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Scanning Motion; Opto-Mechanical Considerations

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1. Introduction

The field of electro-optics has grown enormously in the last 25 years. As a consequence, both optics and optical engineering have mushroomed. The mechanical engineer, during this period, has been patiently providing the necessary support technology to achieve precision instrument design. Within the last 5 years, the discipline of opto-mechanical engineering has been emerging as a driving force to channel information to the precision mechanical engineer. In an overview article, "Opto-Mechanical Instrument Design", one of the key subtopics is "Scanning Motion." This paper is about that subtopic, specifically directed to the precision mechanical engineer and his involvement with Mirror Scanning Motion Systems. The purpose of this paper is to inform the mechanical engineer as to the many considerations necessary during the design and development of a precision instrument.

The logical starting point will be the fundamentals for opto-mechanical engineering as established by Dan Vukobratovich. The glossary at the end is an attempt to define many of the terms in his notes, plus any others that have arisen. These definitions are not for the physicist, electrical engineer, or mathematician, but for the mechanical engineer. The body of this paper covers over fifty papers which can be located by using the key words "mirror" and "scanning" and limiting the search to the past 5 years.

2. Mirror (What is a Mirror Today)

A rapidly moving optical element, principally a flat mirror, is the heart of any mirror scanning motion system. Dynamic load deflections and disturbances are the main concern, rather than self-induced weight deflection static loads. As can be seen in Vukobratovich's notes, many of the principles used to analyze static deflections can be carried over into the dynamic case.

Once the word "mirror" was universally understood. Now, the optical engineer might mean, the mirror facesheet, and the mechanical engineer might mean, the mirror assembly, which is comprised of, the mirror facesheet, the mirror substrate, and the mirror connector (shaft). And the systems engineer might be talking about the mirror scanning motion system, which is everything including the electronics and control system. In the glossary are the following definitions:

- mirror facesheet
- mirror substrate
- mirror connector (shaft)
- mirror assembly
  - facesheet
  - substrate
  - connector
- mirror pivot
- mirror support structure
- mirror drive mechanism
- mirror scanning motion system
  - all of the above plus electronics and control system

Now when someone uses the word "mirror", one should ask what that someone meant!

3. System Considerations

A list of considerations of anything is never complete. The following list of items are considerations which need to be considered when designing a mirror scanning motion system:

- o geometric alignment
- o inertia of total system
  - mirror assembly inertia
  - drive mechanism inertia
  - read-out inertia
- o dynamic deformation
- o dynamic effects
- o drive control electronics
- o surface abrasion/erosion/pitting
- o dynamic forces, mirror assembly
- o dynamic forces, mirror mount
- o fatigue failure
- o thermal deformation
- o bimetallic effects (facesheet)
  - substrate/plating
- o choice of substrate material
- o facesheet material
- o reflectivity
- o surface protection
- o mirror assembly unbalance
- o rotor assembly unbalance

This list illustrates the potential level of detail required when dealing with this subject.

4. Internal Mirror Mounting Considerations

Metal mirrors have been incorporating mounting supports (mirror connectors) as part of the mirror substrate for a number of years. This has all but eliminated the distortions inherent in both bonding and clamping mirror mounting techniques. Mirror replication and diamond machining technology, as well as precision plating and polishing, has contributed greatly to the advancement of integral mirror mounting. These techniques allow for the production of distortion minimized mirror facesheets, mirror substrates, and mirror connectors (shafts) from a single metal material piece. The mirror surface can be precisely positioned to any desired relationship to the mirror connector (shaft), thereby obtaining a rigid low inertia mirror assembly, ready for final balancing. Consideration must be given to the location of the mirror surface so that conventional polishing methods can be applied without interference or complication.

Integral mirror shaft design offers excellent stability during operation, but does not guarantee initial alignment. Misalignment between the mirror surface and shaft axis induces periodic scanning path errors of the scan pattern. Only angular misalignment is critical; translations of the mirror position relative to the shaft axis does not usually affect scan pattern.

Integral mirror mounting is usually the first choice in the area of precision high speed mirror scanning motion systems. Second choice would be bonding, with clamping the last.

5. Bonded Mirror Mounting Considerations

Dimensional tolerances for a bonded mirror mounting are rigorous. Also, the assembly jig to locate and hold the mirror in position during bonding may be as critical as the mount itself. The bonding agent must attempt to satisfy opposing requirements. There are three parameters which would be ideal if all could be satisfied.

- The bond must remain pliable as it cures in order not to distort the mirror facesheet.
- The bond must not expand or contract over the operational temperature range.
- The bond must be of adequate rigidity so that the mounting position remains precise during dynamic loads.

Consideration must be given to the thermal coefficient of expansion of the mirror substrate, the bonding material, and the mirror mounting surface. Ideally, thermal expansion of the metal mirror mount and the glass of the mirror should be closely matched in order to minimize thermal distortion.

Mirrors are usually mounted before installation of the shaft pivots. During shaft installation, there are stresses induced to the shaft which, in turn, may be passed to the mirror facesheet, resulting in distortion. A thicker mirror substrate would assist in distortion prevention but would result in:

- a heavier mirror assembly,
- additional inertia,
- the requirement of a more rigid shaft pivot mount, and
- an increased load which would require greater bonding strength or larger bonding area.

To reduce some deformation, bond mounting the mirror substrate after the shaft is mounted, if at all practical (which is usually not the case), is a better approach.

Bond drift during curing can be considered from two approaches. One is to apply as much clamping pressure as necessary (and no more) to hold the two bonding items in precise position. After curing, the release of the clamping will result in some level of positional shift. It would be helpful if grooves are cut in either or both bonding items, so that the bonding material has a place to flow during clamping. In effect, metal shaft to glass mirror contact can be achieved with a minimum of bonding material between the metal shaft and glass mirror. Most of the holding power would be limited to the groove spaces.

A second approach is to re-adjust the position of the mirror or substrate as the bond is curing. It must be remembered that to minimize bond "spring back" the amount of re-adjustment should be reduced as the bond cures. This procedure also requires that the position must be optically observed as the re-adjustments are performed. This method has been successfully used when positioning optical encoder disks on their shafts. Here rotation is observed in order to minimize disk/shaft run-out. Uniform bonding over the bonding area is required to obtain minimum tilt of the disk axis to the shaft axis. The entire process is carefully timed so that the re-adjustment amounts are reduced close to zero (micro inches) as the bond cures.

An additional note for all bonding procedures is as follows: Test and evaluate all bonding materials. Properties vary from container to container and from batch to batch, especially curing times. It is also a good idea to have separate tests set up to verify the quality and mechanical properties of the bonding material.

6. Clamping Mirror Mounting Considerations

Clamping mirror mounting allows for repositioning and possible removal for replacement. Both integral and bonding mirror mounting are somewhat permanent conditions.

The most successful removable clamping incorporates some form of collet clamp which provides isolation of the mirror substrate from clamping stress. A disadvantage of the collet approach is potential loosening of the collet clamp forces, with resultant drift of mirror position.

Collet clamps, if not tightened, induce only compressive forces that produce no bending movement and thus no distortions in the mirror facesheet. One collet clamp technique is to mechanically isolate the shaft by relieved regions so that the distortions imposed by the clamping screw are not transmitted. However, fastening the mount onto the scanner shaft with set screws is not recommended, as they can deform the shaft. When set screws are properly fitted, removing them is nearly impossible. When not fitted properly, they act as a hinge, allowing wobble excitations. Set screws can fatigue and loosen, and therefore are not recommended.

7. Mirror Pivots, General

The classic mirror pivot is the high speed precision ball bearing. Today, the hydrostatic (air) bearing and the flexure support are being considered for a variety of reasons. Both of these approaches have advantages and disadvantages which must always be traded off against the ball bearing pivot. It is not possible to compare a flexure support with the air bearing because of the very limited scan angle of a flexure support.

8. Mirror Pivots, Air Bearing

- no wear, except for impingement and erosion
- no friction, except for aerodynamic viscous drag
- air (gas) pressure must maintain a pressure head, using clean, dehumidified air
- viscous drag can induce heating which, in turn, can produce an instability

9. Mirror Pivots, Flexure

- very limited scan angle
- very low friction

- o requires no lubrication
- o has both performance (metal fatigue) and positional hysteresis (non-repeatable)
- o can operate in a very hostile environment, especially when compared with the ball bearing and the hydrostatic bearing
- o there can be fabrication, design, and configuration difficulties
- o residual stress can be present during operation
- o question of manufacturing repeatability and matching if a pair is a requirement
- o center shift displacement makes alignment difficult
- o torsional rigidity varies with angular displacement
- o linearity of motion
- o variation due to fitting pressure and vibration considerations

10. Mirror Pivot, Ball Bearing Considerations

- o can be operated at speeds of 50,000 rpm
- o accuracy is determined by errors of the balls and ball track
- o drag torque is sum of viscous drag, hysteresis, and friction
- o viscous drag is due to the lubricant
- o out-gassing of lubricant and retainer is important in space (vacuum) applications
- o accurate rotational axis requires two sets of angular contact pairs as widely separated as possible
- o mounting of the bearing is an important issue; press fit into very round seats
- o second order considerations:
  - thickness of inner and outer race
  - variation in ball diameter
  - sphericity of balls
- o shaft cylindrical characteristics and straightness effect on ball bearing
- o ball bearing preload considerations:
  - eliminates play
  - is critical and must be carefully adjusted
  - minimizes axial movement due to thermal expansion
  - prevents ball skidding under very high acceleration
  - limits the yield of the system

- reduction of non-repetitive run-out
- limiting the change in contact angle between inner ring and outer ring at very high speeds
- if mounted vertically, the weight on the shaft must be taken into account
- spring preload must be 10 times the spring rate of the ball bearing

11. Ball Bearing Lubrication Considerations

For high speed precision ball bearing, lubrication considerations should be evaluated for the following parameters. If necessary, a trade study can be made so that comparisons can be made in a category or between categories.

- o angular velocity
- o usable life (based on environmental requirements)
- o operational temperature range, rate of temperature change, storage temperature, and temperature tolerances
- o driving mechanism heat load
- o load carrying requirements
- o required ball bearing pre-load
- o possibility of out-gassing during space or vacuum applications
- o humidity, dirt, or other hostile environmental condition
- o lubricant cleanliness
- o sealing considerations

12. Actuators

Linear actuators are being used to precisely position large mirror assemblies. The mirror assembly must have two rotational degrees of freedom and can only move through small total scan angles in the two axes of rotation. One method to achieving this would be to use a two-axis gimbal system and drive the gimbals by D.C. stepper torque motors. Another approach is to mount the mirror assembly on a two-axis flexure pivot system and drive the mirror assembly by means of two or more pairs of linear actuators mounted on the back of the mirror assembly, each pair operating in push-pull. In an actuator system there are a number of considerations to be dealt with:

- o The mirror assembly is pivoted so the coil motion is not completely linear (because of axial rotation).
- o The mass of the mirror assembly is large compared to the mass of the coil; the coil mass is therefore relatively insignificant.

- Most large mirror systems require small movements with large high acceleration forces, ideal for coil actuators.

- Symmetry of push to pull characteristics are not too critical for uniform constant angular velocity about the pivot axis.

Larger mirrors require a multi-point mount. For minimum surface deflection, actuator forces should be 90 degrees away from support forces. In a four point support system, minimum deflection under actuator forces occurs when all supports are equispaced on a common circle of a diameter that is 0.7 of the mirror. In the four point system, the mirror pivots about two points on a common diameter while the other two points are used to provide actuator forces.

Fundamental frequency is an important parameter in determining the response of a mirror to dynamic loads. As a rough rule of thumb, if the fundamental frequency of a mirror is at least 10 times higher than the exciting frequency, the mirror will not be driven into resonance.

13. Aerodynamics/Impingement Considerations

Aerodynamics and impingement, which is the result of air flow, can be covered together because of their commonality.

There are four approaches to impingement prevention. The first method presents the high speed rotating scanning mirror with absolutely clean air (which is almost impossible). The second method is the use of a specially designed housing to develop a positive pressure, as one would for a cleanroom. The mirror air flow would have to be carefully matched to the housing's aerodynamic flow in order to achieve the desired results. The last two methods also assist in aerodynamic reduction but require enclosed sealed housing. Vacuum and helium both act to greatly reduce aerodynamic flow and the resulting turbulence. However, these last two approaches require windows of optical quality glass which must be taken into account as part of the optical design. It must be remembered that optical windows not only contribute to optical degradation, but also cause a continually changing off-axis angle optical condition.

An optical beam must pass not only once, but twice through the window. These passes are at different and continuously varying off-axis angles.

The above dynamic considerations are described by many equations. In Vukobratovich's notes, there are useful first order of magnitude estimations. However, better results can be obtained by model testing or scaling from previous design data before finalizing the mirror system configuration.

Collision with dust particles occur with two results. Pitting is the actual collision of a dust particle with the facesheet of the mirror assembly. Erosion is the flow of dust particles along the facesheet. The edge effects of erosion are usually much greater than those near the center of the mirror facesheet. This is due to aerodynamic roll-off as the air flow leaves the mirror facesheet surface. Optically, because of this edge deterioration effect, erosion is usually less of a problem than pitting.

In all cases of aerodynamical and/or impingement consideration, the solution, if at all possible, is the use of hard coating on the mirror facesheet. Again, the optical quality of this hard coating is important because of the continual variation in angles during scanning and a double pass occurs because a mirror system is involved.

14. Balancing Considerations

There are so many detrimental items related to this topic, both first order and second order effects, caused by improper balance that it is imperative to adequately balance a mirror scanning motion system. The only questions that remain are, what components of the system should be balanced separately, what internal subassembly should be balanced, and finally, to what ounce-inch level should each item be balanced. Therefore, there are no balance considerations, just "Balance your system", period.

15. Reactionless Mirror Considerations

A reactionless mirror scanning motion system imparts minimum (or negligible) reaction forces into the mounting surface, or structure to which the mirror support structure is mounted.

As soon as I finish the definition of a reactionless mirror, I immediately send the opto-mechanical engineer to Vukobratovich's notes. In the notes, there is an excellent four-part illustration showing the ground rules necessary to achieve a reactionless mirror situation. The following are the major considerations related to this topic:

- The mirror and counterweight both rotate about their own centers of gravity.
- The effective moment of a rotational inertia of the system is twice that of the original scanning mirror.
- Mirror rotation causes an equal and opposite reaction in the mirror support structure.
- Two conditions necessary to achieve reactionless mirror condition:
  - The center of gravity of the mirror and associated mechanism must remain stationary during rotationing motion.
  - The resultant of all moments acting on the rotating mirror and mechanism must be zero.

As a conclusion to the reactionless mirror considerations, the following is a quotation from Vukobratovich's notes:

> "To be truly reactionless, and not vibrate the optical support structure, a chopping mechanism must satisfy both the reactionless conditions. A simple rotating mirror, pivoted about its back, has a center of gravity shift, and induces a moment in the pivot axis, during chopping. This simple mirror fails to satisfy both the shaking force and shaking moment conditions. Pivoting the mirror about its center of gravity satisfies the shaking force condition, since the mirror center of gravity does not move during chopping. However, in this case a moment is induced in the pivot, so the shaking moment condition is not satisfied. Providing a counterrotating reaction mass satisfies the shaking moment condition by supplying an equal and opposite moment to the chopping mirror moment. To satisfy both conditions, the mirror must pivot about its center of gravity, and a counter-rotating reaction mass, also pivoted about its center of gravity, must be used. This approach has an effective moment of inertia twice that of the mirror. More complex mechanisms move the mirror pivot away from the mirror center of gravity at the cost of increased system moment of inertia."

16. Wobble/Jitter Considerations

The simplest approach to minimize wobble and jitter is to have perfect balance and to drive the system with the lowest possible acceleration and jerk. This often conflicts with the required task for a great many scanner systems. The shortest possible "reversal time" in a reciprocating scanner is obtained with a square wave acceleration and a deceleration drive current. A fast step response with arc second accuracy can be obtained with a constant acceleration, followed by an equally consistent deceleration that does not consume the maximum torque capabilities of the driving mechanism.

In the case of polygon mirror wobble and jitter, the dimension across the flats should be as small as possible. This will reduce both the inertial load and windage and minimize run-out error. This will also reduce the system unbalance and decrease the amplitude of the resonant frequency, giving the motor the ability to run at higher speeds. Because of these high speeds, the greatest probability is the bearing wear, which limits the useful life of most scanner systems. Even if the bearings do not fail, after some time a wobble or jitter may appear that can effect the optical system's performance.

17. Heating Considerations

Heating of rotor and bearings can induce instability in a high speed scanner. Forced air cooling of the scanner interior can be used to limit the temperature rise. External cooling of a scanner is relatively ineffective since heating is localized to the central shaft or rotor. Drive mechanism heating and flow of this heated air relative to the optical system must be taken into account.

Both viscous drag losses and aerodynamic heating in gas lubricated bearings can be reduced by using helium as the lubricating gas. Helium is particularly beneficial in reducing windage by up to 80%. In bearings, viscous drag may actually increase slightly due to the higher viscosity of helium compared to air. Heat transfer through helium, however, is greater.

An error which has recently become of concern is the requirement of mirror cooling during rotation to carry away laser heat (which can be substantial). It must be remembered that mirror cooling can also introduce fluid pressures, variations in fluid pressure, fluid coupler requirements, and the configuration of the heat exchanger. There are also considerations with reaction forces caused by the fluid flow in the heat exchanger and the usual requirement that the coolant fluid flow be in close proximity to the mirror facesheet. Therefore, the flow passages are located between the mirror substrate and the mirror facesheet.

18. Motor Hunting Considerations

The drive mechanism, when in synchronism, is similar to a load being dragged around by a spring attached to a rotating shaft. Any erratic mechanical drag will cause the spring to flex which will put the motor rotor into a hunting mode. This hunting mode will change from unstable to stable and vary again when the next erratic drag occurs. Since the ball bearing is the only non-viscous drag in a mirror scanning motion system, this indicates use of the finest quality bearing available and the proper compatible lubrication. To maintain a smooth running system, oil instead of grease is preferred as grease may cause an inconsistent drag.

19. Polygonal Mirror Errors

Because of its extreme high speed and required high precision, the performance of the polygonal mirror will be examined more closely. Most of these errors are associated with any mirror scanning motion system, but especially those systems with more than one mirror reflecting surface.

The following are the major considerations for polygonal mirror systems:

- o mirror facet-to-axis angular error;
  - mirror facet to mirror facet error
  - pyramidal error

- o strain caused error;
  - thermal consideration, general
  - thermal consideration, laser induced
  - centrifugal forces
  - torsional twisting about the drive mechanism axis

- o angular deviation errors between;
  - axis of rotation and true opto-mechanical axis
  - symmetry axis and true opto-mechanical axis
  - axis of rotation, symmetry axis, and true opto-mechanical axis

- o tolerances of mirror scanning motion system assembly;
  - mirror connector to mirror support structure through mirror pivot

20. Polygon Stability Considerations

Polygon stability takes into account perpendicularity, concentricity, and rigidness of true positioning of the drive mechanism shaft. Today, the typical polygonal mirror facets are diamond cut. Since the mirror facets have been machined, usually using one face plus the bore, the mirror facet concentricity and squareness should be very high in precision. The hub of the drive mechanism should pick up on the same machined bore and face of the polygon. The drive mechanism should have its mounting hub machined, both diameter and face, after the drive mechanism has been assembled. This procedure will insure that the concentricity and perpendicularity will be established off the rotating center line of the ball bearing in the drive mechanism. If tight machined tolerances better than .0001 of an inch are required, there will be a large impact on cost. To prevent other parameters from adding to the shaft/polygon mirror surfaces accuracy, all other areas of the mechanical design should be as tight as practical. One particular area is the fit between the drive mechanism hub and the bore of the polygon. This should be held as close as possible to minimize radial tolerance build-up, or preferably the shaft should be designed as an integral part of the polygon mirror facet structure. An alternative that works for some situations is a tapered fit, which can be lapped for even further reduction of radial errors.

21. Glossary

ACTUATOR: An electro-mechanical device yielding a linear driving force.

AERODYNAMIC BOUNDARY LAYER: The region in the neighborhood of a bearing surface in contact with the gas (viscous fluid) and in motion relative to the gas.

ANGULAR (TORSIONAL) FREQUENCY: Mirror rotational oscillation, with units in the number of vibrations per unit time.

ANGULAR (TORSIONAL) STIFFNESS: The rotational stiffness value about a specific axis of a mirror.

ANGULAR VELOCITY: The time rate of change of scanning angular displacement.

CHOPPING ANGLE: The total angle covered in one complete chop of a chopping mirror.

CHOPPING MIRROR: A mirror scanning motion system which rotates about an axis parallel to the mirror surface; usually, but not necessarily, the axis of rotation is coincident with the plane of the mirror surface.

CONCENTRICITY: The maximum difference between a true circle and the actual circular path formed by the rotating point.

CRITICAL SPEED: The speed (and there may be more than one) that is the resonance condition of a mirror scanning motion system. Any residual unbalance, if present, is greatly amplified; shaft and mirror deflections tend to be large. This is also the angular speed at which a mirror scanning motion system can become dynamically unstable.

DEAD (INSENSITIVE) TIME: The time interval between a change in the input signal (electrical) to a mirror scanning motion system, and the response (mechanical motion) to that signal.

DRAG COEFFICIENT: A characteristic of a bearing surface in a flowing viscous fluid, equal to the ratio of twice the force on the bearing surface in the direction of mass flow to the product of the density of the fluid, the square of the flow velocity and the effective cross sectional area of the surface pushing the body of fluid as it rotates and/or translates.

DRAG POWER (GAS BEARING): The power required to overcome the aerodynamic drag created by a gas bearing. This is usually very small compared to windage.

DRAG TORQUE: The sum of windage between a mirror and the surrounding gaseous medium and the drag torque of the bearings. The sum of viscous drag and friction of a bearing viscous drag.

DRUMHEAD FREQUENCY: The fundamental or natural frequency of a circular mirror vibrating in a direction perpendicular to the plane of that mirror.

DUTY CYCLE: The ratio of the usable scan time to the total scan time for a mirror scanning motion system, usually expressed as a percentage.

DWELL TIME: The frame time divided by the number of resolution elements. The time interval of a mirror scanning motion system during which it may be in a position where it either cannot receive and/or cannot reflect an optical beam.

DYNAMIC BALANCE: A condition which exists in a mirror scanning motion system when the axis of rotation is co-axial with the mass center of rotation. No product of inertia about the center of gravity of the mirror exists in relation to the rotational axis. (Only true for a rotationally symmetrical body.)

DYNAMIC RESPONSE: The transition time between two mirror positions and the dynamic range (maximum angular range) determines the dynamic response of a mirror scanning motion system.

DYNAMIC (ABSOLUTE) VISCOSITY: The tangential force per unit area of two parallel planes when the space between them is filled with a gas and one plane moves in its own plane relative to the other.

EXCITATION FREQUENCY: The frequency of the mirror driving mechanism input to a mirror scanning motion system.

FACET ANGLES: The angle of the mirrors on a polygon scanner relative to the axis of rotation and of the mirror faces to each other.

FACET TO FACET ERROR: Mirror to mirror angular error in a polygon scanner or any mirror scanning motion system with more than one mirror surface.

FLEXURAL RIGIDITY: The ratio of the sideward force applied to one end of a beam to the resulting displacement of this end, when the other end is clamped.

FREQUENCY: The number of cycles of control input or scanning motion output completed in a unit of time (cycles/second).

FREQUENCY RESPONSE: Response of a mirror scanning motion system as a function of the excitation frequency. Also an indication of the positional and phase accuracy with which a mirror scanning motion system responds to the various frequency and amplitude applied to it.

FRICTION TORQUE: The torque which is produced by frictional forces and opposes rotational motion. This may be composed of rolling friction, coulumb (rubbing) friction, viscous torque or drag.

FUNDAMENTAL FREQUENCY: The lowest frequency component of a mirror scanning motion system. It is also referred to as the first harmonic of a mirror scanning motion system.

GAS TURBINE DRIVES: An acceleration device for generating rotary mechanical power from the energy in a stream of high pressure gas.

INSTABILITY: A condition of a mirror scanning motion system in which excessive positive feedback causes persistent, unwanted oscillations in the output performance of the system.

INTEGRAL SHAFT: A shaft (or equivalent of a shaft) which is machined as a part of a mirror substrate (a single piece of material).

INVERTED POLYGONS: Mirror facet planes face in towards the scan rotational axis. May be regular or irregular.

IRREGULAR POLYGONS: Mirror facet planes are not parallel to and face away from the scan axis. Use to provide nonsuperimposed repetitive scan. Variety of non-uniform facet angles.

JITTER: Vibration motion imparted intentionally or unavoidably to a mirror scanning motion system operating in a control system mode.

KINEMATIC VISCOSITY: The absolute viscosity of a fluid divided by its density.

LUBRICATION PERTURBATIONS: An effect caused by the lubrication on consistency which makes small modifications in a mirror scanning motion system performance.

MAXIMUM ROTATION (SCAN) ANGLE: The maximum angle through which a mirror scanning motion system can be rotated (peak-to-peak) rather than a center (no-signal position) to peak angle.

MIRROR ASSEMBLY: Consists of the mirror facesheet, mirror substrate, and mirror connector.

MIRROR CONNECTOR (SHAFT): The connector is mounted to the mirror substrate to provide a means of connecting the mirror assembly to the mirror support structure.

MIRROR DRIVE MECHANISM: The power input means to supply motion to the mirror assembly.

MIRROR FACESHEET: Consists of the reflective surface coating plus a minimum amount of backing material. Usually the facesheet has a very high aspect ratio and is not capable of proper self-support.

MIRROR FACETS: The individual mirrors on a polygon scanner.

MIRROR PIVOT (BEARING, FLEXURE, ROD): Provision to allow rotation of the mirror assembly relative to the mirror support structure.

MIRROR SCANNER: A mirror scanning motion system examines an area or region point by point in a continuous systematic manner, repeatedly sweeping across until the required area or region is covered.

MIRROR SCANNING MOTION SYSTEM: The entire mirror hardware assembly plus the necessary electronic and control system.

MIRROR SUBSTRATE: Supports the mirror facesheet by supplying the required rigidity necessary to meet mirror performance specifications. The mirror facesheet and the mirror substrate may be a structure of continuous material. A mirror cooling system may be located in the mirror substrate, generally as close to the facesheet as possible.

MIRROR SUPPORT STRUCTURE: Carries the mirror assembly by means of the mirror connector and mirror pivot. Also provides a location for the mirror drive mechanism and reference point for rotary measurement of scan angle.

MOTOR FLUTTER: Change in motor angular velocity within one revolution (pole-to-pole) usually very consistent.

MOTOR HUNTING: Change in motor angular velocity over several revolutions, (pole-to-pole) and is very erratic.

NATURAL FREQUENCY: The lowest undamped resonant frequency of a mirror scanning motion system. The frequency with which a mirror scanning motion system oscillates in the absence of external input forces.

PERIOD: Time interval needed to complete a cycle; the reciprocal of frequency.

POLYGON SCANNERS: Multi-mirror high speed rotating mechanism.

PROTECTIVE RING: A metal ring required to prevent a mirror from fragmenting during high speed rotation.

PROTECTIVE SHIELD: A metal structure required to contain mirror fragments (after mirror burst) from doing additional damage. Can also perform an additional function as a housing to reduce mirror windage losses.

PYRAMIDAL POLYGON: Mirror facet planes have a common angle less than 90 degrees with the scan rotational axis. Uniform facet angles. Used to provide smaller scan angles with fewer mirror facets than can be provided with regular polygonal mirrors.

REACTIONLESS MIRROR: A mirror scanning motion system which imparts a minimum (or negligible) reaction force into the surface that the mirror support structure is mounted on.

REGULAR POLYGONS: Mirror facet planes are parallel to and face away from the scan rotational axis. Used to provide repetitive straight scans in a mirror scanning motion system.

RESONANCE: A mirror scanning motion system is said to be in resonance when the excitation driving input frequency matches the natural frequency of that mirror scanning motion system.

RESONANT SCANNER: The rotational natural frequency of the mirror scanning motion system is the same as the required scanning or chopping frequency. Resonant scanners normally operate near resonant frequency and are not well suited for variable motion applications.

RUN-OUT (WOBBLE, TWO AXIS TILT): Describes the maximum distance that a point will deviate from a perfectly flat plane that is perpendicular to axis of rotation.

SCAN EFFICIENCY: The ratio of the dwell time in a perfect mirror scanning motion system to the dwell time of the actual mirror scanning motion system.

SCAN LINEARITY: The uniformity of the scanning speed (angular velocity) during the usable mirror scanning motion system cycle.

SCANNING FREQUENCY: A mirror scanning motion system in which the output frequency is made to vary at a mechanical rate over a desired frequency band and required mirror scan angle.

SHAFT BALANCING (ROTOR BALANCE): The process of redistributing the mass attached to a rotating mirror in order to reduce vibration caused from centrifugal forces of the mass center when displaced from the axis of rotation.

TAUT BAND SCANNERS: The mirror is carried by a taut band flexure. Used for rotational mirror scanning motion systems.

TORSION ROD SCANNERS: The mirror is carried by a torsional flexure. Used for rotational mirror scanning motion systems.

TORSIONAL VIBRATION: A periodic motion of a shaft in which the shaft is twisted about its axis first in one direction and then in the other; this motion may be superimposed on rotational or other motion.

TOTAL CYCLE TIME: The time required to complete one end-to-end scan cycle of a mirror scanning motion system.

TRANSITION TIME: The time required to proceed from one mirror angular position to a second mirror angular position.

TRANSITIONAL FLOW: A flow in which the viscous and Reynolds stresses are of approximately equal magnitude; it is the transitional condition between laminar flow and turbulence.

TURNING FORK SCANNERS: The mirror is carried on a fork flexure. Primarily used to provide translational motion in a mirror scanning motion system.

NOTE: UNDEFINED TERMS

- UNCOUPLED NATURAL FREQUENCY
- ACCELERATION CYCLE
- REACTION FORCES
- SHAFT VELOCITY RATIO
- PERIODIC DEFORMATION
- SCAN PATTERN
- HYSTERESIS (LOSSES)
- FLEXURE SUPPORTS
- RESONANT CURVE
- WOBBLE
- WHIRL
- WINDAGE LOSS