

A Non-Destructive Method to Classify the Correct Installation of Blind Bolts

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ABSTRACT

Aerospace manufacturing requires efficient manufacturing processes. Composite materials are extensively used and manufacturing processes must evolve to overcome composite constraints for manufacturing and joining. Bolting is an extended joining process for composite materials in which a deformable blind bolt is stressed until joining forces are high enough to cause bolt breakage and ensure sufficient compression forces in the joint.

Among bolting methods, blind bolting is an efficient composite joining method that enables the construction of aerospace composite structures accessing joints from a single side of the joint (front side), thus allowing for constructing closed structures where accessing the back side (blind side) is not possible. However, not being able to access the deformed head at the blind side prevents to perform a quality control and ensure a proper bolt deformation and a proper installation.

In this research work a nondestructive method for blind bolt installation is developed. Several potential inspection techniques (shearography, thermography, frequency response methods and ultrasonic methods) are tested for blind bolting inspection suitability assessment. An ultrasonic measurement technique is identified as partially capable of classifying bolt installation. A further development, combining ultrasonic methods and process monitoring data, has led to a blind bolt installation classification method with a hit rate >95% on tested samples.

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INTRODUCTION

The aerospace industry requires high strength, high reliability yet low cost manufacturing and assembling processes for constructing aerospace structures. Structures are composed by a variety of parts and subsystems that are joined between each other. Thus, the aerospace industry has lead an ambitious development in mechanical joining technologies, seeking for low cost, reliable mechanical joints.

Bolting is one of the most extensively used technologies for aerospace assembling; an average airplane holds tens of thousands of bolts. Due to such extensive use, there is a wide variety of bolt types. Blind bolts are of special interest for aircraft construction due to the ability to achieve to join

elements by accessing the joint from only one side (front side of the joint). Complexity of the joining operation is thus substantially lower than for non-blind bolts, automation of the operation is eased and costs are lowered. Blind bolts allow for performing joints where only one side of the joint can be accessible, as it is the case of many common aerospace joints. In the cases where the back side of the joint cannot be accessed the use of blind bolts is a must.

However, since the back side of the joint cannot be accessed, it is not possible to perform a quality control of the bolt installation. Not accessing the back side of the joints is at the same time a strength and a major limitation of blind bolted joints.

For that reason, aerospace manufacturers need to increase design loads so as to account for the uncertainty that bolt installation introduces into manufactured joints, and which cannot be quality controlled. Blind bolted joints are penalized in bolt number, bolt weight, and manufacturing time, increasing both assembling direct and indirect costs, and also aircraft operational costs due to heavier components.

Monitoring the bolting process has been proposed by several authors as a method for obtaining information about the quality of the bolt installation. An assessment method is proposed in [1] in which force and stroke signals over time are acquired during bolt installation, and compared against reference pattern signals which define a band of acceptance. If bolt signals are deviated from such bands, installation is classified as faulty, and as correct if signals are contained within the acceptance bands. Also, an assessment procedure is proposed in [2] in which force and displacement signals are analyzed. Instantaneous force and displacement values at initial, breakage, and certain intermediate positions are contrasted with reference values for bolt installation classification. Based in the same process signals, but under a different approach, an assessment method is proposed in [3] in which after obtaining both bolting force and displacement, the total amount of energy involved in the process is calculated by integrating the instantaneous force over the displacement. Total process energy is calculated as the assessment value to be contrasted for classifying the installation as correct or as faulty. Similar methods based on force and displacement signal monitoring and postprocessing are proposed in [4,5,6,7,8].

Stepinski [9] proposes an alternative method in which a piezoelectric transducer is attached to the bolt and the resulting electrical impedance (which will be influenced by mechanical characteristics of the settled bolt) is used as assessment value for qualifying the installation of the bolt.

In this research work, an innovative blind bolt non destructive evaluation (NDE) method has been developed. At first, a selection of potential methods able to gather data containing information about the quality of the bolt installation has been proposed: i) shearography, ii) thermography, iii) ultrasonic time-of-flight (TOF), iv) frequency response analysis. The feasibility of these technologies has been rated, and TOF has proved to have partial capability for bolt installation classification. A further development of the method, combined with process monitoring has lead to an innovative bolt classification NDE method which has shown a hit rate over 95% on 4 sets of tested samples with about 80 bolts each.

FEASIBILITY ANALYSIS OF POTENTIAL METHODS FOR BOLT INSTALLATION QUALITY ASSESSMENT

Sample Probes

In order to assess the capability of the potential methods for faulty bolt identification, two sample bolted probes have been manufactured. Sample 01 is composed by 70 bolts, type ABS0257-5-350, containing 28 sound and 42 faulty bolts. Sample 02 is composed by 69 bolts, type ABS0257-6-450, containing 43 sound bolts and 26 faulty bolts. The classification of the sample bolts as correctly or incorrectly installed bolts has been performed by a qualified inspector according to industry standards. [Figure 1](#) shows both sample probes, size ABS0257-5-350 seen from the front side and ABS0257-6-450 from the blind side.

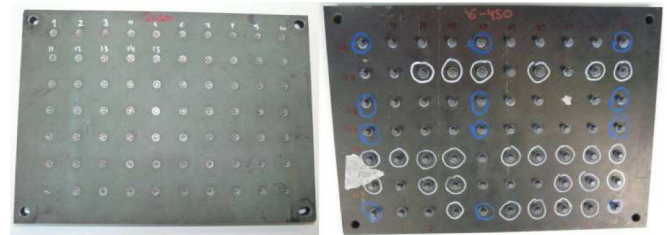


Figure 1. Left: Probe with ABS0257-5-350 bolts, seen from the front side. Right: Probe with ABS0257-6-450 bolts, seen from the blind side.

Feasibility Analysis of Potential Methods for Bolt Installation Quality Assessment

Eligibility criteria

For blind bolt classification method to be considered suitable and industrially productive, the method should comply with the following criteria:

1. Criterion 01: Be valid for CFRP bolted joints.
2. Criterion 02: Not prolong bolting cycle more than 3 seconds.
3. Criterion 03: Be valid for either automatic or manual bolting operations.
4. Criterion 04: Don't damage or harm, nor modify, bolt installation.
5. Criterion 05: Be valid for assessing installation after bolting is completely finished, that is, after pin shaving operation.

Potential method i) Shearography

Hypothesis behind shearography selection

Shearography is an optic interferometry based non destructive testing (NDT) technique. Shearography obtains displacement fields of surfaces between a reference state and a loaded state. Coherent light is projected on the test item and images are captured by an image-shearing camera. The resolution on displacement measured by shearography is so high that needed stressing loads are almost insignificant. Typical loading consist of heating surfaces during 1 to 5 seconds with mid-power (1kW to 2kW) halogen lamps. Loading can also be mechanical, by charging the test item, pressurizing it, applying vibrations; or of other nature.

Shearography allows for short inspection time defect detection in metals and nonmetals. Subsurface defects can also be detected since those defects influence superficial displacements. Of special interest to the aerospace industry, shearography can detect delamination in composites, adhesion failures, cracks and pores[10,11,12]. Hung [13] proposes shearography as NDE technique for bolted joints inspection. His work focuses on detecting bolt looseness and shows the ability of shearography for detecting loosen bolts in a six bolt joint when exciting the item under multiple-frequency sweep.

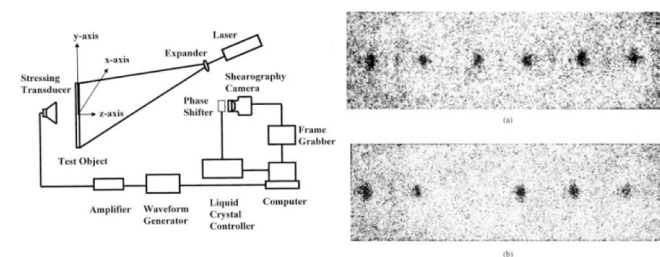


Figure 2. Extract from [13]: Left: experimental setup. Right: (up) joint with 6 tight bolts, (down) third bolt is loosened.

Shearography has been identified as a potential method under the following hypothesis: During its installation, bolt compresses joint elements. Joint elements oppose to that compression, get deformed, bolt shrinks entering plastic deformation and finally breaking. Joint element deformation is an essential parameter in bolt installation.

It is suggested that incorrect installation of bolts may be identified by inspecting the vicinity of bolts seeking for differences between sound and incorrect bolts. Installation failure causes like misalignment, early breakage (low compression force), formed head flattening would result in different boundary conditions on the vicinity of bolts. The resulting superficial deflection may be correlated with the quality of the bolt installation.

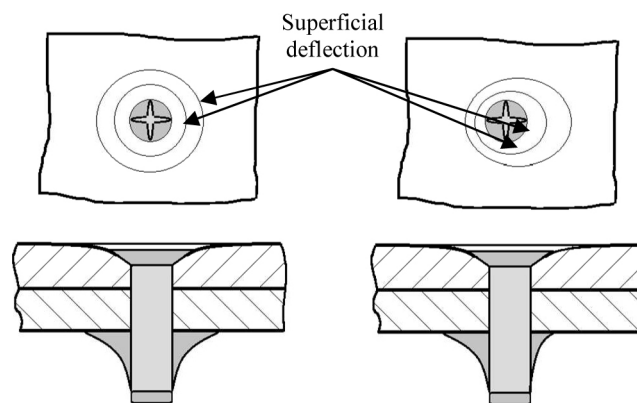


Figure 3. Representation of the hypothesis of divergences in superficial deflection between sound and incorrect bolts.

Preliminary feasibility appraisal of shearography

Test probes have been inspected under three excitation methods: a) vibration in the 0-1kHz range, b) thermal excitation, and c) static loading. For each loading method, shear images have been measured, as shown in Figure 4.

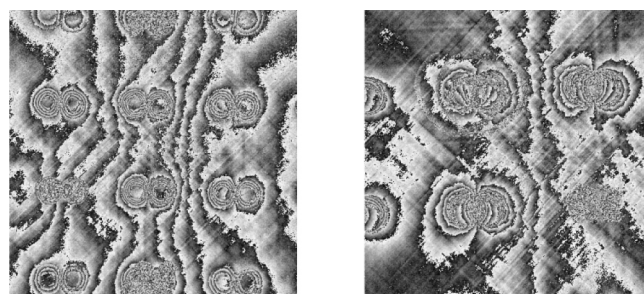


Figure 4. Shear images of bolted joints. Left: Mix of sound and incorrect bolts. Right: A missing bolt can be detected (lower right position).

Shear images has shown no recognizable correlation between shear images and bolt installation quality.

Potential method ii) Active Thermography

Hypothesis behind active thermography selection

Active thermography is an extended NDT method for inspecting surface and subsurface defects, but with which detectable depth is limited. Test items are thermally excited and their thermal response is measured. Surface or subsurface defects are then identified via relation between thermal excitement and thermal response, which is determined by thermal properties of the materials (or the lack of materials).

Similar to shearography, thermography is a non-contact inspection method capable of inspecting extensive surfaces at one time. Active thermography can be a suitable NDT method for inspecting delaminations, cracks, corrosion and bond failures [14].

In a research by Zweschper, Dillenz and Busse [15] bolted joint inspection via active thermography was studied, seeking for joint failure detection. Active thermography method applied was lock-in thermography, in which test item is excited continuously, and both excitement and response are measured simultaneously. Depending on joint materials (Al-Al or Al-CFRP), either amplitude analysis or phase shift analysis was suitable for detecting underpaint corroded bolted joints. Moreover, a single M8 fastener preload thermographic analysis was carried under two thermal loading methods: halogen lamp excitation and by attaching an ultrasonic transducer to the item. High frequency vibration produces friction inside the material, becoming an internal heat source. The analysis showed that preload variations affect thermal response of the bolted joint of aluminum sheets.

Active thermography has been considered a potential method under the following hypothesis: Compression degree on the material around faulty bolts may vary. Differences in compression degree will vary thermal properties, and active thermography will enable identifying such differences. Correlation between such differences and bolt quality installation can result in a bolt classification method.

Preliminary feasibility appraisal of active thermography

Sample probes have been tested by transient active thermography and by lock-in thermography. Figure 5 shows a thermogram of a set of bolts after heating by halogen lamp of 400W of power, with a duration enough to heat the surface above 55°C.

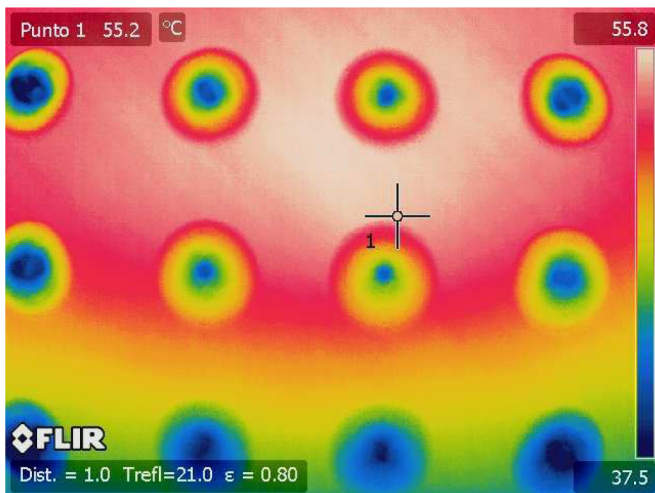


Figure 5. Thermal image of bolted sample.

No significant difference has been identified between sound and faulty bolt's thermographic analysis, nor during heating ramp nor during cooling ramp. Low conductivity of CFRP and high sheet thickness are believed to be main causes for not measuring recognizable variations between sound and faulty bolts.

Potential method iii) Time-Of-Flight (TOF)

Hypothesis behind TOF selection

Ultrasonic pulse-echo measurement is the basic principle for ultrasonic non destructive inspection. In the simplest configuration, an ultrasonic pulse is generated on the surface of the inspection item. The pulse travels through the test item until it finds a boundary. In the interface between the material and the boundary, an echo is reflected back, which travels back to the original point. The time spent by the pulse travelling forward and back from the boundary is called Time-Of-Flight (TOF).

In their research, Nohyu and Minsung [16] loaded a M22 steel bolt and measured TOF for LL and LT wave modes. A single bolt, whose head was slightly modified to fit the transducer, was used; that is, bolt length was constant (except for the elastic deformation due only to loading). They found a linear relationship between TOF-LL and TOF-TT ratio and applied load on the bolt. Hirao, Ogi and Yasui. [17] alleged that stress induced sound speed variations would produce two measurable effects: a) phase shifts of the top-to-bottom propagating wave, and b) resonance frequency shift. Experimental tests on two sets of 10 bolts of different type, which had been slightly machined for experimental setting up purposes, showed that stated effects did indeed take place. However, it was stated that manufacturing tolerances between the individual bolts did not allow for obtaining a defined correlation between phase shift nor resonance frequency shift with bolt stress.

The hypothesis for this potential method consists on TOF variation assumption between sound and faulty bolts. Sound bolts must form a minimum length formed head; and also, should remain under proper mechanical stress. Thus, the hypothesis for this potential method states that there may be a measurable relation between TOF and bolt installation quality.

Preliminary feasibility appraisal of TOF

TOF has been measured for each of the bolts in both sample sheets. A 20MHz transducer has been used for TOF measurements in the attempt of increasing the resolution in time. Figure 6 shows graphically the measured TOF for the bolts in sample 01 and Figure 7 for sample 02. In both cases, horizontal axis corresponds to TOF and vertical axis to bolt numeration.

There is an observable trend in TOF for sound and faulty bolts. Sound bolts tend to have higher TOF than faulty bolts. Taking the first sound bolt as lower TOF limit, and the last faulty bolt as upper limit, a partial NDE classification method can be defined. These limits are shown in Figure 6 and Figure 7 as dashed vertical lines.