Design and Manufacturing Considerations for High Performance Gimbals used for Land, Sea, Air, and Space

Mike Sweeney, Lafe Redd, Tom Vettese, Ray Myatt, Dave Uchida, Del Sellers
CMM Optic, Rochester Hills, MI

ABSTRACT:

High performance stabilized EO/IR surveillance and targeting systems are in demand for a wide variety of military, law enforcement, and commercial assets for land, sea, air, and space. Operating ranges, wavelengths, and angular resolution capabilities define the requirements for EO/IR optics and sensors, and line of sight stabilization. Many materials and design configurations are available for EO/IR pointing gimbals depending on trade-offs of size, weight, power (SWaP), performance, and cost. Space and high performance military aircraft applications are often driven toward expensive but exceptionally performing beryllium and aluminum beryllium components. Commercial applications often rely on aluminum and composite materials.

Gimbal design considerations include achieving minimized mass and inertia simultaneous with demanding structural, thermal, optical, and scene stabilization requirements when operating in dynamic operational environments. Manufacturing considerations include precision lapping and honing of ball bearing interfaces, brazing, welding, and casting of complex aluminum and beryllium alloy structures, and molding of composite structures. Several notional and previously developed EO/IR gimbal platforms are profiled that exemplify applicable design and manufacturing technologies.

Keywords: high performance gimbals, stabilized line of sight (LOS), accuracy, resolution, EO/IR sensor suite, rotary flexures, gas bearings, non-linear FEA, computational fluid dynamics (CFD), SWaP analysis, Beryllium alloy welding, brazing, and investment casting, graphene, amorphous metals, additive manufacturing, 3-D printing.

1.0 INTRODUCTION:

The basic elements of high performance gimbals are the optical payload, bearings, actuators, angular position sensors, and structural embodiment thereof. Optical payloads vary considerably in type, size, and shape and typically include flat mirrors and integrated telescopes and EO/IR sensors. The performance of the optical payload and its pointing accuracy requirements dominate the system design process.

Materials and construction techniques are essential to the mechanical design of the gimbal. High performance airborne and space gimbals are often constructed from beryllium or aluminum beryllium. Commercial airborne applications and land and sea based gimbals typically utilize Aluminum alloys and/or composite materials.

Flexures, ball bearings, and gas bearings are common means to sustain means of support for an optical payload within a gimbal structure and allocate desired compliance and constraint of motion among the six degrees of freedom.

2.0 DISCUSSION:

An outline of a variety of materials, manufacturing processes, and rotary joints for precision gimbals is presented. Size, weight, and power (SWaP), rotational inertia, performance, and cost considerations are central to the development of gimbal systems for scene stabilization and pointing of a wide variety of EO/IR sensor suites. Numerous examples that illustrate the successful use of these elements in various notional and real-life designs are also presented.

2.1 Materials and Processes for Gimbal Structures

Aluminum, aluminum-beryllium, beryllium, and composite materials are all commonly used for gimbal structures.

Beryllium is most noted for its low density and high modulus of elasticity resulting in a specific stiffness that is about a 6.3X greater than most other structural metals such as steel, aluminum, titanium, and magnesium. Beryllium also has superb thermal diffusivity and structural damping characteristics. The coefficient of expansion can be well matched to steel for interface of precision ball bearings. Beryllium is very expensive to produce and to post process into precision parts and is thus generally used when no other material can satisfy stringent mass, inertia, and performance requirements for precision gimbal structures. Generally, structural grades of beryllium produced by Materion Corporation, such as S200F (vacuum hot pressed) or S200FH (hot isostatically pressed), suffice for gimbal structures.

Aluminum beryllium alloys have a reduced, but still impressive 3.0X specific stiffness advantage over steel, aluminum, titanium, and magnesium and low density combined with lower cost and wider range of available fabrication options enabled by combining some of the best properties of both materials.

Cast and forged aluminum alloys are comparatively very inexpensive with highly versatile and producible manufacturing options available. The relatively low elastic modulus, high thermal coefficient of expansion, and inferior structural damping properties of aluminum limits its application in some high performance gimbal applications.

Composite materials for gimbal structures typically consist of high strength fibers or woven cloth embedded in an epoxy matrix. Composite materials are light weight, strong, can be tuned for the desired coefficient of expansion, and have excellent structural damping. Fiber materials for composite structures are constantly evolving. Synthesized Carbon nanotube fibers and graphene sheets are particularly interesting due to phenomenal material properties. It has been estimated that graphene sheets of atomic thickness could be developed that are 3.4X stiffer than beryllium, 100X stronger than alloy steel, with a density similar to aluminum beryllium. Graphene is also seen as potentially having more efficient adhesion than fibers within a composite matrix due to wetted surface area advantages. Fragments of graphene occur naturally in common graphite and this material is exfoliated onto paper when using an everyday pencil.

Manufacturing methods available for aluminum, beryllium, aluminum-beryllium, and composite materials comprising gimbal structures include the following:

Hog out: Modern CNC machining centers can quickly and accurately shape solid rectangular or cylindrical blocks of aluminum or beryllium metal into intricate gimbal shapes often 5-10% of the original mass.

Near Net Shaping (NNS): If the material is expensive or if the part is large, it is practical to fabricate a near net shape of the desired part prior to completing final machining. For example, Materion can design a welded sheet metal steel can that is filled with beryllium powder, welded closed, de-gassed, and HIP consolidated to form NNS substrates for gimbal structures with minimal material waste. A variant of the metal can NNS approach is to fill a rubber-like bag in the shape of the part, fill the bag with powder, seal the bag, and then perform cold isostatic pressing (CIP) so that the powder is consolidated. After stripping away the rubber bag the harvested green form can then be sintered and HIPed.

Investment Casting: Many suppliers specialize in investment casting of aluminum alloys such as A356-T6. Patterns that are “invested” in the process can be made from wax or plastic from permanent cavity injection mold tooling or from 3-D printing methods such as stereo lithography apparatus (SLA). Recently there has been renewed interest in the investment casting of complex structures from AlBe alloys similar to those routinely produced from aluminum alloys such as A356-T6. Pure Beryllium cannot be investment cast in a useful manner due to the large and brittle grain structure that results during re-freezing of the melted metal.

Brazing: Aluminum, beryllium, and aluminum-beryllium can all be joined by various brazing processes. Brazing employs an intermediate alloy having a lower melting point than the parent materials. Beryllium has a much higher melting point than the aluminum alloy commonly used for brazing and is thus minimally affected by the brazing process.

Electron Beam Welding: Recently Materion has been successfully welding AlBe alloys. These processes can produce closed and semi-closed cells for internal pressurization or improved structural efficiency and minimize the heat affected zone due to the efficient, highly controlled, and concentrated application of heat. Beryllium cannot be welded.

Composite Molding: Fiber reinforced composite materials are also being used for gimbal structures. Molds are used to achieve the desired shape and surface finish of the final product. New carbon reinforced composite materials that use nano-tube and graphene allotropic forms may one day revolutionize structures for gimbals.

Hybrid Construction: Combinations of several of the above processes can be used for gimbal structural elements. Closed and semi-closed cavities cannot be investment cast due to the difficulty of removing trapped shell material but hybrid processes that include casting, machining, brazing, and EB welding can be applied.

3-D printing: This technology, also known as additive manufacturing (AM), is already being routinely used to construct the stereo lithography (SLA) generated plastic patterns for rapid prototype investment casting of aluminum and aluminum-beryllium alloys for gimbal components. In principle, this process has few limitations in the creation of semi-closed cellular or lattice construction, and has potential for very little metal waste in the form of added post machining stock allowances, and sprues, runners, gates, and risers used in casting processes. In the future, it will become possible to directly print these types of gimbal components from various metal powder compositions.

Thermal Stabilization, precision grinding, honing and lapping, platings: All metal alloy design solutions for gimbal structural elements require appropriate manufacturing processing to achieve dimensional stability, micron level tolerances for fitting of bearings, and protective coatings for corrosion resistance and wear resistance where applicable.

Table I below summarizes the various processes that can be applied for each material under consideration:

	Manufacturing process	**Al 6061-T6**	**Al A356-T6**	**Be S200F**	**AlBe alloy**	**Composite**
1	**Hog-out**	Yes	no	yes	yes	yes
2	**Near net shape**	No	yes	yes	yes	yes
3	**Investment casting**	No	yes	no	yes	no
4	**Welding**	Yes	yes	no	yes	no
5	**Brazing**	Yes	yes	yes	yes	no
6	**Molding**	No	no	no	no	yes
7	**Hybrid construction**	Yes 1, 4, 5	Yes 2,3,4,5	Yes 1, 2, 5	Yes 1, 2, 3, 4, 5	No
8	**Additive manufacturing**	Emerging	AlSi10Mg	Future	Future	Emerging

Table I: Manufacturing processes that can be applied to candidate materials for gimbal components

2.3.1 Case study #1: Notional Gimbal Design (see figures 1, 2, 3)

A notional gimbal design is presented to portray the relative performance of a variety of structural materials, design configurations, and manufacturing methods including hog-out from block, hog-out from near net shape, investment casting, brazing, and welding. It is assumed that each notional gimbal ring and yoke component will have the same outer dimensions, and must support a 300 mm aperture optical payload having a mass of 10 kg. The rotational range of motion is assumed to be +/-30 degrees in two axes and the rotary joints are assumed to be approximately 25 mm diameter pre-loaded duplex bearings. Both solid and aggressively light weighted versions of the same design profile were modeled for each material under consideration. The typical wall thickness for the light-weighted design was assumed to be 1.0 mm and each pocket would be semi-closed and vented by circular holes.

Casting, welding, brazing, and AM processes all enable the construction of semi-closed cellular structures having greater structural efficiency than open cell types of structures produced by general CNC milling processes. In addition, near net shaped parts significantly reduce the amount of expensive beryllium alloy consumed to manufacture a part compared to machining. Hybrid operations that combine processes are also envisioned to minimize cost while maximizing performance. The relative mass and natural frequency for each scenario is analyzed and then summarized in table II below.

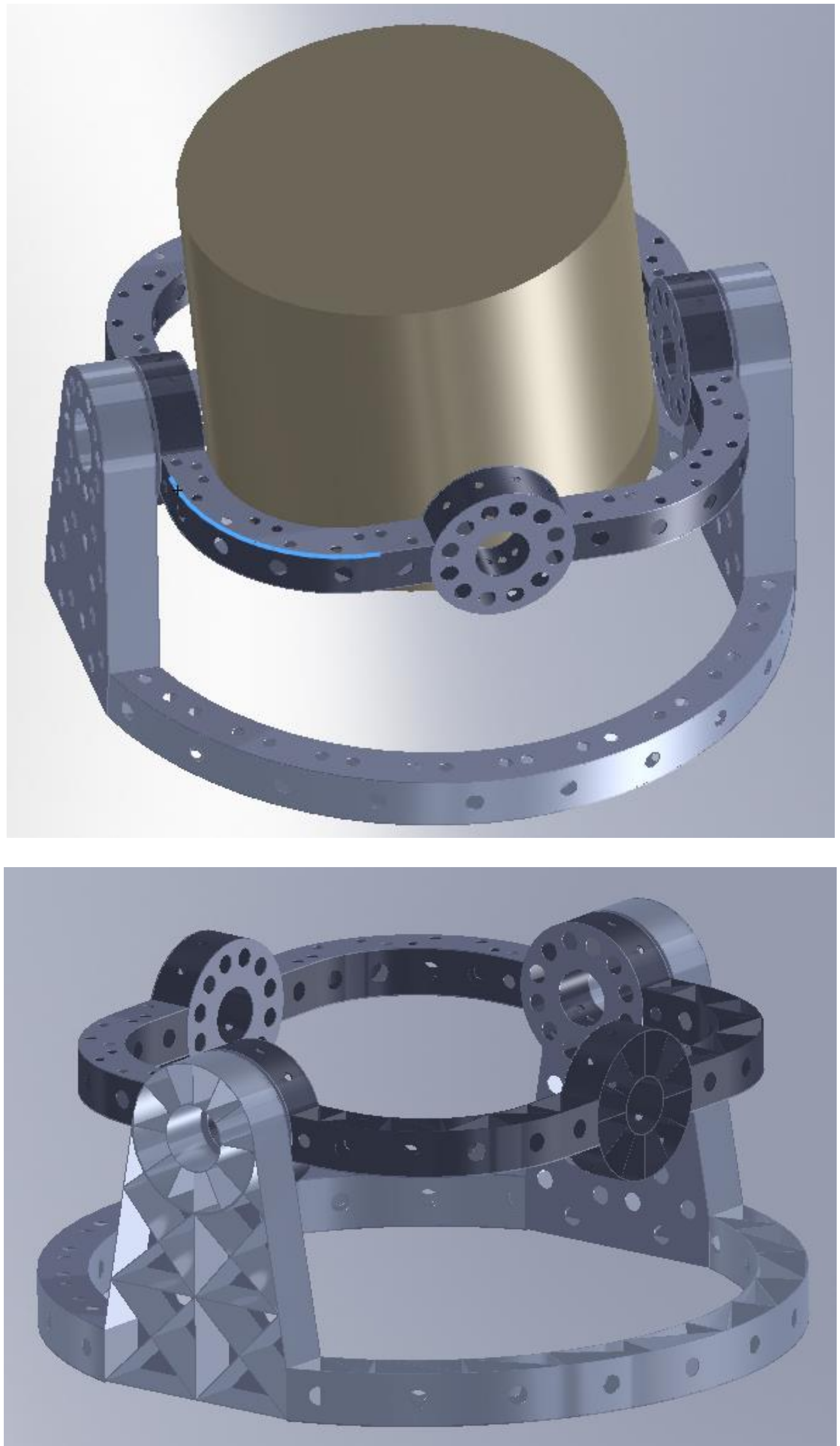


Figure 1: The top view shows the notional gimbal with 300 mm aperture, 10 Kg dummy payload and light weighted and skinned over pocket structure. The bottom view illustrates interior views with the skin removed in some areas to illustrate the rib structure. An all solid design with identical outside dimensions was also modeled for comparison

Scenario	E (MPa)	Density (g/cm^3)	Yield (MPa)	Mass (g)	Mode 1(Hz)
Solid aluminum cast assy					188
• Ring	72.4	2.67	165	4401	393
• Yoke	72.4	2.67	165	8507	175
Solid AlBeMet162 assy					315
• Ring	193	2.071	276	3448	723
• Yoke	193	2.071	276	6666	332
Solid Beryllium S200F assy					401
• Ring	303.4	1.850	207	3045	966
• Yoke	303.4	1.850	207	5887	449
Solid Graphene assy					714
• Ring	1000	2.200	130000	3612	1611
• Yoke	1000	2.200	130000	6983	735
LW cast/braze aluminum assy					70
• Ring	72.4	2.670	165	713	398
• Yoke	72.4	2.670	165	1277	189
LW cast/braze AlBe assy					114
• Ring	193	2.071	276	555	730
• Yoke	193	2.071	276	1001	356
LW brazed S220F Be assy					145
• Ring	303.4	1.850	207	490	977
• Yoke	303.4	1.850	207	883	482

Table II: Summary of FEA results for the notional gimbal design study. The relative material properties and structural simulation of various materials are compared for both solid cross section and aggressively light-weighted cross sections.

General Conclusions from the notional gimbal design study:

1. Welding, casting, and brazing of beryllium based materials enables the creation of gimbal components at reduced cost and resulting in structurally efficient semi-closed cell designs that are impossible to machine.

2. The aggressive light weight portrayal of both the yoke and the ring can be constructed as is by combination methods of EDM extraction, machining and brazing operations for beryllium only. EDM is precise, and beryllium dimensional integrity is minimally affected by the heat required to melt the aluminum alloy braze material

3. The very aggressive semi-closed cellular construction with 1.0 mm thick ribs for both the yoke and ring cannot be investment cast in monolithic form from aluminum or aluminum beryllium unless one of the flat skinned over sides is added on by welding or brazing. Also the quick cast photo curable polymer patterns created by stereo lithography for rapid prototyping of investment castings is currently limited to about 1.7-2.0 mm. This is so a closed honeycomb structure within the pattern can be created and then collapsed under heat after the refractory slurry shell is hardened. 1.0 mm wall thicknesses are feasible with aluminum with wax patterns made from hard mold tooling. Thinner section thickness for AlBe castings may be possible in the future.

4. The percentage of mass reduction achieved by the proposed light weight design is about 15% of solid material. 20-25% of solid material will be more practical for cast and welded design solutions having more uncertain dimensional variations due to casting and heat from welding.

5. Additive manufacturing can now be used to make aluminum components of the notional gimbal design. Since metal cannot be melted directly on top of powder for hot AM processes such as direct laser metal sintering (DMLS) and electron beam melting (EBM), some redesign will be required to accommodate temporary scaffolding and a maximum build overhang. One way of achieving the 45° overhang criterion for most of the

current features of the design is to build the parts when tipped at 45° relative to the build platform. Binder jetting AM can produce the design essentially as is since powder will support consolidation by binding agent. After a green form of the part is cured and de-powdered, it can then sintered and HIPed to nearly 100% density. Aluminum alloys have not yet been developed using the binder jetting process.

6. Imaginary performance of a graphene gimbal assembly is vastly superior to beryllium in terms of specific stiffness and specific strength. Graphene and other carbon re-inforced composite materials may one day revolutionize many types of structures throughout industry.

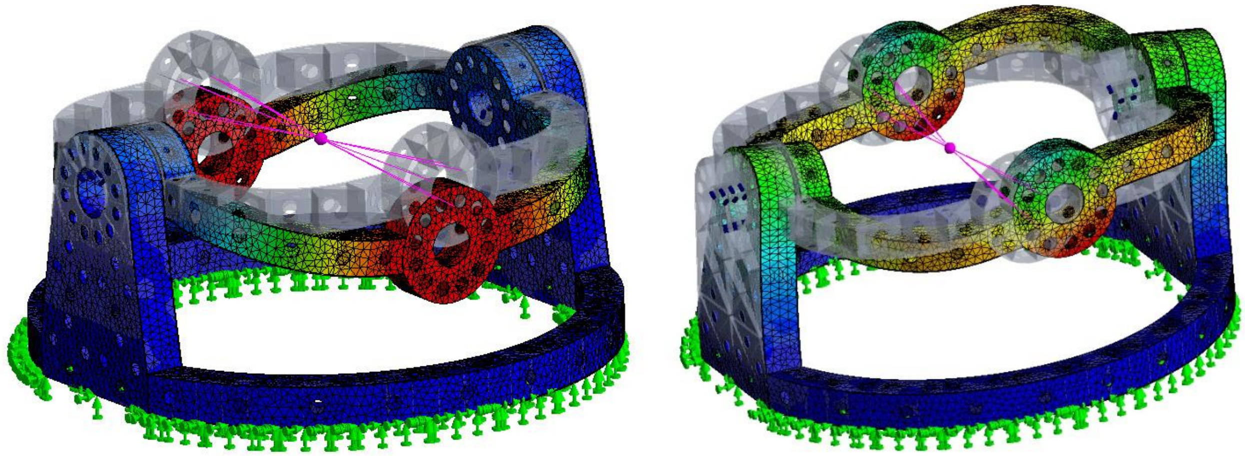


Figure 2: The notional gimbal yoke and gimbal ring solid models were meshed and analyzed by FEA for multiple materials and both solid and light weighted cross sections. A lumped mass attached to the inside of the gimbal ring is used to simulate a 300 mm diameter, 10 Kg optical payload. The approximate spring rate for 1" diameter duplex bearings was also modeled. Mode shapes and frequencies for the individual parts in a free state and for the assembly were considered for each design and material case. The semi-transparent un-deformed model is super-imposed over the exaggerated deformation of exhibited modes of vibration..

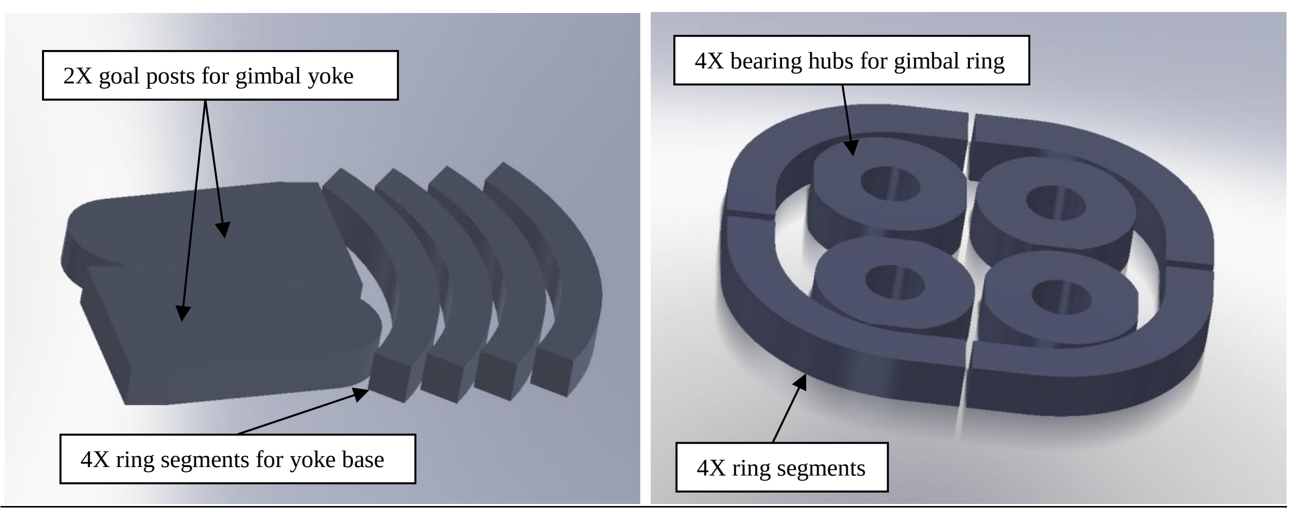


Figure 3: The gimbal yoke (left) and gimbal ring (right) can be efficiently manufactured from blocks of beryllium or aluminum-beryllium material by slicing out the parts, including skin pieces and interior pockets by wire EDM, then brazing or welding all of the parts back together. Individual parts can also be cast or near net shaped prior to final machining and brazing or welding.

2.2 Rotary Joints for Gimbal Designs

Rotary joints are critical for the operation of precision gimbal systems. They are required to be smooth in operation, low in torque, highly stiff in other axes, and operate continuously and reliably under the influences of broad ranges of operating temperature, shock, and vibration. Flexure spring, ball bearing, and gas bearing rotary joint suspension systems are in common use within gimbal systems and are discussed as follows:

2.2.1 Flexure Spring Rotary Joints: Spring system design and material selection are vital criteria to the application of flexure mounted optical payloads. Rotary flexures have limited angular range of motion but have exceptional smoothness and repeatability of motion. Gimbal Systems sometimes employ designs having a comparatively coarser and wider ranging ball bearing supported outer axes with more refined inner gimbal axes suspended with rotary flexures. Such systems are often termed 5-axis or 4-axis gimbals when the optical payload only really moves in three or two axes respectively.

An ideal flexure system has the following attributes:

- Very low stiffness to resist the desired directions of motion
- Very high stiffness in the constrained directions of motion
- Controlled location of the virtual pivot of flexure system
- Near-perfect elastic response in the desired directions of motion
- Very high resistance to metal creep and fatigue
- Compatible coefficient of thermal expansion with the optical payload and support structure

A wide selection of spring materials, spring types and associated manufacturing technologies are available for flexure designs. Also, mature flexure designs such as "Bendix flex pivot" rotary types are commercially available. Generally, attempts are made to conserve energy and reduce actuator force requirements by minimizing the spring rate of the flexure in the compliant directions. This minimizes the holding force that the actuator must express to maintain a commanded position against the resistance of the flexure. Conversely, it is desirable to maintain very high spring rates for constrained degrees of freedom. The appropriate balance of spring rate and range of motion for all of the six degrees of freedom must be accommodated in the flexure design process.

2.2.2 Case study #2: Non-linear FEA of Amorphous metal alloy flexure

An emerging class of materials known as amorphous metal alloys may be suitable for advanced rotary flexures in future gimbal and fast steering mirror systems. These materials are produced by rapid solidification processes that result in an "amorphous" atomic composition rather than the crystalline lattice structure that is typical of metal alloys. Amorphous metals tend to have exceptional strength, elasticity, and surface finish properties that are ideal for flexures. An arbitrary 0.25" diameter Bendix type rotary flexure design with 420 stainless steel internal blades was compared to an identical design with blades modeled with Liquid Metal Technologies' Liquidmetal alloy using non-linear FEA modeling. Non-linear analysis is required to account for the extreme aspect ratios of the flexure blade elements and large deflections typical of flexures. The same amount of torque was applied to both designs in three equal and increasing amounts to assess the relative range of motion achieved versus stress thresholds and spring rate. A significant increase in the achievable range of motion and decrease in rotary spring rate appears to be realizable due to the combination of increased strength and decreased modulus of elasticity.

Flexure Blade Material	E (GPa)	Density (g/cm^3)	Blade Thickness (mm)	Torque (N*m)	Angle (deg)	Stiffness (N*m)/deg)	Blade Stress (Mpa)	Blade Yield (MPa)
Stainless 420	200	7.8	0.07112	0.0028245	11.8	0.000239364	432.12344	1344.525
Stainless 420	200	7.8	0.07112	0.005649	21.4	0.000263972	839.362825	1344.525
Stainless 420	200	7.8	0.07112	0.0084735	27.1	0.000312675	1127.59451	1344.525
Liquidmetal Alloy	93	6.1	0.07112	0.0028245	21.3	0.000132606	409.969805	1861.65
Liquidmetal Alloy	93	6.1	0.07112	0.005649	31.1	0.00018164	627.61048	1861.65
Liquidmetal Alloy	93	6.1	0.07112	0.0084735	34.8	0.000243491	739.53012	1861.65

Table III: Summary comparing non-linear FEA results on a Bendix type rotary flexure

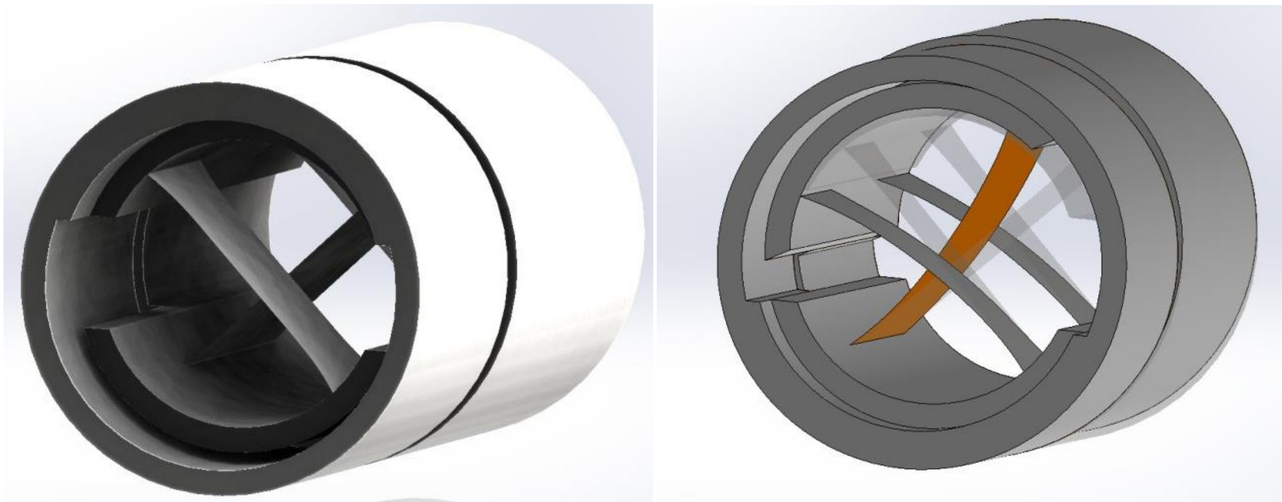


Figure 4: A Bendix type rotary flexure shown in a free state of constraint on the left and after simulation of rotation at the right. Non-linear FEA methods were used to compare the virtual performance of 420 stainless steel to an amorphous metal alloy produced by Light Metals Technologies.

<u>2.2.2 Precision ball bearings:</u> Ball bearings are the most common bearing technology applied to gimbal systems. The technology is very mature, there are excellent reference materials and technical support resources available, and a wide variety of off-shelf ball bearing products are commercially available.

General Rules of Thumb: Ball bearing mechanisms

- Preload: minimize for reduced torque but must be maintained under all environmental conditions
- Duplex bearings are best for controlled preload and accuracy
- Ball Geometry: Roundness of 0.000001-0.000025"
- Race Geometry: 0.000010-0.000100" in contact band
- Accuracy: Approximately 2X geometry errors divided by the separation of the radial bearings
- Surface finish: less than 8 micro-inches RMS per surface
- Stiffness, running torque: proportional to preload, number of balls, race diameter
- Anticipate effects of differential expansion over the operating temperature range

Gimbal Systems present many challenges for accuracy, limited angles, high acceleration and lubrication that push the performance envelope for ball bearings. Poor design practices, or inadequate geometrical accuracy of the bearing housings can result in wear, accuracy, or torque anomalies in the operation of otherwise high quality ball bearings. Limited angles result in uneven wear and distribution of lubricant. Ball bearing selection and assembly tolerances are critical for smoothness, low torque, life, adaptation to temperature changes, and structural stiffness. A pair of axially separated, preloaded duplex bearings is common practice for pointing mechanisms. Duplex bearings allow highly controlled, angular contact, ball preload to be established at the bearing manufacturer. One duplex bearing is fixed and the second widely spaced bearing will have axial "float" to prevent binding of the assembly. Lapped interfaces, interference fits, and compliance are often necessary to ensure that the bearing mounting geometry is retained and such that there is no axial or radial "shake" over temperature. Requirements for fit, geometry of flatness, squareness, and cylindricity, and bearing preload are all essential to the accuracy, smoothness, stiffness and life of duplex bearing operation. Refinements to the hone of bearing raceways, custom grinding and lapping for setting preload, sorting of balls for size matching and geometry, and customized lubrication are essential requirements for many high accuracy space applications. Vacuum applications necessitate the use of low out-gas lubricants or no lubrication within the bearing. Since a primary cause of bearing failure is "brinneling" or dinging of the bearing races by the balls, extreme attention to assembly processes, anticipation of peak shock and vibration, and handling of the completed mechanisms is extremely critical. Tightly toleranced crash prevention features or caging mechanisms can be designed into the bearings or support structure to prevent brinneling of the balls under extreme shock and vibration conditions.

The balls in ball bearings are typically made from hardened steel or ceramic and can be made almost perfectly smooth and spherical. Although the ball bearing raceways are typically hardened steel, it is also feasible to use appropriately finished, plated, and lubricated aluminum and beryllium gimbal parts to comprise the bearing raceways. This approach significantly reduces problems with differential coefficient of thermal expansion (CTE) in the design and can reduce cost, complexity, mass, and inertia if competing design challenges such as wear resistance, and brinneling are overcome. A couple of examples are shown in figure 5 below.

Figure 5: General Dynamics in Nashua, NH specializes in the design of EO/IR optical systems. The photo at left shows a multi-stage infrared zoom lens assembly. Rotational motion of a cam cylinder with ball bearings engaged against coated aluminum races is used to axially translate separate lens groups. The photo at right shows a much larger rotating optical assembly with similar integrally coated aluminum ball bearing raceways. The intricate spoked rotating optical barrel that can be seen within an outer fixed barrel is an A356-T6 aluminum alloy investment casting utilizing a rapid prototype pattern made from a closed cell honeycomb liquid photo curable polymer.

<u>2.2.3 Externally pressurized (aka hydrostatic, aerostatic) gas lubricated bearings:</u> In this scenario, a pressurized gas is introduced into a network of air passages leading to small orifices at the junction between the opposing surfaces. The gas emerges from the orifices at high velocity, impinges upon the opposing surfaces and produces a significant gas film pressure upon the exhaustion of the kinetic energy of the gas stream. Since no sliding contact occurs, mechanical errors in geometry and surface finish between surfaces separated by the gas film are averaged, resulting in exceptionally accurate and smooth motion with very low viscous friction. Although bearing surface finishes and geometry for pressurized gas bearings are similar to those instilled in ball bearings, it is common that the gas bearing will perform with 10+ times greater precision due to the respective differences between averaging and continuous contact error effects.

General Rules of Thumb: Externally pressurized gas Bearings

- Gap: 0.00025-0.00060"
- Geometry: (roundness, cylindricity, sphericity, conical profile, etc): 1/10 Gap
- Accuracy: less than 1/10 geometry divided by the separation of the radial bearings
- Surface finish: less than 8 micro-inches RMS per surface
- Orifice diameter: 0.003-0.020" diameter depending on gas pressure and viscosity
- Stiffness: directly proportional to supply pressure, effective surface area, 1/gap
- Eccentricity: less than 30% of gap
- Gas consumption: proportional to $(gap)^3$
- Power consumption: increases/decreases proportional to $(gap)^2$

Gimbals that employ externally pressurized gas bearing can be comprised of cylindrical journal bearings that replace the role of ball bearing or spherical balls that may be rotated in all three rotational directions. In general, the stiffness of this type of bearing is related to the number of orifices, gas film thickness (gap) supply pressure, gas viscosity, and bearing surface area. Air passages, fittings, small drilled holes, and sometimes bearing sleeves are required for externally pressurized bearings.

2.3.1 Case study #3: Spherical gas bearings

General Dynamics in Rochester Hills, MI specializes in the design and manufacture of gas bearings used for rotary scanners and gimbals. Air bearing gimbals can consist of journal and thrust acting cylindrical bearings similar to ball bearing types of designs or spherical bearings that enable essentially frictionless tri-axial rotation.

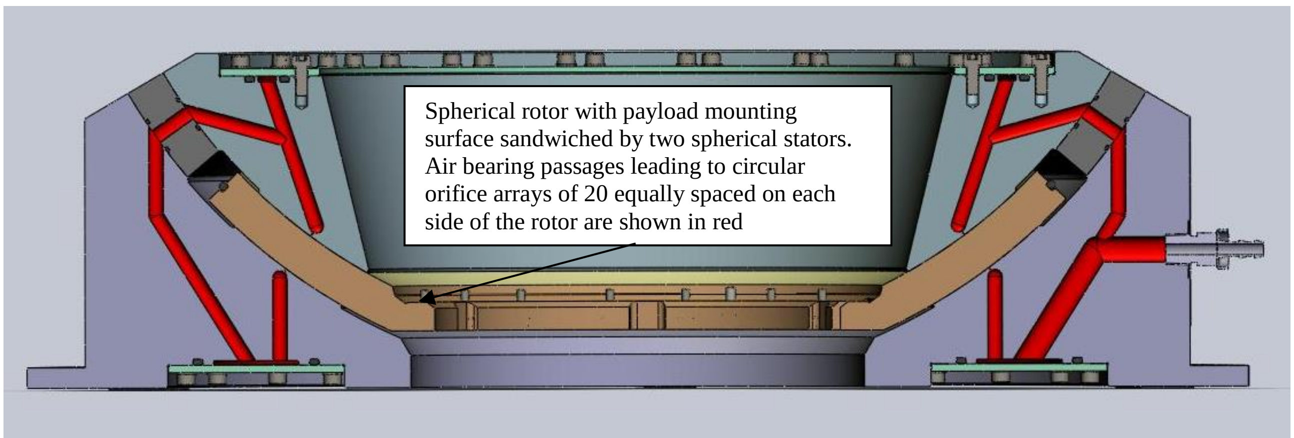


Figure 6: Many configurations of spherical gas bearing gimbal designs have been developed. The above figure illustrates the cross sectional view of a large spherical air bearing gimbal developed as a part of a simulation system. The system provides virtually frictionless motion in three axes and a large load capacity.

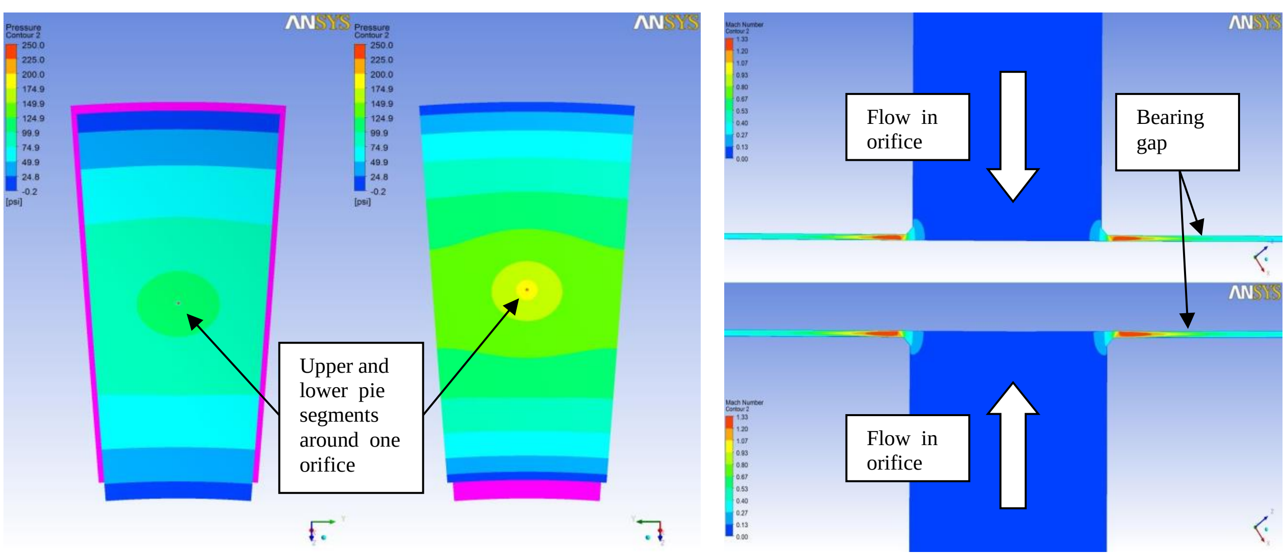


Figure 7: CFD results for the spherical gas bearing illustrated in figure 6. At left, symmetry is used to model the resulting pressure distribution of one of each of 20 equally spaced gas orifices in the stators on the upper and lower side of the spherical rotor. At right an enlarged view of gas flowing through orifices (blue) on the upper and lower side of the rotor and then squeezed and accelerated to supersonic velocity into the pressurized region before exhausting from the bearing to ambient atmosphere.

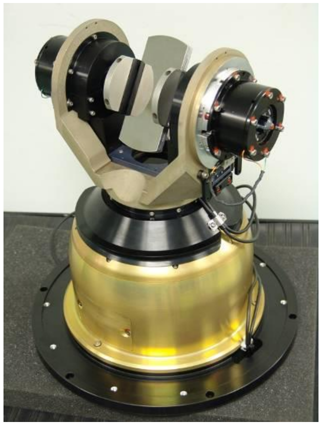
Recently a large spherical gas bearing was designed and manufactured as part of a motion control simulator (see figure 6). Until fairly recently, rules of thumb and empirical methods have been used to predict and optimize the key performance parameters of externally pressurized gas bearings. On this project, computational fluid dynamics (CFD) was used to calculate the gas flow rate, gas velocity distribution, resulting pressure forces and stiffness, and thermodynamic cooling effects. SimuTech in Rochester, NY was engaged to model the design by application of the ANSYS CFX solver. Due to extreme changes in volume and flow velocity, SimuTech used “local timescale factors” to successfully model flow characteristics and demonstrate mass flow and energy balances for solution convergence. This technique allows different time scales to be used in different regions of the calculation domain. The value entered is a multiplier of a local element-based (related to both grid size and flow physics) time scale. Smaller time scales are applied to regions of the flow where the local time scale is very short (fast flow), and larger time scales to those regions where the time scale is locally large (slow flow). This option is very useful when there are widely varying velocity scales in the simulation, for example, jet flow into a plenum chamber. The overall solution is then synchronized in time using constant physical time scale for the entire calculation domain. Figure 7 above illustrates the modeling assumptions, pressure distribution, and gas velocity profile.

2.3.1 Case study #3: Commercial High Fidelity Airborne Gimbal Systems

General Dynamics in Grass Valley, CA (formerly Cineflex) produces numerous airborne gimbaled camera systems. Due to cost considerations in a highly competitive commercial market landscape, aluminum and composite materials are used extensively. The inner gimbal components, comprised of aluminum, are often housed within outer gimbal structures made from molded carbon fiber reinforced composite materials. The composite structures are aerodynamically smooth, strong, light-weight, corrosion resisting, with excellent structural damping characteristics. Known as “4-axis” or “5-axis” systems, the inner two axis gimbal is mounted on a two axis flexure suspension system to enable highly refined, small angle, motion control and scene stabilization. A “fifth” axis is sometimes added for roll stabilization in addition to basic pitch and yaw stabilization. Images from the optical payload on the gimbal are benefitted by data fusion from GPS, on-board navigation systems, and ground point stabilization onto points of interest or points of reference to enable outstanding scene stabilization, positioning knowledge, and situation awareness in demand for a wide range of applications in entertainment, law enforcement, surveillance, security, and military applications.

Figure 8: Two airborne gimbal systems are shown above. At left is a “5-axis” system used for long range zoom and high resolution, vivid color, visible imaging capabilities for cinematography. This gimbal employs aerodynamically smooth composite outer shells. At right is an all aluminum “4-axis” gimbal system with multiple apertures for EO/IR capabilities in demand for law enforcement and surveillance. Both gimbals utilize a flexure suspended two-axis inner pitch and yaw gimbal to achieve premium image stabilization.

2.3.1 Case study #4: Large Volume 3-D metrology Systems



General Dynamics designs and manufactures gimbaled mirror assemblies for an ultra-precision laser radar system used for large volume 3-D metrology. The accuracy of the high density optical encoders and repeatability of custom sorted and assembled duplex bearings is essential to the ultra-smooth, sub-arc second intrinsic accuracy that results after error mapping. Exceptional ball bearing performance is achieved by maintaining low stress, controlled pre-load, and zero clearance assembly of the bearings within gimbal structures manufactured to sub-micron precision when operating over a moderate temperature range.

Such equipment stresses the limits of manufacturing technology for implementation of precision ball bearing design solutions and may benefit from the use of gas bearing technologies for master calibration fixtures and potentially for fielded equipment.

Figure 9: 3-D measurement gimbal

3.0 SUMMARY:

Multi-axial gimbal assemblies are a critical component of systems used to stabilize and point optical payloads for land, sea, air, and space, within commercial, scientific, and defense markets. An overview of the key elements of the mechanical designs of gimbal systems is presented herein. Several notional and actual components and systems are presented to illustrate representative designs, materials, and applicable manufacturing and analysis technologies.

New materials and manufacturing processes are continuously evolving to improve the prospects for both performance enhancement and cost reduction of precision gimbal systems. Aluminum beryllium products can now be investment cast and/or electron beam welded. Beryllium block can be partitioned into smaller pieces, aggressively machined and then assembled by brazing to achieve exceptionally light weight and structurally efficient designs.

Additive manufacturing has transformed investment casting of aluminum and aluminum beryllium alloys for gimbal components by enabling the rapid production of complex hollowed polymer patterns to expedite casting processes. AM is emerging to directly manufacture gimbal components by laser sintering, electron beam melting, and binder jetting of various metal powder compositions. Current hot AM processes such as DMLS and EBM require scaffolding and 45° overhang limitations when building a gimbal part. These processes are also currently slow and expensive for large parts. AM by binder jetting is a much faster and less expensive process and does not subject to overhang limitations and the need to create temporary scaffolding as a part is being built

Amorphous metals having exceptional strength and elasticity have ideal theoretical properties for components such as rotary flexures used in gimbal designs and limited angle fast steering mirrors

Molded composite materials are also a practical solution for gimbal structural elements. Future advances in carbon re-enforced composites, that may perhaps employ layered graphene sheets, could result in structures having unprecedented performance.

Advances in finite element analysis of structures and fluid flow dynamics provide design and manufacturing process engineers the evolving means to continuously improve upon the cost, delivery, and performance of gimbal systems.

4.0 ACKNOWLEDGEMENTS:

1. 411 Engineering, Rochester, MI (Notional gimbal design and analysis excerpts)
2. SimuTech, Rochester, NY (excerpts of CFD analysis applied to spherical gas bearing simulation)
3. Materion Corporation, Elmore, OH (technical support for beryllium fabrication)

5.0 REFERENCES:

1. Sweeney, M. SPIE volume 5176-30 “Design Considerations for Optical Pointing and Scanning Systems”
2. Sweeney, M., et al, SPIE volume 9574-5 2015 “Application and Testing of Additive Manufacturing for Mirrors and Ultra-Precision Structures”
3. Contacts at CMM Optic: msweeney@cmmoptic.com, mvettese@cmmoptic.com