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LARGE AREA, REAL TIME INSPECTION OF ROCKET MOTORS USING A NOVEL HANDHELD ULTRASOUND CAMERA*

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ABSTRACT

Ultrasound is arguably the most effective nondestructive testing method for the inspection of subsurface faults. However, hand scanning of parts is subject to inspector error and fatigue, and automated point-by-point is extremely time consuming. We are reporting on the results of the use of a novel ultrasound camera for the rapid inspection of composite rocket motor cases in both production and in-service settings. This camera technology can be used for a variety of materials of different sizes and geometries. Using this system, subsurface delaminations, voids, cracks and other faults can be seen with high resolution and quantified immediately. This technique results in scans that can be done several times faster than conventional point-by-point or hand scanning. A non-specialized technician can easily understand the resulting imagery. Each frame, presented at TV rates, presents a C-scan image over an area. Image processing performs real time video enhancement such as brightness, contrast, noise reduction, large montage images, etc. The ultrasound system is a lens-based and utilizes a two-dimensional imaging 120 x 120 element array. The array is similar to arrays used in standard video camcorders. However, the new imaging array is sensitive to ultrasound, not light. We will present recent data from the camera system on relevant rocket motor composite parts.

INTRODUCTION

Composite construction is amenable to a variety of aerospace applications due to its high strength-to-weight ratio. However, since this type of construction is not homogeneous and isotropic, its high strength is critically dependent upon its proper manufacture and freedom from subsequent damage. Breaking of the fibers, damage to the matrix, and delaminations of the plies are examples of the types of damage and defects that may occur. Of particular interest to the Air Force is the inspection of composite Solid Rocket Motor (SRM) cases for manufacturing defects and impact damage.

In order to investigate new methods for the inspection of the SRM, the US Air Force Research Laboratories (AFRL) at Edwards AFB, CA initiated a Small Business Innovation Research (SBIR) contract. Imperium, Inc. was awarded a Phase I SBIR contract in March 2002 to develop and demonstrate a prototype system based upon our ultrasound camera. Imperium partnered in this contract with Alliant Techsystems, Inc. (ATK), a major manufacturer of SRM, to provide representative samples and insight into the needs of industry.

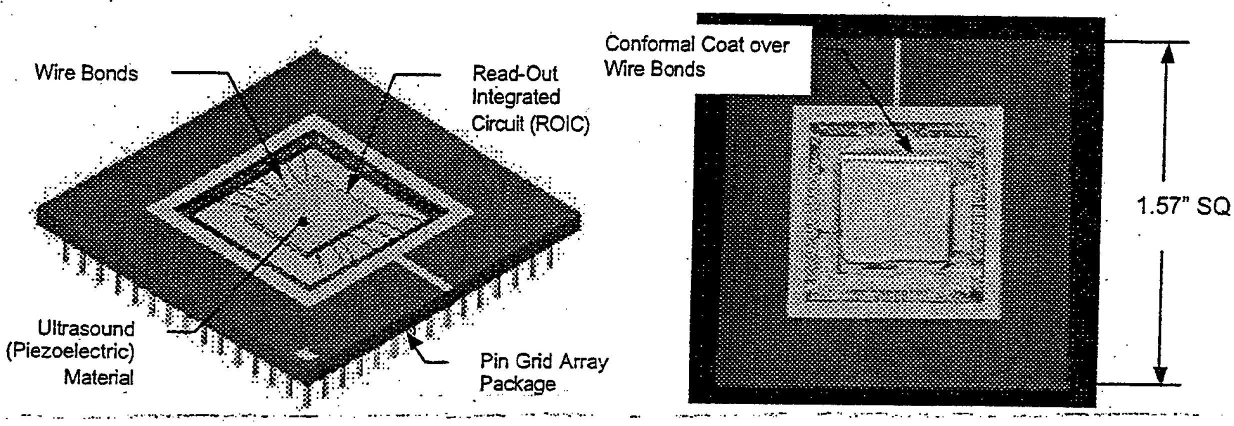
The Phase I program successfully demonstrated the ability of the ultrasound camera to detect representative flaws in SRM samples. As a result, Imperium was requested to submit a Phase II proposal and was awarded a contract in May 2003, again with ATK as a subcontractor. During this program, Imperium was to extent the Phase I work and design and fabricate a camera that can be used in either a portable configuration (for on-site inspection) or one amenable to use on a scanning system used in a production setting.

* This effort was performed under the sponsorship of US Air Force Research Laboratory under contract no. F04611-03-C-0022.

This paper describes the Imperium camera used in this work and the results to date.

IMPERIUM ULTRASOUND CAMERA

The Imperium ultrasound camera can be thought of as a "video camera" for ultrasound instead of light. Like a video camera, the basis for the system is a multi-pixel, silicon-based detector chip that senses the incident ultrasound signal as it has been modified by the Unit Under Test (UUT). This chip is shown in Figure 1.



b. Photograph

a. Array Schematic

Figure 1. Completed I400 Chip

The detector chip consists of an array of 120 x 120 (14,400) pixels at 100 μm spacing, each with integral circuitry that allows the capture and read-out of the peak signal that occurs during the period of time for which the detector is active. On top of the silicon die is a piezoelectric material that converts the incident ultrasound to an electrical signal that can be captured by the detector circuitry. The chip has controls for adjusting for pixel-to-pixel non-uniformities, built-in test, and the full control over detector read-out.

The chip is mounted in a Pin Grid Array (PGA) carrier that can be installed in a socket Printed Wiring Board (PWB) to provide power and control as well as interface to the rest of the AcoustoCam system. This carrier in turn is mounted within a mounting disk and an encapsulant used to cover the active die area and protect it from water.

The ultrasonic camera head is analogous to a light camera in that a lens system is used to focus the ultrasound "rays" on the face of the detector. Three common modes for using the camera, Thru-Transmission (TT), Pitch-Catch (PC), and Pulse-Echo (PE) with a beamsplitter are shown in Figures 2 – 4.

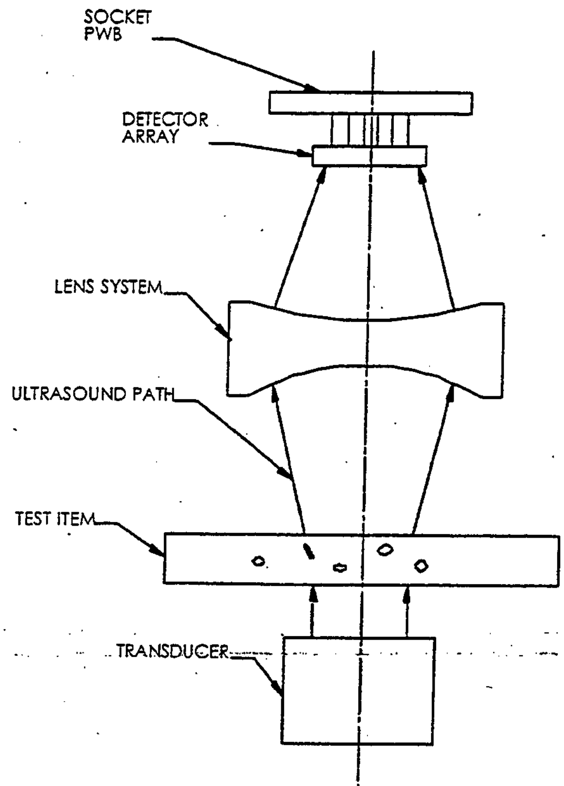


Figure 2. Thru-Transmission Mode

The camera is most easily explained in the TT mode using Figure 2. Here, the wide area transducer (up to a 3" diameter has been used) is used to illuminate the test item with an unfocused "flashlight" of ultrasound. The transducer is normally operated at its design frequency using an adjustable tone burst that may be varied in frequency, amplitude and overall width (in time). The ultrasound wave is transmitted through a low loss medium (typically water) and modified by the presence of the test item where it is both attenuated and modified by any internal structure.

The ultrasound then passes through an acoustic lens system that focuses the energy on the face of the detector. The lens system (which is made from a low loss polystyrene material) is designed such that the pulse leaving the transducer arrives at the same time across the detector face. Most of the lens systems designed for the Imperium camera consist of two separate lenses, one or both which are moved to achieve good focusing.

Once the ultrasound pulse arrives at the detector, the piezoelectric material converts the time varying pressure to an electrical signal. The individual pixel circuitry then detects the peak signal and stores it for future read-out.

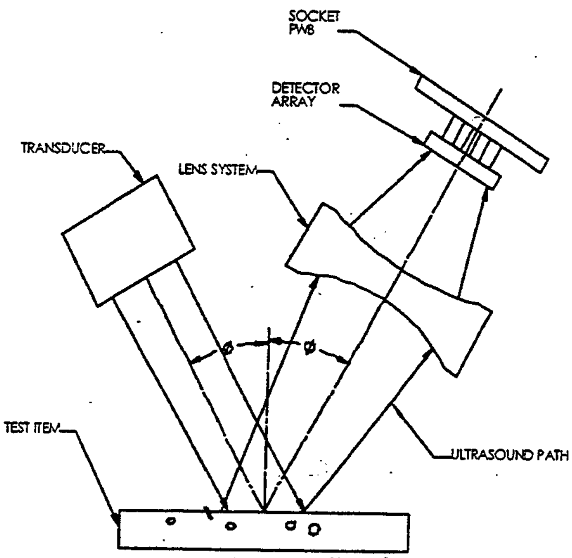


Figure 3. PC Mode

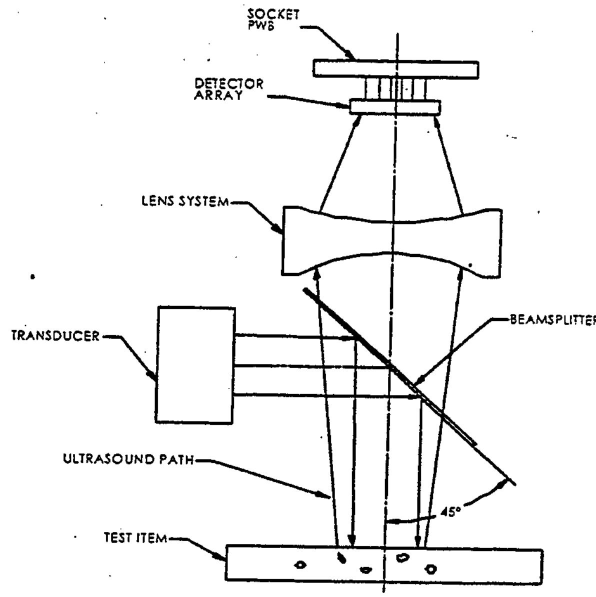


Figure 4. PE Mode with Beamsplitter

The PC and PE modes are similar in many senses to the operation described for the TT mode. In the PC mode, shown in Figure 3, the transducer is inclined to the camera axis. The reflected ultrasound is modified by the test item surface as well as its internal structure. In order to make camera designs that are more compact and utilize an ultrasound beam that is collinear to the camera axis, the PE mode with a beamsplitter (shown in Figure 4) can be used. Here the transducer transmits its pulse train directly towards a beamsplitter (a brass plate has been used successfully) that is inclined at 45° to the camera axis. Approximately, 50% of the energy is reflected at the beamsplitter interface, while 50% is transmitted.

The reflected energy is directed towards the test item where portions are reflected back from the surfaces and internal structure. Approximately 50% of this reflected signal passes through the beamsplitter and continues on through the lens system and to the detector.

While the beamsplitter energy losses are undesirable, it is not quite as bad as it first seems. The Imperium detector chip responds to a peak voltage that is proportional to the incident pressure. The pressure reduction is 50% instead of the 75% energy reduction, a level at which meaningful images can be collected.

By using the building blocks of the system shown in Figures 2 –4, it is possible to configure a number of different configurations of "ultrasound cameras." For example, the system components can be designed to fit in waterproof enclosures and be submerged within a water tank. It is also possible to enclose the detector and lenses within a water-filled cylinder and couple to the test item by using a flexible acoustic membrane.

INITIAL TESTS

To demonstrate the applicability of the Imperium camera to the inspection of SRM cases, Imperium arranged with ATK obtain samples with representative flaws. The cross-section of a typical rocket motor from which the samples were taken is shown in Figure 5. In general, these flaws consisted of SRM cases that had intentional impact damage.

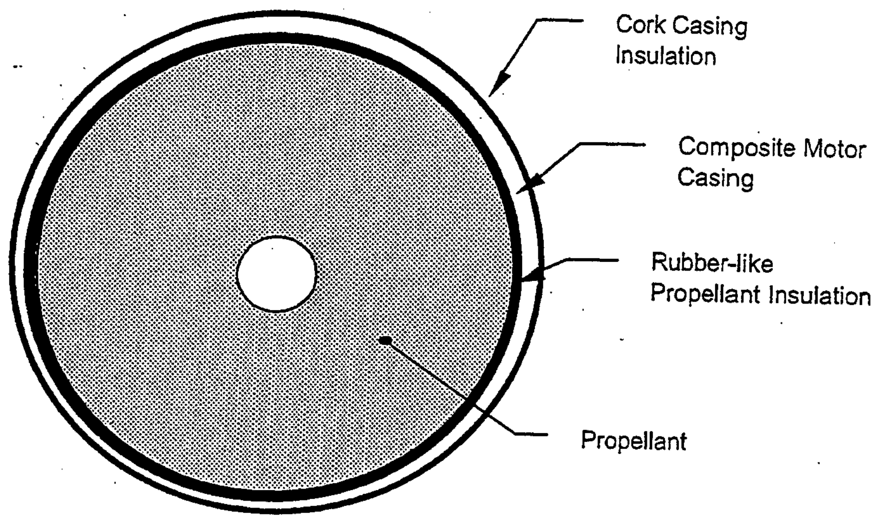


Figure 1. Cross-Section of Typical Rocket Motor

A tank-based system operating in the PC mode was configured to examine these samples as shown in Figure 5.

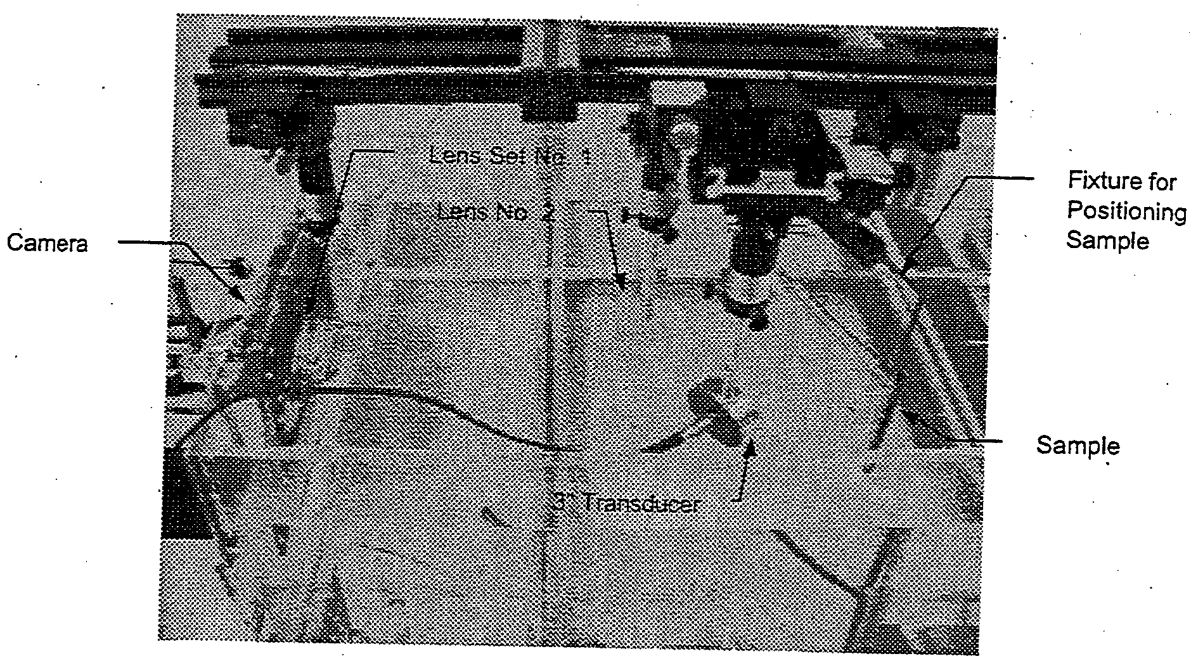


Figure 5. Overall Pitch-Catch Test Set-Up

Here the camera is attached to the sidewall of the water tank, while the lenses, transducer and test sample are suspended in the tank. The transducer and lens set is designed to permit a 3-inch (75 mm) diameter Field of View (FOV). The 1 MHz ceramic transducer was driven at its center frequency by a tone burst. The sample shown in Figure 5 is a 0.38-inch (10 mm) thick graphite epoxy composite with a 0.13-inch (3 mm) propellant liner. The sample has been cut from an SRM and has a radius of 30 inches (762 mm). Images collected from this sample, from both acceptable and impact-damaged areas, are shown in Figure 6.

a. No Damage

b. Impact Damage

Figure 6. Impact Damage as Measured in PC Mode

It can be seen that the images shown in Figures 6a and b are strikingly different. The region of impact damage has resulted in a delamination with an associated air gap that reflects a high level of incident ultrasound and is displayed as a white region in the image. Areas without such delaminations appear as a nominally dark field.

Imperium did further experiments with different samples and at other transducer frequencies. In general it was discovered that good results were achieved with solid composite panels using a 1 MHz transducer. For samples having a honeycomb core, frequencies up to 5 MHz were used to detect flaws. It was not possible to penetrate samples with an exterior cork heat shield at any of the frequencies used.

Based upon the encouraging results obtained with these tests, Imperium was awarded a Phase II contract to extend this work and to develop cameras more suitable for use in production and on-site environments.

CURRENT WORK

In order to achieve widespread acceptance of this technology, it is necessary to remove the camera from the water tank and implement it in some type of more compact, enclosed system. In the case of SRM cases, it was desired to have a system that could be used in either a portable, handheld configuration or one more suited for a factory production environment. In the first configuration, the camera could be used in the factory or on-site to inspect for regions of localized damage. In the production configuration, the camera could be employed to inspect large areas of the case during production acceptance testing. In particular, the production camera could be mounted on a scanning system with many individual images being integrated to create a large composite image.

The handheld system was configured to consist of three major components, a camera head, control unit and computer, arranged as shown in Figure 7 with the actual hardware in Figure 8. The control unit is used to both drive the transducer and to control the detector and read out the digital data that is later converted to video images. The computer is used for operator control through an intuitive Graphical User Interface.

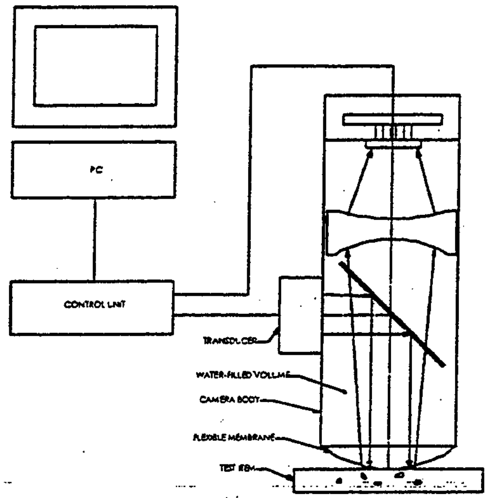


Figure 7. Handheld Configuration

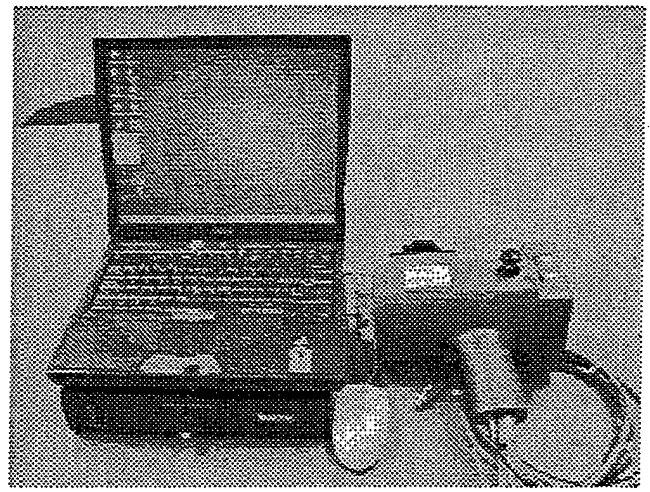
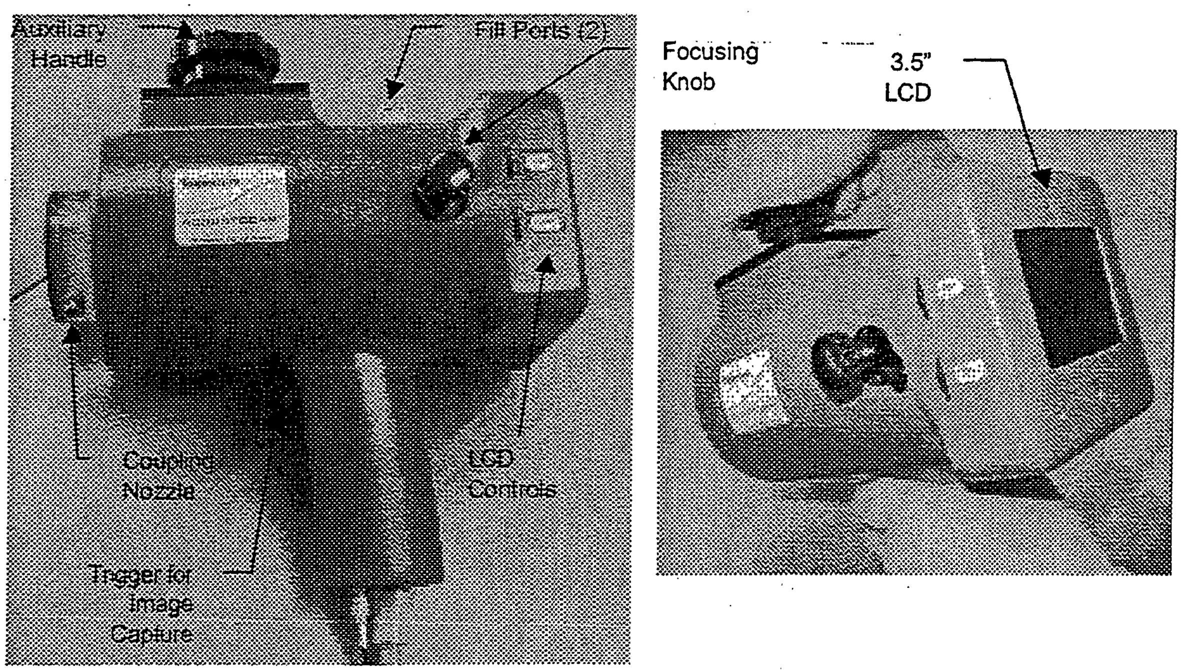


Figure 8. Handheld Hardware

The camera head is the key component that permits this system to be handheld. As shown in Figure 7, the camera head operates in the PE mode with the transducer generating a collinear wavefront by using a beamsplitter. A more detailed view of the camera head (that provides a 1 inch (25 mm) FOV) is shown in Figure 9. This unit is approximately 10 inches (254 mm) in length and weighs about 5 lbs. (2.2 kg.). Coupling between the UUT and the camera head is achieved by a flexible acoustic membrane and a coupling agent (either water or ultrasound gel).



a. Side View

b. Rear View

Figure 8. Camera Head

This system has demonstrated the capability to effectively detect flaws within various composite parts, including those representative of SRM cases. Some typical images are shown in Figure 9. It can be seen that delaminations and intentionally embedded foreign bodies are readily visible.

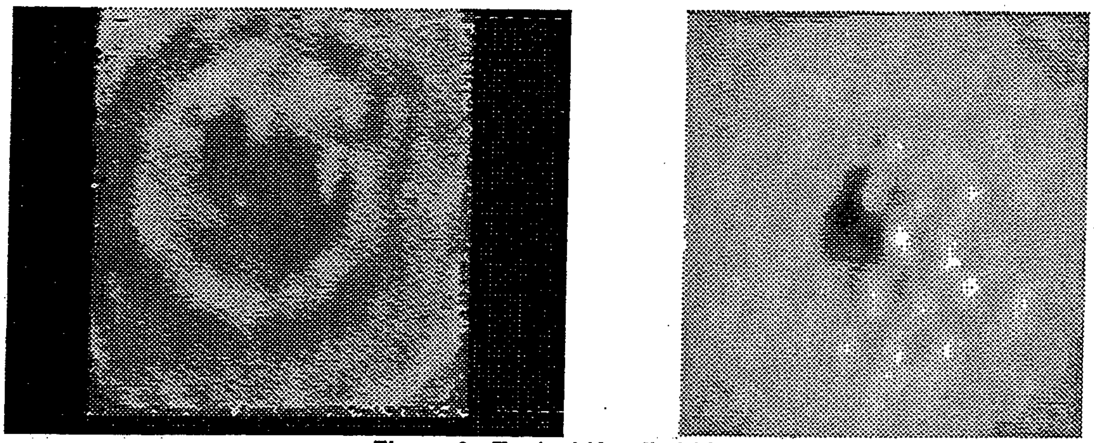


Figure 9. Typical Handheld Images

In order to rapidly inspect large areas of an SRM in a production environment, it is desirable to reconfigure this camera head such that it can be mounted on a scanner device such as that shown in Figure 10.

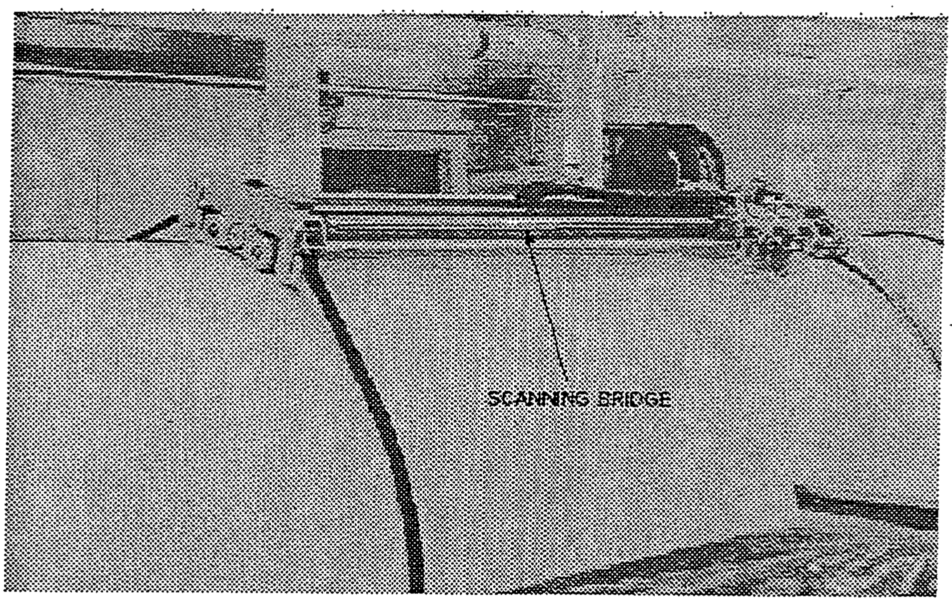


Figure 10. Production SRM Scanning System

In order to do this, Imperium has designed the key interior functioning components of the handheld camera head such that they can be removed and mounted on an SRM scanner. A view of this modified camera head is shown in Figure 11. Tests with this camera head have just begun.

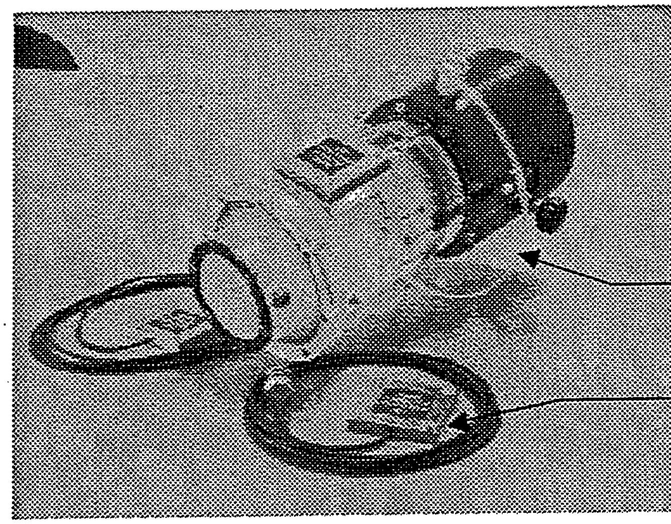


Figure 11. Production Camera Head

SUMMARY AND CONCLUSIONS

The development of an ultrasound camera for the inspection of SRM cases offers the potential for the timesaving inspection of this critical aerospace component. Tests by a major aerospace manufacturer with an earlier version of the Imperium camera concluded, "The Acoustocam has an inspection rate over fifteen times greater than that of manual scanning."

Our work has shown that such a design is practical and has been demonstrated on a prototype unit. The prototype has shown through functional tests that it can detect flaws in composite SRM parts (as well as other composite aerospace parts) and the resulting real-time images are displayed in a manner that is easily interpreted by the operator. This offers the potential for allowing on-site tests to be easily done when impact damage is suspected. Because of the wide area coverage, it should also result in dramatically decreased inspection times in a factory, production environment.

FUTURE WORK

Work is presently underway at Imperium to quantify the performance of the camera in terms of minimum sensitivity, resolution and dynamic range. We are working with ATK to develop standard samples to test these parameters as well to define the performance that can be achieved with real-world SRM samples. In addition, Imperium continues to work on further improvements to this developing technology. These improvements include; improved images, increase in frequency bandwidth, battery operation, improved range-gating, high-speed digital data downloads, greater FOVs, decreased camera head sizes, and other similar improvements that will result in broader commercial appeal.

A parallel effort is underway at ATK to evaluate the production camera when mounted on a scanner unit. One goal of this work is to quantify the potential savings that this system could provide when compared to a traditional point-by-point scan of an SRM case. ATK is currently working on creating a ingle large composite picture from many individual images.

ACKNOWLEDGEMENTS

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