Design of a System for Aircraft Fuselage Inspection

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Abstract - **The average age of commercial aircraft operating domestic flights in the United States is 10.7 years and continues to increase. Advances in robotics and imaging technologies show potential to reduce costs, time and to improve quality of fuselage inspections. A stochastic simulation was developed to evaluate the inspection process. The simulation represents differences in inspection techniques for components of the aircraft, such as the landing gear compared to the lap-splice panels, by categorizing the aircraft with ten representative regions. Simulation results indicates a decrease in the time required to complete inspection while simultaneously improving the overall quality in crack detection by the use of emerging non-destructive inspection technologies in aircraft maintenance: non-contact laser-ultrasonic (average savings of 43.28 minutes per section per inspection), synthetic aperture imaging drone (average savings of 45.60 minutes), and thermographic robotic crawler (crack detection rate increase of 54% with an average increase of 26.86 minutes per section). Using a utility hierarchy focused on performance, safety, and ability to implement, the most viable technological alternatives rank: non-contact laser-ultrasonic with a utility value of 0.824, human inspector with a utility of 0.811, synthetic aperture imaging with a utility of 0.783, and thermographic robotic crawler with a utility of 0.748. Based on the simulation results and utility analysis, it is recommended that MRO facilities implement non-contact laser ultrasonic technology as a method to scan the exterior of their aircraft to detect widespread fatigue damage.**

Index Terms - Aircraft Fuselage Inspection, Airworthiness, Commercial Aircraft, Eddy Current, Laser-Ultrasonic, Maintenance, Non Destructive Inspection, Synthetic Aperture Imaging Device.

INTRODUCTION

Airline carriers today face the challenge of maintaining their existing fleets for longer periods of time than ever before. The average age of a commercial aircraft operating domestic flights in the United States today is more than 11 years. Figure 1 illustrates the average age of commercial aircraft.

As the age of the aircraft increases, the structural integrity becomes compromised unless properly maintained. Many factors influence structural fatigue such as pressurization and depressurization of the fuselage when taking off, landing, and while in flight. When an airplane is preparing for takeoff it pressurizes the cabin for the planned cruising altitude, this process results in a force typically around eight pounds per square inch. The differential pressure results in repeated cycles of stress on the fuselage structure. Figure 2 depicts differential pressure equal to zero on the left when the aircraft is at ground level before takeoff, where as in flight as shown on the right the force is greater on the interior walls of the fuselage.

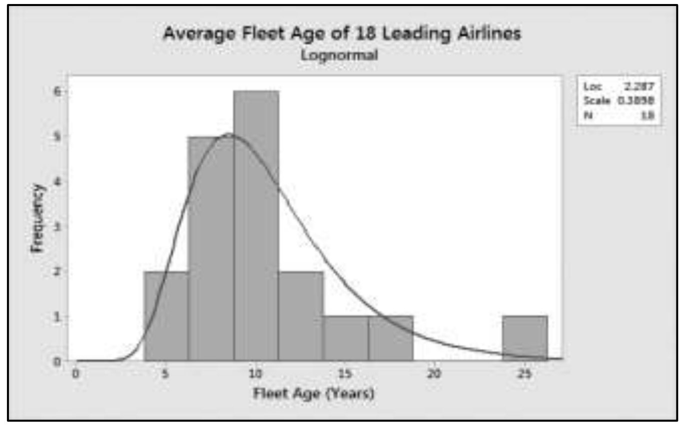

FIGURE 1
AVERAGE U.S. DOMESTIC FLEET AGE

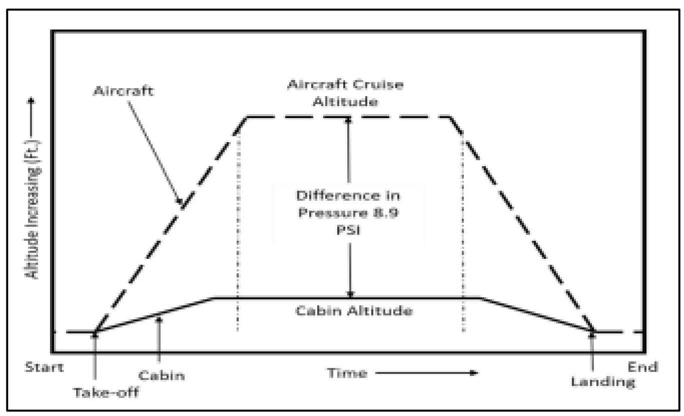

FIGURE 2
FUSELAGE PRESSURIZATION CYCLES

In addition to the pressurization forces, the aircraft is also exposed to weather conditions and the take-off and landing cycles. Over time the fuselage of the aircraft experiences widespread fatigue damage (WFD) where cracking begins to occur where the rivets are located. The increasing number of planes experiencing WFD has created the need for researchers to develop models to calculate the maximum interval between required maintenance checks.

Aircrafts undergo maintenance to ensure optimal performance and airworthiness. In the United States, preventative maintenance is scheduled such that the probability of 1.2 mm sized crack to grow beyond the critical crack size is less than 10^{-7}. Table 1 lists the four main categories of scheduled maintenance and the resources required for each. This project will focus on the “D Check” due to its lengthy duration of two months, and its high costs which can exceed two million dollars.

TABLE 1
PREVENTATIVE MAINTENANCE TYPES AND SCHEDULE

Inspection Category	Time Interval between inspections	Number of Man-hours required	Time required
A	125 flight hours or 200–300 cycles	20–50 man-hours	Overnight
B	Approximately every 6 months	120–150 man-hours	1–3 Days
C	Approximately every 24 months	Up to 6,000 man-hours	1–2 weeks
D	Approximately every 6 years	Up to 50,000 man-hours	2 Months

According to the 2013 benchmark analysis by IATA, maintenance, MRO companies servicing the global fleet spent an estimated $131 billion, including overhead. Commercial flight accounts for approximately 46% of the total with a value of almost $61 billion with future growth estimated for the following year of almost $90 billion. The benchmark report also indicates that direct maintenance cost for the 26 domestic airlines included in the study is on a steady rise. From 2010 – 2013 there was a 32% increase in maintenance costs, much of which can be attributed to structural fatigue [1].

In addition to scheduled preventative maintenance, airlines must also respond to the corrective maintenance requests originating from Airworthiness Directives (AD) issued by the Federal Aviation Administration (FAA). The visual inspection process is the first step in the inspection process. Trained personnel are equipped with various lights and lenses to maximize their potential for identifying deviations. Visual inspection relies on the capacity and ability of human eyesight. [2].

The visual inspection process identifies areas that require additional inspection. Eddy Current, utilizes an electrically induced magnetic field that detects disruptions in the current that flows counter to the magnetic field. Eddy current is primarily used in a hand held design where a trained human operator administers the test in a localized area. The test determines the extent of damage throughout the material that may not be evident on the surface. Currently all FAA approved procedures include a human component [2][3].

STAKEHOLDERS

I. Maintenance, Repair, and Overhaul (MRO) Companies

Objectives: Be able to reduce the cost and time required for inspecting the fuselage while improving the quality of inspection and improving the overall safety of the aircraft.

Tensions: The MRO must allow for the DER to take the necessary time to inspect the aircraft to be able to look for cracks in the fuselage. However, the MRO wants to be able to have the aircraft in and out as quick as possible so that they are able to repair more aircrafts.

II. Airlines

Objectives: Be able to reduce the inspection costs and improving the reliability of the aircraft while reducing the grounding time required for the aircraft.

Tensions: The airplanes being used by the airline must meet the airworthiness directives as well as the time that the airplane is grounded when at the MRO facility will in the long run affect the revenue able to be produced by the airline company since that is one less aircraft in use.

III. Federal Aviation Administration

Objectives: Be able to improve the reliability of the aircraft while simultaneously improving the quality of inspection and ensuring that the aircrafts meet the airworthiness directives.

Tensions: Must ensure that any aircraft leaving the MRO facility meets the airworthiness directives. Due to MRO Company wanting quick turnaround time some planes leaving the facility might not have all the repairs done completely

IV. Designated Engineering Representative (DER)

Objectives: Be able to reduce the overall inspection costs while improving the quality of inspection and reducing the time needed to inspect the fuselage.

Tensions: High tension with the MRO Company and the FAA. The DER must be able to inspect the aircraft quickly to keep the time and costs low for the MRO Company while adhering to the strict rules set by the FAA to ensure that the aircraft meets all the airworthiness directives.

PROBLEM & NEED

I. Problem

For a Type D inspection the process could take of 2 months requiring approximately 50,000 man hours to be able to thoroughly check everything [4]. As a result, the Type D inspection take 12-15% of the airlines annual expenditures in the aircraft maintenance and repair budget [5]. In 2013, approximately $9.4 billion was spent in aircraft maintenance to ensure they met the airworthiness directives [6]. With the current visual inspection method, there is a 43.7% probability for a Type II error to occur [1].

II. Need

There is a need to reduce the cost and time required to identify cracks and deviations in the fuselage in need of repair. The use of automated computer aided imaging will reduce the time required by 30%. The quality of inspection will be improved from 40% detection rate to 95% detection, including a reduction of errors to less than 0.01%. Overall cost of fuselage inspection will be reduced by 10%.

Concept of Operations

I. Concept of Operations

An autonomous fuselage inspection system utilizing non-contact imaging technology enables (i) large sections of external surfaces to be imaged (ii) the use of computer-aided decision tools (iii) archiving of images and data.

TABLE 2
INSPECTION METHOD COMPATIBILITY WITH DELIVERY ALTERNATIVES

		Contact		Non-Contact
		Handheld	Robotic Crawler	Track
Inspection Methods	Contact	Visual	Thermographic	X
		Eddy Current	Eddy Current	
		Ultrasonic		
	Non-Contact	Synthetic Aperture	X	Laser Ultrasonic
				Synthetic Aperture

The proposed system would use a non-contact imaging system to produce detailed diagnostics of fuselage surface structural health. The imaging process would occur early in the heavy D check process, prior to disassemble of the aircraft.

The external systems diagram (IDEF.0), figure 3, depicts how the proposed solution would interact with itself and external systems. The physical delivery system is the method utilized by the design alternative to capture an image of a portion of the aircraft. This image is sent as an output to its partner software for analysis.

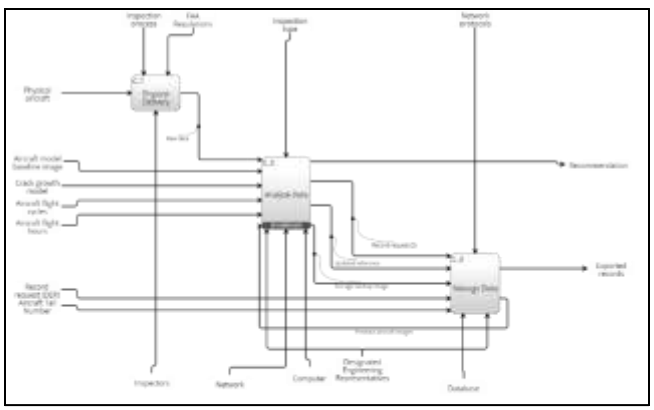

FIGURE 3
IDEF.0 OF AUTONOMOUS NON-CONTACT IMAGING SYSTEM F.0

If the design alternative is not automated, an inspector would be the mechanism that leads to the image being captured. Two controls that will affect the delivery system are the inspection process itself, such as the order the sections of the aircraft are inspected, and FAA regulations that would impact what cracks can be deferred to another inspection.

The software analysis tool is the software package that deconstructs the raw image sent by the physical delivery system into useful information, then outputs the information in the form of a recommended course of action. Three inputs required to derive this recommendation are the base image of the appropriate section of the aircraft used for comparison with the current image, as well as the current flight hours and flight cycles experienced by the aircraft, which impact the crack growth model used by the software.

The inspection type serves as a control, as the same crack is more likely to be ignored if found in a type A inspection, due to the brief nature of the inspection, rather than a thorough type D inspection. Three mechanisms are required for the software to operate. A computer to run the software, a network to link the computer to the physical delivery system, and a Designated Engineering Representative (DER) or otherwise-qualified person to review the recommendation.

If the design alternative includes a record-keeping system, the software gains additional inputs and outputs. An input is a previous image of the same crack from the same aircraft from a prior inspection. By comparing the previous image of the same crack with the current image, the crack can be monitored and the crack growth model can be further refined. Additionally, a copy of the image is sent to the record-keeping system as an output, as well as the initial request for the previous image.

II. System Requirements

Using research and input from the sponsor, the requirements displayed in Table 3 were derived for the proposed imaging system.

TABLE 3
SYSTEM REQUIREMENTS

Req.#	Requirement Description
MR.1	The system shall prevent airframe maintenance cost from exceeding a yearly growth of 1.15%
FR.1	The system shall cost no more than $25K to operate annually
FR.2	The system shall accrue no more than $5000 in Type 1 errors annually
FR.3	The system shall require an initial investment of no more than $2M
FR.4	The system shall process captured images at a rate of 12.5 m^2 per 8 seconds
MR.2	The system shall detect cracks in the airframe of aircraft visible, and not visible by a human inspector.
FR.5	The system shall detect faults with an area exceeding 0.5 mm^2
FR.6	The system shall have a Type II error rate of no more than 0.01%
FR.7	The system shall distinguish between cracks and pre-built parts of the aircraft
FR.8	The system shall capture an image of the airframe of the aircraft of dimensions 12.5 m^2 without repositioning
FR.9	The system shall have sub-millimeter resolution
MR.3	The system shall meet size, weight and power consumption levels for hand-held or track mounted delivery systems.
FR.10	The system shall include an image capture unit no more than 60 cm^2 in size
FR.11	The system shall include an image capture unit with a weight no more than 2.3 kg
FR.12	The system shall operate on 110 or 220 volts power supply
MR.4	The system shall meet Federal Aviation Administration airworthiness standards

DESIGN ALTERNATIVES & SYSTEM VALIDATION

I. Levels of Human Operator Involvement

Due to the differences in inspection techniques required in the ten representative regions, there are three levels of human operator involvement,

A. Human Evaluation

The inspector utilizes human visual inspection techniques to inspect the aircraft without the aid of imaging technology.

B. Handheld Imaging

The inspector utilizes handheld imaging technology such as Eddy Current or Ultrasound to inspect the aircraft.

C. Autonomous Imaging with Computer Aided Evaluation

The automated imaging with computer aided evaluation eliminated the need for the visual portion of the inspection to be done. The device will go across the fuselage of the aircraft in sections determining where the cracks are and then proceeding to record the fault locations so that the repair crew can more easily locate the cracks. The automated device will allow for faster inspection time and will have a greater detection rate with the elimination of the human inspector.

II. Contact versus Non-Contact Delivery Method

Contact methods require that the imaging device must be in physical contact with the surface being inspected. Non-contact delivery methods do not require physical contact and can be used from a distance. Such an alternative could be mounted onto a track around the aircraft.

III. System Validation

Laser ultrasonic (LU) technology is able to detect a crack either outside, or within, the fuselage of aircraft. The technology works by using pulsing lasers to heat the target material, then the resulting pressure from thermal expansion creates acoustical waves in the material, which can then be measured on the surface by another laser, with the wave's distortion determining where a crack is located, if any. Laser ultrasonic technology have been tested and verified as a valid inspection technique on aircraft composites. [7]

METHOD OF ANALYSIS

I. Aircraft Inspection Simulation

The method of analysis for the proposed system is through a stochastic queueing simulation of the aircraft inspection process using Arena. The aircraft is divided into ten representative sections, each section represented by a queue. Each design alternative, defined as a combination of technology and delivery method, has a set of attributes, including a distribution for the time required for any sections for the plane they are set to inspect for that simulation trial, most notably the exterior of the plane, which is approximated by the lap splice panels, then scaled to cover the entire aircraft. The alternatives that are being tested find sections of the aircraft to inspect, after each section has been inspected, the simulation terminates. Output data is focused on the average time to inspect a specific section and its confidence interval half-width.

II. Business Case Analysis

Converting the inspection time data from the simulation output enabled a business case analysis to be conducted. Average wage rates were estimated based on research for trained inspectors in domestic MRO companies. Three scenarios were evaluated for economies of scale, small, medium and large. Small, a regional operation such as HAECO operates in Macon, Georgia where six wide body and one narrow body plane can be inspected at one time. Medium, a slightly larger regional facility such as Delta Tech Ops in Atlanta, Georgia where up to eleven wide body and ten narrow body aircraft can be inspected. Large, a multi-regional, international company such as Lufthansa Technik which operates out of Europe, Central America and Asia where total facilities can accommodate as many as fifty-five aircraft with a total of more than two hundred heavy maintenance checks are completed annually.

III. Simulation Parameters and Variables

The parameters and variables were obtained from research conducted and historical data produced by the U.S. government sponsored Airworthiness Assurance NDI Validation Center at Sandia National Laboratories (AANC) in Albuquerque, New Mexico. Probability of detection for advanced technologies such as Eddy Current and Thermographic Imaging have been verified at 95%, similarly laser-ultrasonic imaging technology as well as Synthetic Aperture Imaging Devices have been held to the 95% detection rate for comparison.

TABLE 4
DISTRIBUTIONS USED IN SIMULATION

	Baseline	**Handheld**	
Job Card	Human Inspector	Ultrasonic	Eddy Current
Midsection Floor	55 + 160 *BETA (0.713, 1.2)	UNIF (137.5,537.5)	UNIF (165,645)
Main Landing Gear Support	TRIA (9.5, 28.8, 45.5)	UNIF (25,112.5)	UNIF (30,135)
Midsection Crown Internal	49.5 + GAMM (24.9, 1.04)	UNIF (125,287.5)	UNIF (150,345)
Galley Doors Internal	NORM (67.9, 14.4)	UNIF (112.5,262.5)	UNIF (135,315)
Rear Bilge External	19.5 + WEIB (18.8, 1.93)	UNIF (50,125)	UNIF (60,150)
Left Forward Upper Lobe	65 + EXPO (38.8)	UNIF (162.5,437.5)	UNIF (195,525)
Left Forward Cargo Compartment	UNIF (54.5, 146)	UNIF (137.5,362.5)	UNIF (165,435)
Upper and Lower Rear Bulkhead	UNIF (19.5, 50.5)	UNIF (50,125)	UNIF (60,150)
Nose Wheel Well Forward Bulkhead	UNIF (9.5, 20.5)	UNIF (25,62.5)	UNIF (30,75)

Lap Splice Panels	
Human Inspector	14.5 + 81 * BETA(0.961, 1.34)
Handheld Ultrasonic	UNIF(33,77)
Handheld Eddy Current	UNIF(45,285)
Crawler Thermographic	UNIF(54,98)
Crawler Ultrasonic	UNIF(85,120)
Crawler Eddy Current	UNIF(60,100)
Track Synthetic Aperture	UNIF(3,6)
Track Laser Ultrasound	UNIF(3.2,9.625)

IV. Case Study Assumptions

Assumptions were required in scaling the data from a testing site such as the Sandia National Laboratories facility in order to apply the results to a larger sized facility.

V. Simulation Implementation

Initialization of the simulation begins with assigning attributes to the different entities that represent different design alternatives. Each entity is limited to specific, predetermined sections of the plane. The number of cracks on each section of the plane is then initialized and the entities move to the actual process. Upon entering the process section of the simulation, the entity enters a decide block that determines what section of the plane to inspect. The two conditions are that the section has not been inspected yet, and that the entity is allowed to inspect that section. If these conditions are not met for any representative section of the aircraft, then the entity leaves the simulation and the final time is recorded. The inspector is sent to the assigned section of the plane, its section marked "active" to prevent other entities from inspecting it, then the actual inspection takes place as a queue. The entity remains in the queue for an amount of time determined by the process' distribution assigned to the entity at the beginning. Upon completion of the inspection, the entity moves upward to the statistics recording section.

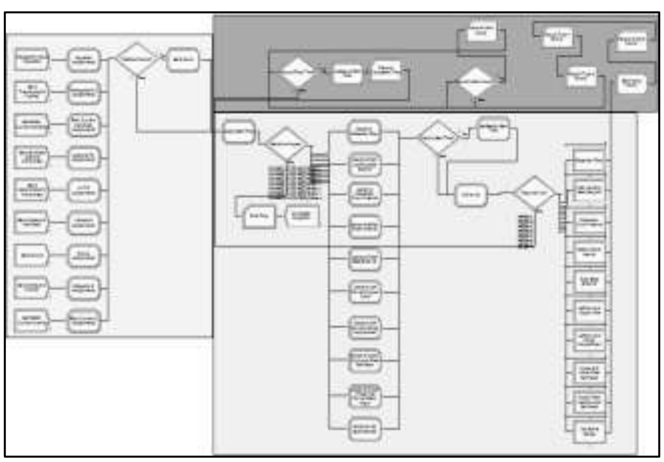

FIGURE 4
ARENA SIMULATION MODEL

The number of cracks found, along with Type I and II errors as determined by the design alternative, is recorded, along with labor hours if a human inspector was used. The amount of time required to inspect the section is then recorded, and the entity is sent back to the process section of the simulation to attempt to inspect another section.

VI. Simulation Validation

The simulation was run with only a human inspector using the distributions obtained from the Airworthiness Assurance NDI Validation Center at Sandia National Laboratories (AANC) and the output relating to time is displayed in table 5.

TABLE 5
SIMULATION OUTPUT: VISUAL INSPECTION PROCESS

Section	Actual (mins)	Simulated (mins)	Diff (mins)	% error
1	122	116.47	-5.53	-4.53
2	28	27.83	-0.17	-0.61
3	75	75.38	0.38	0.51
4	68	67.71	-0.29	-0.43
5	37	36.1	-0.9	-2.43
6	104	105.64	1.64	1.58
7	95	100.23	5.23	5.51
8	35	34.68	-0.32	-0.91
9	16	15.2	-0.8	-5.00
10	48	49.56	1.56	3.25

The difference between the simulated process and actual process varied from 0-5%, but cumulatively came up to within 1 minute of the expected total time over 500 replications, which is an error of approximately 0.1%.

RESULTS

Results were obtained by running the Arena Simulation for 250 replications.

I. Total Inspection Time for Lap-Splice Panels

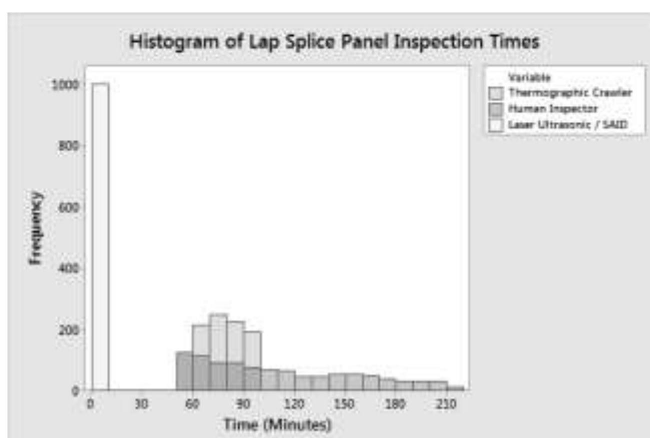

FIGURE 5
DISTRIBUTION OF LAP-SPLICE PANEL INSPECTION TIMES

II. Total Inspection Hours

There are ten representative regions of the aircraft, only the exterior section, fuselage skin including lap-splice panels, can be autonomously configured for the proposed system. The autonomous imaging system equipped with laser-ultrasonic technology would reduce overall inspection time by 30 % for a 737-sized, narrow body aircraft.

III. Utility Analysis

The utility vs cost analysis shown in Figure 6 displays the stark advantage non-contact solutions have, notably the non-contact laser ultrasonic (0.87 utility), over both the human inspector (0.59 utility) and the thermographic crawler (0.37 utility). The trade-off comes from a sharp increase in cost, with human inspectors costing $565,000 over the same period that the laser ultrasonic costs $1,967,000.

FIGURE 6
IMAGING TECHNOLOGY ALTERNATIVES

IV. Business Case Results

A business case model of five different sized maintenance facilities, ranging from 25 to 126 inspections per year, was analyzed to evaluate economy of scale for break-even points and a return on investment for a five-year period, with an average annual ROI ranging from 35% to 182%, respectively.

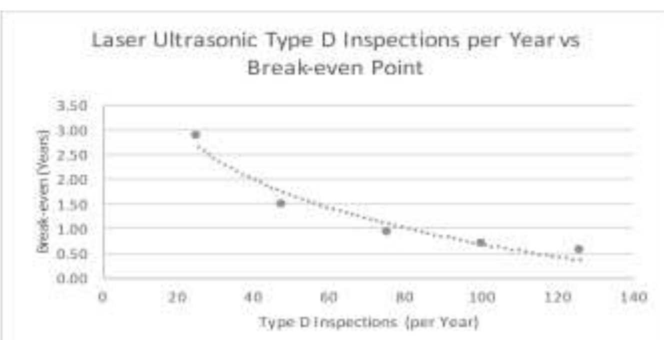

FIGURE 7
ANNUAL TYPE D INSPECTIONS VS. BREAKEVEN POINT

Figure 7 shows that the breakeven point for MRO facilities follows an approximately exponential distribution as the number of annual type D inspections increases, ranging from a 3 year breakeven at 25 inspections per year, to a 0.55 year breakeven at 126 inspections per year.

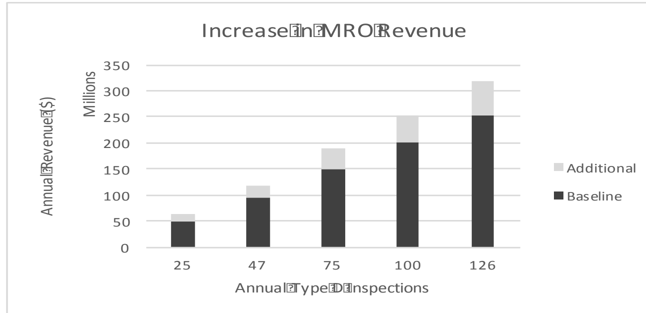

FIGURE 8
INCREASE IN NUMBER OF INSPECTED AIRCRAFT

Faster visual inspections lead to a slight increase in the number of aircraft inspected per year, which increases revenue for MRO facilities. This average facility inspection revenue increase of 26.3% shows greater returns with facilities that already have a volume of annual inspections greater than 100.

CONCLUSION & RECOMMENDATIONS

Automated imaging technology show potential as an improvement to human inspectors for the external inspection of aircraft fuselage. It is recommended that MROs begin researching the potential benefits of implementing automated non-contact laser ultrasonic technology as an inspection method for the exterior of aircraft to increase their annual revenue by up to 26.3% while increasing crack detection rates from 44% to 95%.

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