hexagonal objects can be used in 60° Vs. The vertex-to-centerline distance equals the diameter of the cylinder. For non-laboratory systems, the angle of the V and clamping method are determined jointly to deal with the forces to be encountered. The smaller the angle, the greater the variation of vertex-to-centerline distances due to diameter variations. For 90° and 60° the ratio is 1 4.

An important practical matter is that the angle of the V is not critical for optical elements accurately centered in cylinders. The question of angle only arises at all if cylinders are imperfect and are to be interchanged between different Vs.

V Structure

Aside from the contact strips, the structure can be designed for convenience or to satisfy other requirements. In the laboratory, a convenient choice is that with planar side surfaces in a plane containing the centerline, Fig.5. This provides a convenient azimuthal reference surface that can be located optically with a straight edge. A deeper V permits anti-rotation outriggers or tangent screws for azimuth control, Fig.6 and Fig.27. The V can be asymmetric, that is, with different depths on the two sides, Fig 7 If size or weight are detrimental, material outside of the contact strips can be minimized.

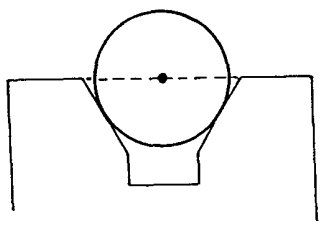

Fig.5 Centerline on the side surface plane

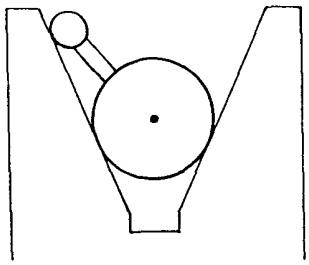

Fig.6 Deep V used with outriggers

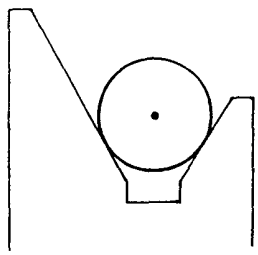

Fig.7 Asymmetric V

The bottom of the V can be designed to provide clearance for the process of producing the contact strips. There should also be clearance for non-cylindrical objects to be put in the V, for example, square objects in a 90° V. The bottom of the V can be used in a variety of ways—as a rectangular trough for elements that are not in cylinders, to hold a scale, for end stops, and for other purposes.

The centerline height can be selected to match the V with other apparatus. It is convenient to chose a round number. The side surfaces can be used as a foundation for clamps, covers, axial position measurement apparatus, and motion actuators. Feet, either a contiguous part of the structure or attached to its bottom, can be used to secure the V to a table and to support it so as to maximize straightness

A structure can contain multiple Vs, which can be parallel, perpendicular, or at arbitrary angles. For example, a pair of Vs at an angle can be used as the base for a fixed-angle ellipsometer or for a light section microscope.

The structure can be monolithic, that is, made from a single piece, or it can be fabricated from more than one piece.

Monolithic Vs

A *monolithic* V is constructed from a single, continuos piece of material. Monolithic Vs can be stiffer and more stable than fabricated ones.

In machining Vs, standard good practice applies, as does precision practice when applicable. The structure should be held with minimal strain, so it does not change shape when released. Feet can be used to hold the V during machining if the structure is stiff enough to deflect negligibly during cutting. It may be necessary to stress relieve the structure after roughing and then remove a small amount of material at a low rate. The machine tool should have sufficient travel to allow the cuts should be made in one pass, so accuracy is not lost by axial repositioning.. The tool should be stiff enough so that there is no appreciable bowing.

Vs can be made with milling machines, grinders, planers, or shapers With a standard end mill, a 90° V can be cut as an L in a single setup with the structure tilted. This results in different finishes for the two sides, since one is cut by the side of the end mill and the other by the bottom. Alternately, the structure can be rotated between cuts and both sides of the V machined the same way. The horizontal and vertical straightnesses of travel of the mill may be different, and this can be taken into account in choosing the machining approach. With numerically controlled mills, it may be possible to program the motion to eliminate systematic errors. Vs can be ground with a wheel dressed to produce both contact strips in the same setup. In such a process, the contact strips may not be planar and there may be some asymmetry in the V. Alternately, the contact strips can be ground one at a time in the more customary fashion.

If the machine tool that creates the V is known to be bowed in the vertical direction, then this defect can be partially compensated. If the tool cuts a surface parallel to the table, then if the V is rotated about its axis between cuts, the resulting V has a bilaterally symmetric error. The angle varies along the V, but the bisector is fixed, so a cylinder moving in such a V always has its axis in the same plane.

High precision Vs can be scraped or lapped to eliminate tool marks, or to re-true after coating. These processes can be affected by the machining marks.

The V is an ideal form for casting and extrusion, since only a small amount of material must be machined to produce contact strips.

Fabricated Vs

A *fabricated V* is made of at least two parts that provide the contact surfaces, and possibly additional structural components. Since two non-parallel planes define a planar V, a planar V structure can be made using two parts with flat surfaces. Fabrication is simplified by the non-criticality of the angle. If the pieces defining a planar V move without changing shape, the straightness of the V is maintained. There may be an irrelevant change in V angle and a change in the centerline direction, which matters only if the V is related to external apparatus.

Some fabrication approaches are shown in Fig.8. Measurement straight edges can be used for the contact surfaces, with a structure that is bolted or clamped together or with inserts cast in polymer composite. The pieces comprising the structure need not be symmetric. For example, Fig.8c, a straight edge and a surface plate comprise a V. Fig.8d shows another asymmetric design[3] based on a piece with a square cross section with one flat surface and a rectangular straight edge.

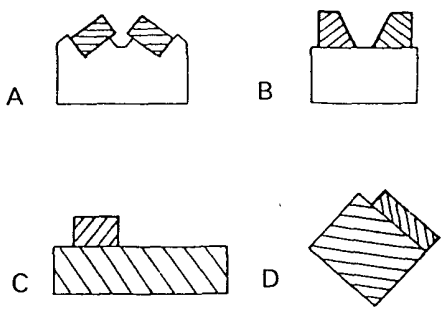

Fig.8 Examples of fabricated planar Vs

A pair of rods can be used to make a V with looser tolerances for larger cylinders. A useful rod material is the hardened shaft sold for linear bearings. A pair of cylindrical rods can be mounted parallel in a number of ways, Fig.9. A rod can be used with a flat, as shown in Fig.10.

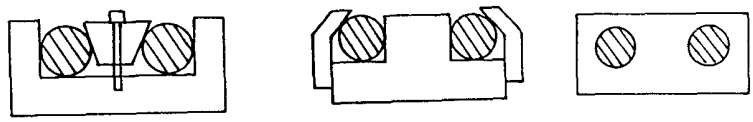
Fig.9 Mounting parallel rods

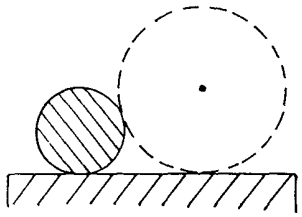
Fig.10 V made from a rod and flat

Vs can be made by replication against a master, with synthetic granite, epoxy, or other materials. The precision surfaces alone can be produced by replication, e.g. using a thin layer of conforming material on a supporting structure.

Materials, coatings, and finish

The materials, coatings, and finish of Vs and mating cylinders should be considered together. There are many coatings to chose from, and discussion with experts is recommended. Low friction between cylinder and V is desirable so the cylinder can easily move into alignment and be rotated for centering. Friction between the clamp and the cylinder may be useful in restraining axial motion. A slippery and durable coating for aluminum Vs is "Teflon hardcoat." Nickel coating on steel gives a slippery surface For most optical purposes, coatings that require lubrication are undesirable. Most aluminums need special heat treatments to ensure dimensional stability over time. Hard steel or ceramic are durable and less likely to brinell. Hard coating reduces wear and scratches, but not brinelling from Hertzian contact stresses.

The thermal environment, including temporal changes and thermal gradients, is important in material selection. If gradients and changes are to be encountered, the best V material may be aluminum, whereas granite is satisfactory in a room held at constant temperature.

[3] We obtained a granite master of this type from the Rahn Granite Surface Plate Co., Englewood, Ohio. The end dimensions are approximately 8"×8". It is straight to 1 μm over a length of 3 feet.

The drawing, specification, and cost of Vs

The principal feature of the V—that only the properties of the two narrow contact surfaces are critical—can be confused in communication, resulting in more accuracy than needed on non-contacting surfaces and consequently excess fabrication time and cost. The optical engineer should be aware that there are different systems of drawing and tolerancing, and be certain that the designer producing the prints understands what is important and correctly conveys it to those who will make the V. It is helpful to speak directly with shop personnel, both for suggestions and because this kind of requirement is unfamiliar to them. To make clear what is critical, it is useful to describe an acceptance test, even though it may not be used. The measurement techniques discussed below might be the basis for such a test.

Measuring Vs

There numerous ways to measure the straightness of Vs, a few of which are commented on here. These methods are identical to or are related to standard methods of measuring straightness and flatness. Some methods measure the motion of a cylinder in the V, while others directly measure the contact surfaces Absolute methods measure straightness by comparison with a master, while differential methods measure change along the V, and require no master. The methods that reference a surface plate are most suitable with planar Vs. The differential methods work with all types of Vs. Some methods measure the contact strips individually; others, the two strips simultaneously.

The autocollimator, a differential instrument, can be used in a straightforward way. A mirror is mounted on the end of a good cylinder, with the mirror normal along the cylinder axis. The autocollimator axis is set near the centerline of the V. The cylinder can be rotated to ensure that the mirror orientation is correct. If the mirror is not oriented well enough, an outrigger can be added to the cylinder so that it does not rotate. A reference mirror that shares the field of the autocollimator can be fixed on the structure to verify its stability during the measurement. The cylinder with the mirror is translated the length of the V. For a 90° V, orient the autocollimator measurement axes so that they are perpendicular to the surfaces.

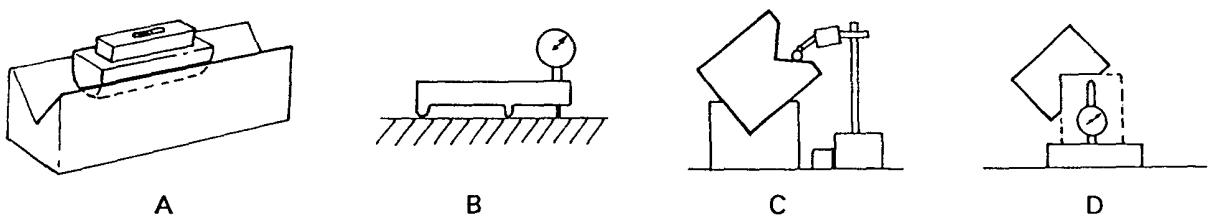

Fig.11 Some ways to measure straightness of Vs

Some other methods are shown in Fig.11. In one, a level on a cylindrical support traverses the V. With the V oriented in the usual way, the level is insensitive to lateral error, but the V can be tilted so the level senses a single contact strip. A beam comparator traversing the V without rotating, can sense a single contact strip. Certain interferometric apparatus can be mounted on an object that traverses the V.

In differential measurements, the V is sampled over the length of the moving object, so errors of certain length scale are not detected. The situation is analogous to sampling, with misinterpretation of errors whose periodicity is less than twice the length of the object.

Other methods, more appropriate with planar Vs, measure straightness with reference to a surface plate. In Fig.11c the V is held above a surface plate so that a contact strip is nominally parallel to the plate. An indicator supported by the surface plate traverses the length of the contact line to measure its straightness. Alternately, a straightedge can be used to guide the base of the indicator To simplify analysis, the supports can be shimmed so the contact lines at the two ends are at the same height.

In the related method, Fig.11d, the V is tilted so the contact strip to be measured is nominally parallel to the granite plate, supported at the same height at both ends. An indicator on a stand again travels along the contact line.

THE CYLINDER

The most useful cylindrical forms for mounting optical elements are shown in Fig.12. The simple cylinder contacts the V over its full length. Undercutting the central portion gives a *bar bell* that is not subject to rocking. With tightly held diameters, a bar bell can be less expensive than a full cylinder, since the critical dimension is held over less length. A *bone* shape, with two rounded ends, engages a V kinematically, with four point contacts for best repeatability. A hybrid bone/barbell is also possible. Numerically controlled lathes can produce bone shapes routinely. Machining bones is simplified since the two rounded portions can be machined independently. For example, the part can be moved between machining the two rounds. A region with a reduced diameter should be used for knurls, centering screws, or other features that could disrupt the contact between cylinder and V. In general, having contacts only near the ends is advantageous, and a diminished contact length is a problem only if the clamping force is great enough to damage the cylinder and/or V.

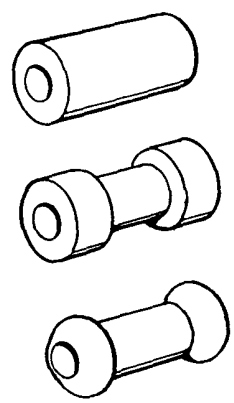

Fig.12 Types of cylinders

The length of the cylinder or separation between the contact regions should be great enough for stability, depending on the application and clamping means. A rule of thumb is that the diameter should be no greater than the length. For the most repeatable interchangeability between cylinders, their lengths should be the same.

With uniform temperature change, cylinder axes moves up and down in the bisector of the V, so bilateral symmetry is maintained. Axes of cylinders of the same diameter that are made of the same material move together, remaining collinear. The orientation of optical elements with bilateral symmetry, e.g. gratings, prisms, and cylindrical lenses, can be selected accordingly.

Defects of cylindricity

There is a variety of deviations from ideal cylindricity, some of which are shown in Fig.13. A piece can be round everywhere, but of varying diameter. All sections can be round, but their centers can fail to lie on a straight line. The sections can be non-round, either rough or smooth. There can be periodic lobing, and centerless grinding tends to produce lobes in multiples of three. Thin walled cylinders deform to give two lobes.

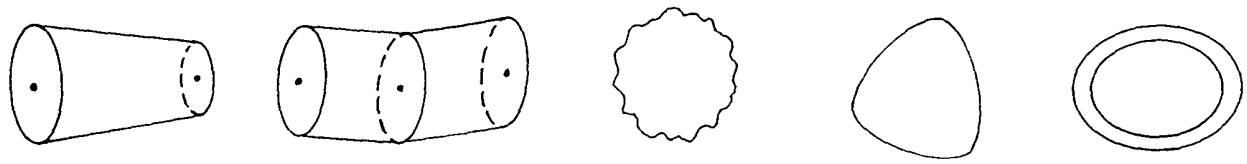

Fig.13 Examples of non-cylindricity

The effects of these errors depend on the angle of the V Cylinders with an even number of lobes have the greater runout in 90° Vs, and cylinders with multiples of three lobes have greater runout in 60° Vs. (This fact is employed in the measurement of roundness, and there are special micrometers[4] with V-shaped anvils for sensitivity to certain lobing properties.)

Roundness measurement is a large subject in itself, treated at length in the references. Note, however, that these treatments are oriented to cylinders used mechanically, for instance, for spindles or roller bearings. What matters here is the effect on an optical element of an imperfect cylinder in a V. A method of measuring cylinder roundness is by rotating it in a V and measuring the runout, Fig.14. An array of four balls can be used for such rotation tests in place of a V.

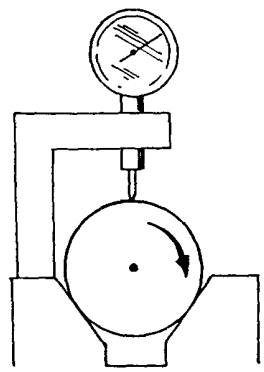

Fig.14 Measuring cylinder roundness in a V

Diameter

For a group of cylinders used only with each other, absolute diameter does not matter, but identicality does.

For most optical setups, the centration tolerance varies from element to element. In this case, cylinders whose outer surfaces only have been made can be sorted, with the best ones being used where tolerances are tightest.

A diameter error results in raising or lowering the axis of a cylinder in a V Bilateral symmetry is preserved. The height error is greater for smaller V angle. The axes of undersize cylinders can be brought into correct position with shims.

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[4] Mitutoyo sells micrometers with anvils at 60° for 3 lobes and 108° for 5 lobes. Starret and others sell micrometers with 60° anvils.

Very accurate cylindrical masters and spheres can be purchased inexpensively from gage houses for comparison measurement.

It is useful to select one or more standard diameter. "Round number" dimensions are preferred, since stock material is available, as are gages and tooling, for example, lathe collets [5]

Squareness of cylinder ends and seats

End squareness is critical if axial spacing is critical or if a cylinder must be rotated without axial motion, using the end as a stop.

When cylinders are made on a lathe, the outside, one end, and the seats facing one direction can be cut in the same setup. This end and these seats are squarer to the axis than surfaces machined after the part is turned around in the lathe, so such cylinders should be designed accordingly. If cylindrical blanks are made for later use, a machined feature can indicate which end is which. If cylinders are not too long, it is possible to cut both end surfaces in the same setup.

If a cylinder that must be rotated without axial motion does not have an end that is square enough, a rounded button can be placed on one end. During rotation, this locator is kept in contact with the accurately perpendicular end of a master square cylinder.

End squareness can be checked by standard methods described in the references. To check squareness in a V, a button is attached to the opposite end of the cylinder, which is rotated against a master square cylinder, while measuring the end being checked, Fig.15a. In another method, Fig.15b, the cylinder end to be tested contacts a fixed axial stop and is rotated with measurements taken at this end. If the measurement is at an azimuthal angle from the stop that is a divisor of 360°, there is insensitivity to errors with particular periodicities. For example, a measurement 180° degrees from the stop is insensitive to end errors with bilateral symmetry, i.e. with two periods of azimuthal variation.

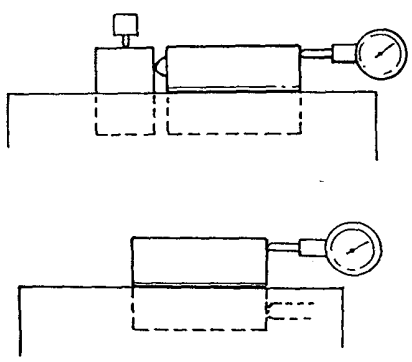

Fig.15 Measuring end squareness in a V

Designing and obtaining cylinders

Cylinders can be made in a variety of ways—on standard lathes, by grinding between centers, by centerless grinding, and on ultraprecision lathes with air spindles. Cylinders can be made in standard machine shops, by gage houses, and by shops that specialize in cylinders. Many gage shops work in tool steel, but not stainless, which is preferable for optics laboratories.

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[5] We use 1" diameter as a convenient small size, easily worked and handled, and large enough for microscope objectives and eyepieces. We use 100mm diameter with 35mm camera lenses and film. This size can be quickly machined from 4" stock.

As with Vs, it is important to communicate to designers and makers of cylinders what is critical and what is not, and to discuss with shop personnel how the cylinders are produced. Simply providing a print can increase cost and production time. For example, for grinding between centers, conical end holes are needed, as well as a small hole near the rim for a dog to drive the part. This is usually acceptable for optics and the dog hole can serve as an azimuth locator. Mechanical gage makers use a system of tolerancing described in various ANSI standards.

In pricing cylinders, find out the cost of "extra" accuracy. Mechanical accuracy beyond what is needed optically may be a surprisingly inexpensive luxury that loosens tolerances elsewhere. Such accuracy may be available from your own shop. Sometimes accuracy is not limited by the machines that make the cylinders, but by the measurement equipment, and metrology improvement may be inexpensive. For example, if measurements are done by hand micrometers, the purchase of an indicating micrometer for a few hundred dollars can improve measurement accuracies several times.

It is sometimes useful to obtain a batch of standard cylindrical blanks to be modified for use as the need arises. For highest accuracy work, keep in mind that subsequent machining may distort the cylinder.

THE CYLINDER AND V TOGETHER

Repeatability and interchangeability

The cylinder-in-V system provides repeatable and interchangeable location because there is line or point contact, that is semi-kinematic or kinematic location, and this is so even with imperfect components Identical ideal cylinders can be removed from and repeatably replaced in the same or other ideal Vs of any angle. In addition, an ideal cylinder can be reversed end to end in an ideal V.

Ideal cylinders of the same diameter and length can be repeatably placed in the same position in an imperfect V. Ideal cylinders with different separations between contact regions are not repeatably located in imperfect Vs.

An imperfect cylinder can be repeatably located in the same place in a V if the azimuth of the cylinder is the same. If imperfect cylinders are switched between ideal Vs of different angles, the switching results in different errors, but the error is repeatable if the azimuthal angle is repeated.

This interchangeability is particularly beneficial in production. If the final product employs cylinders in Vs, a "chain of accuracy" is easily established. A single master V and a few master cylindrical components can be used to establish working cylinder-in-V fixtures, which are used to set up product When questions arise, master cylinders can be used in product Vs, or product cylinders in the master V.

Centering optical elements by rotation

In centering an optical element, the axis of the element is made collinear with that of the cylinder holding it. Centration is verified by rotating the cylinder and checking the element for runout, which can be measured optically, mechanically, or by another means. The rotation can be done in a V or on a rotary table. Runout tests in a V do not depend on overall straightness of the V

In centering optically, an element is positioned in the cylinder so that its effect on light is unchanged as the cylinder that holds it is rotated. Fig.16 shows a basic method of centering a positive lens. An illuminated pinhole is imaged onto a reticle by the lens being centered. As the cylinder holding the non-centered lens is rotated, the pinhole image moves, with the motion diminished as the lens is centered. To center a negative lens or a long focal length positive lens in this fashion, a non-rotating positive relay is added.

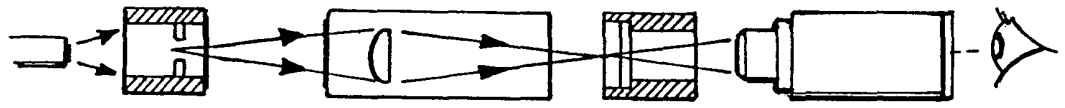

Fig.16 Apparatus for centering a positive lens in a cylinder

Centering rotationally symmetric elements can be done at different wavelengths and at different conjugates from those at which the element is to work. A narrow wavelength range reduces chromatic aberration, giving sharper images. For visual work, green is a good color. Centering can also be done on a rotary table using the same runout detection approach.

The pinhole image on the reticle is relayed to an eyepiece or to a video camera, the final imaging equipment comprising the *viewing apparatus*. The viewing apparatus is an observer of alignment, but not a provider of accuracy. With video, the lateral positions of the relay lens and the camera determine the position of the reticle image on the monitor, but not the position of the pinhole image relative to the reticle image, and likewise with aerial image observation.

Another approach to measuring centration is treating the optical element to be centered as a mechanical one, using a gage to measure mechanical runout. This detection can be more sensitive than optical measurement, but it senses just the surface of the optical element, so refractive index variations of the material do not show up. The gage may be a contact one, a capacitance gage, or an air gage.[6]

Centering by rotation is self-checking. No master is needed. If the centering does not converge, then either the cylinder and/or optical element are not rotationally symmetric, or the centering mechanics is flawed. Centration can be re-verified in another setup by rotating a cylinder.

A bilaterally symmetric optical element can be centered in one meridian by rotating its cylinder back and forth 180°, and adjusting the element so that its effect on light from a fixed source is the same at both positions.

[6] The "Wilson Airless Air Gage" (Wilson Instrument Company, Pasadena, CA) is a low pressure, small, accurate gage suitable for such work.

Centered masters

Centered masters are particularly accurate objects that are used to center and to measure the centration of other elements. Over a straight V, two such masters define an axis with respect to which other elements can be located. The two most generally useful masters are a centered pinhole and a centered crosshair reticle. Other, more specialized masters can be devised, for instance, a centered quadrant detector or other position-sensing detector. Another is a "point source" made by centering the output of a single mode fiber that is fed at its other end by a laser.

Masters should be made with accurately round cylinders, which should have at least one end accurately perpendicular to the axis, to be used as an axial stop for rotation. The surface containing the pinhole, the reticle substrate, etc. need not be especially perpendicular to the axis, since they are used only near the axis.

Although centering by rotation with optical runout detection can be done if the pinhole and reticle are not on axis, it is advantageous if they are. An axial pinhole provides a rotationally symmetric image, which makes the observation more sensitive. Pinhole centration also eliminates error from unintended axial motion of the rotating cylinder and from parallax that arises if the pinhole image is not in the reticle plane. A centered reticle, typically a crosshair, simplifies the observation of runout.

Elements that cannot be centered by rotation, can be aligned using centered masters. In this case, the V must be straight over the length of the apparatus. As an example, the axial pixel of a video camera can be found by imaging the centered pinhole with a centered lens. Masters can also be used to center bilaterally symmetric elements.

Masters are centered by rotation without axial motion. The pinhole and crosshair masters are observed in transmitted light, and good accuracy is obtained with ordinary optics. For example, a pinhole 1μm off axis produces a 2μm shift when rotated. A 20× objective magnifies this to 40μm, easily observed with an eyepiece using crosshairs that are typically about 10μm. Imaged onto a video camera with, say, a magnification of 100×, the 2μm shift gives 200μm, or twenty 10μm pixels, an appreciable fraction of the monitor's field.

A useful centering mechanism for masters is shown in Fig.17. The element to be centered is mounted in a truncated conical piece held with four brass-tipped set screws in opposing pairs. The screws locate the piece laterally and also exert an axial force that holds it against a seat machined in the cylinder. Micron-level adjustment can be routinely obtained with a screw pitch of 32 or 40 threads per inch. The region around the threaded holes on the outside of the cylinder should be relieved by undercutting or countersinking, because the stress produced in this region by tightening the screws can locally deform the cylinder. When opposing screws are moved in the same direction, torque is produced that can lift the cylinder from the V, so a clamping devise is desirable where centering is done. In addition, the portion of the V where centering is done should provide clearance for simultaneous access to opposing screws.

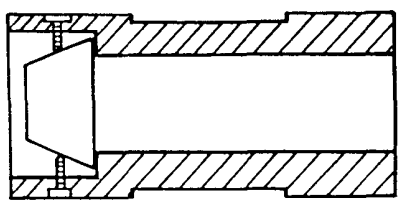

Fig.17 A centering mechanism

Video for alignment

Video has the advantages for alignment over visual observation that fatigue is reduced, parallax variations are eliminated, and the view can be shared by several people. For production work, computer enhancements to the video can be added, and the alignment can be documented with a frame grabber The relatively small number of camera pixels is not a problem for centration, and viewing optics magnification can be selected according to the camera pixel size.

Good video cameras and monitors are recommended, with monochrome preferred for its better resolution. A large number of pixels is not important. Solid state cameras are preferred for their spatial stability. Contrast enhancement is sometimes helpful, as are video reticles. If keeping a physical reticle in place is undesirable, a master reticle or pinhole can be placed in the V, used to set the position of a video reticle or to record a position with a frame grabber, and then removed.

A small video camera mounted on axis in the V is convenient and mechanically stable. If a camera is to be held or repositioned without rotating, it can be put inside a square or hexagonal bar. There are microcameras with round heads as small as 7mm in diameter and remote electronics. If the camera is too large for the V, it can be mounted at right angles, Fig.18a. A non-rotating section in the V, e.g. a square or hexagon, helps stabilize such a system. Video cameras that can support their own weight by their lens threads can hang off the end of the V mounted with a square or hexagonal bar with C-mount thread machined in and a lock nut to secure the camera at a desired azimuth, Fig.18b.

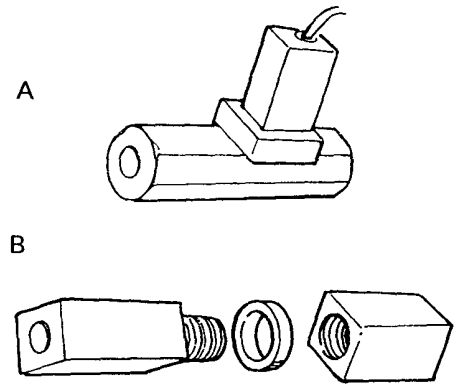

Fig.18 Mounting video cameras in a V

Lateral spacers

One or two spacers with parallel sides can be used in a planar V to translate a cylinder laterally, Fig.19. Identical spacers produce translation along the bisector of the V. With a 90° V, spacers produce orthogonal offsets. Spacers can be used to center a cylinder whose diameter is smaller than nominal or to intentionally de-center to experiment with tolerances. Wedges can be used for variable offsets. Spacers can also provide low friction surfaces for smaller diameter cylinders to be rotated or translated axially.

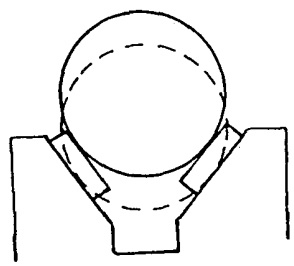
Fig.19 Lateral spacers

Axial position

The distance between cylinders can be measured by calipers, gage blocks, inside micrometers, etc To measure frequently changing axial locations, a gage can be permanently located in the bottom of the V or on a side surface.

Cylinders can be physically located in a variety of ways. For example, a cylinder end can kinematically contacted with a ball on an arm attached to a side surface. Likewise, a rod attached to a side surface can touch a conical surface on a cylinder. Empty cylinders can be used for setting separations or as stops for returning to fixed positions.

Axially spacing lenses in cylinders

After a lens is mounted in its cylinder, the distances from its vertices to the ends of the cylinder can be measured by a depth micrometer or by another means, taking care not to scratch the lens Measuring the cylinder length then provides the information necessary to separate such cylinders. Measuring after lens mounting is often easier than holding both axial distances in the cylinder and the lens vertex thicknesses, and lens separations are easily re-optimized with a lens design program using actual vertex thicknesses.

For highest accuracy work, the shapes of the ends of the cylinder must be considered. For example, a lathe whose cross slide is not accurately perpendicular to the lathe axis produces a conical end. If, say, a depth mike touches the end at one diameter and a lens spacer at another, spacing errors result. This can be avoided with toroidal-like cylinder ends, Fig.20, so all axial measuring and spacing apparatus make contact at the same place,

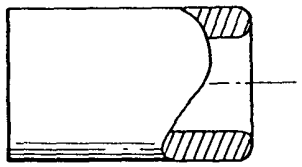

Fig.20 Toroidal cylinder ends

Mounting optical elements

Standard mounting means are used for optical elements in cylinders For large lens assemblies e.g. those with threaded ends, a long cylinder can be used so the center of gravity of the entire assembly is near the center of the cylinder, Fig.21. Long elements can be supported within a cylinder at both ends with sets of three or four screws, Fig.22. More than one optical element can be put in the same cylinder, and an aperture stop can be located along with a lens. When separate cylinders are desirable for nearby lenses, a "snout" can be used, Fig.24.

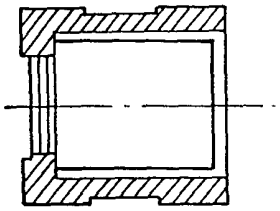

Fig.21 Mounting threaded lens assemblies

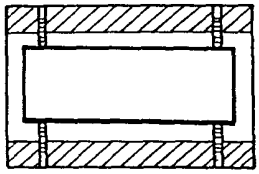

Fig.22 Mounting long objects

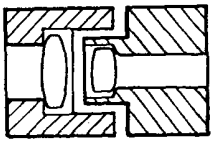

Fig.23 Nearby lenses on separate cylinders

Lenses can be held temporarily using a system like that of the "bell" used in edging, Fig.24. The lens is supported between two cylinders whose ends have toroid-like shapes.

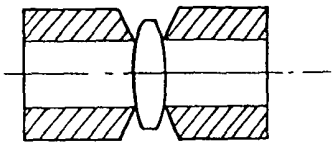

Fig.24 Bell-type mounting

Stops, baffles, and tubes

Aperture stops can be machined into cylinders with optical elements or located on separate cylinders Likewise, baffles to reduce stray light can be machined into lens-holding cylinders, into separate cylinders, or into discs. Tubes that exclude stray light and provide baffling can be suspended between cylinders without touching the V. Telescoping thin-walled tubes are useful in the laboratory.

Clamping

Clamping is the application of force to load cylinders in place in a V. The V and not the clamp should determine the location, so the clamp need not be stiff, and a spring or flexure can be used. Axial location is often maintained by the friction between V and cylinder resulting from the clamping of the two This should be taken into consideration if axial location ought to be determined by a hard stop This section primarily addresses clamping in the laboratory, where cylinders are frequently readjusted, rotated, and swapped in and out. For conditions of vibration, shock, and one-time location, the considerations are different.

Clamping should not move, mar, or deform the V, the cylinder, or the optical element within The clamping force should nominally be symmetrically applied, along the bisector. Single clamps should be applied near the middle of the cylinder to avoid tipping. However, exact symmetry is not critical Marring a portion of the cylinder that does not touch the V, e.g. the "handle" of a barbell, produces no lateral misalignment, but clamping a previously damaged surface can move a cylinder axially The cylinder wall must be thick enough to avoid significant deformation under clamping loads. For single point clamping, a 60° V induces less deformation than a 90° V

There are many clamping methods. The simplest is with a thumbscrew. Soft or soft tipped screws, e.g. plastic or plastic-tipped, can be used with any cylinder material. Soft screws also help prevent excessive force from being applied. A clamping screw exerts a torque on the cylinder that tends to move it. A rounded tip reduces torque. Clamping pressure can be applied without torque in a number of ways. A flexure made from shim stock between the clamping screw and the cylinder, Fig.25, eliminates both torque and marring.

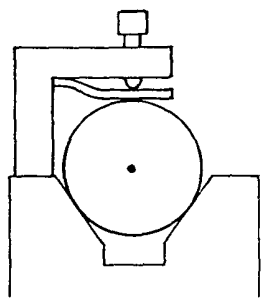

Fig.25 Flexure clamping to eliminate torque and marring

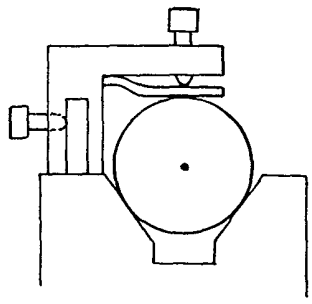

Fig.26 Axially moveable clamps

Clamps can be bolted to the V structure in fixed locations, typically a row of tapped holes along a side surface. For arbitrary axial positioning, the clamps themselves can be clamped to a rail attached to the V structure, Fig.26.

A variety of other methods can be used to restrain cylinders. Taping a cylinder to a V structure works surprisingly well, since axial forces are opposed by the wide dimension of the tape. If both the V and cylinder are made of magnetic materials, magnets on the flat bottom of a V hold cylinders in place. Cylinders can also be held in place by hollow cylindrical end stops that are themselves clamped.

For systems that undergo temperature change, different thermal expansion coefficients of cylinders, V structure, and clamp structure can change the clamping force. The ideal clamp provides the same force under all conditions, and this is best done with a spring-like device.

Rotation, non-rotation, and azimuthal adjustment
Optical devices to be manually rotated about the axis are easily accommodated by mounting them in cylinders, which can be rotated in a V. Low friction spacers can be used with cylinders of smaller than nominal diameter. Alternately, a cylinder within a cylinder can be used. The outer cylinder may itself be a bushing or it may hold bearings in which the inner cylinder is mounted. Examples of rotated elements are polarization components and image rotation devices, e.g. Dove prisms and K-mirrors. Risley prisms to adjust beam directions are made by mounting two weak prisms in cylinders that can be rotated Likewise, a pair of tilted plane parallel plates in cylinders can be used to laterally translate a beam This can also be done with a single plate mounted in a mechanical sphere with a through hole, with the sphere held so that it can rotate in the V or in a cone at the end of a cylinder.

Azimuthal angle measurements can be done with a graduated cylinder or plate on the rotating cylinder, with a fixed pointer attached to the V structure. A convenient azimuthal reference is provided by side surfaces at the height of the cylinder's axis.

For small, accurately controlled rotation, a tangent screw can be used, Fig.27. Using the V itself, rather than a side surface, may give better repeatability in moving between Vs. Fine azimuthal adjustment and measurement can be done with a long arm, which can be temporarily attached to the cylinder.

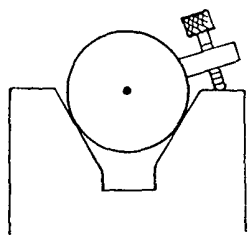

Fig.27 Tangent screw for fine azimuthal adjustment

Such methods also permit axial motion without rotation and the removal and replacement of elements at the same angle. The outrigger can rest within the V or outside the V. If centration is not critical, but rotation is undesirable, square or hexagonal pieces can be used instead of cylinders.

Non-centered elements
Some optical elements that require no centering can be put directly into the V, for example, diffusers and some filters. However, mounting such elements in a cylinder helps to keep them clean.

Components that must be perpendicular to the beam, but whose lateral positions do not matter can be held by two hollow cylinders. Examples are interference filters and Ronchi rulings used to calibrate dimensions.

Light sources
Various sources, including LEDs, lasers, and lamps, can be mounted in cylinders and located in the V Alternately, fibers or fiber bundles terminated in a cylinder can deliver light from remote sources, with the advantage of excluding heat that can deform the V.

Miscellaneous
Cylinder-mounted components can be used elsewhere so long as the cylinders can be held One way to make cylinders compatible with other apparatus is by drilling and tapping a lateral hole, compatible with standard rods. Clamps and other adapters can be devised.

A V structure can be used with other apparatus, for example, mounted on a breadboard table.

Handles can be attached to cylinders that are repeatedly inserted and removed.

Non-cylinders in Vs
Components that are not rotationally symmetrical can be mounted in non-cylindrical structures, e g objects with square cross sections for 90° Vs and objects with hexagonal cross sections for 60° Vs.

More
There is much more, but this is enough for now.

Acknowledgments

The drawings were expertly done the old fashioned way by Ed Fong A number of people have contributed to these ideas and have helped de-bug this paper. They include, in alphabetical order, John Bruning, Peter Clark, Jim Cloherty, Joe Deck, Tony Gonsalves, Wayne Gordon, John Mader, Dave Marshall, Bill Plummer, Jose Sasian, Robin Smith, Paul Yoder, and Jim Zambuto. Special thanks to Jeff Roblee, a real mechanical engineer, who taught me much of what I know about the subject.

Appendix of Virtues - Summary of cylinder-in-V features

The cylinder-in-V system has a number of salutary attributes, many of which are listed below The list is redundant in that certain features manifest themselves in various ways

KINEMATIC ASPECTS

- The location is kinematic or semi-kinematic.
- The contact is on lines or points.
- Location is repeatable, even with imperfect objects.
- There is enough constraint, but no overconstraint.
- There is repeatable rearrangement and quick, accurate swapping between setups
- There is an understandable "flow of accuracy" from masters to working fixtures to product.
- Mechanical errors are repeatable, measurable, understandable, and correctable.
- Cylinders and Vs with different levels of accuracy can be used in any combination.
- The same basic methodology can be used with any level or accuracy and with various materials
- Cylinders can be clamped without their moving
- Axial position can be kinematically determined.
- Angular position can be kinematically determined.

SYMMETRY

- The mechanical cylinder has the same symmetry as rotationally symmetric optical elements.
- There is as much symmetry as possible - rotational and bilateral.
- Some errors and changes in conditions maintain bilateral symmetry.
- Cylinders can be reversed end-to-end and alignment maintained.

MOTION and LACK THEREOF

- The two remaining degrees of freedom are useful.
- These degrees of freedom can be exercised independently.
- Rotation of elements about the axis is straightforward.
- Rotation without other motions is possible.
- Fine, repeatable angular positioning can be done.
- Axial translation is straightforward.
- Axial motion without other motions is possible.
- Fine, repeatable axial positioning can be done.
- The two remaining degrees of freedom can be exercised independently.

TESTING and CENTERING

- The geometry is self checking.
- Centration is tested by rotation.
- Cylinder roundness is tested by rotation.
- Centering can be done in a V or out of it.
- V straightness is tested by translation (as with an autocollimator).
- There are many ways to check straightness and roundness.
- Bilaterally symmetric elements can be set using 180° rotation
- Optical and mechanical alignment techniques can be combined in a variety of ways
- Cylindrical gages and straight edges for measurement are commonplace.

MANUFACTURING

- Only a small amount of material is worked in producing the critical parts of Vs and cylinders
- The angle of V not critical.
- Planar Vs are formed by two portions of planar surfaces whose relative positions are not critical.
- Some machine tool errors can be canceled by reorienting the V between cuts.
- Standard machining gives good enough accuracies for many optical applications.
- Vs can be made by many different machining methods.
- Vs are suitable for castings and extrusions.
- Vs can be fabricated in many ways, e.g. two rods, rod and flat, two flats.
- Rigid displacements of the components of a fabricated V do not affect its straightness.

MISCELLANEOUS

- For elements used intermittently, critical degrees of freedom are adjusted once.
- Optical elements mounted in cylinders can be used elsewhere.
- A cylinder-in-V unit can be used with other apparatus.
- The same basic approach can be used in the laboratory and in the field.
- Other shapes can be used in a V, e.g. squares in a 90° degree V.
- The V structure is a general-purpose base to which other apparatus can be attached.
- There is a general insensitivity to overall temperature change.
- The entire structure is robust.
- There are many ways to do anything, e.g. rotation, translation, rotation 180°, etc.
- The geometry is as simple as possible, but no simpler.

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