ULTRA HIGH RESOLUTION STEPPER MOTORS
DESIGN, DEVELOPMENT, PERFORMANCE AND APPLICATION

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ABSTRACT

The design and development of stepper motors with steps in the 10 arc sec to 2 arc min range is described with detailing some of the problem areas, e.g. rotor suspension, tribology aspects and environmental conditions.

A summary of achieved test results and the employment in different mechanisms already developed and tested will be presented to give some examples of the possible use of this interesting device. Adaptations to military and commercial requirements have been proposed and show the wide range of possible applications.

INTRODUCTION

The stringent requirements to be met by actuators for space applications inevitably increased the work concerning the design and manufacture of such mechanisms.

Communications satellites which provide certain regions of the world with a communications service via radio relay stations have to meet stringent requirements concerning the positioning accuracy of their antennas. Depending on the system configuration there is, for instance, the possibility of tilting the complete satellite including its antennas by means of momentum exchange devices or only the antennas by means of antenna pointing systems. In both cases, high alignment accuracies ($<0.1^\circ$) have to be met by the actuators.

Furthermore, high positioning accuracies are mandatory for actuators and alignment mechanisms used for solar panels and space experiments.

Besides the requirement for high angular resolution and positioning accuracy, a high actuating torque is required in many cases. Conventional actuators can only meet these requirements by an additional input, i.e. by high-quality gears and a high-accuracy angular sensor with the pertinent feedback electronics. However, this input increases the size, the weight and the power consumption, and reduces the system reliability considerably.

DEVELOPMENT

General

Within the scope of a DFVLR contract (Development of a Gimbal System for the Gimbal Suspension of Momentum Wheels) Teldix started in 1972 the development of stepper motors of the type SMR (friction-type version), based on a principle conceived by Prof. Kleinwächter. Further development studies within the scope of ESTEC contracts (Development of a Single Gimbal Momentum Wheel, Development of an Actuator Mechanism for Solar Panels) led to stepper motors of the SMZ type (tooth-type version).

Requirements

Depending on the configuration, the following requirements are to be met by the stepper motors:

High angular resolution

High stepping accuracy

Good step angle reproducibility

High holding torque

High dynamic motor torque

Low power consumption

Low volume and special construction

Low weight and high reliability during the specified mission time

Based on the different requirements the following stepper motors have been realized:

Type SMR 1-0
Stepper motor, friction-type version, O.D. 110 mm. This motor is designed to perform angular steps of about 10 seconds of arc to an actuating torque of ≤ 0.5 Nm.

Type SMZ 1-0
Stepper motor, tooth-type version, O.D. 110 mm. This motor is designed to operate at an actuating torque of ≤ 0.8 Nm angular steps (2 minutes of arc) at a high accuracy (< 20 % deviation from nominal step); a good step reproducibility (better than 10 % in relation to the nominal step) is desired, too.

Type SMZ 2-0 (see Fig. 1)
Stepper motor, tooth-type version, O.D. 150 mm. This motor features a high actuating torque of > 1 Nm and a lower angular step accuracy (< 50 % in relation to the nominal step).

Motor Concept

The constructional requirements set forth for these motors resulted in a pancake design. These motors of circular construction, feature a relatively large center hole. Independent of their function, these motors show further common design characteristics.

Besides the motor drive electronics, the motors consist of two assemblies, the stator and the rotor. The stator consists of a certain number of electromagnets mounted in a circular array and, depending on the motor type, of a conical running surface facing the rotor or of bevel gear teeth on which the rotor rolls off. The electric circuitry of the electromagnets is built into the stator.

Basically, the rotor consists of a specially designed flexible disk (diaphragm) mounted vertically to the motor's inner shaft. The circumference of this flexible disk is provided with a soft magnetic ring having a plane running surface or with bevel gear teeth. The coaxial suspension of the rotor with respect to the stator can be realized either by using a motor support in the system or by a suspension being part of the motor.

Motor Function

After switching one of the electromagnets, the rotor segment facing the electromagnet is attracted (see Fig. 3). Thus, a positive connection between rotor and stator is obtained with the tooth-type version and a non-positive one with the friction-type version. In order to increase the non-positive connection of the latter version, at least two opposite magnets are switched at a time. With sequential excitation of the solenoids, the rim of the rotor rolls off the stator rim acting like a swash plate.

Angular displacement of the rotor with the tooth-type version is obtained by applying a different number of teeth on stator and rotor. If, for instance, the number of teeth differs just by one, the rotor proceeds by the angle of one circular pitch while the magnetic field is performing one complete revolution. This comparatively small angle can therefore be subdivided into as many defined steps as magnets are mounted on the circumference of the stator.

With the friction-type version, angular displacement is achieved in that the rotor diaphragm rolls off at a smaller radius than that of the stator because of the diagonal bending of the rotor. This difference in the circumference of rotor and stator results in a very small displacement with each revolution of the magnetic fields. As with the tooth-type version, the step angle is calculated on the number of the solenoids.

The holding torque with the motor at standstill and the stepping torque with the motor proceeding are obviously higher with the tooth-type version than with the friction-type version. Besides, the latter shows a slight change in the step angle as a function of the load torque.

The tooth-type version features good reproducibility of the step angle (see Fig. 4) and no step angle error accumulation. Thus, it is possible to obtain precisely any angular position simply by counting the number of steps. The step angle, however, cannot be reduced infinitely because of the minimum tooth module necessary.

As mentioned above, the stepper motor is operated by use of an external electronic drive unit. The system electronics unit furnishes a digital signal to the electronic drive unit for the control of motor speed and sense of rotation.

Design of the Electronic Drive Unit

The electronic drive unit incorporates integrated C-MOS components. The command signal for CW and CCW rotation is fed to a ring counter. Power transistors used to switch the solenoids in the stator are controlled via a decoder and logic circuits.

Special Problems Encountered with the Stepper Motor Development

The motor design and its application for space missions required the clarification of the following aspects.

Mechanical Load

The motors have to be designed such that they are capable of withstanding the high mechanical loads occurring during the launch phase. This applies especially to the elastic rotor suspension and to the running surfaces on rotor and stator. It has been proven that maximum stepper motor performance is ensured by using several diaphragms that are screwed or riveted together. The internal friction mechanism of such a packaged rotor suspension also contributes to the damping of possible rotor Q factors.

Oxydation Problems

Oxydation especially occurring on the running surfaces of rotor and stator lead to a decrease in the motor efficiency. To eliminate such a degradation, it is recommended to provide the running surfaces of rotor and stator with a precious metal finish. Hereby, it is to be taken into consideration that the plating thickness has to be very thin because of the magnetic resistance and that there is no change in the friction coefficient between the contacting surfaces. Tests performed with a hard gold plating, Vickers hardness of approx. 1600 N/mm^2, showed good results.

Cold Welding

Under hard vacuum conditions, the problem of cold welding between the contacting surfaces on rotor and stator cannot be excluded. Investigations under vacuum (5×10^{-8} torr) showed that hard-gold plated surfaces do not indicate any signs of cold welding.

Tests

Besides the performance tests, a number of environmental tests have been performed to simulate the loads occurring during the launch phase and the long-term operation under ultra high vacuum conditions. These tests have been performed on individual stepper motors and on motors installed in gimbal systems (see Fig. 5).

Fig. 2 shows the motor torque as a function of the stepping frequency for the stepper motor type SMZ 1-0 installed in the inner gimbal system.

STATUS

SMR Type Stepper Motor

Development funded by DFVLR. Engineering Models subjected to environmental tests with qualification level. Life Test in ultra high vacuum, one motor $25 \cdot 10^6$ steps, alternating direction, against a spring load; two other motors $3 \cdot 10^6$ steps each. Employed for Gimbal System, proposed for Bearing and Power Transfer Assemblies and Antenna Pointing Mechanisms.

High Resolution Stepper Motor (size 155)
ESTEC contract successfully completed.

Single Gimbal Mechanism (Stepper Motor size 110)
ESTEC contract, Breadboard Model completed.

Single Gimbal Mechanism (Stepper Motor size 110)
ESTEC contract for Engineering Model completed.

Ultra high Resolution Stepper Motor (size 155)
ESTEC contract completed.

Employed in Single Gimbal Momentum Wheel and Double Gimbal Momentum Wheel with Self-locking Actuator.

Proposed for:
Bearing and Power Transfer Assembly (BAPTA);
Antenna Pointing Mechanism (APM).

Military applications:
Actuating mechanism for fin control and antennas of missiles.

Commercial applications:
Actuating mechanism for angular control, digital interface.

SUMMARY

The development results obtained with the three motor types SMR 1-0, SMZ 1-0 and SMZ 2-0 show that the requirements set forth for these motors have been met.

As to certain motor parameters, such as motor torque, stepping speed, angular resolution and angular accuracy, it has been shown that the parameter limits have not yet been reached, especially what the SMZ type version is concerned.

Further statements on the motor limits will be possible after competion of the scheduled qualification tests.

REFERENCES

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3. Bowden and Tabor, " Reibung und Schmierung fester Körper". Springer-Verlag, Heidelberg.
4. Several DFVLR and ESTEC Reports.

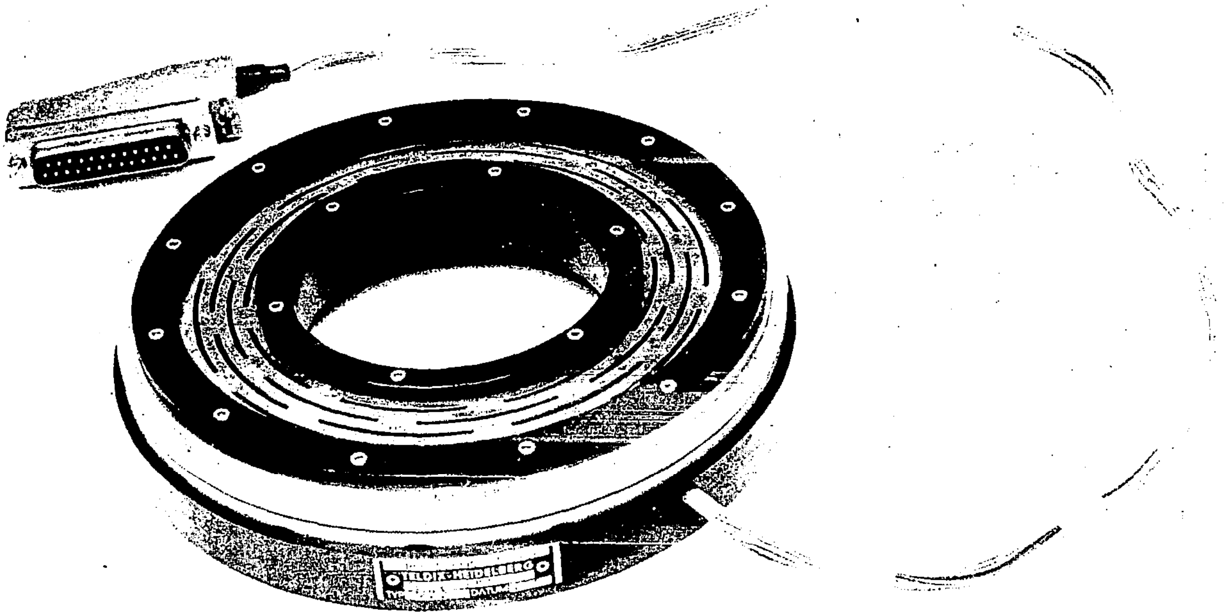


Figure 1 Stepper Motor Type SMZ 2-0 developed for solar pannel attitude control mechanism

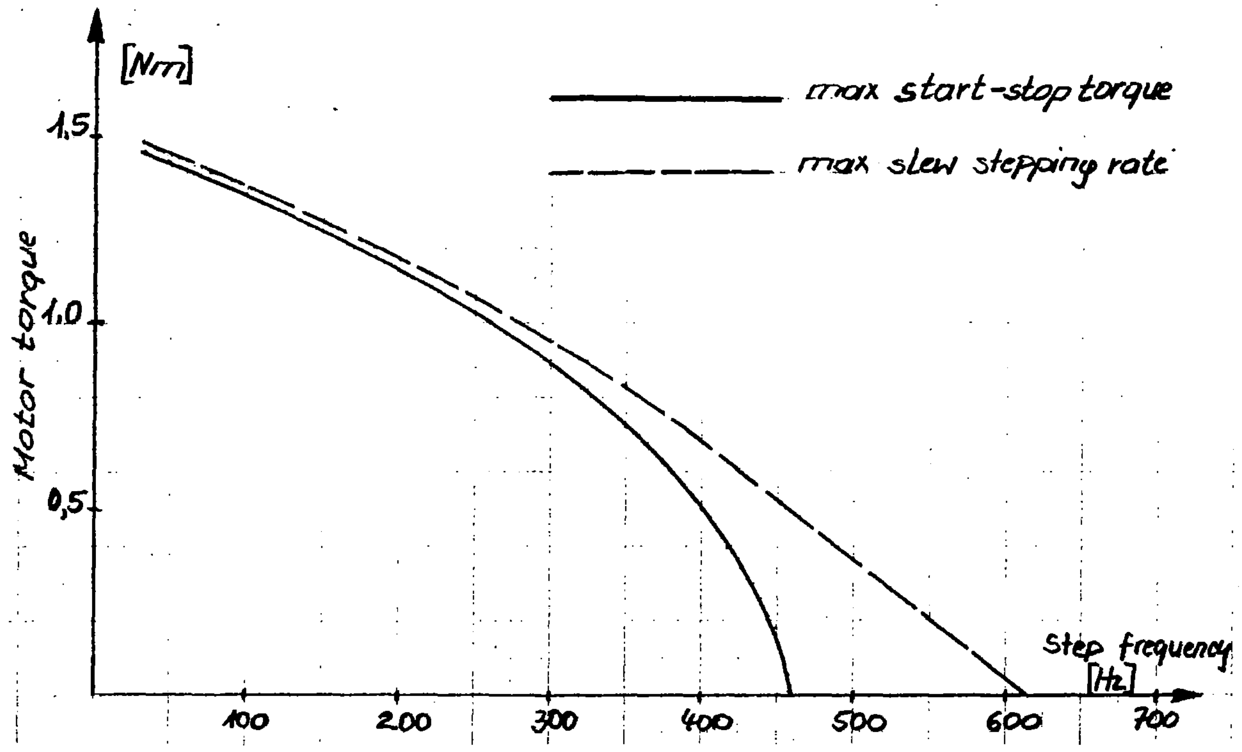
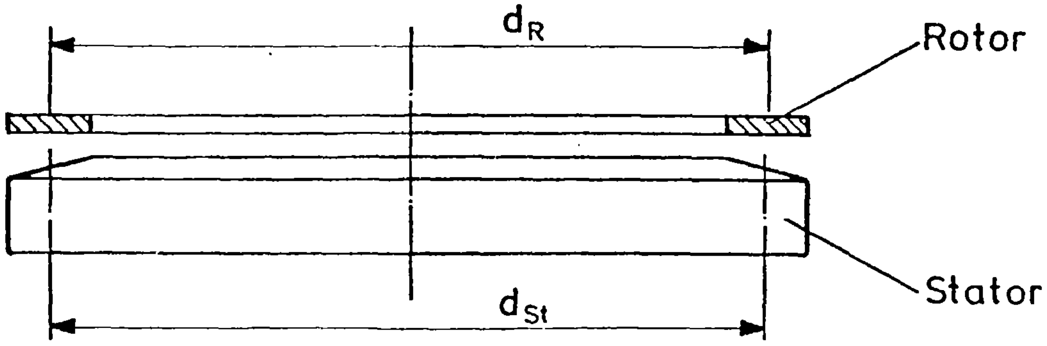
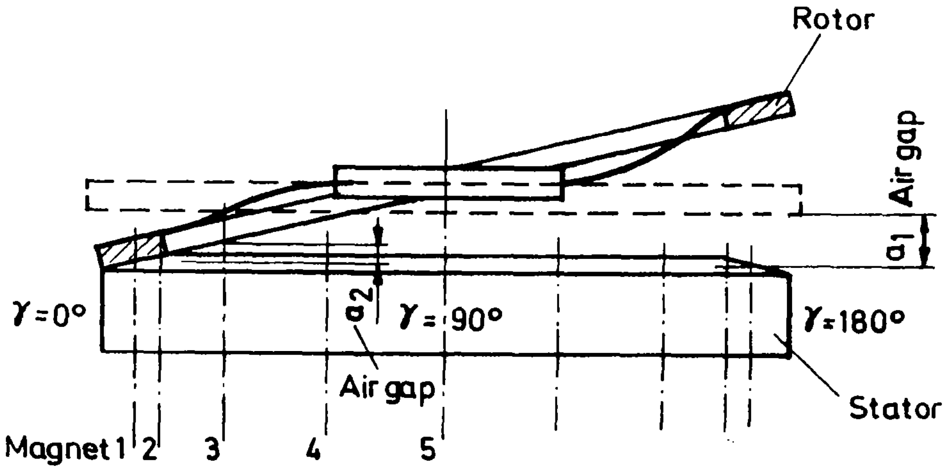


Figure 2 Motor torque as a function of the stepping frequency for the stepper motor SMZ 1-0 installed in an inner gimbal system

Motor de-energized:



Tooth-type Version: Rotor engaged unilaterally:



Friction-type Version: Rotor engaged diametrically:

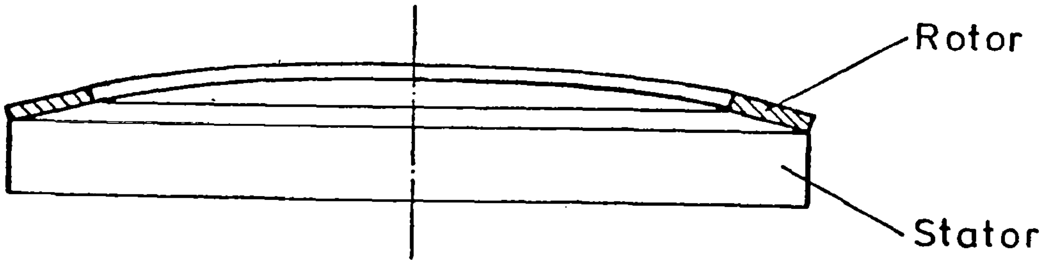
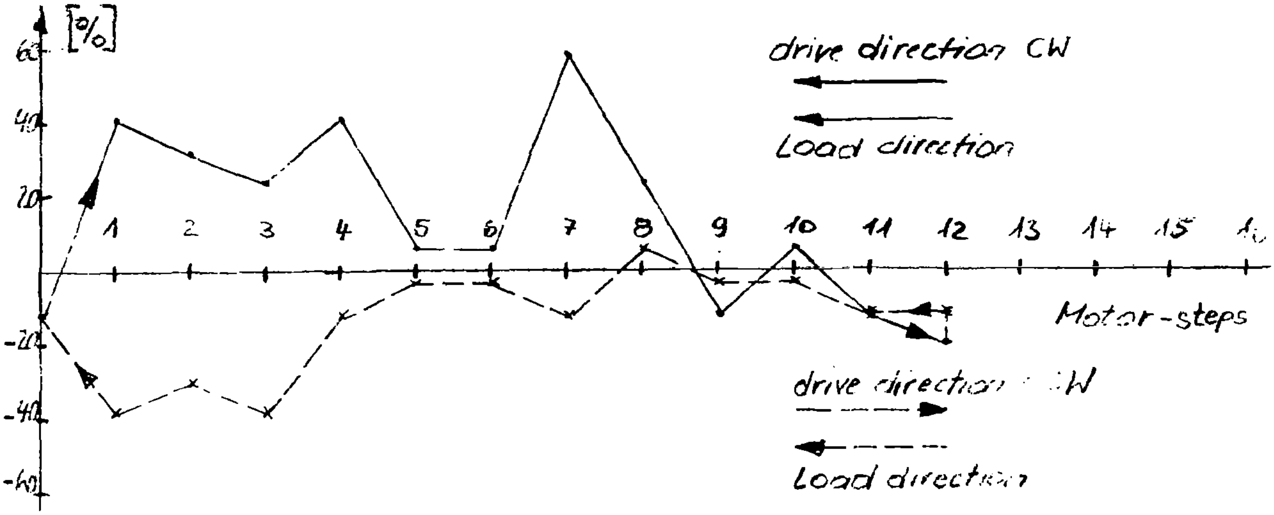
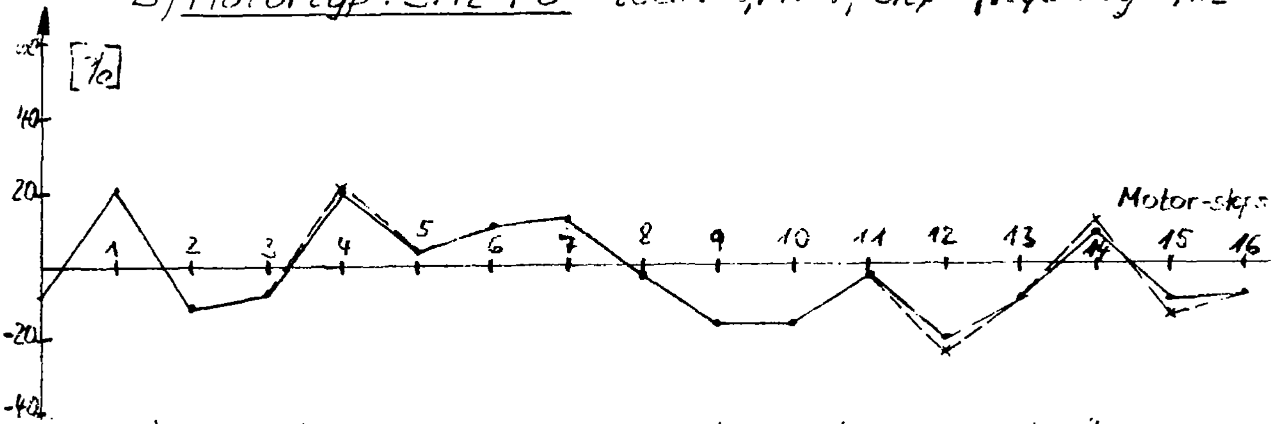


Figure 3 Principle of operation of the stepper motor

a) Motortyp: SMR 1-0 Load 0,3 Nm; step frequency 1 Hz



b) Motortyp: SMZ 1-0 Load 0,7 Nm; step-frequency 1 Hz



c) Motortyp: SMZ 2-0 Load 1,3 Nm; step-f 1 Hz

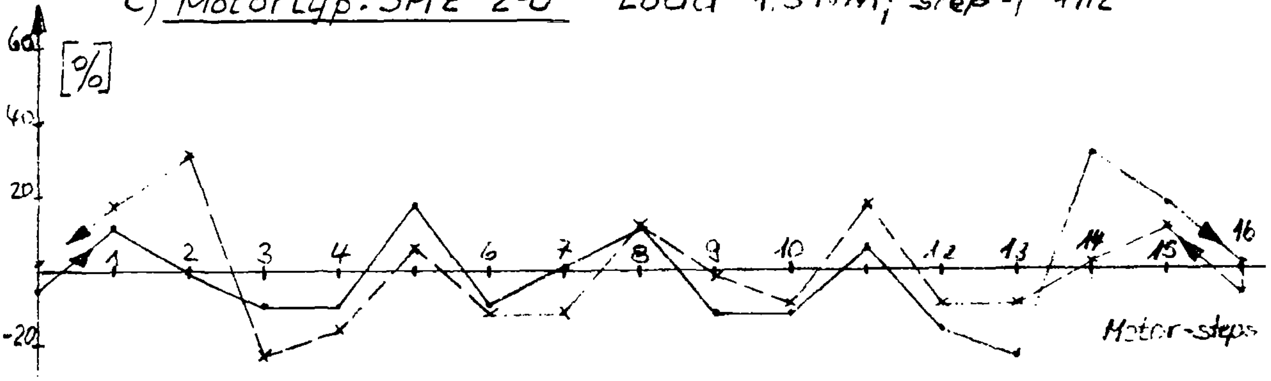


Figure 4 Deviation of the individual step angle from the nominal step angle

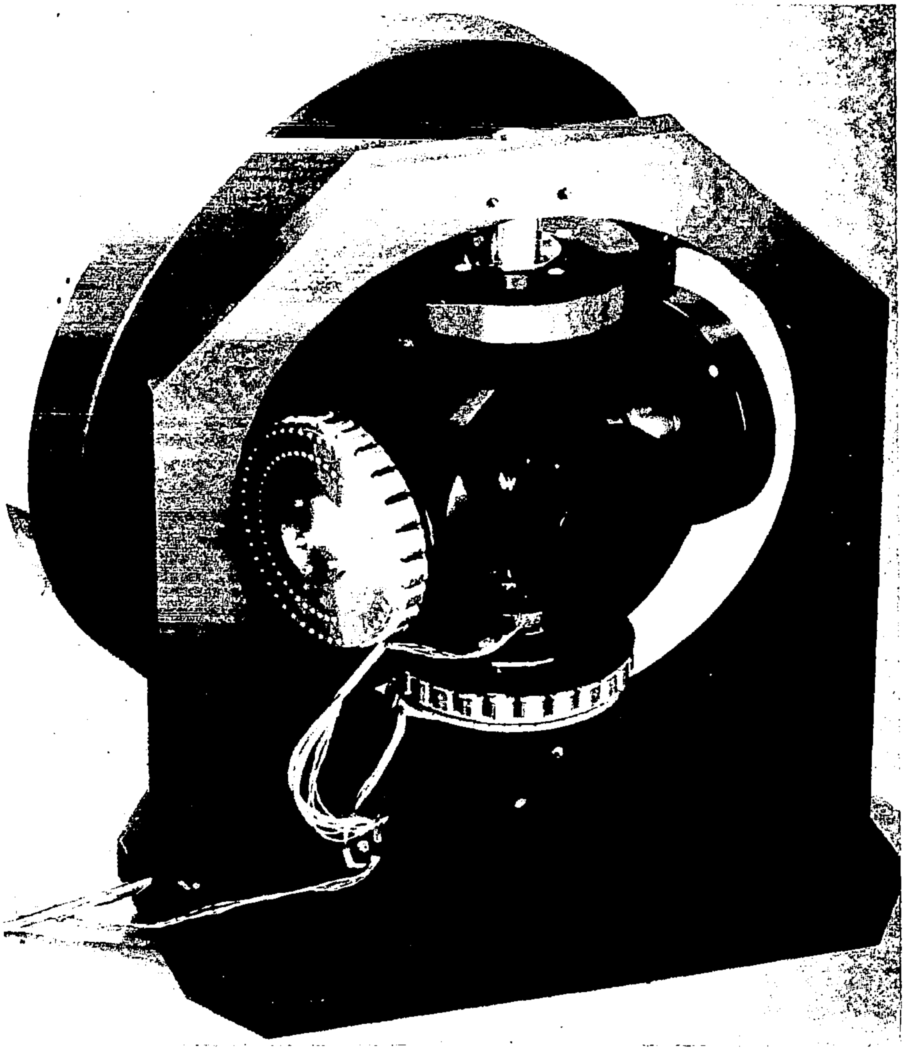


Figure 5 Inner gimbal system with stepper motors for two momentum wheel, one wheel removed