CEN WORKSHOP AGREEMENT

CWA 17454

September 2019

ICS 25.030; 49.025.01

English version

Bionic Aircraft - Quality control of metal ALM parts using the Ultrasonic Technique

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European foreword

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The research leading to these results has funding from the European Union's HORIZON 2020 Programme under the grant agreement numbers 690689 (Bionic Aircraft).

The final text of CWA 17454 was submitted to CEN for publication on 2019-07-19. It was developed and approved by:

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Introduction

Additive Layer Manufacturing of metallic high-performance parts is a cutting-edge manufacturing process which gives rise to a family of materials with a particular inner structure. In addition, this manufacturing process makes possible to manufacture, in a natural way, parts with high geometrical complexity in a single process.

Because this process is already under development for certain material families (such as AlSiSc), not all the properties of those layered materials are fully known yet. Therefore, the issues related to feasible quality control techniques are not fully defined. As a consequence of that, a deficit in specific standards related to this issue has been detected.

BIONIC AIRCRAFT research project (GA nº 690689, founded by the European Union's H2020 Programme) aims to further the knowledge on some of these unknown issues. This document gathers general conclusions derived from some of the results of this project that may be useful to go further in the development of specific standard on this field.

1 Scope

This CWA provides a set of guidelines to control the quality of metal Additive Layer Manufactured (ALM) parts in terms of existence of defects by using ultrasonic technique. With the aim of characterizing the material in the aspects most relevant to the inspection, the measurement of some relevant acoustic parameters of the layered material is proposed first. Secondly, the most important configuration parameters are gathered together with a range of example values. After that, a set of specific guidelines for the automatic inspection under in-line conditions is provided. Finally, the specific highlights and restrictions coming from in-service conditions are explained.

This CWA does not include the basic vocabulary and general configuration and calibration steps for ultrasonic inspections, which are specified by the referenced general standards.

This CWA is not a testing procedure, because the specific parameters and scanning steps depend on each particular material and geometry of the part.

The information provided in this document is based on the results of the BIONIC AIRCRAFT research project.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN ISO 16811:2014, *Non-destructive testing — Ultrasonic testing — Sensitivity and range setting (ISO 16811:2012)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
ALM material
3D solid structure made out of different metallic components by ALM manufacturing process

EXAMPLES AlSi10Mg, AlSiSc alloys.

3.2
part
3D structure with a defined function and targeted geometry

EXAMPLE Complex geometry aeronautical metallic brackets located in the wings.

4 Symbols and abbreviations

For the purpose of this document, the following symbols and abbreviations apply:

ALM	Additive Layer Manufactured
FSH	Full-Screen Height
PDSM	Potential Defects and Severity Mapping
RCA	Root Cause Analysis
CMM	Coordinate Measuring Machine

5 Relevant acoustic parameters of the ALM material

5.1 General

Before setting the ultrasonic parameters for inspections, some knowledge of certain basic acoustic parameters of the ALM material can be useful to contextualize the inspection to perform, reduce the range of possibilities and facilitate the further development of a testing procedure.

A way of measuring and an order of magnitude of them is given below.

5.2 Ultrasonic velocity

The ultrasonic velocity measurement can be based on the ASTM E494-15 standard. Block shaped specimens are used with a thickness between the near field distance and four times the near field distance, and with a width and length larger than twice the -20 dB beam diameter at the thickness distance. Normal incidence transducers are considered for both longitudinal and shear velocity.

The main frequency of the transmitting pulses to be used will be the one used for the inspections (see 6.1).

Two consecutive backwall echoes are considered for the measurement. The TOF is obtained from the measured time difference between the same relative point of both echoes, as an example, the maximums values.

EXAMPLE 1 TOF measured between the second positive maximum of each echo.

EXAMPLE 2 The order of magnitude measured on AlSi10Mg and AlSiSc ALM materials is in the range of 6 400 m/s - 6 600 m/s for longitudinal velocity and 3 200 m/s - 3 500 m/s for shear velocity, these values may vary depending on the ALM process.

5.3 Attenuation due to material absorption

The measurement of the ultrasonic attenuation due to ALM material absorption can be carried out as follows. Block shaped specimens are used with a thickness greater than the near field distance of the transducers. The width and length are larger than four times the -20 dB beam diameter at the thickness distance. Normal incidence transducers are considered for both longitudinal and shear velocity. The main frequency of the transmitting pulses to be used will be the one used for the inspections (see 6.1).

Two consecutive backwall echoes are considered. The attenuation is obtained by measuring the amplitude of the first two backwall echoes in the far field and it is calculated by the following relation:

$$\alpha = \frac{G_1 - G_2}{2 \cdot th}$$

where

α attenuation coefficient due to ALM material absorption [dB/mm];

G_1 required gain to bring the maximum of the first backwall echo to 80 % FSH [dB];

G_2 required gain to bring the maximum of the second backwall echo to 80 % FSH [mm];

th thickness of the specimen [mm].

EXAMPLE The order of magnitude of the measured absorption on AlSi10Mg and AlSiSc ALM materials is in the range of 0,2 dB/mm – 0,6 dB/mm, depending on the working frequency. These values may vary depending on the ALM process.

5.4 Anisotropy

The measurement of the ALM material anisotropy can be carried out in the following way. A cube-shaped specimen, with the same superficial quality in all its faces, is used with a side dimension greater than the maximum of the following values:

— The near field distance.

— Four times the -20 dB beam diameter at the thickness distance.

The building direction of the ALM material shall coincide with one of the axes of the cube (reference direction). In addition, all sides shall have the same surface quality (see Figure 1).

Normal incidence transducers are considered. The main frequency of the transmitting pulses to be used will be the one used for the inspections (see 6.1).

The ultrasonic velocity and ALM material absorption are measured in the three axes of the cube as explained in 5.2 and 5.3. The obtained values shall be referred to those obtained in reference direction.

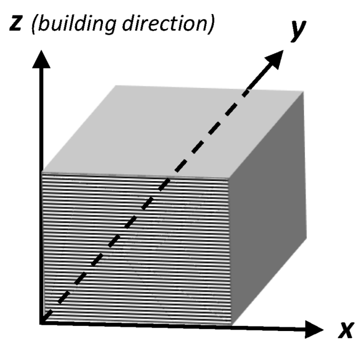


Figure 1 — Depiction of a testing specimen for anisotropy measurement

EXAMPLE The order of magnitude of the measured anisotropy in velocity is less than 1 % with respect to the reference direction and non-significant anisotropy has been found in sound attenuation for AlSi10Mg material.

5.5 S/N ratio

Signal-to-noise ratio of a backwall echo can be measured as follows.

Two plates, with the same surface quantity, are used with a thickness between the near field distance and four times the near field distance and with a width and length larger than twice the -20 dB beam diameter at the thickness distance. One plate (the thick one) shall have double thickness than the other one (the thin one). Normal incidence transducers are considered.

The amplitude of the backwall echo measured in the thin plate shall be referred to the maximum amplitude of the noise signal of the thick plate measured within the same time interval when the backwall echo appears (see Figure 2).

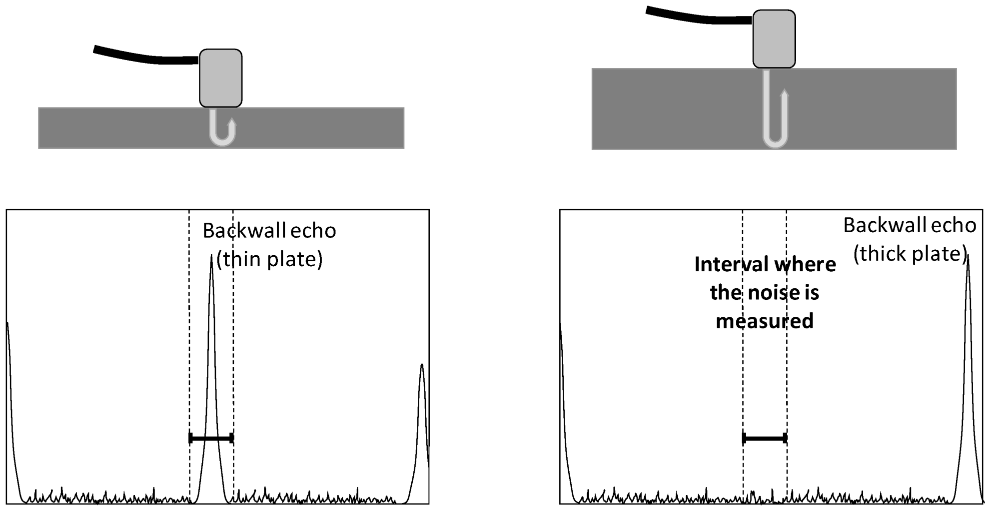


Figure 2 — Measurement of the S/N

In this way, the S/N ratio can be calculated as follows:

$$S/N = \frac{G_B}{G_N}$$

where

G_B required gain to bring the maximum of the first backwall echo of the thin plate to 20 % FSH [dB];

G_N required gain to bring the maximum of the noise signal on the thick plate to 20 % FSH measured within the same time interval where the backwall echo of the thin plate appears [dB].

EXAMPLE The order of magnitude of the measured S/N ratio on AlSi10Mg and AlSiSc ALM materials is in the range of 35 dB - 60 dB for thickness around 20 mm. These values may vary depending on the ALM process.

5.6 Influence of the surface quality

A correction of the amplitude due to the differences in surface quality can be obtained according to EN ISO 16811 standard.

EXAMPLE The order of magnitude of the correction between raw surface (just after ALM manufacturing) and polished surface is in the range of 15 dB - 35 dB, strongly depending on the working frequency for AlSi10Mg material.

6 Ultrasonic configuration parameters for the inspections

6.1 Frequency

The proposed range for the frequency (main resonance) of the transducers and transmitting pulses is in the range of 5 MHz -15 MHz, depending on the specific ALM material and thickness.

The following formula can be used to estimate a more specific order of magnitude for a specific ALM material.

$$\frac{c}{2 \cdot m} < f < \frac{c}{10 \cdot g}$$

where

c	sound velocity of the ALM material (measured as explained in 5.2);
m	maximum admissible size of defects (see 8.1);
g	grain size of the ALM material.

NOTE g is considered as the largest inner portion of the ALM material having the same, or very similar, acoustical properties. Therefore, depending on the material, g can be the grainsize of the basic material itself or the size of the layers produced by the ALM process.

EXAMPLE Specifically, frequencies around 10 MHz are proposed for AlSi10Mg and AlSiSc ALM materials.

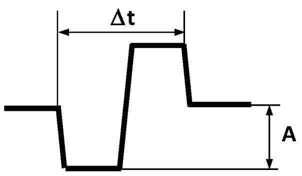
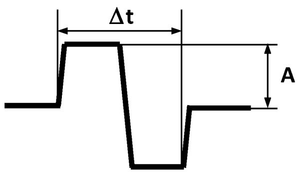
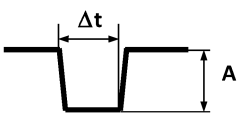
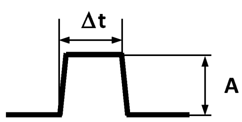
6.2 Type and amplitude of energizing pulse

The type and amplitude of the energizing electric pulse should consider the ALM material to inspect.

Forced oscillation at the main resonance frequency of the transducers is proposed which shall be the same as the working frequency (calculated in 6.1). Therefore, energizing electric pulses having that main frequency are suggested.

In the case of square energizing pulses, the recommended times are given in Table 1.

Table 1 — Recommended times for square energizing pulses

Suitability order	**Pulse form**		**Δt** [nS]
1º			1 000/ f
2º			500 / f

The amplitude (A) depends on the ALM material attenuation and the specific transducers (see 5.3 and 5.6). It should be high enough to make possible to have a backwall echo S/N > 30 dB (see 5.5) for plates with a thickness of 20 mm.

6.3 Reception filters

In order to improve the S/N relation, reception filters can be activated. Bandpass filter centred at the working frequency are suggested.

EXAMPLE The following bandpass filters are suggested for AlSi10Mg and AlSiSc materials: 0 MHz - 10 MHz for 5 MHz and 5 MHz - 15 MHz for 10 MHz.

7 Automatic scanning under in-line conditions (definition of main steps)

7.1 General

Once all the relevant parameters to measure an ALM parts have been defined as explained in Clause 6, the integration of the ultrasonic sensor on a Coordinate Measuring Machine allows a robust and flexible control of parts under in-line conditions.

In this framework in-line conditions mean that the part is checked just after it has been manufactured, thus once it has been detached from the building plate, all supports structures have been removes and all the post- processing processes are finished (if they are planned).

A Coordinate Measuring Machine (CMM) is a "measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface" as it is defined in ISO 10360-1. The CMM can be equipped with different types of probe that determine coordinate values as a result of the interaction with a workpiece. In several CMM the probe is mounted on an articulation system: it can position the probe in various spatial angular positions by means of a manual or motorized position device.

7.2 Selection of the automatic measuring machine

There exists a wide range of both CMM and probes and the selection among them is usually based on the application field. In the case of the ultrasonic inspection of ALM parts the choice of the CMM is not as relevant as the choice of the probing system. In fact, the CMM can be seen as an automatic system able to automatically move the probe and to collect the spatial coordinates. In the Bionic Aircraft project, a vertical bridge CMM was selected but the technology that is hereafter described can be quite easily translated to other types of machines.

On the opposite, the articulating probing system plays an important role in the capability of the whole system to detect defects, especially when part with a complex (freeform) shape has to be measured. A proper position of the ultrasonic transducer on the workpiece surface is required to have a good backwall echo that allows an accurate measurement of the part. The sensor shall be placed as perpendicular as possible to the surface along the whole scanning.

The orthogonality can be simply guaranteed even without an articulating probing system if the workpiece has a prismatic shape. It is only necessary to fix the part on the machine so that the surfaces are perpendicular to the probe during measurement.

On the contrary, in case of complex (freeform) surface it is necessary to automatically and continuously change the angle of the probe (transducer) to keep it constantly perpendicular to the surface.

For that reason, the use of an articulation system (or wrist) with the possibility to change continuously its angular position is mandatory.

A sketch of the system can be seen in the following picture.

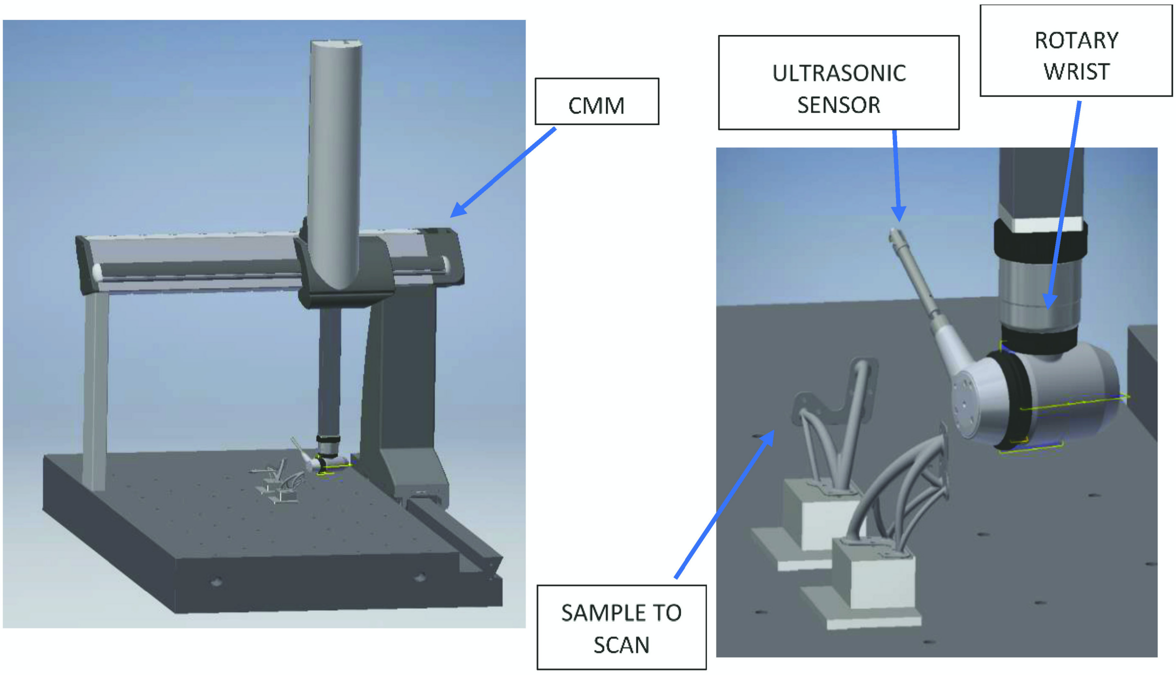


Figure 3 — Overview of the automatic ultrasonic system

7.3 Definition of the part reference system

Once the part has been fixed on the coordinate measuring machine a proper reference system should be created in order to be able to locate the position of the defects on the part. This reference system could be easily created measuring the part by means of any kind of probe that can be mounted on the CMM. It can be a contact or non-contact probe. The selection on the probe is related to the accuracy that has to be achieved in the definition of the reference system.

7.4 Definition of the measuring path in case of complex (free form) surfaces (keeping the sensor as orthogonal as possible to the surface)

A proper scan path to measure the part with the ultrasonic transducer mounted on the wrist shall be defined. To obtain a good path a CAD nominal model of the part is preferable. Starting from the nominal feature a set of three-dimensional points (xi, yi, zi) are derived.

As explained in 7.2 a continuous articulating probing system shall be adopted to guarantee a perpendicularity between the transducer and the surface along the full scan. Thus, the angular positions (Ai, Bi) of the articulating wrist are derived per each of the three- dimensional point belonging to the scanning path.

The accuracy of the angular positioning of the continuous articulating probing system is a key factor to guarantee the possibility to receive a strong backwall echo. In the following table some examples of signal loss are reported on parts with different curvatures and thicknesses.

Values have been computed considering an angular position error of 0,35 mrad and an offset of the probe system of 260 mm. New values can be easily obtained changing those parameters.

Curvature (mm)	**Thickness** (mm)	**Signal Received** (%)
∞	25	99,5 %
8	2	98,7 %
3,5	1,5	97,9 %
8	16	89,8 %
12,5	25	89,7 %

7.5 Automatic application of the coupling fluid

Most UT sensors require a coupling fluid (typically gel or water) to improve transmission of the ultrasonic beam through the sensor/workpiece interface.

To have a completely automatic scan of the workpiece on the CMM, also the application of the coupling fluid (when required by the chosen ultrasonic sensor) shall be made automatic.

A system for automatic application of a coupling gel could be set-up as follows (see also the picture below):

— A gel reservoir and a supply pump located on the main CMM structure.

— Connection tubes running from the pump to the articulating wrist and ultrasonic sensor.

— A gel dispensing nozzle located as near as possible to the UT sensor; the nozzle can be integrated in the sensor holder.

The main parameter to be defined is the required gel flow; a small value is expected as the gel tends to stay in place on the sensor's tip. It will be necessary to clean the part after the measurement.

In case water is used as coupling fluid, the application system shall also include a collection tank and a draining or recirculating system.

Some manufacturers offer UT sensors with integrated nozzle for measurements with water (e.g. "bubbler" sensor by Olympus).

Additionally, the articulating wrist shall be protected against water splashes.

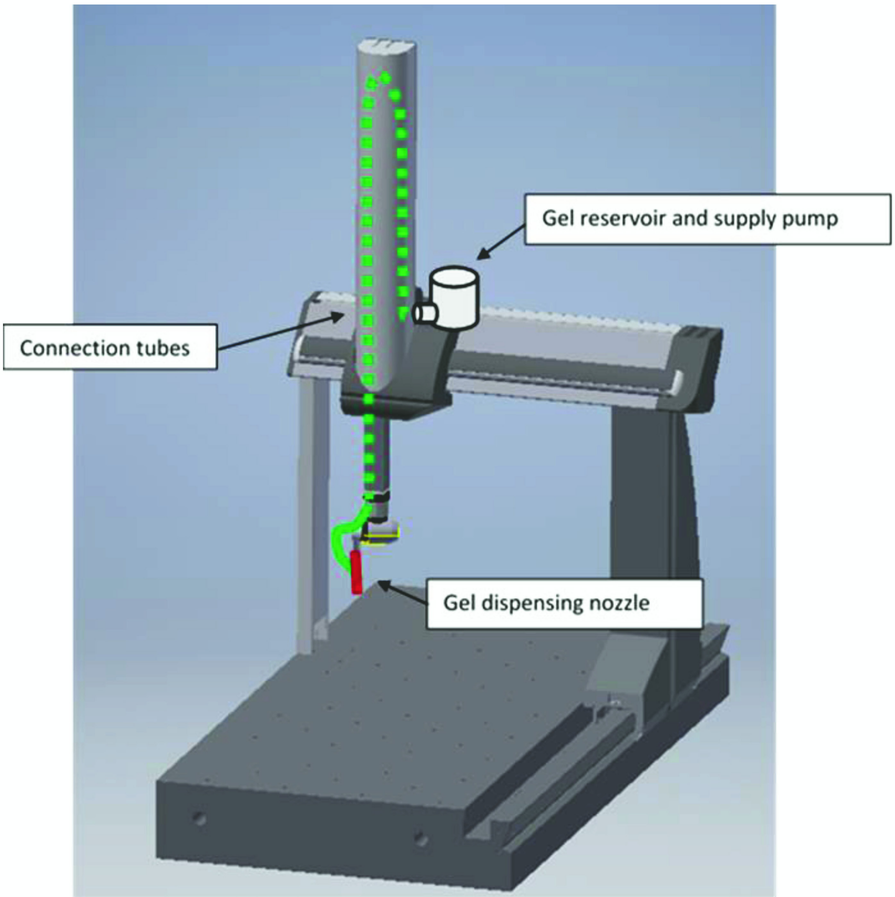


Figure 4 — Design of the system for automatic application of the coupling gel

7.6 Detection of the defects with their position on the workpiece

With the integration of the ultrasonic sensor on the articulation system and after a proper setup of the parameters by considering the part that has to be measured (material, shape, thickness…), it is possible to start the ultrasonic inspection to detect internal defects on the part.

Once a defect is detected by the ultrasonic inspection a signal trigger is sent to machine that can freeze the three-dimensional coordinate to locate the defect position on the part on the basis of the previously defined workpiece reference system.

Tuning properly the parameters it is possible to detect defects of different sizes.

During the experiment carried out in the Bionic Aircraft project it was possible to detect:

— Pores with diameter ≥ to 500 µm located in the middle on a minimum 2 mm thickness wall.

— Delaminations (or cracks) with a thickness ≥ 200 µm and an area ≥ 5 × 5 mm^2 located in the middle of a 2 mm thickness wall.

7.7 Estimation of defect size

With the integration of the ultrasonic sensor on a coordinate measuring machine it is possible to freeze the three-dimensional coordinates of both start and end points of the defect.

With this information a preliminary estimation of the defect size can be obtained as result of the measurement considering either DAC or -6 dB sizing technique, depending the size being sought.

To summarize in the following picture a workflow of the complete process for the automatic ultrasonic inspection of part is reported.

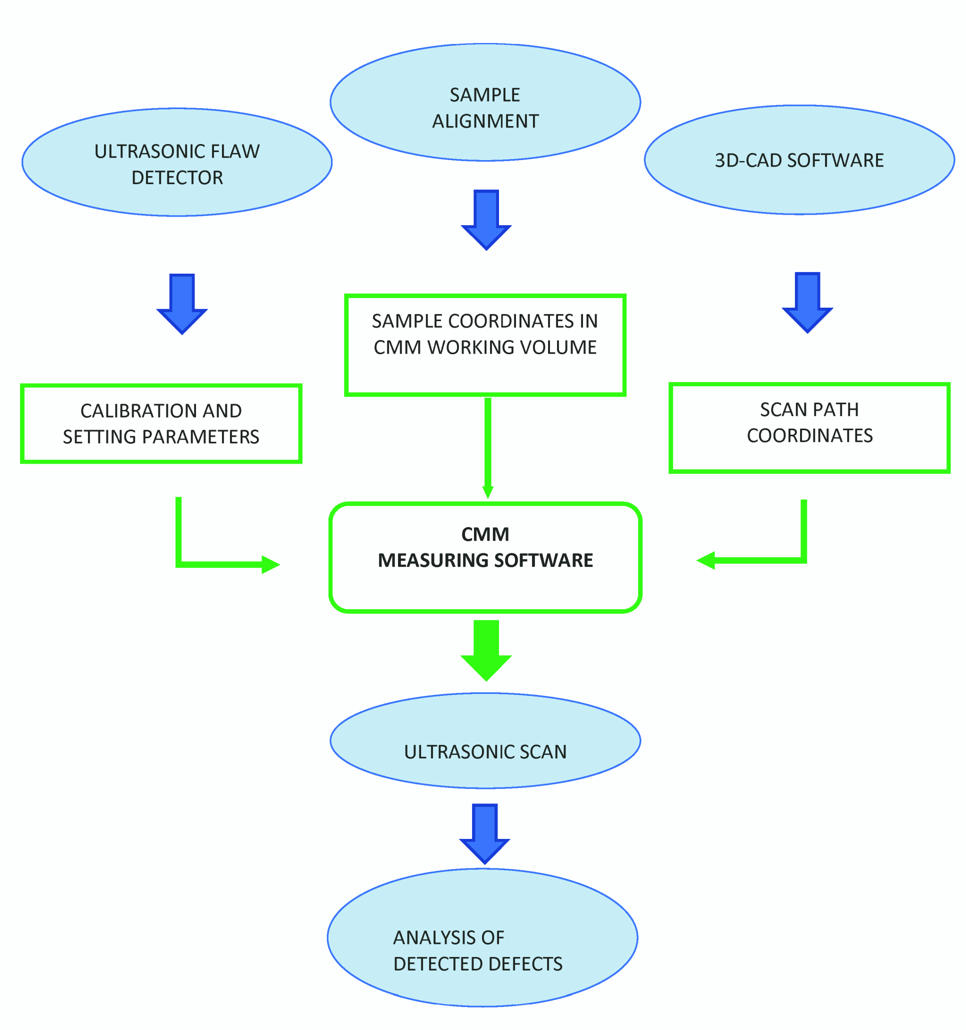


Figure 5 — Diagram of the information flow during the automatic ultrasonic inspection

8 Inspection of areas with difficult access under in-service conditions

8.1 Potential Defects and Severity Mapping

In order to make the inspection under in-service conditions more customized to the part to inspect and more cost-effective, a PDSM can be performed. A PDSM classifies the different areas of the part according to their criticality as well as provides the most likely type of expectable in-service defects and the maximum admissible sizes (*m*) per area. This way, the ultrasonic inspection will be focused on those types and sizes of defects per area that are relevant to be detected.

EXAMPLE JSSG-2006 document could be used as a reference to obtain the mentioned PDSM, for those parts categorized as “Slow Crack Growth” parts.

8.2 Transducer and equipment dimensions

The free space available (accessibility) under in-service conditions shall be known before chosen the transducers and equipment, since this can limit their selection.

The dimensions of the transducers (considering the wedges if they are required) shall be checked together with the access to the areas of the part to be tested.

The volume and weight of the equipment (pulser-receiver) shall be also checked together with the free space of the real environment where the part is installed.

The curvature of the cables shall also be considered.

A flat contact face of the transducer shall meet the following condition (according to EN ISO 16811):

$$l < 10 \cdot b$$

where

l the largest dimension of the transducer's contact face in the inspection direction;

b the bend radius of the part at the inspection point.

If that condition is not met, a shaping of the transducer's wedge should be performed, or a flexible wedge should be used.

8.3 Testing techniques

Pulse-echo is proposed as the basic inspection technique, with normal or angle incidence, depending on the geometry of the part and the zone to be inspected.

Phased array technique based on the mentioned basic parameters of pulse-echo technique is suitable when there is enough free space on the access area and the surface is flat enough considering the size of the transducer (see 8.2).

Through-transmission technique may be also suitable when free space is available for the zones to be inspected, especially under in-line conditions.

8.4 Sensitivity setting

Sensitivity settings will be performed according to EN ISO 16811 standard. The setting technique will depend on the size of the defects to be sought:

— *Technique-1*: DAC technique, when the beam diameter is greater than the defects.

  When inner cracks are sought, DAC curves will be obtained from reference blocks where FBHs will be used, with the size of m as a diameter, as reference reflectors.

  When surface cracks are sought, DAC curves will be obtained from reference blocks where elliptical shaped notches, with dimensions of $a \times b$ as reference reflectors. The parameters a and b will be obtained from the PDSM (8.1).

— *Technique-2*: -6 dB technique, when the beam diameter is smaller than the defects sought.

8.5 Acceptance levels

The acceptance levels for each zone of the part, will be based on the m parameter (see 8.1) stablished by the PDSM. The proposed levels are shown in Table 2.

Table 2 — Acceptance levels for each sensitivity setting technique

Sensitivity setting	Record level	Acceptance level
DAC technique	H_m – 12 dB	H_m – 6 dB
-6 dB technique	¼ *m* defect size	½ *m* defect size
H_m: amplitude level of a DAC plotted from a "*m*" mm reference reflector size (see 8.4).		

9 Advanced ways of ultrasound generation and detection, without couplant agent, by LUS

9.1 Technology and applicability

An upcoming technology for non-destructive ultrasonic testing is Laser-Ultrasound (LUS), where the ultrasonic signal is generated by means of a very short high-energy laser pulse transferring the energy to the surface of the part to be tested. There, an ultrasonic wave with broad bandwidth ranging up to several hundreds of Megahertz is generated. The wave propagates through the material and is (e.g. as an echo from the back wall or from any defects…) detected on the surface again by means of a laser vibrometer.

The LUS technology is well known and developed and researched since many years. Nevertheless, the technology was (a) not in the scope of the Bionic Aircraft project and is (b) not yet defined in any standards (cf. Clause 2 Normative references and the Bibliography).

9.2 Implications with reference to this document

Some technological facts regarding LUS being basically different to standard Ultrasonic testing result in fundamental implications in respect to items pointed out in this document.

- With respect to 6.1: the ultrasonic signal generated by LUS offers a broad bandwidth ranging up to several hundreds of MHz.

- With respect to 7.2: for the CMM selected, slightly different requirements may apply: the stand-off distance to the part may be higher, the weight of the measurement head my potentially be higher. This point should be deeply investigated. Moreover the size of the head can limit the part accessibility.

- With respect to 7.4: there is no need to position the measurement head in an axis perpendicular to the surface. The ultrasonic signal is generated in the surface and it is not depending on the angle of the generating laser beam. This can give the possibility to mount the head on a different wrist (not continuous). Even in this case the real applicability should be deeply investigated.

- With respect to 7.5: no coupling agent is needed / applied.

- With respect to 8.3: puls-echo method is feasible, also transmission mode can be applied. Due to the high flexibility of the laser-beams those, e.g. can be transformed in shape or modulated in time, generating novel ultrasonic sound patterns. Further, the position of generation and detection spot can be chosen very freely, enabling for additional possibilities in materials analysis and characterization.

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