ADAPTIVE FILTRATION OF ULTRASONIC SIGNALS IN CAR BODY ADHESIVE BONDS EVALUATION

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Abstract: Growing incorporation of adhesive joints in automotive body production routine demands development of fast and reliable non-destructive testing methods. The structural geometry of “metal sheet - structural adhesive – metal sheet” makes it complicated to use the convenient pulse-echo ultrasonic technique. A few algorithms of received signal processing were proposed for elimination of reverberation oscillations, detecting and interpretation of the informative signals. These methods based on adaptive filtration and correlation analysis were realized for scanning acoustical microscope data obtained in experiments with epoxy-based polymer adhesive samples. Their advantages and effectiveness were demonstrated and compared. Limitations of these techniques are also discussed. Results of data processing of the acoustical images for basic types of defects (voids, delaminations, uncured regions) are represented and discussed.

Introduction: In recent years adhesive bonding has become an increasingly important part of automotive body production technology, owing to its lightness and durability as well as its ability to join physically dissimilar materials. Its use, either independently or in combination with traditional joints (spot welds and rivets), gives significant cost-effective advantages. As a result, durability of these bonds becomes an essential part of the overall car strength and safety. This fact leads to the necessity of aimed quality assessment, which should be incorporated into the early stages of the production process. Ultrasonic pulse-echo method, which works very well for other applications of non-destructive evaluation, meets with several difficulties here. According to modern technology, the car bearing body is assembled from punched metal sheets. The adhesive joint in this case is a relatively thin layered structure, consisting from two or more metal sheets (0.5 – 3 mm thickness) with adhesive layers between them. Thickness of the adhesive can vary within 0.3 - 2 mm.

Ultrasonic inspection turned out to be more difficult than first thought due to two factors: first, the high acoustic mismatch between the layers, and second, the high attenuation inside the adhesive layer itself. The L-wave velocity in metal (steel) is approximately *6000 m/s* and the impedance is $4.3 \times 10^7\ kg/(m^2\ s)$. The sound velocity for the epoxy-based structural adhesive used in production was measured to be approximately *2300 m/s* with an impedance of $0.3 \times 10^7\ kg/(m^2\ s)$. As a result, the amplitude reflection coefficient from the steel-adhesive interface in the stack is *-0.87*. The attenuation inside the structural adhesive is almost $0.76\ mm^{-1}$ at *7.5 MHz*, and even worse for higher frequencies. These circumstances limit the operating frequency range. Acoustical pulses with a frequency of less than 10 MHz are not able to resolve interfaces of the joint, whereas waves over 25 – 30 MHz do not penetrate through the adhesive. Within the possible frequency band the weak signal reflected from the lower interface to the transducer is covered by strong reverberations in the upper sheet. Employing a spherically focussed acoustic transducer instead of a plane one gives some benefits and reduces oscillations sequence. However, even in this case, the proper interpretation of this complicated and cluttered waveform (Figure 1) requires some careful analysis.

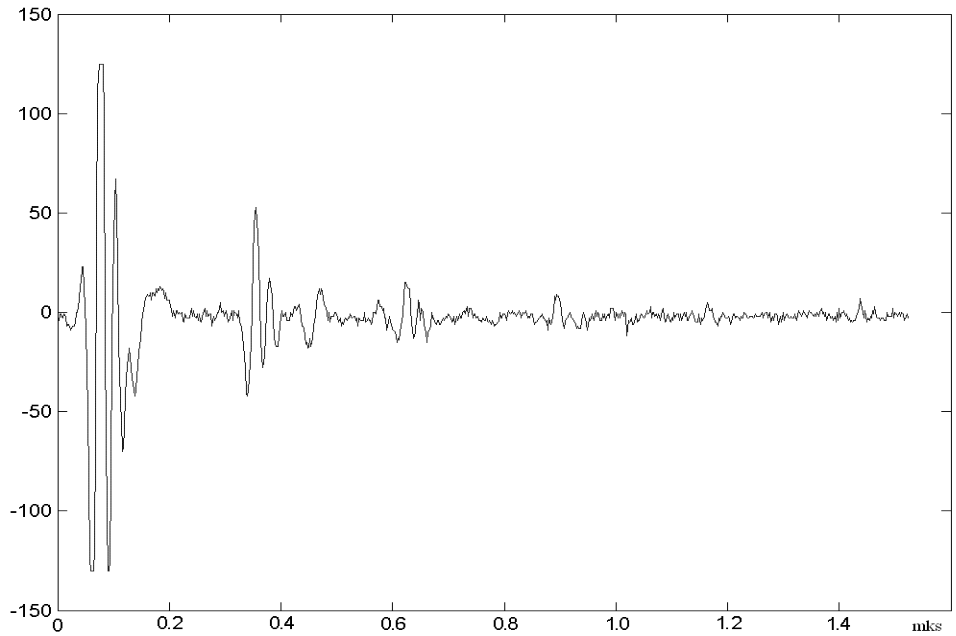

Figure 1 Typical A-scan obtained from 0.7 mm steel-0.3 mm epoxy structural adhesive- 0.7 mm steel structure

Results and discussion: The conventional method of signal processing used in acoustical microscopy is a time gating of the segment from the whole signal received (A-scan) and registration of the amplitude inside this segment. The data obtained represents the reflective capability of the gated layer. The second pulse in the train on Figure 1 corresponds to the first steel-adhesive interface and its level is proportional to reflection coefficient r_{sa}. Suppose acoustical properties of the steel are constant and uniform, it is possible to extract information about adhesion material impedance. The most convenient way is a two-dimensional map of this amplitude (C-scan), produced by mechanical scanning along the sample surface. It gives images of interface conditions, indicating voids and disbonding areas as well as significant variations in adhesive parameters (curing state, density). The main disadvantage here is a relatively low contrast of images – the difference in reflected amplitude between areas with good bonding and with complete absence of the adhesive is approximately 10%, close to the spatial noise level due to non-uniform surfaces (Figure 2a). Other defects, like poorly treated areas or uncured spots are barely detectable without additional processing. For example, Figure 2a shows C- scan of metal-epoxy interface, which was built from a set of three-dimensional data stored by Tessonics AM 1103 acoustical microscope. Here, the dark grey area corresponds to the presence of structural adhesive under 0.7 mm steel sheet. The lighter area is completely unbonded; the convex line between them is the boundary of the adhesive layer. The black strip on the right side signifies the absence of reflected signal beyond the sample. The original set of data was converted into numeric format and used as a source for digital processing.

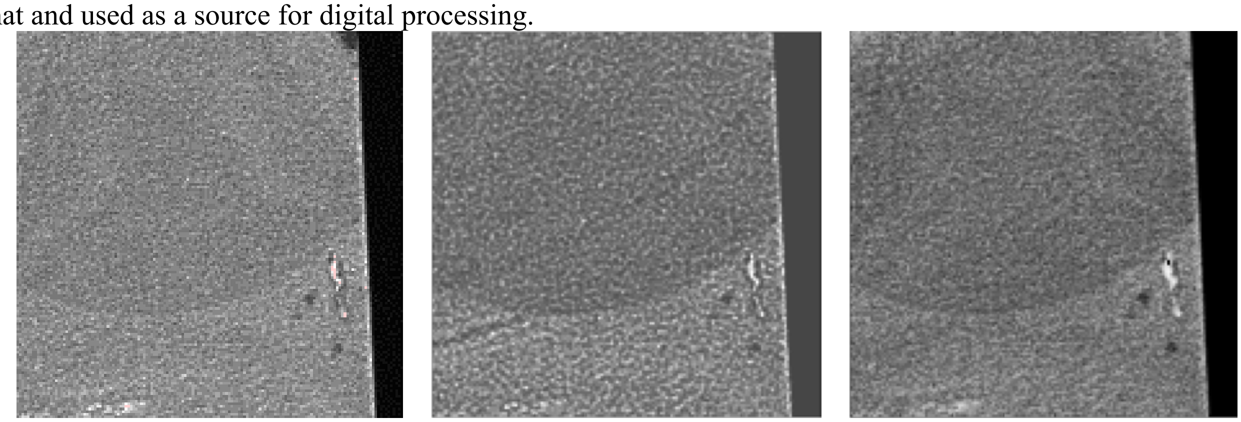

Figure 2. a) C-scan of the steel-epoxy interface (area 20 x 20 mm); b) multiplication of C-scans ,corresponding to several reflections; c) image representing attenuation coefficient distribution

The methods and basic principles of such processing are being developed by many research groups and discussed in a number of publications [1]. The most obvious way is taking into account several peaks of reflection. Each amplitude of bouncing sound is multiplied on the reflection coefficient value r_{sa}, so for n-th pulse on the diagram (Figure 1) its amplitude A_n will be proportional to r_{sa}^n. Each of them should give C-scans with improved contrast; an even bigger effect will be achieved by multiplication of these values. However, the realization of this idea shows that the spatial noise on resulting images also increases (Figure 2b). A more practical idea is to calculate the attenuation coefficient in each point and to collect them into a scan-like image. According to [2], the value θ calculated as

$$\theta = \frac{1}{n}\sum_{1}^{n}\frac{A_n}{A_{n+1}}$$

can properly represent the attenuation coefficient for a sequence of pulse amplitudes. However, processing the same initial set of data this way does not show significant improvement of the image (Figure 2c). Very tiny differences in the brightness of the areas, with and without adhesive presence, prove low performance of the method, at least for focussed acoustical beams.

The main reason, limiting image contrast and voids detectability, is noise visible on images as grain-like structure. It comes from small inhomogenities of metal and adhesive local properties and mainly – from roughness of the surfaces. Part of the noise, coming from electronic receiver input, can be reduced by using a low-pass filter with the properly chosen cut-off frequency (Figure 3a). The spatial averaging or image filtering can make these images look smoother, but it does not improve the informative content. The only difference is that small grains disappear and large-scale inhomogenities become visible instead (Figure 3b,c).

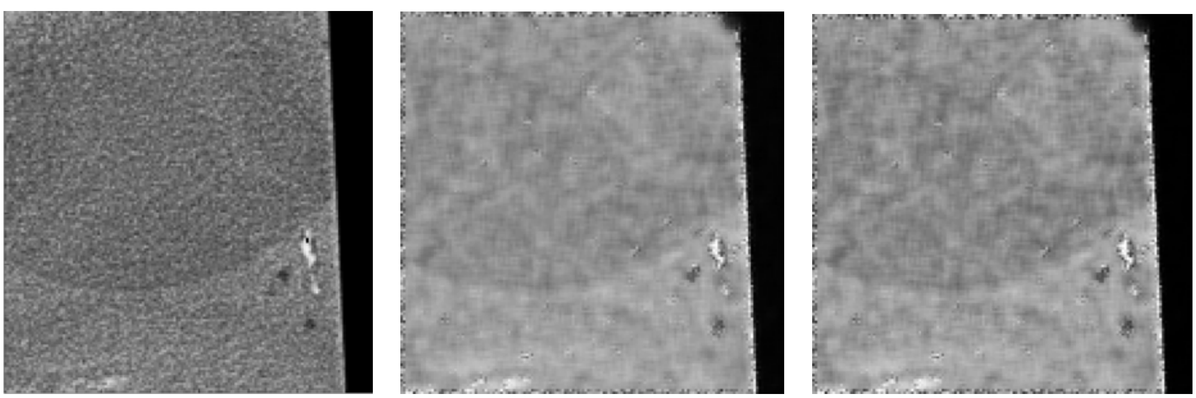

Figure 3. Result of filtering. a) application of low-pass filter to each A- scan; b) spatial filtering of the image; c) combination of the both procedures.

Low effectiveness of the above mentioned simple processing methods stimulates our search for more complicated ones. The attempt to utilize more information, contained in the acoustical signal, than amplitude only was made in [3]. In this case, each A-scan $f_A(t)$ is compared with the pre-determined reference signal and the level of similarity is calculated. The cross-correlation function is used as an indicator of this similarity. For the best results, the most informative segment of the A-scan, which includes four reflected pulses, was used in these calculations. An average of 16 A-scans, obtained on certainly well bonded areas was used as reference signal $f_{good}(t)$ representing a good adhesive joint. The same procedure gives us asecond reference signal $f_{bad}(t)$ corresponding to absence of adhesive material. Finally, the relative value

$$A = \frac{\max(\int_{-n}^{n} f_{bad}(t) f_A(t-\tau)dt)}{\max(\int_{-n}^{n} f_{good}(t) f_A(t-\tau)dt)}$$

was used for creating a scan-like image. The result is shown on Figure 4a. Obviously, the contrast between areas with and without adhesive is higher here. Noise is present here as outstanding individual pixels. Additionally, some interferometric strips appear as a result of integration.

Complete lack of adhesive is the model for a big-scale void. For the other kinds of defects, the same procedure also gives enhanced results. For example, Figure 4b shows an image of the region with artificial disbonding created by application of Teflon spray. Figure 4c represents the boundary between areas with cured and uncured adhesive. These defects are practically invisible on the convenient C-scans due to good sound penetration through them. Here such regions can be recognized, although significant noise is still a major problem.

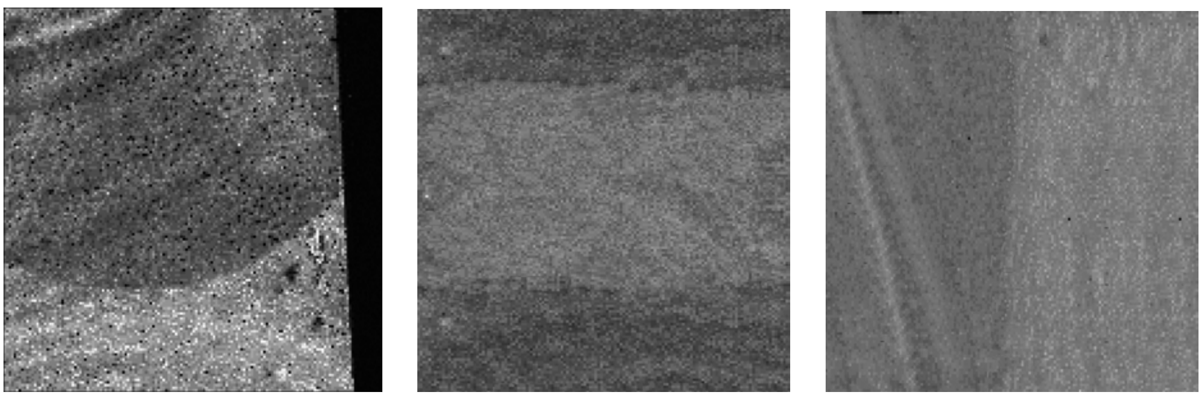

Figure 4 Result of cross-correlation processing of acoustical data. a) boundary adhesive-lack of adhesive; b)strip of Teflon spray on the interface; c) boundary uncured-cured adhesive

The pulse, corresponding to reflection from the bottom of the adhesive layer, provides more information about bonding flaws. However, it is very small in amplitude and usually masked by reverberation oscillations. This pulse appears on B-scan of sample with variable adhesive thickness as an inclined line, crossing the parallel lines of stable sheet reflections. Sometimes advanced operator skills and the proper choice of instrument settings makes it possible to create a second interface image, but it appears to be more like art, not technological process.

The simplest way to reduce reverberation effect is filtration of corresponding frequencies. The spectra of the oscillations excited by the short pulse in metal-adhesive-metal structure contains clearly separable resonance peaks, corresponding to elastic vibrations of different layers. Metal sheets represented by the set of thickness modes (n=1,2,3…). Adhesive layer has its own resonance frequency, presence of which indicates acoustical contact on metal-adhesive interface under the transducer. Higher modes of oscillation here are usually difficult for registration due to their attenuation. Cut-off frequencies of this filtration process should be adjusted for every A-scan in order to follow variations of adhesive layer thickness. When there is a small thickness of adhesive, this resonance peak may be overlapped by the ones from the metal sheet. Beyond this case, its amplitude may be measured and represented in the form of image [4].Large voids are detectable on this image, however spatial resolution is relatively low due to non-local character of oscillations.

Existence of these "dead zones" and low sensitivity reduces the practical value of the resonance methods. More sophisticated digital filtration of masking reverberations [5] can purify the signal, reflected from the second interface of adhesive layer. However, high sensitivity to the acoustical beam parameters and surface conditions reduces the quality of obtained images.

Conclusions: The problem of reliable analysis and interpretation of acoustical signals is still the key point in the ultrasonic evaluation technique. Noise and random factors like surface roughness limits the quality of information obtained, in particular, contrast of acoustical images. Sophisticated digital processing using whole waveform can improve performance of ultrasonic measurements. The cross-correlation method produces images with increased contrast and better detectability for several basic defects in metal-polymer-metal layered structures. Using this method for ultrasonic testing of thin sheets adhesive bonding gives a certain advantage over the convenient C-scan imaging technique.

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