A COMPUTER-AIDED NONDESTRUCTIVE INSPECTION SYSTEM

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ABSTRACT

A Computer-Aided NonDestructive Inspection System (CANDIS) has been designed and built for improving the speed and quality of the ultrasonic evaluation of diffusion-bonded parts of the B-1B aircraft. The system comprises a host computer, a Data Acquisition and Multi-Axis Control (DAMAC) system, and a custom mechanical scanning system.

The host computer uses menu-driven software to provide a user-friendly interface for the operator. Both C- and B-scan images can be displayed on a color image display in real time. In addition, an array processor permits the acquisition of entire waveforms for analysis by advanced flaw detection and characterization algorithms.

The DAMAC will permit raster scans to be performed on parts that lie at arbitrary orientation with respect to the tank to eliminate time-consuming part alignment procedures. The DAMAC also controls the ultrasonic pulser-receiver and synchronizes the data acquisition with the scanning motions. A manual control permits the system to be moved by the operator via both a standard jog mode as well as a novel position control mode.

The custom mechanical scanning system contains three servo controlled linear axes capable of vector movements within a 10 ft x 16 ft x 3 ft volume. The scanning speed is 20 ips. A novel set of three rotary axes with a pointing accuracy of 0.05° permits the ultrasonic transducer to be pointed at angles covering 360° in azimuth and ±135° from vertical.

INTRODUCTION

We describe here a Computer-Aided NonDestructive Inspection System (CANDIS) that has been constructed to provide an automated method for the
ultrasonic inspection of diffusion-bonded parts. Its primary objective is to increase the speed and to improve the quality of the inspection. The system is designed so that the ultrasonic data acquisition, the mechanical scanning of the transducer, and the computer storage and display of the data are fully integrated. Typically, it is difficult to realize the advantages of such a merger with "off the shelf" equipment. Consequently, the equipment performing these functions has been carefully selected to permit such an integration. Custom-built hardware and custom software have been used to realize the interfaces.

The system has been designed so that the operator can start out by using it almost as a manual system. As he learns to use the system and becomes more comfortable with its operation, he can incorporate more of the automatic features into the inspection until the full benefits of the automation are realized. The operator is kept in the loop for key procedures. In particular, the operator interfaces have been designed to permit the operator's eye-hand coordination skills to be used where applicable. These skills are difficult to duplicate in an automated machine, and it is important that they not be lost.

The software for operating the system is menu-driven. The operator is guided through the entire inspection procedure step by step; from the loading of the part to the detailed examination of a flaw. The operator can use a command language to link various operations according to the particular needs of the specific inspection being performed. These operations are then automatically carried out in the specified sequence.

The following description of CANDIS first provides a brief description of the parts to be inspected; second, it describes in-depth the hardware that comprises the system; third, it explains and describes the functions that the system must provide; and fourth, it describes briefly the software that operates the system.

INSPECTION NEEDS

The aircraft frame components to be inspected are the diffusion-bonded titanium parts that comprise the wing carry-through box of the B-1B aircraft. It is located between the two wings at the junction of the fore and aft fuselage. It is a fracture-critical structure that requires careful inspection for flaws in the diffusion bond planes. The structure consists of a number of parts that are made separately. Some are welded together before being bolted into the final configuration.

All of the diffusion-bonded parts are titanium. The individual pieces of the titanium parts are placed in a tooling fixture that in turn is sealed into a retort and placed in a very large press. Pressure is applied and the temperature is raised so that one obtains some flowing of the metal and grain growth across the boundaries between the individual titanium pieces. Bonds made in this way are as strong as the parent metal if the bonding process is done properly. The problem is that, in some cases, impurities can get into the bond plane. For example, oxygen can be present during the process. A poor bond can also result if uneven pressure is applied along the bond plane. In these cases, the resulting poor bond can manifest itself as a gross disbonds, porosity (a group of disbonds loosely joined), or sometimes small pinhead-type disbonds. The ultrasonic inspection must be capable of detecting all disbonds that have a diameter larger than 0.050 in.

One of the parts that is ready to be loaded into the inspection tank is shown in Fig. 1. The photograph gives some idea of the scale of the parts. The diffusion bonds are located at the junctions between the ribs.
and the flat plate under them. The ribs are scanned ultrasonically to detect any disbonds. The inspection plan for each of the parts is developed by the Quality Engineering Department and is known as the Inspection Instructions, or II, for that part. All of the entry planes are flat, but they can lie at arbitrary angles relative to an external coordinate system such as that of the scanning tank. One of the needs of an automatic inspection system is to be able to adjust the scan plane of the transducer to be parallel to the bond plane(s) of the part. CANDIS has been designed to meet the specific needs of diffusion bond inspection.

![Image](image_url)

**Fig. 1** One of the diffusion-bonded titanium parts that comprise the wing carry-through box. This part is on a loading fixture.

**SYSTEM ARCHITECTURE AND HARDWARE**

The configuration diagram for the system, shown in Fig. 2, is divided into three major subsystems. Starting at the bottom of the diagram, we have the automatic scanning system that includes the water tank for immersing the parts and a manipulator for holding the transducer while it is being scanned. The transducer is excited by the ultrasonic instrument. The mechanical scanning axes are controlled by servo loops; three for rotary axes and three for linear axes. The linear encoders are used to generate trigger signals for the ultrasonic instrument so that the ultrasonic pulses occur at regularly spaced intervals along the scan path.

In the center of Fig. 2 is the Data Acquisition and Multi-Axis Controller (DAMAC). The ultrasonic instrument (a commercially available Sonic Mk VI pulse/receiver) is interfaced to this unit. The servo loops for the linear axes are linked together by a controller that provides an interpolation function so that vector moves can be made within the scanning volume. The DAMAC also handles the position display function. A manual control box is interfaced to the DAMAC so that the operator can manually move the transducer. Finally, there is a protection system for stopping the system when any of a variety of faults are encountered.
At the top of Fig. 2 is the host control system that serves as the system supervisor and provides the major interface to the operator through the system terminal. The C-scan images are displayed and stored here. In addition, there is a provision for a digital path directly to the ultrasonic instrument. This path contains an array processor and a high speed digitizer that is capable of acquiring and processing complete ultrasonic waveforms in real time.

AUTOMATED SCANNING SYSTEM

The automated scanning system is built around an integral frame and water tank. The tank dimensions are 10 ft x 16 ft x 3.5 ft. A part handling fixture is used for loading parts into the tank (see Fig. 1). The fixture provides a set of supports and tiedowns that can be adapted for use with all of the parts.

With an automated system of this type, it is important to have good positioning accuracy and repeatability, since the operator will not generally be in the loop during the positioning of the transducer. The analysis of the accuracy of the system was based on an error budget calculation involving the relevant error contributions from each of the six axes of motion plus thermal effects and vibration. The design accuracy of the system constrains the position of the focal spot of a 12 in. focal length transducer, as estimated from the linear and rotary encoder readings, to lie within a sphere of uncertainty of diameter 0.200 in. of its true position anywhere within the volume of the tank. The accuracy is significantly higher within smaller volumes.
The X- and Y-carriages are linked to the drive motors by metal belts that provide a quiet, smooth motion that is free of reversal error. The Z-carriage is linked to its drive motor by a lead screw. All carriages are mounted on linear ball bushings riding on stainless steel rails.

LINEAR AXES SERVO SYSTEMS

The servo systems for the linear axes all have a similar architecture. It consists of a minor loop that regulates the speed through tachometer feedback within a major loop that controls the position through feedback from a position encoder. The chief differences between the three servo loops are the mass of the carriages and the stiffness of the drive linkages. These are accommodated through the compensation circuits. Each of the axes is driven by a dc servo motor and uses a linear position encoder to measure distance. The resolution of the encoder is 250 millionths of an inch. The least increment of distance that the servo systems can be commanded to move is one thousandth of an inch. The bandwidth of the servos is adequate to support accelerations of 40 in./s² on all three axes. The maximum speed of the X- and Y-axes is 20 in./s; that of the Z-axis is 5 in./s.

MANIPULATOR

The manipulator used to rotate the ultrasonic transducer is a custom-built unit that contains three rotary axes. There is a swivel axis that is parallel to the Z-axis and upper and lower gimbal axes. The direction of the transducer can be varied in elevation from straight down to 30° above horizontal and 360° in azimuth. The motors for driving the axes are stepper motors with 36,000 steps per revolution or one step for each 0.01° of rotation. The motors are in waterproof housings and are immersed along with the transducer. The transducer is directly coupled to the motors. There is virtually no reversal error or cross-coupling between axes. The pointing accuracy is 0.05°. A photograph of the manipulator is shown in Fig. 3. The manipulator is mounted on the end of a tube that is attached to the Z-axis carriage.

Fig. 3 Photograph of three-axis manipulator.
The next section of the configuration diagram, Fig. 2, contains the DAMAC. The chief purpose of the DAMAC is to serve as a real-time computer to carry out the instructions received from the host computer and then to return data to the host computer that is acquired based on these instructions. The DAMAC is a single board computer, based on the Motorola 68000 microprocessor, that is interfaced to a Multibus.

The DAMAC controls and acquires ultrasonic data from the ultrasonic instrument. The ultrasonic instrument has many functions that can be read by the DAMAC, such as pulse repetition rate, water path distance, pulse amplitude, receiver gain, and gate width. Some of these functions can also be set by the DAMAC. In addition, the two data outputs are the peak amplitude within the monitor gate and the flaw depth.

The DAMAC controls and acquires position data from the rotary and linear servo axes controllers. The summing junctions for the linear axes position servo loops are contained in a digital controller that links all three axes. The DAMAC generates commands that specify the length, direction, speed and acceleration of the linear moves. As the move is executed, the actual distance moved is read from the linear encoder associated with each of the axes. In addition to entering the summing junction, these data are used to drive a position display module and to generate trigger pulses that can be sent to the ultrasonic instrument. Position data are coupled with the ultrasonic echo amplitude data to form the data blocks that comprise the C-scan images.

The rotary axes are also commanded from the DAMAC. Their positions are set prior to a scan and are not changed during the scan. There is no interleaving of commands to the rotary axes. Each command specifies the axis, extent of rotation, speed and acceleration.

The DAMAC services the interrupts from the protection system. There is a hierarchy of limit switches for preventing the transducer from traveling beyond its safe limits. This hierarchy includes mechanical limit switches that cause a controlled deceleration, followed by a return of the transducer to the permissible region of travel. There are also mechanical limit switches beyond the first set that cause an emergency stop of all motors. In the case of an emergency stop, all position information is lost and the transducer must be manually returned to the permissible region of travel. Other faults can also cause the system to stop.

Figure 2 shows the manual control box interfaced to the DAMAC. This is intended to be the principal interface between the operator and the scanning system. The front panel of the box is shown in Fig. 4. The switches on the left-hand side provide jog controls for each of the linear axes. The track ball and wheel (wheel is viewed edge-on) in the center portion provide a means for controlling the position of the linear axes. The X- or Y-axis will move a distance proportional to the distance the track ball is rotated, with the proportionality constant depending on the setting of the scale control. The Z-axis responds similarly to a rotation of the wheel. The controller will operate in the X,Y,Z coordinate system of the mechanical scanning system unless the entry plane light is on. Then, the track ball will cause motion of the transducer in a plane that is parallel to a defined entry plane of a part and the wheel will cause motion of the transducer in a direction normal to this plane.
The rotary axes are controlled by the three knobs shown to the right of the position control section. The rotary axes move a distance that is proportional to the distance that the knob rotates. The set of four pushbuttons to the right of these knobs allows the operator to enter data into the computer regarding the position and orientation of the transducer, to cause the computer to continue executing a sequence of commands, or to exit from the manual control mode.

The manual control box is connected to the system by an umbilical cord that allows the operator to carry it around the tank. For example, he can move the transducer while observing changes in an ultrasonic signal on the CRT of the ultrasonic instrument. The manual control box gives control back to the operator and allows his eye-hand coordination to come into play.

HOST CONTROL SYSTEM

The final section of the configuration diagram, Fig. 2, contains the host control system. This system contains the supervisory software and the major interface to the operator, as well as most of the input/output functions. All of the peripherals are commercial units that have been suitably interfaced. The host computer is a VAX 11/750; the various input/output devices are a Tektronix color graphics terminal, a high resolution color monitor, a drafting style plotter, a printer, a 512 megabyte hard disk, a 75 ips magnetic tape drive, and a microprocessor-based array processor.

The array processor plus a custom-built digitizer provide a means for digitizing entire rf or video waveforms from the ultrasonic instrument. This capability permits the display of B-scan images, as well as implementation of advanced signal processing techniques.

The layout of the entire system after installation is shown in Fig. 5. The immersion tank and scanning system are seen in the foreground. The ultrasonic instrument and position display unit is held on an articulated arm and can be swung around so that it can be seen by an operator as he works with the manual control box near the edge of the tank. It can also be positioned over the color monitor so that the A-scan can be
Fig. 5. Photograph of CANDIS shortly after installation.
monitored as the C-scan image is displayed. The control console with its control panel is located just beyond the tank. Located on the control console is the operator's terminal that is used to control the system. The color monitor used to display C-scans and other graphic information is at the near end of the console. The computer, hard disk, magnetic tape drive and the drafting style plotter are housed in the environmentally controlled room in the background.

FUNCTIONAL DESCRIPTION

With the foregoing description of the system hardware as a foundation, the system can be described in terms of the functions that it must provide. Four tasks are required for the inspection of diffusion-bonded parts. These are: the loading of the part into the immersion tank; the setup procedures; the C-scan procedures; and the investigation of flaw indications detected during the C-scan.

A part handling fixture is used to put the parts into the tank. The part is placed on the fixture at a staging area. Suitable standoffs and tiedown straps are provided to fasten the part securely. The fixture is then raised over the tank and is guided into place via wheels on the edge of the fixture that fit into guides on the side walls of the tank.

Once the part is in place, the setup procedures begin. These include the orientation of the C-scan plane to be parallel to the diffusion bond plane, the specification of the boundaries and the direction of the C-scan, the scanning of a reference block to calibrate the ultrasonic instrument, transducer calibration to ascertain that the minimum flaw size is detectable, and analysis of grain scattering noise in the part so that a reference block having a comparable level of grain scattering noise can be selected.

A few of these procedures will be described. Once the part is in the tank in the traditional system, the first operator task involves leveling the part, because in these systems the scanning is all done in a horizontal X-Y plane. In this system the different approach makes the scan plane parallel to the diffusion bond plane regardless of its orientation. This is done straightforwardly by using the transducer and ultrasonic signals to measure the orientation of the diffusion bond plane.

The second task involves defining the C-scan boundary. This outlines the region of the part to be scanned. To enter this outline into the computer, using the manual control box, the transducer is moved to a corner of the desired boundary. The enter button of the manual control box is pressed to record this position. The transducer is then moved to the next corner of the polygon defining the C-scan boundary and this point is entered by using the enter button. This procedure is repeated until all of the corners are recorded. The computer then displays the outline of the boundary on the color monitor.

The third task has to do with obtaining the C-scan. The C-scan occurs within the defined boundaries. The speed is defined by the operator with a maximum speed of 20 in./s. The distance between scan lines can be specified by the operator. The nominal value for most scans is 0.030 in. During the scan, all flaws that are detected will be displayed. The amplitude of the returned ultrasonic signal is stored digitally (along with a limited amount of position information) in the hard disk memory of the host computer. This information can be subsequently manipulated and/or permanently stored on magnetic tape. When the
scan passes over the edge of a part, this will be detected through the loss of the front surface echo and the edge will be delineated in a contrasting color. The scan image appears as the scan progresses. It can be in color, grey scale, a binary image, or a variety of combinations of these according to the specifications of the quality engineer. In addition, after the scan is completed and is being studied, the various flaw indications can be annotated. This is done using a joystick associated with the color monitor to position a cursor over the flaw indication. An enter key on the operator's terminal is used to store this information. Selected regions of the image can be magnified. To do so, a rectangular window is superimposed on the image to select the image region for the "zoom". If desired, a hard copy of the image can be obtained showing the annotations.

The fourth task has to do with investigating any flaw indications that are found. After the transducer has automatically returned to a flaw site designated by its annotation, several techniques can be used to characterize the flaw. A B-scan can be used to investigate the extent of the flaw region. The B-scan is obtained by using the manual control box to scan the transducer along the line. The resulting B-scan appears in real time on the monitor. The maximum amplitude of a flaw signal must also be determined. Since the flaw signal amplitude will vary as the angle of the transducer is changed slightly, a routine is provided for keeping the transducer aimed at a fixed point beneath the surface of a part as its angle is varied. The maximum value of the flaw signal is then recorded. For testbed applications, it is also possible to implement routines that will allow entire waveforms to be acquired as the transducer is moved to various positions in a preprogrammed spatial pattern centered on the flaw. These waveforms can then be used as input data for one of the advanced signal processing techniques that use the available inversion algorithms for obtaining quantitative data about the flaw.

SOFTWARE

A full description of the software is not possible in this paper; only a few key features can be noted. The software for the system is menu-driven. For each level of software in the control function tree, the various functions that can be accessed from this level are labeled in blocks displayed across the bottom of the terminal screen. These functions are activated by pressing one of the eight special function keys on the Tektronix terminal. This system of menus guides the operator through the inspection procedure from the initial identification of the part and display of the inspection instructions to the final storage of the acquired data.

Within this system of menus is a set of functions called "operate system" functions. These functions contain a wide selection of tasks or commands that the system can perform. An editor permits a senior operator or a quality engineer to arrange these tasks in a sequence that will lead to an efficient inspection of the part. Once the optimum sequence or program is achieved, it can be stored for subsequent use by all operators.

SUMMARY

We have presented an overview of a computer-aided system in which the various functions required to inspect diffusion-bonded parts have been fully integrated. The system provides a simple interactive way for the operator to set up the ultrasonic instrument, to adjust the orienta-
tion of the scan plane to match that of the part's diffusion bond plane, and to specify the boundaries of the C-scan. After a C-scan has been completed, the image is available for manipulation. The flaws can be annotated and the transducer can be returned to a specific flaw site for further examination. The image and various parameters that are relevant to the examination can be stored and recalled at a later time.

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