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Development of a composite gimbal for a high precision inertial guidance test table

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ABSTRACT

This document discusses material selection, design, and analysis of a composite gimbal for use on a high precision inertial guidance test table with active magnetic bearing suspension. The test table's system performance goals of 0.1 arc second angular pointing accuracy and one part per million angular rate stability, can only be achieved by using a gimbal with high specific stiffness, highly symmetric elastic properties, and high dimensional stability. These characteristics are achieved by proper selection of the gimbal's construction material, configuration, and fabrication processes.

Both traditional and advanced composite materials are considered and evaluated for specific stiffness, coefficient of thermal expansion, thermal conductivity, dimensional stability, fabrication problems, and cost. Using the candidate materials, several gimbal configurations are evaluated with respect to the test table's system performance goals for angular pointing accuracy and angular rate stability. Specific gimbal design parameters affecting the system performance goals for angular pointing accuracy and angular rate stability include: the angular payload deflections due to torsional wind-up and asymmetrical stiffness; the linear payload deflections that cause torque disturbances and shaft wobble; and the natural frequencies affecting the control system bandwidths. Detailed finite element models of each configuration are used to predict the performance characteristics and demonstrate the advantages of the graphite/epoxy composite design.

INTRODUCTION: WHAT IS THE APPLICATION OF THIS GIMBAL?

The composite gimbal is a key component of the Improved Three-Axis Test Table (ITATT) program for the USAF Central Inertial Guidance Test Facility at Holloman AFB. The goal of this program is to improve the state-of-the-art in inertial guidance testing by two orders of magnitude. The specific ITATT system performance requirements are a pointing accuracy of 0.1 arc second, a rate stability of one part per million, and a servo bandwidth of 200 Hz.

Phase I of the ITATT program is currently underway and is the development of a single axis "proof of principle" prototype that is shown in Figure 1. This single axis prototype will be the inner axis of the complete three-axis machine and includes the rotating gimbal, trunnion shafts, active magnetic bearing suspension, a low cogging torque motor, and dual Inductosyn encoders.

What are the performance requirements of the Inner Axis Gimbal?

The overall ITATT system performance requirements place a stringent set of requirements on the gimbal structure. The flow down of these ITATT system requirements to the gimbal is shown in Table 1. The essential gimbal requirements are high specific stiffness, high absolute stiffness, high stiffness symmetry, and high dimensional stability for both the construction material and the configuration. These attributes are needed to make the gimbal act as close to a rigid body as possible. For example, the gimbal stiffness must be sufficient to make all elastic payload angular deflections negligible under any gimbal load orientation. In addition, the dimensional stability must be sufficient to make long and short term gimbal angular distortions negligible.

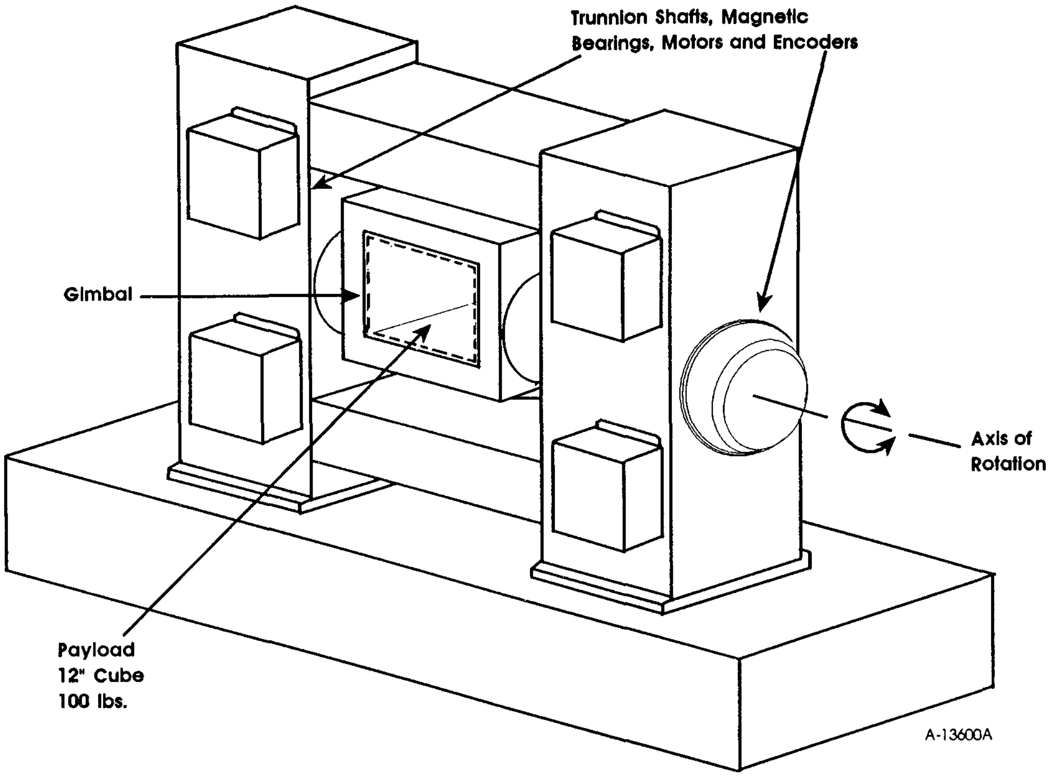


Table 1.
Flow Down of ITATT System Performance Requirements to the Gimbal

System Requirements	Gimbal Requirements	Specific Performance Requirements
0.1 arc second Pointing Accuracy	Support payload with: (100 lb, 12-inch cube) - Stiffness Symmetry - High Stiffness - Dimensional Stability	Negligible angular distortion achieved by: - Low Modulus Variations - High Specific Modulus - High Absolute Modulus - High Transient Thermal Distortion Index - Negligible Hydroscopic and Microcreep Effects - Tight Manufacturing Tolerances
1 ppm Rate Stability	Support payload with: - High Torsional Stiffness - Stiffness Symmetry	Negligible rate errors achieved by: - Low Modulus Variations - High Specific Modulus - High Absolute Modulus - Close Manufacturing Tolerances
200 Hz Bandwidth	Support payload with: - High Torsional Resonances	Resonances greater than 600 Hz achieved by: - High Specific Modulus - High Absolute Modulus

THE KEY DEVELOPMENT ISSUES: MATERIAL AND CONFIGURATION

The gimbal development effort can be divided into two key issues: the selection of the material and the selection of the configuration. To a large extent these decisions can be made independently; the one exception being the manufacturing issues. For example, the material selected may require certain fabrication processes that limit the possible shapes of the final gimbal. Within these manufacturing limitations, the gimbal development is presented as two tasks: material analysis and configuration analysis.

MATERIAL SELECTION ANALYSIS

Several construction materials were considered for the ITATT inner gimbal and their performance characteristics evaluated against the gimbal's requirements for stiffness and stability. The conventional materials considered are aluminum, titanium, magnesium, Invar, and beryllium which are homogeneous metal alloys. The non-standard materials considered are SiC aluminum and graphite epoxy. SiC aluminum is a metal matrix composite that mixes 20 percent silicon carbide particles into an aluminum matrix to produce a homogeneous material. Graphite/epoxy is an advanced composite material that bonds continuous graphite fibers together in an epoxy matrix to produce an in-plane isotropic material.

The important material performance factors considered are the microcreep strength (σmy) (Ref. 1), specific stiffness (E/ρ), the transient thermal distortion index ($K/\alpha\rho$ Cp) (Ref. 1), cost, and producibility. Microcreep strength is the amount of stress needed to produce microinch strains in the material, and specific stiffness is the stiffness to weight ratio. The transient thermal distortion index is the diffusivity (K/ρ Cp) divided by the CTE (α) and is a figure of merit that is useful in describing the thermal dimensional stability of the material. The results of this analysis are summarized in Table 2.

Table 2.
Performance Comparison of Candidate Materials for the ITATT Gimbal (1)

Material	σmy (Kpsi)	E (Mpsi)	ρ (lbs/in^2)	E/ρ (specific stiffness)	CTE (α) (ppm/°F)	Cp (Btu/lb-°F)	K (Btu/hr-ft-°F)	$\frac{K}{\alpha\rho Cp}$ (Transient Thermal Distortion Index)	Cost (1 to 100 Scale)	Producibility
Aluminum	25	10	0.1	100	12	0.22	92	348	1	Excellent
Titanium	80	16.5	0.16	103	5.3	0.12	5	49	10	Fair
Magnesium	-	6.5	0.065	100	14	0.25	31	136	2	Excellent
Invar	10	21	0.29	72	0.8	0.12	8	287	10	Fair
Beryllium	8	42	0.067	627	6.4	0.45	87	451	<25	Poor
SiC Aluminum (20% SiC)	<25	13	0.1	130	8	0.24	70	364	10	Good
Graphite/Epoxy (In-Plane Isotropic) (P55S Tape)	<20	10	0.065	154	0.3	0.22	14	3263	<25	Fair

Material analysis conclusions and comments

1. The microcreep strength of all materials is adequate for the ITATT gimbal, based on the expected low operational stresses.

2. The specific stiffness of beryllium is approximately four times higher than graphite/epoxy and SiC aluminum, the next highest materials. Thus, beryllium will provide the highest bandwidth.

3. The transient thermal distortion index of graphite/epoxy is seven to eight times higher than beryllium and SiC aluminum, the next highest materials. Thus, graphite/epoxy will provide the best thermal dimensional stability.

4. Beryllium and graphite/epoxy are at least 25 times more expensive than the least expensive material (aluminum), and 2.5 times more expensive than SiC aluminum.

5. A beryllium gimbal is somewhat more difficult to produce than a graphite/epoxy gimbal. The conclusion is based on the toxicity and size limitations of beryllium stock. However, the producibility of graphite/epoxy is limited by its non-homogenous properties (out of plane) and the need for elaborate layup and or assembly tooling.

6. One unique limitation of graphite/epoxy is its sensitivity to changes in humidity. This characteristic is well known and the effects can be made negligible using proper design techniques and environmental controls.

INNER GIMBAL STRUCTURAL ANALYSIS

Model and analysis overview

Two groups of finite element models were developed, using ANSYS, to evaluate the achievable performance levels on the ITATT inner axis. Representative models from each group are shown in Figure 2. The first group of models all had spherical outer shells and cylindrical inner shells, with the spherical radius being either 13.0 or 14.75 inches, and the length of the gimbal along the cylindrical bore being from 13 to 19 inches. The second group of models consisted of rectangular gimbals 12 inches or 20 inches in depth and having various wall thicknesses. All models included detailed representations of the shafts and the magnetic bearings.

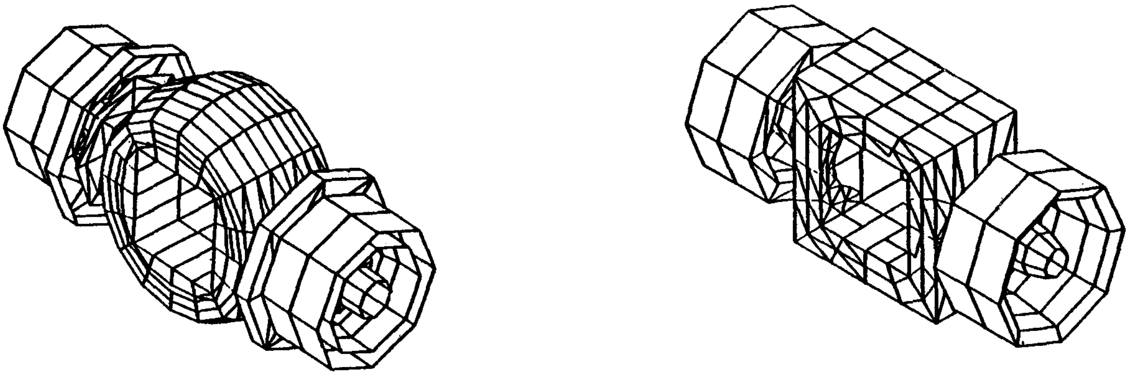


Fig. 2. Representative spherical and rectangular gimbals

Since the inner axis can be oriented in any direction relative to the earth's gravitational field, each model was subjected to gravitational accelerations along the three principal axes. In addition, load cases representing payload and axis imbalance and load cases designed to investigate the effect of mass and structural asymetries were run so that balance requirements and fabrication tolerances for each candidate configuration could be established and compared. The critical displacement results were the net rotations and translation of the payload, and the shaft rotation at the bearings and at the encoder. Finally, a harmonic analysis of the gimbal and the inner axis assembly was completed to predict the open loop transfer function that the servo system will control.

Structural asymmetry effects

Due to symmetry, the angular deflection at the payload is nominally zero for the gravitational cases. Position errors of the payload, relative to the encoder, can still arise because the required drive torque will vary at a 2 per revolution frequency if the gimbal's linear deflection (sag) is not uniform for any gravitational load orientation. The drive torque variation can be related to the work required to change the height and hence the potential energy of the payload and deflected structure between the most compliant and the least compliant orientations. This situation is shown schematically in Figure 3 where it is apparent that a potential energy differential exits between the vertical and horizontal load cases. Torque variations and the resulting payload angular errors were computed for all gimbal configurations. It has been determined that these non-constant linear gimbal deflections are not a significant error source as the position and rate errors do not exceed 0.00021 arc second and 0.002 ppm.

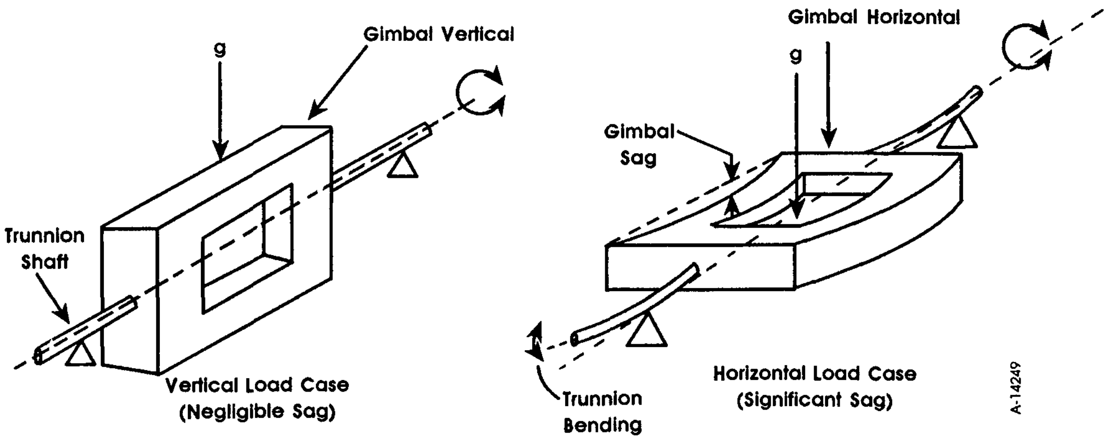


Fig. 3. The an-isoelastic gimbal effect (non constant deflections)

Other errors may be introduced by excessive trunnion shaft rotation (i.e., trunnion bending that is inherent with gimbal sag) since the encoder accuracy is affected by trunnion shaft deflections. The magnitude of shaft angular deflections at the encoders is reduced by using large diameter shafts and by minimizing the space between the radial bearings. In conjunction with the high stiffness of the composite gimbal, these design features make it possible to hold shaft rotation at the encoders to 3.7 microradians.

Mass asymmetry effects

Imbalance and other asymmetries result in angular deflections of the payload (i.e., windup of the gimbal) that vary with a once per revolution frequency. Imbalance about the inner axis results in a sinusoidally varying imbalance torque when the inner gimbal is rotated with the axis horizontal. Since the final inner axis design has the torque motor mounted on the opposite side of the gimbal from the encoder, the effect of torque variations on position and rate accuracy is quite low, 0.0004 microrad/in-lb of imbalance and 0.002 ppm/in-lb of imbalance respectively. A 1 in-lb imbalance due to a mass shift along the inner axis was found to result in a position error of 0.0023 arc second and a rate error of 0.0044 ppm.

Asymmetric mass distributions in a balanced axis can also result in payload position errors. This condition could arise if an unbalanced payload was installed in the gimbal, and then weights were attached to the gimbal to balance the system. This effect was evaluated by running several cases in which an imbalance moment was applied to the payload package and equipollent forces were applied to likely counterweight mounting points on the gimbal as shown in Figure 4. It was determined that the composite gimbal design can tolerate 5 in-lb of payload imbalance with net position and rate errors of 0.0035 arc second and 0.017 ppm, respectively.

Manufacturing tolerance effects

All the gimbal designs considered were nominally symmetrical about a central plan normal to the inner axis but the finite element results demonstrated that stringent dimensional tolerances were required to maintain adequate symmetry in the fabricated part in order to satisfy the design requirements. The dimensional variations expected in the finished part were built into one quadrant of the finite element model, as shown in Figure 5, and the results compared to those for the same configuration but with nominal dimensions throughout.

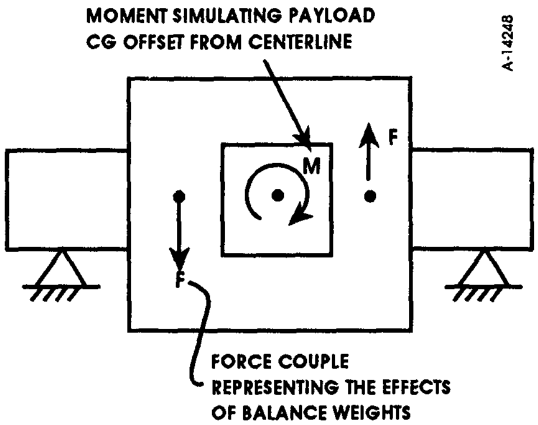


Fig. 4. Simulation of mass asymmetries

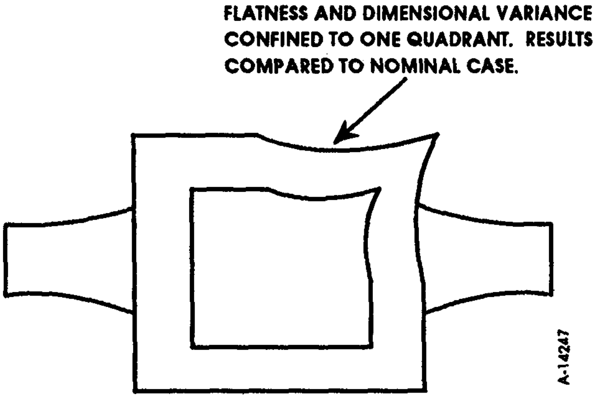
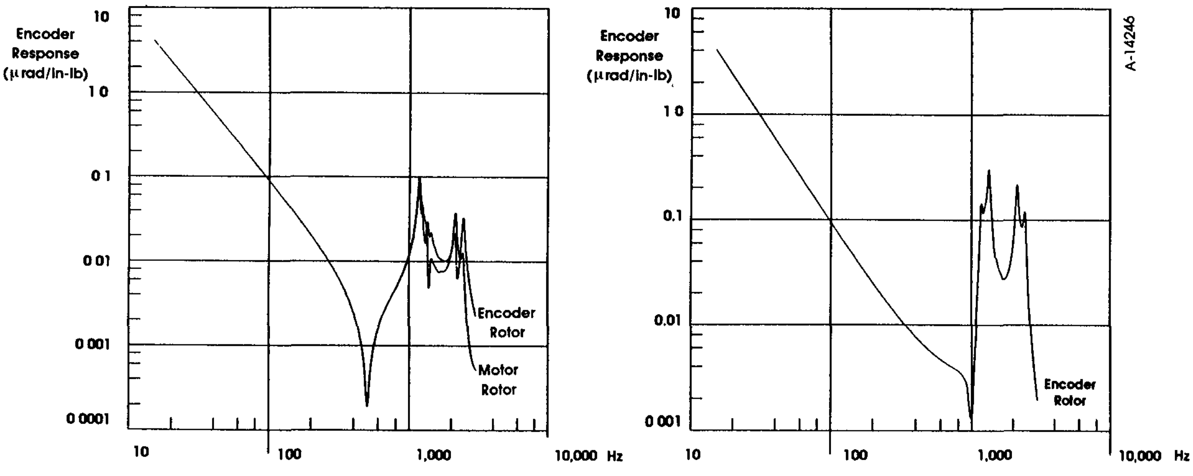


Fig. 5. Simulation of dimensional asymmetry



DRIVE MOTOR ON EACH SIDE

ONE DRIVE MOTOR OPPOSITE ENCODER

Fig. 6. Open loop responses for two possible axis configurations

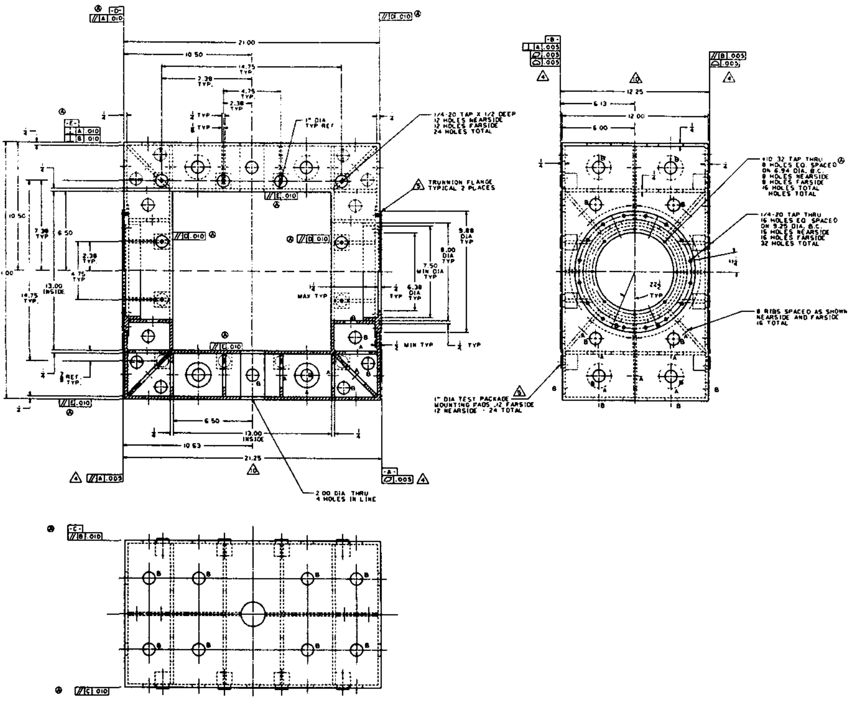


Fig. 7. Inner gimbal configuration

Three distinct areas were addressed in the final design manufacturing tolerance evaluation:

1. Flatness requirements for a single unsupported plate section.
2. General dimensional tolerances.
3. Material uniformity requirements.

The effect of unsupported panel flatness deviations of 0.010" is a payload rotation of 0.000006 arc second. The effect of gross dimensional deviations of 0.020" is a payload rotation of 0.0015 arc second. The effect of a 5% modulus change in one panel is a rotation of 0.0003 arc second.

The results described above apply to both the spherical and rectangular gimbal configurations. The spherical configuration was initially expected to provide better performance because it approximates an axisymmetric configuration. With the axisymmetric gimbal, the bearings on opposite sides were spaced farther apart than for the rectangular gimbals, a significant disadvantage when considering that two additional gimbal axes will eventually be wrapped around the axis currently being evaluated. In the end, the fabrication tolerance requirements drove the design conclusively to the rectangular configuration. Since it is assembled from flat plate segments, flatness and lay-up elastic properties can be controlled more precisely with the rectangular configuration resulting in a significantly more accurate axis.

Harmonic analysis

Having a stiff and highly symmetric inner axis is not sufficient to ensure that the required accuracies are achieved since the control system must have sufficient bandwidth to maintain the axis in precisely the desired position at any given instant. The design goal for this system was a 200 Hz bandwidth which ordinarily means that the first torsional resonance must be above 600 Hz. The open loop response of the axis was simulated using the harmonic response analysis option of the ANSYS finite element code. The input load is motor torque applied to the shaft with the reaction torque applied to the stator at the motor location. The angle encoder response is derived from the complex difference of resulting axis and stator rotations at the encoder location.

Harmonic analyses were performed for several arrangements of axis components including: motors on each side, inboard and outboard of the encoder, and a single motor on one side with the encoder mounted on the opposite side. The results of two of these cases are presented in Figure 6. Both of these configurations provide adequate bandwidth, although the resonances between 1350 and 2150 Hz will probably have to be notched out for the motor opposite encoder case. The motor opposite encoder case was selected for implementation for several reasons: the frequency performance is adequate, it gives a better match between available and required torque within the motor size envelope possible (given the shaft diameter), and it results in reduced imbalance sensitivity since it eliminates shaft drive torque between the encoder and the package.

THE FINAL GIMBAL DESIGN

The final gimbal design is constructed of graphite/epoxy with Invar fittings in a rectangular configuration. This design is shown in Figures 7 and 8 and is summarized in Table 3.

WHY WAS GRAPHITE/EPOXY MATERIAL SELECTED?

The graphite/epoxy material was selected because of its outstanding thermal distortion index and superior specific stiffness. The thermal properties of graphite/epoxy justify the additional costs and manufacturing complexity. The Invar fittings are used for the machining interfaces because they have a CTE relatively close to the graphite/epoxy. The laminate thickness is a constant 0.25 inch throughout the part to maintain symmetric hydroscopic expansion. By using special design techniques[1], the impact of the poor "out of plane" properties of the graphite/epoxy laminate can be made negligible.

WHY WAS THE RECTANGULAR GIMBAL CONFIGURATION SELECTED?

The rectangular gimbal shape was selected because it provides essentially the same sectional stiffness and symmetry properties as a spherical shape yet it has a superior interface to the cubic test payload. The stiffness and symmetry properties are equivalent because the inner gimbal must provide an opening for installation of the test payload. This opening truncates the spherical gimbal and negates its axisymmetric properties.

The manufacturing tolerance requirements proved to be an important link between the gimbal material and configuration decisions. The rectangular gimbal is constructed from flat stock graphite/epoxy laminate glued together to form the shells and stiffeners. This construction method proved to be the most practical method for achieving 5 percent modulus symmetry and 0.010 inch geometric tolerances. In contrast, the spherical gimbal is made using filament winding or special tape laying techniques and achieving the required manufacturing tolerances (with these techniques) is expensive and risky.

FUTURE ISSUES FOR THE ITATT GIMBALS AND STRUCTURAL COMPONENTS

During the development of the ITATT inner gimbal, several new technical issues have been uncovered that require further review and analysis.

Trunnion shaft material

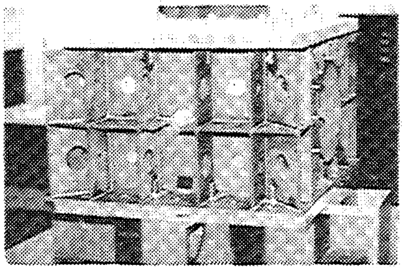
The trunnion shafts, attached to the gimbal, were not part of this initial analysis effort and are currently made of aluminum. Aluminum was selected based on the assumption that all temperature gradients, experienced by the shafts, are axisymmetric. A full review of the magnetic bearings revealed that the radial magnetic bearings produce non-symmetric thermal loads that make the top of the shafts hotter than the bottom. Thus, trunnion shaft thermal distortion is a significant error source that must be considered during the three-axis development effort. Most likely, the shafts will be made from a graphite/epoxy type material.

New and improved materials

Recent advances in graphite/epoxy and graphite/aluminum composite materials may be applicable to Phase II of the ITATT program. These materials have higher specific stiffness, lower CTE (i.e., near zero), and higher thermal conductivity and are just becoming commercially available. The most important improvement will be in the thermal distortion index which is directly affected by the higher conductivity and lower CTE. These new materials will make the larger Phase II gimbals less sensitive to thermal gradients and offset the increased sensitivity that results from increased size.

Trunnion Shaft Deflections (Wobble)

The structural analysis results indicate that the gimbal sag results in average trunnion deflections of approximately 0.6 arc second (see Figure 3) which effects the axis encoders. Deflections of this magnitude are inherent with this type of gimballed system but are magnified by the stiffness characteristics of the magnetic bearings. The magnetic bearings are true pin joints that produce zero moment stiffness and, as a result, maximize the trunnion deflections.



Gimbal in assembly fixture

Gimbal partially assembled

Final assembly

Fig. 8. Picture of gimbal

Table 3.
Inner Gimbal Summary

Shell Material	Pitch carbon fiber/epoxy (Amoco P55S/ERL 1962)
Insert Material	Invar
Configuration	Rectangular
Weight	70 lbs
Modulus Symmetry	Within 5%
Manufacturing Tolerances	Flatness, parallelism, squareness less than 0.010 inch
Encoder Location	Opposite motor
First Major Torsional Resonance	Above 600 Hz
Linear Deflections at Center:	
Gimbal Vertical	50 µinches
Gimbal Horizontal	204 µinches
Shaft (Trunnion) Deflection:	
Average Shaft Angular Deflection	3.06 µrad (0.6 arc sec)
Variation in Shaft Angular Deflection	1.32 µrad (0.26 arc sec)

The effect of trunnion bending on the encoders is a manageable problem for the single axis prototype but will be a serious problem when the second and third axis gimbals are "wrapped" around the inner axis in Phase II. This three-axis machine will tumble the inner gimbal and trunnions through the full range of their compliance. The effect of this tumbling will be an "apparent wobble" at the encoders of twice the static deflection value or 1.2 arc seconds. This is a significant error source for the encoders and must be considered in Phase II.

REFERENCES

1. Graphite/Epoxy Material Characteristics and Design Techniques for Airborne Instrument Applications, J.E. Stumm, G.E. Pynchon, and G.C. Krumweide, *SPIE Vol. 308 Airborne Reconnaissance V (1981).*