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OPTO-MECHANICAL INSTRUMENT DESIGN

Roger S. Reiss
Lockheed Missiles & Space Company, Sunnyvale, California 94088

ABSTRACT

The field of "Opto-Mechanical Instrument Design" is becoming an identifiable discipline. From the time the first optical instruments were designed, fabricated and assembled, optical and mechanical engineering design have been coupled together. Now with the high accuracy and stability required for many optical systems, the mechanical engineering aspects of the main support structure have become of paramount importance (at times equaling the importance of the optical system design itself). Today the world of accurate measurements and alignment is based on the quality and performance of the opto-mechanical instruments available. This paper will highlight the topics that must be considered during the design, development, fabrication, assembly and test of an opto-mechanical instrument: materials of construction, fabrication, jointing, stress analysis, thermal analysis, vibration analysis, transmission (power), rotary motion, linear motion, adjustments and alignment. For additional information on opto-mechanical design, the following references will be useful: "Introduction to Opto-Mechanical Design" by D. Vukobratovich; "Opto-Mechanical System Design" by P. Yoder, Jr.; "Fine Adjustments for Optical Alignment" by R.S. Reiss. Telephone: (415) 965-3888.

1.0 INTRODUCTION, OVERVIEW

The difference between an opto-mechanical instrument and any other precision instrument is not always definable. As a group, opto-mechanical instruments of the past were only a small percentage of the overall group of precision instruments. But today, this is definitely not the case, and one would have considerable difficulty identifying a precision instrument that does not have some portion of its design, operation, fabrication or testing involved with optical or opto-mechanical engineering principles. The first requisite of an opto-mechanical instrument is the use of light and/or optics and a higher accuracy/-resolution/stability than the basic group of precision instruments. From the mechanical design engineering viewpoint, there is little difference between an opto-mechanical instrument and any other precision instrument. The same parameters usually apply, however, various parameters are usually emphasized or de-emphasized based on the physical laws and principles of the instrument.

Opto-mechanical instruments require a main support structure or housing or optical bench usually surrounded by a non-structural enclosure. It is this main support structure and its rigidity which determines the opto-mechanical instrument's ability to perform to the required specifications in the required environment. The parameters of the opto-mechanical instrument must be envisioned in concert with the main support structure before any design concepts or design configurations are finalized. Accessibility to the mounted components, the adjustments, as well as the ability to assemble and disassemble the instrument must be taken into consideration. Future upgrade modifications, wherever possible, should be envisioned during the early design layout phase. A lead opto-mechanical engineer (regardless of background and/or training), must learn as much as possible about the physical laws and principles of the particular opto-mechanical instrument. Also he must become aware and stay aware of any deviation in the specifications and requirements that would require design modifications. "Know your opto-mechanical instrument."

Over the years, I have noticed that a number of major subtopics repeat themselves (see outline below). In the future there may be other papers that enlarge the individual subtopics or that introduce new subtopics. However, the basis for this particular paper is to keep the information on a general basis and save the detail investigation for the individual opto-mechanical engineer. The necessary reference material for this paper is mentioned above. These three references should directly or indirectly lead the engineer to almost everything ever published on opto-mechanical instruments (the authors can be contacted directly).

MAIN SUBTOPICS

1.0 Introduction
2.0 Materials
3.0 Fabrication
4.0 Jointing
5.0 Stress Analysis
6.0 Thermal Analysis
7.0 Vibration Analysis
8.0 Power Transmission
9.0 Rotary Motion
10.0 Linear Motion
11.0 Adjustment
12.0 Alignment
13.0 Miscellaneous

BASIC THINKING

- Opto-mechanical engineering is a multiple disciplinary field.
- Optical component mounting and location is the major consideration.
- Distortion and deflection are more important than stresses.
- An individual must think in terms of micro inches or micro radians rather than in thousandths of an inch or arcsec.
- During the initial design, the areas of fabrication, assembly, test, alignment and flight conditions must be envisioned and considered.
- Opto-mechanical instrument design requires the most up to date precision and advanced mechanical engineering knowledge available.

GENERAL DESIGN FEATURES

- Performance requirements
- Size, shape, and weight limitations
- Interfaces (optical, mechanical, electrical, etc.)
- Operating environment (see separate list)
- Force loads (static and dynamic)
- Duty cycle and useful life requirements
- Maintenance and servicing provisions (access, fits, clearances, torquing, etc.)
- Emergency or overload conditions
- Center of gravity and lifting provisions
- Human-instrument interface requirements and restrictions (including safety aspects)
- Electrical requirements and restrictions
- Materials selection and limitations
- Finish/color requirements
- Corrosion, fungus, rain erosion protection requirements
- Inspection and test provisions
- Electromagnetic interference restrictions
- Special markings or identifications
- Storage, packaging and shipping requirements

PARAMETERS, ENVIRONMENTAL

- Temperature
- Pressure
- Fungus
- Radiation
- Chemical
- Humidity
- Contamination/corrosion
- Vibration
- Acceleration
- Acoustic noise
- Shock
- Static stress
- Abrasion/erosion
- Structure induced stresses

2.0 MATERIALS

MATERIALS OF CONSTRUCTION

- Aluminum

  Aluminum is light (.097 LB/IN^3) and possesses excellent machining characteristics. The major shortcoming of aluminum is its large coefficient of expansion, 13.3X10^6 IN/IN^{o}F in comparison to glass, with a coefficient of expansion of approximately 4x10^6 IN/IN^{o}F. This difference may cause image degradation and may even result in breakage if the thermal requirements are stringent. But because of its low cost, easy machinability, and high conductivity which allows it to achieve thermal equilibrium quickly, aluminum is extensively used in the opto-mechanical field.

- Stainless Steel

  The austenitic (300 series) or martensitic-ferritic (400 series) stainless steels are extensively used when the thermal requirements are stringent. The coefficient of expansion of 416 stainless steel is 5.5X10^6 IN/IN^{o}F, which closely matches that of the glass. The stainless steels, however, are difficult to machine and are heavy. The density of stainless steel is .28 LB/IN^3 which makes it approximately three times heavier than aluminum. Another iron-base material used is invar which is an iron/nickel alloy containing 36 percent nickel. This material possesses a very low coefficient of expansion, .70X10^6 IN/IN^{o}F, but is costly, heavy, and difficult to machine. Super invar has an even lower coefficient of expansion, .60X10^6 IN/IN^{o}F, but has the same disadvantages as the invar.

- Beryllium

  Beryllium with very low density (.067 LB/IN^3), high stiffness, and an acceptable low coefficient of expansion (6.4X10^6 IN/IN^{o}F) is an attractive metal. Its high cost and machining difficulty, however, make this metal sometimes undesirable. Machining beryllium can be hazardous to the operator and is handled by only a few shops.

- Titanium

  Titanium alloys, particularly the TI-6AL-4V, are excellent materials. Titanium has a coefficient of expansion very close to glass, $4.9X10^6$ IN/IN°F, and its density is fairly low, .164 LB/IN^3. Titanium is stable and yields itself to grinding and lapping operations, even though some work hardening is encountered. The shortcomings of titanium are high cost and difficult machinability. A further disadvantage is its low thermal conductivity, which keeps the metal from reaching thermal equilibrium quickly.

- Composite materials (See other sections)

KEY PROPERTIES OF MATERIAL

MECHANICAL	PHYSICAL	METALLURGICAL	FABRICATION
o Elastic modulus	o Coefficient of thermal expansion	o Crystal structure	o Machinability
o Strength	o Density	o Phases present	o Grindability
o Microyield strength	o Thermal conductivity	o Voids and inclusions	o Plateability
o Creep strength	o Specific heat	o Grain size	o Environmental hazards
o Hardness	o Neutron cross section	o Recrystallization temperature	
o Ductility	o Melting point	o Stress relief temperature	
	o Electrical conductivity	o Heat treatability	
	o Vapor pressure	o Texture	
	o Corrosion potential		

Notes: Temperature sensitivity of listed parameters; availability, including size and cost

DIMENSION STABILITY, OVERVIEW

One of the most important requirements for a precision machined metallic support structure is that the dimensions remain constant over a period of time (at constant temperature) in the absence of applied stress. This indicates that the support structure material (and its configuration) is dimensionally stable. A cast aluminum alloy support exhibits better dimensional stability if the material possesses a directional structure pattern instead of a random structure typical of ordinary castings. The change in dimensions observed during thermal cycling are the result of the following conditions:

- Residual elastic stresses which seem to relieve themselves by plastic deformation, with time as a factor
- The microyield strength that opposes plastic deformation and therefore opposes relief of residual stresses
- Micro-creep property found in all metals

DIMENSIONAL STABILITY NOTES

- As long as the item never reaches an operational temperature higher than that used in stress relieving, the item will remain in an annealed condition with enhanced dimensional stability.
- Each major producer of metallic support structure (or other large metallic pieces) has their own proprietary process for thermal cycling and machining items.
- Thermally induced warpage caused by inhomogeneity in weldment can be minimized by matching the coefficient of expansion of the welding material to that of the base material.
- Use of a stress temperature cycling after welding will assist in reducing distortion caused by the welding.

DIMENSIONAL STABILITY, CONTROL

- Instability in metals
  - Metallurgical instabilities
  - Stress related
- Metallurgical instability; proper choice of materials
- Stress related; the release of stresses due to:
  - Heat treatment
  - Mechanical working
  - Machining
  - Applied stresses (operational): static, vibration, acceleration temperature cycling
- For maximum stability, very rigorous process control of part fabrication is required
- Change in dimension as a function of time while under constant stress is microcreep

MACHINE AND STRESS RELIEF SEQUENCE

- o Rough machine: 0.020; Over finish size
- o Anneal:
  - Heat slowly (300°C/HR to 815°C for 1 hour)
  - Cool (50°C/HR to 200°C)
  - Cool in still air (from 200°C to room temperature)
- o Semifinish machine: 0.005; Over finish size
- o Finish machine: 0.003; Over finish size
- o Stress-relieve:
  - Heat slowly (100°C/HR to 800°C for 1 hour)
  - Cool (50°C/HR to 200°C)
  - Cool in still air (from 200°C to room temperature)
- o Fine finish machine: 0.001; Maximum removal - per pass
- o Stabilize: cool, heat, heat, cool, repeat
  - Cool (in 30 min to -70°C and hold 15 min)
  - Heat (in 30 min to R.T. and hold 15 min)
  - Heat (in 30 min to 100°C and hold 15 min)
  - Cool (in 30 min to R.T. and hold 15 min)
  - Repeat

COMPOSITE MATERIAL, DEFINITION

A composite material is a combined material created by the synthetic assembly of two or more components, a selected filler or reinforcing agent, and a compatible matrix binder. This combining of components, filler (reinforcing agent) and a binder is done in order to obtain and maintain specific characteristics and properties of the resulting composite material.

COMPOSITE MATERIAL, EVALUATION

The development of composite material and the manufacturing processes includes analysis and experimental evaluation of these materials sensitivity to the following:

o material content o fiber orientation o cure and thermal cycling conditioning

Mechanical properties tests on specimens usually indicate tensile strength and tensile modulus values compatible with predicted strength and stiffness.

COMPOSITE MATERIAL PROPERTIES FACTORS

- o Component properties
- o Relative proportion
- o Size and shape
- o States of aggregation and agglomeration
- o Relative dispersion and orientation
- o Level of interphase adhesion

COMPOSITE MATERIALS SUMMARY

- o Equations have been developed to reflect the rapid fall-off of properties when:
  - Loads are not applied in the direction of reinforcement
  - The effect of critical fiber length
  - Environmental effects
  - Aging
  - Thermal conditions and other more esoteric conditions

ADVANCED COMPOSITES

HARDWARE REQUIREMENTS	PROPERTIES
o Dimensional stability	Low thermal expansion; high conductivity; no outgassing
o High structural rigidity	High specific stiffness
o High load capability	High specific strength
o Space deployable/erectable-/repairable	Light weight (shuttle transportable); simple joining and fastening
o Modular	Simple joining and fastening
o Radiation hardened	High strength; high temperature; controllable thermo-optical properties
o Rapid track and pointing	Good vibrational damping
o Low cost	Cost-effective manufacturing

3.0 FABRICATION

MACHINING, ALIGNMENT

Full advantage should be taken of modern machine tool developments and of the accuracy of the work that can be done by them. Even the model work shop in which the construction of an opto-mechanical instrument is carried out may not posses all the equipment necessary, it is possible to send out portions of the work to a better qualified, higher precision machine shop.

An opto-mechanical engineer must pay attention to the method in which a metal component is held or clamped in the various types of machine tools. Difficulty may be encountered in the precision machining operations, if provision for clamping has not been made. It is much easier to provide for this clamping provision before the fact (design stage) than after the fact (in the machine shop). Consideration must also be given to the requirement for sufficient rigidity in the item to enable it to be properly precision machined. This is besides the rigidity already required in the design of opto-mechanical instrument. It is difficult to mill a flat surface on the outside of a thin-walled box. The accuracy of the machining achieved is often governed by the rigidity of the item. The amount of rigidity required varies with the machining process employed. A surface grinder will produce satisfactory results with a less rigid item than would be required for milling.

Some idea of the alignment procedure (internal to the instrument) should be formulated early in the design phase; from this vantage point machining accuracy (watch cost carefully) can be built into the main support structure. This will result in savings of time and money during the internal alignment of the opto-mechanical instrument. Parallelness, coplanar and orthogonality should be incorporated on the main support structure to get the most out of the various machining operations. Working in conjunction with a shop qualified individual during the design phase would pay off ten fold. This individual would also assist in the anticipated assembly difficulties that can occur when dealing with close tolerance components. The rule is therefore, design in as much accuracy as possible, followed by machining in as much accuracy as possible, all within a reasonable cost figure.

Be aware of components and subassemblies that must be aligned after instrument assembly and provide view holes. Alignment viewing holes should be developed in the initial design phase of the opto-mechanical instrument.

WELDING

- Gas welding: Head of fusion provided by combustion of flammable gas such as acetylene.
- Shielded metal-arc: Weld puddle protected by gases given off as electrode coating vaporizes in the arc.
- Submerged-arc: Weld puddle shielded by mound of granular mineral deposited on the seam ahead of the arc. Rapidly produces high-quality, low-cost welds, especially in thick plate.
- Gas-tungsten-arc: Are generated by a nonconsumable tungsten electrode; weld puddle shielded by a flow of inert gas. Produces welds of utmost quality, but slower and more costly than other processes. Commonly used on aluminum, magnesium, titanium, or high-alloy steels requiring thorough shielding.
- Gas-metal-arc: are generated by a consumable electrode, shielded by a flow of inert or special active gas. Developed for reactive metals such as aluminum and magnesium.
- Resistance welding: mating workpieces made molten by resistance heating from flow of electric current. No fluxes or shielding needed.

LIGHT WEIGHTING

A number of lightweight mirror technologies can be utilized in opto-mechanical support structure design

- Thin walls: Weight can be approximately 40% of thick wall design. Requires a complex rib support system.
- Plate and radial back ribs: Weight may be 40% of thick wall design. Usually center or edge reinforced.
- Plate and "honeycomb" back ribs: Weight can be 30% of solid wall design. Needs complex back support.
- Cellular core: Weight can be 20% of solid wall design. Needs complex back support. Expensive and fragile.

Note: Finite element methods should be used to obtain predictable deflections.

FABRICATION AND JOINTING TECHNIQUES

The following forms of fabrication and jointing techniques are listed in order of decreasing opto-mechanical instrument desirability:

- o Solid block
- o Casting
- o Welded
- o Bolted (overbolted)
- o Riveted
- o Bolted (normal structural practice)
- o Cemented (structural adhesive)

BASIC CASTING METHODS

- o Sand casting
- o Die casting
- o Shell-mold casting
- o Permanent mold casting
- o Plaster-mold casting
- o Investment casting (lost wax process)

4.0 JOINTING

JOINTING, DEFINITIONS

- o Two surfaces of metals may be joined by an intermediate metal (usually an alloy) which by the application of heat is made to flow and adhere to the metals, as in soldering (hard or soft) and brazing.
- o Two surfaces to be joined are of the same metal and in certain cases they may be made to fuse together at a suitable temperature (welding).
- o Two surfaces of metal may be held together by mechanical forces produced by screw, rivets, etc.

PIN FASTENERS

Pin fasteners are an effective approach to assembly and disassembly. Loading on the pin should be primarily in shear and relocation of the two items is a requirement. Pin fasteners can be separated into two groups:

- o Semi permanent
- o Quick release

Opto-mechanical instruments would normally only be concerned with the semi-permanent pin fasteners. These pin fasteners require application of pressure or the aid of tools for installation and removal. There are two basic types of pin fasteners:

- o Machine pins
- o Radial-locking pins

The machines pins are normally used for opto-mechanical instrument because the radial-locking pins are not positive position locationers. The four types of machine pins are:

- o Hardened/ground dowel
- o Taper
- o Clevis
- o Standard cotter pins (not considered)

General rules for all types of machine pins:

- o Avoid conditions where the direction of vibration is parallel to the axis of the pin.
- o Keep the shear plane of the pin a minimum of one diameter from the end of the pin.
- o Allow pins to protrude at each end for maximum locking effect (assuming appearance and operational interference is not an issue).

When it is required to take apart and replace parts very accurately, screws should not be used for location but only for clamping the parts together. Provide a clearance hole for the screw (counter sink screws are not suitable for this application). Accurate parts location is obtained by taper pins fitting in drilled holes. The holes should be drilled through both parts when they are clamped in their correct location. A taper reamer (to suit the pin) is then run through the holes. Parallel instead of taper pins (known as dowels) are often used for the same purpose.

ADHESIVE BONDING, OVERVIEW

Adhesives are used to join metals for structural and non-structural applications. The generally accepted theories and analysis of the adhesive bond relates to mechanical adhesion and chemical adhesion. Most of the information available on adhesives and adhesion is the result of experiments. From an application standpoint, adhesives are generally classified as:

- o Structural
- o Non-structural

Structural adhesives are those which produce high-strength joints used in high-stress area. The non-structural adhesives are used in areas where stresses are low because of either small applied loads or large bond areas in relation to the load being applied. Chemically, adhesives are divided into:

- o Thermosetting resins
- o Thermoplastic resins
- o Elastomeric materials
- o Organic materials
- o Inorganic materials

Surface treatment of metals to be bonded is an important factor in obtaining strong joints. In designing joints to be bonded, the high shear strength and relatively low peel strength of adhesively fastened metal systems must be considered. The thickness of the adhesive is a contributing factor in bonded joint strength. Generally, the bond strength of the more rigid adhesives used for structural applications decreases as thickness of the bond increases. Adhesives, when performing their function of holding, are always part of a structure or composite. Adhesives never function as separate entities but as materials which influence and are themselves influenced by the materials which they contact.

ADHESIVE BONDING (ADVANTAGES)

- o Uniform stress distribution (with resultant increased service life)
- o Reduced weight
- o Smooth surfaces and contours
- o Ability to join very thin metal sections
- o Does not require high temperatures for joining (U.V. Curing)
- o Ability to join dissimilar metals
- o No need for perforating the metals
- o Can provide leak proof joints
- o Can incorporate vibration damping and insulation properties
- o Can provide corrosion resistance

ADHESIVE BONDS (DISADVANTAGES)

- o The maximum operating temperature of bonded opto-mechanical instrument is determined by the adhesive
- o Structural adhesives generally have high shear and tensile strength, but their resistance to peel and cleavage stresses is relatively poor
- o No reliable non-destructive testing technique exists which will locate unbounded areas or those areas where a very weak bond exists
- o Difficult or impossible to disassemble

5.0 STRESS ANALYSIS

FINITE ELEMENT MODELLING

Finite element modeling can achieve a variety of system engineering analysis. It is particularly valuable if the optical system calculations are integrated with opto-mechanical stress and thermal analysis. This also allows for simulated inputs and/or computerized evaluation of a design before hardware is fabricated. Performance calculations can be made with linear equations. Since performance depends on structural and thermal reactions, the equations can be tied in with the finite element model. Most computers can handle the full range of thermal and structural analysis. The finite element model can be fully used for a great variety of performance calculations, simulations and predictions. Advantages of dynamics analyses are as follows:

- o Can indicate tests necessary to define unknown characteristics
- o Can indicate design weaknesses and areas where changes are desirable
- o Can indicate effects of proposed design changes on system configuration
- o Can indicate specifications of equipment design and test requirements

DEFLECTION CONTROL

- o Opto-mechanical engineers are concerned with deflection control.
- o Deflection can occur due to self-weight, acceleration (g's), vibration, thermal stresses or improper mounting.
- o Deflection is only important when the performance of the system is degraded. The structural support for the system can distort if there is no adverse effect on the optics.
- o Initial design should concentrate on stiffness (natural frequency).
- o Structural connections should be evaluated as part of the stiffness of a structure.
- o Active structural systems; minimum stiffness, actuators, closeloop adjustments, alignment over one meter to many meters.

6.0 THERMAL ANALYSIS

THERMAL MASS MODELING

Mass test models should be fabricated based on computer finite modeling program plus the experience of the personnel on a particular program. The three areas of interest are:

- Stress analysis
- Thermal analysis
- Vibration analysis

There is always the question as to whether one, two or three simulator models have to be fabricated. This could be determined through computer data evaluation. The closer the mass simulator model can come to the actual (or anticipated actual) instrument the more dependable the results would be for predicting modification of the opto-mechanical design.

TEMPERATURE CHANGE

Distortion of optical elements, the expansion and contraction of the opto-mechanical support, and lateral variations all contribute to change in alignment. Loss of boresight accuracy will degrade the optical performance and in turn will reduce overall system performance. The amount of deviation from optimum performance is a complicated relation of every item in an opto-mechanical instrument and each item's thermal parameters. More important than the use of the low thermal coefficients is the matching of the thermal properties of mounting materials and their configuration. The effects of temperature change on an opto-mechanical instrument is to alter size and shape of individual components and to vary the originally aligned component positions.

THERMAL CONSIDERATIONS

- Ambient temperature
- Ambient temperature tolerance
- Ambient operating temperature range
- Ambient storage temperature range
- Rate of temperature change (over the range)
- Material thermal properties with ambient temperature
- Temperature gradients
- Temperature gradient patterns
- Temperature gradient pattern stability (constant ambient)
- Temperature gradient pattern with ambient temperature

Laser diodes are extremely sensitive to change in temperature. Thermoelectric coolers can assist in both limiting the temperature range and holding tight tolerances on temperature variations.

- Beam wander, lateral
- Spot size
- Spot location, focus
- Power level
- Wavelength variation
- Life
- Change of characteristics with time and temperature

INTERNAL THERMAL CONSIDERATIONS

- Light sources
- Motors
- Electrical components
- Cryogenic equipment
- Air movement
- Friction, generating heat
- Switches
- Conduction

ATHERMAL DESIGN

- Same material
  - All glass system
  - All metal system (reflective optics)
- Metering rods
- Low thermal coefficient of expansion
- Low thermal/high thermal coefficient of expansion
- Graphite epoxy composites

HEAT SOURCE DISTORTION

- Heat sources near the optical beam path can cause a distortion in the beam due to air turbulence
- Heat sources should be kept away from the optical beam path
- Failing this, heat sources should be insulated or located where hot air will not rise into the beam
- Laminar or layered still air can also cause problems
  - Perpendicular to optical axis
  - Parallel to optical axis

7.0 VIBRATION ANALYSIS

Vibration can degrade the performance of an opto-mechanical instrument. Vibration isolators are available or can be designed which can attenuate and dampen vibration, but can never completely eliminate it. The parameters and configuration of the isolation system depends on the natural frequency of the structure and the vibration input frequency. For a given input vibration, the optimum solution is a trade off between low end frequency isolation and optical axis instrument stability (boresight alignment shift). Correct choice of the following play a function in vibration tolerance and deflection resistance.

- o Base plate material
- o The material of the items mounted to the base plate
- o The interface between the item and base plate
- o The wall configuration (solid, sandwich or honeycomb)

Parameters which should be taken into consideration are:

- o Material stiffness-to-weight ratio damping
- o Thermal stability
- o Dimension stability
- o Total weight

The interface mounting between the opto-mechanical baseplate and the isolation system must also be designed. The interface mount to the baseplate must be taken into account when overall stiffness (higher natural frequency) is evaluated. Kinematic principles in the interface mounting may assist in reducing deflection and improve overall stiffness (higher natural frequency).

HARD MOUNTING

Primary concern during the opto-mechanical instrument operating temperature range is the strain caused by compressive stresses which result in birefringence and image degradation. Hard-mounting axial positioning of elements is accomplished by machining of the element seats as part of the assembly procedure. Once located the hard mounted element remains in its position within required tolerances during shock and vibration inputs. In hard-mounting the glass elements and the metal seating or retaining parts must be ground to match (very tight tolerances). A thermal stress analysis should be conducted to determine the levels of compressive stresses to which the elements will be subjected through the specified temperature range (glass compressive strength is greater than 50,000 LB/IN^2 but 500 LB/IN^2 should be the limit to minimize birefringence and image degradation). For metal mirror the stress load limit is much higher before mirror distortion occurs. Predicting distortion for metal mirrors under load is difficult.

Hard mounting is therefore the elimination of any resilient material, other than .000500 mylar sheet to take up grinding irregularities. This mylar thickness appears almost as stiff as the metal seat. Even with extreme temperature range both refractive elements and reflective elements have been successfully hard mounted against very high shock and vibration inputs.

VIBRATION ISOLATION

- o Vibration will degrade the performance of an optical system (by how much?)
- o Vibration can cause misalignment of the optical elements
- o Vibration can cause deformation of the optical elements
- o Vibration can excite second order resonances
- o A system isolated from vibration is <u>not</u> a stabilized system (soft flight vs hard mount).
- o Maintenance of the line of sight and minimizing the blur circle requires an I.M.U. (Inertial Measurement Unit) plus software correction.

PRIMARY MIRROR MOUNT TRADE APPROACH

- o Mounting approaches:
  - Hard mount
  - Flexure mount
- o Forms of disturbances:
  - Initial mounting
  - Gravity release effects
  - Thermal stresses
  - Micro-stress release
  - Mounting release
- o Items considered in the trades:
  - Gravity induced stresses
  - Thermal induced stresses
  - Mounting material properties
  - Mirror material properties
  - Machining tolerances
  - Acceleration induced stresses
  - Dimensional stability procedure

8.0 POWER TRANSMISSION

BACKLASH

The movements of the input element (driver) and the output element (driven) of a transmission are linked in a fixed relationship. Every movement of the output element is a function of a related movement in the input element. Departures from this relationship are known as "backlash", "shake" and "play". The latter terms refer to uncontrolled movement caused in the transmission by looseness (clearance) of mechanical parts. The only corrective actions that will reduce these undesirable movements are either spring-loading or reduced clearances between mechanical parts. Backlash quantity can be observed as the lost motion between the input element and the output element whenever the input is reversed (a dead zone of motion). Components (gears, clutches, couplings, etc.) that depend on the tight fit between mechanical parts in a drive train are still susceptible to some residual backlash. Spring-loading is the most reliable method of eliminating backlash, since it insures contact between mechanical parts regardless of the direction of input. Because of the additional friction in the transmission elements, spring-loading can improve the positional resolution but the accuracy remains unchanged.

COUPLINGS

A coupling is a form of linkage between two shafts to correct misalignment between the driver component and the driven component. The three types of misalignment are as follows:

- Axial: Variation in the longitudinal displacement between two shafts
- Lateral: Variation in lateral displacement between two shafts that are parallel
- Angular: Variation in the axial displacement between two shafts

Various combinations of these misalignments occur in the same system and are usually dealt with through use of a single coupling. The choice of coupling will depend on:

- The type of misalignments
- The amount of power being transmitted
- The speed of operation

Typical instrument couplings are as follows:

- Multi-jaw coupling: It is used where some axial displacement and small angular displacement is present. It can also be used as an unidirectional clutch. If it is held closed by an axial pressure it can perform as an overload release clutch. The operational characteristics of this form of coupling is dependent on the tooth engagement configuration.
- Universal coupling: It works well for angular misalignment but should not be considered if lateral or axial displacement might be present. If the drive shaft rotates with constant speed, the driven shaft will turn with a cyclical non-uniform speed. This can be overcome through the use of two universal coupling with an intermediate shaft at the proper orientation.
- Elastic tube: It can handle both angular and lateral displacements of two shafts with light loads. It cannot be properly utilized if accurate shaft to shaft rotation is required.
- Plate coupling: It can be used for angular misalignment with a series of plates increasing its flexibility.
- Elastic material universal coupling: It consists of a pair of yokes joined by a block of elastic material. It has good angular freedom and its flexibility depends on the stiffness of the material.
- Flexible shaft: It consists of cables formed of layers of wires wound in opposite direction and can handle both angular and lateral misalignment. The two main disadvantages are handling of light loads and shaft wind up.
- Spring coupling: It is fastened to one shaft and only wound around the other shaft. Such a device transmits power in only one direction and can act as a form of overrunning clutch. Rotational variations will occur between the two shafts so constant velocity or positional accuracy is not possible.
- Pin-and-slot coupling: It is used for large angular misalignment. It also permits lateral displacement (and some axial displacement). If one shaft rotates at a constant speed, the other will vary cyclically.

CLUTCHES

A clutch is a form of linkage between two shafts to handle disengagement plus speed and power transmission variations between the driver component and the driven component.

Typical instrument clutches are as follows:

- o Viscous/fluid drive clutch: The speed will be independent of minor rapid fluctuations in the speed of the driving shaft. This type of drive or clutch is sensitive to temperature variations both external and internal due to changes in viscosity. If constant speed of the driven shaft is desired the use of a heavy flywheel is a possible solution.
- o Over-running clutch: The inner plate is connected to the driving shaft, the outer ring to the driven shaft. When the driving shaft rotates, the balls are wedged between the plate and ring and transmit the driving power. When the driving shaft rotates in the opposite direction, the coupling is automatically broken. A single revolution clutch has a similar construction but has in addition a ball retainer which can cam the balls out of the power transition position. In this way, it is possible to stop a rotating shaft very accurately in a predetermined angular position without having to overcome the inertia of the driving components.
- o Friction clutch: It is intended when the driving shaft runs continuously and the driven shaft runs intermittently, the facing material should be chosen for high coefficient of friction and wearability. A variation of this clutch is the cone clutch which has more positive engagement.
- o Magnetic clutch: A variation of the disk clutch is the magnetic clutch, where pressure is applied between faces by means of an electro-magnet contained in one of the clutch members. Current to operate the electro-magnet is transmitted to the rotating clutch by means of slip rings. This is a useful device for opto-mechanical instruments provided with automatic electric controls and remote operation.
- o Magnetic fluid clutch: Small iron particles are suspended in a viscous oil. When a current is applied, the iron particles form a chainlike reaction allowing transmission from one clutch plate to the other clutch plate. This type of clutch will allow not only slip but if desired, controlled slip by regulation of the current. They do generate internal heat which can effect the viscosity of the oil which in turn can effect the operation of the clutch. This principle is also used for pressure rotational sealing.

9.0 ROTARY MOTION

ROTARY MOTION, OVERVIEW

For the proper function of the opto-mechanical instrument and the quality of the results, it is necessary that the stability and accuracy of location of all centers of rotation be established and maintained. For these rotations the

- o Eccentricity
- o Out-of-roundness
- o Backlash
- o Other imperfections
- o Undue friction
- o Misalignment
- o Runout vibration

of the ball bearing or shaft will effect the precision of the rotary motion.

The configuration of the ball bearing chosen is influenced by;

- o Requirements of motion
- o Operating conditions

Preloading of opto-mechanical instrument ball bearings must be adequate to prevent unloading and yet not high enough to cause:

- o Excess (unnecessary) friction
- o Brinelling of the races
- o Distortion of the metallic components

AIR BEARING

In the air bearing, air is forced from a central location to a cavity which is sealed, such that the mating component is basically "floating on air". The mating component surfaces must be precision machined. Pressurized clean air is supplied from air holes on a continuous basis. Excellent wear parameters are achieved because the mating surface are never (or should never be) in contact. A readout mechanism (encoder) should be of sufficient accuracy in order to optimize performance. The following elements of the opto-mechanical instrument must be evaluated before a decision to utilize an air bearing can be contemplated; cost, size, configuration, operating condition and function.

- o Air bearings are virtually free of wear and friction.
- o Externally pressurized air bearings are used for precision motion.
- o Although air bearings are virtually friction free, they do require pump power to maintain air pressure head.

- Start-up and shut-down are critical for air bearings. To prevent damage to bearing surfaces, bearing components should be motionless when bearing pressure is zero.
- Air bearings require very clean, dehumidified air for operation. Normal industrial shop air destroys an air bearing.
- Externally pressurized journal air bearings are used in high speed rotary scanners. Viscous drag induced heating in the bearing can lead to instability. Water cooling and the use of helium gas as the bearing working fluid may alleviate this problem.

FLEXURES

- For small rotation angles 0 < 0.1 RAD or small translations about 1 to 2 mm, flexures have the advantages of freedom from:
  - Stick-slip
  - Hysteresis
  - Friction (very low)
  - Lubrication (do not require)
- Flexures work well in adverse environments
- Several types of flexures that are commonly used:
  - Single-strip flexure
  - Parallel spring guide
  - Two strip rotational flexure
  - Circular contour flexure hinge
- Flexures can pose severe fabrication problems. Very rigorous process control is usually required. Fabrication methods that leave very little residual stress in the flexure should be selected.

DEFINITIONS, ROTATION

- Runout (wobble, two axis tilt): Any point on a rotating surface should remain within a perfectly flat plane that is perpendicular to the axis of rotation. Runout describes the maximum distance that a point will deviate from that plane.
- Concentricity: Any point on the surface of rotation should travel along a path that forms a perfect circle. Concentricity defines the maximum difference between a true circle and the actual circular path formed by the rotating point.

10.0 LINEAR MOTION

LINEAR MOTION, OVERVIEW

Linear motion slides of high accuracy are required to move, relocate and adjust components in an opto-mechanical instrument. The motion provided by the slide must be;

- Smooth
- Stable
- Minimum hysteresis
- Repeatable
- Without any free play

The structural design configuration of the slide is determined mainly by the;

- Displacement required
- Load imposed
- Vertical/horizontal motion

The most common of these devices are the following:

- Dovetail
- Crossed roller
- Straight slide
- Ball bearing
- Round bar
- Air bearing linear
- Ball bushing

DOVETAIL SLIDE

The dovetail is made up of two pairs of interlocking angles capable of restraining rotation while providing movement along the straight path. Because of the accurate finish and correct assembly, the shape of the dovetail slide makes it self-retaining. It is also possible to make adjustments with insert strips or strings in a proper procedure which would allow for resetting during operation. Low stiction pads or coating are usually used to minimize friction on the contact lines or planes. An accurate dovetail slide can be achieved by precision machining and the correct use of low stiction bearing material. Dovetails have limitations in fine positioning and are therefore usually used for infrequent movement followed by positive locking position. Care must be taken that the final positive locking device does not upset the position setting.

BALL BEARING SLIDE

Hardened ball bearing travel captured in a vee groove formed by precision machine grinding. Into these hardened vee grooves are placed several balls, held apart by a perforated strip. This strip forms a cage for the ball bearings. Ball bearing linear slides must be assembled with considerable regard to the backlash condition of the balls. Also, the exact alignment and parallelism of the track faces must be taken into account. The quality of the;

- o Ball sphericity
- o Ball concentricity
- o Surface quality
- o Surface hardness

all determine the overall performance of the ball bearing slide.

Instead of the hardened steel, vee grooved bars, the following two methods can be used to make a ball bearing slide:

- o Four hardened steel strips are clamped to form a pair of grooves. After the hardened steel strips have been clamped, their edges are accurately dressed, to serve as a track for the balls forming the ball bearing slide.
- o Two rectangular grooved bars with steel wires pressed into the grooves. These four wires then constitute the ball track forming the ball bearing slide.

BALL BEARING BUSHING SLIDE

Ball bearing bushing linear slides have

- o Low friction
- o Long life
- o Maintain alignment

Three or more oblong ball tracks are in each bearing to establish line contact. Each track has the balls in one of its straight slides in contact with the inner surface of the ball bearing bushing sleeve and the shaft. The weight rolls freely on the balls in this position of the track. Balls in the remainder of the track are free to move in the clearance of the sleeve. A retainer within the sleeve, guides the balls in their proper path. It also prevents the balls from falling out when the bearing is removed from the shaft.

CROSS ROLLER BEARING SLIDE

Rolling cylinders are retained in a track. The larger contact area of the rolling cylinders provide for larger load carrying capacity, however, with an increase in friction. The additional cost over the ball-bearing slide may be justified if a larger load capacity is required without an increase in space. The functional performance and design configuration of the cross roller bearing slide is similar to that of the ball-bearing slide.

ROUND BAR SLIDE

The round bar construction principle consists of two steel bars (rods) fastened to a channel beam. The slide is placed on the round bars forming a vee-groove and a flat guide face. By building up bosses in certain locations, the mating faces of the slide combined with the bars can be made to resemble a three point contact. Instead of the sliding faces, the slide is sometimes mounted on ball-bearings to provide a more free-running round bar slide.

STRAIGHT LINE SLIDE

The width of the straight line slide must not exceed the bearing length, that is, the track length. Stops must be provided at both ends to prevent the slide from running out too far. The configuration consists of a line of caged linear acting ball bearings (a number of lines depending on the width of the table) located between two parallel plates. This configuration can be made to operate in both the horizontal and the vertical.

LINEAR MOTION SLIDES

- o Dovetail
- o Ball bearings
- o Ball bushing
- o Crossed roller bearing
- o Round Bar
- o Air bearings
- o Straight slide

LINEAR SLIDES PARAMETERS

- o Load capacity:
  - \- Horizontal position
  - \- Vertical position
- o Travel: Maximum range overall length
- o Resolution: See section on adjustments
- o Repeatability: See section on adjustments
- o Positional accuracy: Travel distance
- o Straight line accuracy: True straight line

MOTORIZED DRIVES

- o High resolution - high accuracy/repeatability
- o Computer controlled
- o Positioning in hostile, inaccessible and remote circumstances
- o Elimination of loads caused by manual adjustment (thumb)
- o Simultaneous multiple movements
- o Continuous smooth motion over large range
- o Variation in speed (fast, slow, medium)
- o Positional readout (with or without encoder)
- o Human servo

11.0 ADJUSTMENTS

ADJUSTMENT OVERVIEW

During optical alignment, whether internal to the optical instrument as part of the design, or external as references to other items, some physical movement must occur. This motion can be generated by an energy input of manual, electrical or thermal means. When a fine adjustment is performed during an optical alignment, the resolution, accuracy, repeatability and stability of the procedure enter into the error analysis. In designing optical instruments, provisions for adjustments can be difficult, but they can normally be simplified by making changes in design approach, by examining the logistics of the optical instrument, and by understanding the alignment procedure. The designer should strive for simplicity and reduce the number of adjustments to the bare minimum required to achieve system performance. Frequently in making an adjustment for an optical alignment, a displacement must be amplified before it can be compared with a scale of desired accuracy. The most common methods of amplification are mechanical, optical, electrical and thermal, of which the first requires contact with the displacing mechanism. Combinations of these four methods are sometimes employed. In order to achieve a high degree of accuracy in a given system, all sources of random and systematic adjustment errors have to be investigated. The significance of the systematic error depends, of course, upon the magnitude of the random error.

DEFINITION OF AN ADJUSTMENT

- o Range: The difference between maximum and minimum travel of an adjustment while retaining the required resolution and accuracy
- o Resolution: The separation of closely related adjustment movements, and an indication of the degree to which they can be discriminated
- o Accuracy: The degree of exactness of an adjustment approaching the true value of a setting free from errors
- o Stability: The property of an adjustment not to undergo any change without the application of an external input
- o Repeatability: The measure of the accuracy with which an adjustment permits an input motion to return an instrument to a specific position
- o Sensitivity: The ability of an output movement of an adjustment to respond to an input movement
- o Hysteresis:
  - The dependence of an adjustment on its history, causing permanent non-repeatability
  - The maximum separation in an adjustment between up-scale going and down-scale going, or its ability to be repeatable between the up/down readings

ADJUSTMENT GROUND RULES

- o Start with the maximum conceivable adjustments and eliminate those not required
- o Make adjustments from the same direction
- o All manual or non-manual inputs to an adjustment identical
- o Keep adjustments simple
- o Do not combine movement of an adjustment with clamping or locking action
- o Develop an adjustment/clamp/adjustment/clamp/adjustment/final lock procedure
- o Determine the degree of adjustment accuracy for each adjustment
- o Build in as many "do during assembly" adjustments as possible
- o Eliminate need for adjustments by fabrication and assembly tolerance techniques
- o Every degree of freedom does not have to have a fine adjustment
- o Provide adjustments for an element in an optical instrument for following reasons:
  - Aberrations (image quality)
  - Alignment (image location)
- o Determine the frequency of an adjustment and design accordingly
- o Determine reference points, lines parts or planes in a system

SENSITIVITY

Sensitivity can be defined as the number of scale divisions traversed by a pointer per unit change in the quantity being measured. In many cases, various disturbing factors prevent a reading from being taken that is correct to one or even several scale divisions, and the apparent high sensitivity is useless. It should be realized that the useful criterion of performance of an adjustment is obtained by considering the least movement of the adjustment which can be detected by the instrument. Nothing is gained by making the adjustment finer than the sensitivity of the instrument.

HYSTERESIS

- Wearing of parts
- Relaxation of micro stresses
- Permanent deformation due to load

INSTRUMENT ERRORS

The errors due to an instrument, as distinct from those due to the observer's judgment, result from inaccuracies in the instrument or its adjustments. The only errors to be expected after calibration are what may be termed errors due to erratic behavior of the instrument or its adjustments. This may be said to occur if the same instrument reading is not always obtained for a given value of quantity to be measured. Contributory causes of erratic behavior are external disturbing influences, unduly large frictional forces between moving parts of the adjustments, leading to elastic deformation, backlash and indefiniteness of location of parts. External conditions which would affect the readings of the instrument must be kept constant. A plot of instrument readings against the measured quantity will show a closed loop, and this loop should be constant if the instrument is taken through several identical cycles. It is desirable to traverse a few cycles before commencing to take readings, in order that a cyclic condition may be established, when the elastically deformed parts have come into a more or less steady state. If the closed loop is not repeatable, the instrument is not in a proper condition for use, and should be examined.

ERRORS OF AN INSTRUMENT ADJUSTMENT

- Due to instrument/observers judgement (parallax)
- After calibration-erratic behavior (continuous calibration)
- Erratic behavior
  - External disturbances (erratic tides) - Backlash
  - Elastic deformation - Location of parts (shifting contacts and loads)
- Closed loop of error (before micro computers)
  - Constant - Indentical cycle, indentical readouts
  - Closed loop repeatability - Elastic deformation/steady state condition

RANDOM ERRORS

- Primary random errors (measurement process)
  - Measuring errors
  - Setting errors
  - Identification errors
- Secondary random errors (unpredictable variations)
  - Distortion
  - Refraction
  - Random temperature fluctuations during measurements

SYSTEMATIC ERRORS (DATA-REDUCTION PROCESS)

- "Uncorrected for" category
  - Geometry errors
  - Bias errors (calibration process)
  - Disturbance errors
- "Corrected for" category
  - Distortion errors
  - Refraction errors
  - Others

ADJUSTMENTS SUMMARY

- For a precision optical instrument, it is the fine adjustments that determine whether or not the instrument will achieve and maintain the required performance

- The method selected for fine adjustment and the attention to detail of the implementation of the method, will have a substantial influence on the time and effort required to align the instrument initially, and on the stability of that alignment during operation of the instrument.

12.0 ALIGNMENT

PIEZOELECTRIC TRANSDUCERS

Piezoelectric translators are an excellent approach to fine precision motion and positioning. The normal piezo effect occurs when mechanical pressure is applied to certain crystals causing the crystal to generate an electrical current. Reversing this process, a small mechanical movement can be produced by the application of an electrical current to the piezoelectric crystal. It is possible to produce movements of fraction of a micron by varying the voltage, then proportional mechanical movement will occur. This device has no mechanical components. Its repeatability and accuracy is usually acceptable but this should be checked for each particular application. The main disadvantage is the limited range of motion of the individual crystal. This can be overcome by stacking crystals or by ganging through a clamp/movement/clamp sequence arrangement.

OPTO-MECHANICAL TOLERANCES

Parameter	Fairly tight	Fairly loose	Units
o Index of refraction	0.0003	0.003	
o Change in radius	5	30	Fringes
o Departure from spherical or flat	1/8	4	Fringes
o Irregularity, astigmatic	1/8	2	Fringes
o Irregularity, random	1/8 to 1	1 to 10	Fringes per inch
o Thickness	0.002	0.004	Inches
o Air space	0.002	0.010	Inches
o Decenter, optical	1/2	5	Minutes of arc
o Decenter, mechanical	0.001	0.010	Inches
o Axial translation	0.001	0.010	Inches
o Tilt	0.3	2	Milliradians
o Lens roll	0.001	0.010	Inches
o Dimension errors of prisms	0.001	0.010	Inches
o Angular errors of prisms and windows	1/2	5	Minutes of arc

OPTICAL MEASUREMENTS

Use of optical measurement instruments should be considered wherever work must be done in fractions of a thousandth and where it requires moving a member over a portion of the travel area.

- o Surfaces to be measured are inaccessible
- o Distance with respect to required tolerances makes it impractical to use mechanical methods
- o Accuracy is beyond limitations of other measuring devices
- o Physical contact is not desired

AUTOMATIC AUTOCOLLIMATORS SPECIFICATIONS

	1970'S				1980'S			
	Visual setting. Scale graticule reading	Visual setting. Micrometer reading	Photo-electric setting. Micrometer reading	Photo-electric. Automatic setting & reading	Visual setting. Scale graticule reading	Visual setting. Micrometer reading	Photo-electric. Automatic digital reading	Photo-electric. Automatic digital reading (solid state)
Measuring range	60X60min	10min	10min	20sec	60X60min	10min	5min	17min
Repetition at 99.7%	1.5sec	0.5sec	0.2sec	0.1sec	1.5sec	0.5sec	0.2sec	0.1sec
Accuracy	6sec	2sec	2sec	0.5sec	6sec	2sec	2sec	1sec

PIEZOELECTRIC TRANSLATORS

- Piezoelectric actuators can be used for very small translations. A piezoelectric crystal expands if a voltage is applied across it. Typical motion is 1 um for 10^3 volts.
- Mounting piezos in series mechanically can increase the range of travel.
- Inchworm systems can expand piezo travel. Here two (2) piezos in series are alternately actuated and clamped.
- Piezo systems can have large forces, up to 10^5 newtons.
- Piezo systems have hysteresis on the order of 2%.
- Piezo system non-linearity (voltage applied vs travel) is on the order of 15%.
- Typically, piezo systems creep about 2% at constant voltage.
- Closed loop vs open loop.

13.0 MISCELLANEOUS

OPTICAL DRAWINGS INFORMATION

- Radius of curvature: Radius of each surface with corresponding tolerance.*
- Center thickness: Thickness and tolerance are measured along the optical axis for an axi-symmetric element.*
- Centering: Tolerance which controls the wedge in the element.*
- Diameter: Mechanical diameter and tolerance as well as the clear aperture or the diameters of the optically active surfaces.*
- Bevels: Bevels are specified to protect the edge from chipping.*
- Figure: Allowable figure error for each surface. Usually given in wavelengths of 0.633 um. Also given in fringes referenced to test plate fit.
- "Beauty" specifications: Limits on the allowable number and size of scratches and pits ("digs") in the surface. Intended to control scatter.
- Absolute index: Desired index of refraction and dispersion of the chosen glass type.
- Homogeneity: Tolerance on large scale variations in index in the glass.
- Striae: Tolerance on local variations of the index in the glass.
- Stress birefringence: Tolerance on residual stress in the glass.
- Bubble quality: Number of bubbles per volume.
- Glass type:

* Effect mechanical dimensions of opto-mechanical instrument

INSTRUMENT SENSORS

Sensors available
- Secondary electron conduction (SEC)
- Silicon intensified target (SIT)
- Intensified charges couple device (ICCD)
- Micro-channel plates
- Helium cooled bolometers

Design parameter to be considered
- Mounting provision
- Cooling techniques
- Radiation sensitivity
- Format size
- Environmental sensitivity
- Thermal sensitivity
- Light sensitivity
- Laser sensitivity

OPTICAL ENGINEERING DEFINITIONS

- Beam print: A geometric relationship used to define the beam print of a light beam on an inclined mirror.
- Positional optical element accuracy: The tolerances of optical elements in an optical system required to provide acceptable (not optimum) performance.
- Optical schematic (optical layout): Taking computer generated information and producing a drawing (not just the ray trace drawing), such that all the dimensional information of the optical system design can be readily seen and easily understood. This drawing is the basic source of information that the opto-mechanical engineer and/or opto-mechanical designer should be using (not the computer run, leave that to the optical engineer and/or the lenses designer). You want an optical schematic.

References

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