

DESIGN AND OPERATION OF A DUAL-BRIDGE ULTRASONIC INSPECTION SYSTEM FOR COMPOSITE MATERIALS

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INTRODUCTION

The accepted method of inspecting composite aircraft and engine components is ultrasonic testing with a C-scan presentation of results. Within the last few years, analog recording systems have been superseded by digital data acquisition and analysis. Programmable control of mechanical scanning has improved upon earlier machines which could test only simple flat and circular shapes. The equipment described here was designed to inspect complex profiles such as aircraft engine vanes and ducts. A unique dual-bridge design with synchronized eleven-axis motion control was used to achieve this. The success of the system resulted from careful definition of initial design, and from the use of high-level software to supervise the otherwise lengthy task of programming complex scanning profiles.

BASIC DESIGN CRITERIA

Mechanical and electrical design requirements are defined by the type of material and component to be tested, and from the nature and critical size of expected defects. In this case, the components were various aircraft engine parts made from carbon-fiber reinforced polyimide. The material is prone to microvoids in the plastic matrix as a result of gases produced in the curing reaction. These microvoids affect the matrix-dominated properties such as cross-ply tensile and interlaminar shear strengths. It is desirable to measure void content down to 1% by volume and delaminations down to 6mm diameter.

Detection and measurement of microvoids is done by an ultrasonic through-transmission method as described by Stone and Clark [1]. New curves of attenuation coefficient versus void content were derived empirically for the polyimide material. However, a pulse-echo technique is also needed in order to distinguish between microvoids and discrete delaminations or inclusions, as well as to measure the depth of discrete defects. For this reason the design was configured to perform both types of test.

The size and configuration of the engine components also dictated certain design decisions. A number of parts have a double skin, with an internal cavity. This cavity had to be kept full of water during through-transmission tests, a requirement which could be fulfilled easily for an immersion test, but was almost impossible for a squirter configuration.

Another factor in favor of the immersion system was the more compact gimbal design which could be used, facilitating access inside small components. One should recognize that squirter systems are preferable to immersion systems under many other circumstances; the inherent collimation of the ultrasonic beam imposes less restrictions on mechanical positioning, and they eliminate the difficulty of immersing large sandwich structures.

The most stringent requirements were produced by components with compound curvatures. Components with parallel faces (single or double skin) do not cause deviation of the normal-incidence sound beam, and the principal requirement is that the transmitter and receiver are co-axial, with the ultrasonic beam being within 2° of normal to the surface. This could be achieved using mechanical coupling through a rigid yoke, though this would be very cumbersome for large components. However, components with non-parallel sides, such as airfoil sections, refract the ultrasonic beam, requiring independent manipulation of the transmitting and receiving transducers (Figure 1). Three conceptual designs were outlined which could accomplish the required motions. The dual robot configuration (Figure 2a) has been successfully used for inspection of complex configuration parts. The use of commercial robots such as the Unimation Puma can eliminate some of the design and programming effort, but they cannot operate in the immersion environment. The remaining two possibilities are a single bridge with rotary bearing (Figure 2b), and a dual bridge design (Figure 2c). Both of these require control of eleven axes. The rotary bearing design provides a degree of mechanical coupling between the transducers, but it is restricted in range of transducer spacing and in the ability to straddle a large component. The dual bridge design provides more flexibility, and mechanically it is a simple extension of conventional single-bridge designs. The final choice of the dual bridge design was also influenced by the very short time available to procure the equipment: its commonality with existing designs resulted in a shorter procurement cycle.

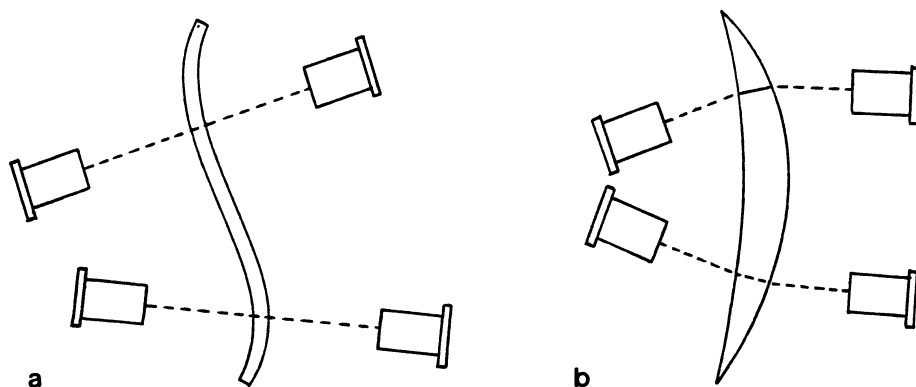


Fig. 1. Transducer alignment needed for scanning of (a) parallel-sided, and (b) airfoil section components.

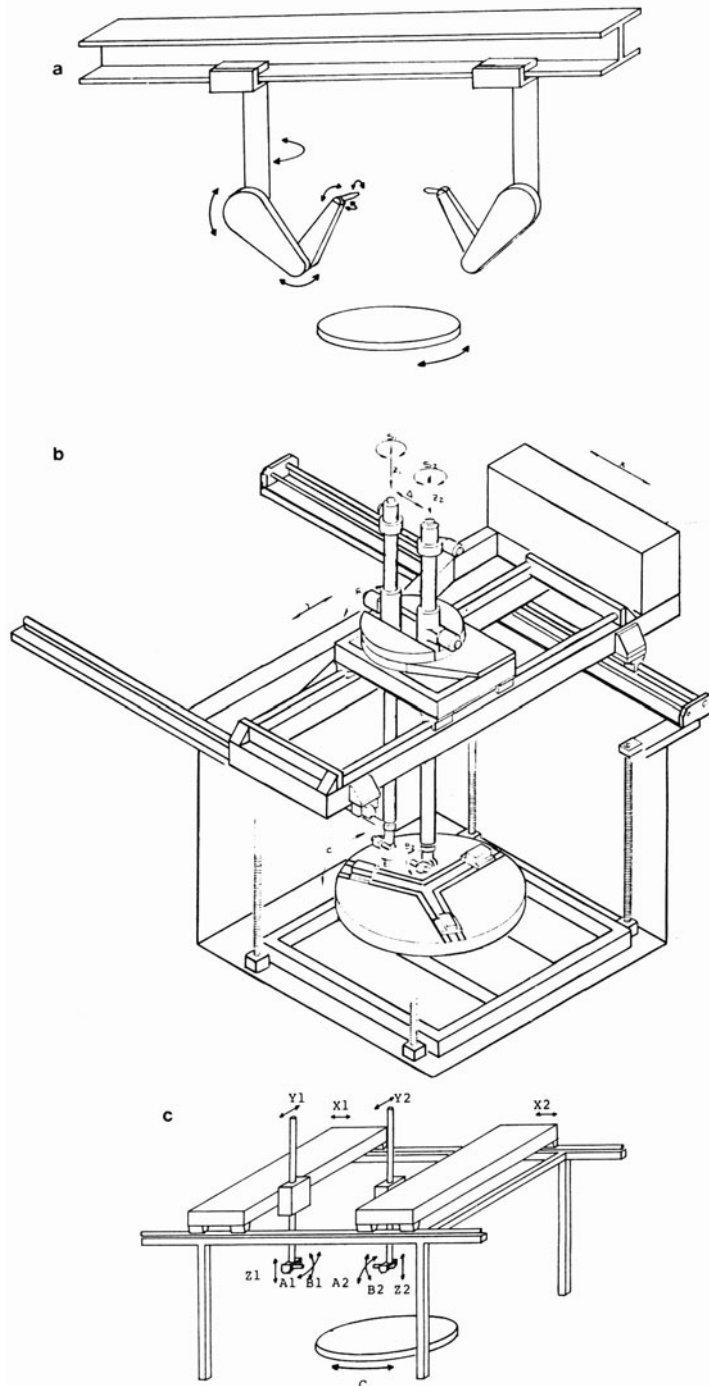


Fig. 2. Mechanical Configurations to Scan Complex Curvatures.
a) Dual Robot (13 Controlled Axes).
b) Rotary Bearing (11 Controlled Axes).
c) Dual Bridge (11 Controlled Axes).

EQUIPMENT DESCRIPTION

Based on the above considerations, a procurement specification was written, covering hardware and software requirements. The limiting constraint on mechanical accuracy was the need to maintain the through transmitted signal constant within 1dB. For the transducers normally used (5MHz, 0.25" diameter), this means that the focal points must be coincident laterally within 1.2mm. This can be accomplished by a combination of gimbal angular accuracy (within 0.1°), and linear accuracy (within 0.4mm) in the Y and Z directions.

The detailed design and manufacture of the system were performed by California Data Corporation. Configuration is shown in Figure 3, and Figure 4 is a view of the hardware. The DEC PDP 11/73 host computer runs under the RSX 11M operating system with timesharing of the motion control, data acquisition, display, and editing functions. Mass storage consists of an 80 MByte Winchester, with a tape drive for archival storage and an 8" floppy disc drive. Motion of the six linear axes is accomplished by DC motors with encoder feedback of rotary shaft position. Positioning of the five rotary axes is controlled by stepping motors. The Krautkramer-Branson KB6000 ultrasonic instrument operates under computer control with up to eight channels active. The multiple channels are used to increase the dynamic range beyond the limits of a single channel, and in pulse-echo mode allow "sectioning" of material into depth slices. An output on each channel of signal amplitude (7-bit) and time-of-flight (12-bit) is passed to the data acquisition system. During scanning, the active channels are sampled typically at a 1.2mm interval. Data from all channels are stored on disc, and one channel is displayed in near real time. Typical scans occupy 1 to 5 MBytes of disc storage. Color hard copy is provided by a Quadram inkjet printer and by a Nicolet plotter.

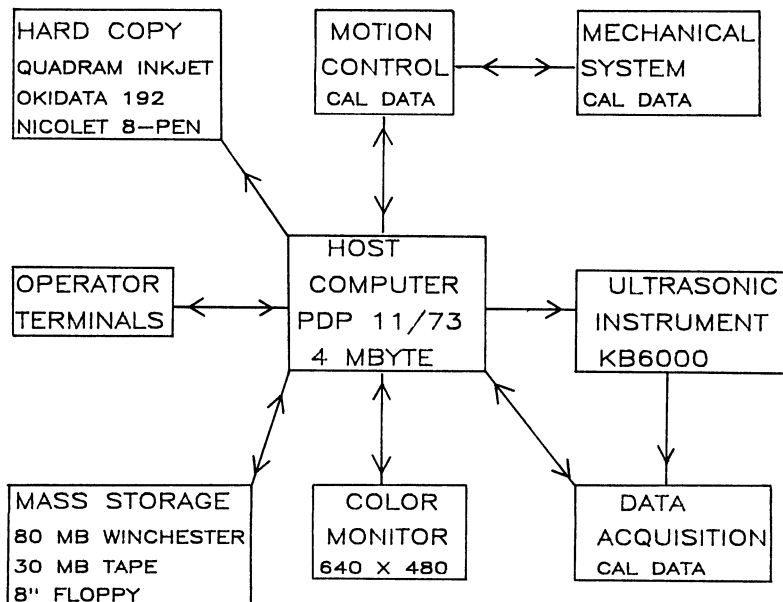


Fig. 3. Equipment Configuration

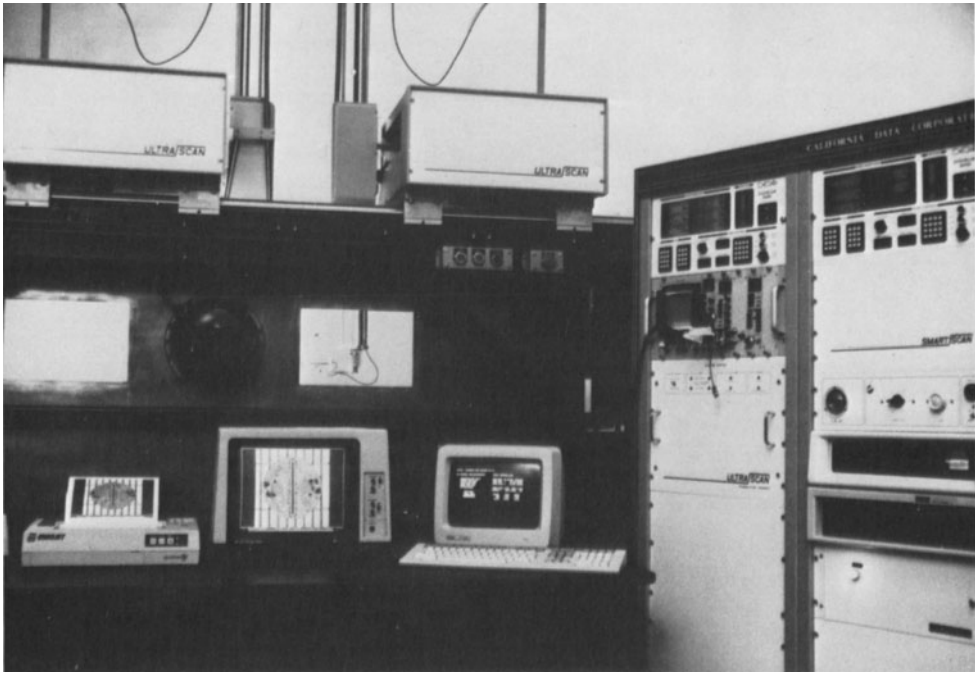


Fig. 4. View of System Hardware.

OPERATING PRACTICE

Inspection of a part is performed by execution of a command file which contains instructions for motion control, instrument setup, and data acquisition parameters. These functions may be included in the command file or called as subroutines. Prompts are displayed on the operator terminal to instruct the operator to perform any steps not under program control. At present these steps are part loading and unloading, initial alignment of transducers to a reference plane, and checking of calibration signal amplitude. Software routines are currently being written to perform these last three functions.

Programming of scan profiles is usually done by a teach process. A component of the type to be tested is fixtured in the tank. The mechanical axes of one bridge are moved under manual control to selected points on the scan profile, and the coordinates of each point are taught by a menu selection. The spacing at which points are taught depends on the curvature, a 25mm spacing is typical. When the points have been taught for one bridge, the positions of the second bridge are generated by the transformations:-

$$\begin{aligned} a2 &= a1 & b2 &= b1 \\ X2 &= X1 + R\cos(a1)\cos(b1) \\ Y2 &= Y1 - R\sin(a1) \\ Z2 &= Z1 - R\sin(a1)\cos(b1) \end{aligned}$$

Where R is the separation between gimbal pivot points and the axis definitions are as shown in Figure 2c.

A utility program then generates the interpolation between the points. The output is a motion control file which is either incorporated in, or called as a subroutine from, the master command file.

The usual data presentation is a color-mapped amplitude C-Scan for each active channel, as shown in Figure 5. The color lookup table can be defined in either color or grayscale, with control over the slope and offset of the table. Image analysis functions include zoom to magnify a selected area, position reports of cursor location, and histogram presentation of amplitude distribution in a selected area. Estimation of void content using attenuation / void content curves is inconvenient using the standard linear amplitude presentation. To simplify this process, a post-processing program was written to provide logarithmic output. This program also extends the dynamic range by combining up to four linear channels which have different amplification levels. The post-processing program acts effectively as a software logarithmic amplifier with a dynamic range of 80dB. For components of constant cross-sectional thickness, a color look-up table is then defined with color thresholds corresponding to 1% intervals in void content.

A more desirable way of incorporating the attenuation / void content relationship is to make thickness measurements at each data point as a part of the scan, and then calculate the local attenuation coefficient at that point. In theory, this may be implemented by a measurement of time delay between front and back surface echoes, or by a pulse-echo location of each surface from the closest transducer. Either method will present some practical difficulties on complex part configurations.

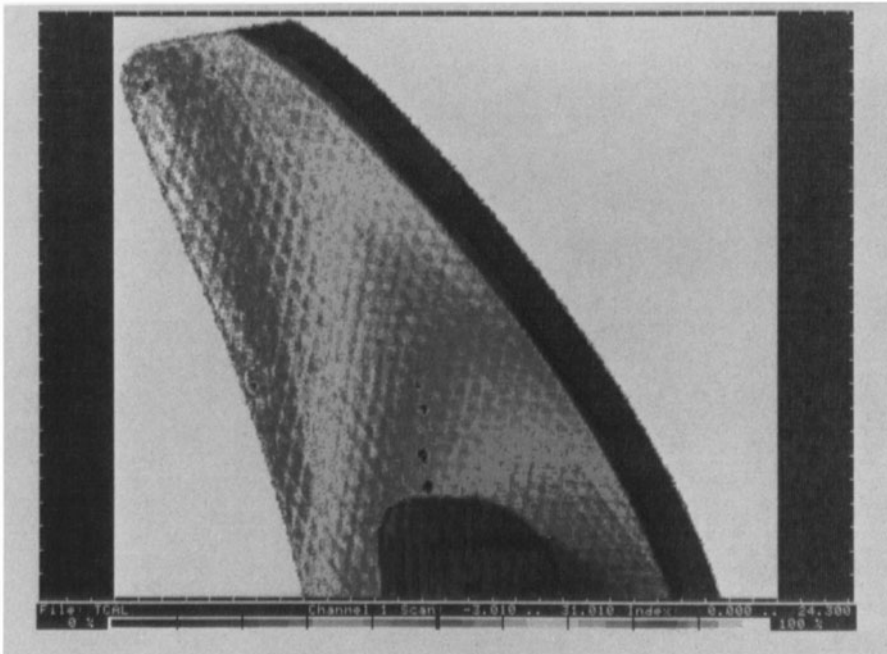


Fig. 5. Amplitude C-Scan of Composite Propulsor Blade.

OPERATING EXPERIENCE

Experience to date has been favorable, with unscheduled downtime below 5%. Most problems have been mechanical in origin, with software and electrical problems being minimal. Time to inspect components has been reduced by a factor of between two and five, compared with previous semi-automated equipment, with the greatest improvement being on more complex components. At present, more time is spent performing initialization and data analysis than is spent scanning parts. For this reason, future developments will be directed towards off-line data analysis, and the automation of the normalization and calibration routines. Another area where development is planned is the generation of scan profiles from geometric data obtained either from computer-aided design, or from an optical scan of the component.

SUMMARY AND CONCLUSIONS

The dual-bridge design has proved to be an extremely flexible and effective configuration for inspecting complex parts. The selection of a well-established computer and operating system (PDP 11/73 and RSX11M) resulted in a smooth introduction of the equipment and ready availability of expert help. Because of time limitations, the design was conservative, using existing modular designs and software wherever possible. Not surprisingly, most of the problems encountered were with the previously untested parts of the system. Improvements are still needed in the areas of interpretation of scan data, and the generation of scan profiles from geometric data.

REFERENCES

1. D.E.W. Stone and B. Clarke. Ultrasonic Attenuation as a Measure of Void Content in Carbon Fiber Reinforced Plastics. *Nondestructive Testing*, 8, 137 (1975).