PLANO LENSES

Memo Written by D. B. Whitney on April 28, 1985
American Optical

The subject of plano lenses is one about which much has been said and written. Even so, I think it might be well for me to put forth a few of the fundamentals once again. My thoughts will be directed toward plano ophthalmic and safety spectacle lenses, but the principles will have application to visors, eyeshields and other special-purpose plano optical devices.

Let's start by remembering that a plano lens does have an optical axis, as well as an optical center which we will define as the point at which the optical axis passes through the front surface. The exception to this statement, of course, is the special case where the 'curves' are flat; here, there is either an infinite number of optical axes (if the flat sheet is prism-free), or there is none at all.

The relationship between the front and rear curves of a plano lens isn't what one might, at first, think. The front and rear curves do not have the same radii; a +6.00 curve on the front coupled with a -6.00 curve on the rear will not result in a plano lens. Rather, such a lens will have some amount of plus power, the specific amount depending on the coflexure (overall steepness of curve), thickness, and index of refraction.

Neither will the front and rear curves be concentric. Such a lens will have some amount of minus power; again, the specific amount will depend on the coflexure, thickness, and index. Concentric curves are what result from bending a flat sheet to a cylindrical configuration; in the curved meridian, such a bent sheet will have minus power and, since the flat meridian will have zero power, such a bent sheet will have astigmatism.

It follows from the above that a plano lens will have a configuration which lies between that of a lens having equal curves and one which is made up of concentric curves. Let's consider what that configuration will look like - will it be thicker at the center than at the edge, or will the reverse be true? Before we can answer this question, we must define what we mean by edge thickness.

There are two kinds of edge thickness to consider in a discussion of plano lenses. The first is the one most commonly used in ophthalmic computations: the edge thickness taken along a line parallel to the optical axis. This is what we get when we figure edge thickness by taking the difference between the depths-of-curve of the front and rear surfaces, and subtract that value from the center thickness. This kind of edge thickness is of value when the coflexure and / or effective diameter is relatively small.

The second kind of edge thickness is often referred to as 'calipering thickness,' for it is the thickness which is obtained when the edge is measured with ordinary thickness calipers. Such an edge thickness measurement is made along the mean radius, rather than parallel to the optical axis. This figure is more meaningful when the overall steepness of curvature is great and / or when the diameter is relatively large.

Keeping all of the above in mind, it is obvious that the calipering thickness is equal to the center thickness for a concentric lens (providing it is prism free). It is also obvious that the other, more common, edge thickness value is equal to the center thickness for lenses having the same curve on the front and rear surfaces (again, providing the lenses are prism free).

From the above we can conclude that, if we were to draw an accurate picture of a plano lens on a blackboard, it would have to be thicker at the edge than at the center when we define edge thickness in the normal manner, but the calipering thickness would have to be less than the center thickness. While it is seldom necessary to be so accurate in a blackboard drawing, such accuracy may be required in an engineering drawing, or when thinking about how a plano lens is to be mounted.

As an example, let's consider a 6-base spherical faceshield having a +6.00 (1.53) front curve, a center thickness of 3.0 mm, a diameter of 110 mm, and an index of 1.498. We find the following comparison:

	Equal Curves	Plano	Concentric
D1 (1.53)	+6.000	+6.000	+6.000
D2 (1.53)	-6.000	-6.069	-6.211
Power	+0.064	0.000	-0.134
Edge Tck (mm)	3.000	3.282	3.877
Caliper Tck (mm)	2.347	2.558	3.000

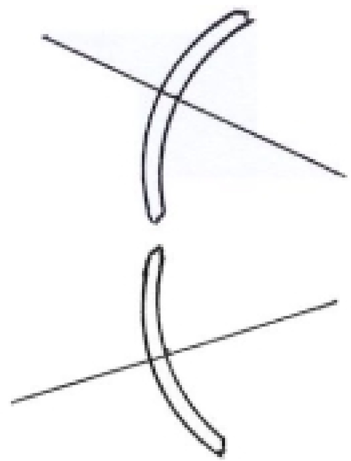
Now let's give some thought as to how a plano lens should be designed and positioned before the eyes in order to achieve optimum, or at least adequate, visual performance. There are several factors to consider, and they are inter-related. We would like our plano lens to have zero power in all meridians, not only for straight ahead gaze, but for all angles of view. We would also like for our plano lens to be prism-free; if not prism-free, we would at least like to avoid prismatic imbalance, again not only for straight ahead gaze, but for all angles of view. Finally, we would like our lens to have zero magnification. If we must have magnification, we would like it to be overall, rather than meridional, and we would like it to be the same for both eyes at all angles of view. If we must have meridional magnification, the magnification axes should be parallel.

It now becomes apparent that the design of a plano lens can be much more complicated than one might, at first, think. We cannot achieve all of our desired optical characteristics, and we probably cannot completely achieve any of them. Our design must be a series of compromises, and what those compromises are depends primarily on the application to which our plano lenses will be put.

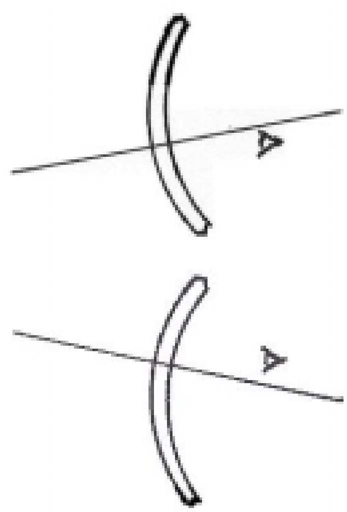
Probably the best overall optical performance would be obtained from a flat sheet, mounted such that the straight ahead line-of-sight is perpendicular to it. However, such a sheet will seldom satisfy a host of other requirements (size, weight, cosmetics, impact resistance, coverage, etc.).

Optically, our next best bet might be to adopt lenses having a moderate amount of overall spherical curvature, and mount them such that each eye is looking along the optical axis for straight ahead vision. Six-base lenses, glazed in a 44-eye, 20 bridge frame (with no face-form) would be an example. This, of course, has formed the basis for a multitude of Safety and Sunglass products over the years.

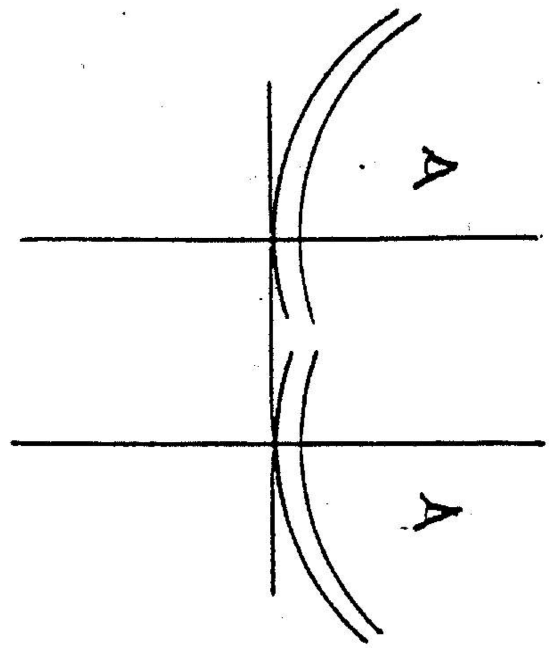
If, for any of a number of reasons, it is desired to increase the eyesize to an extent that the Frame PD (eyesize plus bridge size) is significantly larger than the average wearer's PD, it is common practice to incorporate face-form into the frame. If the optical centers of the lenses were to remain at the center of the eyeshape, the face-form angle would result in the optical axes being tilted with respect to each other.



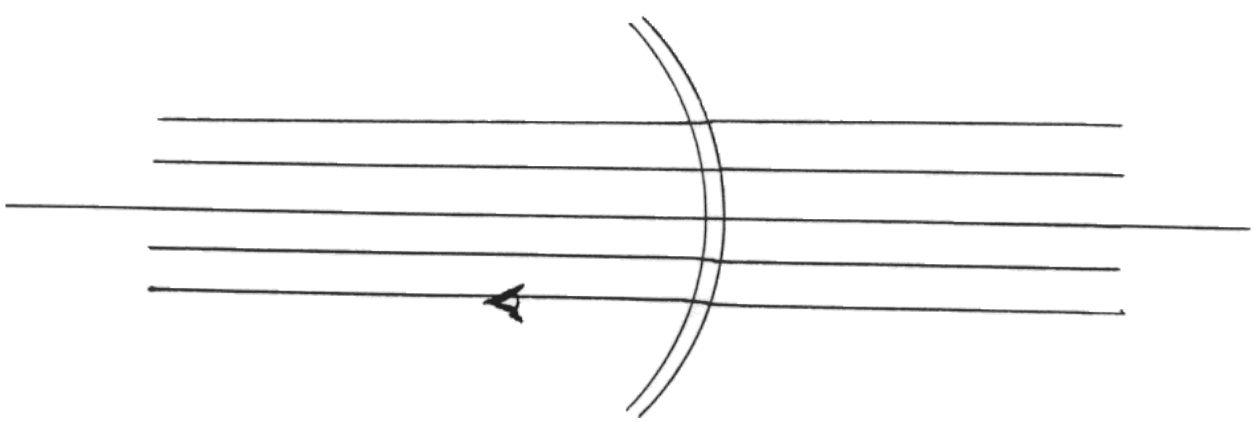
If a large frame were made without face-form, and the lens optical centers located at the wearer's PD, we would again have tilted optical axes:



Such situations would result in unwanted horizontal prism for straight ahead vision. The question now arises as to where the optical centers should be located to eliminate this prism. At first thought, one might expect that the optical centers should be located directly in front of the eyes, such that the wearer's straight ahead line-of-sight would pass through them. However, this is not usually the case. What is important is that the wearer's straight ahead line-of-sight be parallel to the optical axes of the lenses. This requires that the optical axes of the right and left lenses be parallel, and can be accomplished by placing the optical centers at the points where a straight edge would contact the front surfaces of the mounted lenses.



The reason for this is quite simple, and becomes obvious when one thinks of a diagram showing light passing through a cross-section of a plano lens.



Light entering parallel to the optical axis will exit parallel to that axis. Now, if we think of the eye as being located on one of the emerging rays (not necessarily the optical axis), we see that for straight ahead vision, there is no horizontal prism. In other words, as long as the eye is looking parallel to the optical axis, there will be no prism in a plano lens.

There are two key words in the last sentence: one of them is ‘parallel,’ and the other is ‘plano.’ We mustn’t take the word ‘plano’ for granted, for the fact is that there is some power in most lenses which are intended to be plano. Depending on the lens size, thickness and coflexure, as well as the amount of face-form angling, power deviations within tolerance may be enough to introduce excessive horizontal prism. However, though the situation may argue for tighter control on power than would otherwise be the case, we still want to adhere to the policy of keeping the straight ahead line-of-sight parallel to the optical axis, so as to minimize prismatic imbalance.

Up to this point we have restricted our consideration to straight ahead vision. Unfortunately, problems develop as soon as we consider the rotating eye when the straight ahead line-of-sight is displaced from the optical axis, even though it is parallel to it. As the eyes rotate, the right and left lines-of-sight intersect their respective lenses at different angles and at different distances from the optical centers. This introduces unwanted prismatic imbalance between the two eyes, and the extent of such an imbalance can be substantial. Unwanted power errors are also introduced as the eyes are rotated, but these are normally much less serious than the prismatic imbalance.

Let’s take the same example we did earlier - a 6-base spherical faceshield of 3.0 mm center thickness, 110 mm in diameter, and having an index of 1.498. We will position the visor such that the center of its rear surface is 35 mm from a line connecting the centers of rotation of the eyes. We will compute the power and prism for straight ahead vision, as well as for an eye rotation of 30 degrees to the left.

If the lens is exactly plano in power (at its optical center):

	Straight Ahead Viewing	Eyes Rotated 30 Deg Left Eye	Eyes Rotated 30 Deg Right Eye
Prism	0.008 In	0.564 In	0.872 Out
‘S’ Error	+0.002	+0.005	-0.042
‘T’ Error	+0.008	-0.002	-0.152
Astigmatism	0.006	0.003	0.110
Prism Imbalance	0.016	0.308	

If the lens has +0.06 diopters of power on axis:

	Straight Ahead Viewing	Eyes Rotated 30 Deg Left Eye	Eyes Rotated 30 Deg Right Eye
Prism	0.231 In	0.832 In	0.763 Out
‘S’ Error	+0.013	-0.007	-0.025
‘T’ Error	+0.043	-0.004	-0.073
Astigmatism	0.030	0.003	0.048
Prism Imbalance	0.462	0.069	

finally, if the lens has -0.06 diopters of power on axis:

	Straight Ahead Viewing	Eyes Rotated 30 Deg Left Eye	Eyes Rotated 30 Deg Right Eye

Prism	0.216 Out	0.296 In	0.981 Out
‘S’ Error	-0.008	-0.002	-0.059
‘T’ Error	-0.028	-0.001	-0.230
Astigmatism	0.020	0.001	0.171
Prism Imbalance	0.432		0.685

An examination of the above figures shows that our simple faceshield has optical problems. We’re in rather good shape for straight ahead vision if the lens is exactly plano, though we encounter prism problems as the eyes rotate. If the lens has as much as 0.06 diopters of power, prismatic imbalance becomes borderline even for straight ahead vision.

Earlier we mentioned that magnification can be a consideration in plano lens design. this might seem strange, since magnification problems are usually associated with high powered lenses, but it is true, especially if there is asymmetry. Consider the case where two plano lenses of cylindrical configuration are employed. If the axes of the cylindrical surfaces used in the right and left eyes aren’t parallel, meridional magnification differences may result in the wearer suffering from symptoms associated with aniseikonia. Remember, it is small magnification differences which can cause iseikonic problems. When magnification differences are large (more than several percent), fusion usually cannot be achieved and binocular vision is lost. Remember, also, that it is magnification differences, right eye to left eye, which cause iseikonic problems; as long as the magnification is the same in each eye (type, amount, and orientation), aniseikonia need not be a concern.

During the days when aniseikonia was more widely diagnosed and treated, magnification differences of as little as 3/4 of 1% (0.75%) were considered clinically significant in the presence of symptoms. Though aniseikonia is seldom detected with today’s eye examination techniques, the inducement of magnification differences through poor plano lens design should not be ignored, especially in applications where spatial relationships are critical.

Spectacle magnification is made up of two components: power magnification and shape magnification. Power magnification is a function of lens power and vertex distance, whereas shape magnification is a function of front curve, center thickness and index. It is conceivable that, in certain exotic plano lens designs, minus power might be purposely introduced to enable power magnification to partially overcome shape magnification to yield an acceptable total. This is a compromise which must be approached with caution, since most standards have power tolerances (some rather tight), while few, if any, address magnification differences.