Correction of Presbyopia with a New Adjustable Spectacle Lens

Daniel I. Barnea
1 Ugarit St., Tel Aviv, Israel 69016
[Communicated by Eli Peli, Eye Research Institute, Boston, MA 02114]

In the quest for a solution to presbyopia and due to the inability to restore the eye's system itself, man in the last centuries resorted to a continuous evolution of increasingly sophisticated types of eyeglasses (Fowler and Patreas, 1991). What technology has had to offer so far, as practical products, were glasses that utilize rigid lenses. The most advanced solution on the market today is spectacles with progressive addition lenses (PAL) that provide a different, yet fixed power, in each direction of gaze. This is still a compromise with the real need of a dynamically varying power. While in some frequently occurring situations, such a grading approximates real needs, in many other situations the compromise forces uneasy head tilting and partially impaired vision.

More advanced ideas, such as lenses with a controllable dynamically variable power imitating the natural eye system, have been expressed since the beginning of the century (Ohmart, 1893). The most commonly suggested is the deformable lens which has two transparent and flexible plates with a refractive fluid between them. Pumping the fluid in and out causes changes of surface curvature and hence power variations. However, none of these inventions satisfied the quality and the simultaneously required properties of optical precision, compactness, weight, fashion of design or ergometrics needed for mass production of spectacles.

I introduce a new design principle of a deformable lens structure with adjustable power (Barnea, 1990) and summarize its associated features. Theorems for achieving optical precision throughout the range of power variation and some bounds on lens dimensions are derivable from the geometry and elastic properties of the system. Also indicated is the small amount of energy that is required for power variations. Moreover, the paper discusses the feasibility of non-round and fashionably shaped adjustable power lenses.

Background

We define a lens as "round" if its circumference line (edge) is a circle and if the center of this circle is on the optical axis. The lens is "non-round" if any of the above two conditions does not hold. We define d as the maximal distance between the optical center (or axis) of the lens and any edge point on the circumference line. For the special case of a round lens, d becomes the radius (Fig. 1).

For the sake of simplicity, we assume spherical or nearly spherical optics and relative flatness where the radii of curvature of both lens surfaces are large enough (e.g. $R/d > 7$).

The design principle: The lens is composed of the two transparent plates, at least one of which is flexible. A refractive and non-compressive fluid is sealed between the plates, forming with them a unified optical body. The index of refraction is assumed to be similar for the fluid and plates. (The refraction equality assumption is for the sake of simplicity and can be relaxed.) The fluid is sealed within the lens body while the distance D between the edge lines of the plates can be forced to vary (parallel to the optical axis). This "circumferential spacing control" is the key of the design.

The variations of this distance - D, with the volume of the fluid kept constant, causes corresponding variations in the fluid pressure and thus of the curvature of the elastic plates. It can be shown that the system is almost linear in the sense that the fluid pressure, the curvatures and the lens power are all linear with respect to this variable D.

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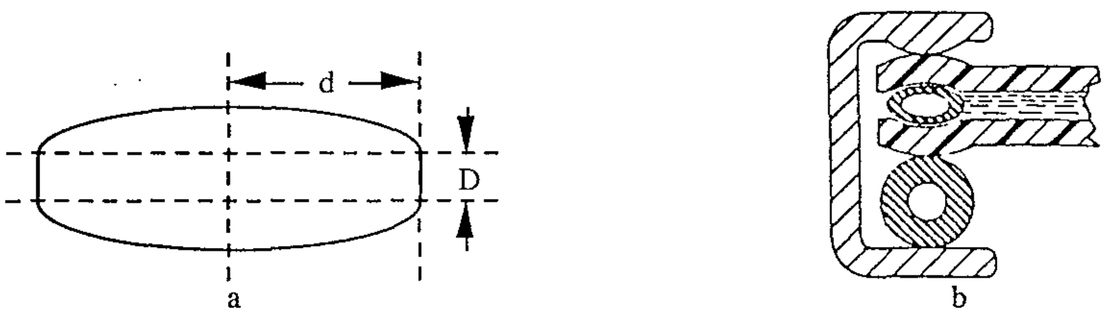

Fig. 1 The adjustable lens power is controlled by varying the distance D along the lens circumference. One experimental mechanism for such control is described in b.

The round adjustable power lens

We start with the simpler round lens and list its main properties. It turns out that most of the properties or theorems may be naturally extendable to the more elaborate non-round case.

The claimed theorems can be proved by the incorporation of the geometry, the elastic properties of the plates under the exerted forces and boundary conditions (Hooke's law) (Shigley and Michke, 1989), and the optics of the system. It is assumed that deviations of surface points are small and occur in parallel to the direction of D (or the axis). This assumption stays substantially true for power variations reaching the order of 2 diopters. (Results should remain similar when second order deviations, occurring in a plane perpendicular to the optical axis, are incorporated as well.)

Power uniformity: Of key importance in ophthalmic application is the optical precision (or power uniformity of the whole lens) throughout the process of power variations. The device can obviously be made to have a precise desired curvature, say spherical, at the "resting position," where D and the fluid pressure are zero. It is also possible to design the plate's thickness function to realize for a certain nominal pressure another precise spherical form. It can then be shown theoretically that sphericity (or power precision) is kept throughout the whole intermediate range of variations with a very small non-uniformity. In fact, a maximal power deviation (non-uniformity) better than $\pm$ 1/80 diopters was computed for a reasonable set of ophthalmic parameters (d = 30mm, n = 1.55 over a power variation range of $\pm$ 1.5 diopters). This excellent result should be compared with the requirement of $\pm$ 1/8 diopters which is commonly specified for a rigid ophthalmic lens - an order of magnitude less stringent. (Note that such a result holds for the counterpart non-round lens.)

Lens thickness: For a rigid lens, with a similar index of refraction, the curvature of lens surfaces is, of course, identical to those of the adjustable lens. Thus, if the distance D between the circumferential lines of the two sides could be zero, the theoretical thickness (or thinness) of the lens is determined. Practical material strength considerations yield for ophthalmic lens D > 1 mm. For our adjustable lens, the value of D required is twice the thickness of a plate at its circumference, in practice some 2mm. Thus, it can be shown that the adjustable lens, throughout the range of variations, is about 1mm thicker than the counterpart rigid elements. This implies an extra weight of about 2 grams for an adjustable lens over its rigid ophthalmic counterparts.

Switching energy: It is important to estimate upper bounds on the energy required to cause a power step of about 1.5 diopters. Here, we approximate the result by considering only the maximum elastic energy change required in the system, where the corresponding pressure variation is estimated to reach 0.1 atmospheres. Geometry considerations used with basic optical and elasticity principles yield, for d = 30mm a result under 0.01 Joul.

The proposed design eliminates the need of viscous fluid pumping in and out of the lens. Such pumping gains relatively high friction and at the required speeds would have increased the required energy by an order of magnitude.

Non-round lens

The facts listed above for the round lens case are extendable to the non-round case. Again, the power variations call for the change of distances between the plates while the refractive fluid within the lens stays sealed and constant in volume. For the round lens, any distance D implies a uniform spacing between the two circumferential lines of the plates. For the non-round lens, this spacing ceases to be uniform and the spacing between each pair of opposite circumferential points is a function of their location along the circumference. This now means the forcing of non-uniform distance changes at points along the circumferential line that depend on the non-constant distance of these points to the non-centric optical axis. (The feasibility of a mechanism as required here is described elsewhere.) It is conceptually simple to see the geometrical boundary conditions needed to be provided at the circumferential lines by starting with a round lens and determining the changes along the required non-round circumference. The existence of a solution to the elastic forming of varying curvatures follows similarly to the round case.

Other extensions of the above described theorems and facts about the round case, hold as well:

Power uniformity: The advantages are similar and depend likewise on d (the maximal radius here) and on the range of power variation.,

Lens thickness: This thickness is again only about 1mm or less) larger than the counterpart rigid lenses throughout the whole range of power variations.

Switching energy: This energy stays also small similarly to the round case.

Summary

A design principle, rendering theoretical and practical feasibility to the building of ophthalmic lens has been briefly discussed with the listing of key results. Details such as lens frame structure and power variation energizing, leading to product development are under study and will appear elsewhere.

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