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BALL BEARING VERSUS MAGNETIC BEARING REACTION AND MOMENTUM WHEELS AS MOMENTUM ACTUATORS

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SUMMARY

For the attitude control of satellites, momentum actuators with different bearing technologies are available. After a short familiarization with the subject, an attempt is made to establish a guideline for the selection of the suitable momentum actuators or momentum actuator configurations to meet given mission goals with high reliability and low cost.

INTRODUCTION

For 3-axis body stabilized satellites, momentum actuators serve, for instance, as a means of averaging out periodical disturbance torques or to turn a spacecraft so as to pinpoint its instruments accurately to different objects. Common to all applications is the goal to save fuel and employ as far as possible electrical energy generated from the sun's radiation.

The discussion about the relative merits of different bearing approaches and technologies of momentum actuators gained has high interest. To establish a basis, some examples of ball bearing and magnetic bearing momentum actuators are first described, together with some typical specifications.

MOMENTUM ACTUATORS

Designs, Configurations and Performance

For the following designs and configurations the main parameters are shown in table I:

1. Ball Bearing Momentum Wheel, BBMW
2. Ball Bearing Reaction Wheel, BBRW
3. Magnetic Bearing Momentum Wheel, MBMW 5, with 5 actively controlled degrees of freedom
4. Magnetic Bearing Momentum Wheel, MBMW 1, with 1 actively controlled degree of freedom
5. Magnetic Bearing Reaction Wheel, MBRW 2, with 2 actively controlled degrees of freedom

6. Magnetic Bearing Reaction Wheel, MBRW 1, with 1 actively controlled degree of freedom

7. T-Configuration: 1 Momentum Wheel + 1 Reaction Wheel with their spin axes perpendicular to each other

8. V-Configuration: 2 Momentum Wheels with an angle on the order of 20 deg between their spin axes

9. Λ-Configuration: 2 Momentum Wheels + 1 Momentum Wheel with cw/ccw running capability, spin axis in the plane of the two others and perpendicular to their momentum vector sum

10. Tripod-Configuration: 3 Reaction Wheels with orthogonal-oriented spin axes

11. Quadruple-Configuration: 4 Reaction Wheels, 3 of which are orthogonally oriented, the 4th inclined to each of the 3

12. Double Gimbal Momentum Wheel, DGMW, with 1 or 2 Momentum Wheels mounted in a gimbal system.

For 1: Flight proven BBMW designs of different suppliers are available. Modern concepts need no load relief or caging mechanisms to survive launch loads. Wheels equipped with well preloaded and lubricated ball bearing pairs and automatic lubrication applicators achieve a life of more than 7 years with a 2% failure probability. The conservatively calculated fatigue life of properly lubricated bearing pairs for a 1% failure probability is more than 20 years. No zero g - 1 g and slew rate problems should be expected (ref. 1). Figure 1 shows the cross section of a BBMW.

For 2: BBRW's are also offered by different suppliers. Newer designs avoid any kind of caging or load relief mechanisms. By appropriate bearing and lubrication selection, an adequate lubrication film can be achieved even at very low speeds. Typically, at normal room temperatures, balls and races are already separated by the lubricant at 1 revolution per second. Therefore, long life with high probability is the consequence. A problem may be the step in the reaction torque caused by friction when the speed is crossing zero. Figure 2 gives an example of a BBRW, which may be equipped with an ac asynchronous or a brushless dc motor.

For 3: Magnetic bearings have been well known for many years. Due to the slogan "no contact between moving and nonmoving members, therefore no wear," one is inclined to expect a high lifetime with an extremely high reliability.

Table I shows reliability figures for a complete wheel with 5 actively controlled degrees of freedom, including motor and nonredundant bearing electronics of 93%, with redundant bearing electronics of 98% for a 7-year life (ref. 2).

The stiffness of an MBMW 5 around the lateral axes is comparable with that of a BBMW. A distinct advantage could be the possibility of tilting the momentum vector of the rotor simply by adding signals to the corresponding control loops. This "vernier gimballing" capability may be used for fine pointing or oscillation (nutation) damping of a spacecraft. In figure 3, an MBMW 5 developed for COMSAT is shown. The emergency ball bearings are able to withstand launch loads without caging.

For 4: Two main approaches of a mainly passive MBMW 1 are known. One utilizes radial repulsive forces of permanent magnet rings, and the other secondary radial forces generated by axial attracting magnets (refs. 3 and 4). Despite the fact that only one control loop (along the spin axis) is necessary, the reliability of a complete wheel, including motor and bearing electronics, is only on the order of 96% for a 7-year life. This can be raised to 99% with redundant bearing electronics.

Because of the low stiffness of these bearings about lateral axes, the transfer of rotational energy of a wheel to the body of a satellite - resulting in nutational motions - is possible and must be counteracted by adequate means (ref. 5).

For 5: One design for an MBRW 2 is shown in figure 4. Actively controlled are the two lateral degrees of freedom. This approach offers simple assembly procedures and a low volume.

The reaction torque noise and ripple as well as the zero speed crossing are mainly influenced not by the bearing but by the motor.

For 6: The design of an MBRW 1 is similar to that of an MBMW 1 but the means for nutation damping are less sophisticated. The reaction torque characteristic is the same as with the MBRW 2.

For 7: This configuration offers active spacecraft attitude control along 2 axes and, in a sequence, probably also about 3 axes.

To achieve higher reliability figures, a TT-configuration is generally necessary.

For 8: This configuration has essentially the same attitude control performance and reliability as the T-configuration; therefore, a VV-configuration must also be taken into consideration.

For 9: In the Δ-configuration, only 2 out of 3 wheels are in operation, and these actively control 2 axes of a spacecraft.

The primary mode is identical with that of the V-configuration. If one of the momentum wheels fails, the third momentum wheel which is capable of running in cw/ccw direction, is switched on in the appropriate sense of rotation to maintain the momentum vector sum direction.

For 10: This system is able to control a spacecraft actively about all 3 axes. Under steady state conditions, all 3 reaction wheels operate at speeds near to or at zero. Therefore, this system belongs to the "zero momentum systems." For high pointing accuracy performance MBRW's could be advantageous, but BBRW's also allow good results when they are kept spinning at low speed during an observation period.

For 11: This configuration is also a zero momentum system. Normally, all 4 wheels are running at a moderate speed, which offers high pointing accuracy.

If one out of the 4 wheels fails, the speeds of the other wheels are adjusted to maintain a zero momentum system.

For 12: This configuration is especially suited for 3-axis active control of geosynchronous spacecraft.

Figure 5 shows an example. Two momentum wheels, which could be operated at the same time, are mounted in a gimbal system. The gimbal axes could be driven by motors (or torquers). Both gimbal axes are equipped with two motors and pick-offs. Therefore, this system is redundant along all 3 axes.

MISSION AND MOMENTUM ACTUATORS

After this brief description of the different momentum actuators, an attempt will be made to relate their capabilities to mission and budgetary requirements. Two mission types are taken into account: communication/tv satellites and observation/navigation/research satellites.

Communication/TV Satellites

These satellites are assumed to be of the geostationary type.

First of all, the pointing accuracy required should be treated as a function of mass for different actuators (fig. 6). The nominal values for SYMPHONIE, OTS, INTELSAT V, ECS and TV-SAT are indicated.

It is evident that from a mass point of view the MBMW 1 has no advantage over the respective BBMW. On the contrary, special measures against nutational instability must be considered. The MBMW 5 shows as a benefit a higher pointing accuracy potential, essentially that of the DGMW. It should be born in mind, however, that a DGMW has a gimballing capability of about 50 times that of an MBMW 5 (about 7.5 deg to 0.17 deg).

Other interesting relationships can be deduced from figure 7. For a 1 degree-of-freedom system (1 DOF) it is interesting to compare the BBMW cost trends with those of the MBMW with and without redundant electronics. One MBMW with redundant electronics costs about the same as two BBMW's, but the reliability of the first one is so low that generally two MBMW's would be needed.

The 2 DOF approaches, Λ, T, TT, V and VV configurations allow the following interpretation. Single T and V arrangements should not be taken into consideration because reliability is so low. The Λ configuration and the TT/VV configuration are comparable in reliability, but the costs of the latter are higher.

In the Λ configuration the nominal total angular momentum can vary between 1 and 2 depending on which 2 wheels out of the 3 are in operation. This is, of course, not the case with the TT/VV configuration where the nominal total angular momentum is the same in the primary and redundant mode.

A 3 DOF control can be achieved with 1 DGMW or with 1 or 2 MBMW 5. A certain compensation for the higher cost and the lower reliability of the 2-MBMW 5 solution could be the higher potential of attitude accuracy.

In figure 8 an attempt is made to estimate the mass of different actuator assemblies for different classes of satellites represented by their masses. For communication satellites of up to the 1000-kg class the 2 BBMW configuration is most suitable. If, however, a higher pointing accuracy is required, and/or only a limited north/south station keeping capability is implemented, the Δ BBMW configuration can meet the specifications.

For TV satellites of up to the 2000-kg class, the most attractive configuration seems to be the DGMW approach. The MBMW arrangements result in a higher mass, but offer a higher angular momentum capability.

The DGMW and the MBMW 5 can both provide active damping of satellite oscillations.

Observation/Navigation/Research Satellites

For these satellites, reaction wheel arrangements are of interest.

A good overall view, giving the reliability/cost relation, is shown in figure 9 for 3, 4 and 6 BBRW's, and MBRW's with and without redundant electronics. For the 2 to 5 N·m/s reaction wheel class, somewhat higher cost of MBRW's compared with BBRW's is assumed.

It is interesting to note that a quadruple configuration of 4 MBRW's with redundant electronics gives a higher reliability than can be achieved with redundant tripod configurations of 6 BBRW's.

Of course, reaction wheel configurations also may be employed in communication satellites.

CONCLUSIONS

After weighing the essential parameters it is believed that the following selection guide can be proposed:

For communication satellites:

With 0.2-deg pointing accuracy:
2 BBMW's, parallel spin axes

With 0.1-deg pointing accuracy:
3 BBMW's Δ configuration, or
4 BBRW's quadruple, or
4 MBRW's quadruple (with redundant electronics)

For TV satellites of:

Medium mass:
1 DGMW, or
4 BBRW's, or
4 MBRW's (with redundant electronics)

High mass:
The same as medium mass plus MBMW configurations

For observation/navigation/research satellites:

Short time missions:
3 BBRW's
3 MBRW's

Long time missions:
4 BBRW's
4 MBRW's (with redundant electronics)

The comparison between ball bearing and magnetic bearing momentum actuators shows that given mission requirements can be economically met by employing the ball bearing technology without decreasing reliability and lifetime.

However, for some special mission requirements, such as "zero friction at zero speed," fine pointing (met by vernier gimballing), and/or active damping, magnetic bearings may be advantageous.

This makes evident that magnetic bearing technology will not replace ball bearing technology for momentum actuators, but will supplement it for some special mission requirements.

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TABLE I.- MOMENTUM ACTUATORS

	Angular momentum, N·m/s	Nominal speed, 10^3 min^{-1}	Output torque, N·m	Power, steady state, W	Power, max., W	Reliability, 7 years, %	Starting torque, 10^{-4} N·m	Dimensions, $\phi \times h$, mm	Mass, kg
BBMW	20-70	3.0-6.0	±0.1	6-20	50-100	98.6	50	350×120	5-8
BBRW	2-25	±2.0-6.0	±0.1	6-20	50-100	97.5	30	205×77	2.4-4
								350×120	5-6
MBMW 5	30-150	5.0-8.0	±0.1	10-15	70-120	93/98*	1	350×150	12-17**
MBMW 1	50-100	7.7-24.0	±0.1	15-20	120-190	96/99*	1	350×220	12-17**
MBRW 2	1-5	±1.5-3.5	±0.1	3-5	20-40	96/99*	1	220×90	3-3.5**
MBRW 1	2	±3.0	±0.1	3	47	96/99*	1	250×120	3**
T-Conf.	1 BBMW / 1 BBRW					96.1	TT		99.85
V-Conf.	2 BBMW					97.2	VV		99.92
Δ-Conf.	3 BBMW					99.9			
Tripod	3 BBRW					92.7	Double Tripod		99.8
	3 MBRW					88.5	Double Tripod		99.5
	3 MBRW*					97.0	Double Tripod		99.97
Quadruple	4 BBRW					99.6			
	4 MBRW					99.0			
	4 MBRW*					99.94			
DGMW	2 BBMW + Gimbal system (redundant motors and pick-up's)					99.8			

*With redundant electronics.
**Including electronics.

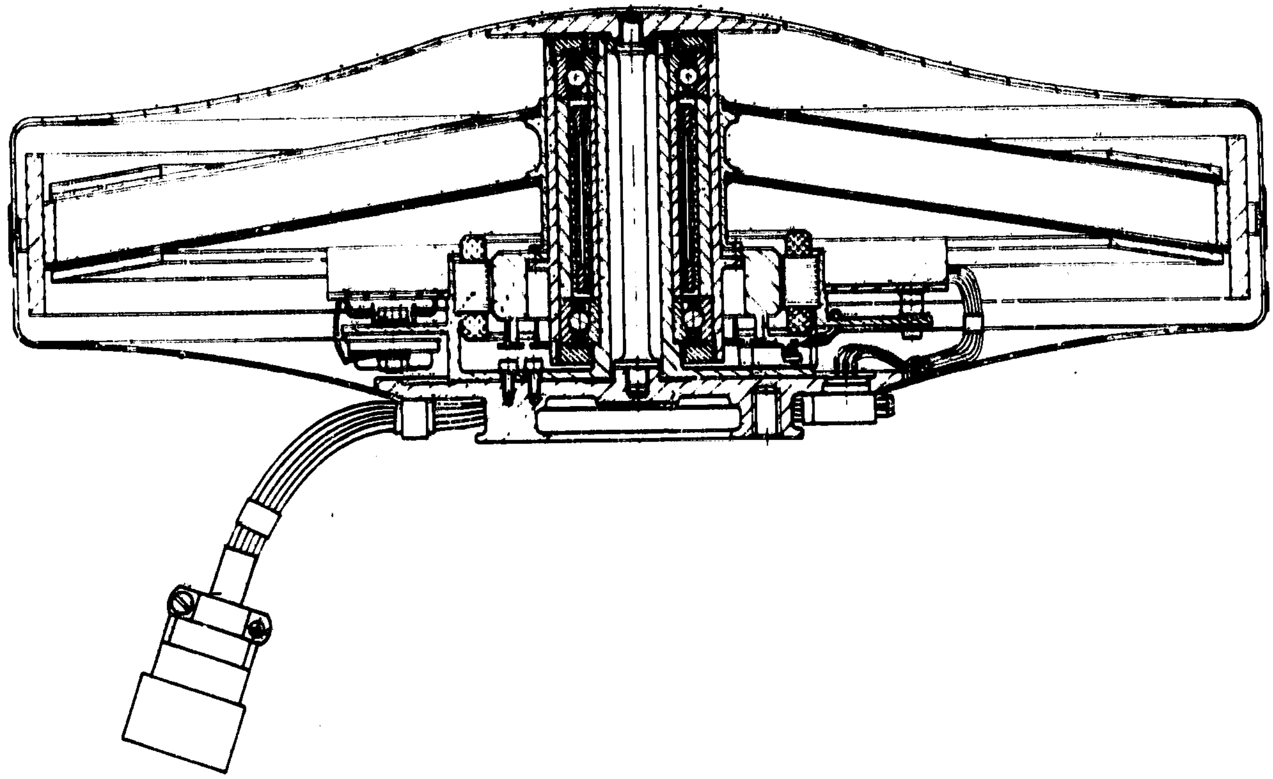

Figure 1.- Cross section of a BBMW.

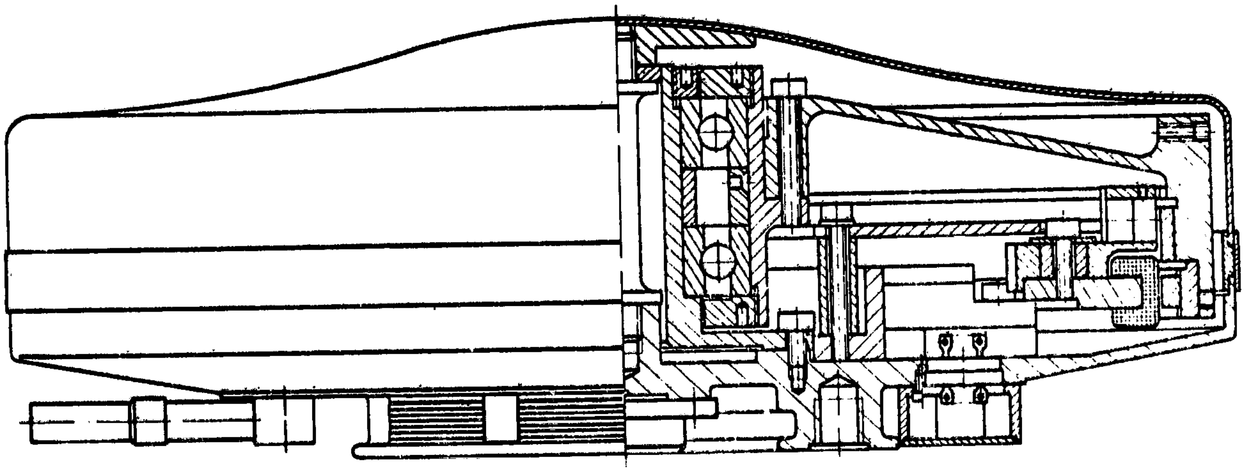

Figure 2.- Cross section of a BBRW.

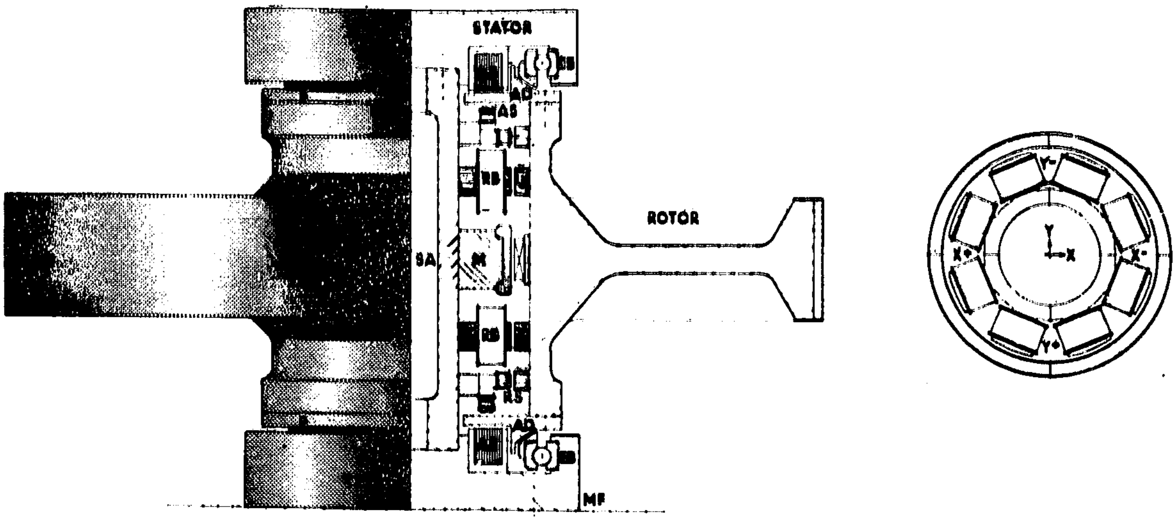

Figure 3.- Cross section of an MBMW 5.

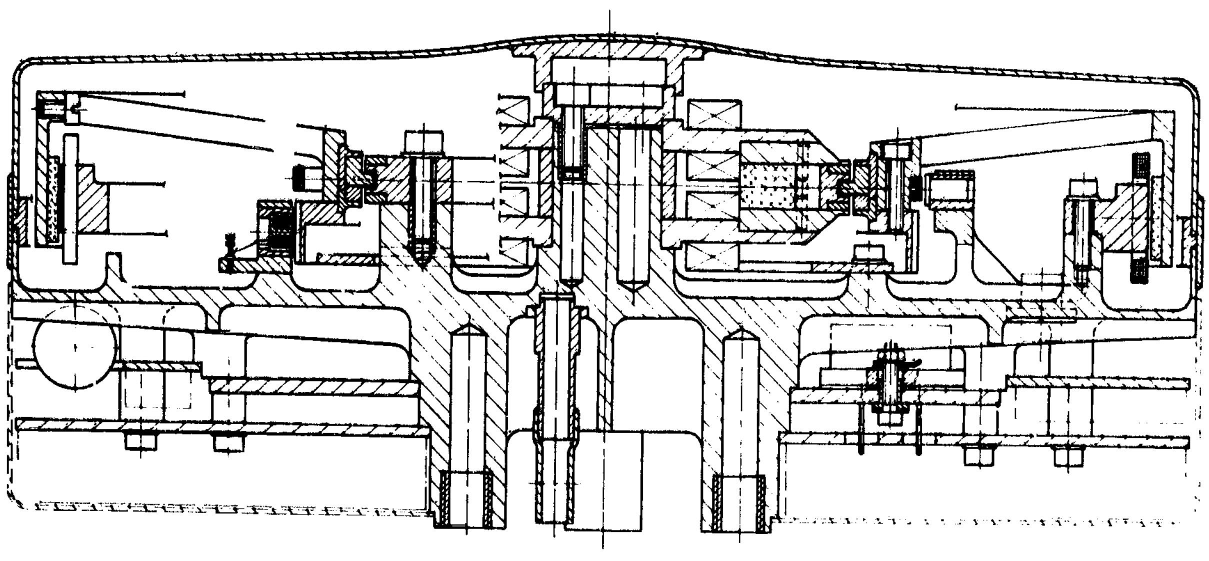

Figure 4.- Cross section of an MBRW 2.

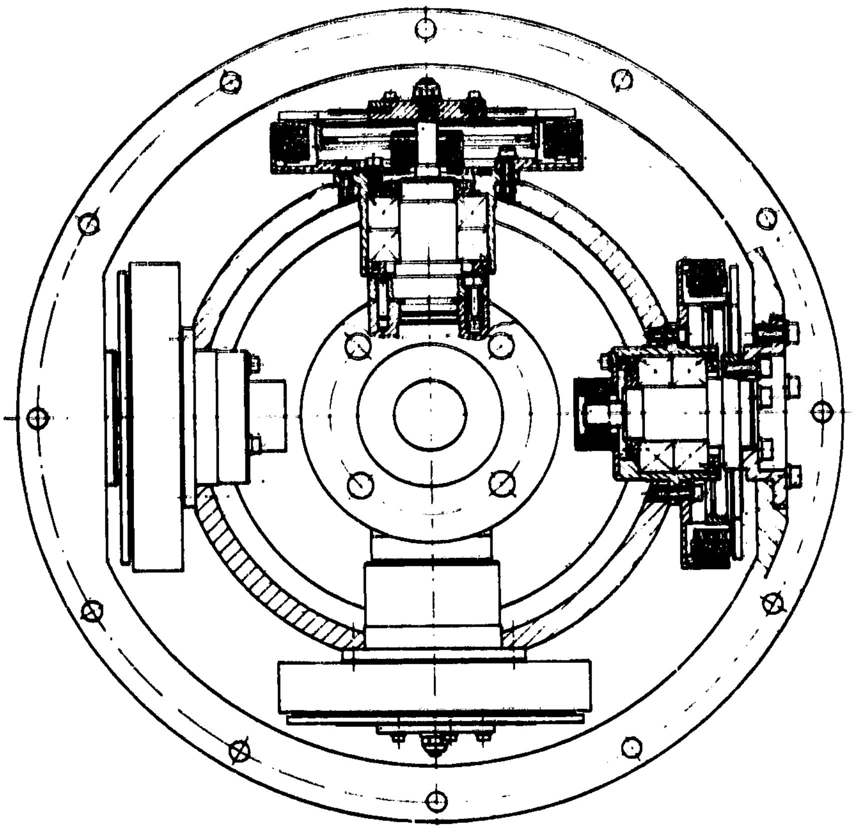

Figure 5.- Cross section of a DGMW.

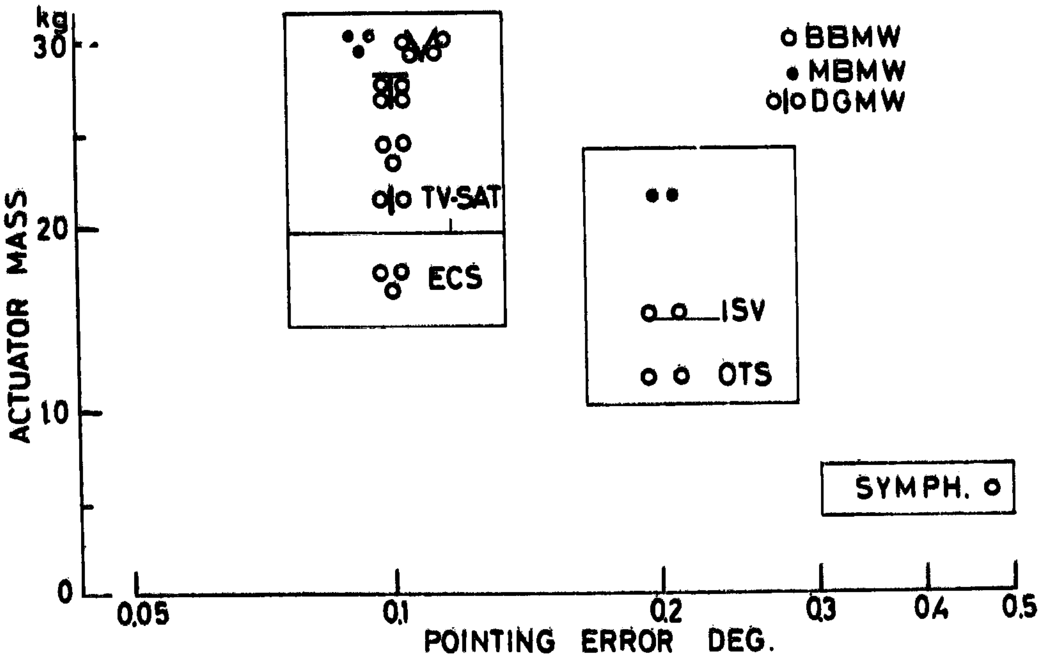

Figure 6.- Pointing accuracy and related actuator mass.

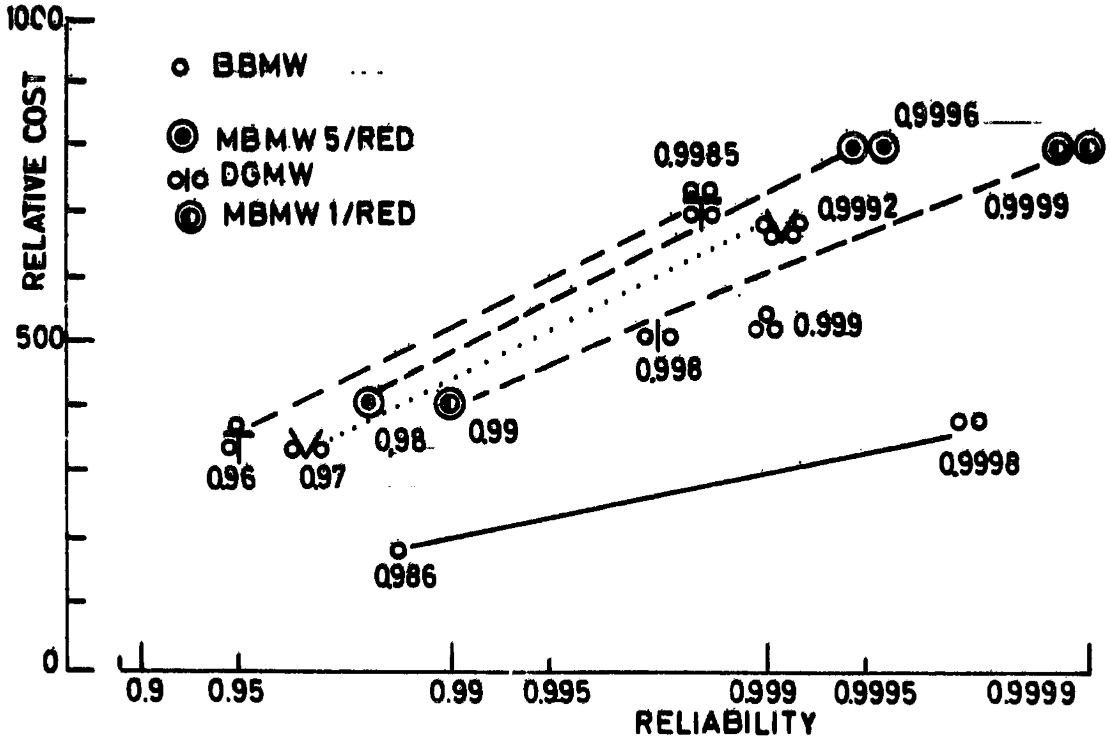

Figure 7.- Relative cost vs. reliability - momentum wheels.

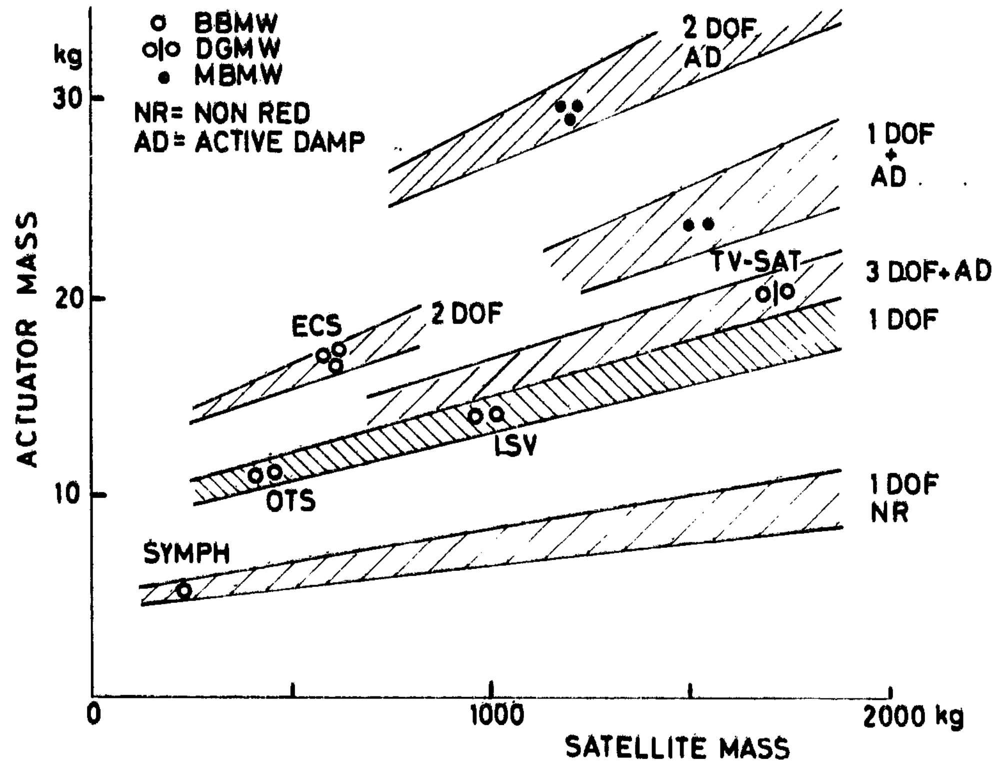

Figure 8.- Actuator/satellite mass.

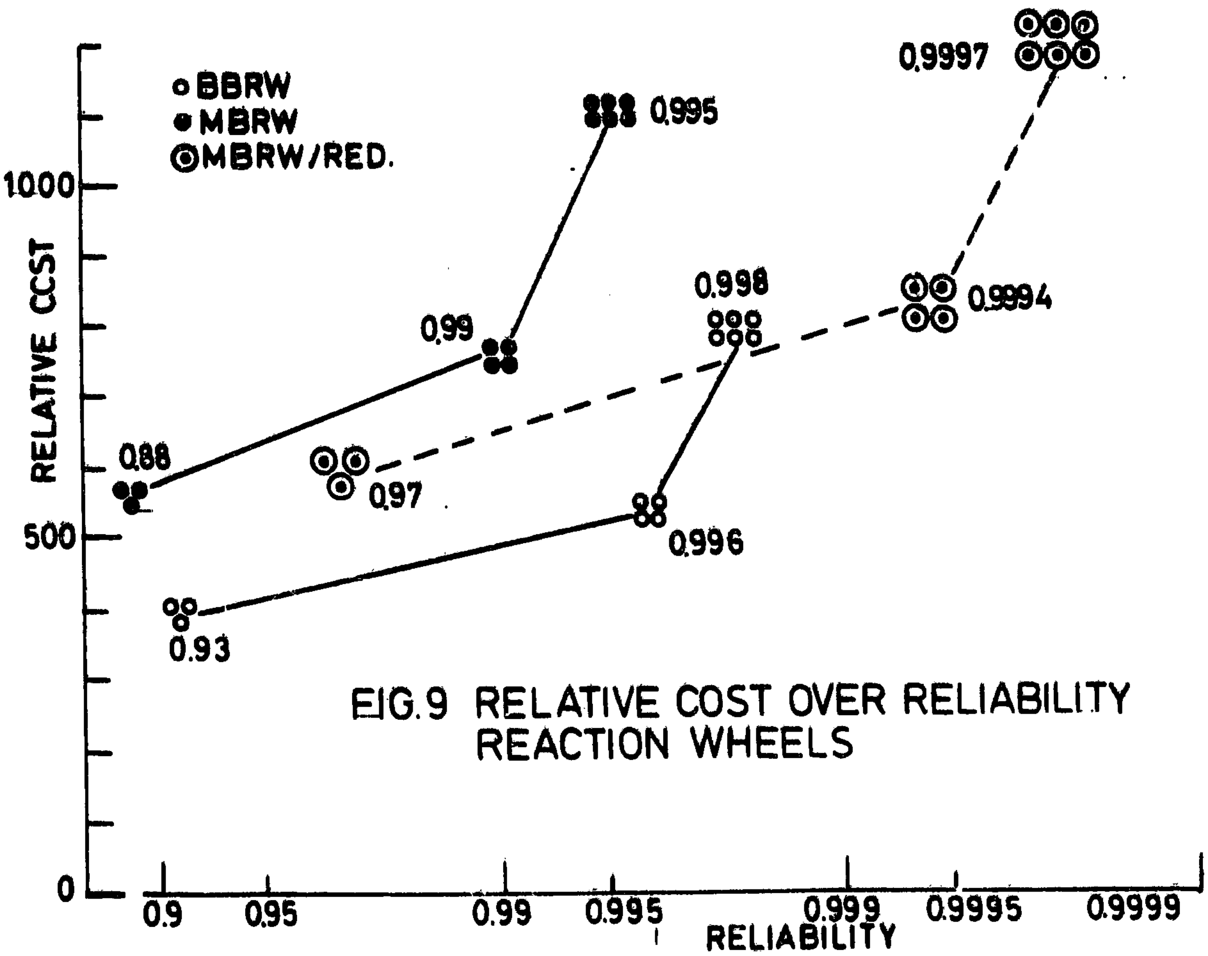

Figure 9.- Relative cost vs. reliability - reaction wheels.