Spectral Distance Amplitude Control for Ultrasonic Inspection of Composite Components

Uwe PFEIFFER, Wolfgang HILLGER,
DLR – German Aerospace Center, Braunschweig, Germany

Abstract. Ultrasonic inspection of sound-attenuating material like Fibre Composites requires correction for the loss of echo amplitude. Conventional Distance Amplitude Control (DAC) is not always sufficient, because it does not count for the spectral shift towards low frequencies after long sound paths. Therefore the detection of small flaws is limited, because they require high frequency ultrasonic signal. Consequently, small and deep defects are underestimated in conventional ultrasonic testing.

In this paper, a method called SDAC ("spectral distance amplitude correction") is presented. SDAC is based on digital signal processing algorithms and consists of a signal analysis module and a signal processing module. Analysis provides the typical sound attenuation characteristics of a specific material. Based on these characteristics, the compensation algorithm in the signal processing module recovers the lost spectral signal components in each A-scan. Processed A-scans look like if there was no sound attenuation. Then flaw echoes can be directly compared with each other, widely independent of the flaw's depth and size.

1 Introduction

Ultrasonic inspection methods are widely used for non-destructive testing of Carbon Fibre Reinforced Plastics (CFRP). However, the heterogeneous build-up of composites affects the sound propagation severely [1-4]. Hence the sound characteristics need to be adapted accurately to the specimen to test. Generally, high frequencies are desirable for good spatial resolution. On the other hand, the highly sound-attenuating composite material requires low frequencies for good penetration. The closer the ultrasound wavelength comes to the specimen's typical grain size, the more is lost. The loss of signal amplitude is usually compensated by additional variable amplification (DAC = distance amplitude correction). However, this approach still neglects the change of sound characteristics in composites.

The required high spatial resolution on the one hand and the inhomogeneous structure with large grain size on the other hand result in a narrow range of optimal transducer spectra for a certain specimen. But the loss due to scattering and absorption at the microstructure leads to a deviation of this optimal spectrum at deep positions.

In order to compare and evaluate two echoes from different reflectors both in signal amplitude and also in signal shape, it is therefore desirable to counterbalance the spectral deviation at each depth. For this purpose, SDAC was developed.

2 Conventional Ultrasonic Inspection of Composites

2.1 Test specimen and devices

For demonstration of the described effects, we use a monolithic CFRP step wedge of excellent production quality. The steps are produced by milling to thicknesses of 5, 10, 20, 30, 40, 50 and 56 mm, as show in Fig. 1. Each step contains at the back wall two flat bottom holes with diameters of 3 and 6 mm and a depth of 5 mm (3 mm at the 5 mm step), producing flat circular reflectors at depths of 2, 5, 15, 25, 35, 45 and 51 mm from the upper surface.

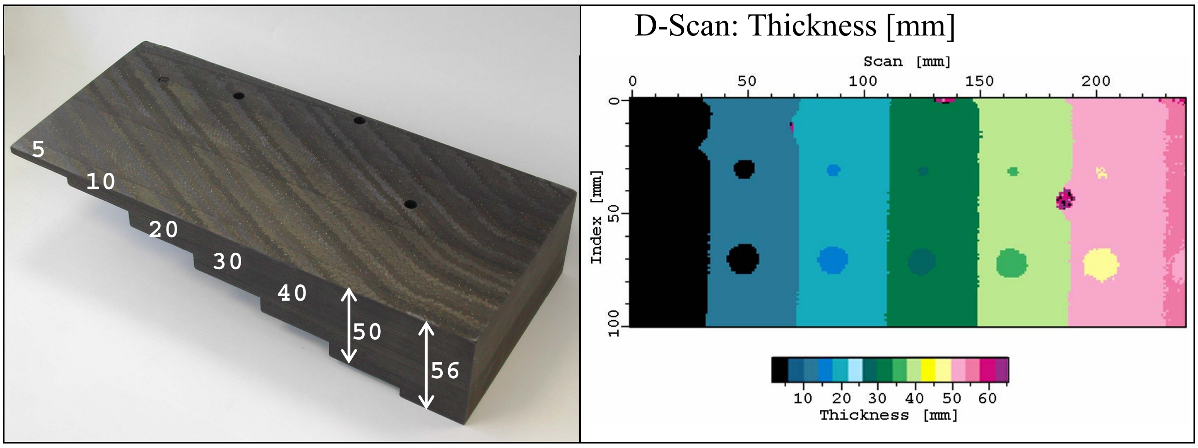

Fig. 1: Left: Monolithic CFRP step wedge with flat bottom holes; Right: Time-of-flight D-Scan

Ultrasonic inspection was performed using Pulse-Echo technique in direct coupling. The device used is a HFUS2400 with both burst and avalanche pulsers, analogue distance amplitude correction (see 2.2) and 12 bit data recording with full data storage [5]. The probe is a Deutsch S12 HB 0.8-3 unfocussed broadband transducer with a diameter of 12 mm and a bandwidth of 0.8 – 3 MHz [6]. Its near field length in CFRP is approximately 20 mm; therefore the 5 and 10 mm steps will not be used for quantitative evaluation.

2.2 Conventional Distance Amplitude Correction

Highly sound attenuating material like CFRP requires compensation for the increasing loss of sound pressure with increasing time of flight by additional amplification in the order of 1 dB/mm. This method is called Distance Amplitude Correction (DAC) and is integrated in every modern Ultrasonic device. For CFRP inspection it is beneficial to have a DAC that amplifies the recorded signal already in the analogue part of the device. This ensures considerably lower noise, especially for thick specimen and 8-bit sampling [2, 3]. Furthermore, ultrasonic testing in immersion technique needs a DAC that is triggered by the interface echo, which is only possible by having an online analogue gate independent of the digital signal acquisition. All of the measurements within this paper are recorded with our HFUS2400 device which is capable of an interface triggered analogue DAC.

In order to calibrate the DAC to a specific material, reference measurements are necessary. Of course, loss of amplitude appears also due to the sound beam divergence. Therefore the decrease of amplitude depends on the type of reflector [7]. We usually calibrate on the basis of large reflectors (back wall echoes). In Fig. 2 we see the amplitude C-Scan of the step wedge's back wall echo after the DAC had been calibrated at the same specimen. Not surprisingly, all back wall echoes have amplitudes of 80%, in spite of the very shallow one due to the transducer's near field.

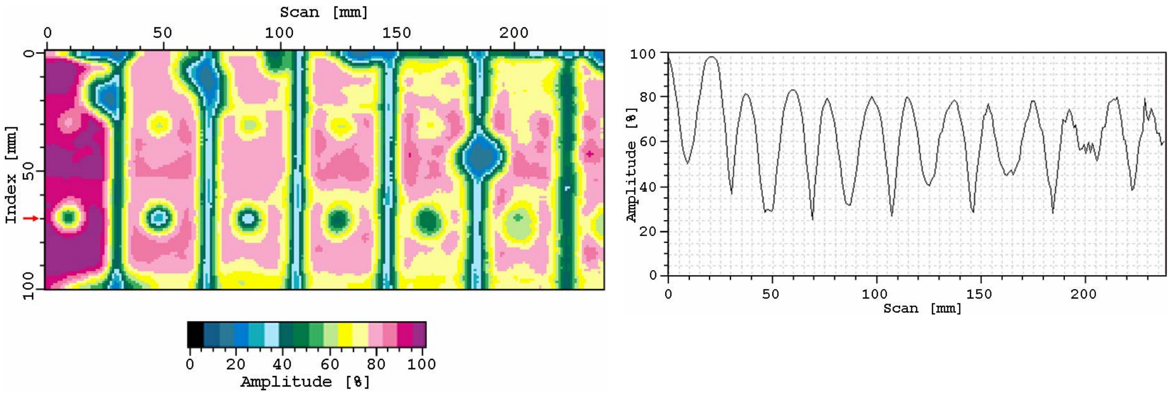

Fig. 2: Left: Back wall echo amplitude of step wedge with optimal conventional DAC.
Right: Echo dynamics at Index = 70 mm

2.3 *Analysis of Ultrasonic Sound Attenuation in Composites*

The conventional DAC is generally a good way for compensating the loss of amplitude. But in CFRP, high frequencies are attenuated disproportionately high. This is due to absorption and scattering at the inhomogeneous and anisotropic microstructure with typical "grain" sizes of the order of the used wavelength. Fig. 3 shows the amplitude spectra of two echoes: Left is the surface echo, on the right is the back wall echo after having passed twice a thickness of 40 mm monolithic CFRP. Both the loss of amplitude in general and also the shifting of the centre frequency f_C towards lower values can be seen clearly. Note that within this paper, the centre frequency (marked orange in Fig. 3) is defined as the frequency with the highest amplitude in the spectrum.

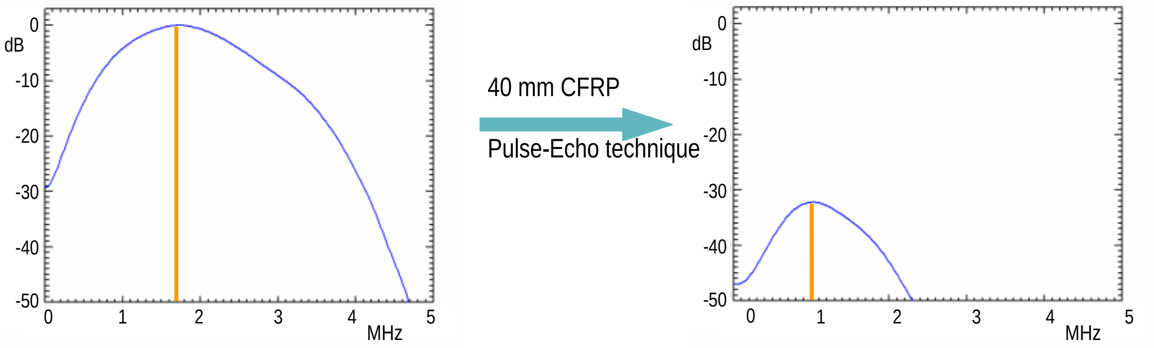

Fig. 3: High frequencies are excessively attenuated due to absorption and scattering.
Left: Amplitude spectrum of interface echo; Right: Back wall echo.

This analysis of spectral loss of sound pressure was performed for each thickness of the step wedge and put into a 3-dimensional diagram as shown in Fig. 4. For an estimate of spectra at intermediate depths, an interpolation was performed by fitting to a polynomial surface of third order.

Although the signal's absolute bandwidth Δf_{-6dB} decreases strongly, the relative bandwidth $\Delta f_r = \Delta f_{-6dB} / f_C$ remains very much constant. In Fig. 5, this effect is illustrated by further analysis of the step wedge's back wall echoes. They were extracted from the single A-scans by using the Blackman window function [8]. After Fourier transformation, the frequency f_C with the highest spectral amplitude was calculated for each A-scan as well as the width of each spectrum at -6dB in relation to f_C.

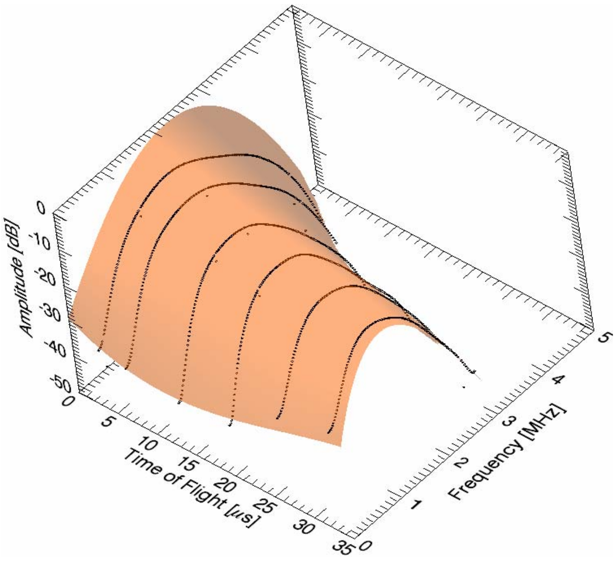

Fig. 4: Spectral loss over thickness (time of flight). Data had been recorded by using conventional DAC already.

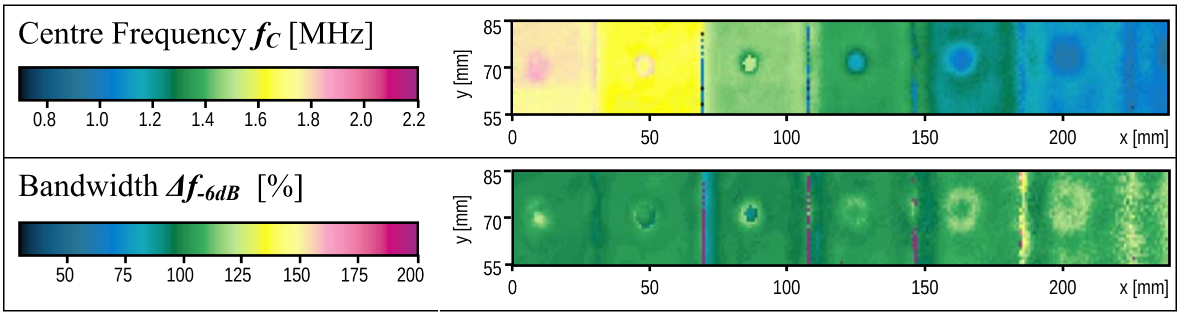

Fig. 5: Spectral analysis of back wall echoes at the step wedge.

The effects shown in Fig. 4 and Fig. 5 pose strong restrictions to the ultrasonic inspection of CFRP. Good sound penetration requires large wavelengths, but for good spatial resolution and sufficient probability of detection of small defects, short wavelengths are desirable [2, 4]. Therefore each specimen to inspect needs its own optimal compromise of these two competing demands. Furthermore, this compromise can only be optimal for a limited range of depth, because the signal characteristics changes along the ultrasound wave path. In pulse-echo ultrasonic testing, the reflected signals from two identical flaws in distinct depths are different, both in amplitude and also in signal shape.

3 Spectral Compensation of Sound Attenuation: SDAC

The approach of SDAC ("spectral distance amplitude correction") is to adjust the signal shape of deep echoes to a reference echo from a shallow reflector. This is done in the frequency domain: A spectral correction coefficient matrix $\Gamma(d,f)$ defines an amplification factor for each depth d and each frequency f in order to generate similar amplitude spectra for similar reflectors, although they are in different depths.

The signal analysis module of SDAC provides the typical sound attenuation characteristics of the specific material. It consists of an algorithm for the calculation of the spectral correction coefficient matrix $\Gamma(d,f)$, as illustrated in Fig. 6. This example is based on a volume data set of the step wedge in Fig. 1. Raw data was recorded by already using a conventional analogue DAC. Therefore the maximal amplitudes of the single spectra do not differ a lot.

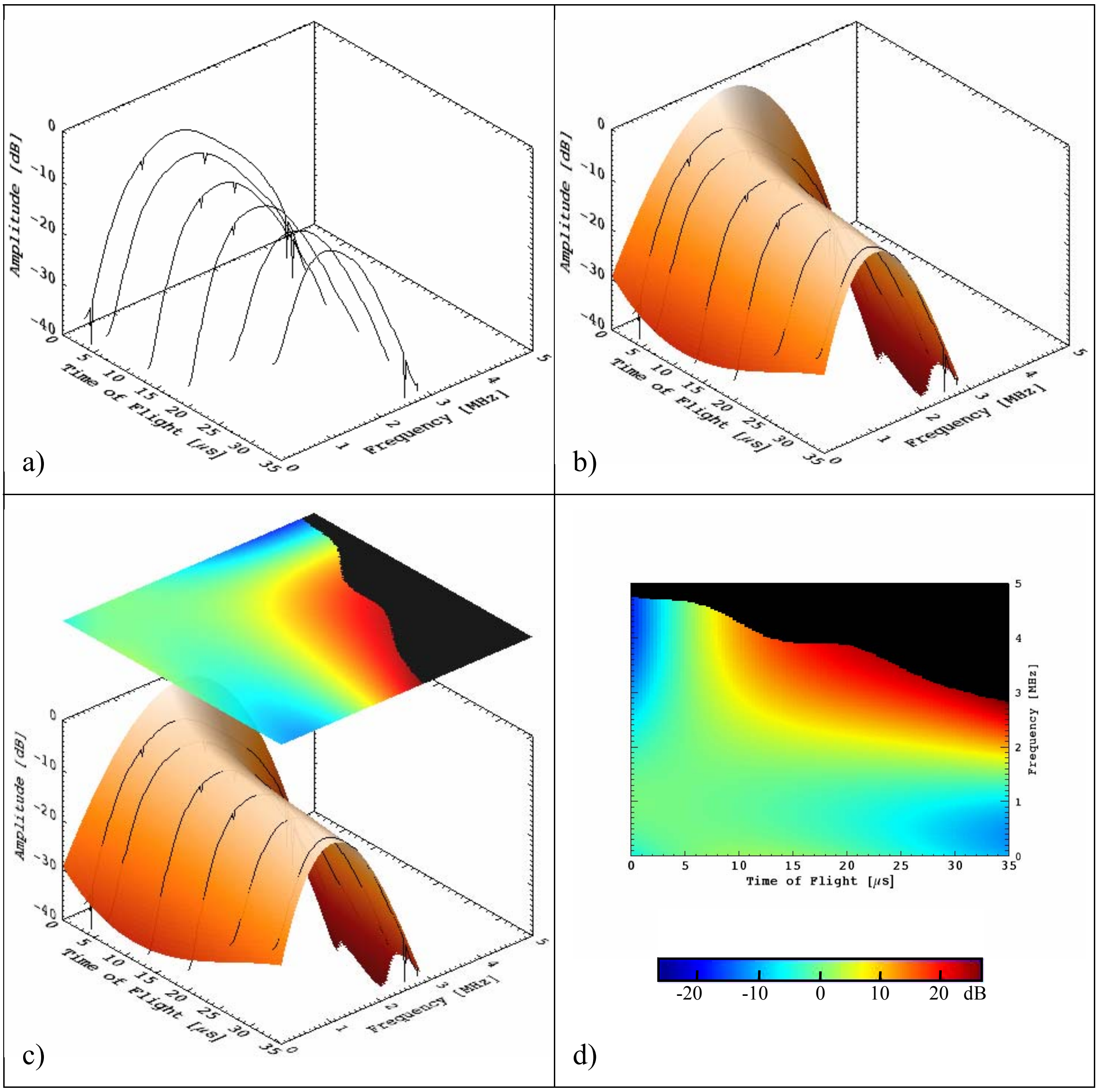

Fig. 6: Generation of spectral correction coefficient $\Gamma(d,f)$

First, spectra of back wall echoes from different depths are recorded and put to the according time of flight (see Fig. 6a, CFRP in Pulse-Echo: 1 µs ≙ 1.5 mm). Similarly to Fig. 4, a surface is then fitted to the spectra (see Fig. 6b). At one depth (or time of flight, respectively), a reference spectrum is defined (here at 5 µs). All deviations from this reference at other depths are recorded at the appropriate position in $\Gamma(d,f)$ as the desired amplification in dB (see Fig. 6c). The result is plotted in Fig. 6d: the spectral correction coefficient $\Gamma(d,f)$. It is recorded once for a certain material and then stored for later use at specimen with similar construction and similar production quality. Note that it can be used only for the same transducer and comparable thicknesses.

At high frequencies, each spectrum is limited because of noise. In Fig. 6, spectra are dominated by noise above 4.5 MHz for shallow back walls (e.g. at 5 µs). At thick regions (e.g. at 30 µs ≙ 45 mm), the spectral components are already at 3 MHz drowned. All high frequency signal portions don’t contain any utilisable information but noise and are therefore filtered away by software. They are set to -80 dB, as seen at the black region in the filter image in Fig. 6d.

The SDAC signal processing module is shown in Fig. 7. Preferably, A-scans have been recorded with conventional DAC already in order to minimize noise amplification during SDAC processing. The A-scan in this example shows one flaw echo of a 6 mm flat bottom hole at 34 mm depth and behind it the back wall echo at 37 mm. From the raw A-scans, a spectrogram is calculated by using Short Term Fourier Transformation (STFT) with appropriate window length and function, as well as appropriate FFT and time resolution. The key feature of SDAC is the spectral correction of the spectrogram, which is done in principle by just adding the correction matrix ***Γ**(d,f)* to the spectrogram (both in dB scale). This results in a corrected spectrogram where the lost spectral components are recovered as far as possible. From there, we gather the corrected A-scan by inverse Short Term Fourier Transformation.

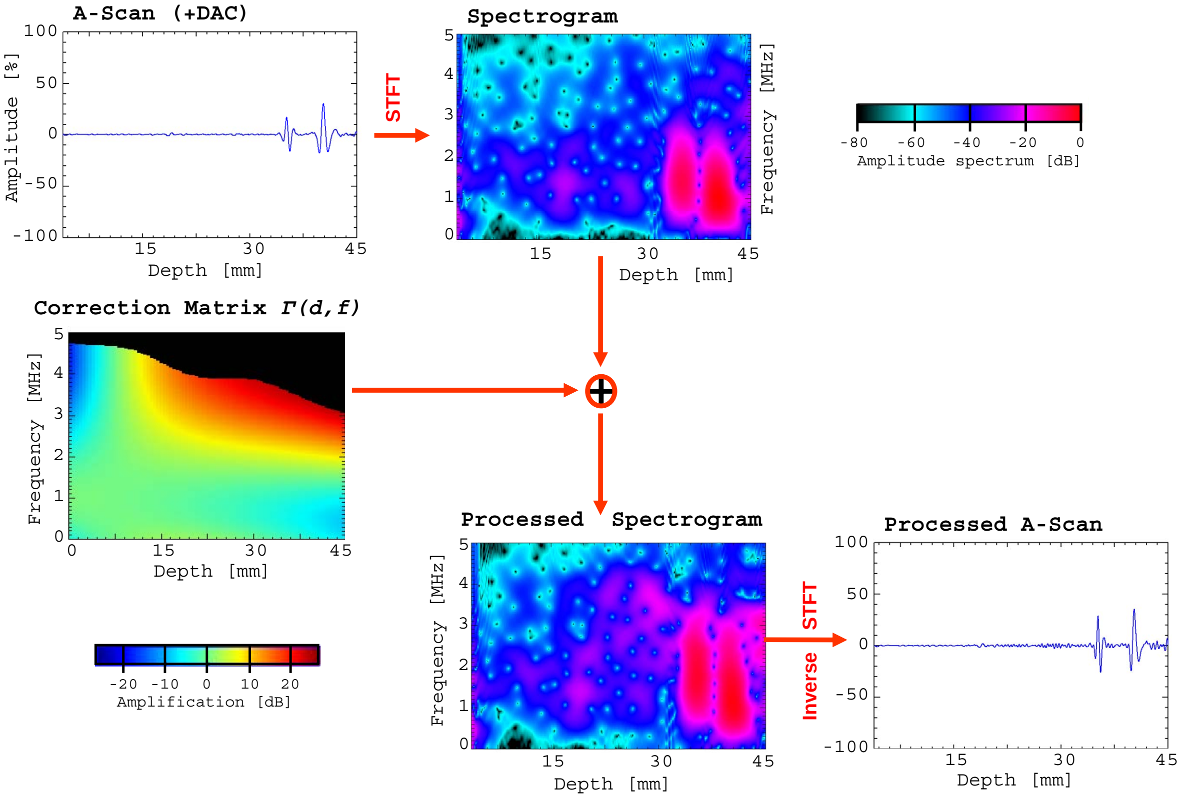

Fig. 7: Principle of processing single A-scans with Spectral Distance Amplitude Correction (SDAC) Algorithm

Processed A-scans now look like if there was no sound attenuation. The back wall echo is similar in amplitude, but narrower in shape; the flaw echo is both larger in amplitude and narrower in shape. Flaw echoes now can be directly compared with each other, independent of the flaw’s depth and widely independent of its size. Only the geometrical laws of amplitude decrease due to beam divergence affect the reflectors echo amplitude, but this can be taken into account easily by the well known amplitude-distance laws [7].

The same volume data set as in Fig. 2 was processed by this algorithm. Afterwards, a new C-Scan was calculated based on the SDAC-corrected data using the same gate settings as before. As expected, we still see constant amplitude of approx. 80% for the back walls (see Fig. 8). However, increased effect of small flaws to the back wall echo amplitude can also be seen: The back wall echo behind a flaw is quite constant independent of the depth.

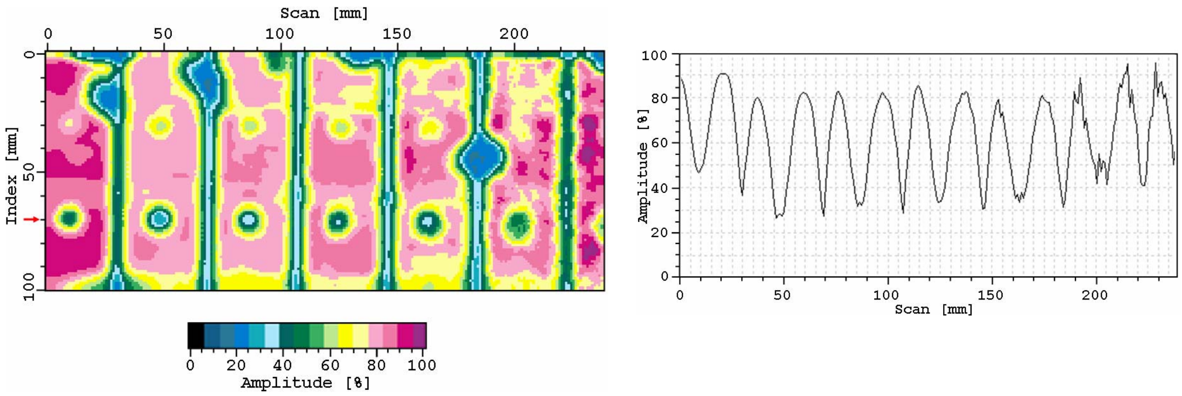

Fig. 8: Left: Back wall echo amplitude of step wedge after SDAC processing.
Right: Echo dynamics at Index = 70 mm

The SDAC algorithm as shown here is implemented in an ultrasound signal processing software which is capable of processing large volume data. The calculation time per single A-scan is in the order of one A-scan duration and can be further decreased by software optimization and/or implementation into a DSP.

4 Results

The SDAC algorithm was designed to improve both spatial resolution as well as probability of detection of small flaws in pulse-echo inspection. Analysis of flaw echoes' amplitude from the 3 mm and 6 mm flat bottom holes in the step wedge show a mean increase of amplitude 1.8 dB @ 6mm and 2.9 dB @ 3mm (see Fig. 9, only depths ≥15mm taken into account). This increase improves the probability of detection.

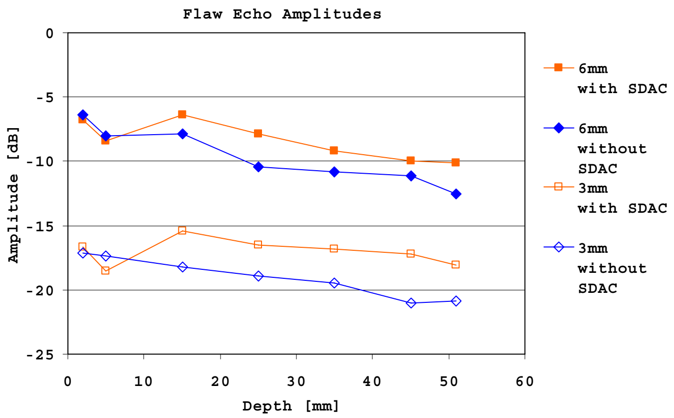

Fig. 9: SDAC compared to conventional DAC: Echo amplitudes from 3 mm and 6 mm flat bottom holes. The amplitude axis is normalized to 0dB @ 80% amplitude.

Concerning the narrowness of flaw signals, also an improvement could be achieved with this technique (see Fig. 10). In positions deeper than the reference, widths of echoes are considerably shorter after SDAC processing. This has direct impact on both the spatial resolution in depth and also the probability of detection of small reflectors.

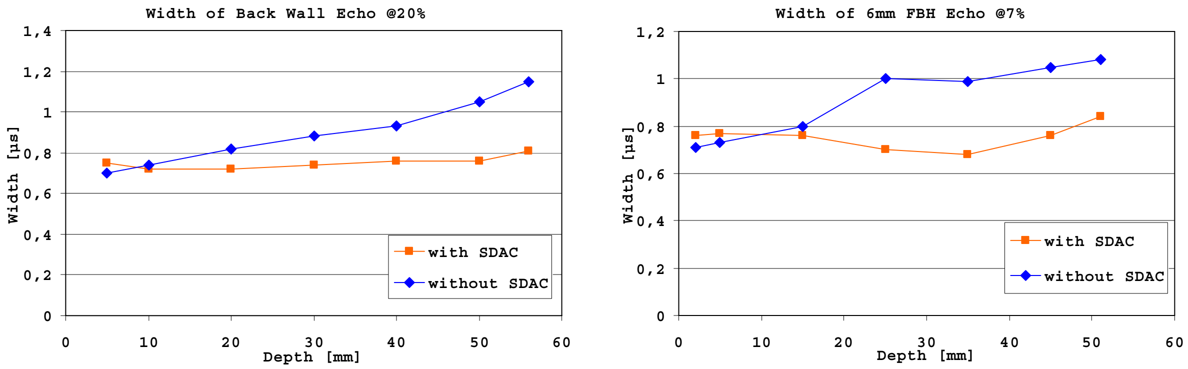

Fig. 10: Signal width of back wall echo at 20% amplitude (left) and flaw echo from 6mm flat bottom hole at 7% amplitude (right).

5 Conclusions

The SDAC algorithm can partly recover the high frequency signal content of echoes in composites. Within a certain range, the echo proportion that is missing due to scattering and absorption can be amplified without being jeopardised by noise. After processing, deep small flaws produce echoes that are higher in amplitude and narrower in shape. Processed echoes from similar reflectors now look similar, widely independent of their sound path. Both result in a higher probability of detection for small defects which is constant for the whole volume of test specimen. The algorithm has proved to be stable and reliable once an appropriate reference had been recorded. The calculation time is feasible and the algorithm can quite easily be included into existing ultrasonic imaging systems, if they provide full data recording.

6 Acknowledgements

The authors would like to thank the Testing Technology Department of Airbus Germany for their support and contribution.

7 References

[1] G. R. Liu, K. Y. Lam, H. M. Shang, Scattering of waves by flaws in anisotropic laminated plates, Composites Part B 27B (1996) pp. 431-437.

[2] W. Hillger, Ultrasonic imaging of internal defects in CFPRP-Components, 6th European Conference on Non Destructive Testing. Conference Proc. part 1, (1994) pp. 449-453.

[3] C. Scarponi, G. Briotti, Ultrasonic technique for the evaluation of delaminations on CFRP, GFRP, KFRP composite materials, Composites Part B 31 (2000) pp. 237-243.

[4] J.-F. Chaix, V. Garnier, G. Corneloup, Ultrasonic wave propagation in heterogeneous solid media: Theoretical analysis and experimental validation, Ultrasonics 44 (2006) pp. 200-210.

[5] http://www.dlr.de/fa/institut/strukturanalyse/versuchsanlagen/hfus2400flex

[6] http://www.karldeutsch.de/PDF/prospekte/P14E04_2005oP.pdf

[7] J. Krautkrämer, H. Krautkrämer, Ultrasonic testing of materials; Berlin: Springer, (1990).

[8] N. Hesselmann, Digitale Signalverarbeitung, Würzburg: Vogel, (1983).