# EUROPEAN DEVELOPMENT EXPERIENCE ON ENERGY STORAGE WHEELS FOR SPACE

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The main thrust of effort has taken place in two companies, both of which have produced high speed fibre composite rotors suspended by contactless magnetic bearings :

- TELDIX, in Germany
- SNIAS, in France

Numerous other companies and establishments have carried out studies only and/or have engaged in related hardware technology developments of more limited scope.

## DEVELOPMENTS AT TELDIX

Work at TELDIX on energy wheels began in the early 1970's with the fabrication of hubless (annular) flywheels suspended on fully active (5-axis) magnetic bearings of the electrodynamic kind. This type of bearing is characterized by the absence of ferromagnetic material on its non-rotating part.

The drivers for the choice of annular geometry and active bearings were :

- OPTIMUM UTILISATION OF UNIDIRECTIONAL STRENGTH PROPERTIES OF FIBRE COMPOSITES
- ELIMINATION OF SPOKES AND SPOKE RELATED STRESS PLUS INTERFACE PROBLEMS
- HIGH ENERGY DENSITY POTENTIAL DUE TO INERTIAL CONTRIBUTION OF MOTOR/GENERATOR AND SUSPENSION MAGNETS IN THE RIM
- VERNIER GIMBALLING MOMENTUM ALIGNMENT CAPABILITY
- FAVOURABLE SHAPE AND VOLUME

Two small scale units for feasibility demonstration purposes were completed by 1977. The essential parameters of these models were :

| | | | |
|---|---|---|---|
| • | KINETIC ENERGY | 20 Wh | 16 Wh |
| • | SPEED | 14000 r.p.m. | 16000 r.p.m. |
| • | MASS (excl. electronics) | 8.5 kg | 5 kg |
| • | DIMENSIONS : diameter | 292 mm | 250 mm |
| | bore | 215 mm | 140 mm |
| | height | 110 mm | 80 mm |
| • | POWER CONSUMPTION (0g) | 40 W | 10 W |
| • | VERNIER GIMBALLING CAPABILITY | 0° | ± 1.25° (2 axes) |
| • | MAX. PRECESSION RATE | 2.5°/s | 2.5°/s |
| • | MOTOR/GENERATOR | D.C. BRUSHLESS | |
| • | MAGNETIC SUSPENSION | ELECTRODYNAMIC, 5-AXIS ACTIVE | |
| • | EMERGENCY SUPPORT | SLIDING SURFACES | |

The originally expected advantages of the hubless ring concept were generally confirmed. However, a number of fundamental drawbacks inherent to this concept were also shown up :

- MECHANICAL COMPLIANCE OF THE ROTOR AND DILATION WITH SPEED ADVERSELY AFFECT THE MAGNETIC SUSPENSION PERFORMANCE. LARGE O.D./I.D. RATIOS ARE NECESSARY.
- STEEP INCREASE OF SUSPENSION POWER WITH SPEED DUE TO INITIAL AND STRESS INDUCED OUT-OF-ROUNDNESS OF THE ROTOR.
- EMERGENCY SUPPORT AND LAUNCH-LOCK DIFFICULT TO IMPLEMENT AT LARGE RADIUS.
- HIGH BURST ENERGY OF METALLIC PARTS IN THE RIM.
- COMPLEX COMPOSITE/METALLIC RIM DIFFICULT TO MANUFACTURE.
- 5-AXIS BEARING EXHIBITS HIGH SUSPENSION POWER ON GROUND

The above mentioned drawbacks of the hubless ring concept led to its abandonment for energy storage purposes. Subsequent efforts at TELDIX were focussed on conventional (hubbed) wheels with 5-axis electromagnetic suspensions. In all, about six development models with small metallic rotors have been built. Characteristics of the MDR 100-1 model (highest speed version with solid beryllium rotor) are as follows :

| | |
|---|---|
| • KINETIC ENERGY | 23 Wh |
| • SPEED | 16000 r.p.m. |
| • MASS : wheel | 9.2 kg |
| electronics | 3.4 kg |
| • DIMENSIONS : diameter | 306 mm |
| height | 180 mm |
| • POWER CONSUMPTION (0g) | 13 W |
| • VERNIER GIMBALLING CAPABILITY | ± 0.6° (2 axes) |
| • MAX. PRECESSION RATE | 2.5°/s |
| • MOTOR/GENERATOR | D.C. BRUSHLESS |
| • MAGNETIC SUSPENSION | ELECTROMAGNETIC, 5-AXIS ACTIVE |
| • EMERGENCY SUPPORT | BALL BEARINGS |

DEVELOPMENTS AT SNIAS

SNIAS have also been engaged for more than a decade on development of energy storage wheels and systems. Initial work took place in the framework of a COMSAT technological research contract which resulted in a prototype wheel with the following characteristics :

| | |
|---|---|
| • KINETIC ENERGY | 35 Wh |
| • SPEED | 24000 r.p.m. |
| • MASS (excl. electronics) | 11 kg |
| • DIMENSIONS : diameter | 350 mm |
| height | 250 mm |
| • POWER CONSUMPTION | 28 W |
| • MOTOR/GENERATOR | D.C. BRUSHLESS |
| • MAGNETIC SUSPENSION | ELECTROMAGNETIC, 1-AXIS |
| • EMERGENCY SUPPORT | BALL BEARINGS |
| • ROTOR | GRAPHITE FIBRE |
| | CYCLOPROFILE CONSTRUCTION |

In 1978 SNIAS was awarded a follow-up contract the objective of which was to demonstrate a complete flywheel based energy storage system.

The development aims were :

- SYSTEM CAPACITY — 2 - 3 kWh (at 75% D.O.D.)
- FLYWHEEL CAPACITY — 500 Wh (4 per system)
- FLYWHEEL ENERGY DENSITY — 20 Wh/kg (usable)
- FLYWHEEL DIAMETER — 500 mm
- FLYWHEEL SPEED — 30 000 r.p.m.

These targets proved unachievable with the original CYCLOPROFILE rotor concept due to poor manufacturing reproducibility.

The next development step was a rotor with high strength graphite fibre rim and light glass fibre spokes. Matching of rim and spoke elongations was assured by small metallic masses incorporated in the spokes at their outermost extremities. This design was fully integrated with the magnetic bearing support but subsequent testing showed the balance integrity of the rotor itself to be inadequate at speeds exceeding 17000 r.p.m.

Recent development effort has been focussed on a modified form of rotor consisting of a high modulus graphite fibre rim supported by a thin metallic alloy disc. In tests on a high speed burst test facility this rotor has consistently achieved speeds of 30 000 r.p.m. (peripheral speed 785 m/s) without balance shift or stress rupture problems.

At time of writing, this latest form of rotor is undergoing further evaluation and detailed design finalisation before being integrated with the existing magnetic bearing support. It is perhaps a little early to be too optimistic but current performance expectations for a fully assembled wheel if no new major problems arise are :

- USABLE ENERGY CAPACITY — 500 Wh
- SPEED — 30 000 r.p.m.
- DIMENSIONS : diameter — 500 mm
  height — 200 mm
- MASS — 25 kg
- USABLE ENERGY DENSITY — 20 Wh/kg
- POWER CONSUMPTION — 15 W

Present indications are that the above indicated performances may even be exceeded. However, allowing a safety margin to cover materials degradation under cyclic stress, and eventual inclusion of containment mass, the indicated energy density figure should be regarded as a realistically achievable maximum for the immediate future.

## COMPARATIVE STUDY OF WHEELS VS. BATTERIES

In 1977, ESA placed a study contract with the French company MATRA to assess the overall mass, volume and cost implications of flywheels vs. batteries in typical mission scenarios.

The study was based on three hypothetical mission models as outlined below :

| MISSION | EOS | LCS | TVBS |
|---|---|---|---|
| Orbit | Sunsynchronous<br>600 - 1000 km | Geostationary | Geostationary |
| Eclipse Duration | 0.58 hours | 1.2 hours max.<br>2 x 42 days per year | 1.2 hours max.<br>2 x 42 days per year |
| On-Board Power Demand | 500 W<br>average | 1500 W<br>continuous | 5000 W<br>continuous |
| Eclipse Energy Requirements | 300 Wh | 1800 Wh | 6000 Wh<br>(24 hour TV service capability) |
| Spacecraft Mass | 600 - 1000 kg | 830 kg<br>(BOL) | 950 kg<br>(BOL) |
| Attitude Control Requirements (3σ) | Pitch 0.05°<br>Roll 0.05°<br>Yaw 0.1° | Pitch 0.075°<br>Roll 0.075°<br>Yaw 0.35° | Pitch 0.1°<br>Roll 0.1°<br>Yaw 0.5° |
| Lifetime | 5 years | 7 years | 7 years |

EOS Earth Observation Satellite

LCS Large Communication Satellite

TVBS Television Broadcast Satellite

The flywheel inputs to the study were based on projected performance parameters supplied by SNIAS and TELDIX for passive and active magnetic bearing wheels respectively.

Comparative data for Ni-Cd, $Ni-H_2$, and $Ag-H_2$ electrochemical batteries was obtained from a leading battery manufacturer.

The essential quantitative conclusions of this study are summarised in the following table :

| MISSION | TOTAL MASS, VOLUME, COST OF ACS + PSS SUBSYSTEMS WITH E.S.W.s | | | | TOTAL MASS, VOLUME, COST OF ACS + PSS SUBSYSTEMS WITH BATTERIES | | | | OVERALL MASS, VOLUME, COST IMPLICATIONS OF E.S.W.'s W.R.T. BATTERIES | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MASS | VOLUME | COST* (MAU) | | MASS | VOLUME | COST* (MAU) | | MASS SAVING | | VOLUME SAVING | COST PENALTY OF E.S.W.'s W.R.T. | |
| | (kg) | (LTR) | Dev't | Flight Eqpts | (kg) | (LTR) | Dev't | Flight Eqpts | (kg) | % of S/C MASS at B.O.L. | (l) | Dev't | Flight Eqpts |
| EOS | 115 | 90 | 3.5 | 2.0 | 131 | 145 | 2.6 | 1.6 | 16 | 2.0% | 55 | 0.9 | 0.4 |
| LCS | 206 | 124 | 3.5 | 2.2 | 211 | 196 | 2.3 | 1.2 | 5 | 0.6% | 72 | 1.2 | 1.0 |
| TVBS | 471 | 589 | 6.2 | 5.8 | 549 | 498 | 2.6 | 2.2 | 78 | 8.2% | -91 | 3.6 | 3.6 |

* Note : Costs indicated are approximate only, based on June 1977 labour rates. Only costs of equipment not common to ESW's and Battery systems are considered.

The main finding is that the mass saving achieved by the use of wheels in place of $Ni-H_2$ or $Ag-H_2$ batteries is rather small as a percentage of overall spacecraft mass. The rather larger mass saving established for the TVBS mission (8.2%) is not realistic as it would be impossible to fit a power/attitude control subsystem weighing 471 kg into a spacecraft of only 950 kg at BOL.

Because of the lack of reliable data, the study was not able to assess the relative merits of wheels vs. batteries with respect to charge/discharge cycle life. Today, the substantially greater cyclic life potential of wheels (of particular importance in low orbit spacecraft), is seen as one of the main drivers for continued research and development effort.

## CONCLUSION

European industry has acquired a considerable expertise in the study and fabrication of energy storage wheels and magnetic suspension systems for space. Sufficient energy density performance for space viability is on the threshold of being achieved on fully representative hardware. Stress cycle testing to demonstrate life capability as well as the development of burst containment structures remains to be done and is the next logical step.

## REFERENCE

1. Nguyen, H. N.; and Mariau, F.: Study of System Implications of High Speed Flywheels as Energy Storage Devices on Satellites. ESA-CR(P)-1168, vols. I and II, 1978.