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**SUMMARY OF SENSOR EVALUATION FOR THE
FUSION ELECTROMAGNETIC INDUCTION EXPERIMENT
(FELIX)**

by

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TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION.....	1
2. STRAIN MEASURING DEVICES.....	1
3. TEMPERATURE MEASUREMENT DEVICES.....	18
4. MAGNETIC FIELD MEASUREMENTS.....	24
5. EDDY CURRENT DENSITY MEASUREMENTS.....	25
6. INSTRUMENTATION - COMPUTER INTERFACE.....	25

LIST OF FIGURES

	<u>Page</u>
1. RESISTIVE STRAIN GAUGE CONFIGURATIONS.....	5
2. SEMICONDUCTOR STRAIN GAUGE.....	6
3. FIBER-OPTIC STRAIN GAUGE.....	11
4. PHOTOELASTIC STRAIN DIRECTION SENSING PRINCIPLE.....	13
5. CROSS SECTION OF FELIX SHOWING FLAT PLATE EXPERIMENT AND VIEWING METHOD FOR FULL FIELD SENSORS.....	15

1. INTRODUCTION

As part of the First Wall/Blanket/Shield Engineering Test Program, a test bed called FELIX (Fusion Electromagnetic Induction experiment) is now under construction at ANL.¹ Its purpose will be to test, evaluate, and develop computer codes for the prediction of electromagnetically induced phenomenon in a magnetic environment modeling that of a fusion reaction. Crucial to this process is the sensing and recording of the various induced effects.

Sensor evaluation for FELIX has reached the point where most sensor types have been evaluated and preliminary decisions are being made as to type and quantity for the initial FELIX experiments. These early experiments, the first, flat plate experiment in particular, will be aimed at testing the sensors as well as the pertinent theories involved. The reason for these evaluations, decisions, and proof tests is the harsh electrical and magnetic environment that FELIX presents.

The following sections do not represent a complete list of all sensors, devices and methods considered but treat only those given serious consideration. Total sensor system cost was a consideration during the evaluation process.

The evaluation process is by no means complete and will continue as new sensor methods are found and additional information is gained for those already considered. During the coming months vendor demonstrations and user evaluations will be used to further refine our decisions.

2. STRAIN MEASURING DEVICES

The measurement of mechanical strain in the FELIX environment appears to represent the most severe instrumentation problem area of the project.² Since strain measuring devices are to be used in three separate but equally important aspects of FELIX, they have been given most of our efforts thus

far. The first use is the instrumentation of the test objects themselves. The interaction of the induced eddy currents with local magnetic fields will produce material stresses which are to be part of the experimental data. The second area of use is as a part of the test object support post which will be used to measure total object forces and torques. This device is sometimes called a "sting balance" and the minute motions caused by object forces and torques are usually monitored by strain gauges. The third area of use is the strain monitoring of the FELIX structural members to insure that mechanical design goals and safety criteria are being met.

Strain measurements represent such a difficult task because of the magnitude of the physical change being measured. The elastic limit of aluminum (the initial test material) is about 1000 micro-strain or a dimensional change of 0.0002 inch for a typical 0.2 inch gauge length. Several different types of phenomena have been used to translate this motion into a usable signal or effect and several of these were studied and are described below.

2.1 Foil Pattern Resistive Strain Gauge

This device consists of a metal foil etched to form a precise zig-zag pattern so that numerous passes are made over the gauge area (see Fig. 1-A). This pattern is bonded to the test surface and allowed to deform with it. Strain magnitude is derived directly from resistance change and materials used usually have gauge factors of 2.0 so that a 2 ohm change will occur in a 1000 ohm gauge monitoring a 1000 micro-strain change.

Normally the gauge pattern area and the signal wire connections (usually recommended to be loops) would constitute a highly susceptible pick-up loop and in fact typical gauge dimensions combined with the 50 tesla/second field change expected in FELIX could produce an apparent strain of 500 micro-

strain. A gauge pattern (MM Type SA-13-125AC-700-B422A) designed to eliminate its effective area has been designed by Micro Measurements, Inc. for Dr. Graham Brown of the Princeton Plasma Physics Laboratory (PPPL) for use on the structural members of PDX and TFTR.³ This gauge, shown in Fig. 1-B, consists of two identical foil patterns sandwiched together with the signal connections made at one end so that no area is presented normal to the test surface.⁴ Brown has also designed the indicated loop-over signal wire connections so as to eliminate that loop area.

To help eliminate the unwanted signal pickup by the signal wires, special small gauge twisted pair (or triplet) wire can be used. A special dual twisted pair wire called Inter-8 Weave made by the Magnetic Shield Division of Perfection Mica Company can also be used to reduce the susceptibility of the wiring by as much as 12 db as compared to normal twisted pair wire.⁵ The location, routing, and dressing of these wires is critical. The use of magnetic shielding with these wires would seem to be impractical since the amount of material required and its location would constitute a field disturbance as well as a structural support problem due to the magnetic interaction forces involved.

Since the signal wave shape of the measured information as well as the error producing fields are both known, it should be possible to use a higher frequency ac excitation instead of the normal dc signal processing. The Model CD90 Carrier-Demodulator unit made by Validine Engineering is designed for use with strain gauges and can be operated with a carrier frequency up to 20 KHz.⁶⁻⁷

The above-mentioned special gauge pattern is currently being made from a Constantan alloy. According to a report by P. L. Walstrom of Oak Ridge National Laboratory, Constantan alloy strain gauges show a negative

magnetoresistance at room temperature.⁸ Although the error is small at fields of 1 T (about 5 micro-strain), the Karma alloy did not show this dependence.

As is the case with all discrete strain measuring devices, the strain magnitude is sensed only along the mounting axis. If the direction of the strain field is unknown, the magnitude and direction at any given point can be determined by a three-gauge "rosette" pattern (see Fig. 1-C). The special gauge pattern described above can also be obtained in a rosette configuration (MM Type SA-13-125YF-700-B422A).⁹

2.2 Semiconductor Resistive Strain Gauge

2.2.1 Operating Principle

This device employs a resistive element made of a single semiconductor crystal which is bonded to the test surface (see Fig. 2-A). The principal benefit of these devices are the significantly higher gauge factors available - typically 50 to 200.¹⁰ Signal processing is the same as for the foil gauges above and it should be possible to employ ac excitation methods as well. Figure 2-A shows one of the possible gauge configurations. It may also be possible to use the same loop-over wiring connection described above for the foil gauge (see Fig. 2-B).

2.2.2 Disadvantages

There are several disadvantages associated with semiconductor strain gauges, however. They have a relatively large temperature dependence (as high as 10% resistance change for 100° F). Although this may not present a problem for flat plate test pieces which are expected to remain within a few degrees of room temperature, later configurations may cause trouble. They are very delicate¹¹ and relatively expensive. They are not produced in rosette configurations

FIG. 1-A
NORMAL STRAIN
GAUGE

FIG. 1-B
"ZERO
AREA"
STRAIN
GAUGE

TOP FOIL

BOTTOM FOIL

FIG. 1-C
A THREE GAUGE ROSETTE

FIG. 1 RESISTIVE STRAIN GAUGE CONFIGURATIONS.

FIG. 2-A
A SEMICONDUCTOR STRAIN GAUGE

FIG. 2-B
A POSSIBLE SOLUTION TO THE WIRE LOOP PROBLEM

FIG.2 SEMICONDUCTOR STRAIN GAUGE.

although the process can be simulated with three separate gauges mounted in the proper orientation. They are difficult to mount on surfaces with small radii due to their rigid and fragile nature. The magnetoresistance effect on the semiconductors used in these devices will have to be determined. Significant Hall-type effect may eliminate them from consideration.

2.3 Capacitive Strain Gauge

2.3.1 Operating Principle

A strain gauge based on a change in capacitance was developed by the Boeing Aerospace Company for use in high temperature applications (above 600° F) where foil gauges cannot be used.¹² It is marketed under license by Hitec Corporation.¹³ While there are no high temperature FELIX experiments, the device is inherently an ac excited system and may be usable in high magnetic fields. It has a co-axial structure such that the central part moves relative to the outer shell as the test surface is strained. A capacitive change of 0.018 pF results from 1000 micro-strain movement and this is converted to a usable signal in a capacitive bridge circuit module. Chord length strain compensation is inherent in the structure.

2.3.2 Disadvantages

The difficulties with this device are as follows: The standard carrier frequency employed is only 3 KHz, not high enough to effectively eliminate the noise effects expected. The structure is very delicate in appearance (and by eyewitness accounts of ANL Components Technology Division personnel)¹⁴ and may not be able to withstand the acceleration caused by hundreds of pounds of force applied to the plate in tens of milliseconds. The price per unit is

high and a refurbishment charge is necessary if the gauge is to be removed and reused. Strain field mapping would be particularly difficult since three relatively large (1.0 inch gauge length) units could not be placed in close proximity to simulate a rosette pattern.

2.4 Inductive Displacement Measuring Device

2.4.1 Operating Principle

A line of displacement measuring devices based on the change in reluctance of an excited coil due to the position change in a target is marketed by Kaman Sciences Corporation.¹⁵ They are normally used for production testing of precision machined parts but one model (KD-2810) has a full scale output for a 0.001 inch change in target position. While not produced as a strain gauge, it should be possible to mount the sensor and target on the test surface so as to give the desired results. The carrier frequency for this device is 1.0 MHz which is quite high enough for signal discrimination.

2.4.2 Disadvantages

Disadvantages include:. The mounting fixture and attachment device or method would have to be made "in-house" and while not a complex task, consideration would have to be given to the acceleration problems cited above. In addition, a compensation technique would be needed to produce chord strain at the test surface. Since the electronics unit is calibrated with a given sensor head, it could not be shared between sensors as is the case with the conventional strain gauges. Of course strain field mapping would involve triple sensor clusters (as in the rosette array) but they could not operate simultaneously in very close proximity.

2.5 Fiber-Optic Strain Gauge

The use of non-electrical phenomena to sense strain (or for that matter any other induced effort) would be a real advantage to the FELIX instrumentation program and in fact it has been the intention to emphasize these techniques in these studies. Fiber-optic based methods would seem to fill this requirement; they have high information carrying capabilities, and are virtually immune to both magnetic disturbances and electrical interference. The translation of the induced effect into optical information or modification is also straightforward. In the case of strain sensing, for example, several methods have been proposed and studied.¹⁶⁻¹⁷

The difficulty with the work done or proposed so far is that the methods are either very expensive to implement (requiring various optical devices and an interferometer to sense a change in fiber length for example) or they are in a laboratory experimental stage making them prohibitively expensive at this point.¹⁸⁻¹⁹ The Navy is studying several methods aimed at converting acoustic motion into a fiber-optic signal (for hydrophone development).²⁰⁻²¹ Such techniques would be adaptable to strain detection since the magnitude and frequency of motion are about equal. Since a separate research and development effort to provide immune sensors is not within the scope of FELIX, consideration has been confined to devices in or near production.

2.5.1 Operating Principle

A development effort which may provide a viable fiber-optic strain device at a reasonable cost (or at least "early post-development" cost) is being conducted by the Grumman Aerospace Corporation. The object is a fiber-optic strain sensor for use within the TFTR vessel.²² According to conversations with Nick Szuchy of Grumman, the results so far are satisfactory but details are not

available because of patent activities. A pair of glass fibers 0.3 mm in diameter axially aligned but offset about one radius (see Fig. 3) is used. One fiber brings in a constant light level and the other returns a light level proportional to the axial alignment offset which is in turn proportional to strain in the test surface since the fibers are supported from opposite ends of a gauge area. The gauge length is 1.0 inch. The signal processing electronics system which is relatively simple and does not compensate for the nonlinearity due to the use of round glass fibers (this must be done by the data processing system) is also being designed.

Grunman is planning to supply five or six systems for installation in TFTR and one or two units for use in FELIX could probably be obtained for the same price (presently unknown). It would be entirely appropriate for us to do so even if the cost were quite high since one of the purposes of FELIX is to test fusion instrumentation. Since this is the only device which is immune to magnetic and electrical interference, it would be useful to use it as a check against other methods as well as a fall-back method in case all others prove to be inadequate.

2.5.2 Difficulties

Since the fiber-holding tabs are bonded to the test surface only at the ends, they will tend to lift off of the surface with the properly applied stress. In Fig. 3, if a torque is applied with its axis parallel to the strain gauge axis, the tabs will move and with them the optical fibers, producing an apparent strain.²³ The use of this device may be limited to single axis fields where the strain directions are known in advance.

FIG.3 FIBER-OPTIC STRAIN GAUGE.

2.6 Full Field Methods - Photoelastic

2.6.1 Principle of Operation

A method allowing the visual observation in real time of an entire two dimensional stress field is in wide commercial use. It is based on the ability of certain materials, notably plastics, to shift the polarization angle of polarized light in proportion to an applied stress.²⁴⁻²⁵⁻²⁶

The test surface is coated with a photoelastic material (usable in sheet or flexible form) using a reflective adhesive. Light is polarized by passing it through a polarizing filter (the polarizer - P), then passed through the plastic coating, reflected and passed through another polarizing filter (the analyzer - A). The angular relationship of A and P are maintained at 90° (see Fig. 4). The nature of the coating is such that wherever the polarization direction is parallel to a principal strain direction, the polarization angle will be unchanged and since the analyzer is at 90° , no light will be passed and black region will be seen. In fact, a field of black lines will be showing the locus of all points having the same angular relationship to the principal strain direction. After a series of such observations are recorded, each with P and A at slightly different angles but always at 90° to one another, a map can be made showing the strain directions over the entire surface.²⁷

While not indicating strain magnitude, the pattern can show the location and direction of strain concentrations. Magnitude information can be obtained as well but because of the complexities involved and the transient nature of the FELIX tests, the necessary procedures may not be practical.

At every point where the Polarizer and Analyzer are parallel to the principal strains, a black line is observed.

When the Polarizer and Analyzer are not parallel to principal strains, the light is transmitted and colors are seen.

FIG.4 PHOTOELASTIC STRAIN DIRECTION SENSING PRINCIPLE.

For the flat plate experiment a mirror can be mounted above the plate at 45° to the test surface to reflect the polarized light from (and to) the location of the polarizer/analyzer location outside FELIX in the axial direction (see Fig. 5). A high power, triggered strobe light source and a camera would be used to illuminate and record the strain field. Relevant experience is available within the ANL Components Technology Division (synchronized strobe lighting and high-speed movies).²⁸

For the initial flat plate experiment, where the strain field is symmetrical and somewhat predictable, the above procedure may seem elaborate, but if holes, slots, or other cutouts are tested, the strain field can become very complex. Mapping this complex field with rosettes or multiple gauge sets of large dimensions may be impractical without some idea of the strain field characteristics. If the strain field changes direction with time, however, this full field method may be the only practical way in which a complete quantitative time analysis can be made.

2.6.2 Difficulties

Besides the difficulties mentioned above, the following aspects must be taken into account: There is a reinforcing effect due to the bonded plastic sheet or coating but this problem is well understood and can be compensated for.²⁹ In addition, high magnetic fields can cause polarization angle shifts within certain materials, the Faraday effect.³⁰ If large enough, this effect could render this method useless and will have to be tested.

**FIG.5 CROSS SECTION OF FELIX SHOWING FLAT PLATE EXPERIMENT
AND VIEWING METHOD FOR FULL FIELD SENSORS.**

2.7 Full Field Methods - Moire Fringes

2.7.1 Operating Principle

In this method two identical ruled line patterns are superimposed on one another and the interference patterns observed, photographed, and measured.³¹ One of the gratings (the specimen grating) is bonded to the test surface and deforms with it. At this point two general procedures can be followed. The strained grating can be photographed and superimposed with an image of an unstrained grating (the reference grating). Of course the photograph must be very high contrast, fine grain, full size and distortion free. Some of these restraints can be relaxed if the reference grating is produced by the same photographic setup. The other procedure involves superimposing the reference grating at or near the specimen grating and photographing the strain-produced fringe pattern directly. The latter method would be preferred for the FELIX setup. The gratings are usually of the order of 1000 lines/inch and if the test surface deforms to a 1000 micro-strain (a one mil length change per inch), a dark fringe will be produced every inch. For lower strains the fringes will be correspondingly further apart.

The above description will produce surface displacement (strain) information for only one direction (that at right angles to the line pattern). The entire procedure is then repeated after a 90° rotation to obtain strain data for the other principle direction. Combination patterns are also used, employing grids or speckles.³²

2.7.2 Disadvantages

According to the literature it is difficult to measure strains of less than 200 micro-strain on anything but large areas of uniform

strain. The method would be difficult if not impossible to use on curved surfaces.

2.8 Full Field Methods - Brittle Coat

2.8.1 Operating Principle

In this method a lacquer is sprayed onto the last surface and allowed to harden. A combination of lacquer-type choice, temperature, and humidity will lead to a somewhat predictable sensitivity to tensile strain. As the test surface is strained, cracks occur along directions perpendicular to the maximum tensile strain.³³ Under the proper conditions these cracks will remain open after removal of the forces. This method is used primarily as a qualitative tool to indicate the areas of high stress concentration and the proper location and orientation of discrete strain gauge placement.³⁴ Although the lacquer cracks at a fairly predictable strain (about 500 micro-strain) and the crack density increases as more strain is induced, quantitative analysis using this method is generally not attempted. It is possible, however, to progressively load a test object and note the extent of the resulting crack pattern after each load level.

The spray lacquers are quite inexpensive, easy to apply, and can be used on curved surfaces as well as relatively inaccessible areas which may prove impossible for the other full field methods.

2.8.2 Disadvantages

There is little data available to indicate whether the cracks will form and stay open under the transient strain conditions of FELIX. The possibility can be enhanced by cooling the test surface with nitrogen gas immediately prior to the test pulse. The

progressive loading technique described above may not be feasible for FELIX since the relationship of the two field components would have to be scaled appropriately. As indicated, cracks only occur in areas of tensile strain and not compressive strain making the method somewhat less useful if compressive strains are induced in an area of interest.

3. TEMPERATURE MEASUREMENT DEVICES

The desire to measure both local temperatures and temperature patterns on the FELIX test articles arises from two somewhat different aspects of the tests. First, medium to high temperature changes may result from certain special object configurations and only local temperatures may be of interest. And secondly, the induced eddy current will cause small temperature rises to occur in patterns and at levels proportional to the square of the eddy current densities.³⁵ These patterns and levels will persist until they are diffused by thermal conduction through the test object. For example, calculations made by L. Turner for the flat plate experiment indicate that a thermal pattern is expected to arise which reaches approximately 5° C above ambient along the edges. The pattern builds up during a 160 ms period and remains essentially unchanged for about 400 ms.³⁶

Normal temperature measurement techniques suffer from the same signal to noise problems that strain measurements do, namely that a very small voltage or resistance change must be sensed in the presence of a large magnetic field disturbance. Sensor preference is placed on those methods which can respond in the required time scale and to which some kind of immunity to the interference can be imparted, either by the nature of the sensor or the way in

which the signal is processed. Thermocouples have not been considered because they are too slow, are self-generating (generating a millivolt dc signal), and cannot be provided with relatively immune twisted pair wiring.

3.1 Foil Temperature Sensors

3.1.1 Operating Principle

These devices are identical in appearance to the foil strain gauges described in Sections 2.1 and shown in Fig. 1-A. They are made from pure nickel and provide about 0.3 ohm/°C change. These devices have the necessary response characteristic being able to indicate temperature changes of 1000° C per second.³⁷ Since they require external excitation, the same high frequency ac excitation method described above should work here as well to discriminate against the effects of the decaying magnetic field. To further cancel these effects, a "dummy" sensor can be used which is mounted immediately above the true sensor but not in thermal contact with the test surface. (The same fold-back pattern described above which results in zero area cannot be used here since the upper layer would be thermally insulated from the lower layer and a thermal lag would result between the two halves.)

3.1.2 Disadvantages

Due to the construction similarity to foil strain gauges, there is, quite naturally, a strain-related source of error. The magnitude is about 1.6° C for 1000 micro-strain if mounted directly along the tensile strain axis, about 0.3° C for the same compressive strain, and essentially zero if mounted at 90° to these axis. There is also a non-linearity to be accounted for. A resistor network can be used to linearize the device, as well as provide for easy-to-use scaling

conversion when the sensor is used with strain gauge conditioning amplifiers.³⁸

Perhaps the most serious disadvantage is that in common with other single point temperature sensors, it would be difficult to use if a thermal map were required. The thermal map requirements of FELIX will call for only a few degrees C of temperature gradient, with a resolution at or near that of these devices (about 0.05° C), in a high noise environment, and with several different devices expected to perform identically.

3.2 Thermistors

3.2.1 Operating Principle

These devices usually employ platinum as the temperature dependent element and are available in a wide variety of sizes and characteristics.³⁹ The firm Thermometrics markets several configurations which have thermal time constants in the 5 to 10 millisecond range. They generally exhibit large resistance changes with temperature (about 50 ohms/°C) and can be chosen to operate quite linearly over a limited temperature range. Since for some experiments, our temperature range is limited to a few degrees above ambient, this works out well. The sizes available are as small as 0.005 inches in diameter for contact-mountable devices.

Since they require external excitation, high frequency ac excitation can be used.

3.2.2 Disadvantages

Since these devices are provided as tiny beads with the two lead wires at one end, a certain minimum loop area will result when the twisted pair signal leads are attached. The devices are delicate with 5/16 inch long leads 0.0007 inches in diameter.

3.3 Fiber-Optic Temperature Sensor

3.3.1 Operating Principle

An instrument has recently come on the market which uses a glass fiber and non-electrical sensor principle to sense temperature.⁴⁰⁻⁴¹ The Luxtron Corporation unit directs ultraviolet light down a glass fiber (up to 15 meters long) where it excites a small quantity (100 micrograms) of a pair of rare-earth phosphors. The resulting light is returned by the same fiber (traveling in the opposite direction) where it is split into two beams, filtered to separate the two wavelengths and detected. The temperature at the tip of the fiber is proportional to the ratio of the light intensity emitted by the two phosphors. The system would appear to be immune to magnetic and electrical interference and the low mass fiber tip should have fast response.

3.3.2 Disadvantages

The chief disadvantage is the processing time within the instrument itself. Apparently very low levels of emitted light are obtained and to achieve the stated 0.1° C accuracy and resolution, a one second integration time is used. This time can be reduced, but with an attendant loss of accuracy.⁴² The possible effect of the FELIX magnetic field on the phosphor performance would have to be questioned or at least tested.

3.4 Full Field - Infrared Scanning

3.4.1 Operating Principle

Two dimensional infrared scanning represents a method whereby a complete test surface temperature map could be made in a manner completely immune to magnetic and electrical interference.⁴³⁻⁴⁴ The infrared energy radiating from the test surface is scanned by a motor-driven set of mirrors (some units use crystal lenses) so as to direct a small region of the scene onto an infrared detector. The detector is cooled by being mounted on the side of a small liquid nitrogen dewar. The detector is chosen to provide the best sensitivity at the wavelength region of interest (for FELIX Mercury Cadmium Telluride for the 8-12 micron range). The fast scanning horizontal mirror and the slower scanning vertical mirror systems are synchronized with each other and the units produce TV-format synchronization and information signals so that the images can be viewed, processed, and stored using conventional video equipment.

The optical elements of the camera and any other elements in the optical setup are made from Germanium for the 8-12 micron spectral range but front-silvered mirrors could be used as well. A front-silvered mirror mounted at a 45° angle over the test surfaces as with the photoelastic strain viewing system would be used for the flat plate experiment (see Fig. 5). The possibility of using the top access port of FELIX has been investigated, but a special "relay lens" system would have to be custom made at considerable expense in order to view the entire plate.⁴⁵ This lens system would probably have shape and focus distortions as well. If the Germanium lenses tend to heat up due to eddy current heating, they may not be usable in the

infrared imaging system. Even the silvering of the mirror may have to be segmented if its eddy current heating and emission proved troublesome.

Infrared scanning systems from four vendors have been studied (AGA Infrared Systems AB,⁴⁶ Inframetrics,⁴⁷ U.T.I,⁴⁸ and Hughes Aircraft Company).⁴⁹ The units have a wide variety of different features, capabilities, and specifications, but the best combination of these seem to be available in the Inframetrics Model 525. A vendor demonstration of the equipment will be held at ANL. One of the critical parameters to consider is the full field scan time which must be short enough for the FELIX experimental needs. The Inframetrics unit has the ability to scan a single line of the thermal scene at an 8 KHz rate and this should be fast enough for any expected thermal phenomenon.

The necessity to store (on video cassette) thermal scenes and whether or not digital processing capability is needed will have to be assessed before the equipment is ordered.

3.4.2 Disadvantages

The scanner unit will be operating in the external solenoid field at a distance of about 5 meters from the center of the test volume so proper operation of its motor-driven mirror system will have to be checked. If a problem does occur, magnetic shielding may be practical at this distance from the test volume. It may be however that some of the thermal mapping tests can be made with the solenoid field off since it is the dipole field which creates the eddy currents and thus the thermal gradients.

Shielding of the optical system from nearby sources of heat (such as the magnet coils of FELIX itself) may also have to be considered.

4. MAGNETIC FIELD MEASUREMENTS

There are several different aspects of the FELIX program which will require the measurement of magnetic fields: the FELIX test volume itself will be checked and tested for magnitude and uniformity; the surrounding region will be tested for leakage field intensity; the test volume will be surveyed for field distortions caused by the test objects; and finally, the fields caused by eddy currents in the test objects will be measured.

Of the two methods considered for making real time measurements of transient magnetic fields, the search coil and the Hall probe, the Hall probe is the preferred method. Modern Hall probe systems are externally excited with a high frequency ac carrier current making them somewhat immune to noise pickup by the lead wires. Search coils on the other hand, are self excited and produce signals which are in the same frequency range and timing as the noise signals picked up by the lead wires, making discrimination on that basis impossible. The Hall system carrier frequencies are high enough that magnetic field signals up to 5 KHz can be measured, although a frequency response up to 400 Hz should be high enough for FELIX. Hall probes are available in a wide variety of single and multi-axis designs and sizes as small as 0.04" in diameter by 0.06" thick (active volume).⁵⁰

Differential probe assemblies are available, making possible the direct sensing of field gradients with one set of electronics.

While having a lower initial equipment cost outlay, the search coil system has a high labor cost involving the coil construction, integrator system design and troubleshooting, and calibration procedure, so that the Hall probe system is the most cost-effective.

5. EDDY CURRENT DENSITY MEASUREMENTS

The most feasible method for detection and measurement of eddy currents flowing in thin plates seems to be by sensing of the differential magnetic field generated by that current. The method consists of sensing the magnetic fields at points above and below the current-carrying plate in a direction sensitive to the magnetic field surrounding the current. The current density will be proportional to the integral of the differential voltage from two search coils mounted at the described positions. Alternatively a pair of differential Hall probes could sense this field as well. In any case, either system would have to be carefully used to avoid sensitivity to the dipole field operating normal to the plate surface and at right angles to the field of interest.

6. INSTRUMENTATION - COMPUTER INTERFACE

The instrumentation and control system of FELIX will include a mini-computer, mass storage system, and operator interaction devices. The control functions include the setting of current and timing limits for the FELIX power supply system, the timing control of the data taking system, the monitoring of various system parameters for safe operating limits, and the triggering of the "shot" itself including the timing of repetitive cycles. The same computer will gather shot data from the various interface systems, perform preliminary computations such as averaging, linearizing, and conversion to proper engineering units, and store the data for archival and early processing purposes.

Since it is desired to time-relate data from the various sensors (field, current, torque, temperature, etc.) and since the number of data channels can be as high as 20-30 for simple configurations, it has been decided to digitize the data during the shot rather than using intermediate analog signal

recording equipment. In this way the number of data channels can be increased easily and early reduction and "quick-look" information display can be programmed to occur after each shot. The simultaneous A-D conversion of many channels can be accomplished with either multi-channel transient recorders or multi-channel "fast loggers" depending on the allowable time-lag between conversions.⁵¹ (The transient recorder conversions are simultaneous to within one nsec while the "fast logger" conversions have a spread of 2 msec from first to 32nd channels.)

The above A-D converters are marketed by LeCroy and are packaged for the CAMAC (Computer Automated Measurement and Control) standard.⁵² There are a great many modules available for this standard making possible the easy interfacing of other system parameters such as status signals, non-synchronous temperatures from FELIX support systems, timing pulses for FELIX control, the triggering of strobe light and camera functions, etc. Interfacing the CAMAC standard to the computer is straightforward and there is wide in-house experience in its use. Much of the described equipment will be provided during the FELIX construction phase as part of its control system.

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