Mechanical stability of optical structures

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ABSTRACT

Mechanical stability is an important consideration in the design of optical systems. Optical performance parameters will be affected by a combination of optical sensitivity to environmental effects and structural deformation.

Traditional approaches have been constrained by limitations in design tools and in particular in structural design tools. An approach is presented here which takes advantage of recent improvements in computer aided engineering and which enables stability effects to be considered early in the design process

Key optical performance parameters are identified and typical results are presented.

KEYWORD LIST

Analysis, Boresight, Design, Environment, FEA, Performance, Stability.

1. INTRODUCTION

In the past, performing a comprehensive opto-mechanical analysis involving complex geometries has been difficult. Besides the high level skills required, cultural difficulties existed. Long term historical practice had sufficed to produce adequate designs, even though these design adequacies were generally accompanied by undemanding customer specifications. There was thought to be no need for any extensive performance analysis, and even if there was, it was frequently not possible to do it anyway ! Thus the procedure tended to be to "draw" the product based on experience, and if in doubt, to "over design" it. Now, however, with increased awareness and higher performance being continually demanded, this practice is no longer sufficient on its own.

Fortunately, the improvement of computational tools (many of which were written for stress analysis, but which now have been adopted by opto-mechanical companies for stability analysis), along with the increase in computing power, has made user friendly packages which can consider highly complex geometry that could not be analysed manually. Even the tool costs have reduced significantly from their original mainly prohibitive prices.

However, a number of practical problems have still tended to limit the ability of Mechanical Designers to carry out useful mechanical and opto-mechanical analysis in the design of opto-mechanical systems. This contrasts with the ability of Optical Designers to produce near perfect models of optical designs. Even where structural models have been produced, using techniques including Finite Element Analysis and Computer Aided Fluid Dynamics, these models have been at best approximate and have relied heavily on the judgement of the engineer. The approximate nature of these models arises from a number of sources.

For FEA, they may be effects such as manufacturing tolerances (even between like units), material property non-linearities, anisotropy (or even lack of data !), damping ratio estimations, interfacial stiffnesses / frictions etc. Whilst for thermal analysis using CFD, there are problems of modelling real environmental conditions in terms of heat transfer co-efficient, boundary layer type, interfacial conductions etc., with an additional difficulty of knowing the effect of customer

 0-8194-2159-6/96/$6.00

equipment heat sources surrounding the optical assembly which provide other heat sources and change the convection / radiation conditions.

However, in the pursuit of improved Opto-mechanical solutions, a process is described in the following sections, which is being continually developed to improve the efficiency of all mechanical design concepts at an early stage in the design.

2. OPTICAL SENSITIVITY ANALYSIS

Specifications for optical systems frequently include the requirement that there shall be no degradation of (optical) performance parameters over the specified operating environment. This is clearly an extremely optimistic proposition ! In practice, any change in environment applied to an optical configuration will result in changes in the way in which that configuration will perform. Different performance parameters will be affected in different ways depending on the detail design and the sensitivity of that design to environmental effects.

Some environmental effects on optical performance lend themselves to analysis using traditional optical analysis software. For example, the effect of temperature on transmission of infra-red systems is relatively easy to compute for the optical designer.

However, this paper is primarily concerned with the effect of structural changes on optical performance.

For example, at the level of an individual optical component, the mounting of a lens in a stress free condition under all environmental loads is essential to minimise any reduction in MTF. Such a situation may occur due to thermally induced radial clamping of the lens under a temperature drop - leading to a change in the lens surface curvatures. On a larger scale, the reduction in boresight stability of an entire optical system may be affected by the onset of an inertial load (a static change), or a vibration (a dynamic change).

At a general level, the Mechanical Designer needs to understand the reason for change in only a small number of Key Optical Parameters in order to consider the design of a system to meet specification. These parameters are typically Boresight Stability, MTF and Vignetting. He need not consider analysing these key parameters directly though if he knows what effects cause them to change.

In practice, driving effects such as lens tilt, decentre, axial displacement, surface deformation and material properties are responsible, and so if these can be calculated or measured for the system under design, a method is available for the improvement of the system optical performance.

The following table lists these effects.

Key Optical Parameter	Driving Effect	Reference Co-ordinate System
Boresight Stability MTF Vignetting	Optical Tilt Optical Decentre Optical Axial Displacement. Surface Deformation Material Properties	Optical Axis Critical Element Mounting Axis Minimise Boresight Error

Table 1 : Key optical considerations

The *degree* to which the Key Optical Parameters are affected, are dependant upon three major areas. These are Environment, Physical Arrangement and Optical Sensitivity.

Obviously, the level of the environmental loads and the stiffness characteristics of the physical arrangement will directly affect the magnitude of the "Driving Effects" that are shown in table 1. However, perhaps less obvious is the sensitivity of the optical design to changes in these "Driving Effects". Some optics in the system are likely to have a much larger affect on the Key Optical Parameters than others. Typically in many telescopes, the front lens will have a very significant boresight stability sensitivity. This may be stated in microradians per micron decentre for example, where for small movements, this value may be considered constant.

Knowing these Optical Sensitivities, and combining the effects of environment and structural stiffness, it is then possible to consider a procedure to assist the Designer in his pursuit for a suitable mechanical design.

A diagram is included below which shows the inter-relationship of the Key Optical Parameter(s) to the effects which drive their magnitude.

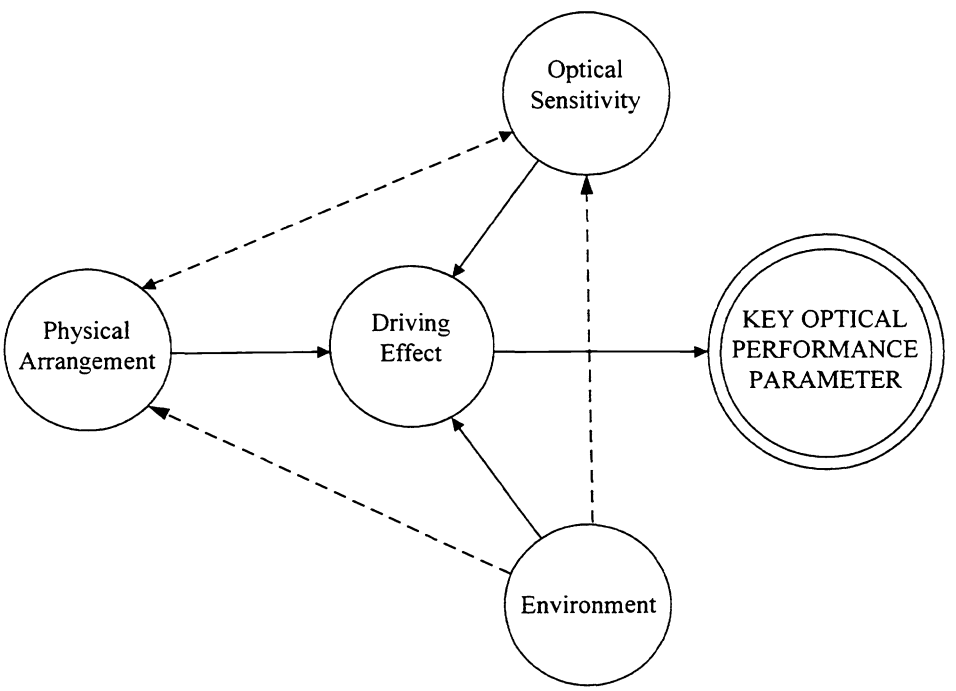

Figure 1 : The inter-relationship between the Key Optical Parameters and their Driving Effects

As is shown, there are links between the surrounding effects. For example, the physical arrangement is designed with consideration to the environment (such as applied stress levels) and the optical sensitivities (such as mounting high sensitivity optics in high stability mounting arrangements). The optical sensitivities themselves (i.e. the optical design) may also be driven by environmental considerations (such as temperature specifications) and the physical arrangement (such as a constrictive space envelope). Because of the variation in sensitivities, it is also necessary to consider the reference point / axis for the measurements.

3. CURRENT APPROACH

The current approach that is being used and continually developed at Pilkington Optronics to improve the mechanical design of optical structures is described in this section. It is based upon the discussions made in section 2.

3.1 Selection of Key Optical Performance Parameters

Initially, the Key Optical Parameters for the mechanical designer are defined and quantified by the Optical Design function. As stated, these may be such quantities as Boresight Stability or MTF. However, for the purposes of this paper, boresight stability will be considered as the single most important driver in the design of the system - this basis being made on the assumption that meeting the requirements will result in a system which as a bi-product will also meet the majority of other optical parameters, and provide a good basis for the proposed mechanical design. This being decided, it is necessary for the levels to be quantified in a form which links the Key Optical Parameter to a mechanical measurement. This is described in sections 3.2 and 3.3.

3.2 Direct Effects on the Optical Performance Parameters

As described earlier, the Key Optical Parameters are directly affected by "Driving effects" such as optical tilts, decentres, axial movements, surface deformations and material properties. Since these effects are quantifiable by analysis and test techniques, a link between these and the Key Optical Parameters will allow the mechanical designer to make predictions about optical performance.

The link is defined in terms of Optical Sensitivities. These are now discussed.

3.3 Optical Sensitivities

For small displacements, it is possible for the optical designer to calculate the boresight sensitivity of the optical design to optical displacements. For example, for a two field of view telescope, it will generally be necessary for the following quantities to be defined.

WIDE ANGLE Field of View		
Optical Element	Boresight sensitivity to decentre (μRad/μm)	Boresight sensitivity to tilt (μRad/μRad)
Front Lens (Objective)	✓	✓
No. 2 Lens (Objective)	✓	✓
No. 3 Lens (Objective)	✓	✓
No.4 Lens (Field of View)	✓	✓
No.5 Lens (Field of View)	✓	✓
No.6 Lens (Eyepiece)	✓	✓
No.7 Lens (Eyepiece)	✓	✓
No.8 Lens (Eyepiece)	✓	✓

NARROW ANGLE Field of View		
Optical Element	Boresight sensitivity to decentre (μRad/μm)	Boresight sensitivity to tilt (μRad/μRad)
Front Lens (Objective)	✓	✓
No. 2 Lens (Objective)	✓	✓
No. 3 Lens (Objective)	✓	✓
No.6 Lens (Eyepiece)	✓	✓
No.7 Lens (Eyepiece)	✓	✓
No.8 Lens (Eyepiece)	✓	✓

Table 2 : Typical Optical Sensitivities required for a 2 field of view telescope

These quantities can then be used by the mechanical designer to recognise the critical optics in the system and to design accordingly. Additionally, they provide the basis for any analytical techniques which may be employed to calculate theoretical predictions for boresight stability performance under environmental loads, and are the link between the Key Optical Parameters and a set of mechanical measurements.

Note that decentres and tilts are often the major drivers in boresight instability, and have been considered here as such. However, others must not be ignored and each optical design should be considered on an individual basis.

3.4 Physical Arrangement

The first iteration physical arrangement of the mechanical design is determined by consideration of the Optical Sensitivities, the environmental loads and any material or spatial restrictions. It is generally coarse in definition so that the geometrical configuration can be optimised at an early stage without committing to a limited performance solution which will hinder development at a later date. Being simplistic in definition and early in the process, it is also easier for analytical techniques to be employed, and more effective when changes are suggested.

Typical kinds of analyses which may be performed are optimisations of various mounting point locations / numbers, natural frequency calculations and artificial thermal gradient effects on displacements. These give the designer a "feel" for the behaviour of his proposed solution and provide a guideline towards the best geometrical configuration to be employed before going into detailed design.

3.5 Key Environmental Loads

The typical key environmental loads which indirectly affect the optical performance are :

a) Static Inertias
b) Sinusoidal Vibration
c) Random Vibration
d) Pressure
e) Thermal Gradients

Again, this list is not necessarily applicable to all situations, and a list should be drawn up based upon the individual situation. However, if performance levels can be theoretically calculated to be acceptable for these loads, then the Mechanical Designer should be confident that his design will satisfy the majority of applied environmental conditions.

3.6 System Budget and Derivation

In calculating system performance parameters - such as those mentioned in section 3.1 - over an accumulation of loading conditions, it is necessary to create a "budget" for the system. This will combine a number of effects which are then statistically accumulated in a suitable manner. The statistical analysis will not be considered in this paper, but is generally tabulated in a manner similar to that shown below.

Optical Parameters	Load Cases or Conditions				Statistical Accumulations	TOTAL
	LC1	LC2	LC3	LC4		
MTF,						
Boresight Stability						
Vignetting						
etc.						

where LC1, LC2 etc. refer to conditions such as static inertias, temperature changes, vibration etc.

Table 3 : Typical System Budget Calculation Matrix

The optical parameters which have been selected are listed in the left most column. The key loading cases are then listed, and against each entry the prediction for performance is entered. The statistical accumulation for the various loads cases should be decided upon by the user (e.g. addition, average, RSS etc.). The right most column of the completed table produces estimations for the degree of optical performance of each parameter under the combined environmental loading conditions. Note that the "Loading Cases" columns should also include the effects of other conditions such as manufacturing tolerances.

The important aspect of the process with respect to this paper is the calculation of the performance v load case cell entry. It is at this point that the link between the Key Optical Performance Parameter and the mechanical analysis can be made. This is done by using the following equation for small displacements.

$$\textbf{Optical Performance} = \sum_{1}^{n} \left(\sum_{1}^{s} \textbf{[(Optic [n] Sensitivity for s) x (Driving Effect Magnitude of Optic [n] for s)]} \right)$$

where the calculation is made for all ***n*** optics in the system and ***s*** sensitivity combinations about a ***single*** axis for a ***single*** load case).

For example, for the two field of view telescope cited in section 3.3, boresight shift in ***azimuth*** may be calculated using the following values :

n = 8 (i.e. 8 lenses) for wide field of view operation,
s = 2 to represent sensitivity combinations of decentre in the lateral axis and tilt about the vertical axis,

If shifts about other axes (e.g. in pitch) are required, a similar calculation will be required with the relevant change in axes. Randomly applied loads also need to be calculated slightly differently.

3.7 What will the displacements be ?

Obviously, the calculation of the entries which are made in table 3 are significant to the process. In particular, for the discussions that are being made here, levels of displacement being calculated from computational analysis tools are essential. Results of some theoretical examples are given in the following section.

3.8 Additional assumptions based upon Key Contributors

With the knowledge of the Optical Sensitivities, it is sometimes possible for the mechanical designer to make quick sizing performance calculations based only upon a small number of optical element displacements. For example, telescope front lens elements often have a much higher boresight stability sensitivity than many of the other elements in the system. Combined with the likelyhood of this element displacing more than any other due to its greater mass and possible geometrical overhang, it may thus be possible to gain an idea of potential boresight instability based upon a small number of optics.

4. TYPICAL RESULTS OF THEORETICAL CALCULATIONS

Examples of the process being described and currently implemented at Pilkington Optronics are given within this section. Below is shown a typical FEA model of a telescope, which was used in the initial design configuration stage to assess the suitability of various potential mounting point locations. Unit static inertias are initially applied to make comparative displacement analyses between options. Modal, sinusoidal and random analyses can then be applied to the preferred options to assess dynamic boresight stability.

A plot of a typical FEA model is given as follows.

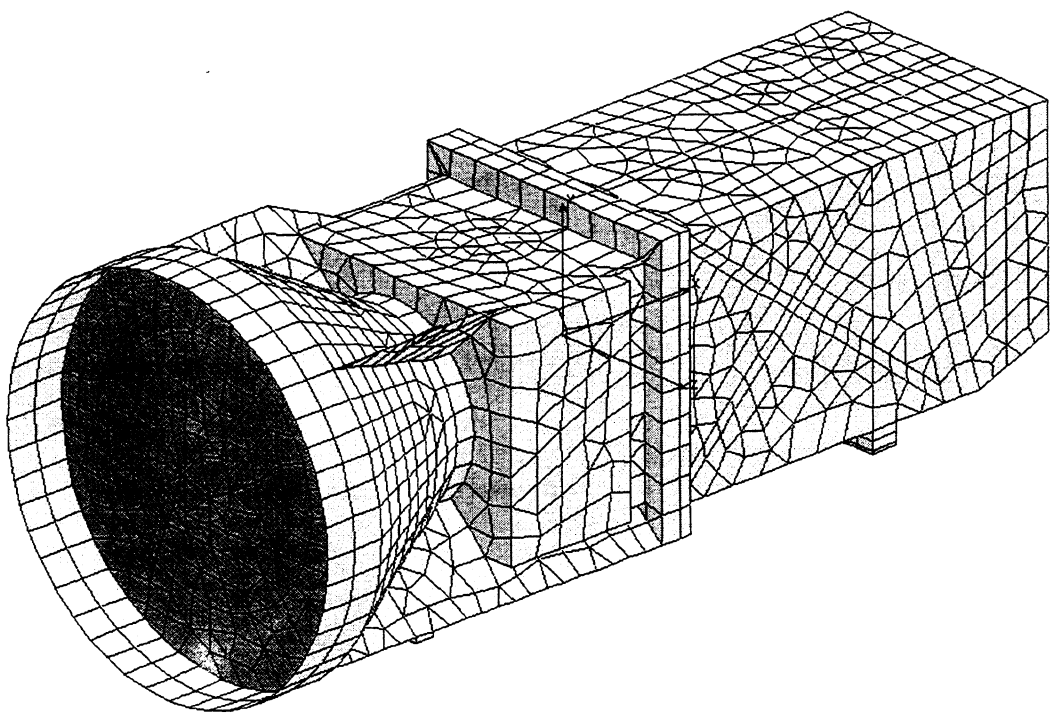

Figure 2 : Typical FEA model of a telescope - used to optimise mounting point locations

From this type of model it is then possible to obtain an initial estimation of the full system optical boresight stability under environmental loads. A typical output is summarised in the table that follows for a static inertia of 10 g, applied in 3 orthogonal directions to a three field of view system.

	Boresight shift in microradians					
Field of View	10 g (axial)		10 g (lateral)		10 g (vertical)	
	Azimuth	Pitch	Azimuth	Pitch	Azimuth	Pitch
Wide	64	91	-287	-72	-12	-399
Medium	33	35	-99	-38	5	-156
Narrow	20	15	-39	-24	3	-30

Table 4 : Typical Boresight Stability predictions from the FEA modelling of a telescope

Calculations such as these can be generated automatically from the FEA software by writing a simple macro in the system language to calculate them directly from the database results of displacements. This enables access to system boresight estimations immediately after the environmental load case has been analysed.

This technique has also been extended to cover thermal gradient loads and dynamic (sinusoidal and random vibrations) loads, where dynamic boresight stability predictions can be made.

4.1 Advantages from a theoretical prediction

The advantages from the described process are significant. They include :

a) Reductions in testing times and costs
b) Improvements in the initial configuration - leading to better performing, more competitive and marketable products
c) Increases in customer up-front confidence levels
d) Lower risks - both to customer and vendor
e) Creation of a breakdown of the performance variance against individual optics and load cases. This highlights key environmental conditions and design features to monitor during the design process.

5. SUMMARY OF DESIGN / ANALYSIS PROCESS

The process which has been described in this paper for the improvement in design configurations to meet optical performance parameters under environmental loads is summarised in the following flowchart.

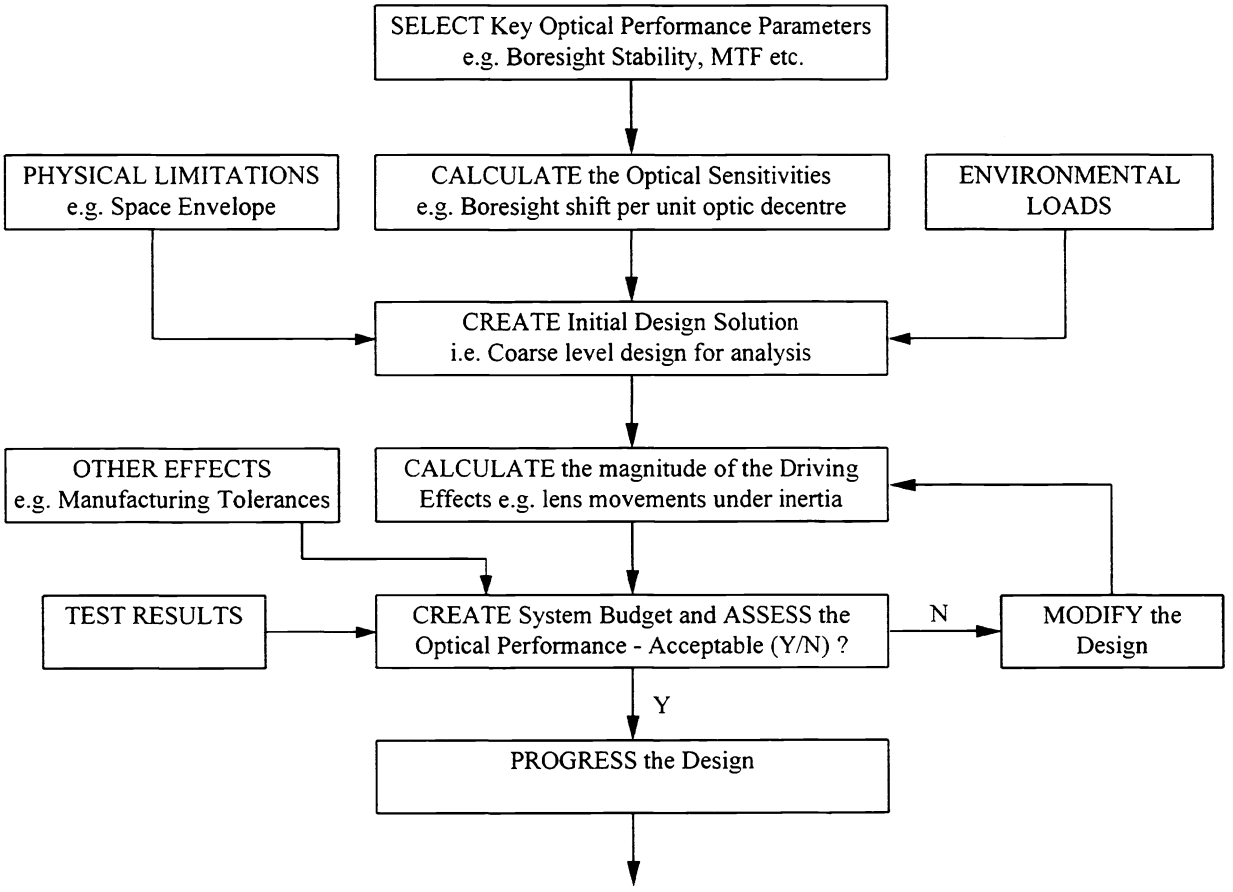

Figure 3 : A flowchart of the process for improving the stability performance of designs under environmental load

6. ACKNOWLEDGEMENTS

This process was developed within the Mechanical Design Department of Pilkington Optronics, St. Asaph, UK.