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DESCRIPTION OF A LABORATORY MODEL ANNULAR MOMENTUM CONTROL DEVICE (AMCD)

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AMCD BACKGROUND

The basic concept of the Annular Momentum Control Device (AMCD) is that of a rotating annular rim suspended by noncontacting magnetic bearings and driven by a noncontacting electromagnetic spin motor. A brief discussion of the AMCD concept, applications, and advantages (as a momentum storage device) was presented at the first OAST Integrated Flywheel Technology Workshop (Ref. 1). A more detailed discussion of the AMCD concept is presented in Reference 2. The purpose of this paper is to highlight some of the design requirements for AMCD's in general and describe how these requirements were met in the implementation of a laboratory test model AMCD. An AMCD background summary is presented in Figure 1.

☐ CONCEPT

- Magnetically suspended rotating rim powered by a noncontacting electromagnetic spin motor.

☐ APPLICATIONS

- Attitude Control
  - Spin assembly for conventional momentum storage devices such as CMG's, reaction wheels, etc.
  - New, large radius, large momentum applications made possible by unique geometry.
- Energy Storage
  - Rim shape allows full utilization of the filament strengths of composite materials by allowing a unidirectional layup.
- Combined Attitude Control/Energy Storage
  - Tradeoff between optimum H/M and energy density rim design.

Figure 1

LABORATORY MODEL AMCD PARAMETERS

Figure 2 presents a summary of the laboratory test model AMCD hardware characteristics. It should be pointed out that the laboratory model was not sized to meet the requirements of a particular mission but was sized to fit an existing torque measuring fixture.

☐ MOMENTUM
  - 3000 ft-lb-sec

☐ RIM DIAMETER
  - 5.5 ft.

☐ RIM WEIGHT
  - 50 lb.

☐ RIM SPEED
  - 3000 RPM

Figure 2

LABORATORY TEST MODEL AMCD

Figure 3 is a photograph of the laboratory model AMCD. Using this figure, and subsequent figures, a description of the model will be given and related to general design requirements in three different areas. These areas are rotating assembly, electromechanical/electromagnetic, and dynamics and control. The following discussion will, of necessity, be brief. For a general discussion of AMCD spin assembly hardware considerations, see Reference 2 and for a detailed description of the AMCD laboratory test model, as originally delivered, see Reference 3.

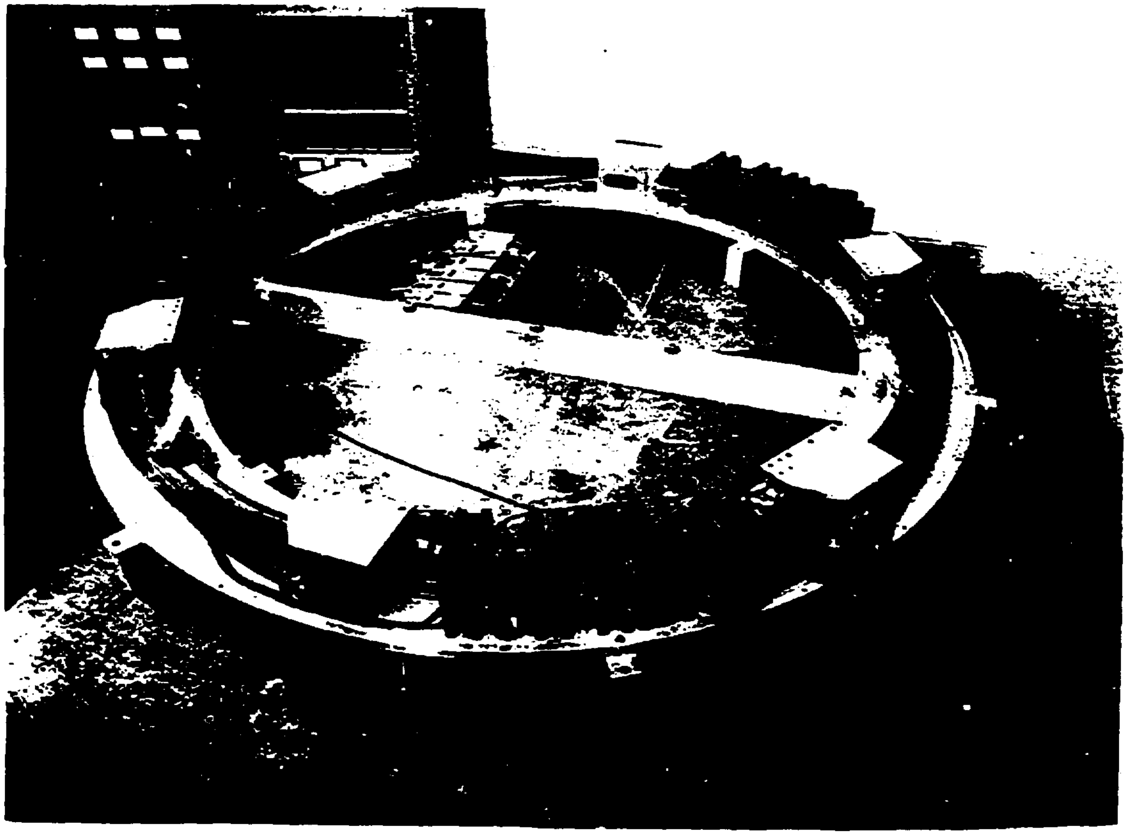

Figure 3

ROTATING ASSEMBLY (RIM)

The basic requirements for an AMCD rim (Fig. 4) are that it have high structural strength, good magnetic suspension characteristics, and good motor characteristics. Since these are conflicting requirements, at present the only solution appears to be an integrated structure. In the AMCD laboratory model (See Fig. 3), the basic rim structure consists of a high strength graphite-epoxy composite material with unidirectional layup. In order to provide a magnetic circuit for the magnetic suspension, a low loss ferrite material is embedded in the rim. For the motor requirements, there are 72 equally spaced samarium cobalt permanent magnets embedded in the outer part of the rim that act as motor poles.

☐ RIM MATERIAL REQUIREMENTS

- High structural strength.
- Good magnetic suspension characteristics
  - Low reluctance
  - Low eddy current and hysteresis losses
- Good motor characteristics
  - Good conductor (if induction motor)
  - Discontinuous ferromagnetic or permanent magnet (if commutated or other motor design).

☐ AMCD LABORATORY MODEL DESIGN

- Basic structure of graphite epoxy with unidirectional layup.
- Low loss ferrite material embedded in rim (magnetic suspension).
- Samarium Cobalt permanent magnets embedded in rim (motor poles).

Figure 4

ELECTROMECHANICAL/ELECTROMAGNETIC (MAGNETIC SUSPENSION)

The basic requirements for an AMCD magnetic suspension system (Fig. 5) are segmented bearings, active control of the momentum vector (axial direction), and linear actuator characteristics over the suspension operating range. In the AMCD laboratory model (Fig. 3), the rim is suspended by three equally spaced suspension stations. Magnetic bearing elements located in the suspension stations interact with the previously mentioned ferrite material, embedded in the rim, to produce axial and radial suspension forces. The suspension system is active in both axes. The control approach used for the magnetic bearing elements was permanent magnet flux biasing which provides linear force characteristics over a small region about a fixed operating point. This approach is discussed in more detail in Reference 4.

- ☐ MAGNETIC SUSPENSION REQUIREMENTS
  - Segmented bearings to minimize weight (minimum of three stations)
  - Active in axial axis to provide control of momentum vector
  - Linear over control range
- ☐ AMCD LABORATORY MODEL DESIGN
  - Three suspension stations
  - Active in axial and radial axes
  - Permanent magnet flux bias

Figure 5

ELECTROMECHANICAL/ELECTROMAGNETIC (MOTOR)

Basic requirements for an AMCD drive motor (Fig. 6) are segmented stator elements, relatively large gaps to allow rim motion, and minimum interaction with the magnetic suspension. Interaction with the magnetic suspension can take the form of magnetic interaction or, for high torque capacity motors, side forces that interfere with the magnetic suspension. In the case of the laboratory model AMCD (Fig. 3) the spin motor forces are much lower than suspension forces so the concern was magnetic interaction. The laboratory model AMCD motor is basically a large permanent magnet brushless d.c. spin motor. The motor consists of stator elements, located in the suspension stations, that push and pull against 72 samarium cobalt permanent magnets, embedded in the rim near the outer edge, to produce spin torques. The stator-element drive electronics are commutated by signals from a Hall effect device which senses the position of the magnets.

☐ **MOTOR REQUIREMENTS**

- Segmented stator elements
- Relatively large gaps
- Minimum interaction with magnetic suspension

☐ **AMCD LABORATORY MODEL DESIGN**

- Segmented stator elements (located in suspension stations)
- Brushless d.c. spin motor with permanent magnet poles in rim
- Motor poles separated from suspension elements maximum amount allowed by size constraints

Figure 6

SUSPENSION STATION CROSS-SECTION

In order to provide a better view of the elements previously discussed, a cross-sectional drawing of a suspension station is presented in Figure 7. This drawing shows the magnetic bearing elements, motor stator elements, and rim, with ferrite and permanent magnet inserts, in more detail. The magnetic-bearing gaps with the rim centered are 0.1 inch.

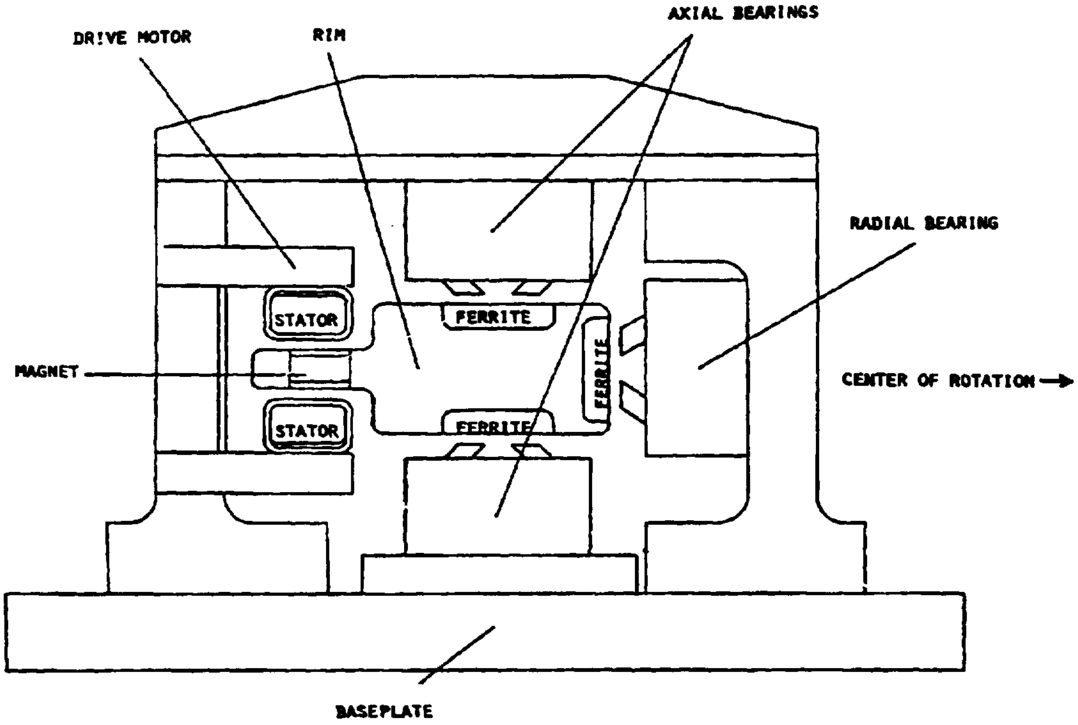

Figure 7

DYNAMICS AND CONTROL (MAGNETIC SUSPENSION)

The basic requirement for an AMCD magnetic suspension system (Fig. 8) is to provide 5 degree-of-freedom control of a rotating rim whose motion is coupled through a momentum vector that changes magnitude as the rim is spun up. In the laboratory model AMCD, the magnetic suspension system provides active positioning control of the rim in both the axial and radial directions. The original axial control approach was to use independent control loops for each suspension station. At zero rim spin speed (zero momentum), for three magnetic bearing suspension stations spaced equidistantly around the rim and for theoretical rim inertia distribution, it can be shown (Ref. 5) that axial motions of the rim in each of the bearing stations are uncoupled. Consequently, at zero momentum the axial magnetic bearing control system can be represented as three identical independent systems; and a single design, using a simplified suspended mass model, can be performed. In the radial system, all three stations are coupled since the radial actuators can only produce a unidirectional force.

☐ MAGNETIC SUSPENSION REQUIREMENTS

- Basic Requirement: 5 degree-of-freedom control of rotating rim with motion coupled through momentum vector that changes magnitude as rim is spun up.

☐ AMCD LABORATORY MODEL DESIGN

- Separate axial and radial control systems.
- Single station, single input single-output control approach used for axial system
  - Because of geometry (thin rim, three suspension stations) rim motion in each suspension station uncoupled at zero speed.
- Three station coupled radial control system
  - Unidirectional magnetic actuators at each station.
- Rigid body dynamics assumed.

Figure 8

AREAS REQUIRING FURTHER DEVELOPMENT

Tests conducted with the laboratory model AMCD have identified two general areas requiring further development (Fig. 9). These areas are magnetic suspension and magnetic suspension control system. A discussion of preliminary test results is presented in Reference 6. Reference 7 discusses an alternate magnetic bearing control approach which was implemented for the laboratory model, and Reference 5 presents a linear analysis and nonlinear simulation of the original magnetic suspension and magnetic suspension control approach.

- □ ELECTROMECHANICAL/ELECTROMAGNETIC
  - • Magnetic Suspension
    - Permanent magnet flux-biasing presented problems from control system standpoint (bandwidth required to stabilize bearings too high).
    - Zero bias-flux magnetic bearings investigated as alternate approach but proved to be very sensitive to calibration and alignment accuracy.
    - Other approaches currently being investigated include flux feedback and force feedback.
- □ DYNAMICS AND CONTROL
  - • Magnetic Suspension Control System
    - Initial approach using classical single-input single-output control theory and single station control will be replaced by multi-input multi-output control approaches.
    - Combination of rim parameters and overall control requirements may result in requirement of flexible body control of rim.

Figure 9

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