Phase Statistics and Spectral Analysis of Ultrasonic Signals for CFRP Component Assessment

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PHASE STATISTICS AND SPECTRAL ANALYSIS OF ULTRASONIC SIGNALS FOR CFRP COMPONENT ASSESSMENT

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ABSTRACT

The established and industrially applied ultrasonic inspection and monitoring techniques typically use the amplitude values of the ultrasonic signals for assessment of flaws. However every individual signal value has the phase information, in addition to the amplitude information. Through analysis of the statistical distribution of phase values provided by state-of-the-art measurement systems and an appropriate consideration of this information in the signal evaluation, a significant improvement in flaw detection capability of an ultrasonic test can be achieved. Moreover, the phase and the frequency of ultrasonic signals carries information that can be correlated to the inner structure and existing inhomogenities of the material to be assessed. The two novel approaches for increasing the information content of the classic ultrasonic test - phase statistics and spectral analysis - are new and promising. Use of these approaches, even for on-line measurements has become possible particularly through modern computer science and signal processing. It is particularly significant that these methods are based exclusively on the analysis and processing of “conventionally" acquired ultrasonic signals, so that in-depth rework of the measurement technology or ultrasonic hardware can be added with additional useful information on the material’s condition to be obtained.

KEYWORDS : *ultrasonics, phased array, linear predictive coding, CFRP*

STATE OF THE ART OF ULTRASONIC MATERIAL TESTING

Today's overall process chains for production of CFRP components for aviation applications are characterized by a variety of highly complex process steps and particular requirements [1]. The crucial difference to known and easily mastered process chains in the area of aluminum lightweight construction is the formation of the material during component manufacturing. Due to this fact the interactions of the individual processes are in some cases strongly pronounced over the entire process chain, and have not been completely explored as an entity.
For testing of CFRP components, different techniques are used for ultrasound coupling, depending on the material structure [2]. In areas with a sandwich structure - i.e. a honeycomb core with CFRP top layers – through-transmission technique with free-jet nozzles (squirters) is usually used today. Compared to other testing techniques the signal to noise ratio is indeed reduced but no depth information is supplied (location of defect or component thickness). However manufacturing defects of approximately 100 mm^2 can be reliably detected. With through-transmission techniques assessment of porosity in CFRP is only possible with extreme restrictions and the technology in question is not state of the art.
A relatively new successful development that is increasingly establishing itself in practice is the so-called phased array technique [3]. It is being used with increasing frequency and is even used as a

replacement for conventional test techniques as well as for new test tasks. With the phased array test technique a variety of possibilities arise for specific improvement of various NDT solutions such as on structural aircraft components in manufacturing and maintenance applications [3]. The fundamental principle consists of temporally controlled excitation of piezoelectric transducers in a linear or matrix-like arrangement. The desired characteristics relative to the direction of sound intromission and focusing are achieved electronically through a defined time offset excitation in the resulting sound field. The advantages are better defect detection due to the variable focal point, more economical testing due to large area capture (electronic scanning, no meandering scans), back wall echo from diagonal back walls up to 15° through an electronically controlled sound field, and simultaneous microsection-like presentation.
In recent years the latest development in ultrasonic phased array technology is referred to as sampling phased array (SPA). While conventional phased arrays systems use sound field control through so-called time-controlled excitation of phased array elements or time controlled reception of ultrasonic echo signals and thus permit the "scanning" of the object to be examined via ultrasound, the new sampling phased array technology reconstruction of the ultrasound picture occurs purely on a mathematical basis, such that the advantages of modern computer technology and microelectronics, as well as signal and image processing can be fully taken advantage of. The new testing concept has been named sampling phased array because one or more phased array elements are excited in succession ("through cycled"), where one or more phased array elements receive the ultrasonic echo signals. From this information the ultrasonic signals for any intromission angle and depths of field can be calculated via special reconstruction algorithms.
In comparison to the conventional phased array technique, SPA offers several advantages, such as significant acceleration of the test, improvement of the informative value through synthetic focusing in each point of the test volume, quantitative quality of the ultrasonic test results through 2- and 3-dimensional imaging [4 - 8].

FREQUENCY AND PHASE CONTENT IN ULTRASONIC SIGNALS

All existing ultrasonic techniques for flaw identification such as pulse echo with single-element test heads, phased array procedures, through transmission technology, Synthetic Aperture Focus Technique (SAFT) and others only use the amplitude values of the ultrasonic signal. However every individual signal value has the phase information, in addition to the amplitude information. It has been shown [9] that through analysis of the statistical distribution of phase values provided by phased array transducers and an appropriate consideration of this information in the signal evaluation, a significant improvement in flaw detection capability of the ultrasonic test can be achieved. Moreover, the phase and the frequency of the ultrasonic signals as information carriers can be considered via the inner structure and existing inhomogeneities [10]. The two approaches for increasing the information content of the classic ultrasonic test - phase statistics and spectral analysis - are new and promising. Use of these approaches, even for on-line measurements has become possible particularly through the modern computer science and signal processing. It is particularly significant that these methods are based exclusively on the analysis and processing of “conventionally" acquired ultrasonic signals, so that in-depth reworking of the measurement technology or ultrasonic hardware is not required.

EXISTING NDT TECHNIQUES FOR POROSITY EVALUATION IN CFRP

Based on outstanding work dedicated to non-destructive evaluation of CFRP materials [10-16] a conclusion can be drawn that good quantification of porosity grade by non-ultrasonic techniques can be obtained on components with rather small wall thickness and simple geometry [13-16]. At the same time there are several ultrasonic techniques for CFRP testing which are discussed in review articles. The most common inspection approach consists of the measurement of backwall signal attenuation. Furthermore there are results on porosity testing of CFRP components based on measurement of ultrasonic sound velocity performed in the past. Besides few methods were presented that utilize measurement of the carrier frequency by changing the porosity grade in inspection objects. In [17, 18] some results have been reported which were obtained on laser based ultrasonic testing.

EXISTING SIGNAL ANALYSIS/PROCESSING APPROACHES

The main impossibility signal parameters taken into account in the review articles are signal attenuation, shift of carrier frequency, change of ultrasonic phase velocity. Typically for implementation of signal processing procedures the so called backwall echo signal as the most “strongly pronounced” event in the amplitude / propagation time series is taken for explicit consideration. It provides conclusive interpretation of signal features and robust quantification of the porosity grade in most of the cases. Due to complex geometry of the inspection object (e.g. radius testing) or/and large material thickness in combination with high sound attenuation (e.g. from porosity) when considering practical applications those approaches can’t be applied, since the backwall signal is simply not available. A newly proposed method termed Linear Predictive Coding allows overcoming this common limitation of the techniques by utilizing a novel approach based on phase analysis of ultrasonic signals.

THE LINEAR PREDICTIVE CODING APPROACH

Linear Predictive Coding (LPC) is a useful signal processing method widely applied in speech processing and speech estimation applications such as speech encoding and computation of the spectral envelope. Here we use the LPC-technique for the estimation of very small variations of instantaneous phase, frequency and the amplitude of ultrasonic signals. Due to interaction of emitted ultrasonic signals with porous media the analytic parameters of the signal recorded may become locally alternating in time. Theses alternations may be difficult to detect by any integral spectral method or series of time-frequency distributions. Here the detectability by LPC was practically verified on a large number of specimens with known porosity content.

The mathematical formulation of the LPC-technique is given below. It determines the coefficients of a forward linear predictor by minimizing the prediction error in the least squares sense. The coefficients of a p^{th}-order predict the current value of the real-valued time series $\boldsymbol{x}$ based on past samples:

$$LPC: R^n \rightarrow R^n\text{, where } x'(n) = -a(2)x(n-1) - a(3)x(n-2) - \ldots - a(p+1)x(n-p),$$

such that $\boldsymbol{p}$ is the order of the prediction filter polynomial $f = [1\ a(2) \ldots\ a(p+1)]$.

In order to reach higher time resolution i.e. to allow estimation of parameters throughout the inspected volume a windowing of the recorded ultrasonic signal must be introduced. Thus, an input signal x is divided in to m sample bins such that

$$x = [x^1\, x^2 \ldots x^k], \quad \text{where } x^i = x_j \ldots x_{j+m-1}.$$

In such a case LPC is applied to each $\boldsymbol{x}^i$.

The prediction error can be eventually used for the estimation of porosity of the inspected specimen. This instantaneous prediction error can then be computed as a difference between the original signal $\boldsymbol{x}'$ and the LPC-signal $\boldsymbol{x}$. In case of computation of separate segments $\boldsymbol{x}^i$ the LPC-signal must be smoothed by means of a low-pass filter first which will suppress possible computational leakages in the frequency domain.

APPLICATION OF LPC FOR POROSITY QUANTIFICATION IN CFRP

The LPC method has been utilized for quantitative evaluation of the porosity grade in CFRP components. The goal of the project was the development and validation of an inspection technique for pulse-echo ultrasonic testing by non-backwall-echo based evaluation of ultrasonic signals. The technique had to be independent of material thickness and shape.
A set of specimens with different known porosity grades was preliminarily investigated by X-ray CT, whereby the reference data were obtained. For check-up the a-priori values provided by the manufacturer as volumetric data sets were processed with respect to the porosity grade. Therefore the mean value of the CT volume amplitude values was determined and the values were set as thresholds by a mean value of + 10%. The volume elements (voxels) exceeding the threshold values were counted as so called volume hit values. Fig. 1 represents the correspondence between volume hit values and a-priori porosity values.

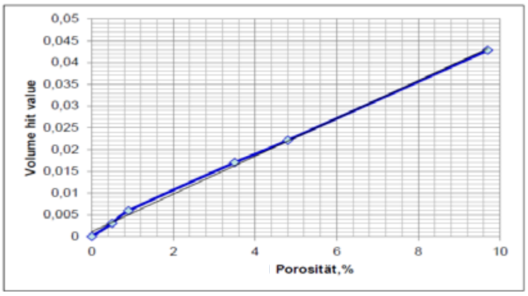

Fig. 1: Representation of volume hit values corresponding to a priori porosity values

The CT measurements were conducted on specimens with wall thickness range from 4 to 6 mm and porosity grade between 0% and 10%. The specimens were inspected in immersion pulse-echo technique by ultrasonic transducers with central frequency of 5 and 10 MHz respectively (Fig. 2).

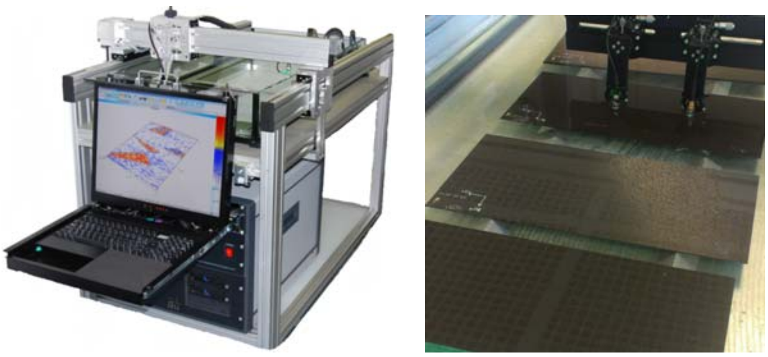

Fig. 2: Automated ultrasonic inspection set-up and test specimens while scanning

The certified technique for ultrasonic porosity testing in CFRP components consists in measurement of backwall signal attenuation with respect to backwall signal on the defect-free area. Thus, at first the relationship between the backwall signal and the porosity grade was investigated for available specimens (Fig.s 3 and 4). The same ultrasonic signals were then undertaken to LPC processing. Instead of the backwall signal the initial area of the echo-signal was processed (Fig. 5). Finally the correspondence of LPC coefficient from porosity grade was obtained for both 5 and 10 MHz signals (Fig.s 6 and 7). Fortunately, the dependence has a monotone character and allows an invariant calibration of the measurement equipment. In contrast to backwall attenuation measurement (see Fig. 3) also high frequency transducers (10 MHz) provide distinct results with a near to linear dependency. The LPC based inspection results can be represented in form of common C-scan views (Fig. 8).

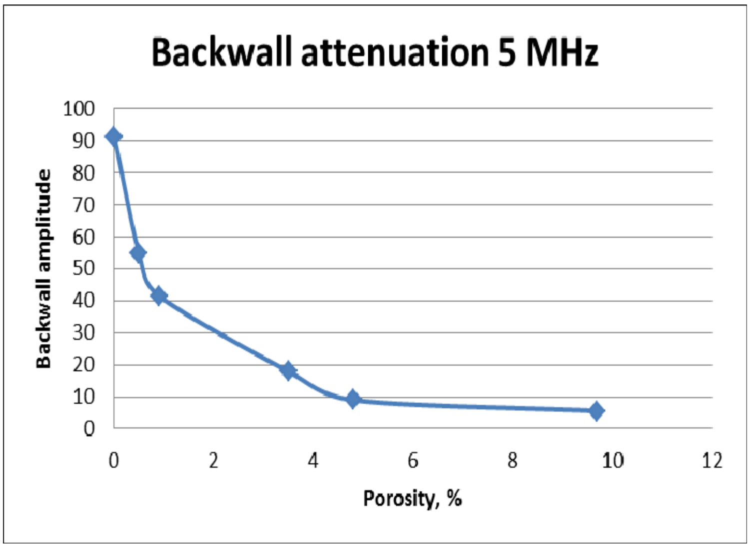

Fig. 3: Backwall attenuation as a function of porosity at 5 MHz

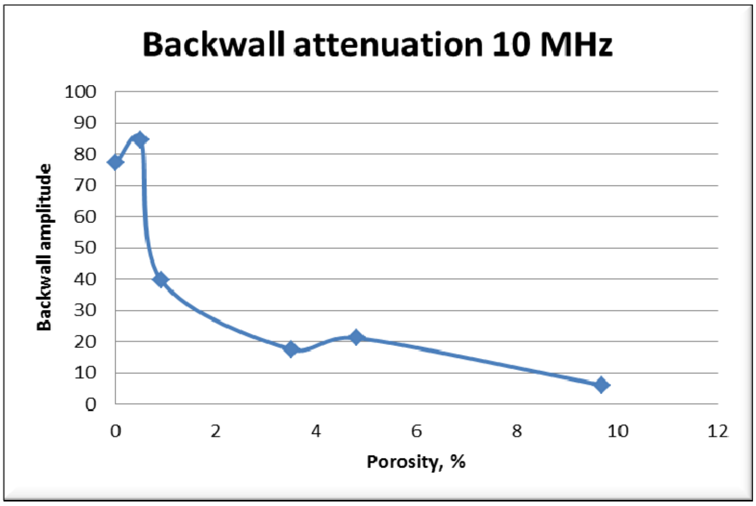

Fig. 4: Backwall attenuation as a function of porosity at 10 MHz

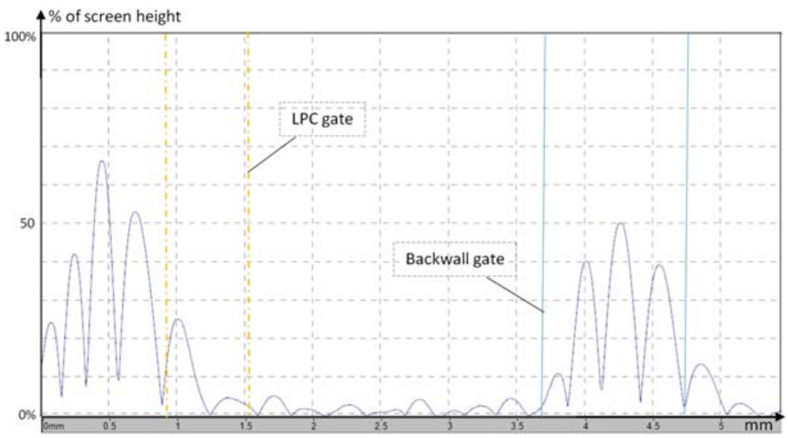

Fig. 5: Processing gates for backwall and LPC analysis

RECOMMENDATIONS FOR LPC INDUSTRIAL APPLICATION

Typically ultrasonic testing of CFRP components in industry is conducted by means of phased array transducers that significantly increase performance of inspection machines and its applicability on components with complex geometries. LPC can be easily applied on single element pulse-echo transducers as well as on phased array systems by processing the local ultrasonic signals (A-Scans) while scanning CFRP components (Fig. 9).

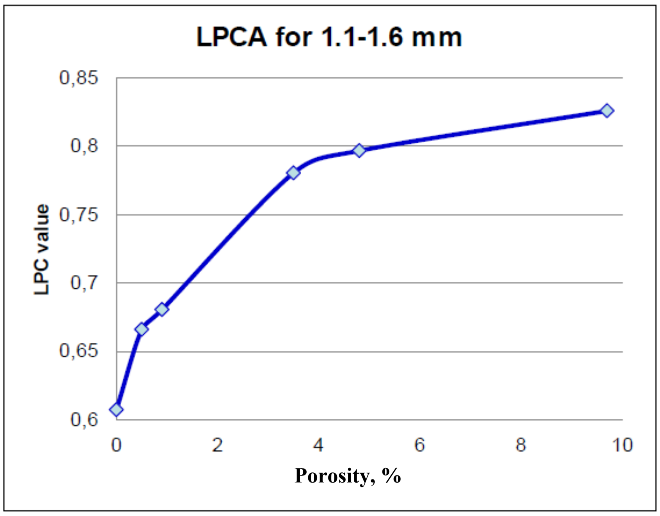

Fig. 6: LPC coefficient as a function of porosity at 5 MHz

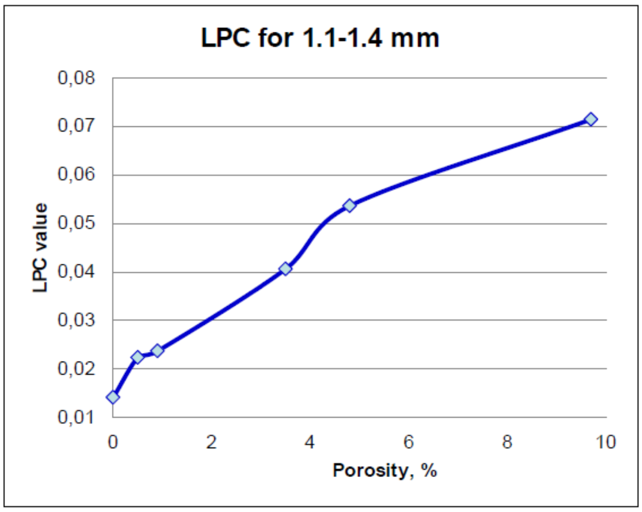

Fig. 7: LPC coefficient as a function of porosity at 10 MHz

CONCLUSION

The proposed inspection technique utilizes a novel approach for processing of ultrasonic measurement data that significantly improves the applicability of ultrasonic nondestructive testing of CFRP material. The novelty consists in change from traditional amplitude-based analysis of echo-signals to the phase-based processing. Apart from direct practical advantages, such as porosity inspection in thick and / or highly attenuative components, the technique can be applied in the existing industrial inspection set-ups including phased array systems due to its rather simple processing principle, which allows its in-line implementation in realtime. Further development steps are aimed to demonstrate the possible use of LPC on components with complex shapes, such us radius testing. A certain methodical difficulty in this respect consists in the rather challenging technological implementation of specimen manufacturing with specified porosity grade. At the same time the high potential of the proposed measurement and processing approach has generated large interest for industrial application which is currently pursued along further R&D projects.

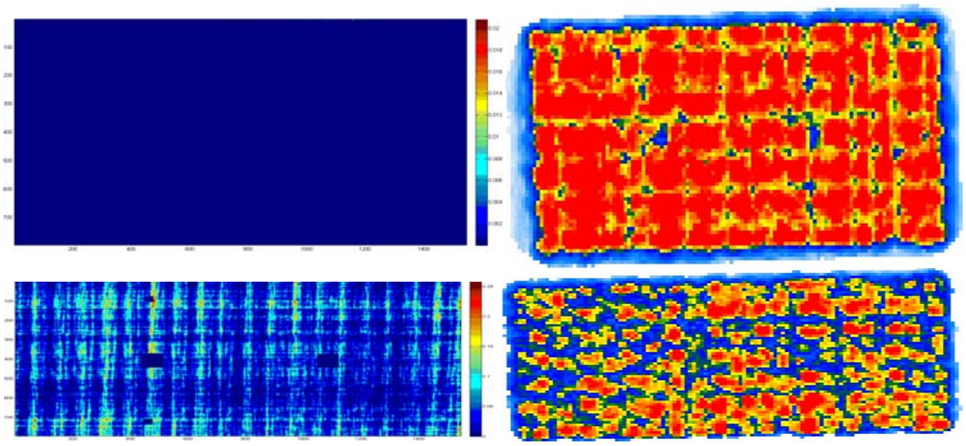

Fig. 8: Visualization of 0% (top) and 9.7% (bottom) porosity by CT (left) and ultrasonic testing (right)

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