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A Century of Boeing Innovation in NDE

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***Abstract* – This past year Boeing reached its 100 year birthday. The author has been inspired by this significant milestone to provide a review of the advancement of a specific technology area—namely NDE (Nondestructive Evaluation)--that has been an important part of Boeing's success during its first century of building airplanes. Boeing has been a world leader in NDE innovation, developing technology and methods for ensuring the structures with which it builds its many aerospace products are safe and are performing as-designed. This paper introduces the reader to the subject and purpose of NDE, and then goes on to address important past, present, and future elements of NDE development at Boeing.**

Index Terms – Inspection, Nondestructive Evaluation. NDE, NDT, NDI, Testing, Ultrasound, X-ray, Eddy Current, Bond Strength, Composite, Laser Ultrasound, Backscatter, AUSS, Blade Crawler, ROVER, Laser Bond Inspection

I. Introduction

As the Boeing Company enters its second century of flight, it is worthwhile to review the advances that have been made in an important technology area—namely Nondestructive Evaluation (NDE)—that have paralleled and sometimes enabled so many others. At times this core competency is referred to NDI (Nondestructive Inspection) or NDT (Nondestructive Testing), depending upon its particular application or industry of use.

NDE can generally be defined as the evaluation of a structure without harming or affecting its purpose. This definition sets NDE apart from destructive or mechanical testing of subscale or full-scale structures, which allows the determination of properties or flaws, but which makes the part unusable afterwards.

The specific goals of NDE (and NDI or NDT) have been expressed very well by Robert McMaster in 1959 in the American Society of Nondestructive Testing (ASNT) Handbook [1]:

- Ensuring Reliability of the Product
- Preventing Accidents and Saving Lives
- Making a Profit for the User
    - Ensuring Customer Satisfaction
    - Aiding in Better Product Design –Weight and Cost Savings
    - Controlling Manufacturing Processes
    - Maintaining Uniform Quality Level
    - Providing Early Warning of Impending Maintenance Issues
    - New Products and Business Opportunities

Ensuring reliability of the product and preventing accidents and saving lives are important and obvious goals for NDE. The goal of "making a profit for the user" is often underappreciated, yet is essential to the effective use of NDE for a manufacturer like Boeing. As aerospace manufacturing platforms have grown more competitive in the recent decades, NDE development as a cost and flow time-reducer has become more critical to Boeing.

NDE research and development has been organized in various forms and organizations over the last century. This responsibility currently resides within the Advanced Inspection Technology (AIT) group, under the Advanced Production & Inspection group within Boeing Research and Technology (BR&T). AIT's mission is to be the provider of NDE innovation and technology for all Boeing products, services, and customers. This mission is accomplished through NDE and measurement research, NDE system development, analysis for advanced materials and structures, and NDE/Measurement support to business units and the enterprise as a whole.

NDE for aerospace industry covers two distinct but related application areas: NDE during production, and NDE during in-service usage. NDE for both these application areas has evolved dramatically over the last 100 years. The tremendous advancements in aerospace materials and structural designs—from cloth bi-planes, to largely aluminum structures, to composite primary structure—have required aggressive and innovative advancements in NDE.

II. History of Aerospace NDE

The early history of NDE emergence into aerospace is a fascinating one. When the Boeing Company was founded in 1916, only three industrial NDE approaches existed at that time: visual inspection, the "oil and whiting" method (which would later become what we know as penetrant inspection), and radiography. These methods were developed from non-aerospace applications and applied to Boeing airplanes. Visual inspection processes were developed in the mid-19th century in response to boiler failures, including the famed Sultana incident which killed almost 1900 POW's returning from the Civil War. This was the first maritime disaster in US history. The oil and whiting method was developed in the mid-19th century to support rail inspections for the railroad industry due to a number of catastrophic failures. Wilhelm Roentgen developed the first x-ray inspection process in 1895 and his first paper discusses the possibility of flaw detection for industry [2].

Visual inspection was exclusively used in the early years of aircraft up to the early 1930s, when the first all metal airplane, the Boeing Model 247 was introduced. From an NDE perspective, the 1920s saw the introduction of industrial radiographic inspection processes for metals developed by Horace Lester [2] and the first magnetic induction/magnetic particle inspection approach by DeForest and Doane [3]. These were applied on a limited basis for inspection of Model 247 components as well as the more mass-produced Douglas DC-3 that came along in 1936.

DC-World War II saw the development of the first eddy current instruments as well as the first ultrasonic testing method developed by Floyd Firestone [4]. These became the crux of aerospace NDE as Boeing entered the jet age in the mid-1950s. As the space program came along in the 1960s, Boeing (McDonnell) had a hand in the development of the first sondicator to support inspection of heat shield bonds on the Gemini spacecraft, probably the most critical element of the vehicle. The early sondicator led to development of more advanced low frequency bond testing methods still used today for inspection of adhesive bonds.

III. Progress in Aerospace NDE

The first commercial Boeing airplane structures, like the one shown in Figure 1, were visually inspected during manufacturing to verify proper wood frame assembly, fabric attachment and adhesive application during fabrication. These early airplanes were periodically visually inspected during in-service use for damage such as fabric tearing, adhesive failure, and wood frame damage or degradation. No instruments beyond the human eye were used, except possibly lighting aides or magnification to improve defect detectability.

The rather rapid move from wood, cloth and glue to aluminum aircraft structure (Figure 2) required the development of NDE technology and methods that are still used today in one form or another. New material systems with new risks and uncertainties were often prevented from finding widespread use on aircraft until NDE technology was available to address the unknowns.

Figure 1. Early Boeing airplanes like this one were visually inspected.

Figure 2. Airplanes made of aluminum structure, like this Boeing 707, increased the inspection challenges and opportunities, and led to many applications for emerging NDE methods.

Several major air catastrophes drove the need for better NDE. F-111 airplane crashes (late '60s and early '70s) due to fatigue-induced cracking led to a 'damage tolerance' strategy for design and inspection. The F-111 crashes led to the introduction of the fail safe / damage tolerant design philosophy [5]. The first aircraft designed in the damage tolerance era was the Boeing (McDonnell) F-15. Boeing, along with Pratt & Whitney from the engine side, took the lead in addressing inspection reliability in conjunction with all NDE processes used to support manufacturing. Boeing also was the first to utilize structural analysis and NDE reliability assessments to define in-service inspection intervals. The well-known 1988 Aloha Airlines fuselage peeling led to an 'aging aircraft' monitoring approach. The Aloha Airlines explosive decompression incident in 1988 was caused by widespread fatigue damage. This incident, along with the United Airlines DC-10 crash in 1989 (engine) and corrosion failures associated with the KC-135 in the early 1990s led the FAA to join with the DoD and NASA to cooperatively address aging issues. This resulted in significant funding going to aging aircraft research, including NDE. Much of the funding that was applied to development of new AUSS Mobile (page 4, and Figure 5b) capabilities was derived from the aging aircraft initiative. The Columbia STS-107 disaster, when the orbiter broke up on re-entry, was also a driving force for new NDE. Boeing had a major role in NDE development associated with the shuttle "return to flight," including new inspection processes for carbon-carbon ceramic materials, spray on foam insulation, and thermal barrier systems. Boeing also brought visual inspection to a new level during this time, having a hand in development of a visual inspection process performed in space.

Airplanes, like many other structures today, are designed to be damage tolerant, so that NDE of detectable damage occurs before part failure. Inspections designed specifically for monitoring aging mechanisms, like corrosion, are used to prevent failure of the structure. In-service NDE would be used to identify damage while it was within the designed tolerance and safety limits, so that repair or replacement could be done before the part fails. The result of a failure will depend upon whether it is critical flight hardware or secondary (non-critical) structure.

While visual inspection continued to be the primary NDE method, visual inspection could no longer address the defect and damage detection needs, especially in-service. Metal fatigue caused by the cyclic stresses of aircraft flight produces small cracks that must be identified before they grow to the point of structural failure. These fatigue cracks, and cracks generated by excessive loads or corrosion could be identified using an NDE method called dye penetrant, which relies on a dye wicking into surface cracks. Structural parts made with most steels could be inspected with magnetic particle inspection. Both these methods essentially enhanced visual inspection, and continue to be used today for tubes, brackets, housings, etc. Visual inspections require human reckoning that require high skill interpretation and judgment. As the need for inspection increased new instrumented methods had to be developed to allow discovery with less judgment.

An electric current-based method called Eddy Current (EC) testing, developed first in the industries making and inspecting pipes and tubes, was the first significantly utilized instrumented method of NDE in aerospace. With this method, a changing electromagnetic field is generated by a coil containing alternating or pulsed electric current. The field produces corresponding electric (eddy) currents in the metal, whose paths are modified by cracks. The same coil or a separate receive coil senses the field change that the eddy currents produce, thereby allowing detection of cracks using electronic circuitry and (first) analog then (later) digital display. Figure 3 is a photo on an inspector using an eddy current instrument to find cracks in an airplane structure. Magneto-Optical Imaging (MOI) was developed in the '80s to enable 2-D EC-based imaging of cracks around fasteners in fuselage lap joints and other structures. Linear EC arrays have more recently been developed that can be swept along a lap joint for in-service inspection for cracks around fasteners.

Film x-ray was the first radiographic NDE method used for aerospace structure, to find cracks, voids, and foreign material. It was also very effective with moisture detection in metal honeycomb used for flight control surfaces, like flaps and trim tabs. Boeing was involved in the development and implementation of advanced radiographic inspection processes in the 1990s, including Digital Radiography (DR) and X-ray Computed Tomography. The film-to-digital transition was driven by the advantages of digital data sets as well as the cost reductions and environmental benefits of eliminating film, processing chemicals and disposal. Digital forms of X-ray like DR and CT have replaced film x-ray for many aerospace applications in recent decades, due also to the development and advancement of X-ray detector panels.

Image Courtesy of Cessna Aircraft Company

Figure 3. An inspector is using a portable eddy current instrument to inspect for cracks on an airplane structure.

Boeing R&D work under Air Force sponsorship in the early to mid-1990s established standards for CT evaluation of aerospace components and the resulting reports are still referenced today [6]. CT provides 2-D and 3-D imaging of material density, voids, porosity, and geometry, with very high resolution capability for smaller parts. Boeing uses these systems today mostly for structure and material system analysis and manufacturing R&D. Today, CT is a key technology in supporting qualification and certification of metallic parts fabricated using additive manufacturing processes.

Ultrasonic Testing (UT) is another important NDE method for aerospace structure. UT uses high frequency stress waves generated at the surface of a structure to interrogate a structure for defects that reflect or attenuate the signal. UT can be performed from one side of a part with a single transducer that sends and receives an ultrasonic signal, or in a through-transmission mode, with a sensing transducer listening for losses in transmission that is caused by flaws. UT has the benefit of being able to see deeper flaws than EC, and will work in non-electrically conductive media. UT's use on aluminum aircraft structure has grown over the years, in particular with identifying in-service damage and degradation [7][8].

As the complexity and design criticality have increased, composites, as a percentage of an airplane structure, have increased as well. Boeing (McDonnell, at the time) pioneered the use of structural composites, starting with the boron/epoxy rudder developed for the F-4 back in the 1960s and then expanding dramatically with the development of the F/A-18 and AV-8B Harrier II back in the late 1970s. The AV-8B, 27% by weight composite, was the first aircraft to employ an all-composite wing. These accomplishments drove the development and commercialization of automated ultrasonic systems in the late 1970s and early 1980s.

While secondary structure on commercial aircraft, like flaps or ailerons have been made for years with composites, significant use is relatively recent. The Boeing 787 uses just over 50% by weight of composite materials on its primary structure (Figure 4), and the 777X is being developed to have composite wings and metal fuselage. Composite materials are ideal for an airplane. Composites are conducive to larger, more integrated designs. Composites allow for tailored properties, such as stiffness or tensile strength, they are fatigue and corrosion resistant, enabling reduced maintenance costs and fewer inspections. But the complexity of composite structure has driven the need for innovation in NDE, directed at cost-effective methods that will assure manufacturing quality and safe in-service performance.

Figure 4. Boeing 787 Dreamliner, whose structure is just over 50% composite by weight.

Ultrasonic inspection of composites has benefited from improvements over the years with electronics, automation and computing power, so that 2-D and 3-D imaging and analysis of UT data is now common place. Boeing has been a world-leader in the development of automated ultrasonic scanning systems, for production and in-service inspection of composite structure. Boeing researchers have developed and implemented many ultrasonic x-y-z automated gantry, water tank UT, feed-through, and (recently) robotic scanning systems that are used internally and also sold world-wide under the Boeing AUSS (Automated Ultrasonic Scanning System) moniker. Composite aircraft wing and fuselage skins, spars, stiffeners, floor beams, and other laminate structures are inspected with a Boeing AUSS, with a single operating system that enables elements such as inspection path planning, probe signal activation and collection, and data display and analysis. Two examples of Boeing AUSS options are shown in Figures 5a and 5b.

The current Boeing AUSS product line offers a standard user interface, modular hardware interfaces, sensors and motion control systems, and is critical in supporting current and future Boeing composite aircraft manufacturing.

To date, over 70 AUSS gantry systems (such as shown in Figure 5a) are used across the aerospace industry by OEMs, composite part manufacturers, as well as Department of Defense maintenance facilities. The AUSS Mobile systems (Figure 5b) used for portable multi-modal (UT, EC, etc.) on-aircraft scanning, have become standards for a broader range of maintenance operations, including corrosion detection, crack detection and disbond detection in bonded structure. Over 130 systems have been sold to industry, government and academia in support of manufacturing, maintenance and research and development. In total, the impact of Boeing's advances in automated systems have resulted in over a hundred million dollars in equipment sales and billions of dollars in cost savings, through reduced inspection time and improvements in quality.

Figure 5a. Boeing AUSS Tower, used for NDE of large composite structure during manufacturing.

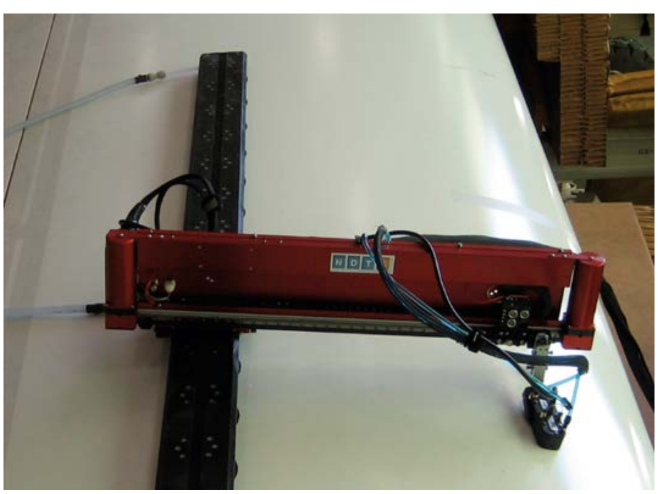

Figure 5b. Boeing AUSS Mobile, used for on-aircraft in-service NDE applications.

IV. Recent Advancements in Aerospace NDE

There have been many innovations in NDE technology and methods in the last several decades that have impacted the aerospace industry. Increases in computed-based data collection speeds and storage capacities have transformed many industries, including NDE. One NDE method that has benefitted has been ultrasound, with the innovation of phased array ultrasound (PAUT), which was originally developed in the medical field for looking into the human body. With this technology, a linear set of transducers can be activated in various time-phased or simultaneous options that dramatically increase ultrasounds' speed and capabilities over traditional single transducer inspections. Boeing researchers have developed and implemented many end effector innovations using ultrasonic PAUT technology [9]. Most composites structure fabricated by Boeing or its suppliers is now inspected with PAUT-based inspection systems, and PAUT is fully integrated into the Boeing AUSS family. Boeing has also taken advantage of the development of robotics to develop advanced NDE systems for the 777X. One excellent example is the 777X wing spar inspection cell that uses multiple robots to handle the spar and move out of the way when the inspection robot moves past to collect PAUT data (Figure 6).

Figure 6. 777X Wing spar Robotic NDE Cell. The row of robots on the left hold and spar, while the robot on the right inspects it.

New NDE approaches are also needed to support in-service commercial and military aircraft and space systems. Improved in-service NDE sensors and methods are being developed to rapidly conduct fleet inspections with less disassembly. These sensors generally fall into three categories: 1) limited access inspection tools that enable inspection of interior structure without disassembly, 2) structural health monitoring or In-Situ NDI sensors, systems, and 3) sensors with speed, defect sensitivity, cost, simplicity of use, or networkability improvements.

The goal of Boeing in-service NDE R&D is ultimately to increase business revenue through the development, and implementation of in-service NDI equipment and procedures. There has always been an important role for NDE support to the Boeing business units, and Enterprise as a whole. This support includes in-service FAA responsiveness (fleet inspection procedures, airworthiness directives), supplier 911 calls, service bulletins, personnel certification requirements, NDE inspector roles, NDE equipment qualifications at Boeing and its suppliers, NDE standards, and rapid support for unplanned event needs across the world.

Business-related NDE benefits Boeing has enabled and passed on to its customers include: reduction of inspection time and cost, increased inspection intervals, reduction of tear-down and re-assembly costs, and critical structure/system implementation. We have delivered improved NDE technologies and methods to depot and field-level personnel, and provided high-value NDE support services to our commercial and military customers. Several examples are described below.

A ‘Surgical NDE’ tool is any device, whether hand held or fully automated (or anything in between) that allows an NDE sensor to be guided through an access hole of a closed space, and placed on or near a region to be inspected. The primary purpose for Surgical NDE tools is assessment without disassembly. When the 787 program needed a means for customers to inspect the center section of the horizontal stabilizer through multiple bulkheads, a Boeing NDE team applied what they learned building and testing a tool for the Air Force [10] shown in Figure 7 to a more advanced next generation motorized ‘Extended Reach Tool.’ The ‘Extended Reach Tool' is baselined for use on up-coming 787 maintenance D-checks and is expected to cut Boeing and customer inspection cost and time by more than 50% by eliminating disassembly and re-assembly shown in Figure 8.

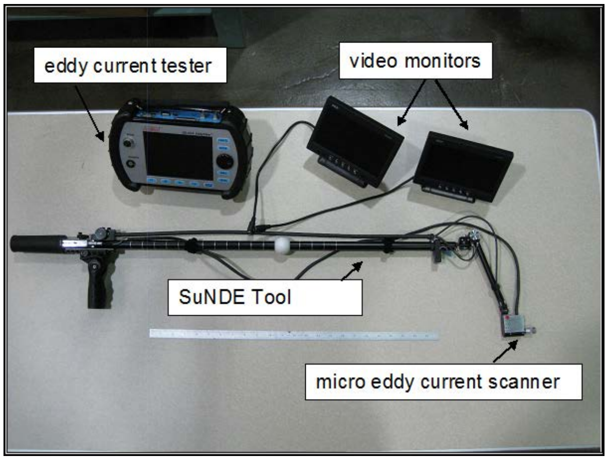

Figure 7. USAF Surgical NDE Tool developed under contract to Boeing.

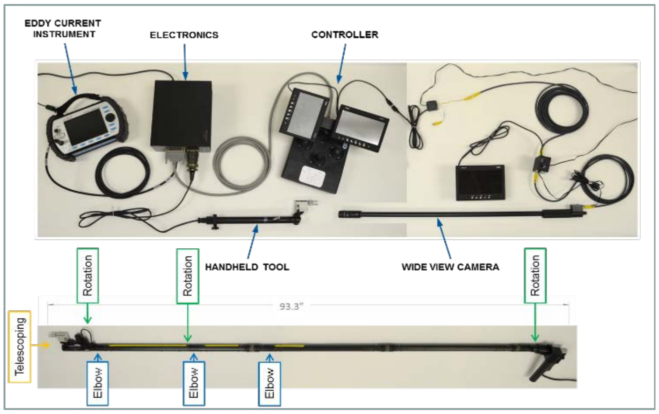

Figure 8. The Boeing Extended Reach NDE Tool was developed for surgical inspection applications, including the inspection of fastener areas in the interior bay of the 787 horizontal stabilizer center box. The tool contains multiple rotating motorized joints, a telescoping end joint, and a camera for situational awareness.

‘In-Situ NDE’ is the name for the general application of NDE sensors directly on a structure structural testing or in-service use. In the structural test application, multiple NDE sensors are mounted using various methods at locations where failure is expected to initiate or grow under load. In-Situ NDE enables precise correlation of loading conditions and levels to specific composite damage, thereby allowing the validation of designs and failure models/predictions.

Boeing NDE researchers developed and patented the sensor attachment and data collection method, which is now used on virtually all Boeing composite structural testing. In-Situ NDE provided critical location damage monitoring on the 787 sub-scale and full-scale tests used to validate structural performance. In-Situ NDE is now implemented on all 787 and 777X composite structural tests. An estimated $2-4M per year is avoided by replacing a percentage of costly tests with advanced analysis methods enabled and validated by In-Situ NDE. A $1M/yr estimated additional value comes from improved damage monitoring of more than 100 tests per year. In 2015 a costly 787 side-of-body repair was avoided with the help of In-Situ NDE data. Figure 9 is a photograph of In-Situ NDE ultrasonic transducers attached in various means to structures under test.

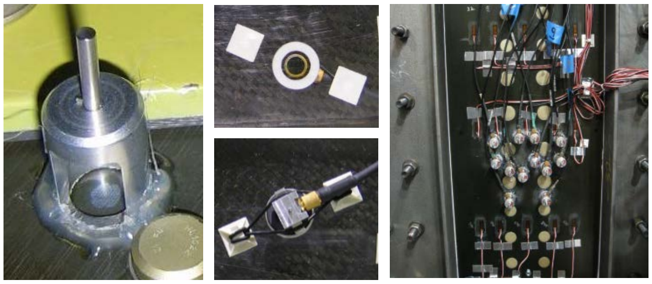

Figure 9 (left). Photographs of various In-Situ NDE sensors attached to test structure. The left photo is of a patented spring-loaded mount for ultrasonic transducers that maintains a well-coupled contact with the surface. The right photo shows an array of mounted sensors to track damage initiation and growth. The center photos are a bottom and top view of an alternative mounting for In-Situ NDE.

In-Situ NDE for inspecting in-service aircraft is also being developed by Boeing and the aerospace industry in general (In the in-service context, In-Situ NDE is often referred to as *Structural Health Monitoring* or SHM). The method involves the application of ultrasonic, eddy current, comparative vacuum, or other kinds of sensors directly to a specific structure that has limited access, is critical, or is known to be subject to damage. A reliable In-Situ NDE method can reduce the high cost and time of disassembly, NDE activities, and re-assembly that would otherwise be required [11].

The benefits of NDE automation for in-service applications include process speed improvements, data consistency improvements, reduced labor cost, and increased personnel safety. Boeing has taken the initiative to develop various automated tools for NDE that can extend or supplement the important AUSS product line, particularly for in-service inspections, and provide for greater personnel safety by eliminating the requirement to be on or adjacent to the aircraft under inspection. Two recent innovations are the ROVER (Remotely Operated Vacuum Enabled Robot) for aircraft exterior structural inspection, and the Boeing 'Blade Crawler' for rotorcraft rotorblade NDE. The Boeing ROVER system (Figure 10) was developed to reduce the manual labor and inspection time associated with in-service aircraft wing and fuselage inspections [12]. The Boeing ROVER system uses a crawling robot with specially designed floating vacuum heads that hold the crawler to the surface while still allowing it to move over laps, gaps, and minor surface perturbations. Holonomic (or Mechanum) wheels allow movement of the crawler in any direction or any rotation, independently or simultaneously. This feature optimizes scanning capability and area coverage. Crawler guidance and locating is done using one of two off-board positioning systems: the low cost portable Boeing-developed Local Positioning System (LPS) (shown in Figure 10), or the higher resolution Motion Capture (MoCap) technology that enables the tracking of multiple crawlers at the same time. Current efforts are underway to assess ROVER implementation opportunities with military and commercial aircraft customers. There has also been interest in a modified ROVER for oil tank inspection, using magnetic attachment instead of vacuum.

The Boeing Blade Crawler (Figure 11) is a spin-off technology from the ROVER development. It is a self-propelled automated inspection system that scans one or more NDE probes or arrays over the surface of a helicopter rotorblade, as it crawls from one end of the blade to the other. Because the Blade Crawler can operate on rotorblades in-place, in-service blades can be inspected faster and without costly and time-consuming removal, reinstallation, and re-balancing. In additional, the automated data collection improves the quality and consistency of the information over hand-held methods, and enables damage trend analysis and improved repair planning. Boeing recently licensed the Blade Crawler technology to NDT Solutions, which will enable Boeing to offer this innovation to rotorcraft customers, like the U.S. Navy.

Figure 10. Boeing ROVER (Remotely Operated Vacuum Enabled Robot) for aircraft (and other) exterior structural NDE. In the left photo the system is shown during an inspection demonstration, with the mobile automated boom that provides fall protection, power, and communication to the crawler, which is shown in the lower left photo. The LPS (shown in the upper right photo) is one method that is used for guidance and tracking of the crawler.

Figure 11. The Boeing Blade Crawler is shown traversing a helicopter rotorblade during an inspection.

Other Boeing developed NDE technology innovations are changing the way the industry assesses aerospace structures. One example is the Boeing-developed X-ray Backscatter system, that creates an image of the interior of a structure by scanning an x-ray pencil beam across it and collecting the x-rays that scatter back (X-ray Backscatter was originally proposed by Boeing as a method of NDE in the 1970s, but then set aside due to the cost and speed limitations of legacy technology. Because of terrorism and border security concerns of the 1990s, the security industry rapidly evolved the technology to decrease the cost and size and increase its capability, therefore, making it more attractive to develop as an NDE tool). X-ray Backscatter does not require access to both sides of a structure in order to do an inspection, which is an advantage for NDE of both large and in-service structures. It also selectively scatters from and discriminates between materials. The method is particularly sensitive to adhesives, moisture ingress, density changes, voids and foreign object debris. It has recently been shown to be able to characterize composite heat damage and detect wrinkles in composites. More research is needed to quantify these new capabilities.

Figure 12 is a photo of the Boeing X-ray Backscatter system and several imaging examples. The inspection head can run on a track during data collection, or be mounted on the end of a robotic arm.

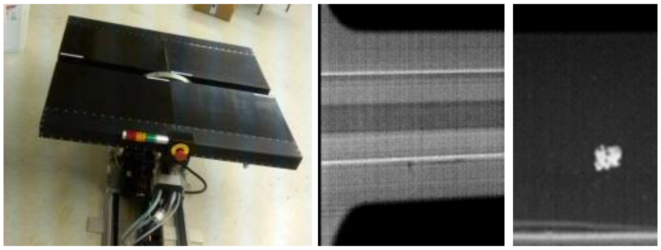

Figure 12. Boeing X-ray Backscatter system photograph (left), imaged hat stringer with a crack due to a blunt impact (middle), and water in a honeycomb panel (right).

Laser Ultrasonic Testing (LUT) is an alternative approach to traditional UT that has been developed for application to composite aircraft structure. Ultrasonic stress waves are generated by a laser pulse (instead of a piezoelectric element) and detected (after interacting with the structure) with a second laser interferometry system. The benefits include non-contact (no couplant), no perpendicularity required with the surface, and broader frequency content that provides improved flaw characterization. LUT systems, manufactured by companies such as iPhoton (Fig. 13), PaR, and Technatom, have shown cost benefit usage for certain complex parts built by Lockheed Martin (F-35 production) and Airbus (in development). But these systems are high enough cost ($3-$7M) that the cost-benefit trades haven't yet worked for Boeing applications.

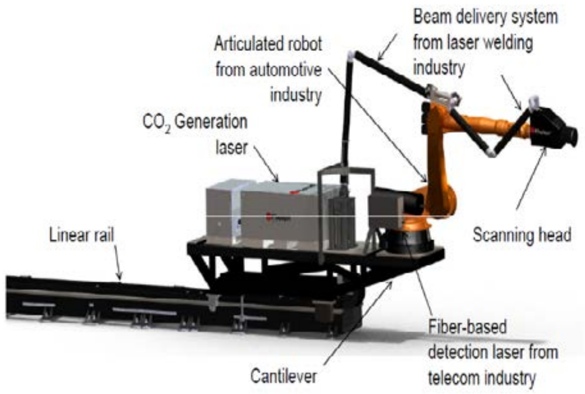

Figure 13. The iPhoton Robot Mounted System is commercially available off-the-shelf, but has proven too expensive for any Boeing applications.

Fortunately, Boeing has been working with the University of Washington to invent a lower cost LUT alternative, called the PULSAR (Pulsed Ultrasonic Laser Scanner And Receiver). The Pulsar is a Laser UT system that uses a low cost, lower energy fiber-based laser that is pulsed at a high repetition rate. While it shows much promise, the PULSAR still requires modifications and development before it can be used for production use. Lab prototypes in Seattle and Charleston will be used for this purpose (Figure 14). Complex geometry and edge inspection of Boeing composites (including the 777X wing skin edge trim) are under consideration, among other applications for LUT. A 2015 invention called ISAFE (Integrated Shielding Apparatus for Factory Environment) that enables Laser UT to be used safely in a manufacturing environment is slated to be developed in 2017 under a NASA-funded program.

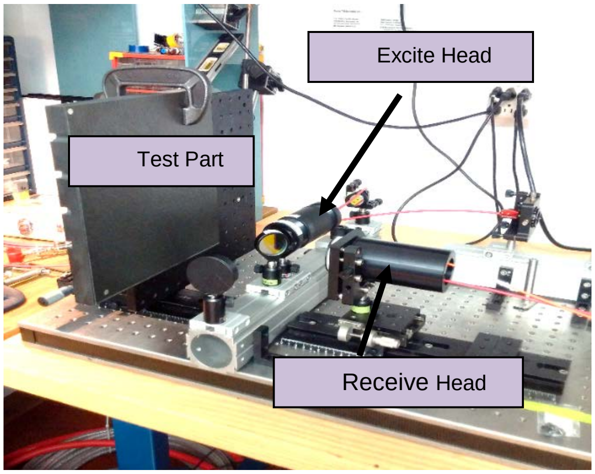

Figure 14. Boeing PULSAR (Pulsed Ultrasonic Laser Scanner And Receiver) lab set-up.

Because of the manufacturing cost and weight benefits, all-bonded structures are being considered for replacement of fastened composites. However, design of bonded structure assumes that there is full adhesion, and that bonds will not weaken over time. NDE techniques can measure parameters or features such a void fraction, wave speed, bulk modulus, thickness, etc., but not strength. Validation of the strength of bonded primary structure currently requires proof testing, but proof testing of bonded structure can be very expensive and difficult.

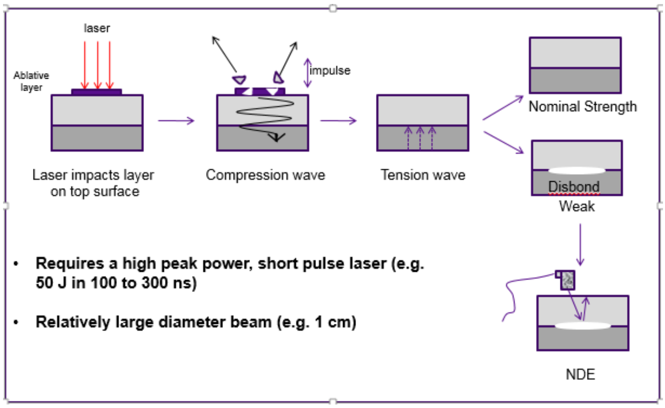

Figure 15. Laser Bond Inspection methodology for measuring bond strength.

Former Boeing Senior Technical Fellow Dr. Richard Bossi and his team invented an alternative method using stress waves generated by a high energy pulsed laser to provide localized proof testing. The approach is nondestructive to nominal strength bonds, but fails weak bonds and acts as an indicator of bond strength. The way Laser Bond Inspection (LBI) works is shown below in Figure 15.

The LBI device actually measures bond strength. A photograph of the test panel with three levels of bond strength is shown in the upper left of the Figure 16. The ultrasonic C-Scan image of the panel revealing no difference in the attenuation due to the various levels is shown in the upper right of the figure. The included table compares the LBI results with various mechanical tests, showing the effectiveness of the method.

	Mechanical Tests			LBI
Area	Relative Tensile Strength	DCB Relative G_{1c}	Lap Shear Relative Strength	Laser Bond Inspection Relative Failure Power Level
3	100	100	100	100
2	80	14	62	65
1	64	7	33	40

Figure 16. A panel with a range of bond strengths, traditional NDE (through-transmission ultrasound) revealing no differences, and the LBI Device results that show bond strength differences.

Figure 17 shows a photograph of the LBI Device and its application to testing composite structure. LBI works well on composite to composites, though there are limitations due to thickness and quality of materials. Over the last few years, the USAF has been funding Boeing, together with other aerospace companies, to conduct research to quantify LBI capability for a certified bond strength measurement. Automation of LBI, using robotics, is also being assessed at Boeing, for potential manufacturing verification of bonded structure [13]. It is worth noting that the NDE technologies developed and matured by the Boeing team have found valuable applications beyond characterizing defects during inspection. Imaging technology and methodologies like photogrammetry and profilometry that were originally developed to characterize defects in the shape or finish of a surface, are now being used for reverse engineering applications to support 3D modeling of legacy aircraft during modification and upgrade efforts. Past NDE related radio frequency research has now been spun to create RFI technology used to track products and inventories in our factories.

Figure 17. A photograph of the LBI Device (left) and its use testing composite structure (right) The LBI Device was developed by Boeing, with funding from the USAF, and built and sold by LSP Technologies Inc, Dublin, Ohio. Dr. Al Stewart conducts the test while Marc Piehl looks on.

IV. Boeing's NDE Future

Probably the best question to ask as we approach the conclusion of this paper is this: What are key NDE development areas that we can expect to see within Boeing ask we look into the future [14]? Below are some preliminary answers to that question:

NDE in the future will include automated data analysis (ADA) that increases throughput by reducing time-consuming human-based data analysis. Lower cost pedestal and modular NDE robots will replace the current higher cost, large footprint, stationary scanning systems [15].

Factory flow will be optimized for speed and cost with automated crawling NDE platforms. NDE sensors will see significant technology innovation. Waterless stand-off NDE sensors, such as Laser Ultrasound Arrays, will inspect complex shapes and edges faster, without having to touch the part or deal with water collection and recirculation issues. Thinner laminates, like the 787 barrel skin, could soon be inspected with faster, large area NDE methods, such as Infrared Thermography (IRT), with UT used only for characterization of flaws (Boeing has previously advanced IRT for inspection of SPF/DB titanium parts and moisture detection in radomes, and we are exploring IRT for inspection of non-critical composite parts).

The value of utilizing NDE and other measurement data as a process control tool is only now being fully appreciated. The goal is to move inspection (such as UT, IRT, CT, etc.) back up the manufacturing chain so it becomes transparent to the fabrication process. This approach will drive quality improvements through trend analysis, and reductions in process variations. In-process sensor feedback during manufacturing will be expanded to newer manufacturing methods, like additive manufacturing [16].

Ultimately this approach will tie the NDE and measurement data into a "digital thread" that supports cost-effective implementation and maintenance during the entire life cycle of the aircraft. Better NDE during the design process reduces the uncertainty of new manufacturing capability and allow design teams to have confidence to optimize the design and not add costly overdesign to account for uncertainty. Better NDE during development optimizes production, resulting in fewer requirements for NDE in perpetuity.

Fully bonded composite aircraft are an important part of the future for Boeing, because they can be made lighter, and will cost less to build, fly, and maintain. While the LBI device discussed above is a good initial solution for bond strength verification, lower cost alternatives will be discovered and developed.

For in-service NDE, some new capabilities that are likely to be implemented to reduce NDE costs include nanotechnology, self-sensing structures and surfaces, robotic surgical NDE, and fully networked remote expert (tele-operational) NDE that extends the reach of the expert to virtually any place in the world. New advanced NDE sensors will improve damage characterization capability and extend the time required between inspections. For example, Magnetoresistive and Millimeter Wave Sensors (for crack detection, and Frequency Selective Resonance (FSR) methods (for honeycomb/sandwich structure) are being developed at Boeing today, for future implementation on in-service aircraft. Advances in radiographic methods, including Computed Tomography, X-ray Backscatter, and Neutron Radiography are also part of Boeing long-term R&D plan to provide the best possible NDE tools when new critical, difficult, or time-sensitive challenges arise [17][18].

Of course, the future is impossible to fully predict. Many factors will determine the direction of technology development in any field. However, we can point to the fact that Boeing has been a leader in NDE innovation this past century. We should make every effort to continue that passion for innovation that includes minimizing non-value-added costs of inspection and maximizes the discovery and utilization of the important NDE data. NDE researchers need to work closely with NDE practitioners, as well as designers, and manufacturers of our structures. If we do so, Boeing NDE R&D will continue to play a key role in Boeing's future as the world's premiere aerospace company.

VI. CONCLUSION

NDE is a critical technology area for Boeing, that has grown and developed along with the company these past 100 years. A brief overview of the highlights of NDE development at Boeing has been provided in this present paper. As we move into our second century as a company, the future of Boeing will continue to rely on NDE innovation. If the past is any indicator of the future, many of these innovations will come from Boeing personnel working diligently to overcome the technical barriers to new structure verification, while keeping an eye on Boeing's current and future business needs.

ACKNOWLEDGMENT

The author wishes to acknowledge the many Boeing engineers, scientists, and technicians who have contributed to the development of NDE technology and methods over the past 100 years. Their innovative ideas, unique designs, and tireless efforts aimed at solving challenging inspection problems have made Boeing today's world leader in aerospace NDE. Unfortunately, there are too many to mention by name here. However, several of these deserve specific mention for their significant contribution to key developments described in this paper: Dr. Richard Bossi and Dr. Al Stewart (CT, LBI, LUT); Dr. Don Palmer (AUSS Mobile, in-service NDE, SHM); Morteza Safai, Talion Edwards, and Jim Engel (X-ray Backscatter); Jeff Thompson (IR Thermography) Tyler Holmes (IRT, Remote Expert NDE); Dr. Jill Bingham, Jim Kennedy, Bill Motzer, Dennis Sarr, Chris Vaccaro (UT advancements for composites, LUT and UT ADA), Paul Rutherford, Jeff Kollgaard and Nate Smith (Surgical NDE, Remote Expert NDE, in-service NDE and EC advancements), Nancy Wood, Scott Black, Barry Fetzer (AUSS and Robotic UT), Dr. Jim Troy, Karl Nelson, Scott Lea, and Dan Wright (ROVER, LPS), Mike Fogarty, Bill Tapia (In-Situ NDE), Bill Meade (X-ray ADA); Martin Freet (general NDE advancements) and Joe Hafenrichter (Blade Crawler). Sincere apologies are offered to those deserving mention whose names or technology developments the author has failed to include in this survey paper.

Wayne Woodmansee (Boeing), Don Hagemeier (Douglas), and Bob Roehrs (McDonnell) deserve special mention as fathers of modern aerospace NDE, who were about a generation ahead of those of us acknowledged above. Hagemaier did more than anyone in developing in-service inspection approaches, primarily eddy current, to support commercial airlines. Much of his work led to established standards used by ASTM, ASM and SAE. Roehrs was the key driver in bringing an aerospace flavor to the American Society for Nondestructive Testing, which had its beginnings in industrial radiography. He was also instrumental in establishing standards for NDT system and personnel qualification, and in the early years of the damage tolerance era, defining protocol for probability of detection. Woodmansee had some pioneering work back in the 1960s relative to automated UT systems development and signal processing, well before automated systems became accepted standards for large area inspection.

DEDICATION

The author would like to dedicate this Boeing Technical Journal article on NDE innovation to Mahender Reddy, the Advanced Inspection Technology (AIT) Senior Manager who retired this past year from Boeing after a long and highly respected career. His consistent leadership and strategic vision—supported by the entire AIT management team—have produced a fruitful environment for high impact NDE development, advancement, and implementation at Boeing.

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NDE Resources:

An extensive list of books on NDE techniques can be found on the ASNT.org site on the 'NDE Method References' page: https://asnt.org/Store/Browse?category=NDT%20Method%20References

Boeing Nondestructive Evaluation Technology Forum Archive Server (Contact author for access.) \\NW\data\NDETechForumArchive\

Boeing Enterprise Composite Handbook http://catalog.web.boeing.com/search/i?SEARCH=D950-11193&SORT=DX&searchscope=22

ISU CNDE NDT Resource Center web site – http://www.nde-ed.org/index_flash.htm

ASNT Industry Handbook: Aerospace NDT, R. Bossi, Ed. 2014

ASM Handbook, Volume 21 Composites, "Nondestructive Testing," pp 699-725

Additional articles and presentations can be obtained on the subject of NDE by searching the author's name in the Boeing Library:
http://catalog.web.boeing.com/search/a?SEARCH=georgeson+g&searchscope=22

BIOGRAPHY

Gary Georgeson is the Boeing Senior Technical Fellow in NDE. He holds a Ph.D. in Materials Science from the University of California at Santa Barbara, and has worked for Boeing in the Puget Sound area since 1988. In his current role, Gary provides technical leadership aimed at advancing NDE for aerospace structures, particularly composites, during manufacturing and aircraft service.

Gary is a prolific inventor of NDE systems or methods. His innovations have supported various Boeing platforms, and helped Boeing win contract R&D programs from the USAF, USN, NASA, and the FAA. He is often called upon by the U.S. government and industry for advisory roles regarding NDE. He has published or presented over 130 technical articles, government reports, journal articles, as well as a section of the ASNT NDE Handbook.

Gary has received five Boeing Breakthrough Technology Awards, four Boeing Special Invention Awards, and holds nearly 200 patents worldwide. He also received the ASNT 2016 Research Award for Innovation and the 2016 Robert C. McMaster Gold Medal Award for NDE industry impact, the 2015 Mentoring Award from the American Society of Nondestructive Testing, and the 2015 Jud Hall Composites Manufacturing Award from the Society of Manufacturing Engineers.

Gary is the currently Chairman of the Research Council of ASNT, where he is a Fellow. His professional affiliations include ASNT, SAMPE, SME and SPIE.

He also holds a master's in Theology, and is the founding pastor of a local church, with a focus on serving the poor and disenfranchised, and making a difference in people's lives.