Characterization and Evaluation of Composite Laminates by Nonlinear Ultrasonic Transmission Measurements

Sigrun HIRSEKORN, Ute RABE, and Walter ARNOLD, Fraunhofer Institute for Nondestructive Testing (IZFP), Saarbrücken, Germany

Abstract. The research work on Nonlinear Elastic Wave Spectroscopy (NEWS) of this contribution is focused on nonlinear ultrasonic transmission through damaged composite laminates for quality assessment. The generation of higher harmonics by a quasi-monochromatic excitation is evaluated. Specially designed and fabricated narrow-band transducers reduced the inherent probe nonlinearity. The transmitted ultrasonic signals were detected by a broad-band transducer, recorded, and Fourier transformed. The resulting amplitude spectra were stored in dependence on the transmitting power. The technique was applied to composite laminate samples with different damage levels. The samples may contain micro-crack fields, cracks, and delaminations. The local ultrasonic transparency, the second and the third-order nonlinearity parameters, and the distortion factor were obtained and are discussed in order to ascertain the significance of the parameters for quality assessment.

Introduction

Interfaces in composite materials influence significantly the mechanical behavior of components and limit their load capacity. To assess the quality of a material compound the nonlinear part of the stress-strain relation which is mainly governed by interfaces and interstices in a composite can be exploited. This property entails the appearance of a variety of nonlinear effects in both quasi-static and dynamic experiments, such as down-shift of resonance frequencies with increasing excitation amplitude, the generation of higher and sub-harmonics, frequency mixing, etc. These effects increase with the weakness of bonds and hence may be used for quality evaluation. A large amount of research has been carried out with the objective of relating the generation of higher harmonics in ultrasonic transmission through bonded structures to the quality of bonds [1-8]. Commonly used are the second order nonlinearity parameter β, a measure of the second harmonic generation [1], and the distortion factor K, a measure of the total nonlinear content in the response [6].

The experimental and theoretical research work on Nonlinear Elastic Wave Spectroscopy (NEWS) at the IZFP is, so far, focused to investigations of nonlinear ultrasonic transmission through bonded interfaces to assess the local bond quality [2, 7-14]. The generation of higher harmonics by a quasi-monochromatic excitation is evaluated. The experimental set-up has been described in detail previously [2, 6, 7] and will be only briefly summarized here. Compressional waves are insonified perpendicularly to a bonded interface by a narrow-band transducer. In most cases specially fabricated single-crystal transducers are used to minimize the higher harmonics content in the excitation. To provide an almost monochromatic signal, rf-pulses of 10 to 30 cycles are generated at a carrier frequency of about 2 MHz. The transmitted ultrasonic signals are detected by a broad-band transducer (Panametrics V110, 5 MHz center frequency), recorded with a sampling rate of 400 MHz with 8 bit signal depth, and Fourier transformed. A phase-sensitive detection unit was added to measure the phase of the ultrasonic signals relative to the rf-carrier [15] which excites the transducer. The resulting amplitude and phase spectra were stored in dependence on the transmitting power. The transmitting and receiving transducer were coupled to the sample by a thin (2 µm) lubrication oil-layer and firmly pressed on it. It was ensured by many tests that this coupling procedure guaranteed a linear and reproducible behavior in the measurements.

For thin bonded interfaces with a thickness much less than the ultrasonic wavelength a description only by binding forces, without taking into account explicitly the material parameters of the adhesive, is used. This description renders possible the determination of local interaction forces in the bond by the amplitudes and phases of the transmitted ultrasonic waves [8-13]. Samples consisting of aluminum plates of 4 and of 5 mm thickness joined together by epoxy adhesive layers of 30 to 50 µm thickness were investigated [9, 12-14]. In order to allow both ultrasonic transmission experiments and tensile loading, the ultrasonic set-up was integrated into a small laboratory scale tensile-test stage [16]. The ultrasonic transmission data were related to destructive tensile tests of the adhesive bonds. The absolute ultrasonic strain amplitudes were determined by using an optical interferometer for calibration. A threshold behavior of the transmitted harmonics was observed [9, 14]. Their amplitudes depend on the excitation following the power series expansion of a quasi-static interaction force at low amplitude excitation, and the phases of the signals vary little. Exceeding the threshold causes a considerable change in the dynamic behavior of the interface. It turned out that for these samples the phase of the transmitted wave at the excitation frequency and the interaction forces in the interface correlate with the tensile strength rather than with the second and the third-order nonlinearity parameter and the distortion factor [14].

This contribution reports about the application of the technique of nonlinear ultrasonic transmission to composite laminate samples provided by the aircraft industry within the European project AERONEWS [17]. The samples are damaged by impacts of different energy and may contain micro-crack fields, cracks, and delaminations. Those defects form contacts similar to thin weak bonds, and thus, similar measuring effects are expected. In this case not only one adhesive bonded interface in a component, but many small nonlinear defects might be involved. The measured amplitudes of the first three transmitted harmonics and the distortion factor are evaluated and discussed.

1. Specially Fabricated Narrowband Single Crystal Transducers

The experiments on higher harmonics generation and evaluation require an extremely linear behavior of the complete measurement equipment and therefore narrow-band transmitter probes of high amplitudes. For the electrical excitation of the transducers an advanced measurement system from the company Ritec [15] was used. Transmitting probes were specially designed and fabricated (GE Inspection Technologies GmbH, Hürth, Germany) taking advantage of the linear response properties of piezo electric single crystals when electrically excited. Single-crystal materials investigated so far are ZnO, $LiNbO_3$, and PMN-PT ($Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$).

The comparison of the radiation of a $LiNbO_3$ probe, 2 MHz center frequency, with the commercial transducer Panametrics A133, 2.25 MHz centre frequency, which is one of the transmitting probes we have recently used in nonlinear ultrasonic transmission measurements [14], clearly shows the lower inherent nonlinearity of the single-crystal transducer. Convenient electrical matching even renders possible a higher irradiation amplitude than achieved with the Panametrics 133 A while keeping the linearity [18].

Because of severe aging problems with PMN-PT a few years ago we now use specially fabricated $LiNbO_3$ and ZnO sending probes with electrical matching. The continual development of PMN-PT single-crystal material and its higher quality now [19] encourages one to try again PMN-PT materials. Probes with advanced PMN-PT transducer material are ordered by GE Inspection Technologies GmbH, Hürth, Germany and will be available soon.

2. Nonlinear Ultrasonic Transmission Measurements

2.1 Sample description

Impact is considered as the main source of in-service damage for composite structures [20]. The company Bodycote CSM, Linköping, Sweden, provided with nine samples of carbon-fiber/epoxy laminate with a quasi-isotropic lay-up of 32 plies. The cubic samples have a size of 18 x 30 x 4 mm^3. One of the samples (CSM-8-Ref) was not degraded in order to serve as a reference. Eight samples (CSM-8-1, CSM-8-2, CSM-8-3, CSM-8-4, CSM-8-5, CSM-8-6, CSM-8-7, and CSM-8-8) were conditioned by impacts of different energy levels (2, 5, 5, 7, 10, 12, 12, and 14 J).

2.2 Experimental Results

First, at two of the samples nonlinear ultrasonic transmission measurements were carried out at three different positions, which were in the middle and at both edges of the length axis. A specially fabricated narrow-band $LiNbO_3$ transmitting probe of 2 MHz center frequency and a broadband receiver probe Panametrics V110 of 5 MHz centre frequency were used. The coupling medium was machining oil as in the measurements described above. The detected signal was Fourier transformed to obtain the strain amplitudes of the transmitted fundamental frequency (A_1) and of its second (A_2) and third (A_3) harmonic, which yield the distortion factor $K=\sqrt{\left(A_2^2+A_3^2\right)/\left(A_1^2+A_2^2+A_3^2\right)}$, i.e. the overall nonlinear content of the signal. So far, no harmonics of higher than third order could be detected above noise. The excitation voltage at the transmitter probe was swept from 0 up to 250 V peak to peak. As an example the results of the experiments on the reference sample (CSM-8-Ref) are shown in Figs. 1 to 4. The amplitudes of the transmitted waves increase with the excitation. For the fundamental frequency a linear dependency was observed (Fig. 1). The three different positions show a small difference in the absolute values. Because of measurement inaccuracies mainly caused by noise reliable results for the amplitudes of the transmitted second (Fig. 2) and third (Fig. 3) harmonic and thus also for the distortion factor (Fig. 4) are obtained only with excitation voltages above about 150 V. The distortion factor of the reference sample CSM-8-Ref is very low (less than 0.1) and varies little in dependence on position and excitation.

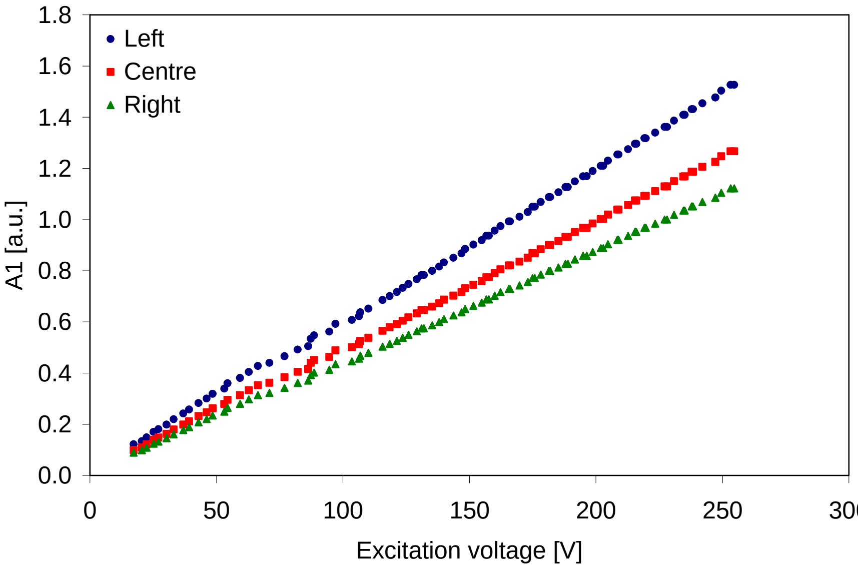

Figure 1: Nonlinear ultrasonic transmission through the carbon-fiber/epoxy laminate reference sample (CSM-8-Ref), strain amplitude A1 [a.u.] of the transmitted wave of excitation frequency versus excitation voltage; specially fabricated narrow-band $LiNbO_3$ transmitting probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz center frequency; coupling medium lubrication oil.

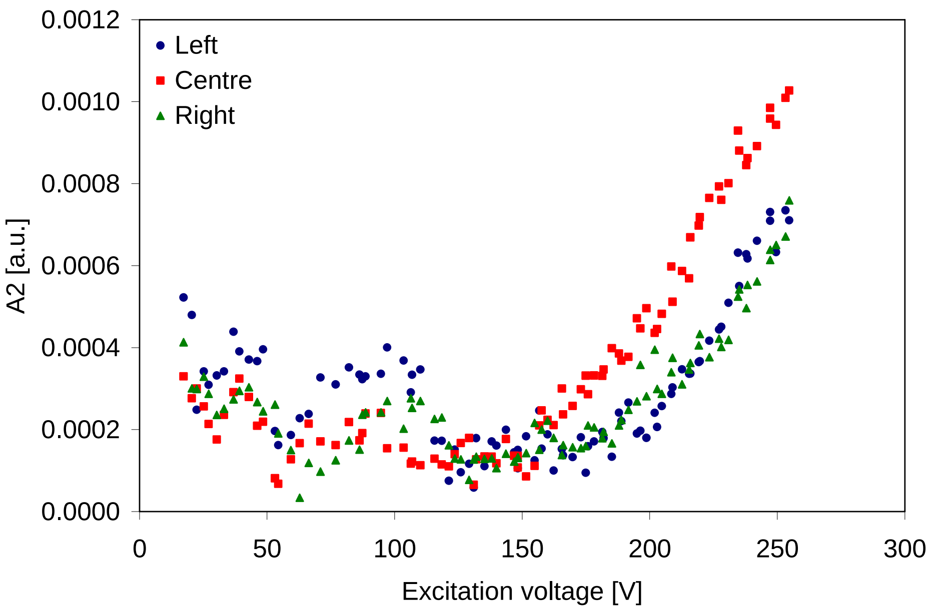

Figure 2: Nonlinear ultrasonic transmission through the carbon-fiber/epoxy laminate reference sample (CSM-8-Ref), strain amplitude A2 [a.u.] of the transmitted second harmonic versus excitation voltage; specially fabricated narrow-band $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz center frequency; coupling medium lubrication oil.

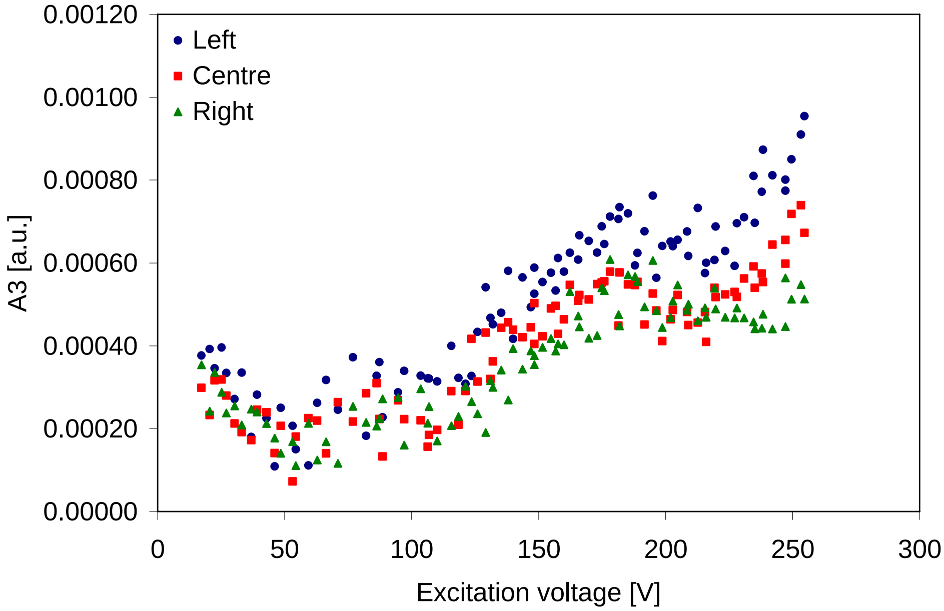

Figure 3: Nonlinear ultrasonic transmission through the carbon-fiber/epoxy laminate reference sample (CSM-8-Ref), strain amplitude A3 [a.u.] of the transmitted third harmonic versus excitation voltage; specially fabricated narrow-band $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz centre frequency; coupling medium lubrication oil.

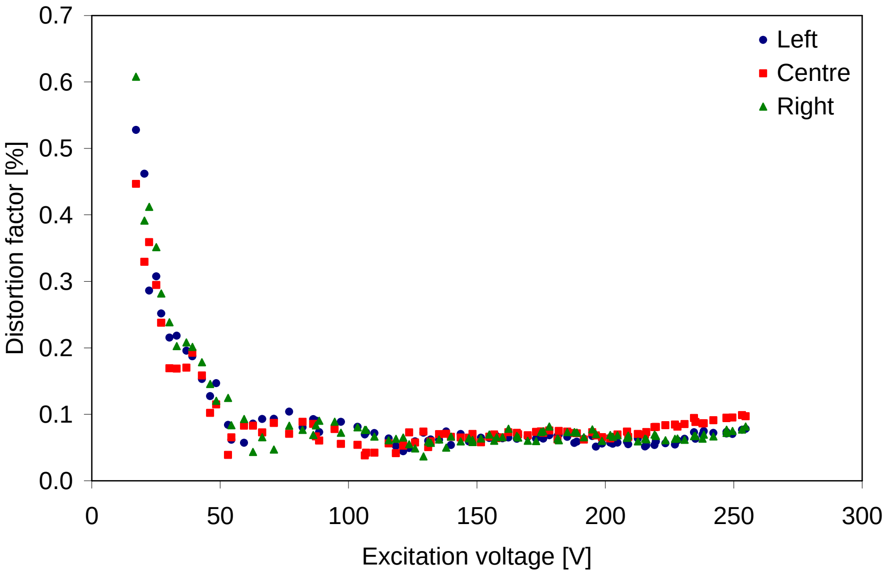

Figure 4: Nonlinear ultrasonic transmission through the carbon-fiber/epoxy laminate reference sample (CSM-8-Ref), distortion factor K versus excitation voltage; specially fabricated narrow-band $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz center frequency; coupling medium lubrication oil.

The second measurement series was restricted to the maximal excitation of 250 V peak to peak at the transmitting probe. The samples were scanned in length direction, and transmission measurements were carried out at 15 different positions of 1 mm distance in the middle of the length axis. Figs. 5 to 8 show the strain amplitudes of the transmitted fundamental frequency (A_1), of its second (A_2) and third (A_3) harmonic and of the resulting distortion factor K for the nine samples in dependence on the position.

The transmitted wave amplitudes of excitation frequency on the reference (CSM-8-Ref) and on the sample with the lowest damage level (CSM-8-1) are almost the same and vary little with position (Fig. 5). But the second (Fig. 6) and third (Fig. 7) harmonic generation in CSM-8-1 is larger than in the reference, showing maxima at the position where the impact has taken place. This entails a higher distortion factor in CSM-8-1 than in CSM-8-Ref (Fig. 8). The strong decrease of the transmitted wave amplitudes of excitation frequency on the other seven samples (CSM-8-2 to CSM-8-8) in their center, almost down to zero in some cases, (Fig. 5) indicates that the impact has caused real delaminations. Of course, in almost opaque regions also the amplitudes of the higher harmonics generated in transmission are low (Figs. 6 and 7), nevertheless mostly resulting in an increase of the distortion factor (Fig. 8) because of the low transmitted fundamental amplitude. With the decrease of the transmitted amplitudes below a certain level the achieved results of the distortion factor are more and more dominated by noise.

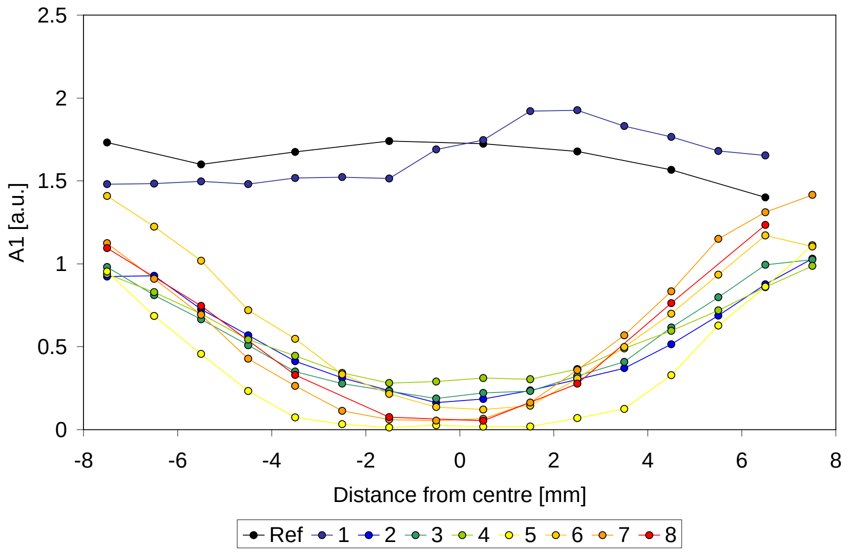

Figure 5: Nonlinear ultrasonic transmission through carbon-fiber/epoxy laminate samples, strain amplitude A1 [a.u.] of the transmitted wave of excitation frequency versus position at 250 V peak to peak excitation; specially fabricated narrow-band $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz centre frequency; coupling medium lubrication oil.

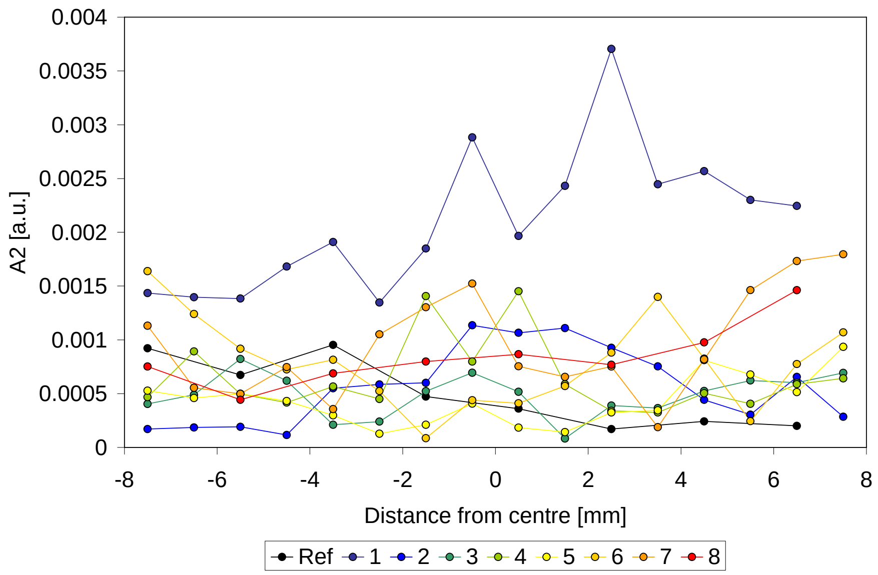

Figure 6: Nonlinear ultrasonic transmission through carbon-fiber/epoxy laminate samples, strain amplitude A2 [a.u.] of the transmitted second harmonic versus position at 250 V peak to peak excitation; specially fabricated narrow-band $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz center frequency; coupling medium oil-layer.

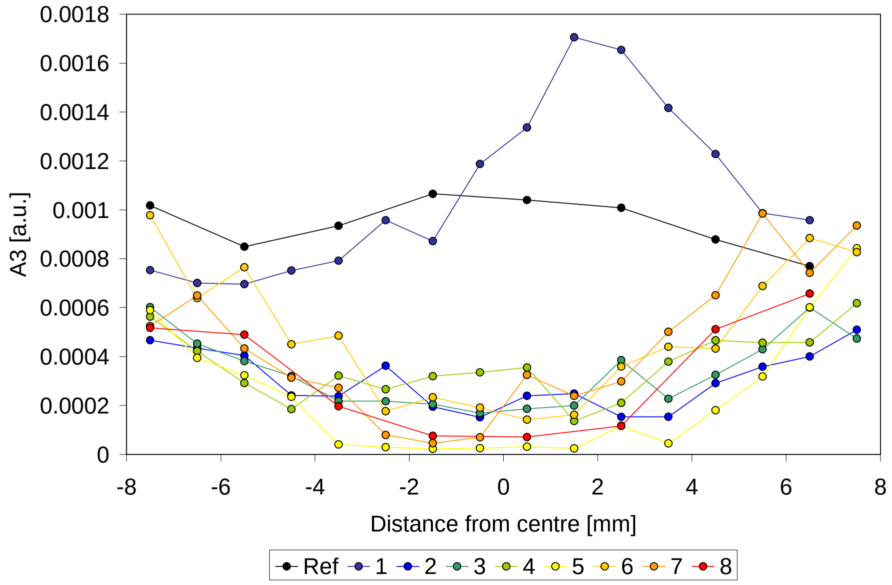

Figure 7: Nonlinear ultrasonic transmission through carbon-fiber/epoxy laminate samples, strain amplitude A3 [a.u.] of the transmitted third harmonic versus position at 250 V peak to peak excitation; specially fabricated narrow-band $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz centre frequency; coupling medium lubrication oil.

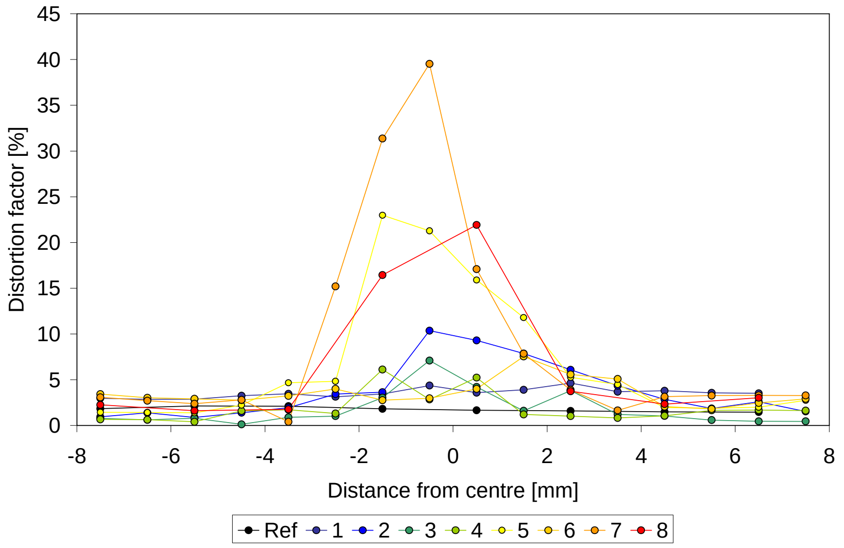

Figure 8: Nonlinear ultrasonic transmission through carbon-fiber/epoxy laminate samples, distortion factor K versus position at 250 V peak to peak excitation; specially fabricated narrowband $LiNbO_3$ sending probe of 2 MHz center frequency; broad-band receiver probe Panametrics V110 of 5 MHz center frequency; coupling medium lubrication oil.

3. Summary

The application of the technique of nonlinear ultrasonic transmission to composite laminate samples was presented. The samples investigated were damaged by impacts of different energy and probably containing micro-cracks, cracks, and delaminations. The local amplitudes of the first three harmonics generated in transmission and the distortion factor were measured, evaluated, and discussed. The transmitted amplitude of fundamental frequency first decreases with increasing impact energy level while the distortion factor simultaneously increases. At regions of complete delaminations caused by high impact energy the samples locally became almost opaque.

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