THE NRL MULTI-MEGAJOULE INERTIAL-INDUCTIVE ENERGY STORAGE SYSTEM

by

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ABSTRACT

In the NRL multi-megajoule pulse power system, energy is transferred from inertial storage (flywheels) to inductive storage by a self-excited homopolar generator. Reliable operation of the inertial storage at 5 MJ per flywheel is obtained from recent improvements in flywheel mounting, bearing lubrication, cooling and hydraulic power systems. This approach to energy conversion is only possible by use of copper-graphite fiber brushes which can follow rapid variations in wheel radius. Experimental efforts are being devoted to reducing the presently high frictional wear of these brushes.

Introduction

The NRL inertial-inductive energy storage system was developed as a pulsed power source for possible use in large scale plasma experiments requiring energies of several megajoules. It was designed to have a (mechanical) energy storage of 10 MJ and coil current of 90 kA. The current selected was based on the rating of the circuit interrupter which uses the mechanism of a Westinghouse SFV-series circuit breaker. It has ratings for 60 Hz AC of 63 kA RMS and voltage recovery to 200 kV after 100 μs following current zero.

The inductance of the magnetic storage coil is determined by the energy to be stored and the current to be used. For efficiency the current must be built up in the coil in a time less than the L/R time constant of the coil. The shorter the charging time, the greater the efficiency. Thus the power level required of the charging power supply becomes proportional to the resistance permitted for the coil. To avoid the complexity of a superconducting coil the NRL design philosophy is to use a homopolar generator capable of several MW which could charge a simple copper coil in seconds.

This paper will give only a brief description of the system since it is described in detail elsewhere[1,2] and discuss several improvements which have been made during the past year to increase the reliability of the inertial storage and homopolar generator.

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System Description

The 1700-kg, copper coil is charged by a homopolar generator. Such a generator has an inherently low internal impedance and can be used to provide current for the storage coil without seriously decreasing its L/R time. Since the homopolar current is necessarily equal to the coil current, steps were taken to provide an adequately high output voltage. This was done by designing the rotors to operate at high speed (300 Hz) and using an air-cored coil capable of providing a high exciting field (40 kG).

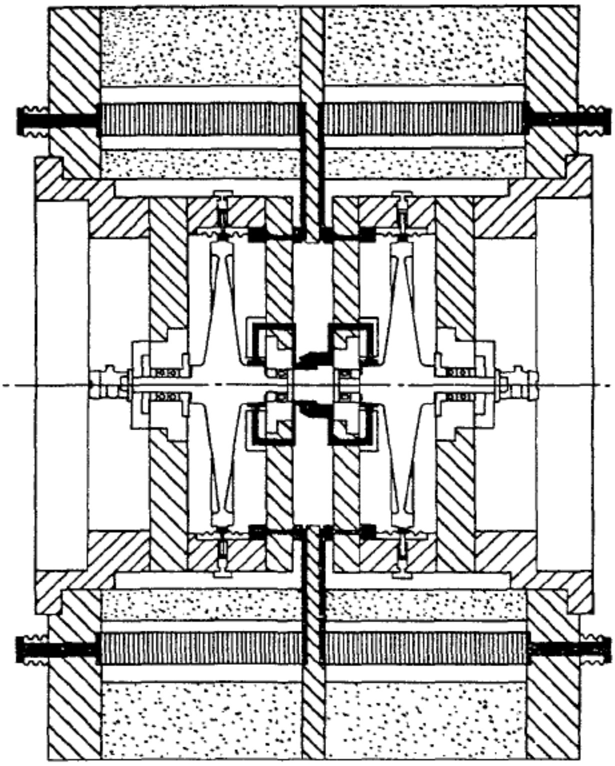

Fig. 1. Layout of the NRL 10 MJ module.

The homopolar generator consists of a pair of counter-rotating, series-connected flywheels situated in the center of the energy storage coil as shown in the cross-sectional view of Fig. 1. The storage coil itself provides the magnetic field for excitation. When the brushes are pushed in, the series circuit (wheels, coil and circuit interrupter) is completed. If some initial current has been provided by an auxiliary "starter" circuit, the system will then self-excite and transfer the energy from the flywheels to the coil. Earlier papers have described the theoretical analysis of the circuit[1] and measurements of output pulses.[2]

The coil is wound from 1 cm x 7.6 cm copper bar as a double-lead (two bars in parallel) single-layer solenoid. It is split at its center for connection of the homopolar generator, which thus remains near ground potential during discharge. The circuit interrupter (not shown on this figure) is connected across the high voltage output ends. The room temperature coil resistance is 2 mΩ and its time constant is 0.7 s. This time constant can be increased as much as a factor of 6 by cooling the coil with liquid nitrogen. The coil is held in compression with respect to the end plate by Belleville washer springs to accommodate the resulting thermal contraction. The thermal insulation is indicated by the dotted region in Fig. 1. The coil has been cooled for the purpose of checking its mechanical performance and to make resistance measurements. All discharges have been made without cooling, however. The room temperature efficiency ranges from 0% at 100 Hz (the critical speed) to 40% at 300 Hz, so output pulses of less than 4 MJ can be obtained without cooling.

The single layer solenoid design with mylar sheet insulation between turns has a uniform voltage gradient and could be capable of working with high voltages up to the limit set by circuit breakers and fuses. At present the voltage capability is limited by the output terminals at the right and left ends of the coil which are in open air and relatively close to other ground-potential components.

Modifications to Inertial Storage

The initial design of the flywheel and housing used bearings of 30 mm bore located close to the wheel for stability and rotating vacuum seals outboard of the bearings. Conventional wisdom dictated selection of the small diameter to facilitate operation of these two components at high rotational speeds. This design required grease-packed bearings running in vacuum. Although the outer bearing raceway was water cooled, the inner raceway relied on cooling by thermal conduction through the balls or into the shaft and wheel. Experience showed that the wheels could not be operated at 300 Hz without bearing failure. Although local temperatures of the rotating shaft were not measured, it has been inferred that inner raceway cooling may have been inadequate. In addition thermal expansion associated with increasing shaft temperature would increase the degree of interference fit between bearing and shaft and result in an unpredictable speed dependent loading of the balls.

In an effort to improve its reliability, extensive modifications have been made to the mechanical storage system over the past year. The position of bearings and rotary seals have been interchanged to permit the bearings to be forced-air cooled and lubricated with oil mist. The shaft diameter has been increased to 45 mm for increased rigidity in machining. The new flywheel mounting was fabricated as shown in Fig. 2.

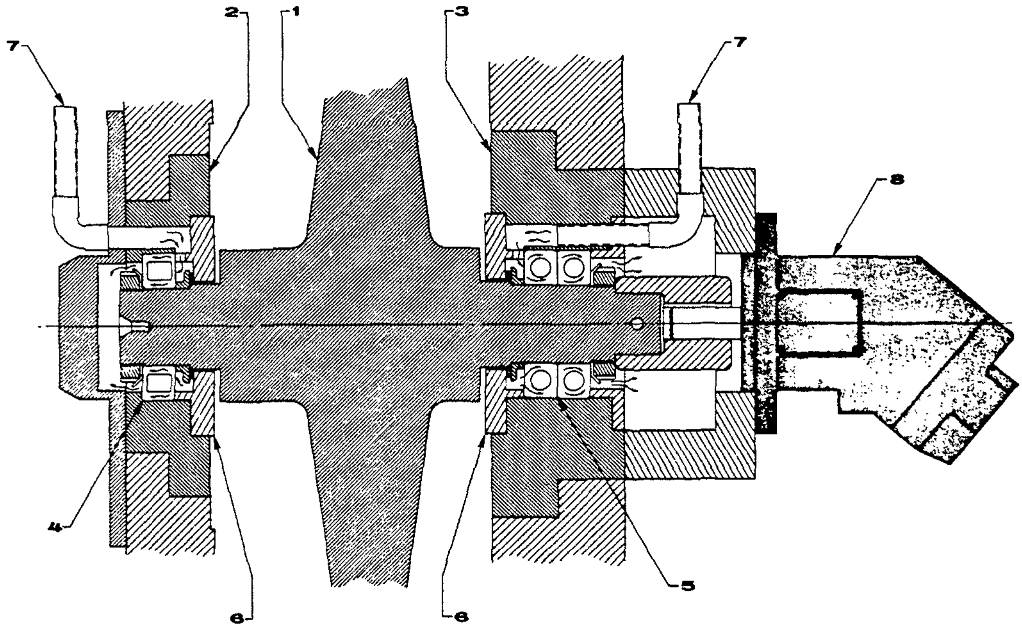

Fig. 2. Inertial storage flywheel and motor assembly.

The flywheel (1) is shown mounted between bearings 23 cm apart. A pair of 45 mm bore, 25° angular-contact ball bearings (5) secure the wheel and withstand the thrust loads on discharge. The roller bearing (4) permits axial motion of the shaft relative to the housing resulting from the atmospheric pressure difference and from thermal expansion of the wheel during operation. The rotary vacuum seals are shown at (6). High velocity cooling air is forced through the bearings from inlets (7).

Problems were also encountered with the reliability of the small hydraulic motors used to power the wheels in the previous system. These have been replaced with Volvo F11B-5 motors having a 5 cm^3 displacement and increased torque. One of the new hydraulic motors is shown at (8) in Fig. 2.

Inertial Storage System Performance

Each of the new wheel assemblies has been operated to 300 Hz. The larger rotary vacuum seals perform satisfactorily in spite of their increased rubbing velocity. Adjustment of the preload on the ball bearing pair is important. Too little preload may not produce an adequately stiff bearing. On the other hand too much preload increases the frictional heating of the bearing. In practice the torque required to rotate the bearing at assembly is used as an indicator. This has been set to values of about 0.1 N-m and satisfactory preload verified by monitoring bearing temperatures on subsequent high-speed runs. On runs to 300 Hz bearing peak temperatures have been in the range of 114° F to 148° F.

A non-contacting displacement sensor is located in the flywheel housing about one mm away from the wheel rim. This device gives an output voltage signal proportional to the distance between sensor and wheel and is used to determine wheel expansion and vibration. The measured increase in wheel radius for a typical run is shown plotted as a function of the square of the rotational speed in Fig. 3. In such a plot purely elastic expansion due to centrifugal force will be a straight line. As the wheel accelerates it expands elastically due to centrifugal forces and thermally due to heat input from residual air friction, bearings and motor. The elastic component of wheel growth is seen to be 0.031 in. at 300 Hz. The residual thermal growth of 0.005 in. after the run corresponds to an average wheel temperature increase of 50° F.

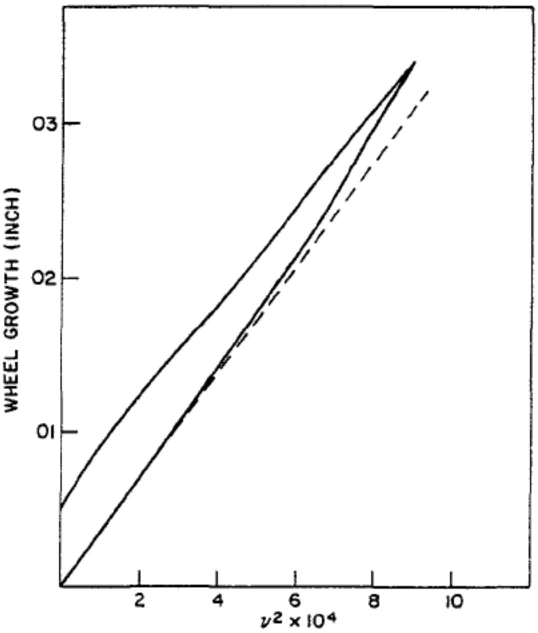

Fig. 3. Speed dependent change in wheel radius.

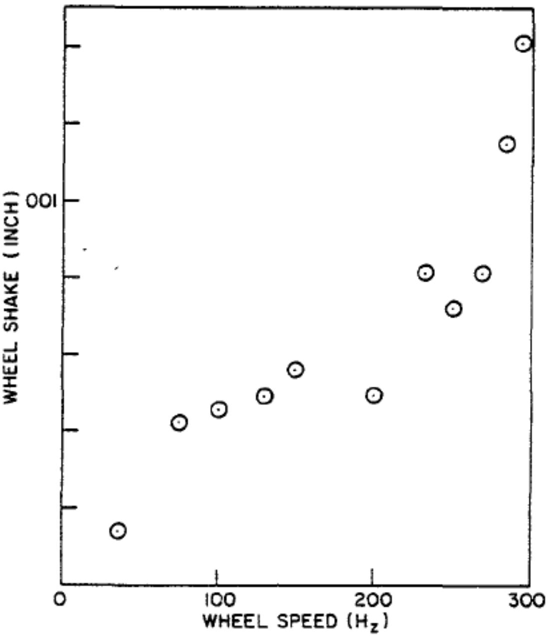

Fig. 4. Speed dependent vibration (shake) of wheel radius.

The AC component of the proximity sensor output is proportional to the indicator run out of the wheel rim. Any departure from its low speed value indicates a speed dependent departure of the wheel's geometric center from its center of rotation. Fig. 4, labeled wheel "shake" shows one measurement of this departure as a function of speed. Although there is a possibility of systematic errors in the measurements due to case vibration, they are not believed significant because different wheels give different results. Wheel unbalance is a departure of the wheel's center of mass from its center of rotation. Dynamic measurements of bearing deflection and radial loading must be made to determine unbalance. If such measurements are made in the future it may be possible to resolve the question of whether the observed wheel shake is due to unbalance or due to inhomogeneity of the wheel material.

Brush Operation

The wheel growth and shake measurements presented here are of importance because the wheel rim is the slip-ring surface used to remove current from the homopolar generator. In addition to dynamic variations there are small permanent irregularities in this surface. It has been speculated that these are the result of variations in material hardness which prevent grinding of a perfectly smooth surface. It has been found that copper-plated graphite fiber brushes[3] are the only ones capable of following these irregularities. These fiber brushes are considerably stiffer than analysis of individual fibers would predict. When they are set to contact a stopped wheel there is considerable additional force of compression against a high-speed wheel as a result of the wheel growth (Fig. 3). This leads to heating and wear which may become excessive as wheel speed is increased. At a speed of 200 Hz the observed loss of brush material is about 20 mg per brush per shot. A recent modification now permits air pressure to be applied to the brush actuators in stages. This makes the brushes follow the receding surface of the decelerating wheel with much less force on the wheel at high speeds.

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