Active Fiber Composites for Application as Acoustic Emission Sensors: Principles and Characterization

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Active Fiber Composites (AFC) manufactured at EMPA with commercially available piezoelectric ceramic fibers have been investigated for their potential use as Acoustic Emission (AE) sensors. AFC elements have been evaluated with methods derived from AE sensor characterization as well as additional measurements. Some commercial AE sensor types have been evaluated with the same methods for comparison. For both, AE sensors and AFC elements, sensitivity versus frequency and electrical impedance versus frequency measurements yield indications of the respective resonance frequencies of the piezoelectric sensor. Simulated AE applied on test plates shows an additional anisotropy of the sensitivity of the AFC for AE signals arriving from different directions relative to the fiber orientation. This anisotropy of the sensitivity of the AFC elements can, in principle, be applied to enhance the sensitivity of the AFC elements along certain fiber orientations of the composite structure. Their planar design and lower mass, combined with their intrinsic conformability make AFC elements seem well suited for structural integrity monitoring applications.

Introduction

Active Fiber Composite (AFC) elements as initially developed by Bent and Hagood [1] consist of piezo-ceramic lead-zirconate-titanate (PZT) fibers, aligned uniaxially between two foils, each with two sets of electrodes arranged as interdigitated electrical contacts. Analogous to thin PZT-patches, they function as actuators and sensors [2, 3]. Since the PZT-fiber properties are determined by the piezoelectric strain constant d_{33}, i.e., polarized along the fiber length, it is interesting to compare them with conventional piezoelectric sensors using the d_{31} polarization direction. The present paper compares the Acoustic Emission (AE) sensing properties of AFC elements with those of commercial 150 kHz resonant AE sensors. This comparison is based on established methods for AE sensor characterization or verification as well as methods developed to explore specific characteristics of the AFC.

Experimental

The AFC elements manufactured at EMPA have an active area of 31 mm (length) x 20 mm (width), and a total area around 31 mm (length) x 40 mm (width), an electrode width of 200 μm, and an electrode spacing of 900 μm. The manufacturing and processing details of the AFC are described in [3].

Electrical impedance measurements were performed on an impedance analyzer (type HP4194A) in the frequency range from 100 Hz to 500 kHz or to 1'000 kHz. The devices were connected through a test fixture (type 16074D) and short wires. A total of 270 and 400 data points was recorded over the frequency range up to 500 kHz and 1'000 kHz, respectively, and the data converted to a text-file for further analysis.

A commercial AE sensor tester (type VST from Vallen Systeme GmbH) consisting of a frequency generator (type 33120A from Agilent), ultrasonic transducers (type V-101 or V-103 from Panametrics), an AMSY-4 AE equipment with preamplifier (type AEP4) and dedicated software (from Vallen) was used to verify the sensor response characteristics (resonant sensors SE150-M from Dunegan Engineering Corporation Inc., DECI or R-15 from Physical Acoustics Corp, PAC). Devices were tested in the frequency range between 5 kHz and 500 kHz, scan step size was 2 kHz, and the signals band-pass filtered between 3 kHz and 3'000 kHz, and recorded with an offset of –135 dB, –155 dB, or –175 dB. Various types of coupling to the ultrasonic transducer were used: face-to-face, face-to-back (device mounted on an Aluminum plate), face-to-wedge (device mounted on a polymer-wedge made from polymethylmethacrylate, PMMA), with an inclination of the wedge of 40° with respect to the horizontal base). The PMMA-wedge was used to enhance the in-plane component of the excitation, the longitudinal wave speed of PMMA (2760 m/s ± 25 m/s) yielding a limiting angle for total reflection around 40°.

Hsu-Nielsen sources (lead pencil breaks, 0.5 mm diameter leads, hardness rating HB) were used to simulate AE signals 20 cm from the AFC element on a PMMA plate to generate polar plots of the axial sensitivity characteristic of the AE sensors and AFC elements. Alternatively, so-called auto-calibration pulses generated by the AE equipment (type AMS-3 from Vallen) with the amplitude and duration dials set to maximum and minimum, respectively (typically yielding 60 V peak-to-peak and about 1 μs duration), were used as stimulus for AFC elements and AE sensors (SE150-M or SE1000-H flat response displacement sensor with small aperture, both from DECI) and the resulting AE signals were recorded by the AE sensor and the AFC element, respectively, mounted on the PMMA-plate 20 cm apart. Full waveform signals were recorded for some of these tests yielding frequency spectra via Fast-Fourier-Transformation (FFT).

A silicone-free, temperature resistant vacuum grease was used as coupling agent in all interfaces between transducers, test plates, AE sensors, and AFC elements. Contact pressure was either supplied by a special fixture (spring-loaded plates between which transducer and AE sensor or AFC were put), dead weights (AE sensors on test plates), or scotch tape (AFC elements on test plates).

For all measurements, one set of the interdigitated electrodes on each side of the AFC was connected to mass (ground) of the preamplifier or impedance analyzer, while the other provided the signal level. Typical AE instrument settings were a threshold of 40 dB_{AE} or 31 dB_{AE}, preamplifier gain of 34 dB, and a rearm-time of 3.28 ms. Signals were band-pass filtered either between 30 kHz and 1'000 kHz or between 95 kHz and 1'000 kHz.

Results

Impedance Measurements

Fig. 1 shows the electrical impedance determined from the applied voltage and current in the form of a) the absolute value |Z|, and b) the phase angle, both as a function of frequency for AE sensor and AFC element. Typically, the absolute value is rapidly decreasing with increasing frequency (note the logarithmic scale), except for certain frequencies. The phase angle plot clearly indicates these frequencies.

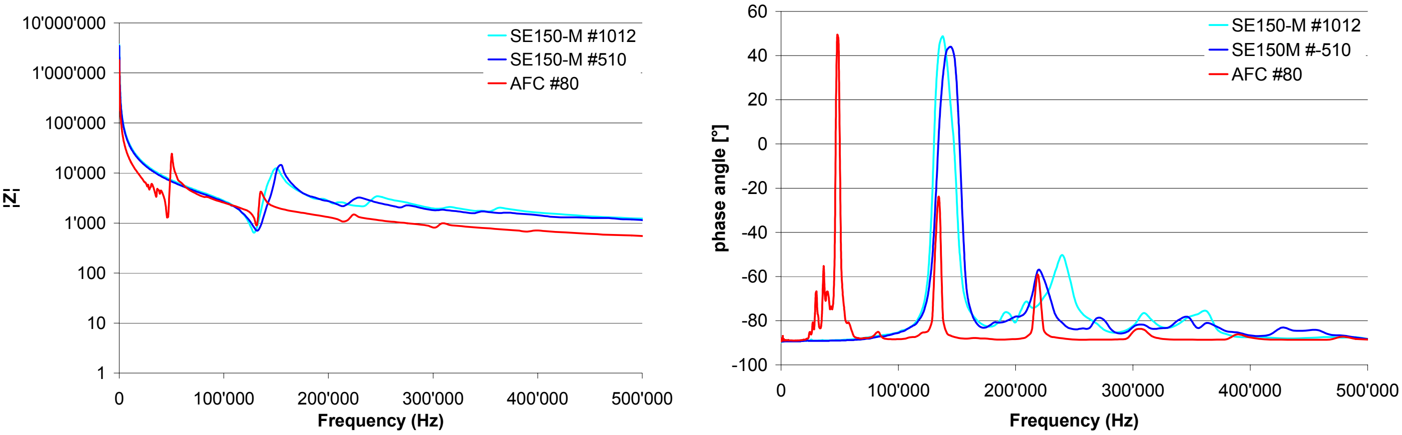

Fig. 1: Electrical impedance measurements (impedance analyzer HP4194A) as a function of frequency from 100 Hz to 500 kHz for two AE sensors (SE150-M) and one AFC, (left) absolute value |Z|, (right) phase angle.

Verification with Sensor Tester

Fig. 2 shows the sensitivity curves obtained with the commercial AE sensor tester (VST) for AE sensors and AFC, again as a function of frequency between 5 kHz and 500 kHz (transducer type V-101). AE sensor and AFC were tested both, coupled directly to the transducer (AFC supported on the back with an Aluminum plate), and coupled to the back-side of an Aluminum plate sitting on top of the transducer. Fig. 3 shows the measurements for AE sensor (SE150-M) and AFC when mounted on the slope of PMMA wedge with 40° inclination with its basal plane coupled to the transducer in order to enhance the in-plane-component of the excitation.

Characterization with simulated AE

Fig. 4 shows the polar diagrams obtained from Hsu-Nielsen sources applied at 20 cm distance for AE sensor and AFC mounted reversibly on a PMMA plate. The values indicated in the diagram are maximum AE signal amplitude averages of at least three lead pencil breaks per polar angle performed by one operator and recorded by the AE sensor or AFC at 20 cm distance from the source location. Analogous polar diagrams (not shown) were obtained with the AFC recording AE signals generated by the autocalibration function of the AE equipment by applying transient voltage pulses to AE sensors (SE150-M or SE1000-H) coupled at 20 cm distance from the center of the AFC to the PMMA plate.

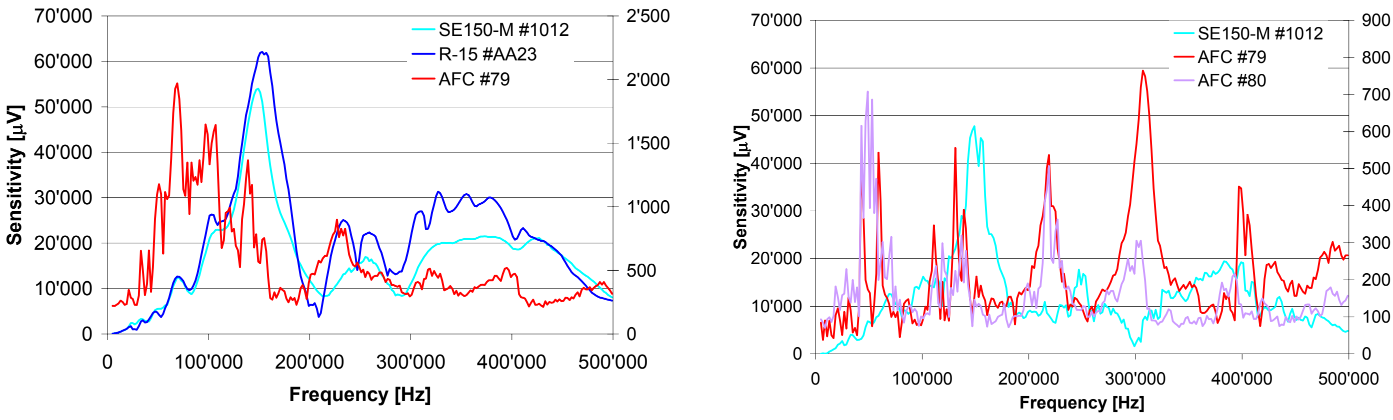

Fig. 2: Sensor tester characterization (VST, transducer V-101) for AE sensors (SE150-M and R-15) and AFC as a function of frequency from 5 kHz to 500 kHz, (left) coupling directly to the transducer (face-to-face) with AFC mounted on an Aluminum plate, (right) coupled through an Aluminum plate (face-to-back), left hand scale for AE sensors, right hand scale for AFC (all scales linear, offset removed).

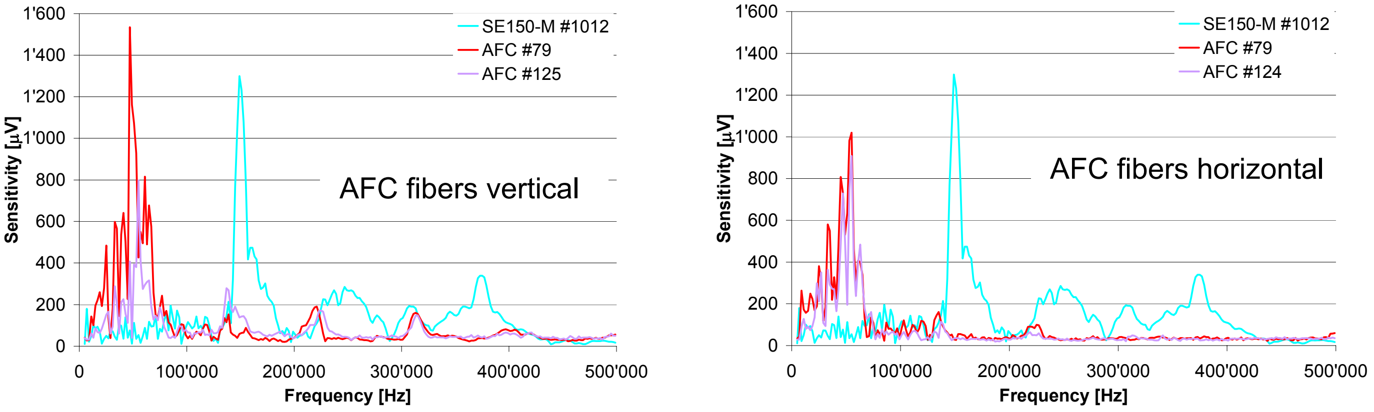

Fig. 3: Sensor tester characterization (VST, transducer V-101) as a function of frequency (linear scale, offset removed), AE sensors and AFC coupled on a PMMA wedge (see text for details), (left) AFC fibers oriented vertically, (right) AFC fibers oriented horizontally on the inclined plane of the PMMA wedge.

Fig. 5 shows selected frequency spectra from FFT from Hsu-Nielsen sources on a PMMA plate and recorded with the AFC centered at 20 cm from the source location. Both orientations of the AFC, i.e., AFC fibers parallel (II) and normal ($\perp$) to the source-AFC center line, frequency filtered between 30 kHz and 1'000 kHz, as well as between 95 kHz and 1'000 kHz are shown. Finally, Fig. 6 shows selected waveforms and corresponding FFT spectra generated by applying auto-calibration pulses to the AFC and recording the emitted signals with an AE sensor (SE1000-H) located on the PMMA plate 20 cm from the center of the AFC.

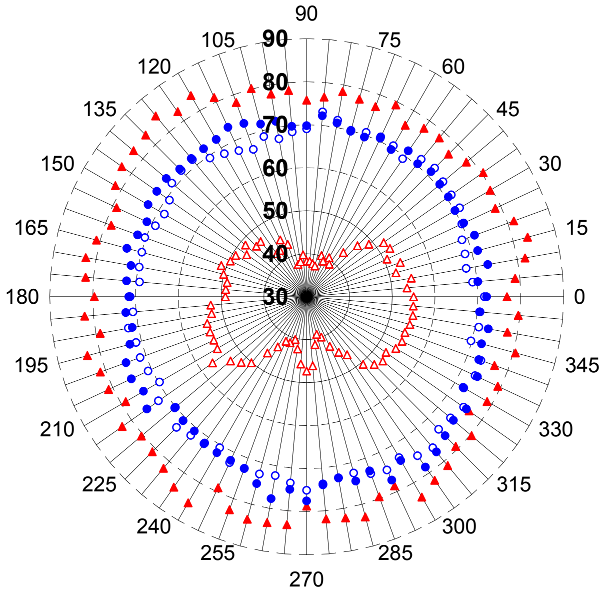

Fig. 4: Polar diagrams of maximum AE signal amplitudes from Hsu-Nielsen sources applied 20 cm from the center of the AE sensor (type SE150-M, circles) and the AFC (triangles) with its fibers oriented along the 180°-to-0° axis. Open and closed symbols indicate 95 kHz to 1'000 kHz and 30 kHz to 1'000 kHz band pass filters, respectively.

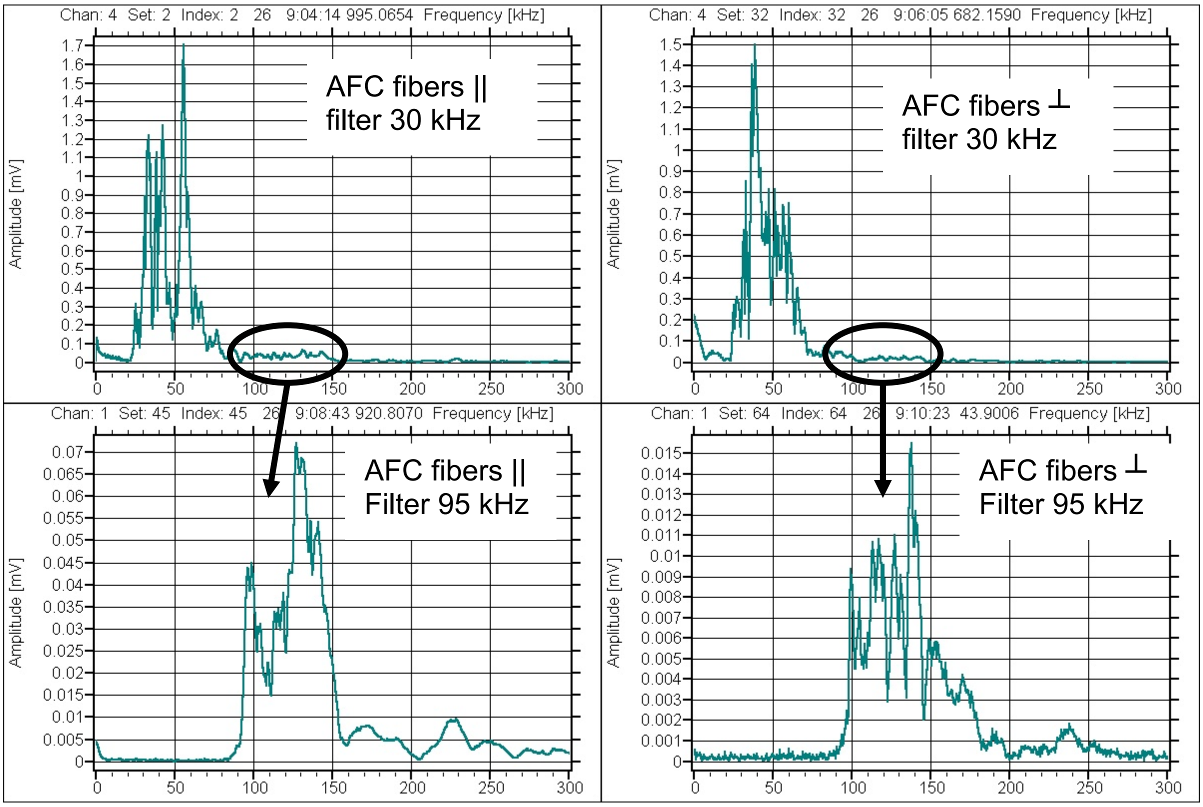

Fig. 5: FFT spectra from AFC recorded waveforms generated by Hsu-Nielsen sources located 20 cm from the center of the AFC on a PMMA plate, (left) AFC fibers parallel (II) and (right) normal to the source-AFC center line (⊥), frequency filter 30 kHz to 1'000 kHz (top), frequency filter 95 kHz to 1'000 kHz (bottom).

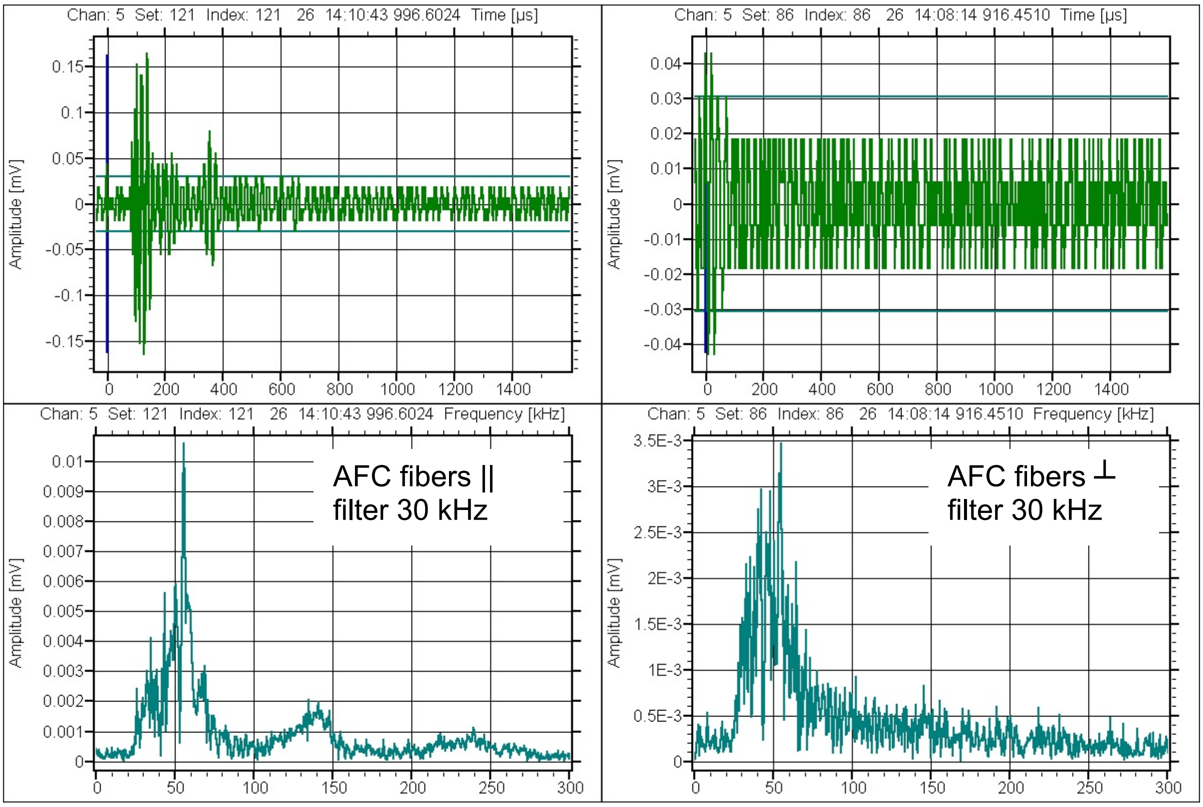

Fig. 6: Waveforms (top) and FFT spectra (bottom) of signals emitted by an AFC recorded with an AE sensor (SE1000-H) on a PMMA plate located 20 cm from the center of the AFC, (left) AFC fibers parallel (II) and (right) normal to the source-AFC center line (⊥), frequency filter 30 kHz to 1'000 kHz.

Discussion

Both, impedance and sensor tester measurements indicate that the AFC is sensitive to AE signals similar to the commercial resonant AE sensors. The main difference is that the peak sensitivity of the AFC lies around 50 kHz, i.e. lower than that of the 150 kHz resonant AE sensor. The face-to-face and Aluminum plate data from the sensor tester also indicate that the AFC is considerably less sensitive in this set-up. However, when mounted on the PMMA wedge, AFC and AE sensor yield comparable sensitivity. The main difference between face-to-face and wedge mounting the devices is quite likely the relative amount of out-of-plane to in-plane excitation. The pronounced increase in sensitivity observed for the AFC when switching from face-to-face to wedge mounting is tentatively attributed to the d_{33}-polarization of the piezoelectric fibers. This is consistent with the effect of the d_{31}-polarization of the AE sensor, yielding a clearly lower sensitivity on the PMMA wedge than mounted face-to-face on the transducer.

The PMMA wedge used to compare the sensitivity of AFC and AE sensors with respect to in-plane excitation clearly has to be regarded as an empirical tool for limited comparative purposes. Developing this approach into a standardized method for sensor response characterization would require detailed investigations, among others, e.g., of the influence of the geometry and size, as well as possible, multiple reflections and mode conversions, or wave polarization.

The AFC sensor tester measurements on the PMMA wedge (Fig. 3) also provide an explanation for the observed anisotropy in the polar diagrams on a PMMA plate, when the AE signals are band-pass filtered between 95 kHz and 1'000 kHz (Fig. 4). Changing the orientation of the AFC fibers on the PMMA wedge from vertical to horizontal clearly reduces the intensity of the peaks observed at about 130, 210, and 310 kHz. This yields a sensitivity differing for signals arriving parallel and normal, respectively, to the orientation of the AFC fibers. If the signals are band-pass filtered between 30 kHz and 1'000 kHz, where the intensity of the dominant sensitivity peak around 50 kHz changes much less with AFC fiber orientation, this anisotropy is hardly noticeable.

Frequency spectra of Hsu-Nielsen sources applied on PMMA and recorded at 20 cm distance from the source with a flat-response AE sensor (SE1000-H) show a maximum in the frequency range between 30 kHz (high-pass filter) and about 70 kHz [3]. Fig. 5 shows the frequency spectra of such signals recorded by the AFC with its center at 20 cm from the source. The frequency spectra for 30 kHz to 1'000 kHz filtering (Fig. 5 top) show a relatively minor contribution in the frequency range above about 100 kHz (shown for 95 kHz to 1'000 kHz filtering in Fig. 5 bottom). From Fig. 4 it is evident that maximum AE signal amplitudes are reduced by 20 to 25 dB_{AE} when 95 kHz instead of 30 kHz high-pass filters were used.

The waveforms and FFT spectra shown in Fig. 6 indicate that the AFC, when acoustically coupled to a solid and excited by transient voltage pulses (using the autocalibration feature of the AMS-3 equipment) emits transient elastic waves into the solid. The emission seems to mainly occur in the frequency range around 50 kHz, i.e., the same range where the maximum sensitivity of the AFC was observed. Recording the AFC emissions along the fiber axis of the AFC at 20 cm distance also yields noticeable frequency components above 100 kHz that are missing when emissions normal to the AFC fiber axis are recorded. Therefore, the anisotropy noted in the sensitivity of the AFC in the frequency range above 100 kHz also occurs when the AFC is used as acousto-ultrasonic emitter. At frequencies below 100 kHz, this effect is much less pronounced. Possible explanations are coupling among the different polarization coefficients of the piezoelectric fibers and frequency dependent wave propagation in the epoxy matrix used to embed the piezoelectric fibers.

A comparison of AFC with other types of planar AE sensors based on piezoelectric polymers such as poly-vinylidene-fluoride (PVDF) [4, 5], however, is still lacking. On the other hand, some specimens of AFC elements fully integrated into glass-fiber reinforced laminates were manufactured and successfully tested, both as sensors for AE signals and acousto-ultrasonic (AU) emitters [6].

Summary and Outlook

Commercial 150 kHz resonant AE sensors have been compared with new Active Fiber Composite (AFC) elements manufactured from piezoelectric fibers. Properties such as AE signal sensitivity and others have been compared for a range of measurement methods. It has been shown that the AFC elements investigated in this paper are essentially low-frequency AE sensors, being most sensitive around 50 kHz. Band-pass filtering eliminating the frequency range below 95 kHz, on one hand reduces the sensitivity of the AFC but, on the other, yields an anisotropy in the sensitivity characteristic. Due to their conformability, both, parallel and normal to the fiber direction, these AFC elements are promising for continuous AE monitoring for, e.g., leak detection in pipelines, at least for pipe diameters > 70 mm. The process for manufacturing the AFC is compatible with that used for composite laminates and integration of these thin, planar, light-weight AFC elements into glass- and carbon-fiber laminates has been achieved. Therefore, continuous health monitoring of composite structures with AE testing or periodic inspection with AU using integrated AFC elements does seem feasible.

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