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The Impact of Tight Tolerances and Other Factors on the Cost of Optical Components

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Abstract

We report here on the extension of earlier work to incorporate additional tolerances and requirements that have an impact on the cost of optical components. We include information reported by other authors which correlates well with our own findings. An example case is shown where the data base developed was used in a simple computer program to quickly calculate the cost impact of extensive tolerance changes on a large number of components. The possibility of an automated Lens Estimating System is discussed.

Introduction

In two previous papers, we discussed economics in optical design[1] and we have described principles and methods to minimize the cost of an optical assembly through tolerance distribution.[2]

The purpose of this paper is to describe some simple analytical tools and provide data to assist in estimating the impact of tolerances and other factors on the cost of optical components. We further explore some of the factors which are required to have a viable automated optical component estimating system.

Estimating is somewhere between an art and a science. We cannot foretell a future condition, we can only predict it. The probability that the prediction will materialize as expected depends on the accuracy and completeness of the model and the history on which the coefficients of the model are based. One might say that the reliability of an estimator (human or otherwise) depends on his/her/its experience and the relevance of the experience to the question at hand.

It appears to now be possible to construct reasonable automated estimating systems for a broad class of optical components which can incorporate the experience of many experts in a form which allows an inexperienced person to quickly provide estimates with accuracies comparable to those of the experts. In the field of Artificial Intelligence, such a system might be called an Expert System. We here pursue some of the elements of such a system which can be applied now in simple form, and we give our view of the next steps toward an Expert Estimator.

Costs of Tolerances and Other Factors

The cost to produce a mechanical or optical dimension increases with the reduction of the allowed deviation from the nominal dimension. At one extreme, if absolutely no deviation from the nominal (zero tolerance), the time and cost to meet the requirement would go to infinity. At the other extreme, if any and all deviations from the nominal were allowed, the cost to produce the dimension would be some base cost including material and the time (cost) to perform the rudimentary operations required. We take these two assumptions plus the simplifying assumption that cost is inversely proportional to tolerance and we arrive at Equation 1.

$$\$(i) = A(i)/T(i) + B(i) \tag{1}$$

$\$(i)$ is the contribution to the overall cost of the i-th dimension or parameter. $B(i)$ is the base cost independent of tolerance. $A(i)$ is the constant for the tolerance dependent part of the function. The assumption of the reciprocal relationship is the simplest form which we have been able to devise. We believe that what it might lack in exactly representing nature it makes up for in simplicity and usability.

Figure 1 shows an example of Equation 1 where the relative cost of producing a lens to a given diameter increases as the tolerance is made more and more restrictive. The abscissa has been plotted as the reciprocal of the tolerance to give a rectilinear display. The intercept of the plotted data line with cost axis is B(i), the base cost. Figures 1 to 4 have been derived from our earlier paper[2] where our own data was correlated with that reported by Plummer and Lagger.[3] Their data and ours seem to be in good agreement. More detail on our data is given in the earlier paper.

FIGURE 1.

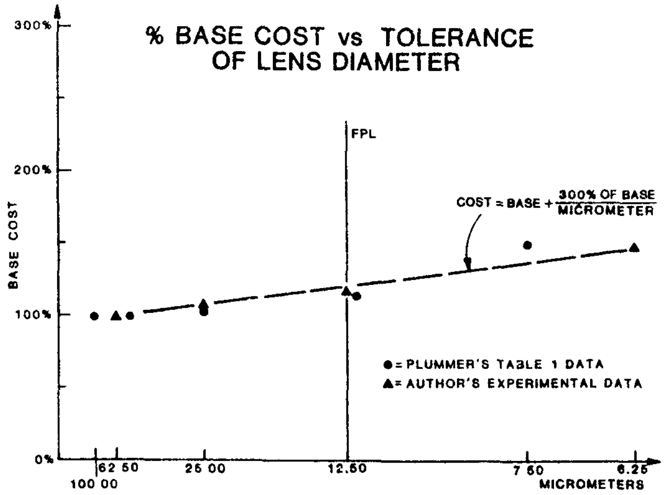


FIGURE 1. LENS DIAMETER TOLERANCE (PLOTTED ON RECIPROCAL SCALE)

FIGURE 2.

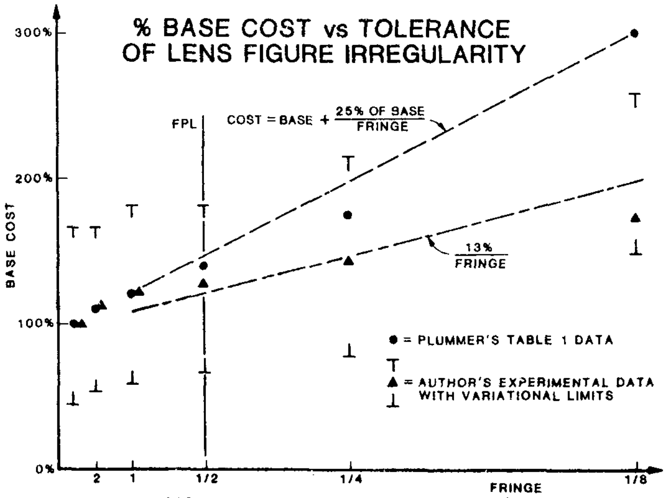


FIGURE 2 IRREGULARITY TOLERANCE ON LENS FIGURE (PLOTTED ON A RECIPROCAL SCALE)

FIGURE 3.

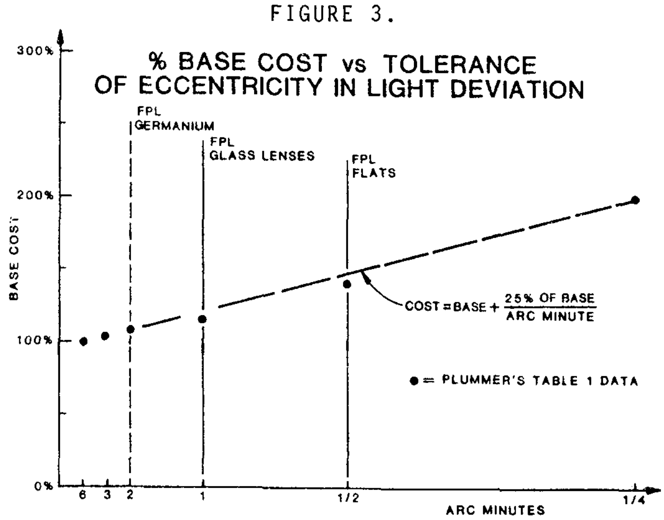


FIGURE 3 ECCENTRICITY TOLERANCE IN LIGHT DEVIATION (PLOTTED ON RECIPROCAL SCALE)

FIGURE 4.

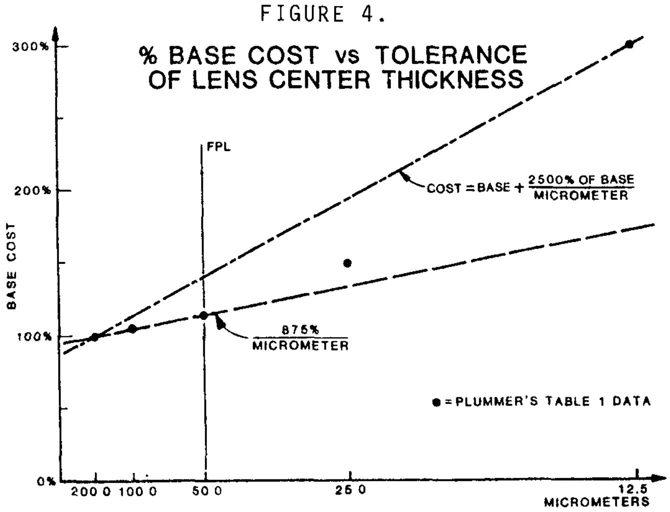
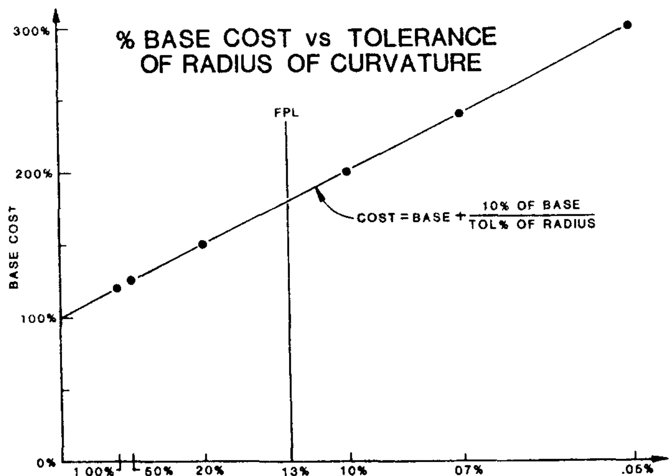


FIGURE 4. LENS C T TOLERANCE (PLOTTED ON A RECIPROCAL SCALE)

FIGURE 5.



%= RADIUS TOLERANCES / RADIUS

FIGURE 5. RADIUS OF CURVATURE TOLERANCE (PLOTTED ON A RECIPROCAL SCALE)

FIGURE 6.

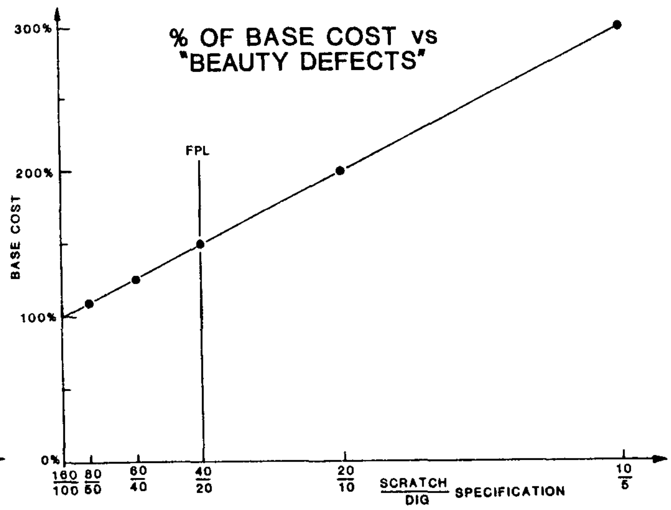


FIGURE 6 EFFECT OF SURFACE FINISH REQUIREMENTS

FIGURE 7.

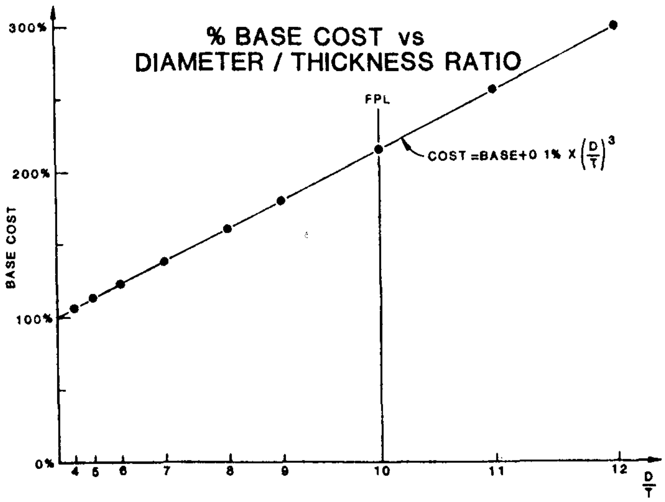


FIGURE 7 EFFECT OF DIAMETER TO THICKNESS RATIO

FIGURE 8.

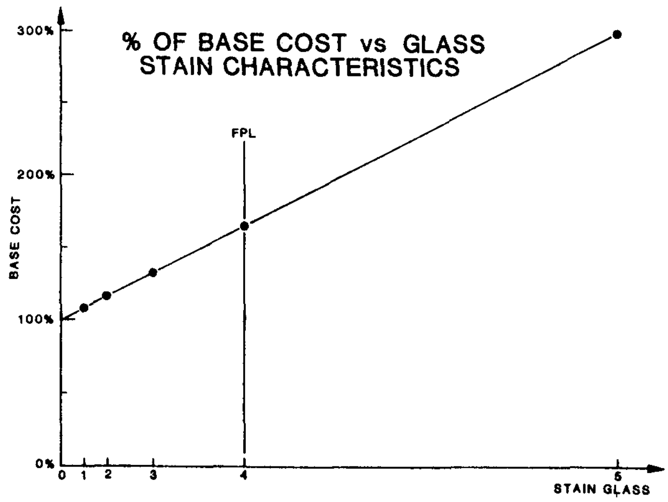


FIGURE 8 EFFECT OF GLASS STAIN CHARACTERISTICS

Figures 2 and 4 show a marked increase in cost beyond that predicted by Equation 1 at the extreme restrictive end of the tolerances. We believe this to be due to those values beginning to exceed the capabilities of the technologies being applied in these cases to produce a predictable/controllable result. We held a meeting of some of our experienced people and reached a consensus on what tolerance limits we felt were currently producible in our shop on a predictable enough basis to make firm cost and schedule commitment. We call this our FPL or "fixed price limit" for internal purposes. This is represented on Figure 1 to 8 as a vertical line. We expect that these limits can be moved to the right as technology, skill, and experience are added to the processes. Since we frequently work beyond these limits, we can only say that tolerances beyond the FPL become more related to a Research and Development environment than a Production environment.

TABLE 1. Cost factor for fabrication labor on different Materials, dones not include material cost

Material Type	Percent of Base Cost
BK7, Germanium	100%
Pyrex, Fused Silica	125
Zerodur	150
Natural Quartz, ZnSe	160
Cultured Quartz, ZnS, FK2, BaF2	175
LaKN9	200
Electroless Nickel	250
SF56,CaF2,LiF	275
KZFSN4,Si,MgF2	300
AMTIR,Electrolytic Nickel,As293	350
Ruby	700
Sapphire	800

This is based on: 80/50 finish, 1 fringe, 5:1 Thickness Ratio, .001" Diameter Tolerance, .004" Thickness Tolerance, 1/4% Radius, 2 arcminutes wedge.

After we had set our FPL lines, we were amazed to discover an article by E. G. Kosman[4] where he listed tolerances for various classes of optics including "extra precise". These agreed entirely with our consensus values of the FPL on Figures 1 to 4. As a result of Plummer's data, Kosman's, and our own, we believe the Figures 1 to 4 are a fair representation of the relative cost of tolerances at this time.

Figure 5 through 8 represent our current internal consensus on experience, but do not have any extensive rigorous data gathering to support them. Figure 7 is based on the simplifying assumption that the effects of flexure and other problems are approximately proportional to the cube of the diameter to center thickness ratio of a lens or mirror. Table 1 is somewhat subjective, but again represents our particular rating of the difficulty of various materials. Other shops may well have processes or experiences which make given materials easier for them to work than for others.

This collection of cost versus parameter functions then forms the beginning of a data base from which we can estimate the cost of a given set of parameters. The next section describes an example where this data base has been applied.

Computing the Effects of a Tolerance Change

We were confronted recently with a new analysis of the tolerances required on a system which contains a large number of optical components. As a result, many dimensional tolerances changed from their earlier values, some tighter, some easier. We then had to assess the impact of these changes on the cost of producing those components. The data base described above became very useful to us in making that assessment.

TABLE 2. Form for Tolerance Change Cost Impact

PART NUMBER	XXXX
Description	Lens Element No. 4
Material	F 5
Current Cost	$275.56
Current % of Base Cost	139.7%
Base Cost	$197.27
New % of Base Cost	113.5%
New Cost	$223.92

Parameter	F.P.Limits	Was	To Be	Was % of Base Cost	To Be % of Base Cost
Radius R1	± .13%	.07%	.14%	242	171
Radius R2	± .13%	.10%	1.68%	200	106
Surface R1	1/2	1/2	3	150	108
Irregularity R2		1/2	3	150	108
Wedge (flat 1/2')	0^{o} 1'	0^{o} 3'	0^{o} 1.2'	108	123
Center Thickness	± .002	± .002	± .010	150	108
Diameter	+ .0005	± .001	± .001	112	112
Surface Quality	40/20	80/50	80/50	110	110
Diameter/C.T. Ratio	10:1	4.6	4.6	109	109
Stain	4	1	1	106	106

Table 2 shows the kind of data that was processed by a microcomputer to evaluate the cost impact. The process was done generally as follows:

Enter current cost to produce component
Enter all "was" tolerances
Enter all "to be" tolerances
Compute current % of base cost
Compute new % of base cost
Compute new cost

The computation of the current % of base cost proceeds from the knowledge or assumption as to how the total current cost is partitioned between the various dimensions or parameters. We assume that the total component cost $(T) is described by Equation 2, where each $(i) are the contributions from each independent dimension or parameter.

$$\$(T) = \$(1) + \$(2) + \ldots + \$(n) \qquad (2)$$

From a given current cost $(i) and current % of base for that dimension, we can calculate B(i). The total of all n of these base costs gives the total base cost. These B(i) plus all of the new tolerance costs A(i)/T(i(new))give the new total cost of the component.

This procedure was applied to all of the components with changed tolerances and new costs were estimated as fast as the data could be entered from a keyboard. There is also a benefit in being able to see at a glance from the form in Table 2 where any tolerance violates the Fixed Price Limit. This provides an early warning system for potential problems and delays in the production when the limits for a given shop are violated.

The current cost data came from actual cost records and the new estimate comes from that and the actual experience represented by Figures 1 to 8. The execution of the estimate was done by some individuals who were non-experts in estimating the cost of optical components using this modest Expert System. In the next section, we will discuss the possibilities and some of the requirements to extend this Expert System to be able to give a reliable estimate of the cost of a new component for which there is no current cost data.

An Automated Optical Component Estimating System

When we begin to consider building an Expert System to estimate the cost of optical components in general, the number of parameters which should be considered is large. The outline below lists some of the things that must be considered and undoubtedly has some elements missing that we have overlooked. If many of the elements of the outline are common to most of the components to be estimated, then variations of these may be negligible. It is only necessary to make the non-expert user aware of the limitations within which the system is valid. For example, if one is normally concerned with visible optical glasses in standard configurations, it may be possible to neglect configuration and most material parameters. If the investment items are relatively constant, then they may be neglected in the model. A useful model might include only II, IIIA&E, IV, V, and VI.

I. Configuration
II. Dimensions
   A. Diameter
   B. Thickness
      1. Center
      2. Edge
   C. Radii
   D. Bevels
   E. Diameter/Thickness Ratio
   F. Clear Aperture/Diameter Ratio
III. Material Including Coatings
   A. Cost/Volume
   B. Hardness
   C. Cold Flow & Stability
   D. Rigidity
   E. Solubility & Stainability
   F. Thermal Conductivity & Expansion
IV. Tolerances
   A. Dimensional
   B. Surface Finish
   C. Transmittance/Reflectance, bulk and coatings
   D. Durability to Environment
V. Quantity
VI. Experience
VII. Investment
   A. Process Development
   B. Tooling, Quantity
   C. Fabrication & Test Equipment
   D. Floorspace
   E. Skilled Manpower

We have not yet touched on the Quantity and Experience aspects of cost. The Industrial Engineering profession has developed a variety of tools for us to use here. The Learning or Experience curves allow us to estimate the effect of past quantities produced on future cost versus quantity. We will not belabor the theories and practice here since they are well developed elsewhere. Kosman's data implies about a 95% learning curve in these terms.

The incorporation of the costs versus basic dimensions in the model should be straightforward although not trivial. We will have to develop a model for the cost as a function of each type of dimension and define the limits of expected viability for each type.

Once a reasonable model is developed, the constants can be refined by comparing historical data with respect to the model, providing the historical data is reliable.

It therefore, appears feasible to develop an Expert Estimating System for optical components within certain limitations that could be valuable and reliable without being excessively complex to use. We would want to be cautious, however, and avoid constructing a system with high versatility but low usability or one with high precision but low accuracy. We should keep in mind that the future result can only be predicted, not foretold.

Conclusions

We have shown a set of cost versus tolerance/parameter relations that correlate well with others in the industry. This data was used in an actual application to determine the probable impact of certain tolerance changes. We have further outlined how this work might be extended to develop an Expert System for estimating the cost of optical components. Such a system is not likely to displace the expert estimator, but should extend his influence and allow his daily activities to be more creative rather than repetitive. This situation shows significant similarity to the evolution which the computer has brought to optical designers.

References

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