N79-21392

DEVELOPMENT OF A SATELLITE FLYWHEEL FAMILY OPERATING ON "ONE ACTIVE AXIS" MAGNETIC BEARINGS.

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ABSTRACT

Since the Samarium-Cobalt magnets were available at industrial level, new possibilities appeared in the area of magnetic bearings with the radial passive centering and axial active control of the rotor position. This paper describes magnetic bearings of this type on which a wide effort was made towards the optimization for satellite flywheel applications. It describes also the momentum and reaction wheels already developed or presently under development and the extension of this work to the kinetic storage of energy for satellites.

⊠ Parts of the work described in this paper were performed under the sponsorship of : - International Telecommunications Satellite Organization (INTELSAT) ;
- European Space Agency (E.S.A.) ;
- Centre National d'Etudes Spatiales (CNES).
Views expressed are not necessarily those of INTELSAT, ESA, CNES.

I-ADVANTAGES OF THE "ONE ACTIVE AXIS" MAGNETIC BEARINGS FOR SATELLITE FLYWHEELS.

The interest of the magnetic bearings for satellite momentum and reaction wheels, allowing the operation of the equipment without any mechanical contact between rotor and stator, was often described ; therefore it is only useful to summarize the advantages of such a system.

- Elimination of the life limiting wear processes of ball bearings.
- Reduced mass ; it is possible to replace two or more conventional wheels by one magnetically suspended rotor wheel, with "no single point failure" the redundancy being implemented in the active part only.
- Improved performances concerning stiction and friction torques which are reduced by several orders of magnitude with elimination of the temperature effect ; consequently, the friction power is reduced.
- Higher speeds allowing a significative improvement in the momentum/mass ratio of the wheels.
- Higher reliability of the "one active axis" magnetic bearings compared to other types of magnetic suspension and to the ball bearings.

II- MAIN PARAMETERS OF SATELLITE FLYWHEEL MAGNETIC BEARINGS

The main parameters on which is based the design of satellite flywheel magnetic bearings are indicated here :

- The radial stiffness which defines the critical speed of the suspension together with the mass of the wheel rotor.
- The transverses stiffness (angular stiffness about an axis perpendicular to the axis of rotation of the rotor) ; for a given angular momentum it defines the maximum slew rate that the flywheel can accept taking into account the possible angular displacement of the axis of the rotor towards the axis of the stator.
- The damping of radial oscillations for critical speed crossing when the maximal speed exceeds the critical speed and the nutation damping.
- The mass of the overall device.
- The power necessary for the axial servoloop, and to compensate the overall losses in the range of useful torques and speeds.
- The reliability of the electronically controled axial servoloop and the possibility of redundancy with no single point failure in the overall equipment.

III - DEVELOPMENT OF "ONE ACTIVE AXIS" MAGNETIC BEARINGS FOR THE WHOLE RANGE OF SATELLITE FLYWHEELS.

The design of a magnetic suspension oriented towards the optimization from the point of view of the above indicated parameters was undertaken ; models were fabricated and tested. The successfull operation of the magnetic suspension gave birth to a family of satellite flywheel engineering and qualification models, the objectives consisting in covering the range of following applications (the numerical figures are given as order of magnitude) :

- Medium speed momentum wheels from 10 Nms up to some hundred Nms and 12.000 RPM.
- High speed momentum wheel angular momentum in the range of 100 Nms for 24.000 RPM ; this technology gives the possibility with further development, to provide kinetic energy storage capacity with mass improved characteristics and long life reliability compared to the chemical batteries.
- Reaction wheels up to 15 Nms and 3000 RPM.
- Reaction or momentum wheels with specific characteristics (low level of vibration, high angular momentum reaction wheels, etc..).

IV - DESCRIPTION OF THE MAGNETIC BEARINGS.

IV.1) Radial Centering

The radial centering of the rotor is provided by magnetic rings operating in attraction, the dimensions, disposition (side by side axially or radially) and number of which are defined according to the specific characteristics of each equipment.A centering ring on the rotor faces a centering ring on the stator. Each ring is constituted by two iron sleeves with an internal segmented ring of samarium-cobalt magnets. The axial magnetic field between the iron sleeves produces a restoring force as soon as the rotor magnetic ring axis is not exactly coincident with the stator one. The radial stiffness is currently in the range of 1.5 to 5.10^5 N/m (15 to 50 kg/mm) and can be extended to several times these values in increasing the number of centering rings. The choice of the different parameters of the centering rings (thickness and height of magnets and iron sleeves) gives a wide range of possible characteristics such as : radial to axial stiffness ratio, e.g. 2.1 to 3.5 and radial stiffness to mass ratio e.g. 6 to 8.10^5 N/m/kg.

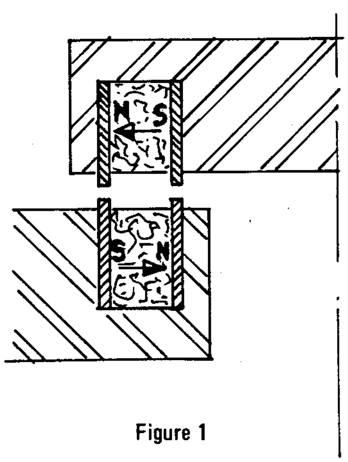

Figure 1

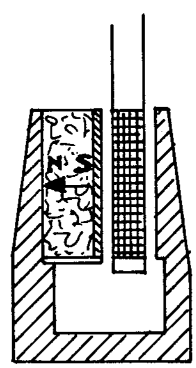

Figure 2

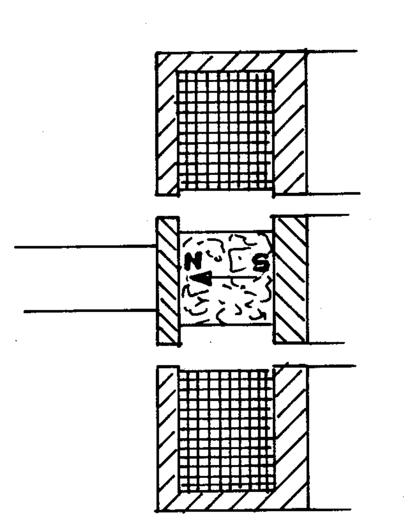

Figure 3

IV.2 Axial position control of the rotor.

The attraction between the iron sleeves providing the radial restoring force involves an axial negative stiffness and consequently an instable equilibrium position which is made stable by an electronically controlled servoloop. This servoloop includes :

- An axial rate electrodynamic sensor (Figure 2) .
- An axial actuator constituted by two electromagnets attached to the stationnary central shaft and a magnetic biaised circuit fixed to the rotor (Figure 3).
- An electronics circuit controlling the current in the coils of the electromagnets.

The input signals of the electronics are :

- A voltage signal proportional to the axial rate of the rotor.
- A voltage signal proportional to the current in the electromagnets.

A lift-off logic enables initial operation of the servoloop from the rest position when the power supply is switched on.

IV.3 Damping system

The damping system is necessary for the critical speed crossing. The system chosen is of the electrodynamic type. A magnetic circuit on the rotor, constituted by samarium cobalt segmented rings, provides a magnetic induction in a gap in which a copper disk is fixed to the stationary central shaft. The magnetic field has a revolution symetry without azimuthal variation of induction ; there is an energy dissipation only when the rotor translation or nutation oscillations occur.

The smoothing of the magnetic field variations in the gap is provided by iron (or ferromagnetic material) sleeves according to two configurations (Figures 4 and 5).

The damping ratio obtained for 50 to 100 Nms wheels, according to the radial stiffness and to the mass of damper material, is in the range of 0.02 to 0.08.

Instead of a copper disk, it is possible to adapt three coils at 120° or four coils at 90°. When these coils are electronically short-circuited, they provide the damping on the same bases as the copper disk ; but it is also possible to amplify the current induced in these coils and to provide a higher damping coefficient in this active damping configuration.

Another application of the damping system in which the copper disk is replaced by coils consists in modifying the orientation of the axis of rotation of the rotor by sending permanent currents in the coils. The electrodynamic forces produced between these currents and the magnetic field, are vectorially added. (Figures 6 and 7).

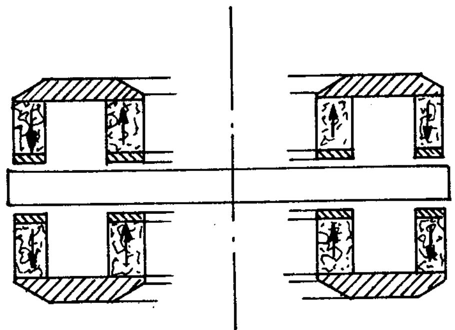

Figure 4

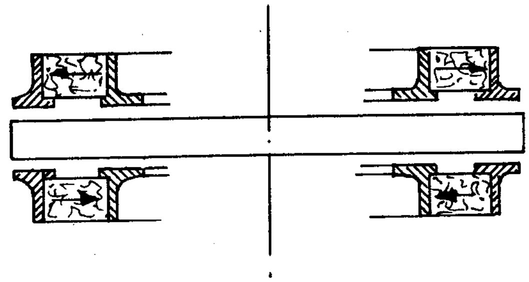

Figure 5

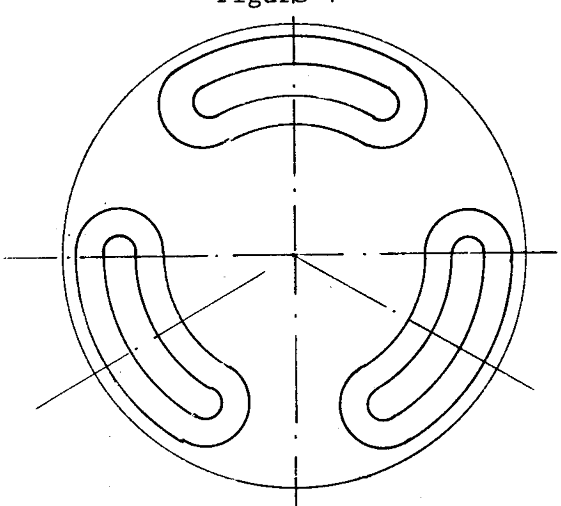

Figure 6

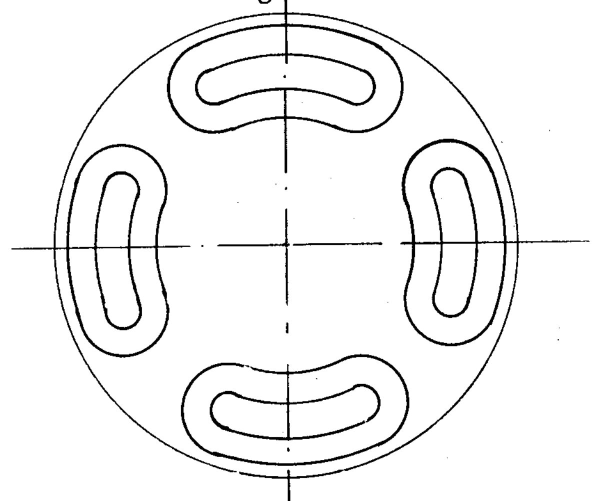

Figure 7

Combined with the restoring forces of the centering rings, these electrodynamic forces allow a rotation around an axis different of the centering ring axis. This solution has a possible application in the energy storage system. It allows the compensation of mechanical misalignments between the axis of the two counter-rotating bodies and of the misalignment of the resulting angular momentum in relation to its nominal position.

V ASSOCIATED SUBSYSTEMS IN A MAGNETIC BEARING SATELLITE FLYWHEEL

Motor

The acceleration and deceleration torques are provided by an electronics commutation iron-less DC motor-generator. According to each specific wheel design the number of poles was, till now, between 12 and 24. It can be adapted for each case. In the case of a reaction wheel the rotating magnetic circuit of the motor is integrated in the rim of the wheel in order that the mass of the motor can participate to the inertia.

For the deceleration the motor operates as a generator. Several systems of commutation were developed and tested :

- Photo-diodes/ photos transistors commutation.

- Hall effect cells commutation.

- Electromagnetic sensor commutation, which is chosen for equipments presently under development ; a windowed sleeve on the rotor crosses the magnetic flux of stator ferrite coils fed with a high frequency signal. The Q factor of the coils is modified by the windowed sleeve, according to the relative angular position of the rotor in relation to the stator.

The resulting signals are utilized to open or close the gates controlling the current in the motor coils. Two types of windings were successively experimented with 3 and 4 circuits sequentialy commuted. The useful torques were either 0.05 or 0.1 Nm. Much higher torques can be produced. The efficiency of the motor itself without the control electronics is of 95 % at the maximum torque at nominal speed and higher for lower torques.

Rotor

The rotor is constituted of several functional parts :

- The central part which contains the elements of the magnetic bearings and, generally, for momentum wheels the magnetic circuit of the motor.

- The rim which produces the main part of the inertia and which includes the magnetic circuit of the motor in the case of reaction wheels.

- The connexion between the central part of the rotor and the rim.

Two main problems are in relation with the rotor rim and its connexion to the centering rings although the central part of the rotor.

- To accept the stresses due to centrifugal forces.

- To keep an accurate balancing : i.e. to maintain the coincidence between the axis of the rotor centering rings and the main axis of inertia with a high level of accuracy. This accuracy will have to remain stable in spite of launch vibrations, of elongation due to centrifugal forces, of temperature variations, of time effect associated to the above indicated parameters.

Several solutions were developed and tested :

- Aluminium alloys rim with two different centerings on the magnetic bearing : by spokes and by cônes.

- Composite filament material rim also with two different centerings : by spokes and by a special technique called "eyeloprofile".

The high speed rotors need filament material, and special techniques to achieve a stable balancing. The following one was selected for the 24.000 RPM. The rotor consists of three parts : an aluminium alloy hub that is used as interface between the filament rotor assembly and the rotor shaft, a circumferentially wound filament rim, and the cycloprofile envelope windings that attach the rim to the hub. The rim is wound about a mandrel. After curing, the mandrel and rim are finish machined. The envelope winding consists of two layers of filament tape. After the tape is cured, the mandrel is washed away. Three complete rotors have been fabricated, one in glass fiber, one in graphite fiber, and one in KEVLAR 49.

Emergency bearings.

Ball bearings specially treated for ultra vacuum are utilized for touch down operation of the rotor ; they are able to allow the deceleration of the rotor, in the case where the power supply or the axial servoloop are disrupted. In normal operation, there is not contact between the rotor and the emergency bearings.

Caging mechanism

The first solution which was designed and tested to lock the rotor on the fixation flange of the wheel was similar to the Marman clamp locking a satellite on the upper stage of its launcher. This solution is available when it is considered that the wheel can be locked after its tests and installed on the satellite without any further test before orbital operation. In many cases, it will appear necessary to have a test controling the operation of the wheel during the count down operation. A locking device which can be operated by remote control was developed and is now a part of the basic concept.

Housing

In the early model a light alloy ventilated housing was adopted. On the models presently in test and development, the housing is replaced by a very light carbon fiber structure with three arms. Its purpose is principaly to stiffen the upper part of the central fixed shaft by a mechanical connexion to the lower flange of the wheel.

Electronics

The electronics which is specific of a wheel provides two functions :

- The data processing of the input signals of the axial servoloop to control the current in the biaised electromagnets.

- The commutation of the motor.

The axial servoloop has to operate in stable conditions with sufficient phase and gain safety margins. This is obtained by adjusting the transfer function taking into account the negative axial stiffness of the magnetic centering

ring added to the axial stiffness of the axial actuator, the rotor mass and the mechanical resonances of the different parts of the rotor.

A lift-off logic provides the necessary signals for initial operation when rotor is resting on one of the emergency bearing and when the circuits are switched on. The electronics of the early models was based on the utilization of operational amplifiers. When the feasibility of the magnetic bearing was demonstrated, the electronics was completely redesigned. The new concept utilizes only conventional transistors which allows the operation exclusively on the 28 volts power supply. In the case of lack of the 28 volts power supply, the motor operating as a generator, is able to feed the electronics of the axial servoloop in the momentum wheel configuration during about half an hour before the rotor goes back to the emergency bearings.

The electronics is able to operate in "hot redundancy or cold redundancy" for the axial servoloop. In hot redundancy, the coils of the electromagnets are doubled and the two coils are energized simultaneously by two separate electronics circuits. If one of the circuit operation is wrong, it is detected by a surveying logic and the concerned circuit is switched off.

The electronics is presently existing in discrete components. The transposition in hybrid thick film circuit is presently under development. The operation of the discrete component electronics was tested in the range - 30° C to + 70° C. The mass of the electronics with a redundancy of order 2 is the following :

Cordwood technology : 1.4 Kg

Hybrid thick film circuit : 0.6 Kg

In the cordwood technology the electronics package is outside of the wheel with interconnecting plug. The hybrid circuits are fixed inside the wheel on the lower flange with direct interconnexion. A wheel drive electronics was developed : it allows as well the control of the torque as the control of the speed.

VI - APPLICATION OF THE MAGNETIC SUSPENSION AND ASSOCIATED SUBSYSTEMS TO SATELLITE FLYWHEELS.

The above described subsystems were first applied on in-house laboratory models for verification of their validity. Later they gave birth to a complete family of satellite flywheels. Several models were developed and submitted to functional and environmental tests ; others are presently under development up to qualification tests and long duration operation.

VI.1 - In house momentum wheel engineering and prototype models.

Several models were successively developed since 1969 for the experimentation of the different subsystems and for the experimentation of the overall concepts.

- EM1 and EM2 models ; Period 1969-1971 :

These models were utilized for the initial application of peripheral ironless brushless DC motor to laboratory model of flywheels operating on self lubricated journal and pivot bearings.

- EM3 model ; Period 1971-1973 :

This model was utilized for comparison of different types of magnetic suspensions of the rotor :

. attraction compared with repulsion radial centering ;
. radial compared with axial polarisation of magnets for the centering rings operating in attraction ;
. axial control provided by separated centering rings and actuator compared with actuator integrated in the centering rings ;
. motor with iron in the stator contributing to the radial centering compared with motor without iron in the stator and producing no radial or axial stiffness.

In each case the subsystems were studied and tested separately and later they were tested in operation on the EM3 model.

- EM4 model ; Period 1973-1974 :

This laboratory model was a preliminary experimental configuration of a satellite flywheel leting appear all the experimental aspects of the assembly of the different subsystems already theoritically studied and experimented in the EM3 model. The EM4 model was a direct preparation of the medium speed and high speed engineering momentum wheel models, developed respectively since november 1973 and february 74 in the frame of the ESA and INTELSAT contracts.

- EM5 model ; Period 1975-1977 :

This model was utilized to prepare the final optimization of the magnetic bearing momentum wheel. The optimization of the centering rings, actuator dampers, motor was separately performed and the choices were tested in the EM5 model. This model will be delivered to CNES for tests or an air bearing.

- Medium Speed Qualification Prototype ; 1975-1977 :

This model was developed in order to have a prototype made on the bases of complete set of drawings and procedures at the level of satellite hardware quality. This model is realized on the same principles as the EM5 model. After the qualification tests performed in 1976, three sets of equipment will be utilized in long duration experimentation for demonstrating the operational validity of the system by long term systematic operation. The purposes of these tests are to demonstrate the operational validity of the system and particularly to confirm the stability of the axial servoloop.

The existence of this model will make possible the utilization of magnetic bearing momentum wheels for early program. The developed medium speed prototype covers the range of applications of geosynchronous telecommunications satellites of the Intelsat V class.

With a mass of 11 Kg5 all the active electric circuits of the wheel are redundants ; the possibility of remote control of the caging mechanism allows the complete verification of the axial servoloop and motor torque capability during the count down before launch.

VI.2 - Momentum wheels engineering models developed under contracts.

- ESA Medium Speed Momentum Wheel engineering model - Period 1973-1975 :

This model was developed on the ESTEC 2038/73 contract starting in november 1973. It was involving a 50 Nms ± 10 % wheel rotating at 7.700 RPM ± 10 % The characteristics are given in the annexed table and the concept in the annexed plate.

- INTELSAT High Speed Momentum Wheel engineering model - Period 1974-1976 :

This model was developed on the INTELSAT IS 555 contract (Fébruary 74). It was involving a 100 Nms wheel rotating at least at 24.000 RPM. The characteristics are given in the annexed table, the concept in the annexed plate. The experimentation of this model up to 24.000 RPM demonstrated several points :

- the validity of the "one active axis" magnetic suspension for high speed rotors ;
- the wide safety margin of the axial servoloop towards the excitations of the high rotation speed ;
- the validity of the damping system even at high speed without excessive eddy current losses ;
- the possibility of operating composite filament rotors at rotation speeds enabling to envision kinetic energy storage for long life satellite at the place of chemical batteries.

This model was successfully submitted to environmental tests (thermal between - 20° C and + 50° C; vibrations tests according to COMSAT specifications).

- ESA Medium Speed Momentum Wheel optimization prototype ; Period 1975-1977

This model was developed in the frame of the ESTEC 2481/75 contract since november 1975. The purpose is to have an optimization of the "one active axis" magnetic bearing momentum wheel for the range of 50 Nms taking into account :

- the mass and dimensions ;
- the power ;
- the slew rate ;
- the caging mechanism ;
- the reliability and redundancies ;
- the hybrid thick film electronics.

The characteristics are given in the annexed table.

The realization is made in order to be able to adjust some characteristics according to each program equipment with or without remote control of clamping mechanism, slew rates from 0.01 to 0.1, level of redundancy of the axial actuator, level of torque in the range up to 0.1 Nms, without questionning the overall concept. From the minimal to the maximal capabilities, the range of mass is from 8 to 11 Kg.

VI.3 - In-house reaction wheel engineering model - Period 1976-1977

A 2 Nms reaction wheel engineering model utilizing the same principle of magnetic suspension as the momentum wheels was designed, fabricated and tested. It utilizes the rotating parts of the motor to contribute to the inertia of the rim. The rotating speed is 2.000 RPM and the radial stiffness of the centering rings added to the radial stiffness of the axial actuator is sufficient to avoid the crossing of the critical speed which is at 3.000 RPM. The concept can be extrapolated up to 15 Nms (Characteristics and view in annexed table and plate). This model will be delivered to CNES in 1977 for tests on an air-bearing table.

VI.4 Reaction Wheel engineering model under ESTEC contract - Period 1976-1977

This development, in the frame of the 2470/76 contract, covers the study of an optimized concept of magnetic bearing reaction wheel for the range of 1 to 5 Nms. An engineering model of 2 Nms is being realized. The characteristics are given in the annexed table. The concept can be extrapolated up to 15 Nms.

VI5 In-house studies and development in the field of kinetic energy storage for satellites.

The successfull operation of magnetically suspended high speed rotors performed in the INTELSAT IS 555 contract demonstrated the possibility of storing energy under kinetic form by two counter-rotating wheels. The range of stored energy is from 10 Watt/hour per kilogramme to 50 Watt/hour per kilogramme for peripheral speed of the rotor going from 500 m/sec. to 1000 m/sec. and for level of energy of 0.5 to several KW/hour. As well the magnetic bearing as the characteristic of composite filament material such as carbon fiber-epoxy or kevlar 49 (1) - epoxy let appear the validity of the research work in this field. Such a work is in progress: it utilizes 2 wheels of the High Speed Momentum Wheel type developed under INTELSAT contract (and one spare). The control of the operation is made by a microprocessor. The purpose is to verify the following points :

- the capability of the system to provide the control of the torque on the two wheels in order to maintain the resulting angular momentum along the main axis of the wheel at the right value, in spite of input and output of power into and from the two wheels : correlatively, the system has to provide the control

(1) Dupont de Nemours trade mark.

of this resulting angular momentum by the attitud control signal of the satellite for the concern axis.

- to cancel the components of the angular momentum due to residual misalignment of the two wheels even if they are very small, taking into account the large angular momentum of each wheel.

The first step in this long term development is the control of the torques of the two wheels taking into account the maximal and minimal output of power and the variation of moment of inertia due to elongations, variations of the rotor when the speed is varying. This phase is foreseen to be completely covered in 1977.

VII - CONCLUSION

After a considerable development effort including functional and environmental qualifications, satellite flywheels (momentum and reaction wheels) operating on "one active axis", magnetic bearings are now at the level of industrial production. In the same time, a great need appears for this type of equipment.

This development carried on largely with in-house effort, benefited from wide international participation. We take this opportunity to mention and to state our appreciations for part taken by the Representatives of international organizations involved in this programm : C.J. PENTLICKI for INTELSAT/COMSAT High Speed Momentum Wheel and A.A. ROBINSON for ESA Medium Speed Momentum and Reaction Wheels. Their suggestions and advices were of the greatest interest, particularly when difficult technical choices and trade offs were to be made.

	TYPE OF FLYWHEEL	DIAM. mm	HEIGHT mm	MASS Kg	TORQUE Nm	SLEW RATE rad/s	STEADY STATE POWER Watts	RELIABILITY
MEDIUM SPEED MOMENTUM WHEELS	ESA ENGINEERING MODEL 50 NMS - 7.700 RPM	350	220	10,5 ⊠	0.1	0.04	9	0.98 to 0.995 according to the type of electronics circuits for 2 redundant channels.
	ESA PROTOTYPE 50 NMS - 7.700 RPM	350	180	8.5 to 11.5	0.1	0.04 to 0.1	9	
	IN-HOUSE QUALIFICATION PROTOTYPE 50 NMS - 7.700 RPM	350	220	11.5	0.1	0.06		
HIGH SPEED	INTELSAT ENGINEERING MODEL 100 NMS - 24.000 RPM	350	220	11	0.05	0.02	9 W at 8000 RPM 25 W at 24000 RPM	
REACTION WHEELS	IN-HOUSE ENGINEERING MODEL 2 NMS - 2000 RPM	230	150	5	0.1	0.1	8	
	ESA ENGINEERING MODEL 1-5 NMS - 3000 RPM	250	120	3.7 to 4.5	0.1	0.1	3	

ELECTRONICS

<u>COORDWOOD TECHNOLOGY</u>
- 0.7 dm^3 ; 0.7 Kg (1 channel)
- 1.3 dm^3 ; 1.4 Kg (2 redundant channels)

<u>THICK FILM TECHNOLOGY</u>
- 0.3 dm^3 ; 0.350 Kg (1 channel)
- 0.5 dm^3 ; 0.6 Kg (2 redundant channels)

⊠ Without caging device for launch restraint.

Figure 8. Magnetic Bearing Momentum and Reaction Wheel Characteristics

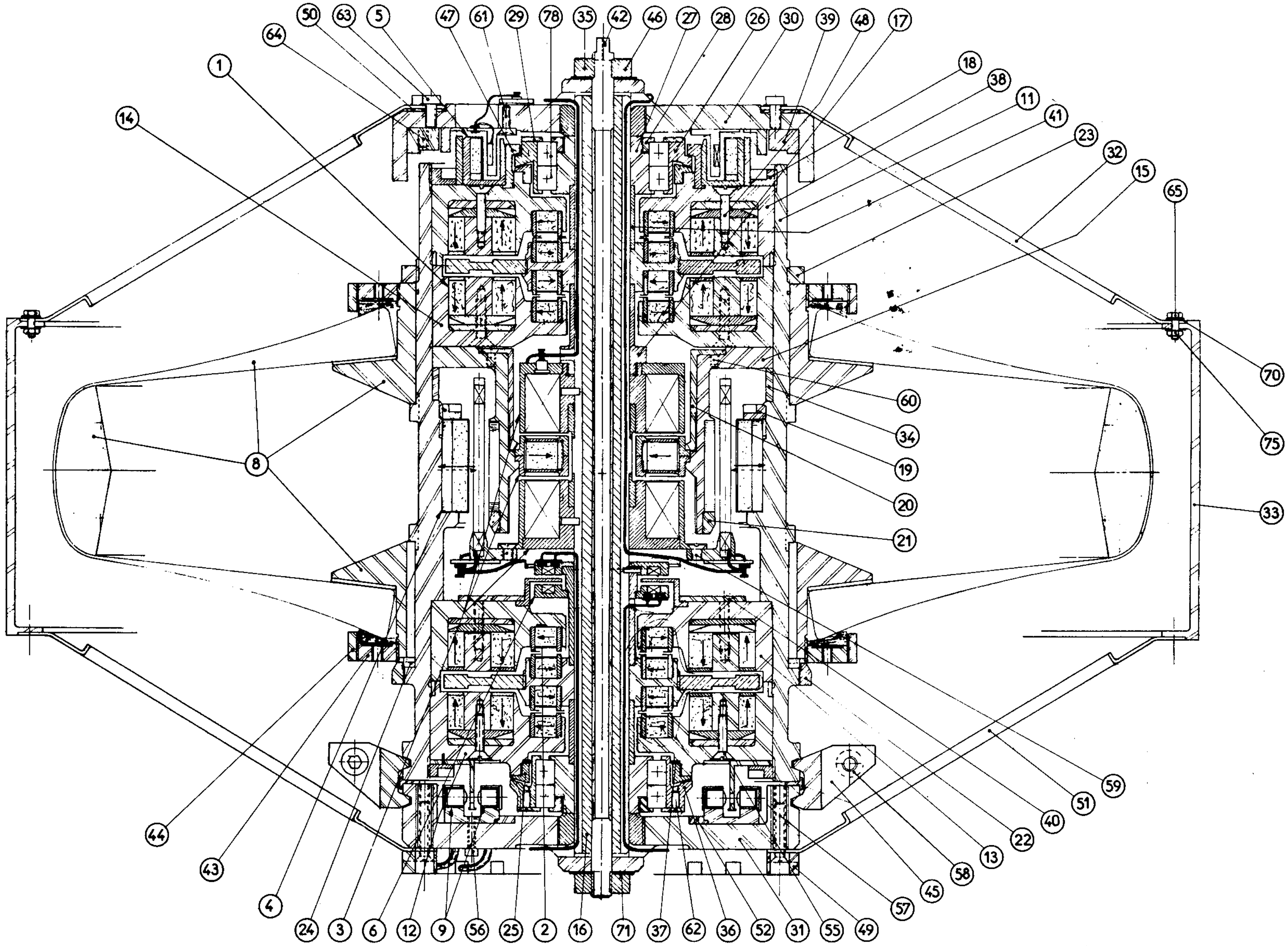

Figure 9. High Speed Momentum Wheel

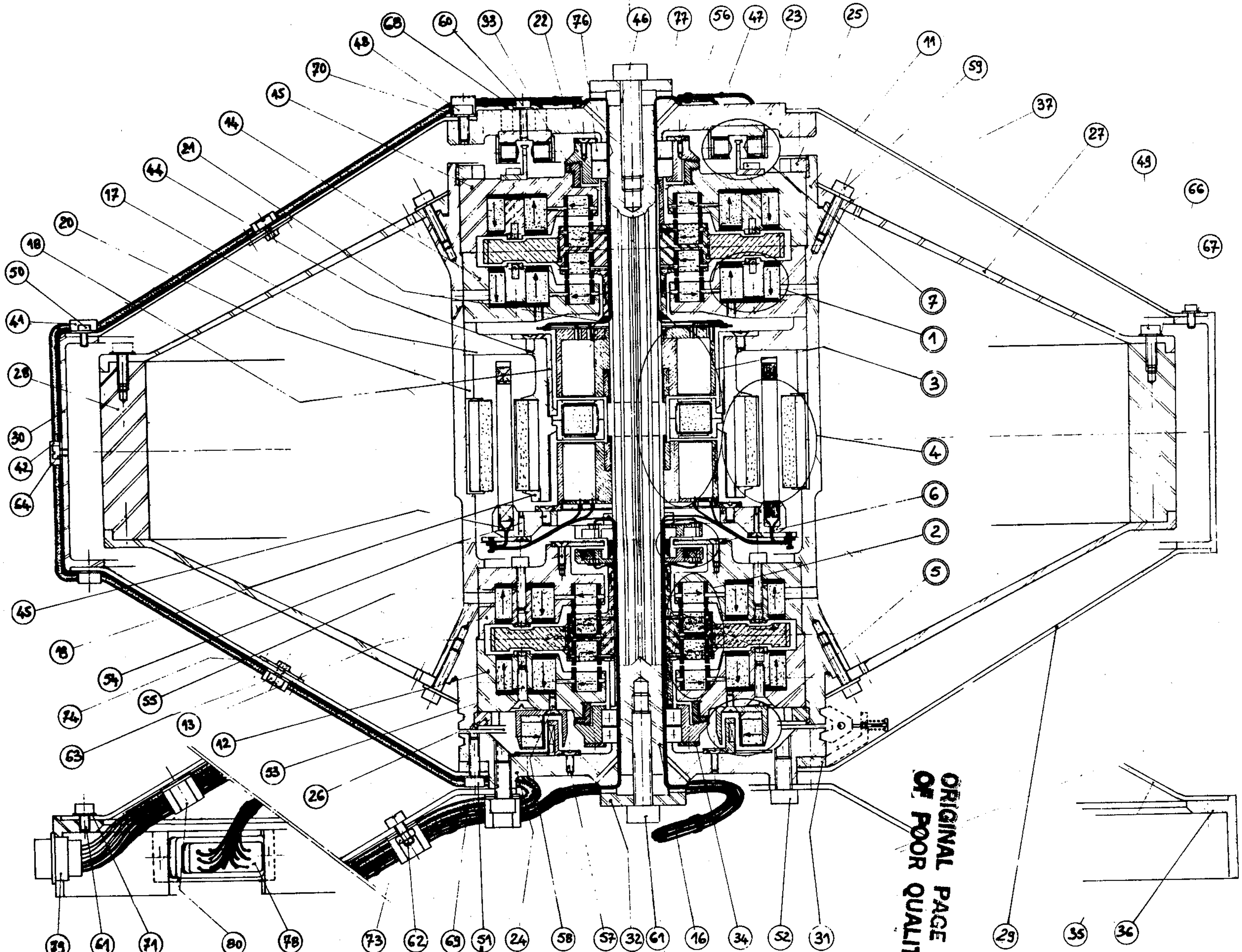

Figure 10. Medium Speed Momentum Wheel

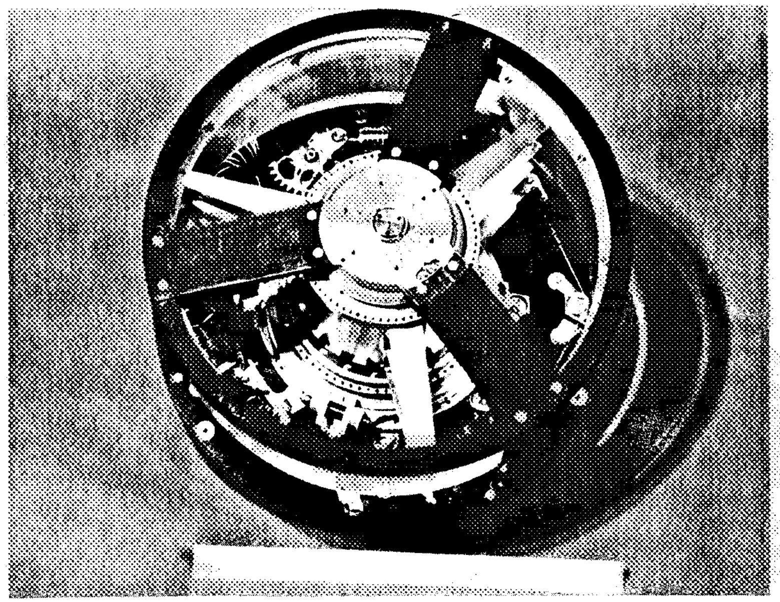
Figure 11. 50 Nms Momentum Wheel Qualification Model

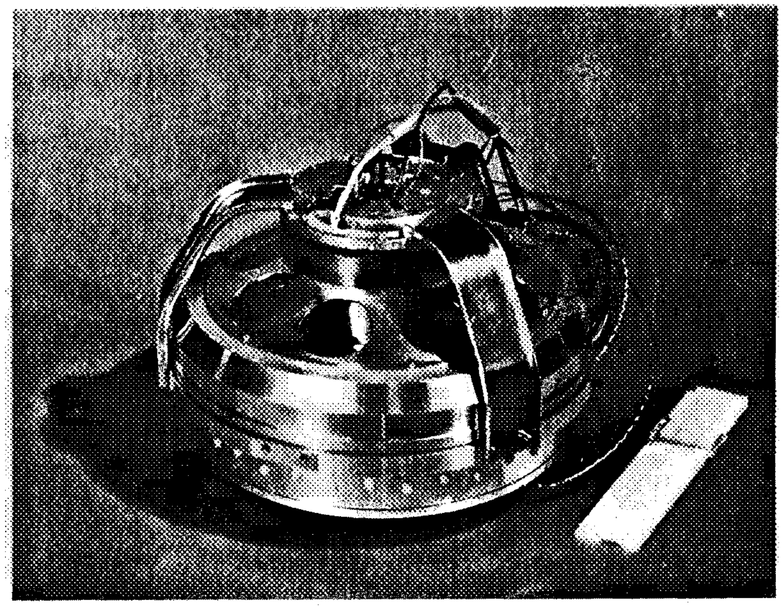
Figure 12. 2 Nms Reaction Wheel Engineering Model

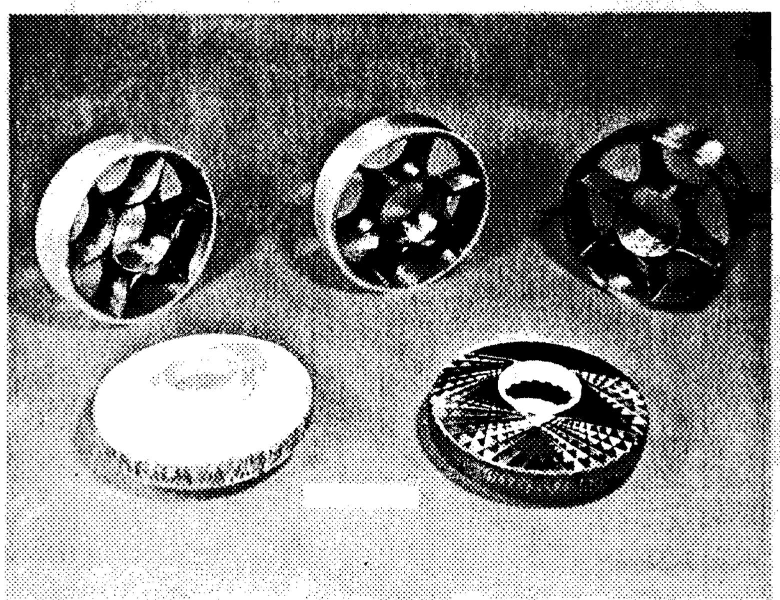
Figure 13. Composite Filament Rotors

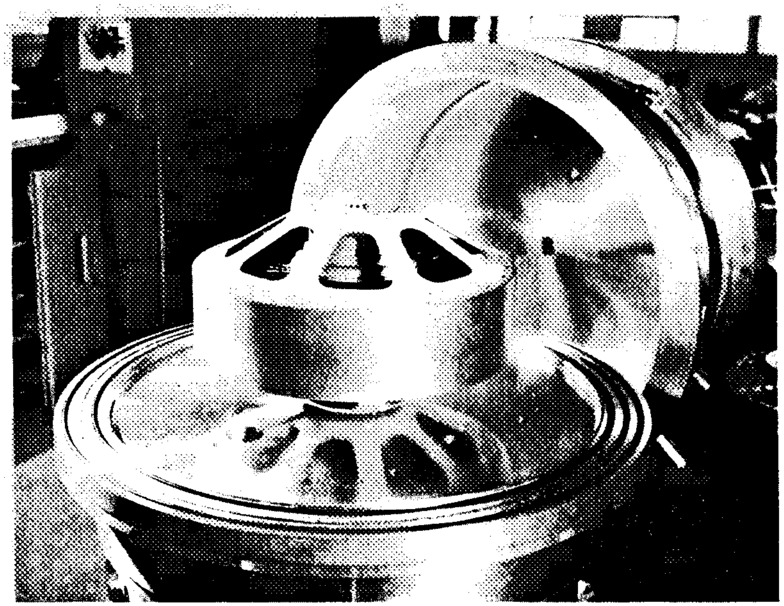
Figure 14. High Speed Momentum Wheel in Vacuum Chamber

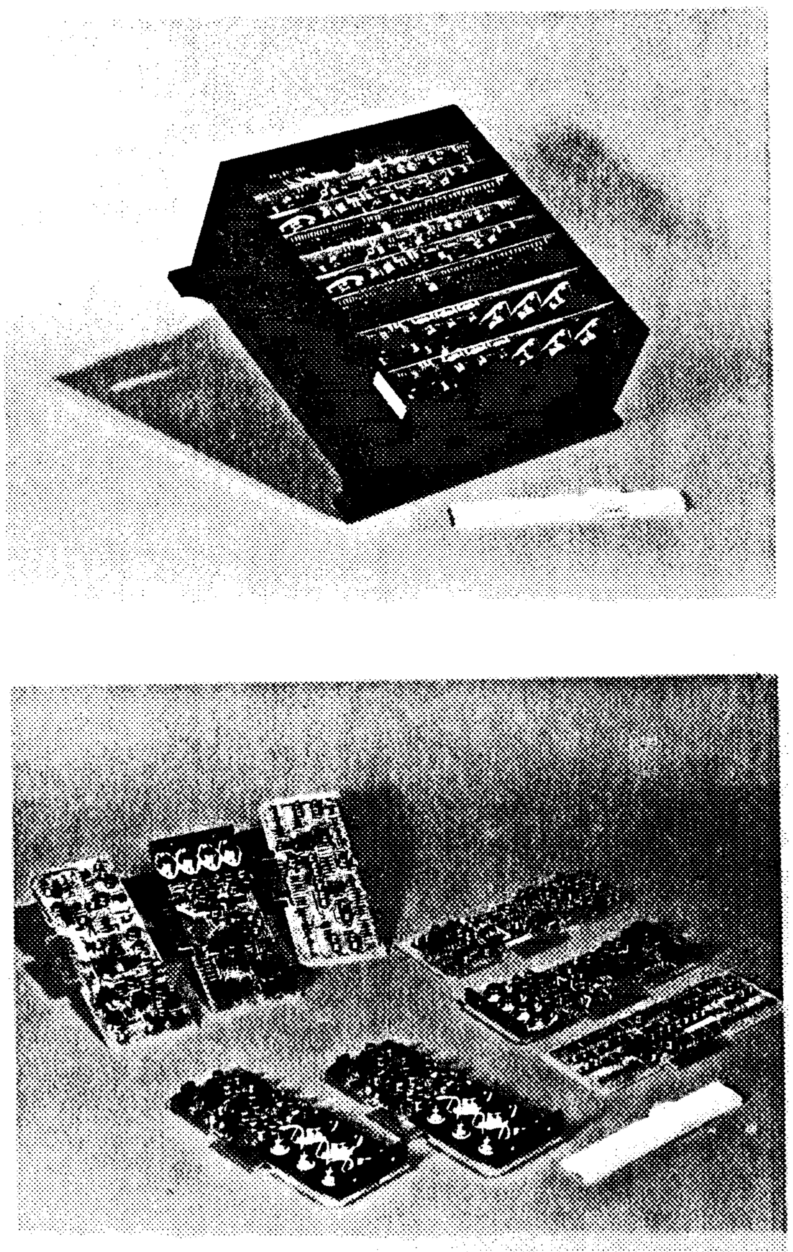

Figure 15. Control Electronics for Momentum and Reaction Wheels

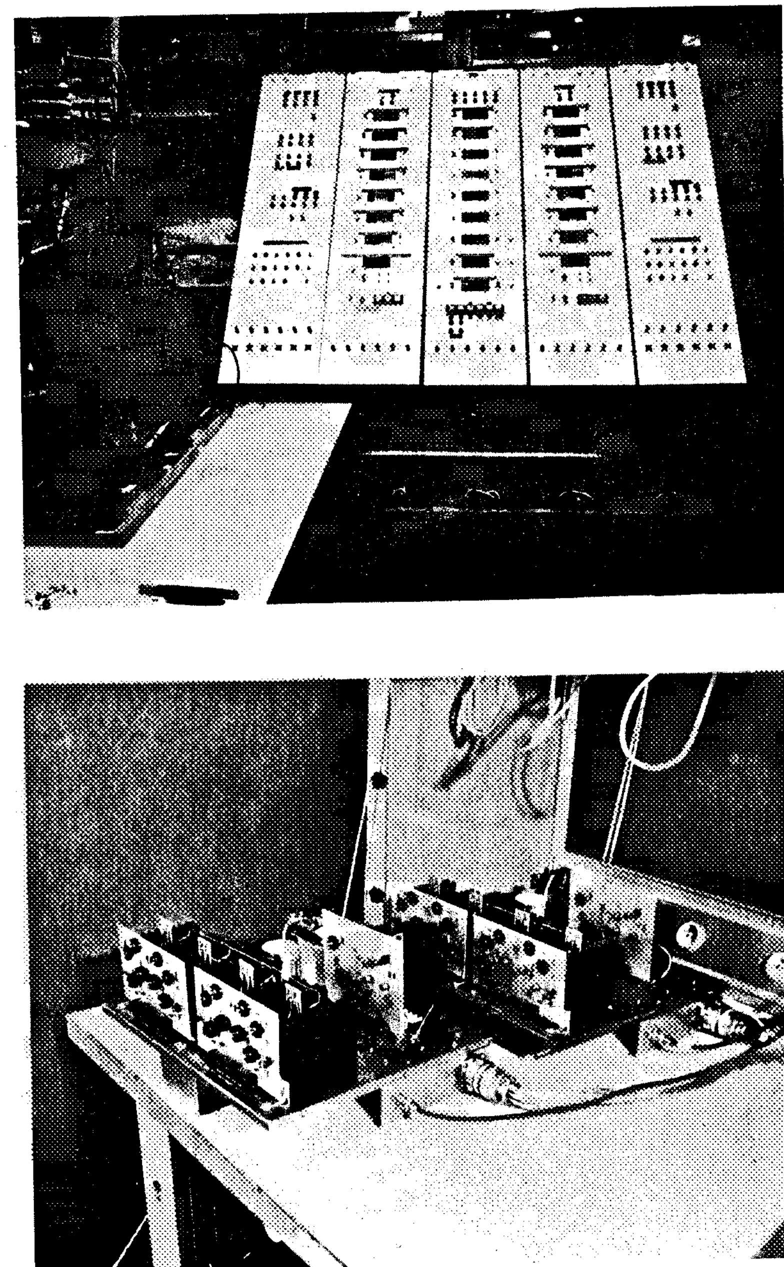

Figure 16. Electronics Breadboard Model for Kinetic Energy Storage