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ON-ORBIT NDE—A NOVEL APPROACH TO TUBE WELD INSPECTION

Kerry Michaels
McDonnell Douglas Aerospace
5301 Bolsa Avenue
Huntington Beach, CA 92647

Greg Hughes
Oceaneering Space Systems
16665 Space Center Boulevard
Houston, TX 77058

ABSTRACT

The challenge of fabrication and repair of structures in space must be met if we are to utilize and maintain long-duration space facilities. Welding techniques have been demonstrated to provide the most reliable means to accomplish this task. Over the past few years, methods have been developed to perform orbital tube welding employing space-based welding technology pioneered by the former Soviet Union. Welding can result in the formation of defects, which threaten the structural integrity of the welded joint. Implementation of welding on-orbit, therefore, must also include methods to evaluate the quality and integrity of the welded joints. To achieve this goal, the development of an on-orbit tube weld inspection system, utilizing alternating current field measurement (ACFM) technology, has been undertaken.

This paper describes the development of the ACFM on-orbit tube weld inspection tool. Topics discussed include: requirements for on-orbit NDE, basic theory of ACFM, its advantages over other NDE methods for on-orbit applications, and the ACFM NDE system design. System operation and trial inspection results are also discussed. Future work with this technology is also considered.

INTRODUCTION

To successfully utilize long-duration space facilities, adequate consideration must be given to maintenance and repair. In low Earth orbit, space structures are subject to significant risk of damage from debris impact, thermal cycling, and radiation exposure in addition to degradation from normal operational stresses and wear. Because of this adverse operating environment and the expense of replacing large structures, performing repair operations in space is the best approach to ensure long-term utilization.

For pressurized systems, welding offers the most reliable method for permanent repair of metal joints in space. McDonnell Douglas Aerospace (MDA) has advanced this technology since 1986 using tools and procedures developed by MDA as well as incorporating state-of-the-art electron beam space welding hardware developed by the Paton Welding Institute located in Kiev, Ukraine. Welding is a critical process involving many variables to produce acceptable quality hardware. Even under controlled conditions on Earth, weld quality is not guaranteed and nondestructive evaluation (NDE) methods are commonly used to ensure weld quality. Verification of weld quality through NDE becomes even more significant in the remoteness of space, where the absence of process controls and the effects of a single flaw in a critical structure could prove catastrophic.

One of the most likely and challenging maintenance problems to be encountered on a complex structure such as Space Station Freedom is the repair of pressurized tubing. For this reason, the initial development of space welding capabilities at MDA has focused primarily on tube welds. With the help of the Paton Welding Institute, an automated electron beam device for welding small metallic tubes (0.5 in. OD, 0.035-in. to 0.063-in. wall thickness) is being developed and evaluated for use in a zero-gravity vacuum environment as part of a MDA Independent Research and Development (IRAD) task during 1993.

On-Orbit NDE of Tube Welds

In conjunction with this welding effort, an IRAD task to develop an on-orbit NDE system to inspect tube welds has been undertaken by MDA and Oceaneering Space Systems (OSS). The first step in the system development was to select the NDE method most suitable for this application. To objectively evaluate candidate NDE methods, the Kepner Tregoe analysis method was employed. This technique is a formal methodology for objectively selecting among numerous technical solutions by organizing requirements into MUST and WANT categories. Each candidate NDE method must first satisfy all of the MUST criteria. The successful methods are then evaluated against the WANT criteria through a weighted comparative process. Design requirements used for this analysis consist of the following MUST and WANT criteria:

1. **MUST Criteria**—The capability to detect welding flaws in the size range of interest without consideration for flaw position comprise the MUST criteria. Maximum allowable defect sizes derived from MDA tube welding specifications were used to develop these criteria. The specific flaw types and sizes selected are shown in Table I.

Table I. MUST Design Criteria

Sharp Flaws	Value	Notes
Maximum length	1.57 in.	The circumference of the tube
Minimum length	0.035 in.	The tube wall thickness
Maximum depth	0.035 in.	The tube wall thickness
Minimum depth	0.0175 in.	50% of tube wall thickness
Blunt Flaws	**Value**	**Notes**
Burn through	ALL	
Minimum diameter of single pore	0.0123 in.	35% of tube wall thickness
Minimum area of scattered porosity	0.011 in.^{2}	20% of weld area per inch of weld

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2. **WANT Criteria**—The following criteria and desired features, listed in Table II, were used to provide a weighted comparison between candidate NDE methods.

Table II. WANT Design Criteria

Criteria	Desired Feature
Safety	Low radiation hazard
	No sharp edges
	Low thermal output
	Low electrical discharge risk
Simplicity	No moving parts
	Loose positioning tolerances
	No system calibration
	Little operator training
	Easy data interpretation
Size	Probe head less than 2.0 in. in diameter
	Single hand manipulation
Power	28 VDC or less for use in Shuttle bay
	120 VDC or less for use on Shuttle flight deck

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Of 15 initial candidate NDE methods, only radiographic, ultrasonic (shear wave, surface wave, and plate wave), eddy current, alternating current potential drop (ACPD), and alternating current field measurement (ACFM) offered the potential to meet all of the MUST criteria. Further comparisons utilizing the weighted WANT criteria resulted in the selection of ACFM as the best NDE method for on-orbit inspection of tube welds.

ACFM technology was first pioneered in 1988 by mechanical engineers at University College, London. Inspection systems utilizing this method have been developed for underwater inspections of offshore structural welds since 1990 by Technical Software Consultants, Ltd. (TSC). Currently, ACFM arrays are being developed for remote operated vehicles (ROVs) and have been tested in the North Sea.

ACFM offers many advantages over other NDE methods for remote on-orbit operations. ACFM technology allows complete mathematical modeling of the signal response, thereby rendering repeated system calibration unnecessary. ACFM coils can be multiplexed in array configurations to provide fast inspection times and eliminate the need for scanning and moving parts. Furthermore, ACFM is relatively insensitive to liftoff variations and direct contact with the part surface is not required. These features allow for simple operation by just placing the probe over the area to be inspected and energizing the coils. Data analysis is accomplished by computer with permanent storage of results. Packaging of the electronics allows the ACFM NDE tool to be contained in a hand-held, lightweight device.

Basic Theory of ACFM

ACFM is an electromagnetic technique which induces or injects a uniform electrical field into a conductive material and measures the magnetic field above the specimen surface (Reference 1). The current is confined to a thin layer of the material at the surface, known as skin depth, similar to eddy current fields. These surface currents produce alternating current (AC) surface magnetic fields which decay with distance from the surface. Uniform fields used with ACFM, however, decay more slowly than the non-uniform eddy current fields, making ACFM much less sensitive to liftoff and probe misorientation. A non-contacting probe coil is used to record the magnetic field strengths. Size and shape of the probe coil can be selected to provide optimum sensitivity to suspect defects.

When the uniform field current encounters a defect in the conductor, it is forced to flow around the defect, diverting some of the current away from the defect center and concentrating it near the ends. When the probe crosses the defect, perturbations in the primary components of the magnetic field result. An illustration of the uniform field at a crack and the resulting magnetic field components is shown in Figure 1.

The uniform AC field can be injected or induced by separate field injectors unlike eddy current methods which use the same coil to induce a non-uniform field and measure the material response. Because the field in ACFM is uniform, theoretical predictions for the magnetic perturbations are possible, eliminating the need for system calibration during use. Topp and Dover (Reference 2) have shown that Laplace and Born type approximations can be used to model the response from cracks in conductive materials. Figure 2 shows the comparison of experimental and theoretical distributions of magnetic field components over a grid in the x-y plane above surface breaking defects in mild steel (Reference 3). Changes in the Bx component of the magnetic field (Figure 2a) reflect the changes in current density so that Bx is below its background level over most of the crack length but rises above that level near the crack ends. The component By (Figure 2b) is determined by the current flow parallel to the crack edges and thus peaks

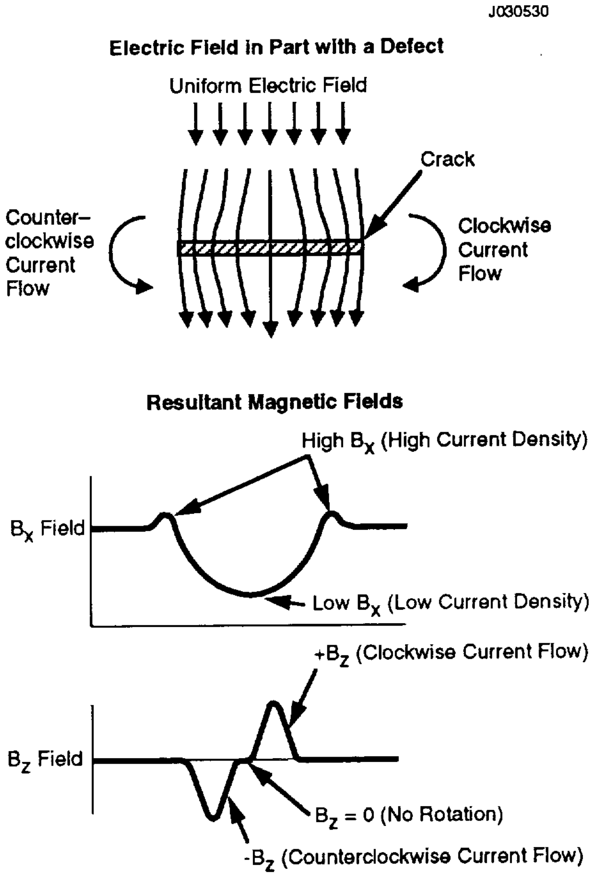


Fig. 1. ACFM electric and magnetic fields

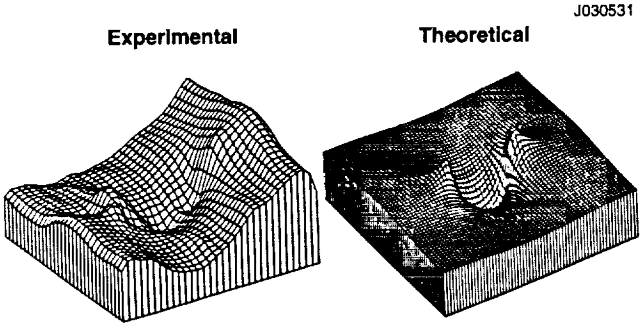
toward the crack ends and is of opposite sign on each side of the crack. The vertical component Bz (Figure 2c) is determined by the circulation of the current around the crack ends. Since this circulation is clockwise at one end but counterclockwise at the other, the Bz signal consists of a peak at one end and a trough at the opposite end of a crack. This characteristic response of the Bz field in the presence of a flaw is the most identifiable of the three components and offers the greatest sensitivity for the detection of surface breaking flaws.

Quantitative predictions of the magnetic field response have been produced for various crack shapes and sizes in a variety of metals. These predictions can then be used to determine not only the presence of a crack but also its length and depth. Utilization of uniform fields also makes the implementation of sensor arrays easier, eliminating the need for scanning. The following sections detail how this innovative technique has been applied to the development of a proof of concept (POC) NDE system for the inspection of tube welds.

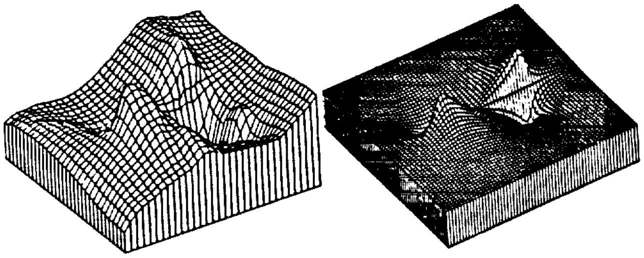
ACFM ON-ORBIT NDE SYSTEM DEVELOPMENT

System Design

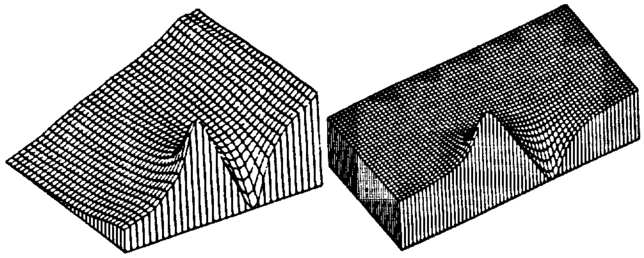
The POC ACFM NDE system is made up of three major components, all interconnected by umbilicals. The first of these is the extravehicular activity (EVA) tube inspection hand tool which is connected by a tool umbilical to the second component, the U10 data acquisition unit. The third unit is a standard 486 33-MHz personal computer (PC) which communicates with the U10 by a serial line. Separation of the POC system into these three individual components allows maximum use of currently available equipment and provides easy development into a subsequent flight system. Configurations for both the POC system and a proposed flight system are shown in Figure 3.



a. B_x at 3 mm Liftoff for a 40 by 3 mm Fatigue Crack



b. B_y at 2 mm Liftoff for a 6 by 3 mm Fatigue Crack



c. B_z at 2 mm Liftoff for a 20 by 10 mm Notch

Fig. 2. Comparison of experimental and theoretical distributions of magnetic field components

Hardware Description

1. **ACFM NDE Tube Weld Inspection EVA Hand Tool**—The EVA tube inspection hand tool is shown in Figure 4. Its function is to place the ACFM array around the tube weld and to inject a uniform AC field into the weld area. Multiplexing in the tool head switches through the array coils, sending the voltages they are experiencing to the U10 data acquisition unit. The control computer makes the decisions based on the data collected by the hand tool and relays these decisions to the hand tool where appropriate light emitting diodes (LEDs) are illuminated to inform the EVA operator of the status of the inspection. LEDs also

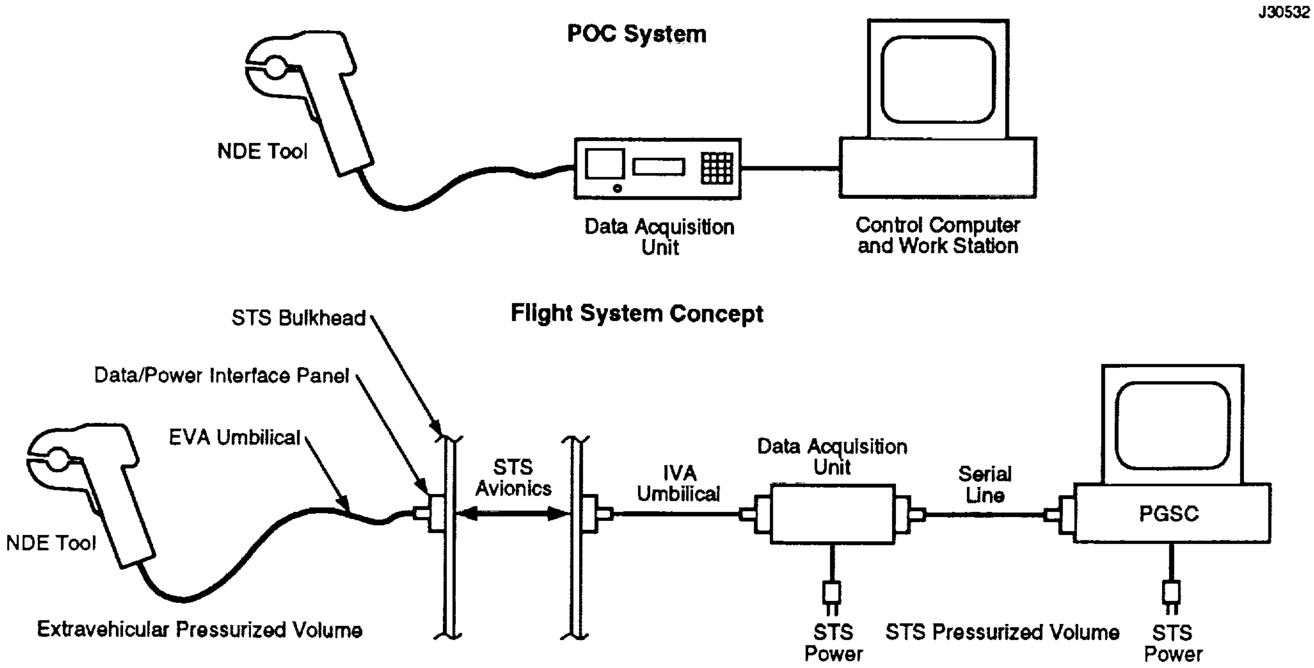


Fig. 3. Proof of concept and flight system configurations

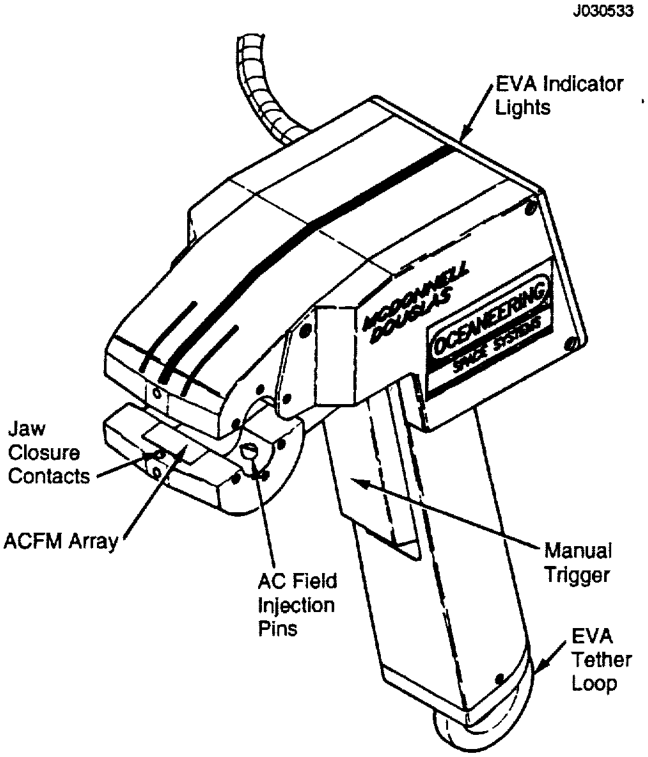


Fig. 4. EVA tube inspection hand tool

reflect whether the hand tool jaw is properly closed and whether the AC field has been successfully injected.

Jaw opening and closure is manually controlled by a squeeze trigger. The jaw opening is designed to accommodate a tube with a maximum diameter of 0.5 in., thus reducing the EVA pinch risk. The jaw closure is sensed by contacts in the mouth of the jaws and an LED is illuminated. The hand tool grasp interface is designed to conform to Manned Systems Integration Specification (MSIS) EVA gloved hand requirements. A jaw opening actuation force of approximately 5 lb has been selected to provide easy but deliberate activation. Injection of the AC field occurs through eight contact pins; these are designed to ensure a uniform input field. Four LEDs are mounted on the back plate of the hand tool with clearly marked labels.

The ACFM 96-coil array is housed in two semicircular blocks designed to accept 0.5-in. diameter metal tubes. The total array is made up of 3 rows of 32 rectangular coils each measuring 0.197 in. long by 0.039 in. wide and inspects the entire tube circumference for a length of 0.5 in. Each coil is oriented perpendicularly to the tube surface to provide optimized measurement of the resultant Bz magnetic field. The rectangular coil arrangement provides maximum resolution in the circumferential direction (coil width direction) while maintaining the total number of coils at a manageable level. Fast multiplexing electronics built into the tool head reduces the amount of cabling required to transmit data back to the U10. A sketch of the ACFM probe head depicting the coil arrangement and field injector locations is shown in Figure 5.

2. **U10 Data Acquisition Unit**—The POC system will use a modified TSC U10 data acquisition unit. The U10 contains a 68000 series microprocessor and communicates with a PC by an RS232 serial line. The function of this data acquisition unit is to control sensor readings from the ACFM array, provide the AC field for injection into the test piece, and to distribute the inspection data to the control computer. The

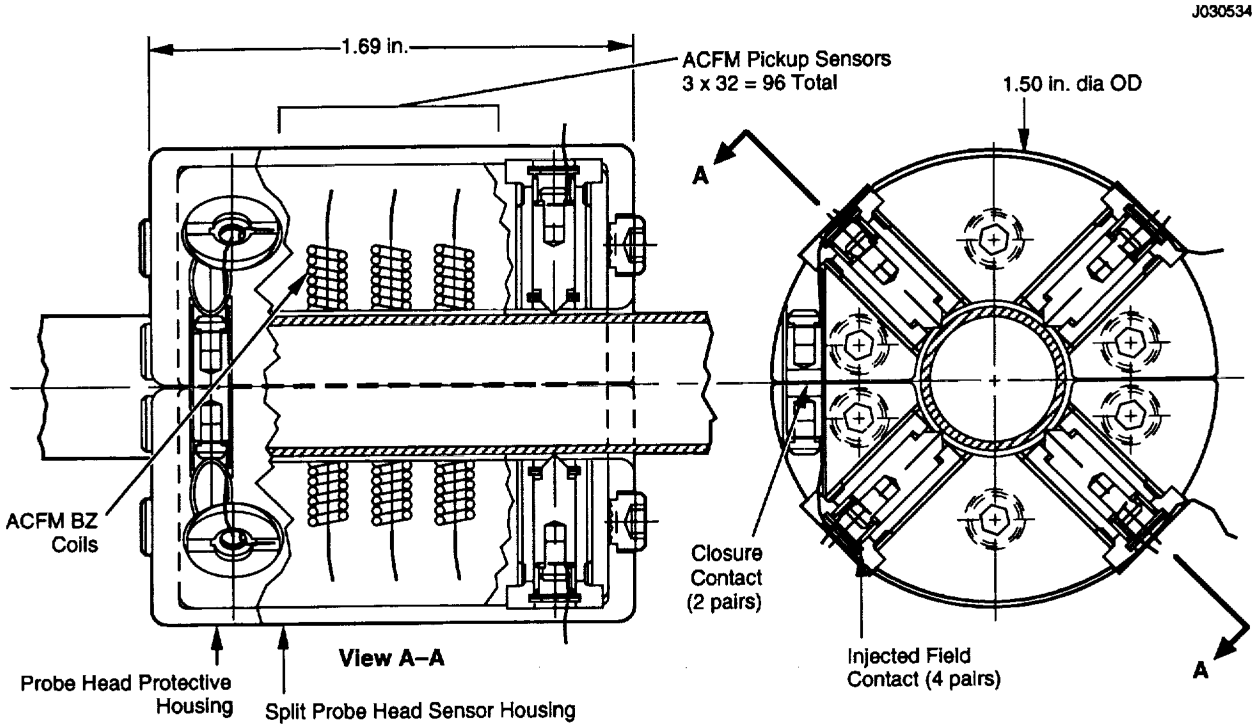


Fig. 5. ACFM probe head

U10 is the standard laboratory ACFM data acquisition unit manufactured by TSC.

3. **PC Control Computer**—Computation and data storage are performed by the 486 PC. The PC also controls the U10, collects inspection data from the U10, analyzes the data through the use of algorithms derived from the experimental results, and displays the results through a customized graphical user interface. The inspection data will take the form of a two-dimensional false color map of the inspected area and three Bz amplitude representations. A pictorial representation of the anticipated operator display is shown in Figure 6. All data will be capable of being labeled and stored to hard or floppy disk.

Control and Interface Software Description

The control system is split between software on the PC, firmware on the U10 instrument, and local logic on the NDE tool. A schematic of the system architecture is shown in Figure 7.

The PC software is written in C++ with Visual Basic graphics at the front end for easy customization. This software controls initiation and override of scan sequence and provides the user with an interface for data display and storage. PC software also analyzes the data through comparisons to programmed acceptance criteria models and determines the defect accept/reject status.

The U10 firmware is written in assembler and installed on electronically programmed read only memory (EPROM) chips. It sets up the instrument parameters and checks for field high/low resistance by A/D channels. The firmware also controls LEDs for field contact and defect accept/reject status as well as the hand tool multiplexer for data collection.

ACFM ON-ORBIT NDE SYSTEM OPERATION

Inspection Procedure

The ACFM on-orbit NDE system is designed for simple reliable operation. In an on-orbit scenario, the system will utilize two operators—one crew member at the PC computer on the shuttle flight deck (PC operator) and another crew member in the Shuttle cargo bay with the umbillically linked ACFM hand tool performing the EVA weld inspection (EVA operator). The following steps outline a typical weld inspection procedure:

1. Using the graphics interface on the PC, the PC operator selects one of the three inspection control modes (single shot scan, continuous scan, or diagnostic). The continuous mode is assumed in this scenario.

2. The EVA operator squeezes the tool trigger and opens the jaws. He then moves the tool over the weld and releases the trigger which closes the tool around the tube weld.

3. The computer confirms that the injected AC field is present and that the jaws are closed, lighting two LEDs on the hand tool, then initiates a scan.

4. The computer decides if a significant defect has been located, displays the result on the PC screen, and lights the appropriate LED on the hand tool.

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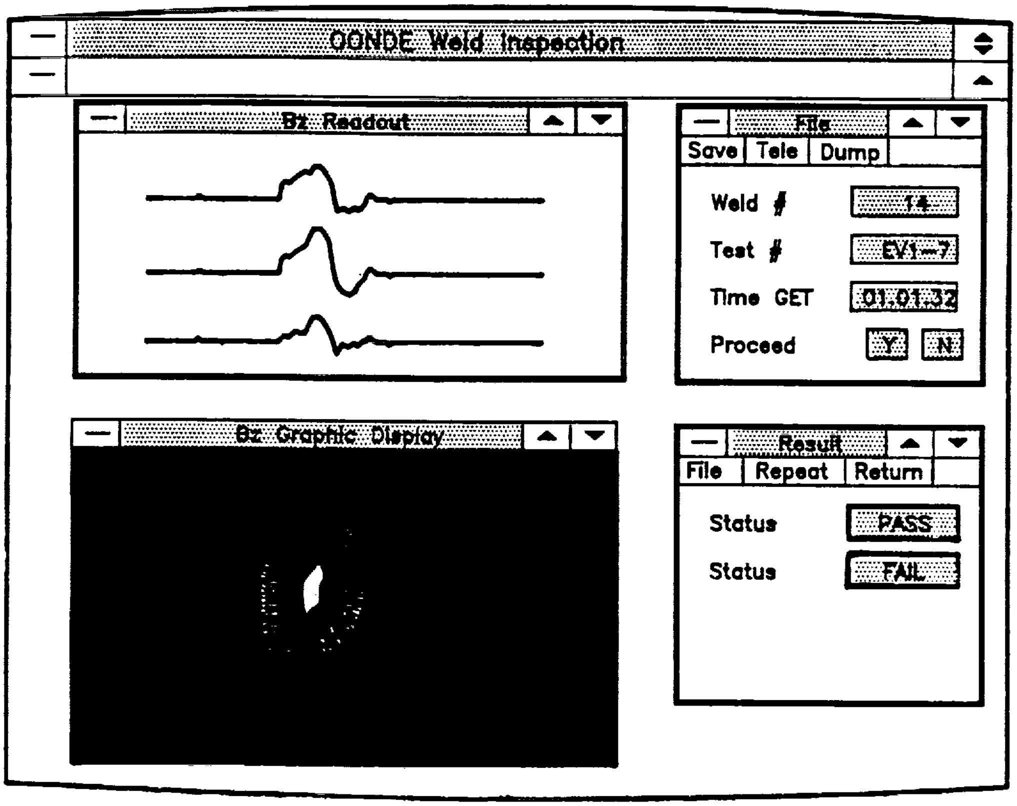

Weld # 14
Test # EV1-7
Time GET 01.01.32
Proceed Y N

Status PASS
Status FAIL

Fig. 6. Operator display screen

5. If the EVA operator does not open the jaws to move on to the next inspection another scan is initiated.

6. The PC operator now has the option to permanently store the inspection results on floppy or hard disk.

Preliminary Test Results

Although integration of the entire system is not yet complete, initial tests have been conducted by TSC using a partial ring array on man-made defects in a sample of 0.5-in.-diameter stainless steel tubing. The partial ring array is a semicircular block of 16 coils (one-sixth of the total POC array). Data was collected with this array using the completed POC electronics and control software. In each of the reported tests the partial ring array was clamped over the inspection area and the uniform AC field was injected via crocodile clips at either end of the tube. Using the PC interface, the array was sampled by the U10 and the results of the inspection displayed on the PC screen. Because only 16 coils were used, representing one-half of a complete ring, only one line of data appears on the screen rather than three.

The results of these inspections are shown in Figure 8.

Figure 8a illustrates the inspection results from a 0.2-in.-long, 0.018-in.-deep saw cut in a stainless steel tube. This large defect is clearly seen in the line plot of the Bz amplitude. The dashed lines on the Bz display indicate the thresholds for defect detection. Figure 8b illustrates the response of a smaller defect, in this case a 0.02-in.-diameter through hole. Again, the defect signal response exceeds the threshold and the inspection is successful. Figure 8c illustrates the response of a defect-free area of the tube with the instrument sensitivity identical to the previous tests.

CONCLUSIONS/FUTURE WORK

The on-orbit NDE tube weld inspection system, utilizing ACFM technology offers a viable approach to tube weld inspections. The preliminary results indicate that the sensitivity of the system should allow the detection of the minimum defects while providing a clear and automatic indication to the operator of the inspection status. Once integration of the entire system has been completed, comprehensive testing will be performed throughout the remainder of 1993 to more fully establish the performance capabilities of the system.

As previously mentioned, this POC system has been designed to facilitate development to a flight ready system. Future plans include the development of a flight system for demonstration onboard the Space Shuttle as a part of the proposed Welding In Space Experiment. The NDE flight system will utilize the same major components as the POC system and will be its functional equivalent. The major difference between the two systems is the design of the

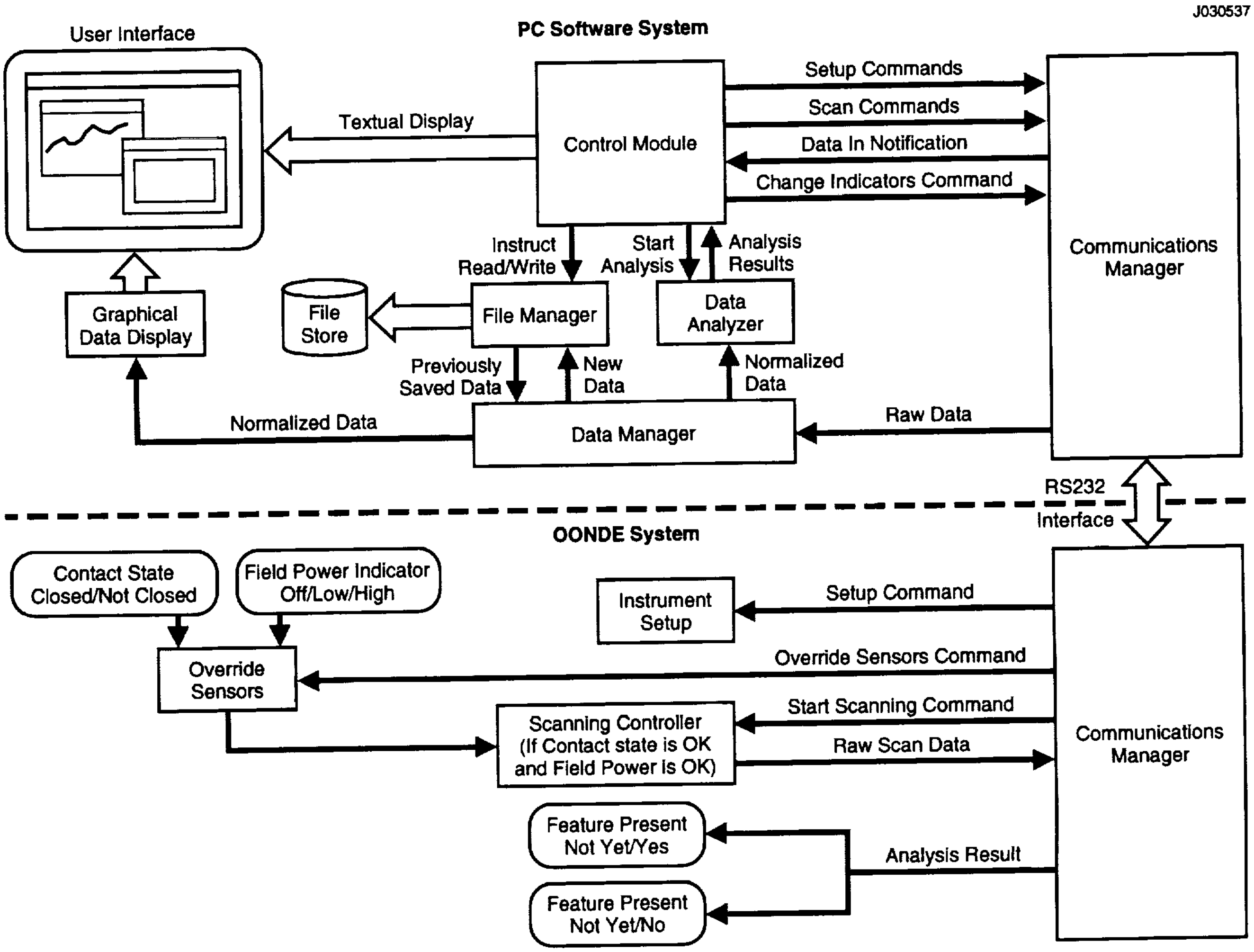

Fig. 7. ACFM on-orbit NDE system architecture

individual components and their interconnection with each other and with the Space Shuttle intravehicular and extravehicular systems.

ACFM array technology may also offer a competitive alternative to conventional NDE for Earth applications as well, considering the obvious advantages of operational simplicity, speed of inspection, small size, and data retention capabilities over conventional NDE techniques. Furthermore, ACFM arrays offer the flexibility to design specialized inspection tools for specific geometries, configurations, and defect types with remarkable sensitivity.

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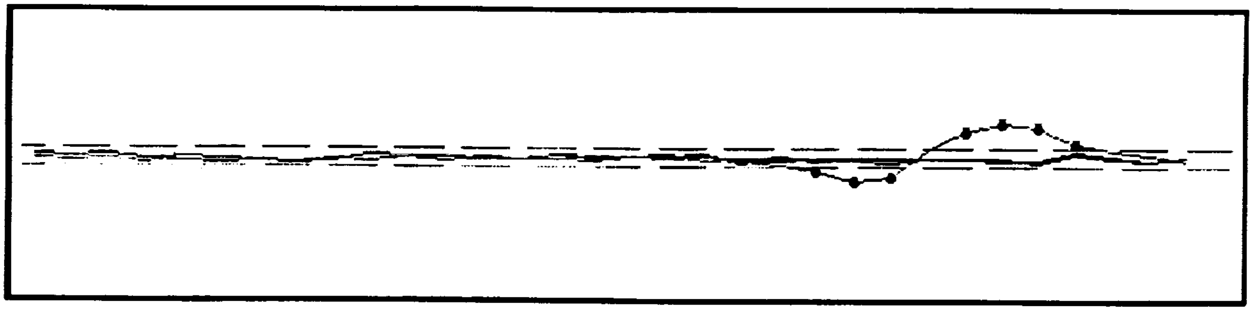
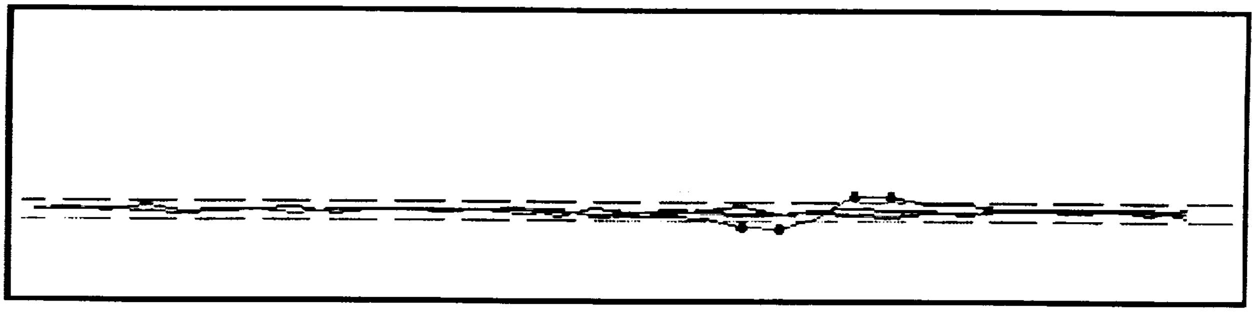
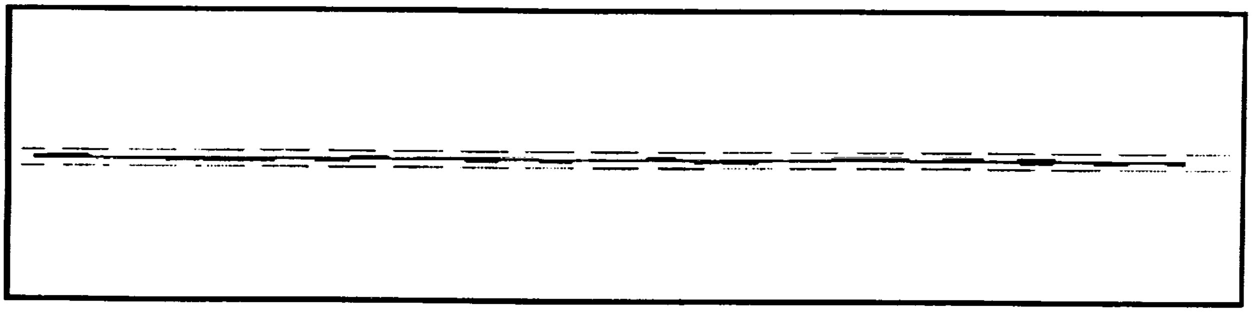


a. Response From 0.2 × 0.018-in. Saw Cut



b. Response From a 0.02-in.-Diameter Through Hole



c. Response From Defect Free Area

Fig. 8. Preliminary test results