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A SYNCHRONOUS CHOPPER MECHANISM FOR USE AT CRYOGENIC TEMPERATURE

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ABSTRACT

This paper describes a mechanically resonant synchronous chopper mechanism for use at cryogenic temperatures. The mechanism is a critical optical component of the Diffuse Infrared Background Experiment (DIRBE) and has been operating on orbit without incident since November, 1989. The requirements, electromechanical design, and testing of the mechanism are described. A description of the problems encountered and solutions implemented during the development of the mechanism is provided. Finally, a modified chopper design, which incorporated lessons learned and that has several advantages over the flight chopper design, is offered.

INTRODUCTION

DIRBE Overview

The DIRBE is one of three instruments on the Cosmic Background Explorer spacecraft (COBE). Designed, fabricated, and tested at the Goddard Space Flight Center (GSFC), the COBE spacecraft was launched into a polar orbit on November 18, 1989. Originally designed to be launched on the shuttle, the spacecraft was redesigned to be launched on a Delta.

The three instruments of the COBE spacecraft have mapped the electromagnetic spectrum of the the entire universe in the region between infrared and microwave wavelengths. The DIRBE instrument detectors operate over the range from 1-300 micrometers. The detectors and the instrument are cooled to approximately 2 Kelvin (K) and are located in the Cryogenic Optical Assembly. DIRBE was designed to search for the light of primordial galaxies and other celestial objects that formed after the big bang. The DIRBE instrument has successfully completed its primary scientific mission.

Functional Description

A critical optical component of the DIRBE instrument, the synchronous chopper mechanism, operates at less than 2 Kelvin at a frequency synchronized with the spacecraft data rate of 32 Hz. The chopper mechanism modulates the incoming light beam from the sky to allow continuous comparison of sky brightness to the cold reference source. The entire DIRBE instrument is located in a liquid helium (LHe) cooled dewar. The location of the chopper mechanism within the DIRBE optical system is shown in Figure 1 (Ref. 1). When the chopper is open, the incoming beam is transmitted to detector assembly 2, and the cold reference source is viewed by detector assemblies 1 and 3. When the chopper is closed, the incoming beam is reflected to detector assembly 1 and to detector assembly 3 via a beam splitter, and the cold reference source is viewed by detector assembly 2.

The mechanism consists of a vibrating tuning fork with mirror vanes mounted on the end of the tines (Figure 2). The tines are electromagnetically excited near their resonant frequency by the drive coil. Feedback for the closed-loop control system is provided by the sensing coils.

History/Trade-off Studies

The basic chopper mechanism configuration was designed and fabricated through a contract with Frequency Control Products Inc. Programmatic problems were encountered, so the task of completing the design, fabrication and test of the chopper mechanism was reassigned to the Electromechanical Branch (Code 716) at the GSFC . Several chopper units were developed; a test unit, a spare unit, the flight unit, and a modified design unit.

A mechanism trade-off study was completed during the conceptual design of the instrument. A rotating disc with cut-outs and other alternative mechanism concepts were investigated. However, because of the large number of cycles required (over one billion) and the thermal environment (~2 K), mechanisms which utilized ball bearings were considered likely to fail. Therefore, the vibrating tuning fork concept which exhibited no wear was the baseline for further development. Similar chopper mechanisms have been flown on other spacecraft such as Mariner (Ref. 2). To our knowledge, a mechanism meeting the optical and thermal requirements of the DIRBE chopper has not been previously developed.

MECHANISM OVERVIEW

The requirements, electromechanical design and operation, balancing procedure, nonlinear characteristics, and mechanism testing are described.

Requirements

The environmental and performance requirements listed below were developed at the DIRBE system engineering level.

1) Continuous operation for 1 year on orbit at less than 2 K (1.0 billion cycles)
2) Average power dissipation less than 1.0 milliwatt
3) Survive launch loads
4) Vanes to chop a 10-millimeter diameter pupil
5) Vanes to act as a high-quality infrared mirror
   Optical vane flatness - $\lambda/4$ at $\lambda = .6$ micrometers
   Vane reflectance $\geq .9$ for $\lambda > .9$ micrometers
6) Vane temperature less than 5 K
7) Chopper frequency synchronous with spacecraft data rate (32.0 Hz)
8) Withstand thermal cycling between room temperature and 2 K
9) Dual windings and electronics for redundancy

It should be noted that as the development of the chopper mechanism proceeded, some of the requirements changed. A major impact to the design of the chopper was the change in launch vehicles from the shuttle to the Delta. This resulted in increased vibration loads on the mechanism. The Delta launch vehicle vibration environment transmits significant vibration input to the payload in the frequency region between 27 and 32 Hz. The increased vibration loading resulted in the redesign of the chopper mirror vanes.

During initial testing, as the DIRBE instrument became better characterized, some of the optical requirements placed on the chopper mechanism were relaxed. It was determined by means of system level testing that the chopper mechanism operated quite satisfactorily. Power dissipation of less than 1.0 milliwatt (mW) was not achieved. The actual power dissipation of 4.8 mW shortened the mission lifetime by approximately 2 weeks due to the slight increase in cryogen boil-off rate.

Perhaps one of the most important lessons learned should be mentioned here. The system design of the chopper required that the mechanism must operate synchronously with the spacecraft data rate of 32 Hz. It is a difficult task to fabricate, control, and test a mechanism which exhibits nonlinear behavior, is sensitive to its orientation to gravity, and operates at 2 K. It would be a less difficult task if requirements allowed for asynchronous operation, although the command and data handling electronics would become slightly more complex.

Electromechanical Design and Operation

The chopper mechanism was designed to modulate a 9.80-mm (0.3858-in.) diameter light beam on approximately a 50 percent open/50 percent closed duty cycle. Light is transmitted half the time and light is reflected off the mirror vanes half the time. The amplitude of vibration (apex diameter or largest opening) of the vanes is approximately 13.15 mm (0.518 in.). The vanes move in opposite directions from the apex diameter to a closed position where the offset vanes act as a continuous mirror and overlap by a minimum of 0.12 mm (0.005 in.). The gap between the vanes in a direction perpendicular to the mirrored surfaces is 0.30 mm (0.012 in). The chopper was balanced to operate at the desired amplitude and frequency with minimal power output at LHe temperature. The mechanical amplification factor (q) of the chopper was measured to be approximately 138.

The chopper is a mechanically resonant assembly driven by the drive coil in two modes; free running and synchronized. The control system of the chopper mechanism utilizes positive feedback from the sensing coils which are connected in series. A phase lock loop (PLL) technique is used to drive the chopper slightly above its resonant frequency. The amplitude of vibration is controlled. A pseudo-sine wave current input is applied to the drive coil. If the amplitude starts to increase above desired levels, the drive signal is decreased. The control circuitry has two independent channels which connect to the dual wound drive and sensing coils and is therefore fully redundant. Either the A or B side can fully operate the chopper.

The following chopper mechanism telemetry is available: power on/off status bit, free run override switch, and chopper in phase and out of phase components. From this telemetry and science data the following characteristics of the chopper operation can be determined: safe operating ranges, the relative phase of the vanes, and the absolute phase.

Figure 3 is a photograph of the flight chopper. A detailed description of the primary components of the chopper is presented below. The dimensions of the chopper are shown in Figure 4.

The chopper mechanism consists of the following primary components:

• **Vanes** - Two gold-plated copper mirror vanes were machined by a diamond turning process. Several mirror vane sets were fabricated by Aero Research Associates, Inc. The vanes were gold plated to meet the optical reflectivity requirement. They were aligned, bonded with epoxy (Stycast), and pinned to the end of the tines of the tuning fork. The shape of the vanes was an optimized compromise to allow the most uniform modulation of the three detector assemblies. The flight vane design dramatically changed from the original vane design for reasons which are described in the problems/solutions section.

• **Tuning Fork** - A one-piece tuning fork made of Ni-Span C was machined using a wire electron discharge machining (EDM) process. Ni-Span C was picked as the tine material because of its stable material properties over a large temperature range, magnetic properties, and fatigue properties. The tuning fork was bolted to an aluminum baseplate. Several forks were made and the spring constant of the tines was determined. Forks with the most closely matched spring constants for both tines were selected for balanced operation.

• **Baseplate** - An aluminum baseplate was bolted and pinned to the flat mirror number 2 mirror mount. The baseplate supports the fork, coils, and thermal strapping. The leads from the coils were bonded (Uralane) to the plate. The chopper was aligned to the optical system through this interface.

• **Coils** - The drive and sensing coils were wrapped on round bobbins. Each coil has independent redundant windings and is encapsulated with "Scotchcast #3 3M." Permanent magnets are bonded with epoxy inside both the drive and sensing coils. The magnets supply a D.C. bias magnetic flux. When current is applied to the drive coil, the D.C. bias flux is modulated, thus creating the driving force. As the tines vibrate, the magnetic flux through the sensing coils is modulated, and a current is generated which is proportional to the tine velocity. A fixture was made to align the 3 coils and magnets with each other and the tines. The polarities are indicated in Figure 4 . Several coil/permanent magnet core configurations were investigated; alnico magnet cores, samarium cobalt magnet wafers bonded with epoxy to both sides of an iron rod, and neodymium iron wafers bonded with epoxy to an iron core. The coils with alnico magnets were installed on the flight chopper.

• **Bumpers** - Bumpers are required to assure that the tines do not hit the pole faces of the coils. The bumpers were made of aluminum and were bolted and epoxied to the base. To obtain maximum attainable clearance between the bumper and tine, the bumper alignment is critical.

• **Straps** - Thermal strapping is required to heat sink the chopper to the DIRBE optic plate. Indium foil was placed between thermal interfaces to assure good thermal contact. The thermal strapping of the chopper was essential to the optical performance of the mirror vanes because they reflect signals at infrared wavelengths and very low intensity.

Balancing Procedure
The balancing of the flight chopper was done in 3 iterations. Balance weights made of tungsten were clamped and eventually bonded with epoxy to the end of the tuning fork tines. They were made heavier than required and then filed to tune the free running frequency of the chopper. Frequency, apex diameter, and power measurements were made at both room temperature and 4 K. These parameters were also measured with the chopper in the horizontal (zero g for tines) and vertical orientations and in the free running and synchronized drive modes at both temperatures. The free running frequency would shift as the chopper was cooled down to LHe temperature. The final balancing iteration resulted in a room temperature free running frequency of 32.9 Hz and a LHe free running frequency of 31.8 Hz. It should be noted that the orientation of the chopper and the electronic component values also affected the free running fundamental frequency. Apex and power measurements in both free running and synchronized drive modes were taken to verify a satisfactory balanced condition.

Nonlinear Characteristics
The tuning fork material is used as a primary magnetic flux path for the drive coil magnetic circuit. As the tines vibrate, the gaps between the tines and the permanent magnets change. The attractive force applied to the tines by the permanent magnets is proportional to the flux density squared. The flux density is inversely proportional to the gap. Therefore, as the gap changes in the magnetic circuit, nonlinear characteristics result.

Magnetic flux measurements were made on individual coils and on the chopper as a whole system. The coils which exhibited the most uniform magnetic characteristics were selected. Approximately 1.45 kilogauss was measured on both the left and right side of the drive coil. To give an indication of the magnetic field and circuit of the chopper mechanism, a piece of paper with iron filings was placed just above the chopper. The iron filings line up in the direction of the field lines. Figure 5 shows the magnetic field lines of the magnet configuration used on the flight chopper. Several other magnetic configurations were also investigated.

The spring constants of the tines of the chopper mechanism were measured with and without the magnets in place. Figure 6 shows the force versus displacement curves for the two tines as they were moved in both directions: toward the drive coils and toward the sensing coils. As the tines move closer to the coils, the attractive magnetic force of the permanent magnets in the coils acts to decrease the spring constant of the system. Therefore, the resonant frequency of the system is amplitude dependant. This results in nonlinear behavior and the system is said to have a negative spring. This is undesirable because performance is affected by the mechanism's orientation to gravity.

Due to the dependence of the system spring constant on amplitude of vibration of the tines, different amplitude versus frequency plots result when the drive coil input frequency is swept in an increasing or decreasing manner through the mechanical resonance of the system. Figure 7 is a plot of the output of the sensing coil versus the frequency of the drive input in the vicinity of the mechanical resonance of the tuning fork. Sweeping up in frequency yields a higher system resonance than when sweeping down in frequency. The nonlinear characteristic of the system is apparent between the frequencies of the sweep-up resonance and the sweep-down resonance, since two stable vibration amplitudes exist for a given frequency. To assure that the chopper mechanism operates in a stable manner (with margin), the chopper was designed such that the sweep-down resonance is below the desired synchronized frequency. Therefore, the chopper mechanism operating in the synchronized mode operates slightly less efficiently than if the mechanism operated directly at the sweep-down resonance where little margin for stable operation exists.

In addition, because of this behavior, a start-up circuit is required in the control system. The system is allowed to free run until a particular amplitude is achieved. Once the amplitude threshold is reached, the control system activates the phase lock loop control and the chopper synchronizes with the spacecraft data rate of 32 Hz. If, during start-up of the mechanism, the amplitude becomes too large and the tine hits a bumper, a windshield wiper mode can develop. In the wiper mode, the two vanes move in the same direction instead of opposite directions as desired. This phenomenon has only occurred twice in ground testing. To halt this mode of operation, turn off the chopper, wait several minutes, and then turn the chopper back on. This mode has not occurred on orbit.

Mechanism Testing

Optical - Extensive measurements were made of mirror orientation, optical figure, and vane motion. The above parameters were measured at both room and LHe temperature. The amplitude of vibration (apex diameter) is a critical factor in the performance of the chopper. Apex diameter of the vane motion was measured with a stroboscope and a traveling microscope. The chopper was balanced and the control system component values were selected at the required apex diameter. A stroboscopic auto-collimating theodolite developed at GSFC was used to measure mirror orientation (twists and tilt) both statically and dynamically. A Zygo interferometer was used to perform metrology measurements on the mirror vane flatness.

Life Test - A life test of the mechanism was not conducted. However, throughout the testing of the flight chopper and the DIRBE instrument, the chopper operated at cryogenic temperature for approximately 2.5 months. It was shown through analysis that the maximum stress in the tines was below the fatigue limit of Ni-Span C. The maximum calculated stress in the tine was 207 MPa (30 ksi). The fatigue limit of Ni-Span C is approximately 414 MPa (60 ksi). A determining factor in not performing a life test was that it would take a year. As the chopper design evolved, no two of the choppers were exactly the same. The schedule did not allow a year to evaluate a particular design. There was no clear way to perform an accelerated test. The chopper has been successfully operating on orbit for over a year.

Vibration - Sine burst, random, and sine sweep vibration tests were conducted on the chopper mechanism at both room and cryogenic temperatures. Figure 8 gives the levels, frequencies, and duration of the vibration tests. The chopper mechanism resonates in the windshield wiper mode as the input vibration frequency approaches the tuning fork resonance. Due to the relatively high q of the mechanism, launch vibration levels cause the tines to impact the bumpers with significant forces. The bumpers limit the amplitude of vibration and dissipate energy during these impacts. The nonlinear characteristics of the mechanism were observed during the tests. The second mode of the individual tines was verified to be approximately 370 Hz.

Two problems became apparent during the tests. The first problem was that the surfaces on the mirror vanes were compromised due to vane clashing during vibration. The second problem was concern that the increased vibration input of the Delta launch environment would make the integrity of the epoxy joint which connected the vane to the vane holder marginal. These two problems led to the redesign of the mirror vanes, which is described below.

Thermal Vacuum - The chopper was cycled from room temperature to less than 4 K seven times. Several dewars were used during the testing of the mechanism. Both optical and vibration tests were performed at LHe temperature. One dewar was equipped with a window so that optical measurements could be made, another dewar was used for vibration testing, and a third larger dewar was used to vibrate the entire DIRBE test unit.

Problems/Solutions

Three major problems were encountered in the development of the chopper.

1) The mirrored surface of the vane was scratched during vibration testing. As vibration input frequencies approach the resonance of the chopper, the tines start to hit the bumpers. This impact loading on the tines causes the vanes to clash against each other.

2) There was concern that the original mirror/vane holder epoxied interface would not survive launch loads and the fatigue cycling over the lifetime of the mechanism.

3) During an instrument-level test of the optical system and detectors at LHe temperature, it was determined that the vanes of the chopper were heating up to an unacceptable level. It was later determined that the temperature of the vanes was approximately 18 K. Vane heating was due to eddy current losses in the tines and molecular friction created by vibration of the tines.

The solutions to these problems which are incorporated in the flight chopper are described below. In addition, the modified chopper design is described. The modified design could eliminate heating of the vanes and other problems which were encountered due to the nonlinear characteristics of the flight chopper design.

The first two problems were solved by changing the mirror vane design. The original design of the mirror vane consisted of two parts: a polished mirror and a separate vane holder. The mirror was bonded with epoxy to the vane holder and the vane holder was then bonded with epoxy and pinned to the end of a tine. The orientation of the mirror/vane holder joint was in the direction of the tine motion (see Figure 9). This joint would therefore be subjected to significant launch loads and continuous fatigue loads during operation.

The redesign of the mirror vanes resulted in an integral mirror vane (vane and vane holder machined as one piece) with an additional 0.038 mm (0.0015 in.) plating of gold on the top edge of the vanes. The integral vane eliminated the need for a vane holder, minimized mounting stresses in the mirror, and elimination of the mirror/vane holder joint relieved concern that the epoxied joint would fail under launch loads and fatigue cycling. The thin plating of gold on the top of the vanes (outside of the useable area) solved the problem of scratching of the mirror surfaces under vibration loading by assuring that any contact between the two mirrors would be limited to the area of increased gold plating. Figure 9 shows the comparison of the original and flight vane designs. The mirror vanes were made by a diamond turning machining process which allowed overhang of the mirror mount. An overhang of this type is difficult to accommodate when conventional mirror polishing techniques are employed. Other solutions to these problems were developed, however the integral vane with a gold plated strip was the simplest and most reliable solution.

The third problem, heating of the chopper vanes, turned out to be a very challenging one. It was cleverly solved by modifying the tine design to allow 0.25-mm (0.010-in.) diameter copper wires to be incorporated into a keyhole slot along the length of the tine. The copper wires are captured in the keyhole and silver epoxied to the end of the tine and to the vane. A wire EDM was used to cut out a key hole on both edges of each tine. The copper wires came out of the aft end of the tine and were looped and then soldered to a copper T-bar which was installed at the base of the tuning fork. The copper T-bar was then heat strapped to the side of the aluminum base plate. Figure 9 shows a cutaway of the aft end of the chopper, the T-bar and the thermal strap. The heat from the vane and tine was conducted away via the copper wires to the optic plate. The wires are redundant. Only one wire for each tine is required to cool the vanes. Analysis on the fatigue of the wires shows that the maximum stresses developed in the wires are below the fatigue limit of copper.

A test was conducted in which the chopper was driven in the synchronized mode at LHe temperature. One side of the chopper had copper wires installed and the other side did not. The side which did not have the wires reached an equilibrium temperature of approximately 18 K. The side with the wires installed reached a temperature of less than 3 K.

The Modified Chopper Design

A modified chopper mechanism incorporating lessons learned was designed and fabricated toward the end of the DIRBE/COBE program. Figure 10 is a drawing of the modified chopper design. This design employs a magnetic circuit that is common to commercially available choppers. A magnet is bonded with epoxy to each tine. The magnets are centered in coils mounted on each side of the tuning fork. One coil is used as the drive while the other is used as a sensing coil. A magnetic configuration of this type was considered in the early development of the DIRBE chopper, however, problems were encountered when the mechanism was cooled to LHe temperature. Since the magnets were directly mounted to the tines, the tines were deformed in the regions of the magnets because of the differential thermal strains of the magnet and tine materials. The modified design provides mounting tabs which isolate the strain to the tab and leaves the tine undeformed.

There are several advantages to using a chopper of this design. The chopper operates in a linear manner because the motion of the magnets through the coils does not affect the magnetic flux flow through the mechanism. Sensing coil output amplitude vs. drive coil excitation frequency in the region of the mechanical resonance of this design is shown in Figure 11. The traces of the sweep up and the sweep down are essentially the same. The second peak is the desired operating mode (out of phase) while the first peak is the undesirable windshield wiper mode (in phase). The geometry of the chopper mechanism can be optimized to decrease the q of the undesirable mode. This clear definition between the two modes and the linear characteristics of the mechanism greatly simplify control of the mechanism. The mechanism can be driven with stability at the resonance of the fork. Power dissipation is greatly reduced. Milliamps are required to drive the flight chopper. In this design, only microamps are required. Balancing, testing and calculation of system margins are also simpler because the mechanism is less sensitive to its orientation to gravity. Unlike the flight chopper, eddy currents are virtually nonexistent. The fact that the eddy currents are minimized in the modified design may eliminate the need for thermal wires to be incorporated into the tines to conduct heat away from the mirror vanes as in the flight chopper.

A test is currently pending in which the modified chopper design will be cooled to LHe temperature and driven at the free running frequency. The temperature of the vanes will be measured without the thermal wire attached. Therefore, the heat generated by the molecular friction of the mechanical motion and the eddy currents in the tines will not be conducted away. It is expected that the temperature of the vanes will be well below the 18 K measured in the test performed on the flight mechanism. One indication that a lower temperature should result is that the q of the modified chopper is approximately an order of magnitude greater than that of the flight chopper. It is hoped that the heat generated by the mechanism motion of the vibrating tines and the eddy currents can be separated and quantified.

Conclusion

The flight chopper operates with an apex diameter of 13.15 mm (0.518 in.) and was tuned to have a free running frequency of 31.8 Hz at LHe temperature. The power dissipated at this temperature is approximately 4.8 milliwatts. The vane temperature during operation is less than 3 K. The optical performance of the chopper is highly satisfactory.

An integral vane with gold plating on the top edge was incorporated to eliminate an epoxy joint and prevent the vanes from rubbing under vibration loads. Thermal wires were incorporated into the tines to conduct heat away from the mirror vanes. In addition, a modified design chopper is offered as a potential solution to several of the problems encountered in the buildup and test of the DIRBE chopper.

The DIRBE synchronous chopper has been continuously operating on orbit without incident since the COBE spacecraft was launched on November 18, 1989. The DIRBE has fulfilled its primary mission requirement to map the electromagnetic spectrum of the entire universe between the wavelengths of 1 to 300 micrometers. Although the dewar liquid helium coolant was expended on schedule as expected, several of the detectors are still providing valuable scientific data. It is anticipated that the DIRBE instrument will continue to produce world-class scientific data.

References

1) Magner, T., "Diffuse Infrared Background Experiment (DIRBE) Optics Module Breadboard Alignment Methods and Results," Optical Engineering, March 1987, Vol 26. No. 3, Pg. 264-269.

2) Reich, S. M., Brill, H. L., "An Unconventional Chopper For Infrared Applications," Proc. of 21st International Technical Symposium of the Society of Photo-Optical Instrumentation Engineers.

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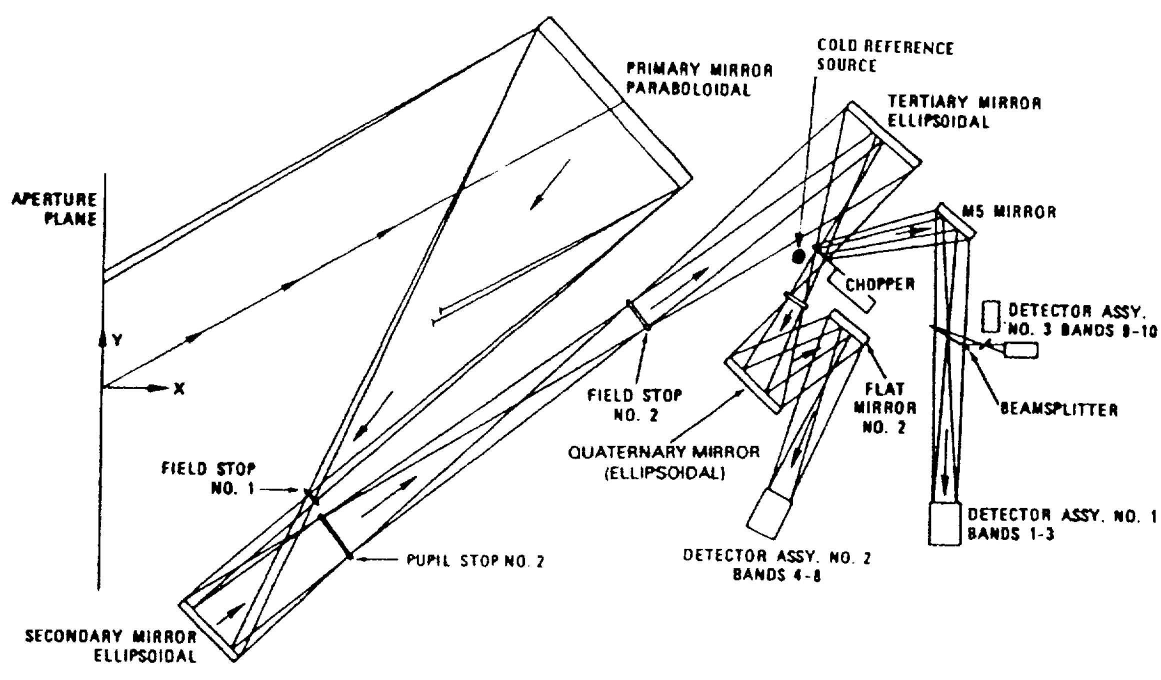

Figure 1 - The DIRBE Optical System

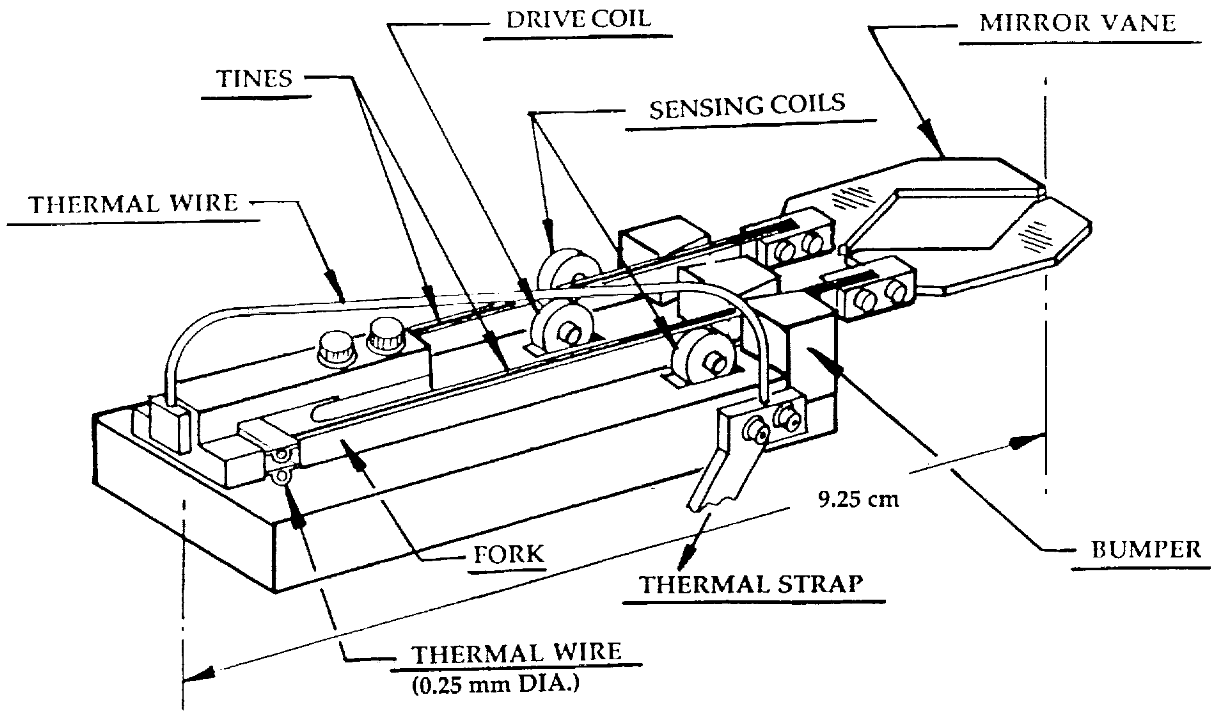

Figure 2 - The DIRBE Chopper Mechanism

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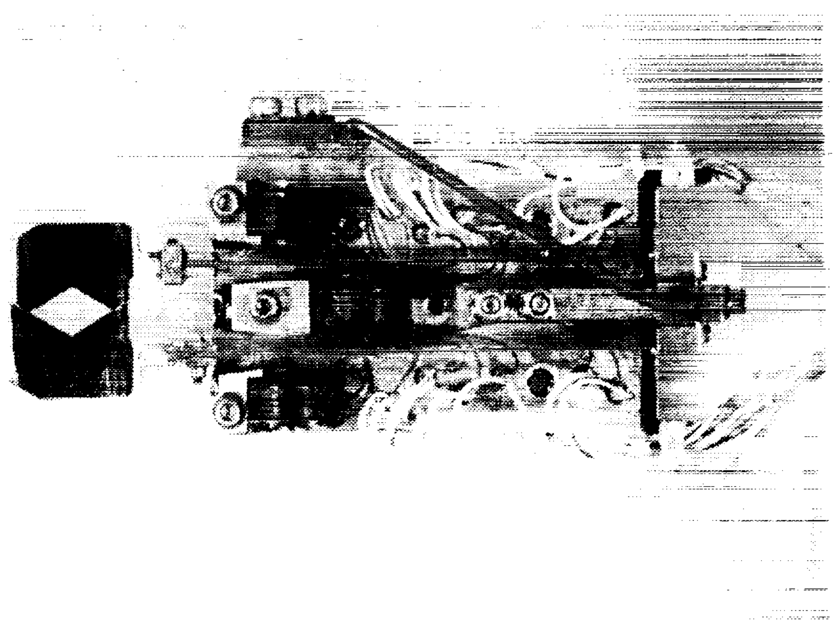

Figure 3 - The DIRBE Chopper Mechanism

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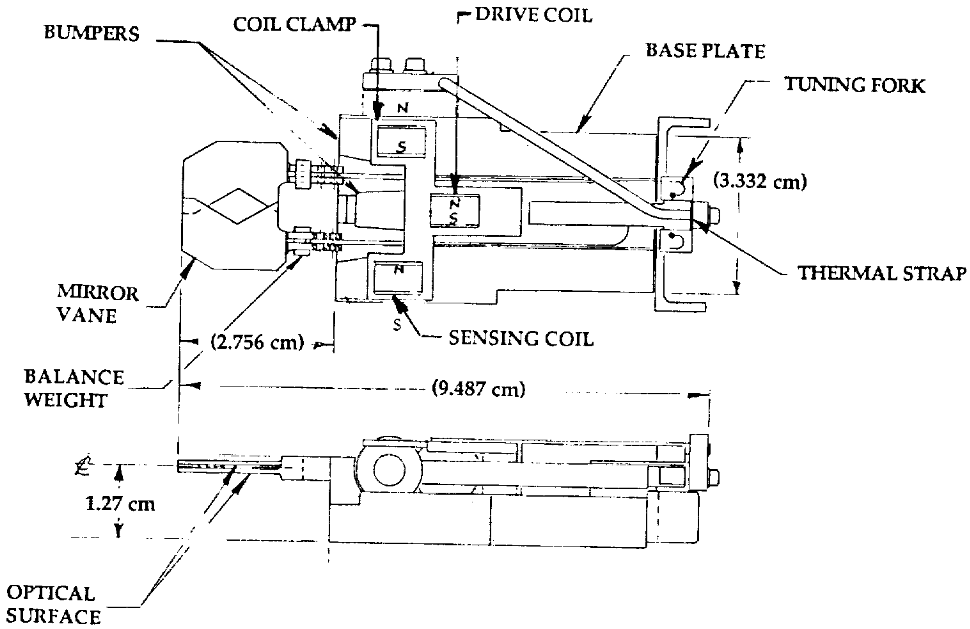

Figure 4 - The DIRBE Chopper Mechanism

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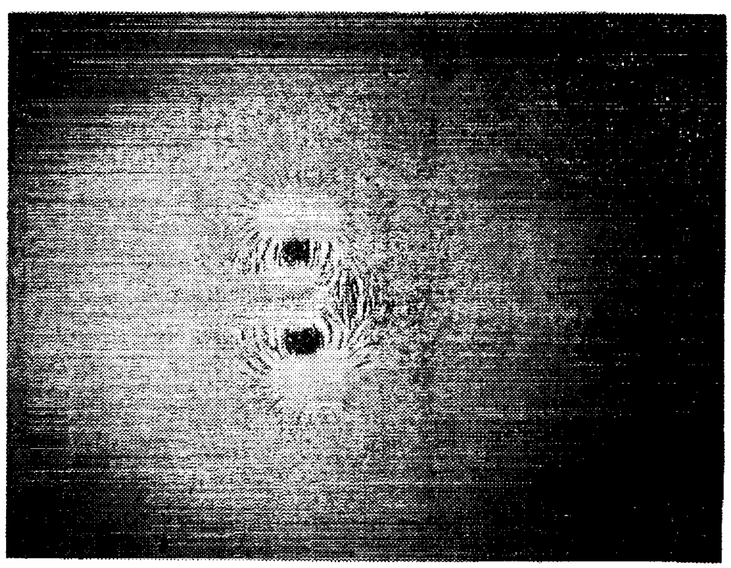

CHOPPER ORIENTED AS SHOWN IN FIGURE 4
(TOP VIEW)

Figure 5 - The Chopper Magnetic Field

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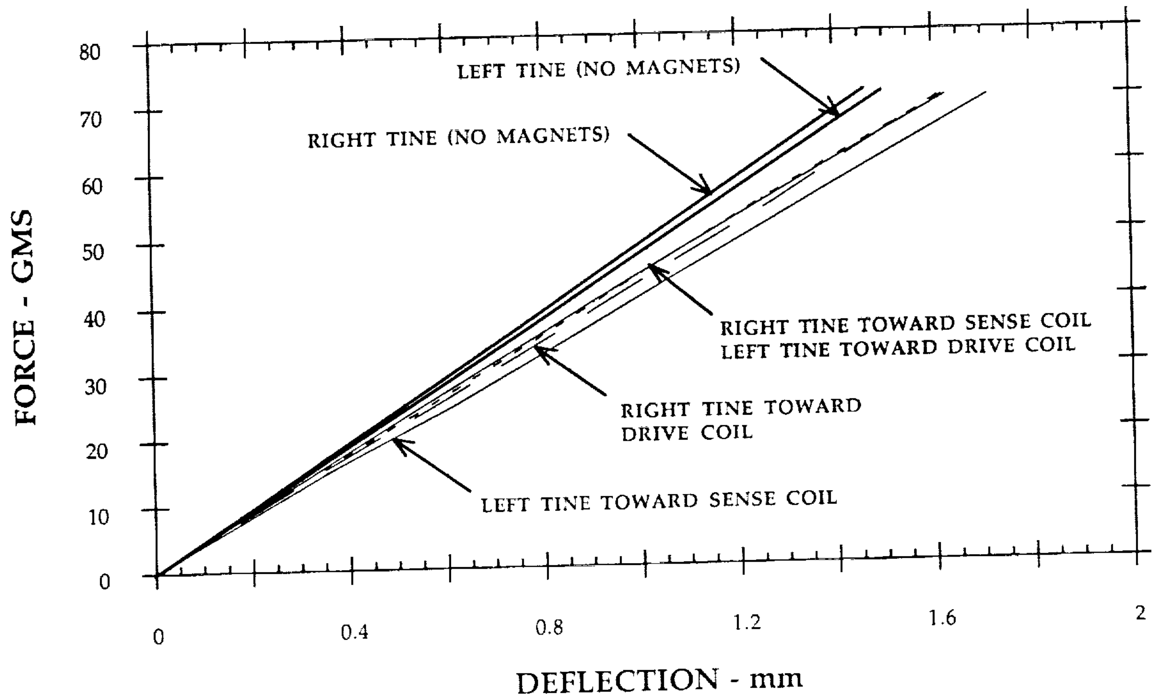

Figure 6 - Tine Force vs. Displacement Plot

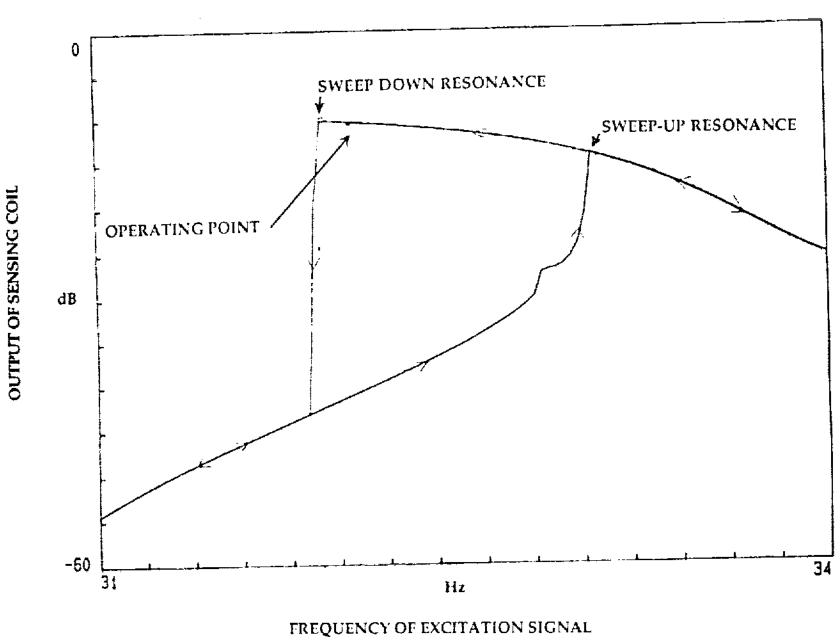

Figure 7 - The DIRBE Chopper Frequency Response

	AXES		
	X	**Y**	**Z**
SINE BURST (G's)	±14.0	±5.9	±5.9

RANDOM **X-AXIS**

FREQ RANGE (Hz)	**Level**
20	.0001 g^2/Hz
20-125	+11.0 dB/oct.
125-300	.08 g^2/Hz
300-2000	-10.6 dB/oct.
2000	.0001 g^2/Hz

Overall Level = 5.1 grms
Test Duration = 30 seconds

SINE SWEEP

AXIS	**FREQUENCY** (Hz)	**LEVEL**	**SWEEP RATE**
X	15-21	±6.5g	
	21-30	±4.0g	2 oct./min.
	30-40	±1.0g	
Y & Z	15-21	±1.4g	
	21-30	± .6g	2 oct./min.
	30-40	±1.4g	

Figure 8 - The DIRBE Chopper Vibration Specification

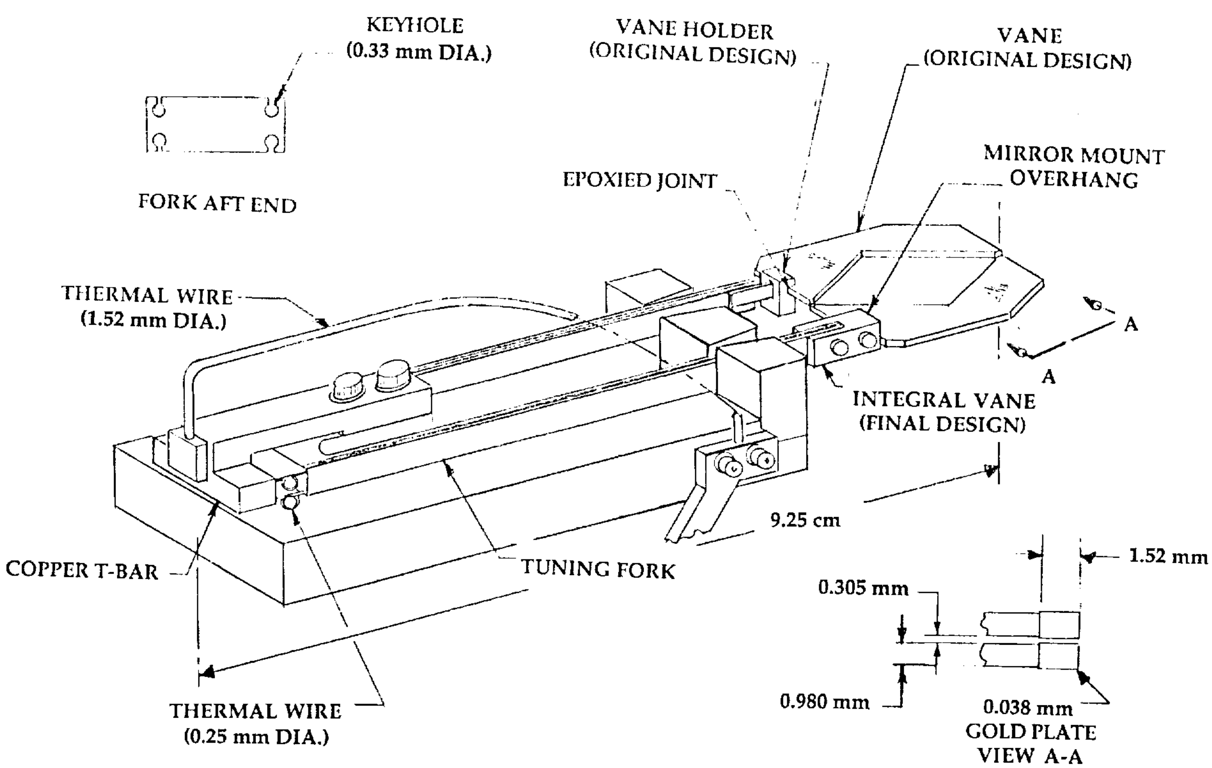

Figure 9 - Chopper Mechanism Solution Summary

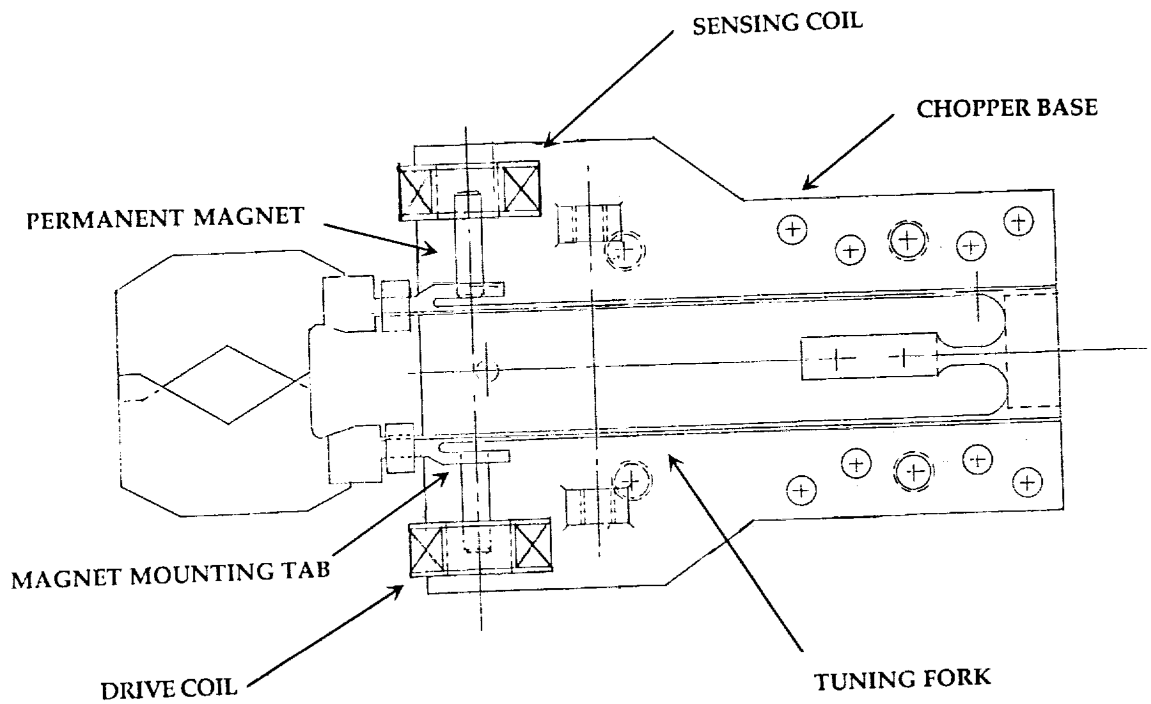

Figure 10 - Modified Chopper Mechanism Design

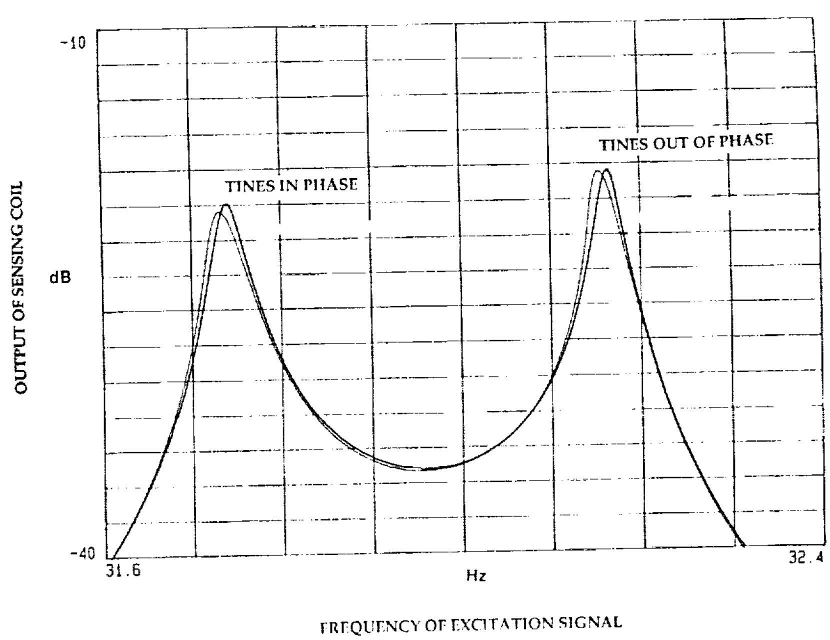

Figure 11 - Modified Chopper Frequency Response