Ultrasonic Characterization of ASTM A307 Bolts

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of SEREN I ABULAIL find it satisfactory and recommend that it be accepted.

Chair

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This work is dedicated to the memory of my father Ibrahim Abu-Lail. Without his faith in me all the time I could never have finished this work. I am so proud to be your daughter.

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ABSTRACT

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Steel bolts are commonly used in timber and steel connections. Since the failure of the whole structure may result from a connection failure, it is important to find a methodology for testing these bolts in place without causing any destruction to the structure. In this study 290 ASTM A307, Grade A, standard bolts ("Standard Specification" 2003) were inspected ultrasonically to assess the characteristics of the ultrasonic signals. These characteristics will be the baseline for future analyses of ultrasonic signals from defective or damaged bolts either in timber or steel structures. The three ultrasonic signal parameters analyzed included the peak frequencies of the first back echo and associated first and second trailing echoes, the centroid of the first back echo and associated first and second trailing echoes, and the ratios of peak amplitudes for the first and second trailing echoes to the peak amplitude of the first back echo.

The most effective ultrasonic signal parameter to characterize the bolts was the centroid of the first back echo and associated trailing echoes, because it had the lowest

coefficient of variation among all the parameters investigated. The second best parameter was the ratio of peak amplitudes of the trailing echoes to the first back echo. The parameter with the highest coefficient of variation was the peak frequency of the individual echoes.

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CHAPTER I

INTRODUCTION

> "In the last few years, the number of reported bolts and stud bolt failure has increased. Consequently, the NDT of these bolts and stud bolts has become a concern for many utilities. In the past, bolts have been inspected in two different ways. One way was to remove the bolts and do a magnetic particle or a penetration exam; however this method is tedious and time consuming. The other method was to conduct an ultrasonic inspection of the bolt while it was in place."(Light et al. 1986a)

Ultrasonic testing uses very short ultrasonic pulse-waves with center frequencies ranging from 0.1-15 MHz for flaw detection/evaluation, dimensional measurements, and material characterization, and it can be an incredibly precise, fast, and economical method to identify and plot discontinuities. Ultrasonic testing is often performed on steel and other metals and alloys, though it can also be used on concrete, wood and composites, albeit with less resolution. It is a form of non-destructive testing used in many industries including aerospace, automotive and other transportation sectors.

Steel bolts are commonly used in timber and steel connections. Since the failure of the whole structure may result from a connection failure, it is important to find a methodology for testing these bolts in place without causing any destruction to the structure. Unfortunately it is difficult to inspect bolts by visual inspection because in most of the cases they are embedded in the connection or hard to reach. If they can be reached the defect may be internal and cannot be inspected visually. That makes the ultrasonic technique useful for inspecting bolts in place. Ultrasonic inspection is often preferable to other nondestructive techniques, because they are difficult, impractical or expensive. For example, magnetic particle or dye penetrant inspections require the bolt to be removed from its place in the structure. Other nondestructive techniques such as radiographic inspections are time-consuming or expensive if the bolt must be tested in place.

The ultrasonic technique was used in several previous studies to determine stress measurements for tensioned steel bolts, and to detect damage or defects in bolts and dowels. However the characterization of undeformed and undamaged bolts based on their time domain signals has not been studied extensively in previous research. If the main characteristics of the ultrasonic signals for various bolt grades and geometries can be established, then these signal characteristics could be used for comparison to bolts having defects or damage in structures.

Objectives

The main goal of this research is the ultrasonic characterization of various ASTM A307 bolts by analyzing time domain and frequency domain signals from ultrasonic pulse echo inspection of the bolts. The specific objectives are the following:

1. Determine the effects of bolt length, bolt diameter, and transducer frequency on ultrasonic characteristics of steel bolts, as a baseline for comparison in further testing of defective or damaged bolts.
2. Determine which ultrasonic signal parameters are the most effective for characterizing bolt geometry.

CHAPTER II

LITERATURE REVIEW

Ultrasonic inspection of steel is “a means of locating defects in steel. When acoustic energy in the ultrasonic range is passed through steel, the sound waves tend to travel in straight lines, rather than diffusing in all directions as they do in the audible range. If there is a defect in the path of the beam it will cause a reflection of some of the energy, depleting the energy transmitted. This casts an acoustic shadow which can be monitored by a detector placed opposite the transducer or energy source. If the acoustic energy is introduced as a very short burst, then the reflected energy coming back to the originating transducer can also be used to show the size and depth of the defect. Ultrasonic techniques can be used to detect deeply located defects or those contained in the surface layer.” (Wikipedia 2008).

A review of the literature showed that the ultrasonic technique was used in previous studies, some of which were relevant to this study. The majority of the earlier studies could be described as having two foci: the first was tensioning stress measurements in bolts, and the second was detection of bolt defects and corrosion. There also were related studies concerning the use of A-scans of long copper alloys (Witherell et al. 1992) to inspect ship fasteners, and B-scans of bridge pins (Komsky and Achenbach 1996) to detect pin failures.

Tensioning Stress Measurements

The ultrasonic technique was frequently used in bolt stress measurements. The idea behind this approach was that for acoustic waves propagating in an elastic medium the time delay was slightly altered by applying a mechanical stress to the propagation medium. This alteration was due to two causes: (1) stress produces strain, which results in a length change of the propagation path; (2) the stress causes an acoustic wave velocity change, or change of the delay time, and this change in the time domain delay was found to be linearly related to the applied stress at the elastic limit of deformation. The short pulse propagated from one end of the bolt to the other produced an echo, the time delay was measured and the time delay change was determined (elongation), which was related to the bolt stress (Joshi and Pathare 1984).

Preload measurement was another approach that employed ultrasonic bolt stress measurement. The theory was that the ultrasonic transducer was coupled to the head of a sleeve bolt as in Figure 1, and then the bolt length was measured by an ultrasonic bolt gage. When the bolt was loaded the length changed, and this change in the bolt length was measured by the ultrasonic bolt gage and called “ultrasonic stretch”. The preload was obtained by multiplying the ultrasonic stretch by a constant called a “load factor”.

Detection of Steel Defects and Corrosion

The detection of steel defects and corrosion was the second major focus in previous research using the ultrasonic technique for inspection of fasteners. The main difference between previous research and this study was that the ultrasonic detection of bolts focused on the inspection of defective bolts to detect defects or corrosion, while this study focused on the inspection of nondefective bolts to establish a comparison baseline for future studies of defective bolts.

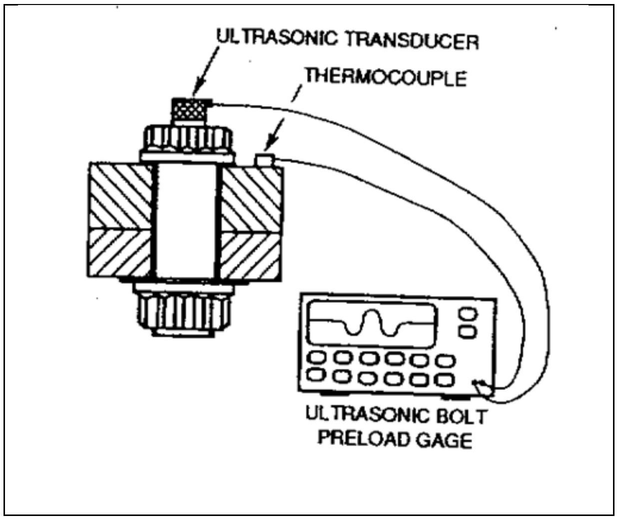

Figure 1- Schematic of preload measurement setup. Ultrasonic transducer is coupled to the head of the sleeve bolt (Koshti 1996).

A cylindrically guided wave technique for bolts and studs was developed by (Light et al. 1986a) at Southwest Research Institute. The main idea was that the ultrasonic wave propagation in a long cylinder depended on the geometry of that cylinder. The end of the stud and cracks were detected by arrival of the first back echo. The corrosion wastage was detected by mode conversion of the waves from longitudinal to transverse and vice versa (see Figure 2).The tests were conducted on a large number of stud diameters and lengths. The diameter ranged from 0.5 to 4.5 inches (1.3 to 11.4 cm) and the length ranged from 5 to 12 inches (12.7 to 30.1 cm). The result of the tests was that any crack with depth greater than 0.08 inch in the threaded region was detected in all bolt diameters and lengths. Other tests were conducted on simulated corrosion models to determine the corrosion wastage, and it was found that corrosion wastage of 15-20 percent was detectable.

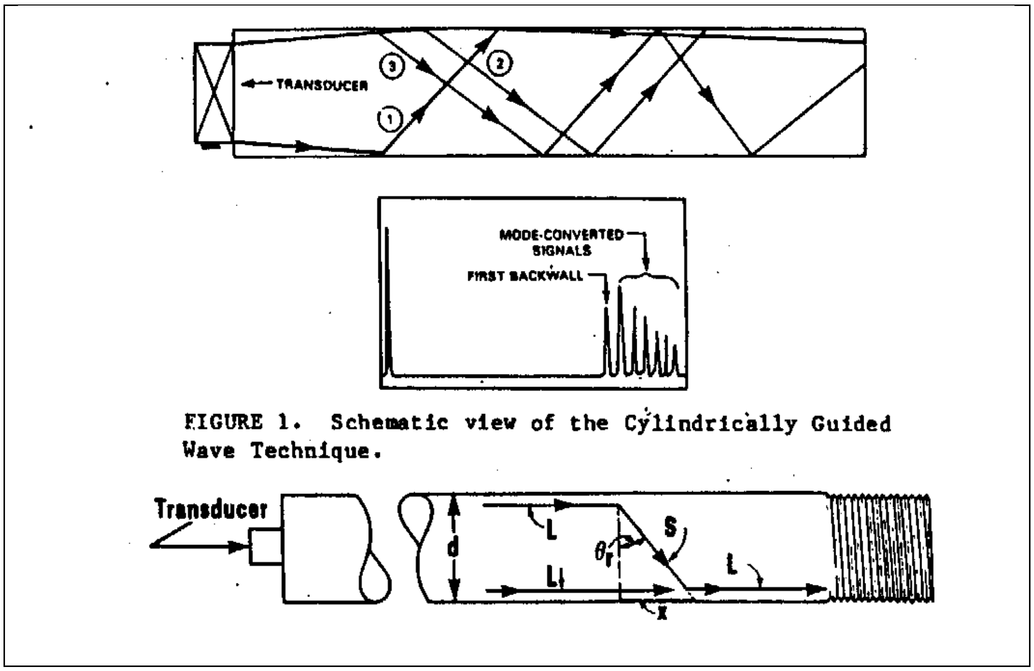

FIGURE 1. Schematic view of the Cylindrically Guided Wave Technique.

Figure 2- Schematic view of the cylindrically guided wave technique (Light et al. 1986a).

The same technique was also used in another test to determine the smallest flaw size that can be detected through long metal paths (Light et al. 1986b). The experiment was conducted using a Metrotek MP215 pulser to excite the piezopulser transducers. The ultrasonic power in that test generated by the application of high electrical current to the moderately damped transducer was enough to penetrate the longest stud of 112 inches (284.4 cm). The result was that the back echo and its trailing pulses were shown clearly for the undefective bolts when inspected using the cylindrically guided wave technique. The threaded regions were cut and then re-inspected using the cylindrically guided wave technique to determine the detection sensitivity. The minimum detected notch for each bolt size was determined.

Using the same cylindrically guided wave technique, simulated corrosion wastage could be determined. The importance of this test was due to the failures of anchor studs in reactor pressure vessel hold-down systems at nuclear power plants. Nuclear regulatory commission (NRC) bulletins were concerned about the ability of nondestructive testing (NDT) to detect stress corrosion cracking in those studs prior to failure. In the case that the outside diameter of the bolt or stud had been reduced or corroded there was corrosion wastage. Ultrasonic testing of embedded bolts was difficult due to the cracks, corrosion, threads, and the bolt length.

The geometry of the specimens used in this study is shown in Figure 3. The specimens had different defects such as spread, taper, or just a single notch. An undefective sample was also used. The theory behind the test was that the signal can be separated into two parts, the main pulse and the trailing pulses. The time interval (Δt) between the main pulse, and between the first and the second trailing pulses was

$$\Delta t = \frac{d}{v_1 v_2}(v_1^{\ 2} - v_2^{\ 2})^{1/2} \qquad \text{Eq. 1}$$

where d is the diameter of the stud, and v_1 and v_2 are the longitudinal and transverse wave velocities in steel.

If more than one set of trailing pulses appears, the specimen must have more than one diameter, which indicated the reduced diameter of the corrosion wastage. The results showed that the relative changes in the amplitudes of the echo signals from the back and from the reduced cross section can identify the one-sided simulated corrosion wastage. The cylindrically guided wave technique was found to be useful in detecting hourglass-shape corrosion wastages due to its ability to produce two sets of trailing pulses.

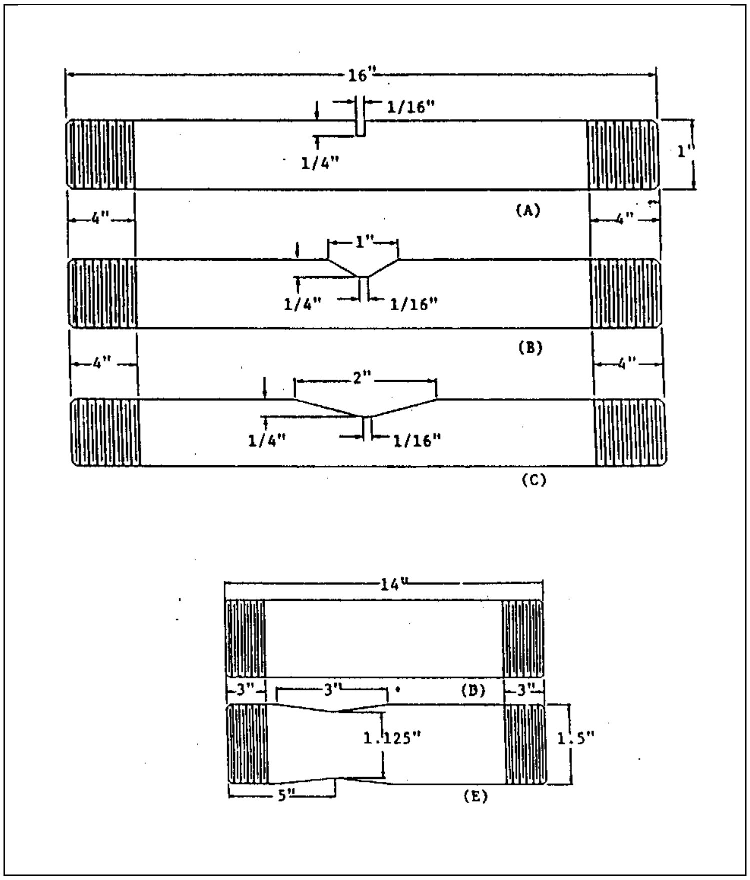

Figure 3- Geometry of specimens used in testing simulated corrosion wastages (Light et al. 1986a).

The detection of defects and corrosion in steel bolts were covered in previous work (Light and Joshi 1987; Light et al. 1986a; Light et al. 1986b; Pollock et al. 2001). The shift in overall signal centroid was found as the best parameter predictor of plastic hinge formation in bolts, using the undeformed bolt initial signal as a baseline. The relationship between the shift in overall centroid and the plastic hinge angle was found to be linear (Pollock et al. 2001).

CHAPTER III

EXPERIMENTAL METHODS

290 ASTM A307, Grade A, standard bolts ("Standard Specification" 2003) were inspected ultrasonically to assess the characteristics of their ultrasonic signals. These characteristics will be the baseline for future analyses of ultrasonic signals from defective or damaged bolts in either timber or steel structures. Bolts in this study were identified by letters. Each letter referred to a set of bolts (see Figure 4), and each set was characterized by the bolt nominal dimensions given in Table 1. Bolts were purchased for this study from a variety of suppliers.

Figure 4-One bolt of each group of the tested bolt groups.

Table 1 – Nominal dimensions of tested bolts

Bolt	Quantity	Diameter		Length		Thread length	
		(in)	(cm)	(in)	(cm)	(in)	(cm)
A	20	0.50	1.3	4.75	12.1	0.65	1.7
B	60	0.75	1.9	5.00	12.7	1.30	3.3
C	20	1.00	2.5	5.00	12.7	1.20	3.1
D	20	0.75	1.9	5.75	14.6	1.40	3.6
E	20	0.50	1.3	6.75	17.2	0.70	1.8
F	20	0.75	1.9	7.25	18.4	2.00	5.1
G	20	0.50	1.3	7.25	18.4	0.70	1.8
H	20	0.50	1.3	7.50	19.1	1.60	4.1
I	20	0.50	1.3	7.75	19.7	1.50	3.8
J	20	0.50	1.3	9.75	24.8	0.75	1.9
K	10	0.50	1.3	10.75	27.3	1.60	4.1
L	20	0.50	1.3	11.25	28.6	0.65	1.7
M	20	0.75	1.9	11.50	29.2	1.20	3.1

Since this technique will be used for getting typical time domain signals as a standard reference for comparison, different ultrasonic signal parameters were considered in the analysis such as peak frequencies of the first back echo and its trailing echoes, the centroid of the first back echo and associated trailing echoes, and the ratios of peak amplitudes for the trailing echoes to the peak amplitude of the first back echo. The goal was to determine the best ultrasonic signal parameter for characterizing the bolts.

In this research an ultrasonic M1042, 0.5 inch (1.3 cm) diameter, 5MHz magnetic probe and a XACTEX CH-HP, 0.5 inch (1.3 cm) diameter, 10MHz probe were coupled to the head of each bolt after applying a thin layer of commercial gel couplant to ensure ultrasonic coupling of the probe (see Figure 5). A computer-based LabVIEW 8.2 digital oscilloscope software package was used in conjuction with an analog-to-digital card installed in a personal computer to display and record the ultrasonic signal at a speed of 250 MHz. The test was repeated for all the 290 bolts using the two probes mentioned above. The time domain signal display was shifted so the first back echo with the trailing echoes appeared on the display screen, and the attenuation was adjusted so the first back echo height was approximately 80% of the screen height. Time domain signals for one bolt from each group tested with 5 and 10 MHz probe frequencies are provided in Appendix A.

Actual dimensions (bolt diameter, bolt length, length of threaded region) of each bolt were measured using digital calipers and vernier calipers. The actual dimensions of every bolt are provided in Appendix E.

Figure 5- A 5MHz magnetic probe and a 10MHz probe were coupled to the head of the bolts.

CHAPTER IV

ULTRASONIC SIGNAL ANALYSIS

The ultrasonic signal characteristics can be determined by studying different parameters of the ultrasonic signal in both the time and frequency domains, such as the area under the rectified signal, the centroid of the full or partial echo, the ratios of peak amplitudes of the trailing echoes to the first back echo, and the peak frequencies of back echoes and trailing echoes. In this study the three parameters that were analyzed were the following. The peak frequencies of the first back echo and associated trailing echoes were selected because earlier research indicated that back echoes and trailing echoes exhibit characteristic peak frequencies, and these peak frequencies may change with bolt deformation (Pollock 1997). However, that study only considered one size of bolt. The centroid of the first back echo and associated trailing echoes was selected because it was found in earlier research (Pollock et al. 2001) that a shift in signal centroid was an effective indicator of bolt deformation due to structural overload within connections. Furthermore, research by Light and Joshi (1987) showed that simulated corrosion wastage resulted in additional trailing echoes in the ultrasonic signal. These additional trailing echoes would also cause a shift in the signal centroid. The ratios of peak amplitudes for the trailing echoes to the peak amplitude of the first back echo were selected because earlier research (Pollock 1997) showed that changes in echo amplitudes were the most easily observed changes associated with bolt deformation.

Since signal amplitudes may also vary due to different coupling pressures or contact with surrounding materials in a connection, it is important to develop a "normalized" measure of relative changes in echo amplitudes. The amplitudes of all echoes in the time domain signal will vary with changes in coupling pressure or contact with surrounding materials. However, changes in bolt geometry will cause only the amplitudes of individual echoes to change. Thus, amplitude ratios were selected because they are "normalized" and are sensitive to changes in bolt geometry (i.e. bolt deformation or corrosion wastage) but are not sensitive to changes in coupling pressure or contact with surrounding materials. Other parameters such as the area under the rectified signal were not considered in this study because they were studied previously (Pollock et al. 2001) and were not found to be effective parameters to characterize deformation of steel bolts.

In the time domain, the pulse energy that traveled along the bolt length as a longitudinal wave was the initial back echo. This was reflected from the end of the bolt and returned to the head of the bolt. The first trailing echo in the time domain represented the pulse energy portion which reflected from one side of the bolt as a transverse wave, then converted to a longitudinal wave again as it reflected from the other side of the bolt. The second trailing echo resulted from the pulse energy that crossed the bolt twice as a transverse wave. The arrivals of successive trailing echoes were spaced a constant distance apart in the time domain of the ultrasonic signal, resulting in a series of trailing echoes for each back echo (Pollock et al. 2001).

> "Ultrasonic signals are typically recorded as a series of points (t_i, a_i) in the time domain. Time coordinates (t_i) represent the elapsed time following pulse initiation from the ultrasonic probe, and amplitude coordinates (a_i) represent pressure at the surface of the probe. The frequency spectrum can be generated through a Fourier transform of time domain points (t_i, a_i) into a set of points in the frequency

domain (f_i, m_i). For any series of transformed data, the frequency domain amplitudes (m_i) represent the relative magnitude of individual frequency components (f_i) which combine to make up the ultrasonic signal" (Pollock 1997).

The parameters of the time and frequency domain signals analyzed in this study were the following:

Time Domain Analysis

As mentioned previously, each ultrasonic signal was recorded as a series of (t_i, a_i) points. The (t_i, a_i) series of points were plotted using a spreadsheet program to get the time domain signal for every bolt. This time domain signal plot was the basis for the analysis of the three parameters discussed in this study. The typical full time domain signal plot consisted of successive echoes named first back echo, second back echo, etc, (see Figure 6). This study focused only on the first back echo and associated trailing echoes. The echoes were started at the zero-crossing preceding the first peak of the echo with amplitude higher than the signal noise amplitude. The end of each echo was defined as the zero-crossing following the last peak of the echo with amplitude higher than the signal noise amplitude (see Figure 7).

Every time domain signal was converted to a rectified signal by taking the absolute values of the amplitudes of the signal, and was re-plotted so only positive peaks appear on the time domain signal (see Figure 8). The maximum amplitudes of the rectified signal for each of the first back echo, first trailing echo, and second trailing echo were recorded. The importance of analyzing the amplitude ratios refers to the fact that the echo is composed of pulse energy. The great portion of that energy propagated directly down the bolt when short, thick bolts were tested, resulting in high first back echo amplitudes. When long, slender bolts were tested, a large portion of the pulse energy did not propagate directly down the bolt. Instead it hit the sidewalls of the bolt and then is reflected as a transverse wave resulting in high trailing echo amplitudes. The first back echo peak amplitude was used as the basis for all amplitude ratios, and the following ratios were calculated to describe the pulse energy distribution of the first back echo, first trailing echo, and second trailing echo.

a_{1p}/a_{mp} = ratio of first trailing echo peak amplitude to first back echo peak amplitude.

a_{2p}/a_{mp} = ratio of second trailing echo peak amplitude to first back echo peak amplitude.

The centroid of the partial signal was considered in this study, because, in an earlier study of the centroid of the full signal (Pollock et al. 2001), it was found that there was a correlation between the centroid of the signal and plastic hinge formation in damaged bolts. The location of the signal centroid can be used to measure the distribution of the pulse energy content. In other words, if the centroid location was found to be near that of the first back echo, this means that the majority of the pulse energy was concentrated in the first back echo. Alternatively, if the centroid shifted toward the trailing echoes, this means that the pulse energy was concentrated in the region of the trailing echoes. Thus, the centroid location could be related to the bolt geometry. Further knowledge of the location of the signal centroid for undeformed bolts would help if it were available, in order to provide a baseline for the field assessment of bolts in wood and steel structures.

The centroid calculated in this study was the centroid of the first back echo and associated first and second trailing echoes, all taken together as an entire signal including the noise between the echoes. All the time values were reset to (t = 0 μs) at the start of the first back echo (see Figure 9).The centroid was calculated according to the following equation:

$$t_c = \frac{\sum t_i |a_i|}{\sum |a_i|} \qquad \text{Eq .2}$$

Frequency Domain Analysis

The main goal of the frequency domain analysis was to convert the (t_i, a_i) series of points to a (f_i, m_i) series of points, and determine the peak frequency of each echo. The (f_i, m_i) points were the frequency domain points. Referring to the typical first back echo time domain signal, each echo was composed of a set of points located between (t_1, a_1) and (t_n, a_n). The subscript 1 indicates the start of the first back echo, and the subscript n indicates the end of the first back echo. A fast Fourier transform (FFT) was conducted on the data points for each echo. Each set of data points must have a number of points equal to (2^x) where 2^x = 512, 1024, or 2048 in this study. Depending on the size of the data set (the number of data points in the echo), if the number of data points was less than 2^x then the data set was padded with zeroes to obtain a total of 2^x points.

The result of this analysis was a frequency spectrum for each echo. This spectrum was characterized by constant spaced points where the spacing between points was related to the number of time domain data points used to get the frequency spectrum. For each bolt, probe, and echo, the frequency spectrum was plotted and the frequency peak was determined. The peak frequency was simply recorded as the frequency corresponding to the highest amplitude for unimodal frequency spectra (see Figure 10).

For bimodal and multi-modal frequency spectra, the first peak frequency was recorded as the frequency corresponding to the highest amplitude. If other frequencies had amplitudes exceeding 70% of the first peak frequency amplitude, then second and third peak frequencies were recorded (see Figure 11). For some of the frequency spectra it was difficult to determine a characteristic peak frequency (see Figure 12).

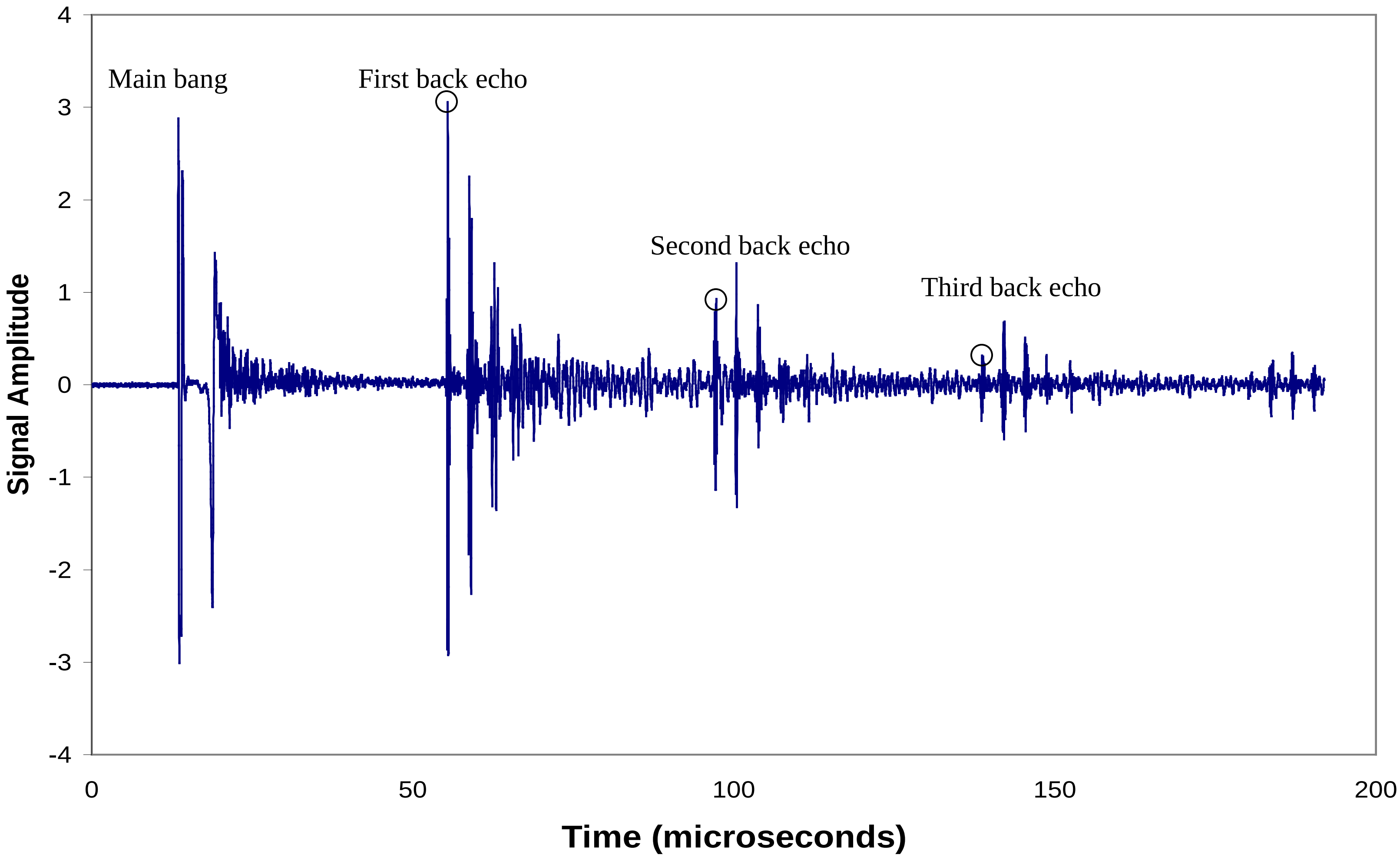

Figure 6- Typical full time domain signal for ultrasonic pulse-echo inspection of a straight bolt.

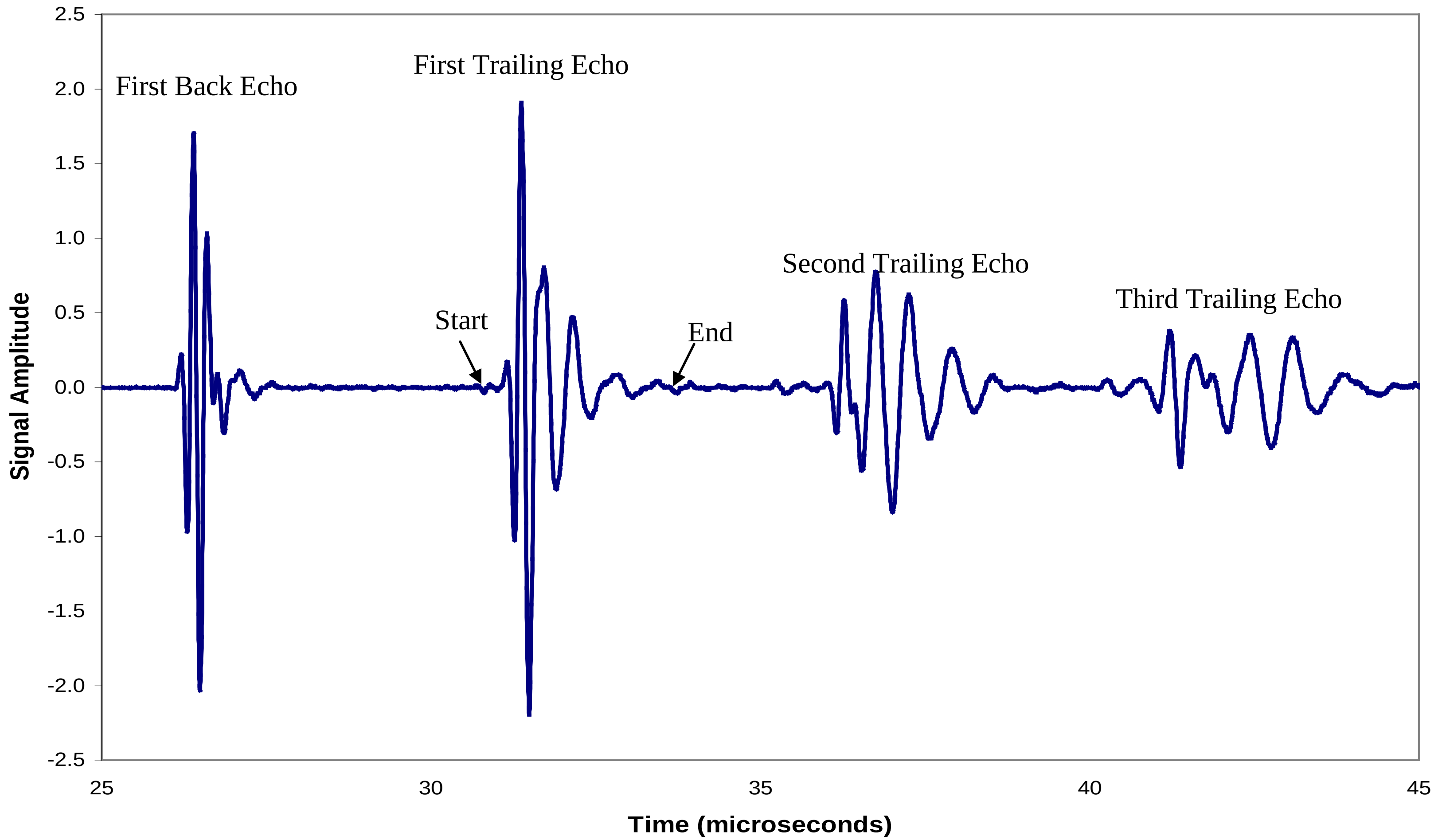

Figure 7- Typical first back echo and associated trailing echoes for ultrasonic pulse-echo inspection of a straight bolt.

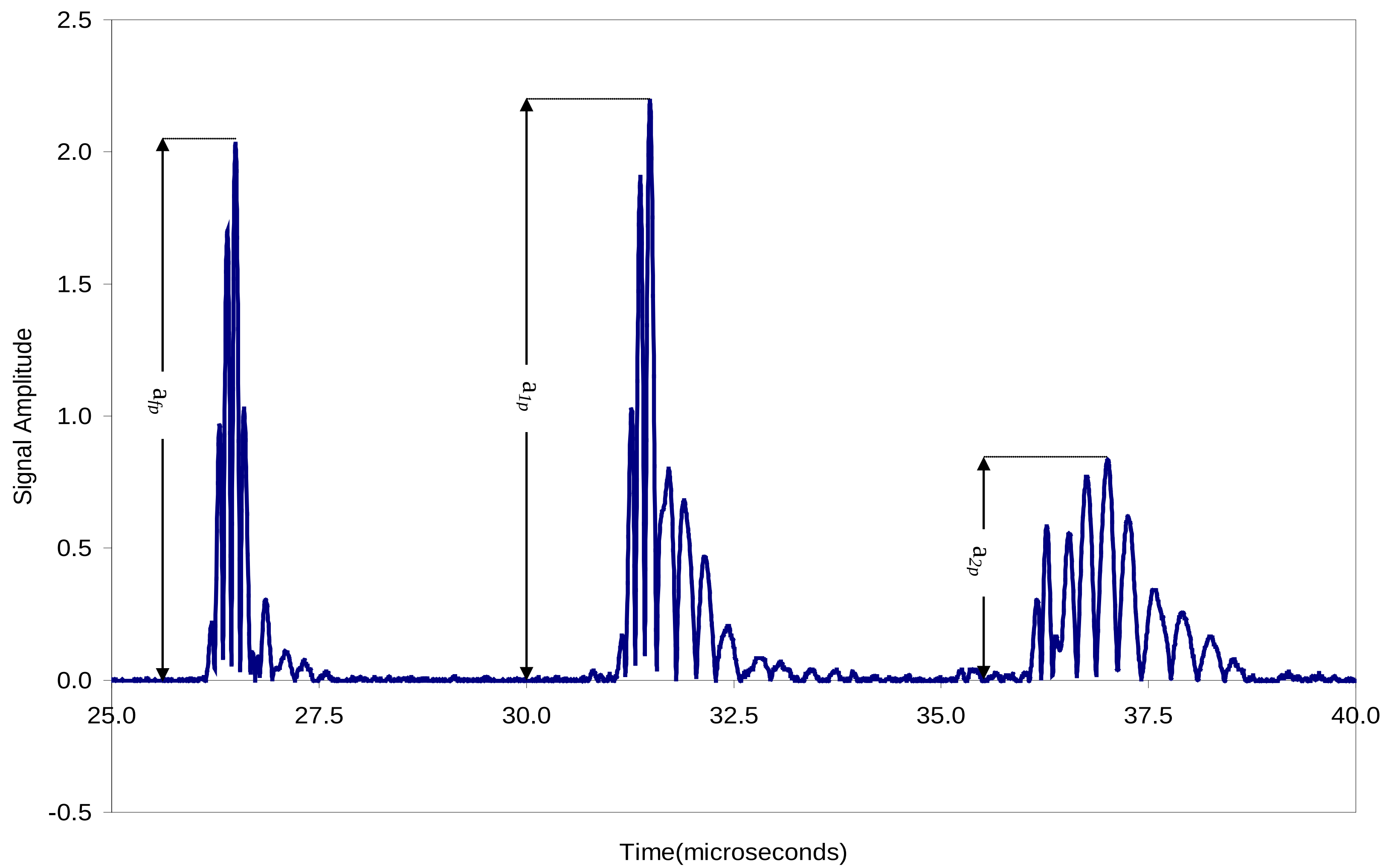

Figure 8- Rectified first back echo and associated trailing echoes for ultrasonic pulse-echo inspection of a straight bolt.

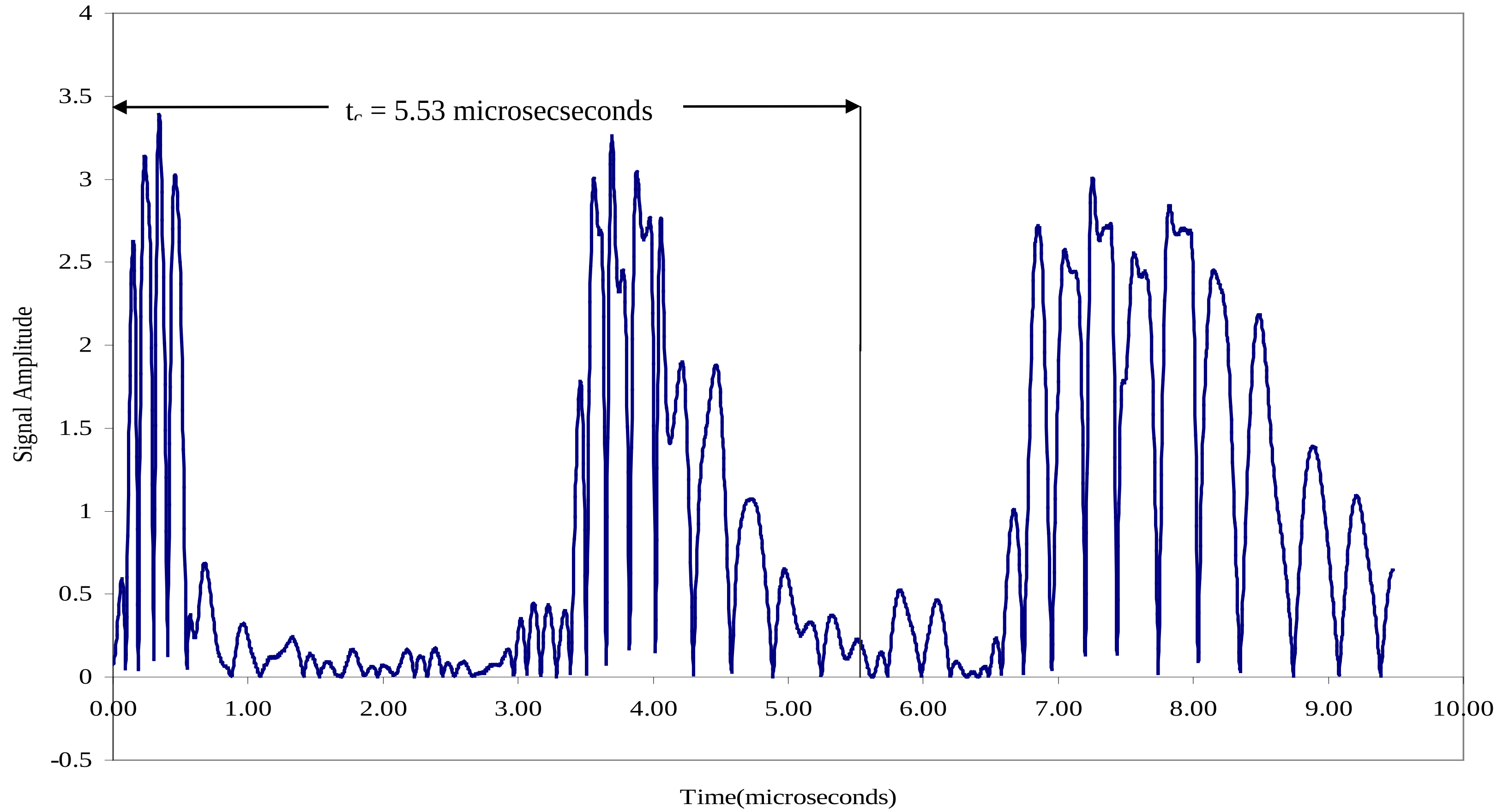

Figure 9- The centroid of the first back echo, and associated trailing echoes for ultrasonic pulse-echo inspection of a straight bolt.

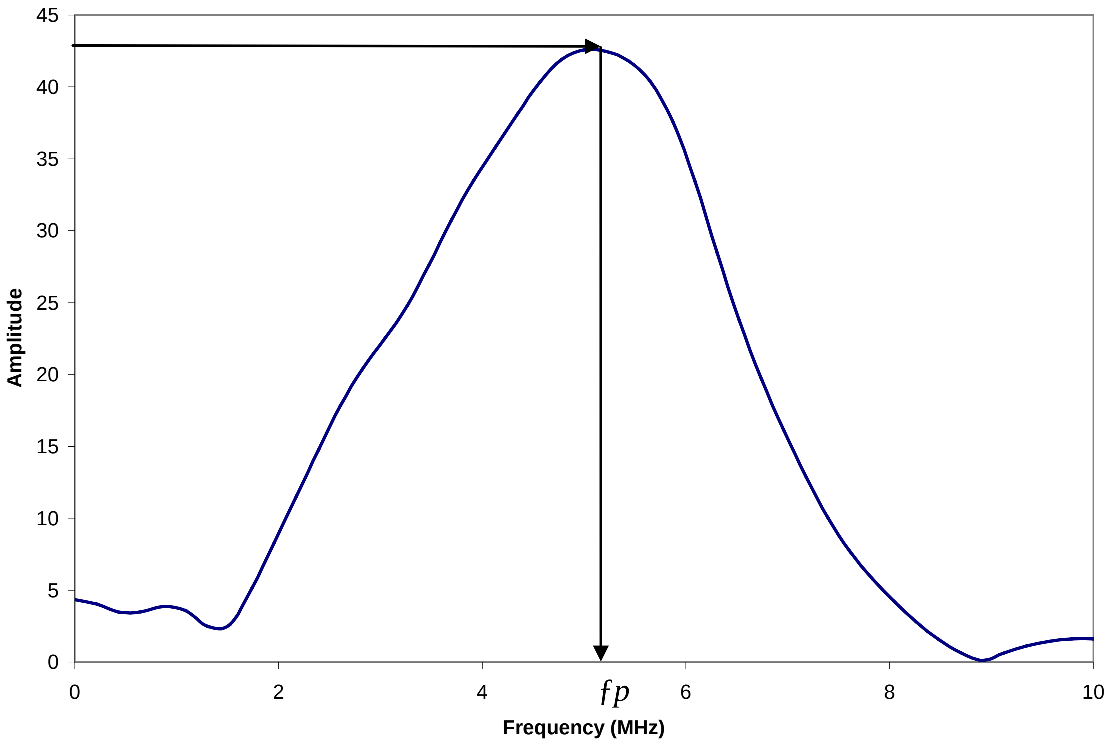

Figure 10- Typical unimodal frequency spectrum.

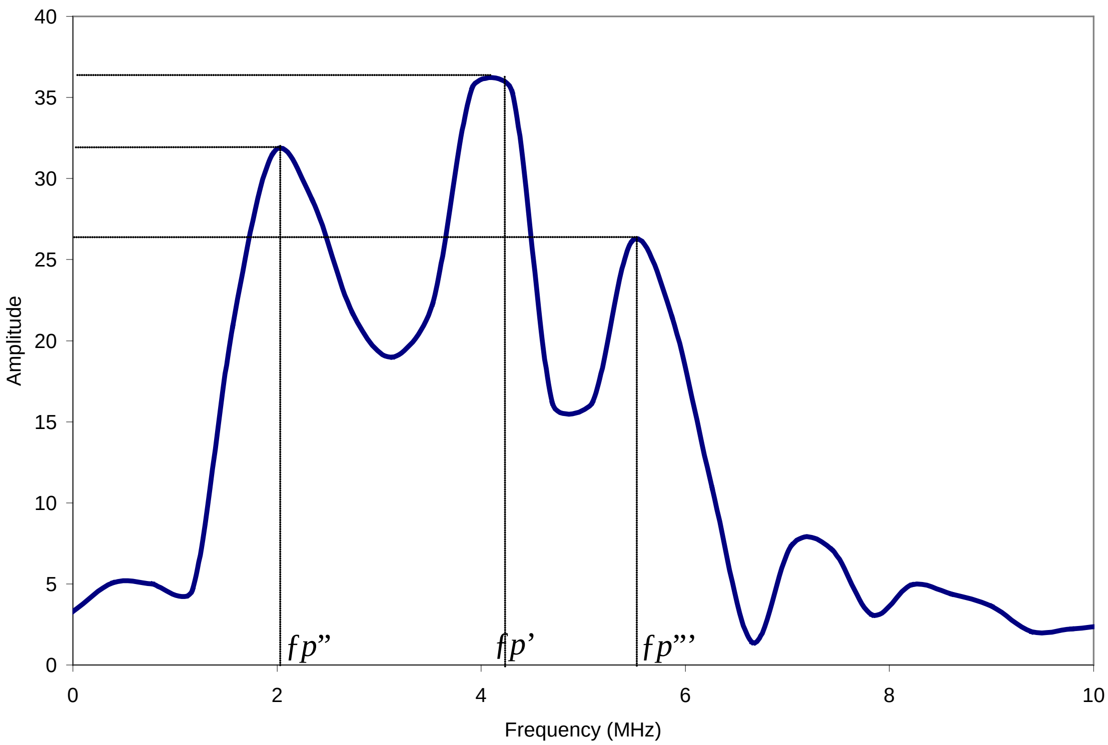

Figure 11- Trimodal frequency spectrum.

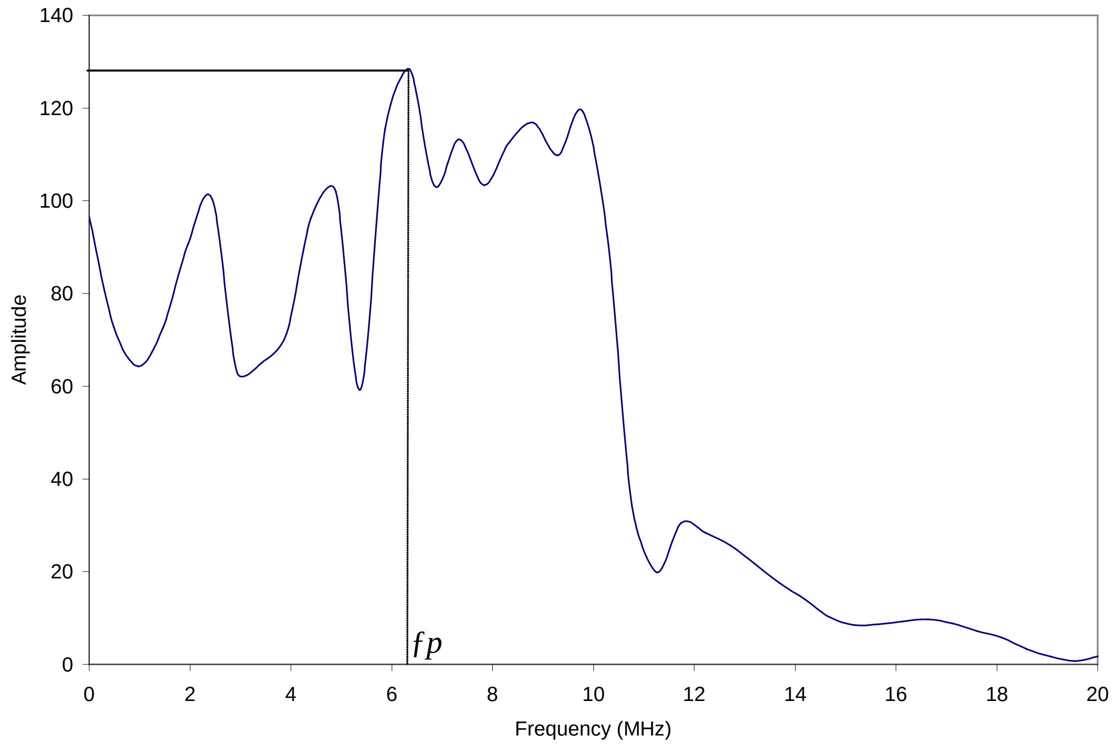

Figure 12- Unusual frequency spectrum.

CHAPTER V

RESULTS AND DISCUSSION

Three parameters were investigated in this study to determine the best parameter to characterize undeformed ASTM A307 bolts. The statistical analysis of groups of bolts was limited to bolt groups A, B, C, D, F, and M. The effect of bolt length was assessed using data from groups B, D, F, and M. The effect of probe frequency was assessed using data from group A. The effect of bolt diameter was assessed using data from groups B and C.

Ratios of Peak Amplitudes of the Trailing Echoes to the First Back Echo

Ultrasonic signals for seven bolt groups were analyzed to get the amplitude ratios of the first and second trailing echoes to the first back echo (a_{1p}/a_{mp}, a_{2p}/a_{mp}). The cumulative results are shown in Table 2. Detailed result tables are given in Appendix D.

Table 2 – Amplitude ratios for seven bolt groups

Bolt Group	Diameter (in)	Length (in)	Nominal Probe Frequency (MHz)	Echo Amplitude Ratios a_{1p}/a_{mp} Average		a_{2p}/a_{mp} Average	
				Average	COV (%)	Average	COV (%)
A	0.50	4.75	5	93.85	10.00	88.43	86.13
	0.50	4.75	10	91.71	8.28	15.71	16.38
B	0.75	5.00	5	93.38	9.00	78.08	14.34
C	1.00	5.00		88.38	19.95	72.86	32.66
D	0.75	5.75		97.99	2.72	80.57	9.32
F	0.75	7.25		100.29	12.81	76.21	29.23
M	0.75	11.50		103.43	10.12	50.40	27.76

From Table 2 it was observed that for the groups with the same bolt diameter and tested with the same probe frequency (5MHz), as the bolt length increased, the a_{1p}/a_{mp} ratio increased as in the cases of the B, D, F, and M bolt groups. This is due to the fact that the echo is composed of pulse energy and a portion of that energy did not propagate directly down the bolt, but hit the sidewalls of the bolt and reflected as a transverse wave due to bolt beam spreading as the pulse propagated away from the probe. As the bolt length increased, the transverse wave amplitude was higher and thus the a_{1p}/a_{mp} ratio increased. The a_{2p}/a_{mp} ratio decreased as the bolt length increased as in the cases of B, D, F, and M bolt groups, because the pulse energy had to reflect twice across the bolt length, which caused higher attenuation of the wave amplitude. More time was needed for the transverse wave to reflect across the bolt length with higher attenuation expected. This was due to the fact that transverse wave velocity was lower than the longitudinal wave velocity.

For the groups with the same length and tested with the same probe frequency (5 MHz), as the bolt diameter increased both the a_{1p}/a_{mp} and a_{2p}/a_{mp} ratios decreased, as in the cases of B and C bolt groups. As mentioned before, the echo was composed of pulse energy and a greater portion of that energy propagated directly down the bolts with large diameters. Only a smaller portion of the energy was reflected as a transverse wave, which means lower trailing echo amplitudes and lower a_{1p}/a_{mp} and a_{2p}/a_{mp} ratios.

For bolt group A, which was tested with two probe frequencies (5 and 10 MHz), as the probe frequency increased from 5 to 10 MHz both the a_{1p}/a_{mp} and a_{2p}/a_{mp} ratios decreased. This could be explained since the attenuation is frequency dependent. As the frequency increased the attenuation increased, and lower trailing echo amplitudes were expected along with lower a_{1p}/a_{mp} and a_{2p}/a_{mp} ratios.

For every bolt group size tested with one probe frequency the a_{2p}/a_{mp} ratio was observed to be always less than the a_{1p}/a_{mp} ratio. This could be because the second trailing echo was composed of the pulse energy that was reflected two times across the bolt, and the longer path means higher attenuation and lower a_{2p}/a_{mp} ratio.

The coefficient of variation for a_{2p}/a_{mp} ratio ranged between 9.32 % and 86.13 % which was observed to be higher than the coefficient of variation for the a_{1p}/a_{mp} ratio that ranged between 2.72 % and 19.95 %.

Ultrasonic signals for one bolt of each bolt group tested with both probe frequencies (5 and 10 MHz) were analyzed to get the a_{1p}/a_{mp} and a_{2p}/a_{mp} ratios. The results are shown in Table 3.

Similar trends were not evident from Table 3 when compared with the groups of bolts given in Table 2. Even though the analysis of one bolt from each group gives a larger range of bolt geometries, one observation may not necessarily be a good representative of a population of bolts. The trends observed based on groups of bolts would definitely be more representative than trends based on tests of only one bolt from each group.

For bolt groups with the same diameter and approximately the same length as in bolt groups (G, H, and I), the amplitude ratios were different when tested with 5 and 10 MHz probe frequencies. The reason might be that these bolts were from different manufacturers. Therefore the attenuation of the pulse energy could vary with bolt material, even when bolt geometry was nearly identical.

For 0.50 inch (1.3 cm) nominal diameter bolts, the amplitude ratios either remained the same, as in bolt groups A and K, or decreased as in bolt groups E, G-J, and L, when the probe frequency increased. This was similar to the trend observed in Table 2 for groups of bolts.

Table 3 – Amplitude ratios for one bolt from each bolt group

Bolt	Diameter (in)	Length (in)	Nominal Probe Frequency (MHz)	Echo Amplitude Ratios	
				a_{1p}/a_{mp}	a_{2p}/a_{mp}
A1	0.50	4.82	5 10	96.45 95.56	88.46 90.83
B2	0.75	4.93	5 10	92.41 98.85	86.71 82.18
C2	1.00	5.13	5 10	98.55 95.28	80.64 87.32
D1	0.75	5.92	5 10	99.71 85.67	83.04 55.52
E1	0.50	6.89	5 10	108.61 85.76	95.90 70.87
F1	0.75	7.26	5 10	100.29 100.00	81.45 83.43
G1	0.50	7.38	5 10	184.91 65.61	129.25 45.24
H1	0.50	7.65	5 10	103.64 75.38	89.39 36.26
I1	0.50	7.73	5 10	135.83 65.56	58.00 32.33
J1	0.50	9.84	5 10	184.08 117.99	180.82 70.37
K1	0.50	10.84	5 10	102.97 102.37	102.08 102.37
L1	0.50	11.38	5 10	266.67 124.18	266.67 94.38
M1	0.75	11.41	5 10	103.27 77.30	42.04 30.33

Centroid of the First Back Echo and Associated First and Second Trailing Echoes

Ultrasonic signals for seven bolt groups were analyzed to get the centroid of the first back echo and associated first and second trailing echoes. The results are shown in Table 4.

The primary reason for the centroid shifting towards or away from the origin was due to the number of data points used to calculate the centroid. For large diameter bolts the number of data points till the end of the second trailing echo needed for centroid calculation was greater than the number of data points needed for centroid calculation for small diameter bolts because the trailing echoes will show at further distance for large diameter than for small one. Thus the centroid for larger diameter bolts would be shifted away from the origin.

Table 4 – The centroid of the first back echo and associated first and second trailing echoes for seven bolt groups

Bolt Group	Diameter (in)	Length (in)	Nominal Probe Frequency (MHz)	Centroid of First Back Echo with its 1st and 2nd Trailing Echoes	
				Average (Seconds)	COV (%)
A	0.50	4.75	5	4.99E-06	7.94
	0.50	4.75	10	4.96E-06	8.65
B	0.75	5.00	5	6.36E-06	8.05
C	1.00	5.00		7.53E-06	9.38
D	0.75	5.75		6.95E-06	3.81
F	0.75	7.25		6.74E-06	9.13
M	0.75	11.50		6.46E-06	5.92

From Table 4 it could be observed that for the groups with the same bolt diameter and tested with the same probe frequency (5MHz), as the bolt length increased the centroid of the first back echo and associated first and second trailing echoes were almost the same with slight decrease within 8.5 %. However, the shift in the centroid could be explained by the fact that the centroid shifting towards or away from the origin was due to the number of data points used to calculate the centroid. As the number of data points till the end of the second trailing echo needed for centroid calculation increased, the centroid would shift away from the origin as in the cases of the D, F, and M bolt groups. The coefficient of variation for the centroid of the first back echo and associated first and second trailing echoes ranged between 3.81 % and 9.38 %.

For the groups with the same length and tested with the same probe frequency (5MHz), as the bolt diameter increased, the centroid of the first back echo and associated first and second trailing echoes increased as in the cases of B, and C bolt groups. This due to the fact that the echo was composed of pulse energy, the great portion of that energy propagate directly down the bolt. Higher first back echo amplitudes were recorded, which means that the centroid of the first back echo, and associated first and second trailing echoes, would shift towards the origin which was counteracted by the increase in the time intervals between trailing echoes would shift away from the origin.

For the bolts in Group A tested with two probe frequencies (5 and 10 MHz), as the probe frequency increased from 5 to 10 MHz, the centroid of the first back echo and associated first and second trailing echoes was nearly identical. The centroid decreased less than 0.6 % for the 10 MHz probe versus the 5 MHz probe.

The ultrasonic signals for one bolt from each bolt group tested with both probe frequencies (5 and 10 MHz) were analyzed to get the centroid of the first back echo and associated first and second trailing echoes. The results are shown in Table 5.

Similar trends were not evident from Table 5 when compared with the groups of bolts given in Table 4. In particular, the centroid from the 10 MHz probe was not identical to the centroid from the 5 MHz probe for each bolt. In some cases, the signal centroid differed by as much as 74.65 % to 118.99 %. Thus, while the signal centroid is primarily dependent on bolt geometry (diameter and length), the signal centroid will also shift slightly based on the frequency of the probe used for inspection.

Table 5 – The centroid for one bolt of each bolt group

Bolt	Diameter (in)	Length (in)	Nominal Probe Frequency (MHz)	Centroid of First Back Echo with its 1st and 2nd Trailing Echoes (seconds)
A1	0.50	4.82	5 10	5.53E-06 5.28E-06
B1	0.75	4.93	5 10	4.92E-06 6.59E-06
C1	1.00	5.13	5 10	6.53E-06 7.83E-06
D1	0.75	5.92	5 10	7.09E-06 7.11E-06
E1	0.50	6.89	5 10	5.10E-06 5.06E-06
F1	0.75	7.26	5 10	7.24E-06 7.16E-06
G1	0.50	7.38	5 10	4.95E-06 4.16E-06
H1	0.50	7.65	5 10	4.37E-06 4.12E-06
I1	0.50	7.73	5 10	4.07E-06 3.92E-06
J1	0.50	9.84	5 10	4.74E-06 4.07E-06
K1	0.50	10.84	5 10	4.48E-06 4.55E-06
L1	0.50	11.38	5 10	5.02E-06 4.18E-06
M1	0.75	11.41	5 10	6.18E-06 5.52E-06

Furthermore, one observation was not necessarily a good representative of a population of bolts. The trends observed based on groups of bolts would definitely be more representative than trends based on tests of only one bolt from each group.

The Peak Frequencies of the First Back Echo and Associated First and Second Trailing Echoes

Ultrasonic signals for seven bolt groups were analyzed using fast Fourier transforms to get the peak frequencies of the first back echo and associated first and second trailing echoes. The results are shown in Table 6.

From Table B.3 in Appendix B it was observed that there were two outliers B46, B57 and when these two outliers were ignored the coefficient of variation decreased significantly from 57.19 % to 10.44 %. These results were rewritten in Table 7.

For the groups with the same bolt diameter and tested with the same probe frequency (5MHz), as the bolt length increased, as in the cases of the B, F, and M bolt groups, the peak frequency of the first back echo increased. This was particularly evident when the outliers were ignored as in Table 7. The peak frequencies of the associated first and second trailing echoes also increased as the bolt length increased, as in the cases of the B, D, F, and M bolt groups.

For the bolt groups with the same length and tested with the same probe frequency (5MHz), as the bolt diameter increased the peak frequencies of the first back echo and associated second trailing echo increased, as in the cases of the B and C bolt groups when the outlier in bolt group B was ignored as in Table 7. In contrast, the peak frequency of the first trailing echo decreased as the bolt diameter increased, as in the cases of the B and C bolt groups.

For the bolts in group A tested with two probe frequencies (5 and 10 MHz), as the probe frequency increased from 5 to 10 MHz the peak frequency of the first back echo and associated first trailing echo increased. This trend was expected since the frequency content of the pulse increased as the probe frequency increased. In contrast, the peak frequency of the second trailing echo was almost identical for both probe frequencies. There was only a 2.75 % difference in peak frequency of the second trailing echo for each probe.

Table 6 – The peak frequencies of the first back echo and associated first and second trailing echoes for seven bolt groups considering outliers.

Bolt	Diameter (in)	Length (in)	Nominal Probe Frequency (MHz)	Echo Peak Frequency (MHz)					
				First Back		1st trailing		2nd trailing	
				Average	COV (%)	Average	COV (%)	Average	COV (%)
A	0.50	4.75	5	4.59	7.98	2.47	7.12	1.82	12.59
	0.50	4.75	10	8.17	3.42	2.76	33.90	1.77	18.44
B	0.75	5.00	5	2.14	57.19	1.59	5.43	1.23	8.00
C	1.00	5.00		1.81	40.90	1.40	10.14	1.38	10.53
D	0.75	5.75		1.98	8.90	1.70	7.30	1.30	9.08
F	0.75	7.25		3.40	19.45	1.89	49.86	1.39	12.10
M	0.75	11.50		4.90	4.19	2.54	5.74	1.76	3.84

Table 7 – The peak frequencies of the first back echo and associated first and second trailing echoes for seven bolt groups ignoring an outliers data points in group B.

Bolt	Diameter (in)	Length (in)	Nominal Probe Frequency (MHz)	Echo Peak Frequency (MHz)					
				First Back		1st trailing		2nd trailing	
				Average	COV (%)	Average	COV (%)	Average	COV (%)
A	0.50	4.75	5	4.59	7.98	2.47	7.12	1.82	12.59
	0.50	4.75	10	8.17	3.42	2.76	33.90	1.77	18.44
B	0.75	5.00	5	1.75	10.44	1.59	5.43	1.23	8.00
C	1.00	5.00		1.81	40.90	1.40	10.14	1.38	10.53
D	0.75	5.75		1.98	8.90	1.70	7.30	1.30	9.08
F	0.75	7.25		3.40	19.45	1.89	49.86	1.39	12.10
M	0.75	11.50		4.90	4.19	2.54	5.74	1.76	3.84

For all the bolts the peak frequency of the first back echo was always higher than the peak frequency of the first trailing echo which had a higher peak frequency than the second trailing echo due to the attenuation and loss in the frequency content with time.

Ultrasonic signals for one bolt of each bolt group tested with both probe frequencies (5 and 10 MHz) were analyzed to get the peak frequencies of the first back echo and associated first and second trailing echoes. The results are shown in Table 8.

Similar trends to that observed from Table 7 were evident in Table 8 that the peak frequency of the first back echo was always higher than the peak frequency of the first trailing echo which had higher peak frequency than the second trailing echo. Also, it was observed that for the same bolt length and diameter the time difference between any two successive trailing echoes and the time between any two successive back echoes was constant. This is consistent with the results from previous studies (Pollock et al. 2001) regarding the location of the first back echo and the time (Δt) between trailing echoes. This means that the bolt geometry could be determined ultrasonically if the bolt were hidden in any structural connections. The peak frequencies of trailing echoes were observed to be approximately 40 – 60 % of the frequency of the ultrasonic probe used.

In comparing the coefficient of variation for the parameters investigated in this study, the coefficient of variation for the peak frequencies was the highest.

Testing groups of 60 bolts may not be required in future studies because the coefficient of variation for group B with 60 bolts was similar to the coefficient of variation for groups of 20 bolts. For example, the coefficient of variation of the a_{1p}/a_{mp} ratio was 9.0 % which was slightly less than the average coefficient of variation of 11.2% for other groups of 20 bolts. In the case of the centroid of the first back echo and associated first and second trailing echoes, the coefficient of variation for the group of 60 bolts was 8.05 %. This was slightly higher than the average coefficient of variation for other groups of 20 bolts, which was found to be 7.24 %.

The coefficient of variation for the peak frequency of the first back echo changed dramatically when the outliers B46 and B57 were removed from 57.19 % to 10.44 %.
So, the coefficient of variation for the peak frequency of the first back echo for the group of 60 bolts after the outliers were removed was in the range of coefficient of variation for the peak frequency of the first back echo for other groups of 20 bolts, which was found to be between 3.42 % and 40.99 %. The coefficient of variation for the peak frequency of the first trailing echo ranged between 5.43 % and 49.86 %. The coefficient of variation for the peak frequency of the second trailing echo ranged between 3.84 % and 18.44 %.

Table 8 – The peak frequencies of the first back echo and associated first and second trailing echoes for one bolt of each bolt group.

Bolt	Diameter in	length in	Nominal Probe Frequency (MHz)	Echo Peak Frequency (MHz)		
				First Back	1st trailing	2nd trailing
A1	0.50	4.82	5	4.40	2.45	1.71
			10	8.32	2.2	1.71
B1	0.75	4.93	5	1.57	1.37	1.17
			10	1.71	1.71	1.22
C1	1.00	5.13	5	3.42	1.47	0.98
			10	1.47	1.47	1.47
D1	0.75	5.92	5	1.96	1.71	1.22
			10	7.34	1.47	1.22
E1	0.50	6.89	5	5.09	3.13	2.35
			10	7.44	3.13	2.35
F1	0.75	7.26	5	3.13	1.37	1.37
			10	2.94	2.2	1.96
G1	0.50	7.38	5	5.03	4.47	2.52
			10	7.83	2.94	2.28
H1	0.50	7.65	5	5.22	4.57	2.61
			10	7.83	3.91	2.74
I1	0.50	7.73	5	5.22	4.89	2.61
			10	8.48	3.26	2.61
J1	0.50	9.84	5	5.03	4.47	3.08
			10	7.83	7.83	2.94
K1	0.50	10.84	5	5.54	4.57	3.26
			10	8.56	4.16	3.18
L1	0.50	11.38	5	5.09	4.70	3.13
			10	8.48	8.81	3.26
M1	0.75	11.41	5	5.00	2.16	1.74
			10	4.24	2.94	1.96

CHAPTER VI

CONCLUSIONS

The following conclusions were reached from testing 290 ASTM A307, Grade A, standard bolts (“Standard Specification” 2003) using the ultrasonic pulse-echo inspection technique:

- The best ultrasonic signal parameter to characterize the bolts was the centroid of the first back echo and associated trailing echoes, because it had the lowest coefficient of variation among all the parameters investigated. Furthermore, this parameter does not vary much with probe frequency, which means that selection of probes by individual inspectors would not dramatically influence the results of field inspection of bolts.
- The second best parameter to characterize the bolts was the ratio of peak amplitudes of the trailing echoes to the first back echo. The coefficient of variation for peak amplitude ratios was higher than that for the centroid of the first back echo and associated trailing echoes.
- The least effective parameter for characterizing the bolts was the peak frequency of the first back echo and the peak frequencies of associated first and second trailing echoes. The coefficient of variation was high for peak frequencies of echoes, mainly due to the consideration of outliers in the data.
- Each combination of bolt geometry (diameter, length, thread length) and the ultrasonic probe frequency used provides a unique ultrasonic pulse-echo signal.
- The peak frequency of the first back echo was found to be near the frequency of the ultrasonic probe used for the bolt groups with nominal diameter of 0.50 inch (1.30 cm). However, the peak frequencies of trailing echoes were approximately 40 – 60 % of the frequency of the ultrasonic probe used.

During the analysis of the three ultrasonic parameters investigated in this study, it was not possible to establish comprehensive trends regarding the effects of bolt diameter, bolt length, and probe frequency on the ultrasonic signal parameters. Therefore, it is recommended for future research to test bolt groups with the same diameter and manufacturer with a range of bolt lengths. Similarly, bolt groups with the same length and manufacturer with a range of bolt diameters should be evaluated. The probe frequencies used in this study were adequate, but if six groups of 20 bolts, three of them with the same diameter and the other three with the same length, would be tested with 2.25, 5, 10, and 20 MHz probe frequency, the influence of probe frequency on the ultrasonic parameters investigated would be best studied. Sample sizes of 20 bolts would be sufficient and the study of amplitude ratios for additional trailing echoes is recommended.

There was one difficulty that could be avoided in future research. The magnetic ultrasonic probe used in this study provided constant pressure and consistent ultrasonic coupling with the bolt head. However, when hand pressure was used with the nonmagnetic probe (see Figure 5) it was impossible to achieve consistent ultrasonic coupling. Thus, the use of magnetic probes is strongly recommended.

Another possible source of human error was that the ultrasonic probe may not have been applied at the exact center of the bolt head, and the propagating pulse energy was not centered on the longitudinal axis of the bolt. This error could be minimized by constructing a probe fixture to consistently center the probe on the bolt head. Finally, the presence of threads obscures the accuracy of the test because thread characteristics were not consistent in all the bolt groups. Unfortunately, the source of error cannot be eliminated for field inspection of bolts in structures since the threads are part of the overall bolt geometry.

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APPENDIX A

TIME DOMAIN SIGNAL FOR ULTRASONIC PULSE-ECHO INSPECTION FOR BOLT FROM EACH GROUP TESTED WITH (5 AND 10 MHz) PROBE FREQUENCIES

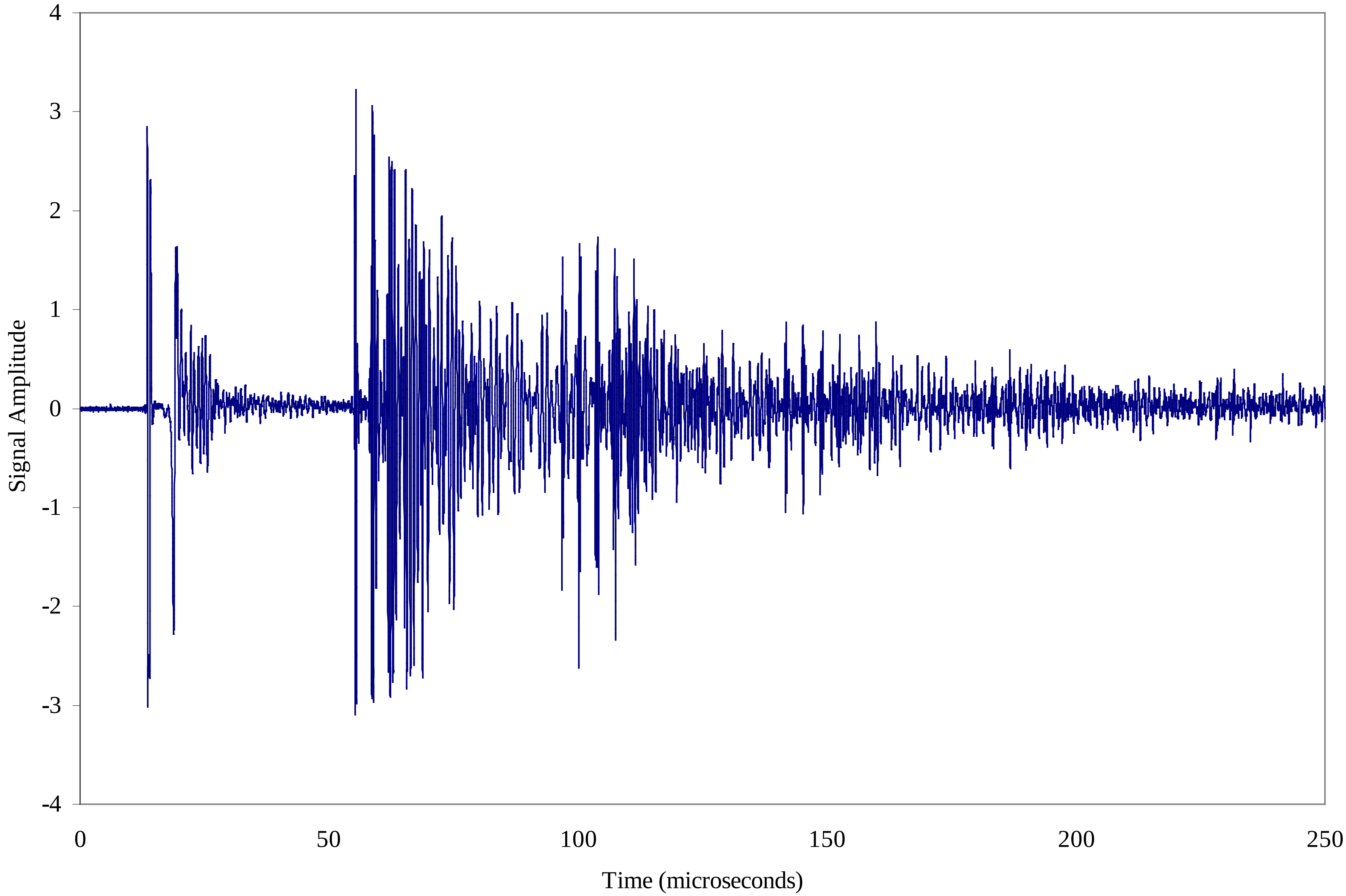

Figure A.1- Full time domain signal for ultrasonic pulse-echo inspection of bolt A1 tested with 5 MHz probe frequency.

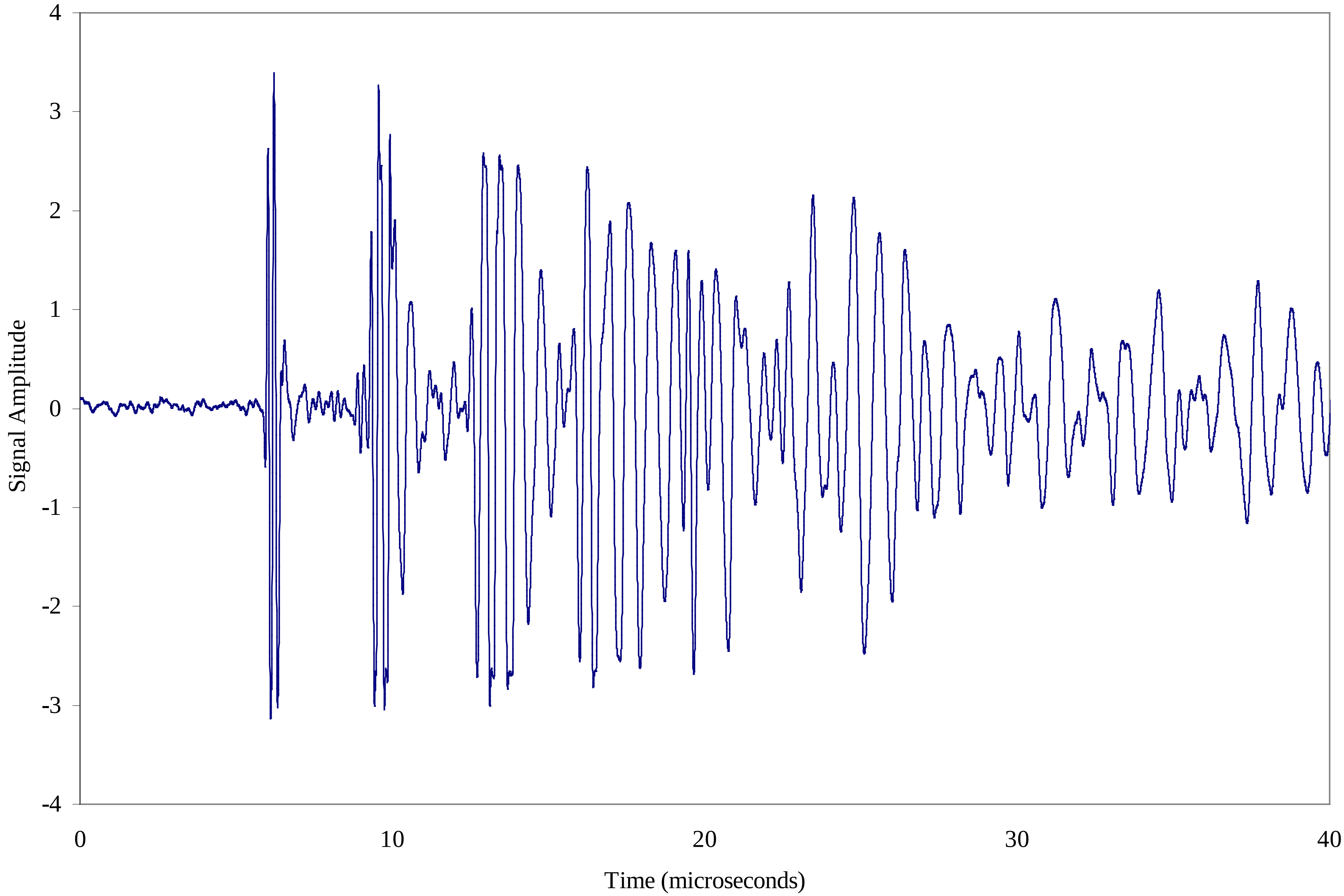

Figure A.2- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt A1 tested with 5 MHz probe frequency.

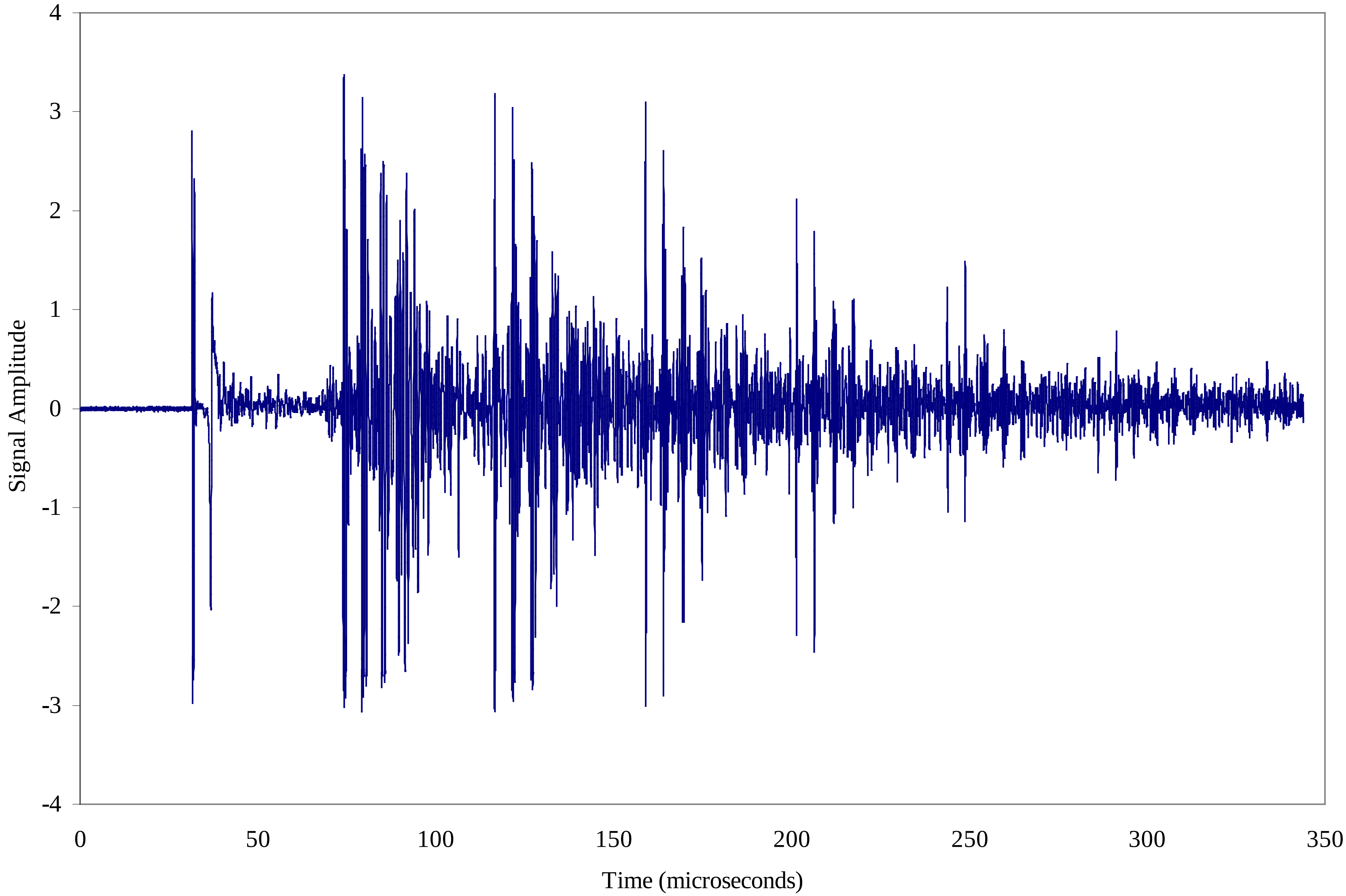

Figure A.3- Full time domain signal for ultrasonic pulse-echo inspection of bolt B1 tested with 5 MHz probe frequency.

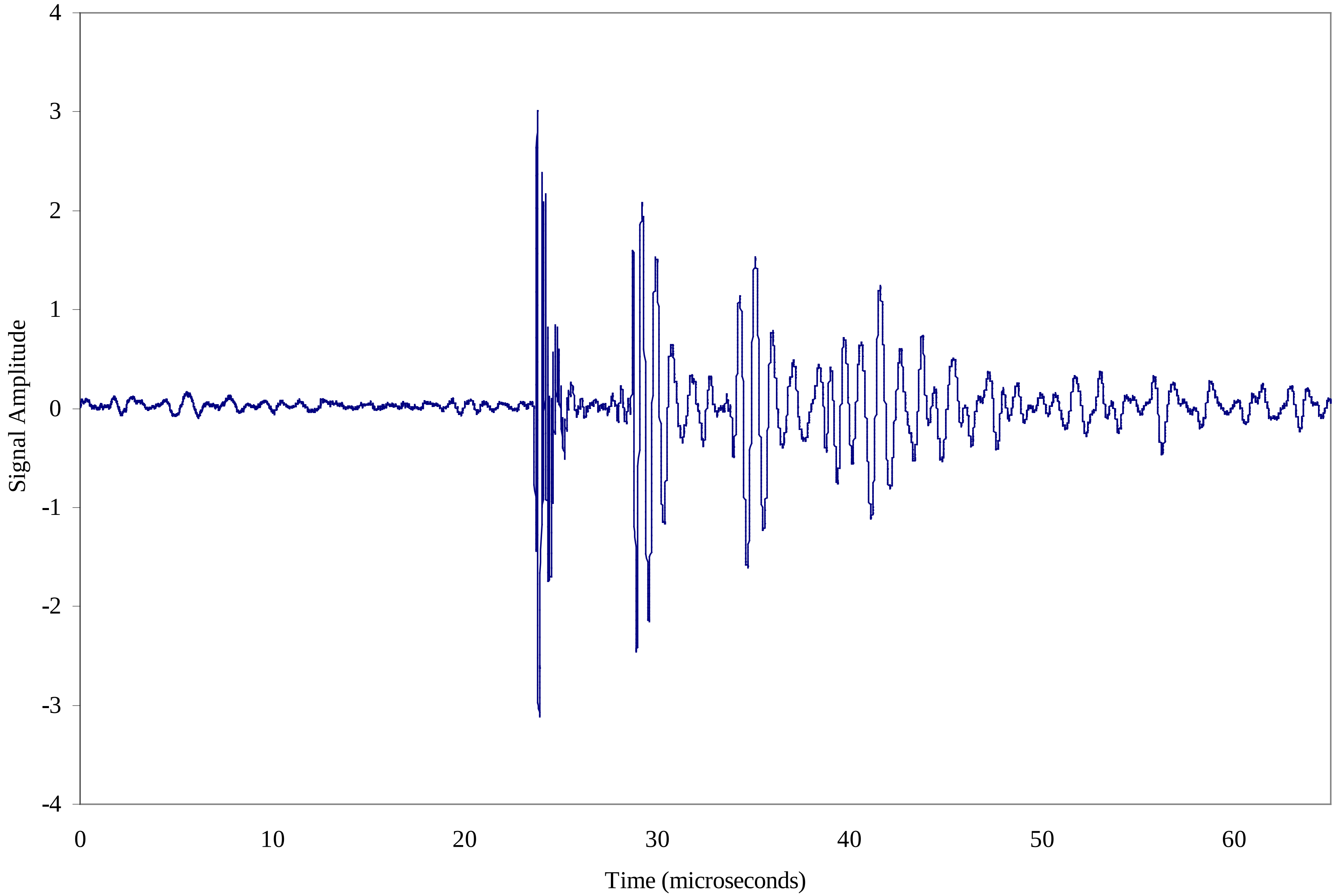

Figure A.4- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt B1 tested with 5 MHz probe frequency.

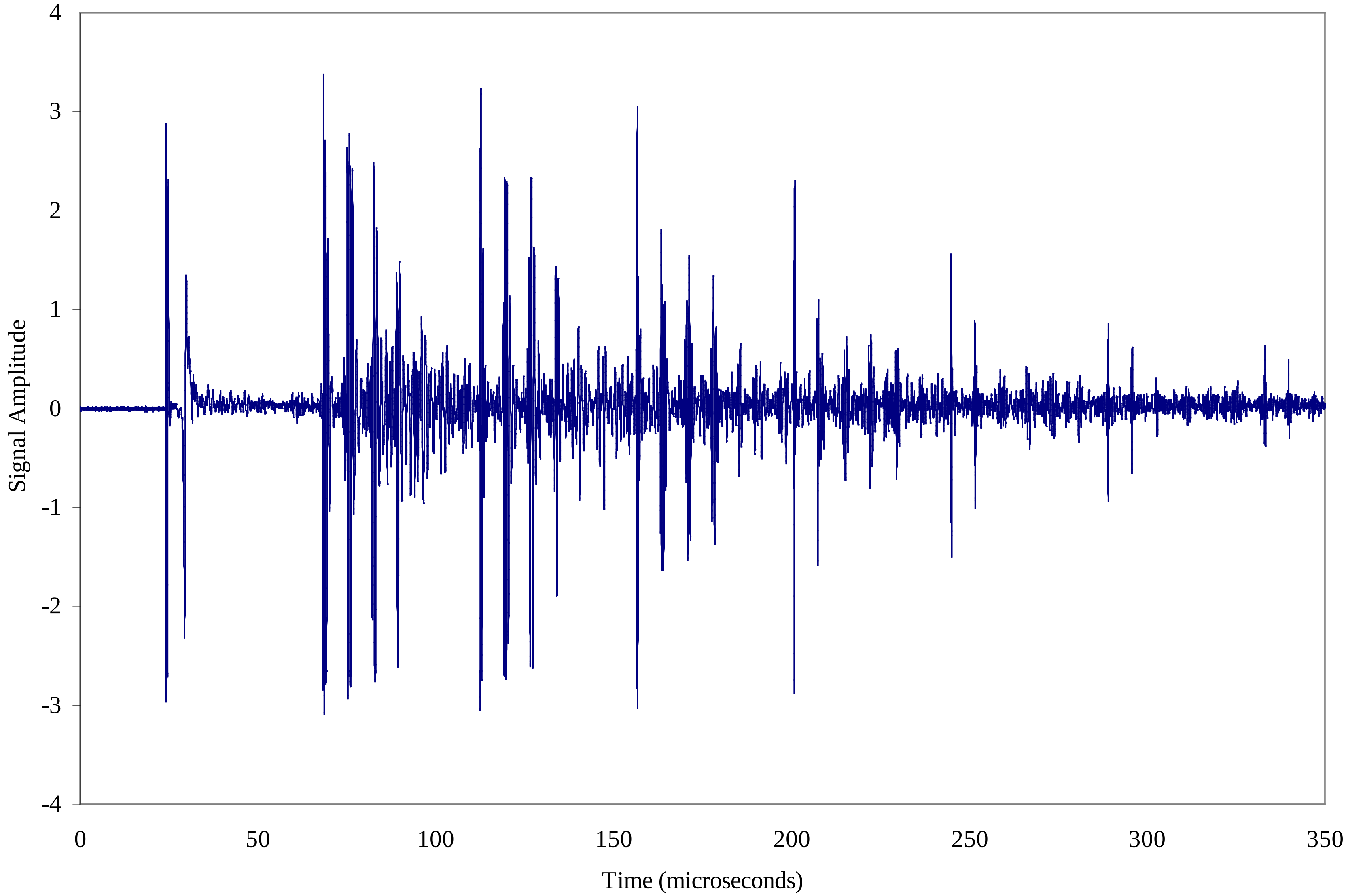

Figure A.5- Full time domain signal for ultrasonic pulse-echo inspection of bolt C1 tested with 5 MHz probe frequency.

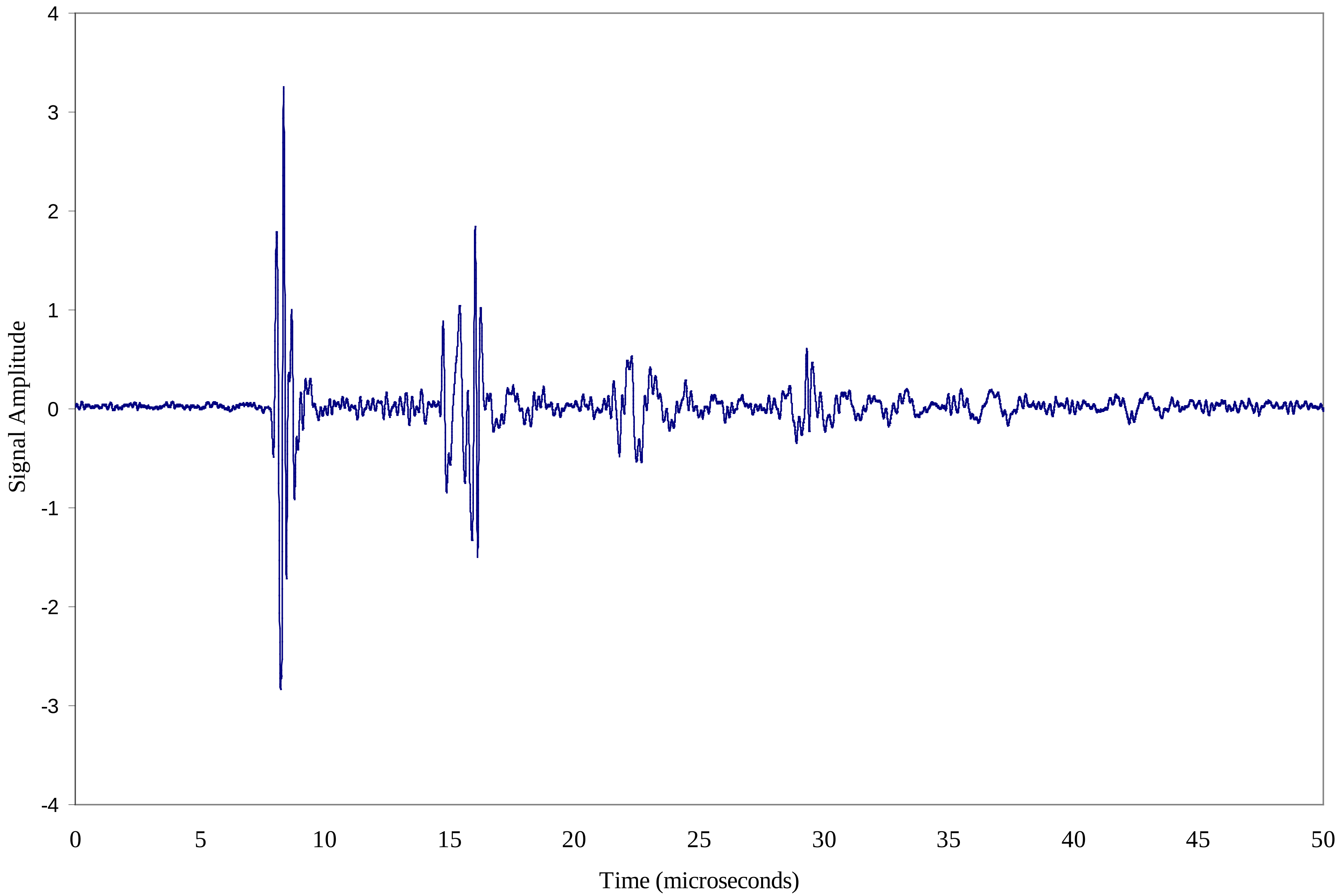

Figure A.6- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt C1 tested with 5 MHz probe frequency.

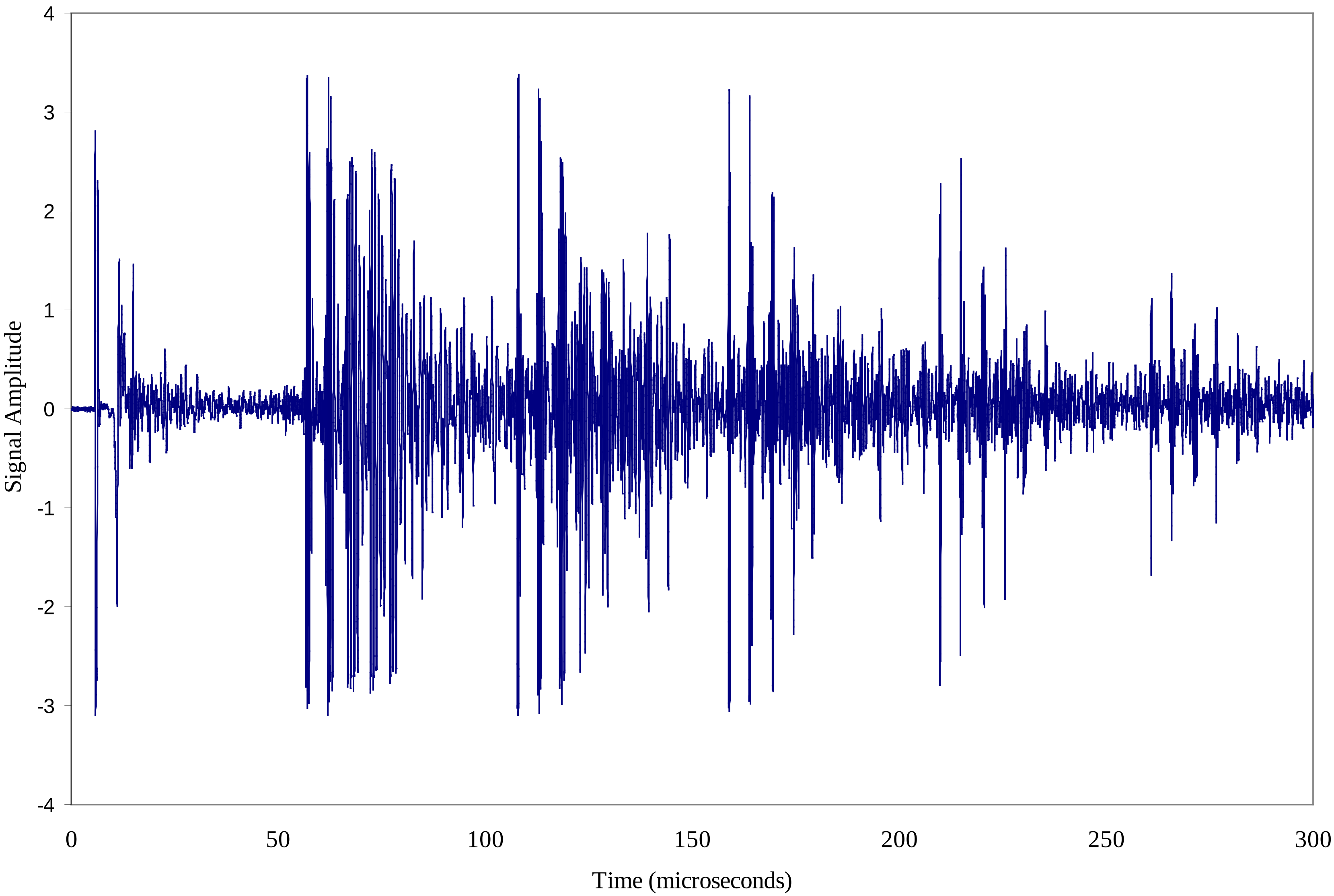

Figure A.7- Full time domain signal for ultrasonic pulse-echo inspection of bolt D1 tested with 5 MHz probe frequency.

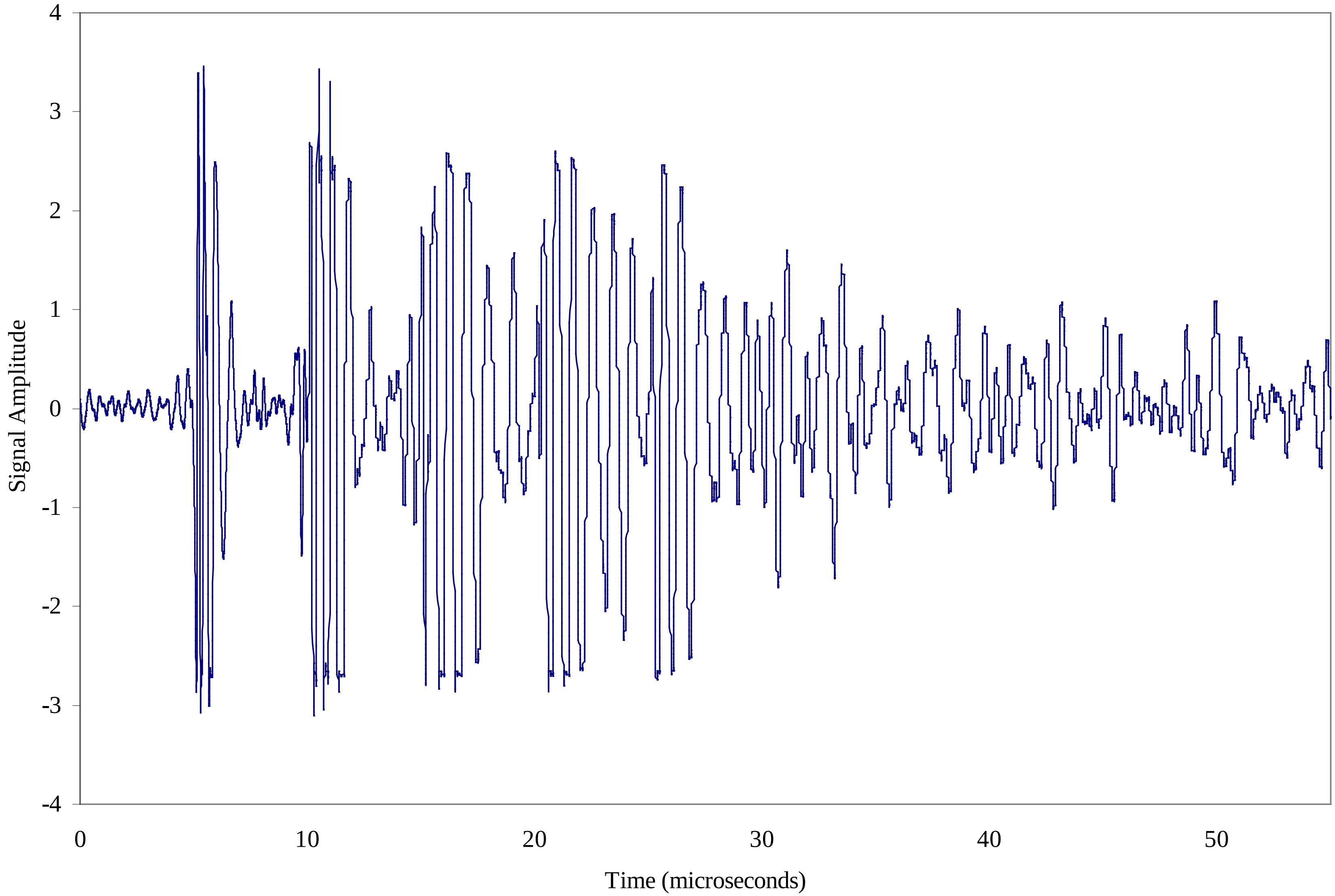

Figure A.8- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt D1 tested with 5 MHz probe frequency.

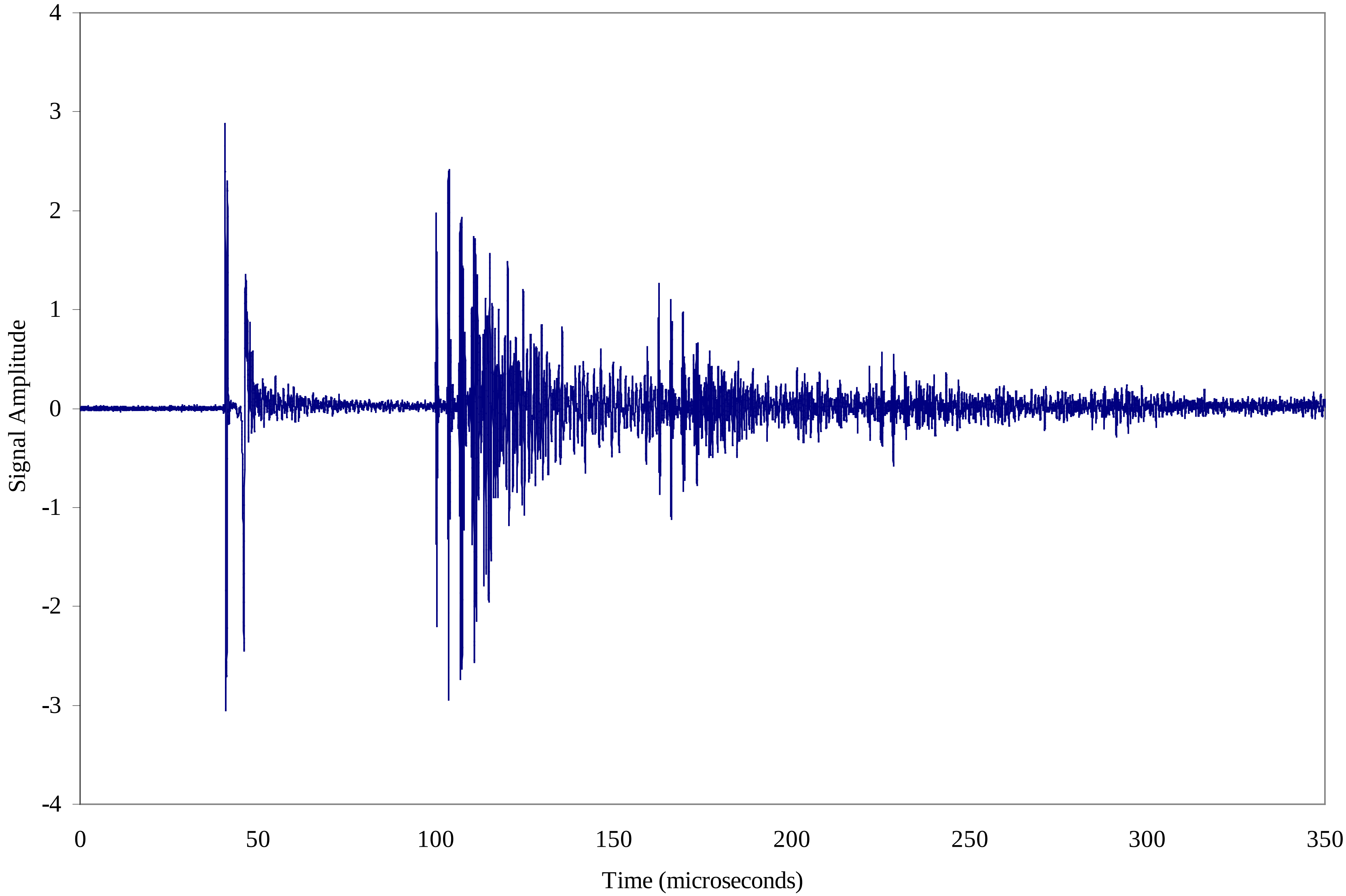

Figure A.9- Full time domain signal for ultrasonic pulse-echo inspection of bolt E1 tested with 5 MHz probe frequency.

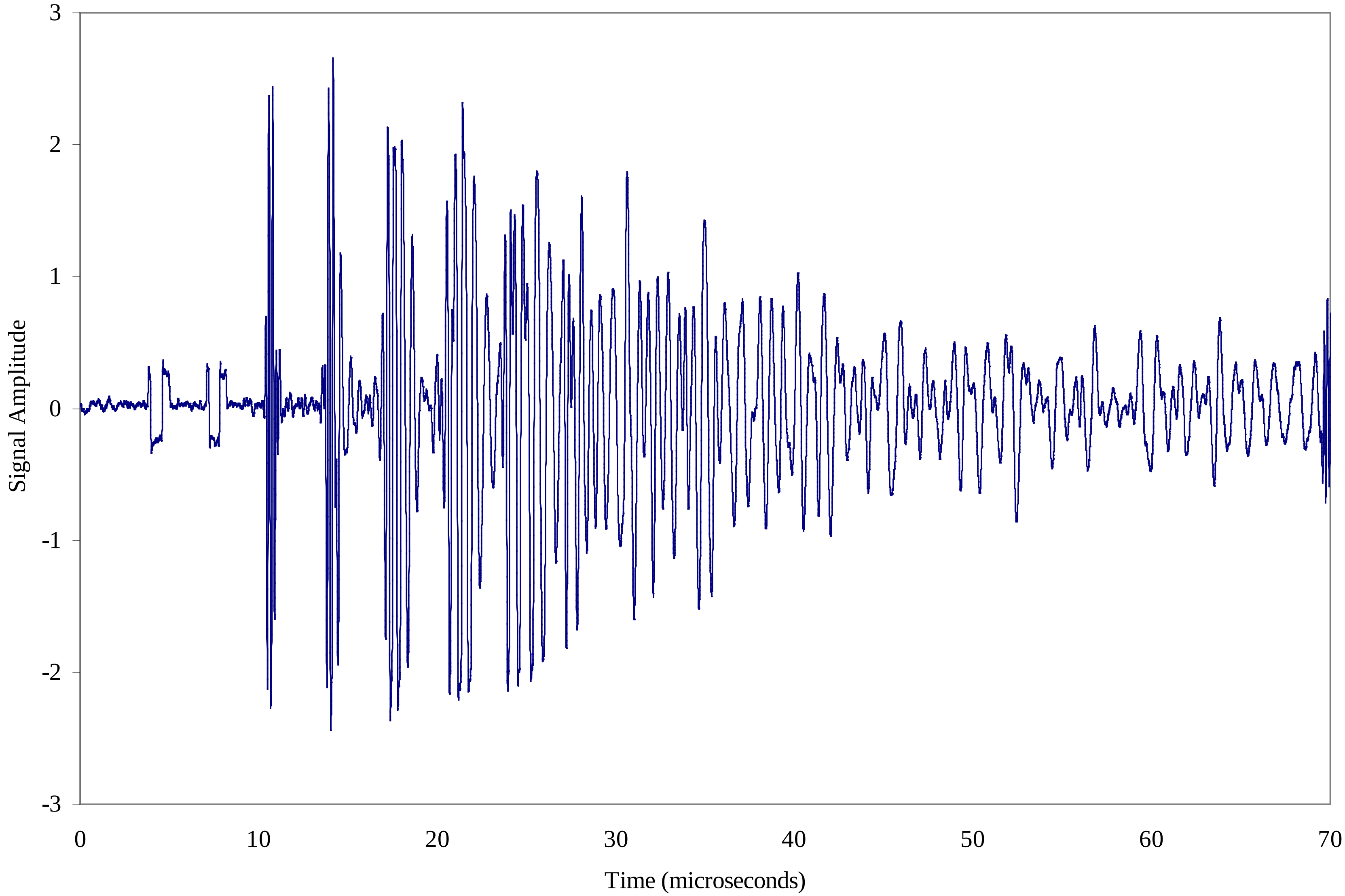

Figure A.10- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt E1 tested with 5 MHz probe frequency.

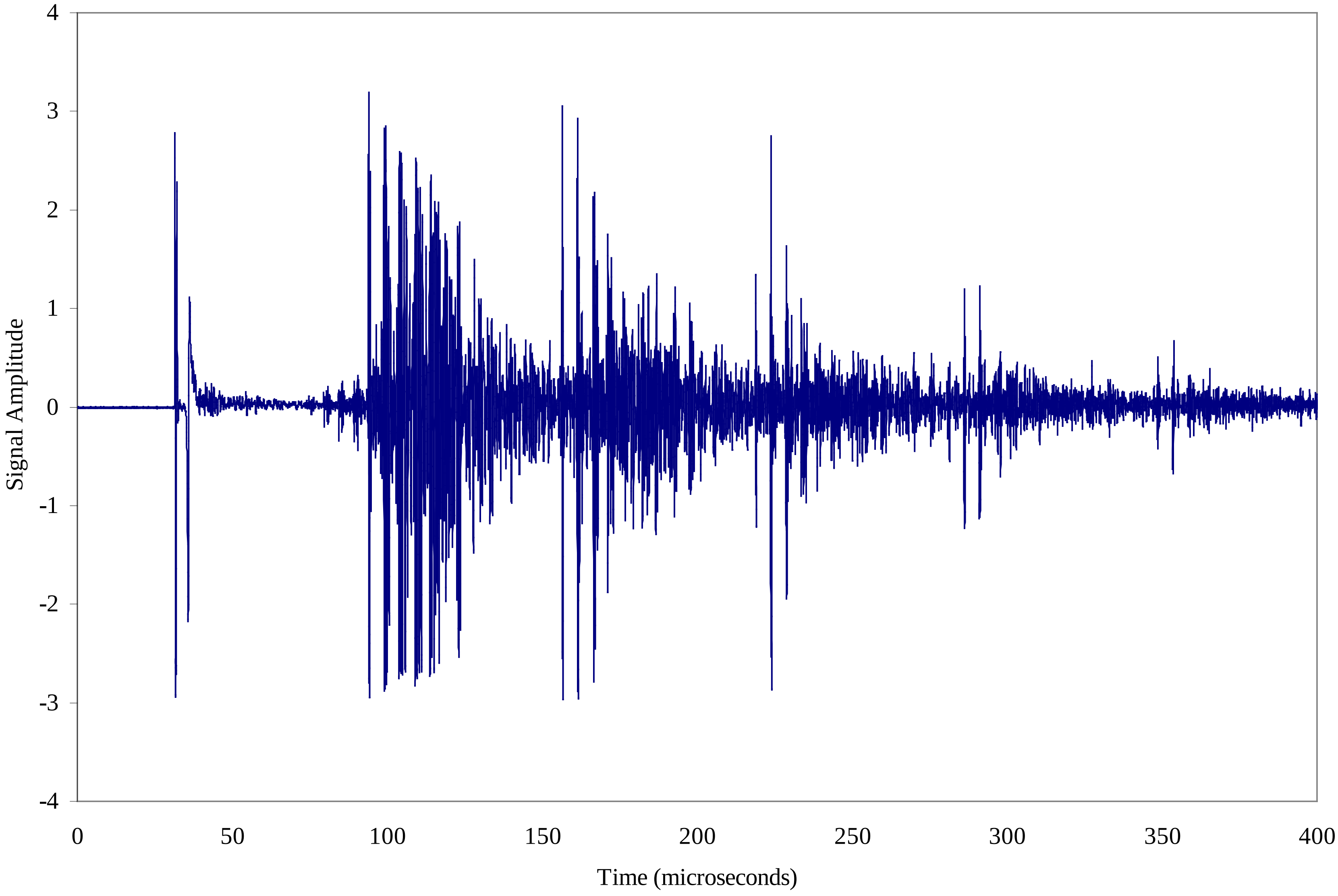

Figure A.11- Full time domain signal for ultrasonic pulse-echo inspection of bolt F1 tested with 5 MHz probe frequency.

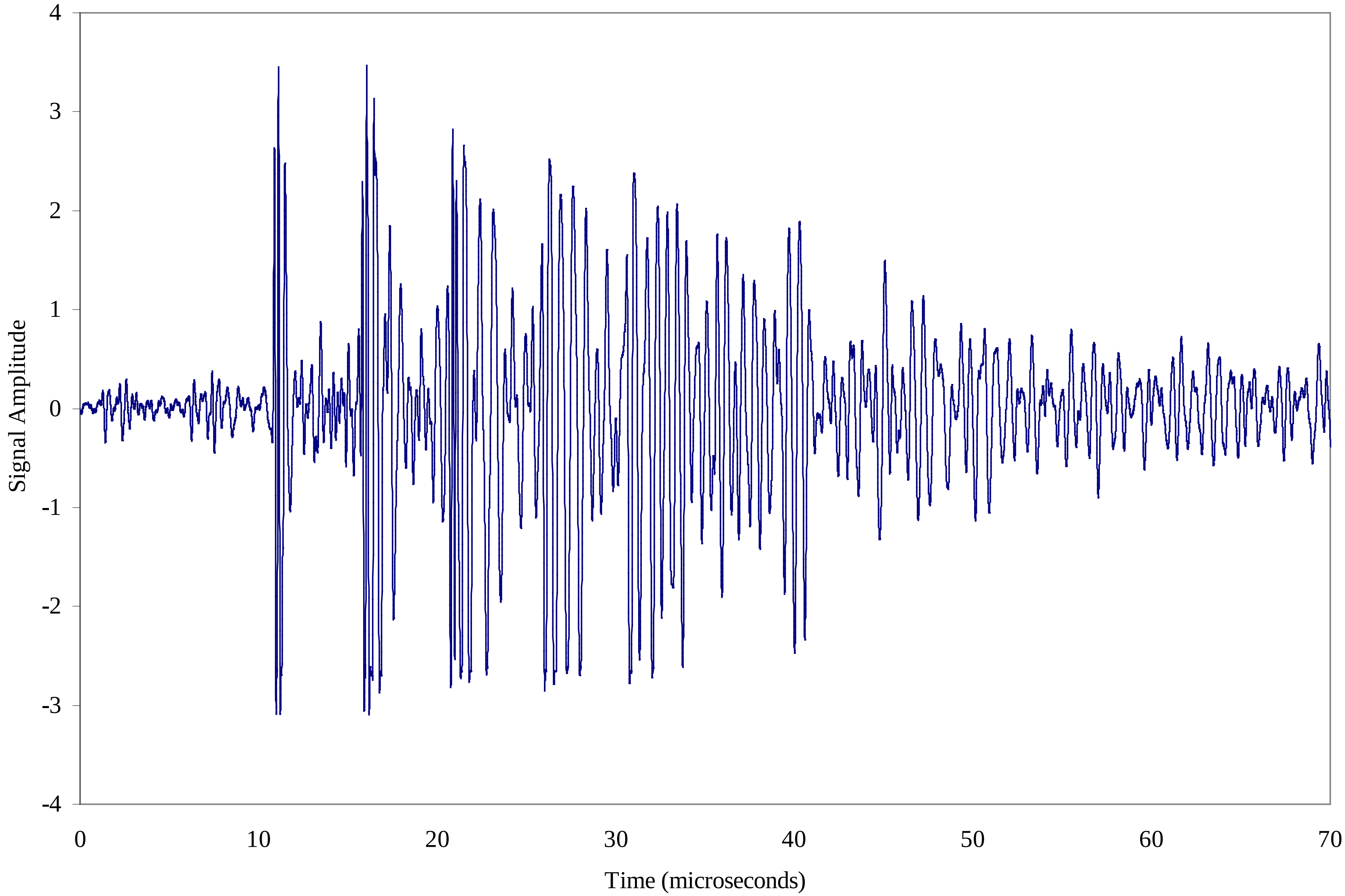

Figure A.12- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt F1 tested with 5 MHz probe frequency.

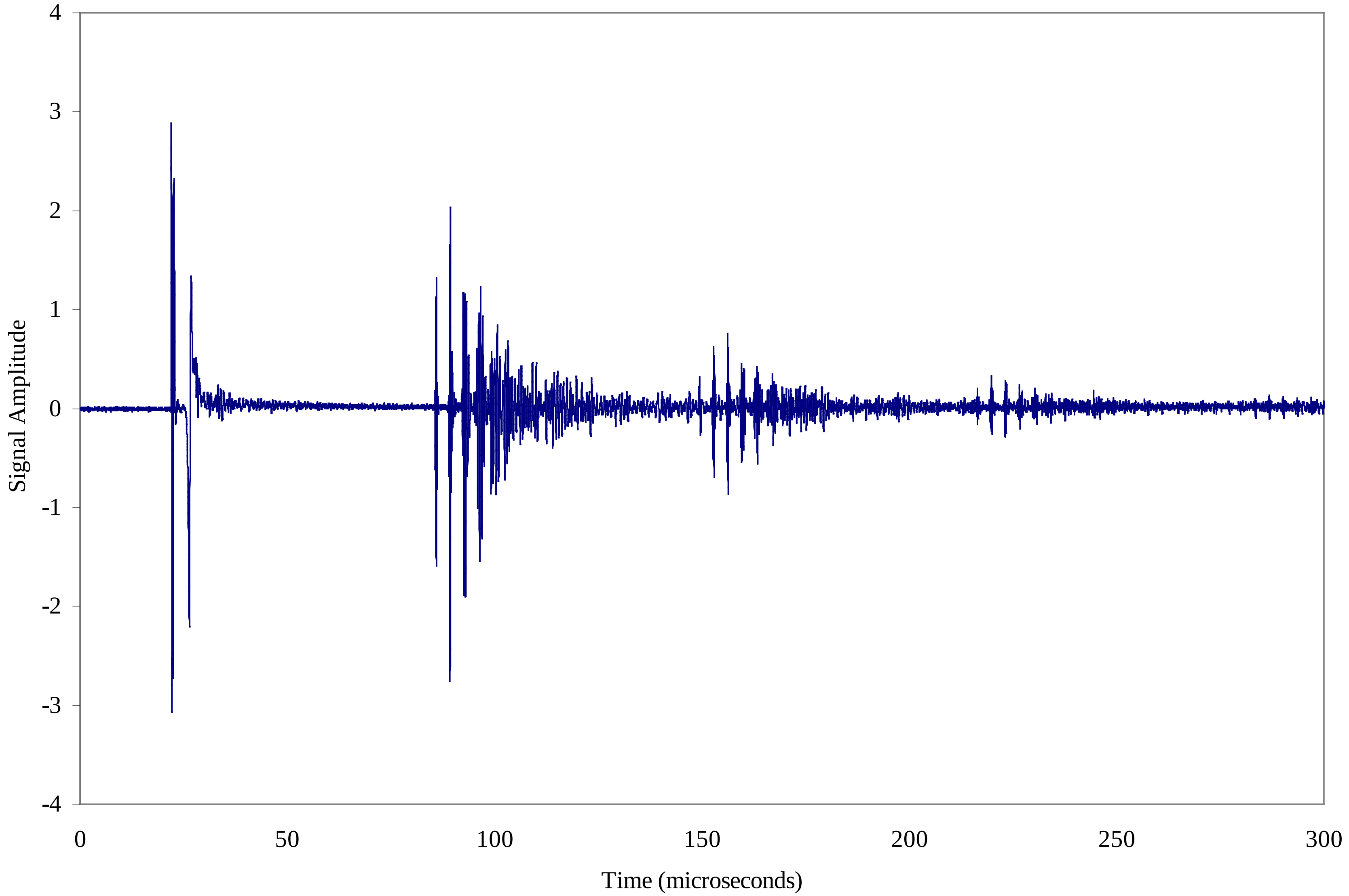

Figure A.13- Full time domain signal for ultrasonic pulse-echo inspection of bolt G1 tested with 5 MHz probe frequency.

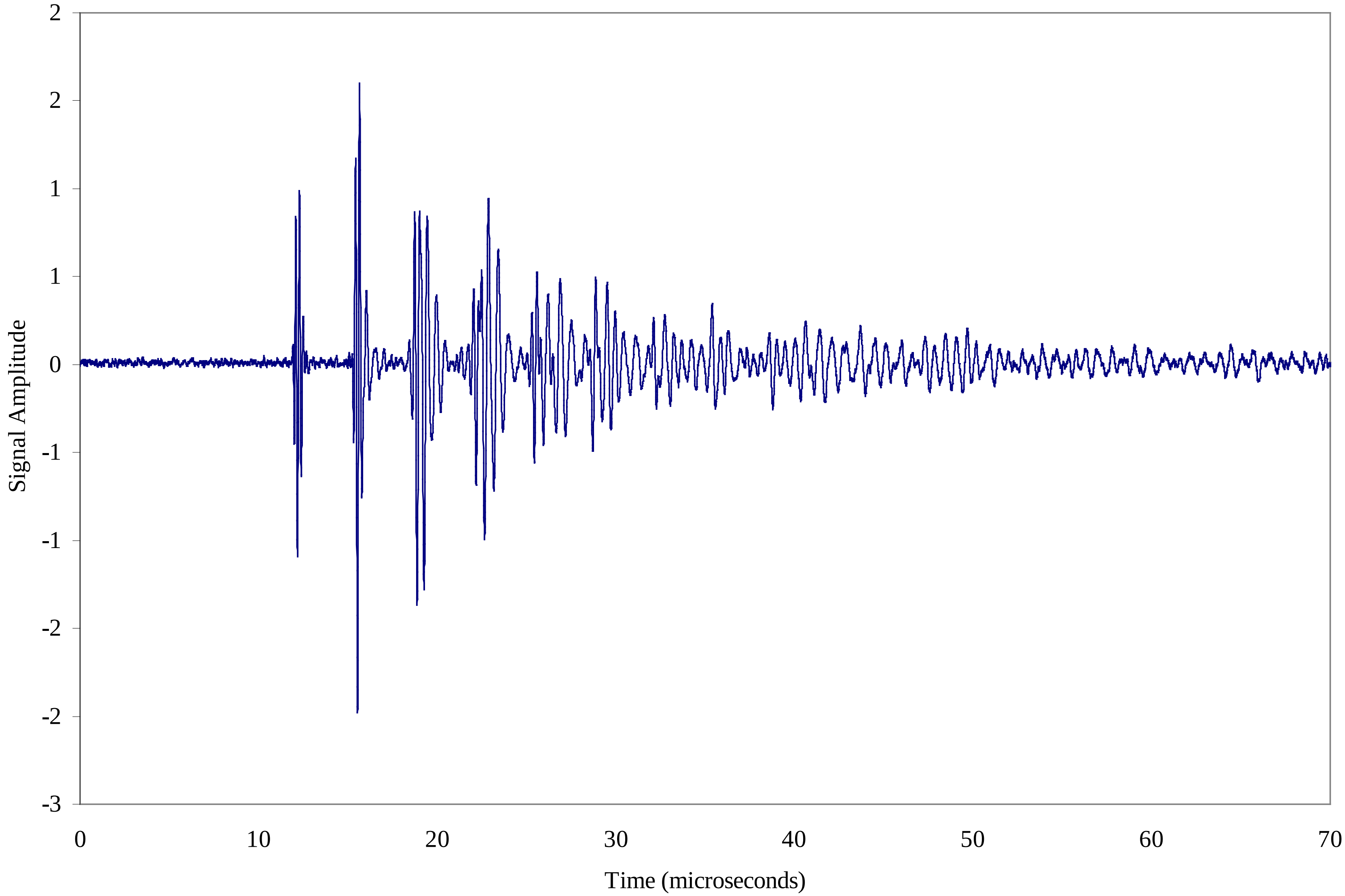

Figure A.14- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt G1 tested with 5 MHz probe frequency.

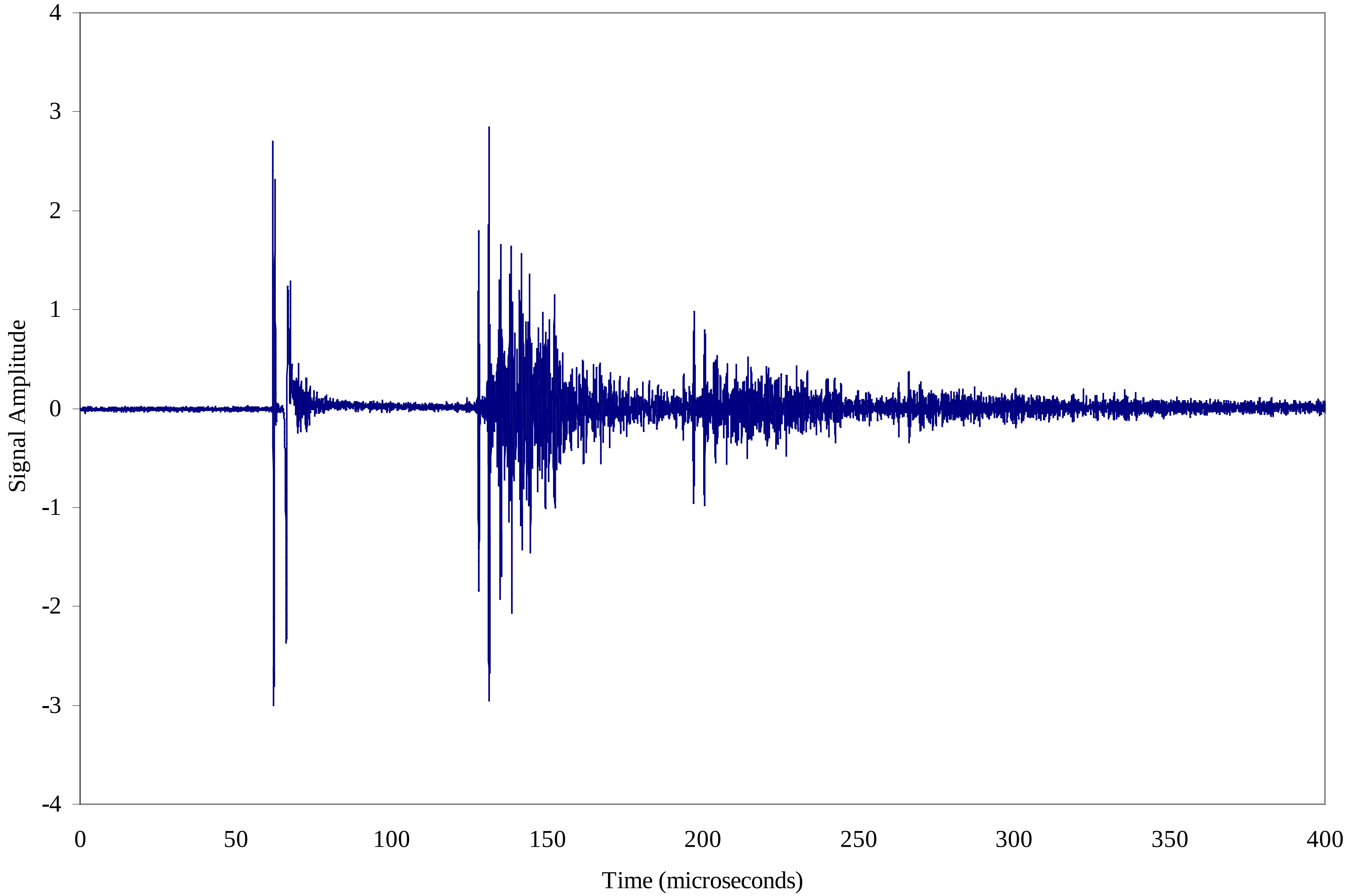

Figure A.15- Full time domain signal for ultrasonic pulse-echo inspection of bolt H1 tested with 5 MHz probe frequency.

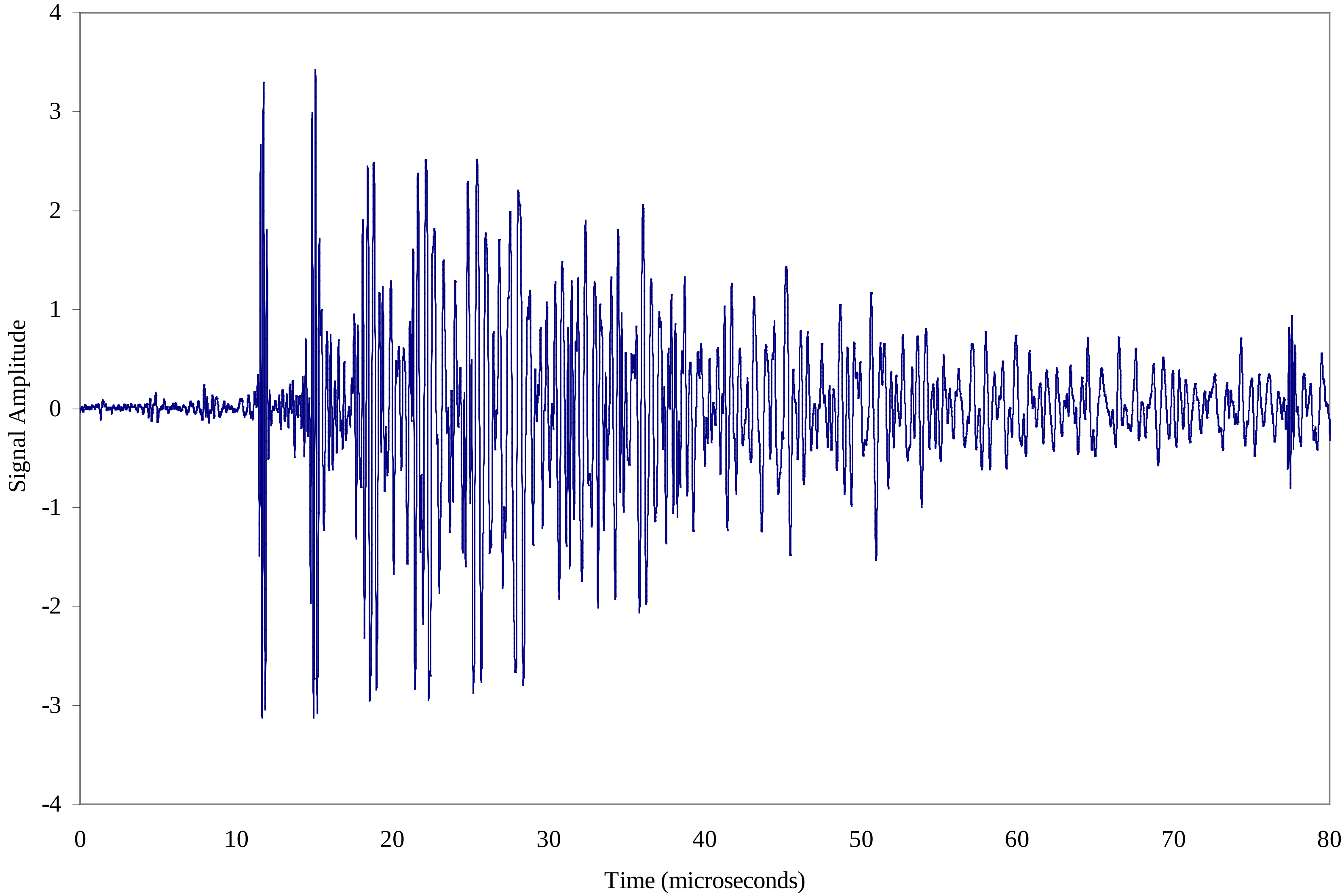

Figure A.16- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt H1 tested with 5 MHz probe frequency.

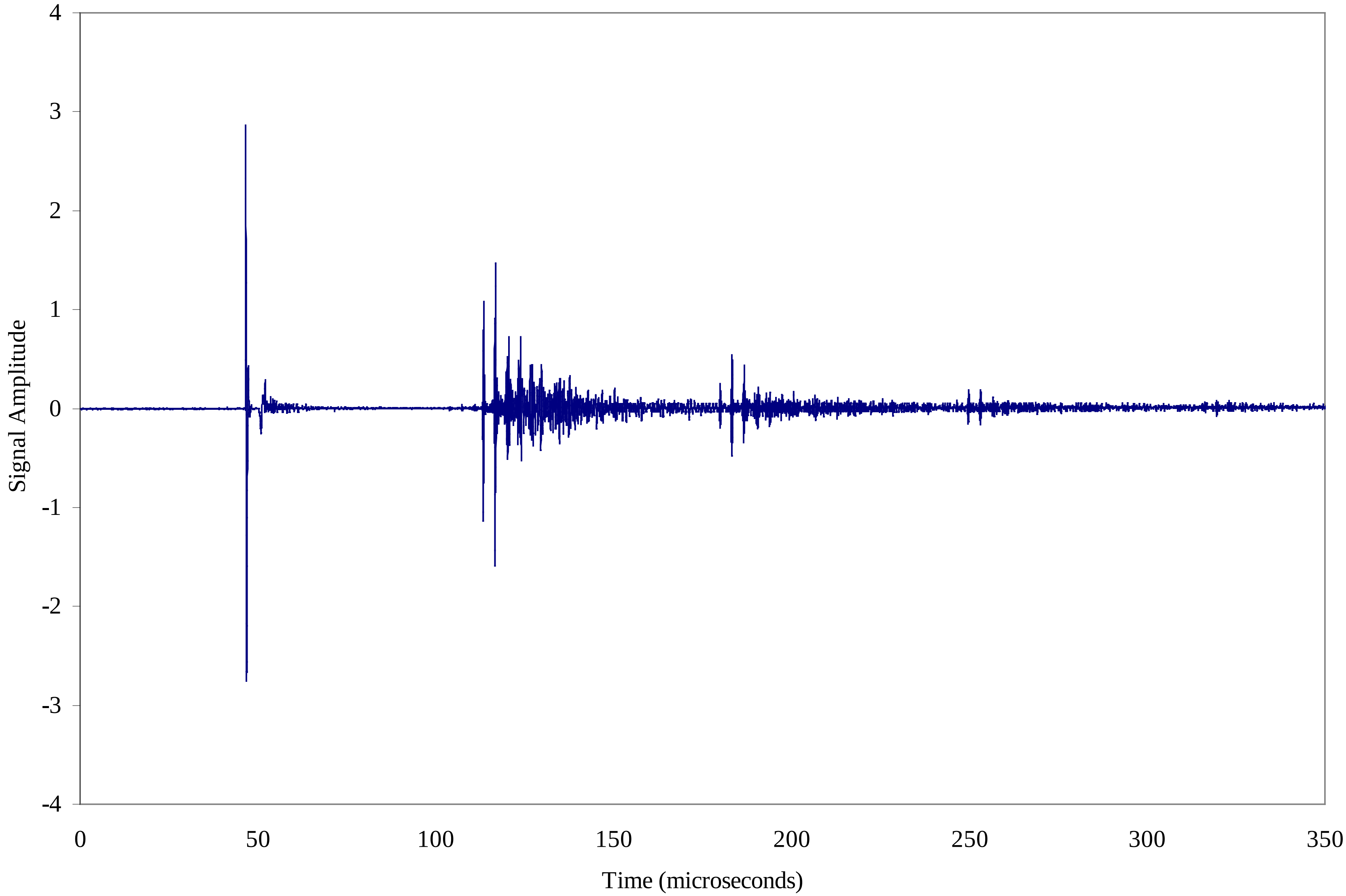

Figure A.17- Full time domain signal for ultrasonic pulse-echo inspection of bolt I1 tested with 5 MHz probe frequency.

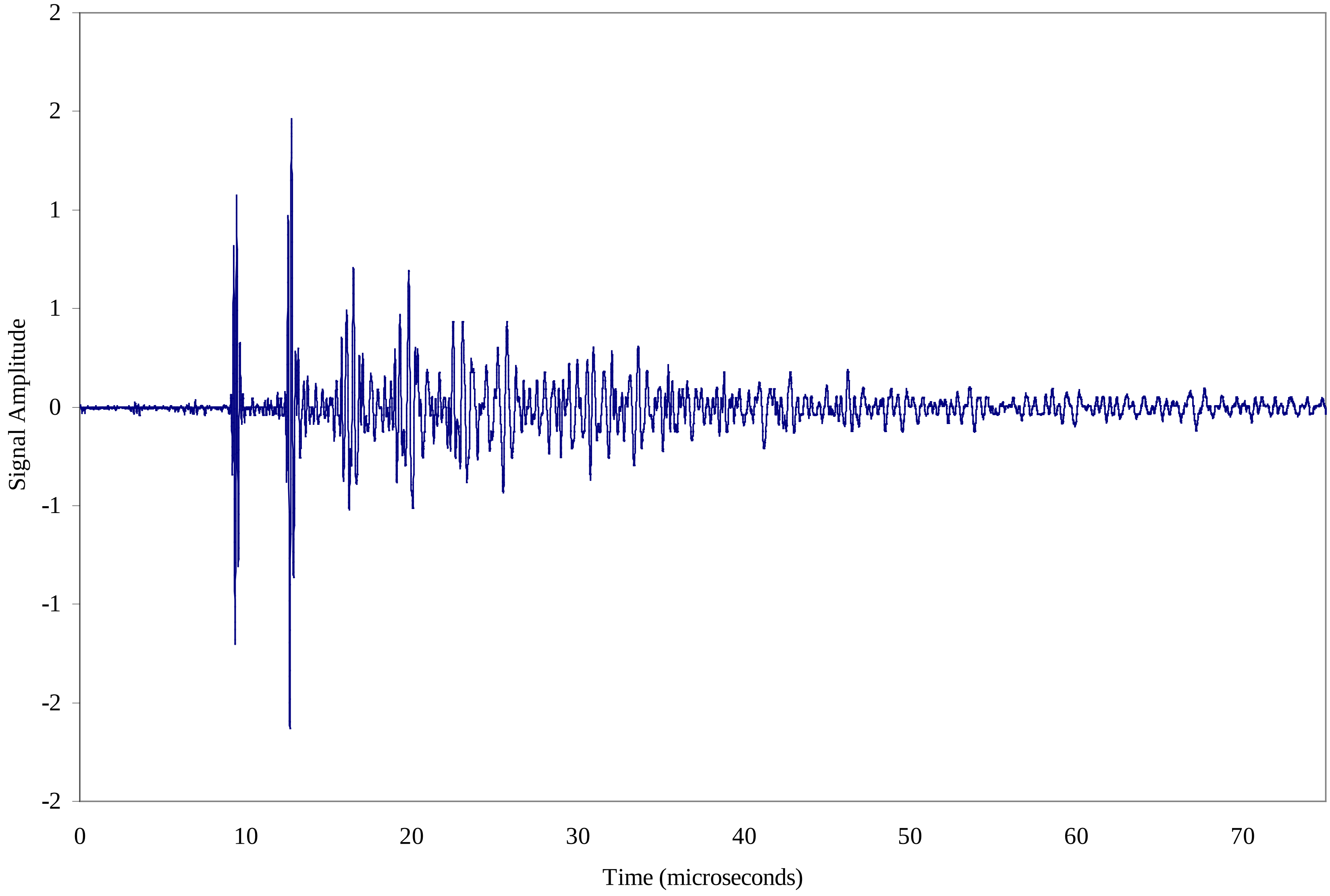

Figure A.18- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt I1 tested with 5 MHz probe frequency.

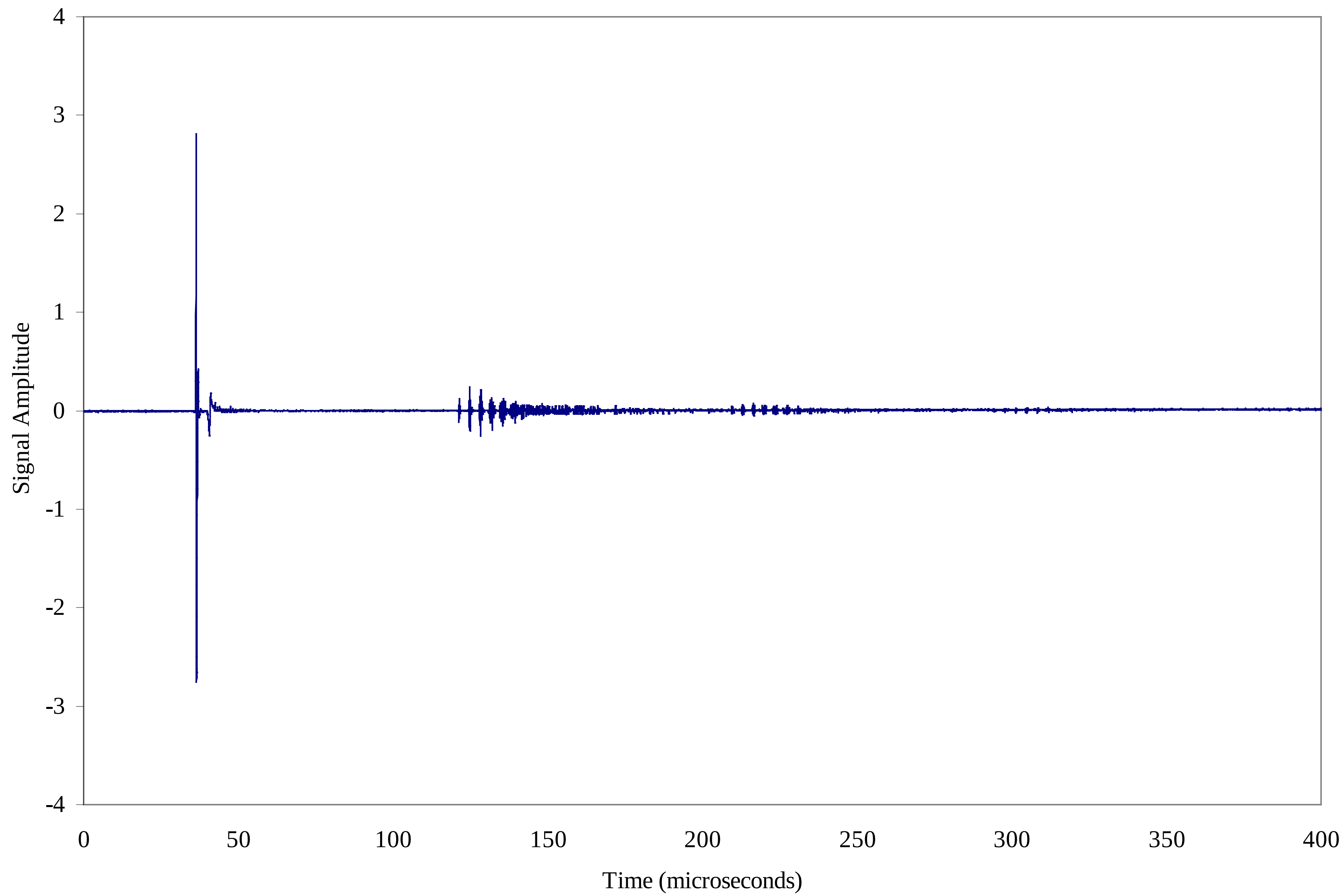

Figure A.19- Full time domain signal for ultrasonic pulse-echo inspection of bolt J1 tested with 5 MHz probe frequency.

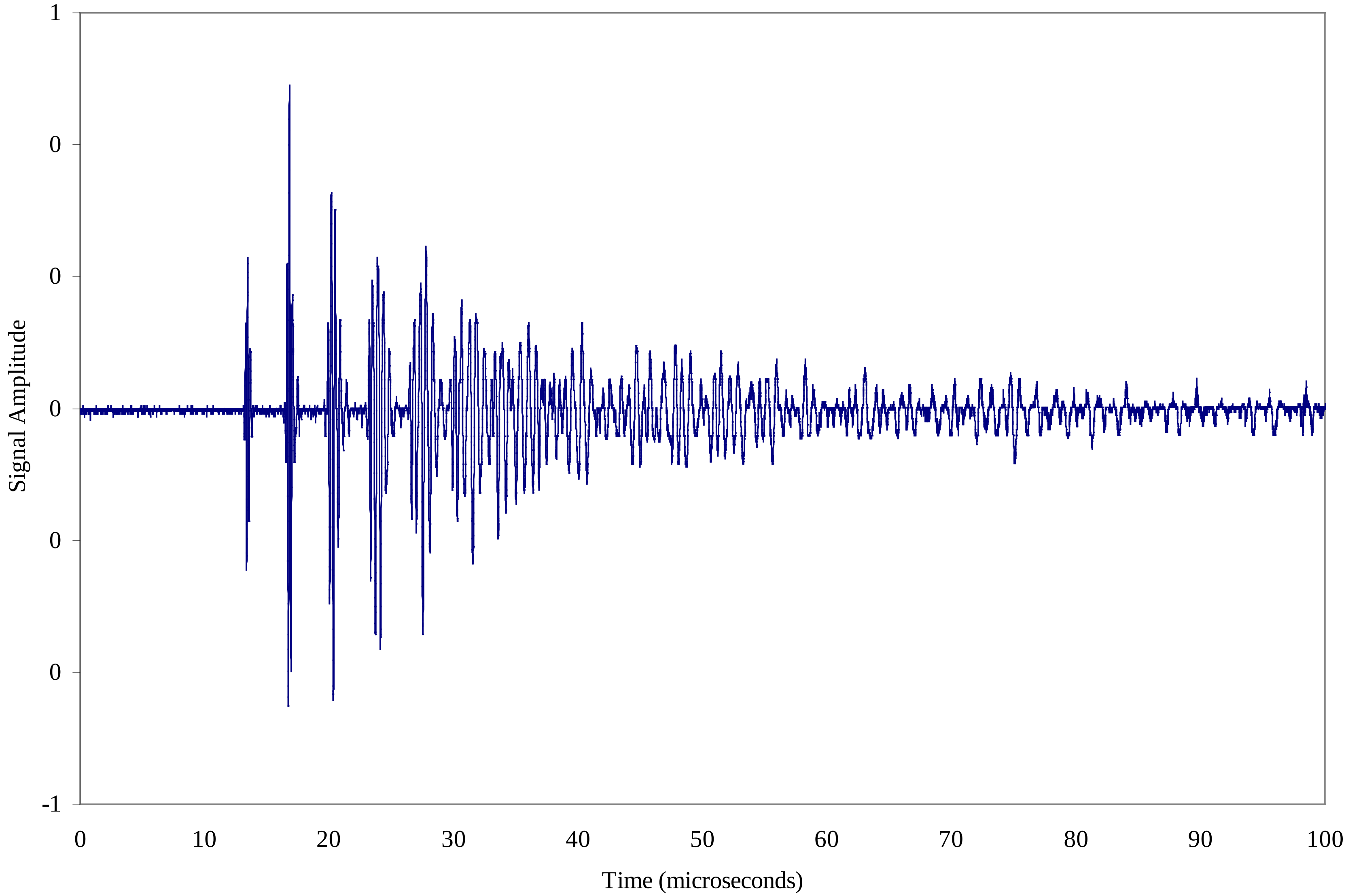

Figure A.20- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt J1 tested with 5 MHz probe frequency.

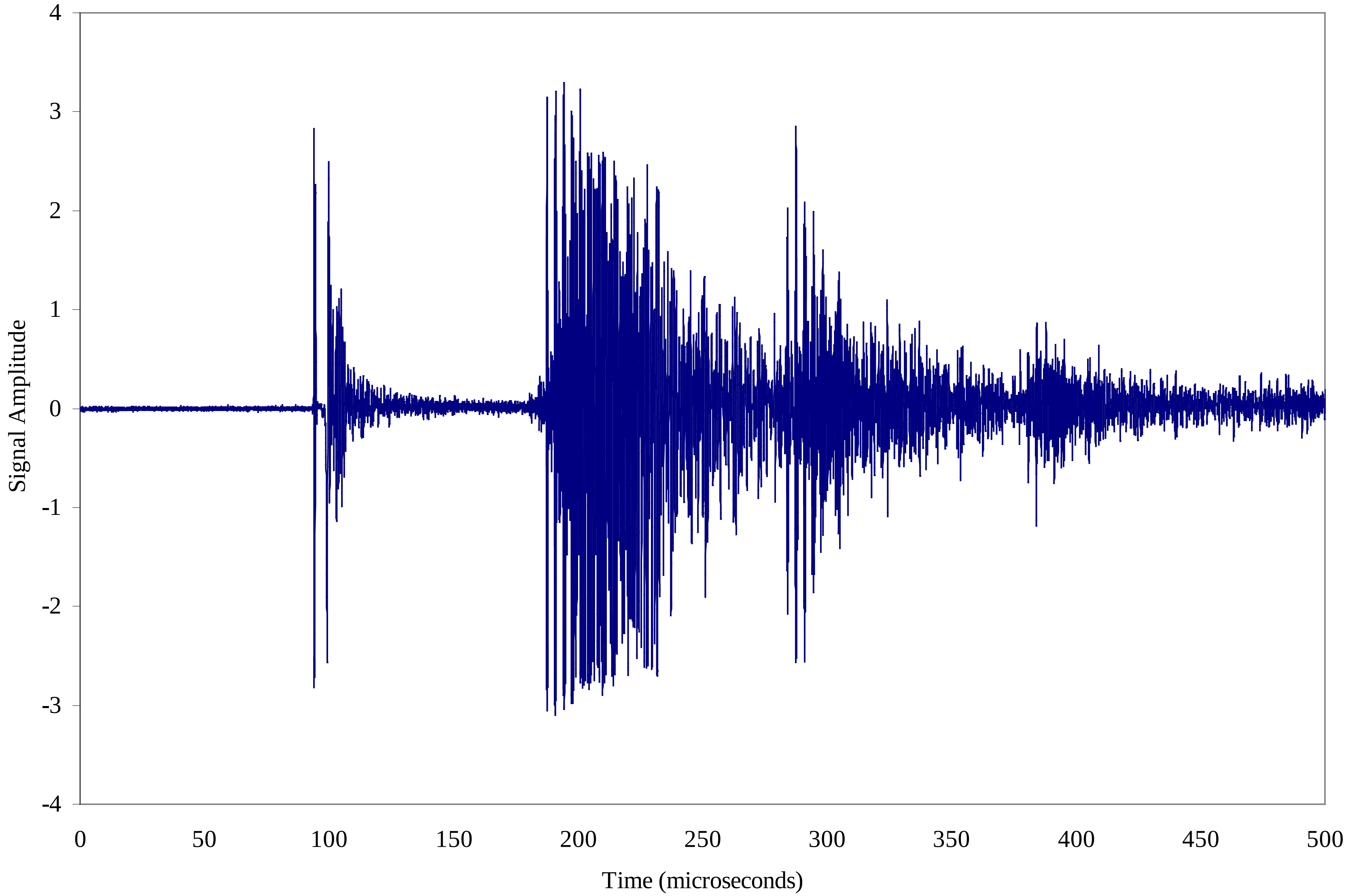

Figure A.21- Full time domain signal for ultrasonic pulse-echo inspection of bolt K1 tested with 5 MHz probe frequency.

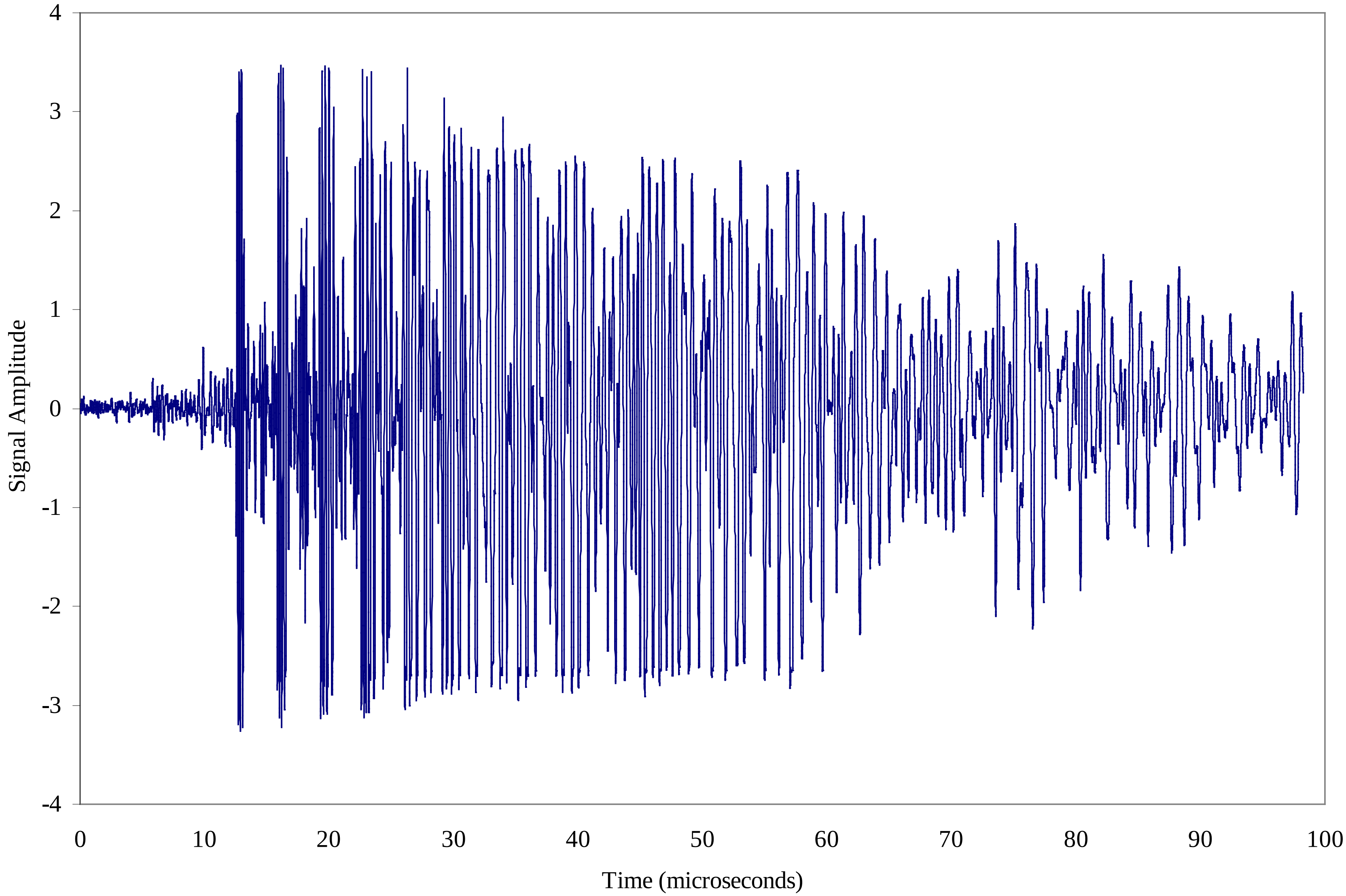

Figure A.22- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt K1 tested with 5 MHz probe frequency.

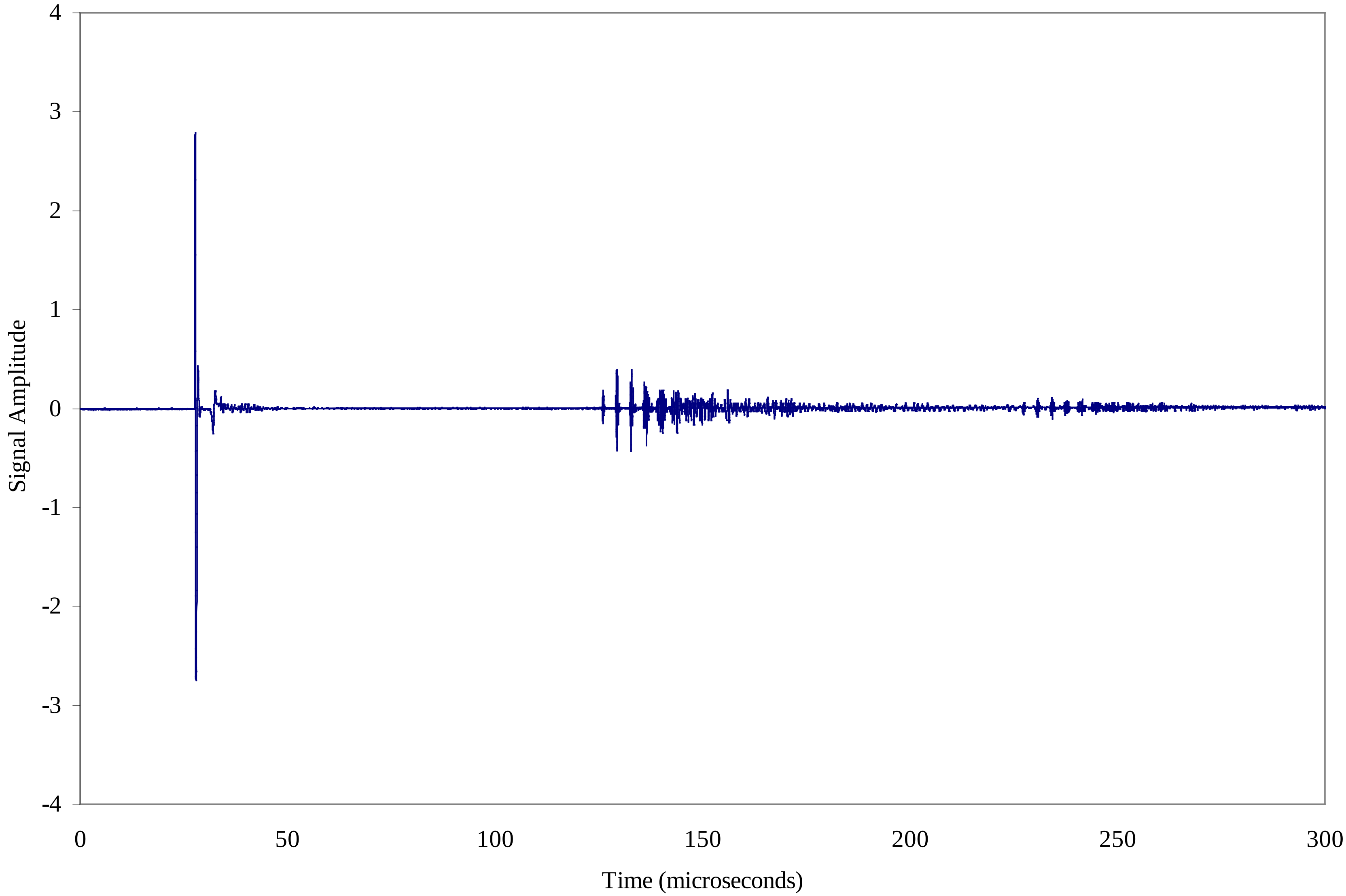

Figure A.23- Full time domain signal for ultrasonic pulse-echo inspection of bolt L1 tested with 5 MHz probe frequency.

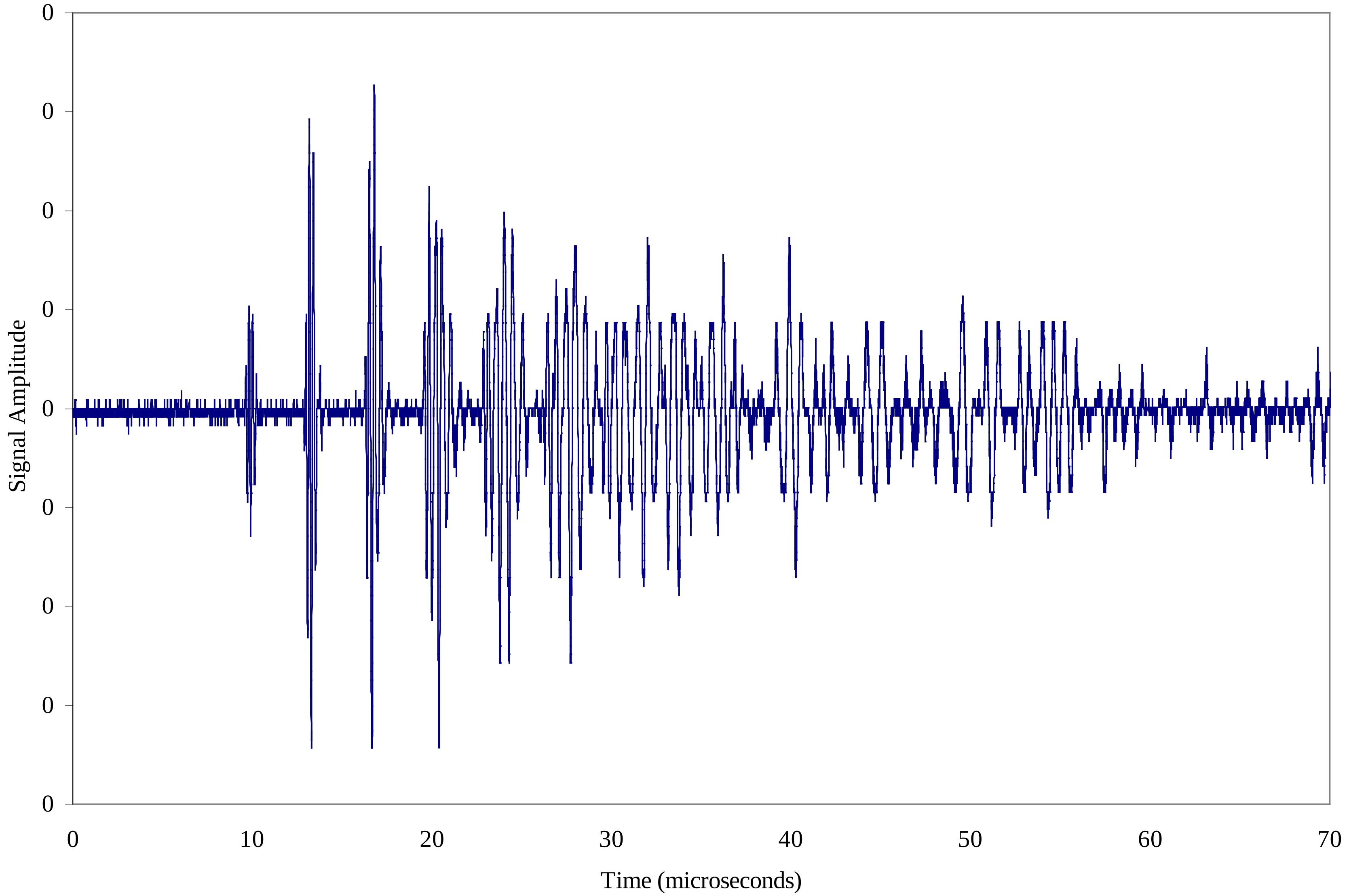

Figure A.24- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt L1 tested with 5 MHz probe frequency.

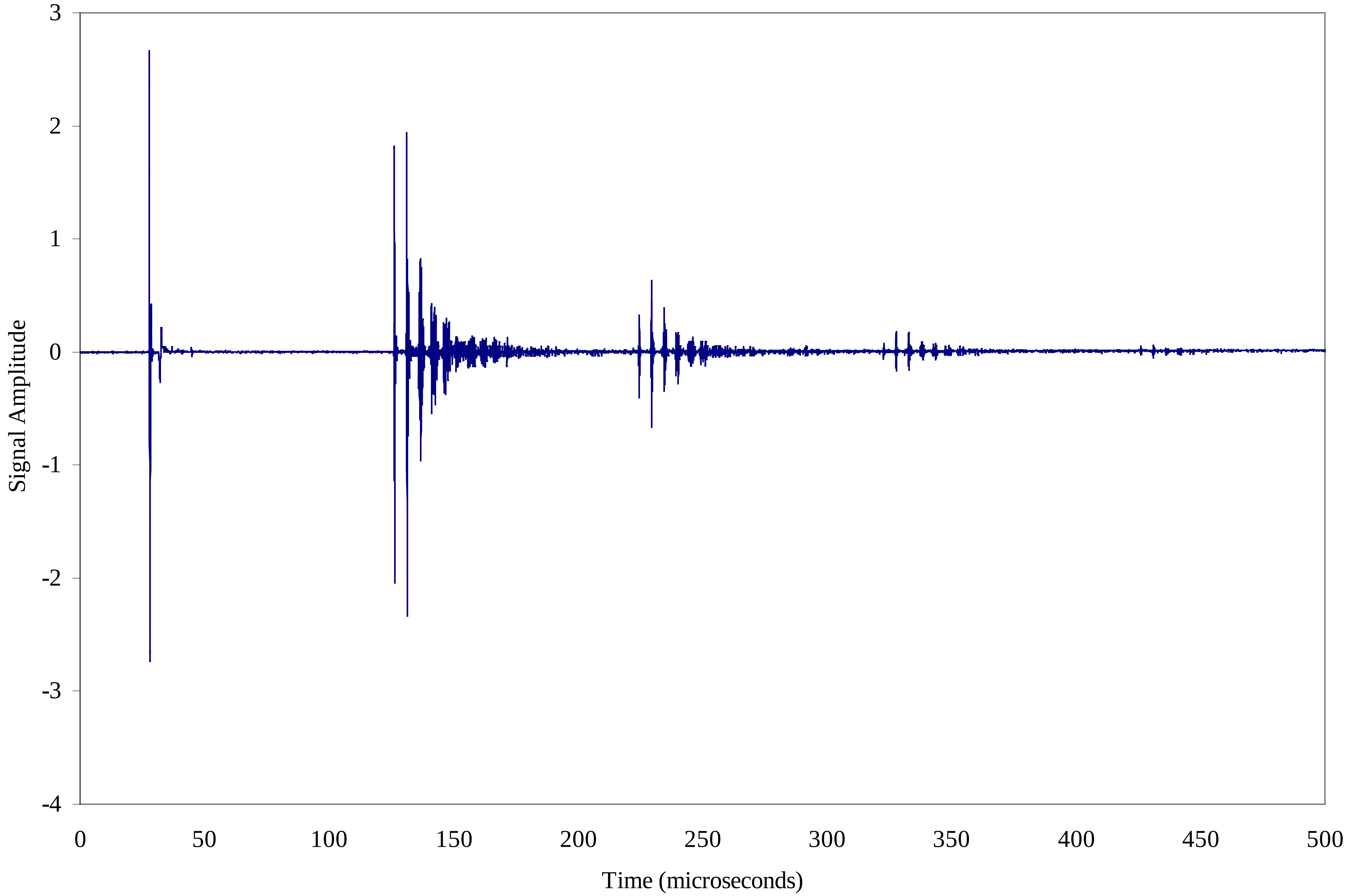

Figure A.25- Full time domain signal for ultrasonic pulse-echo inspection of bolt M1 tested with 5 MHz probe frequency.

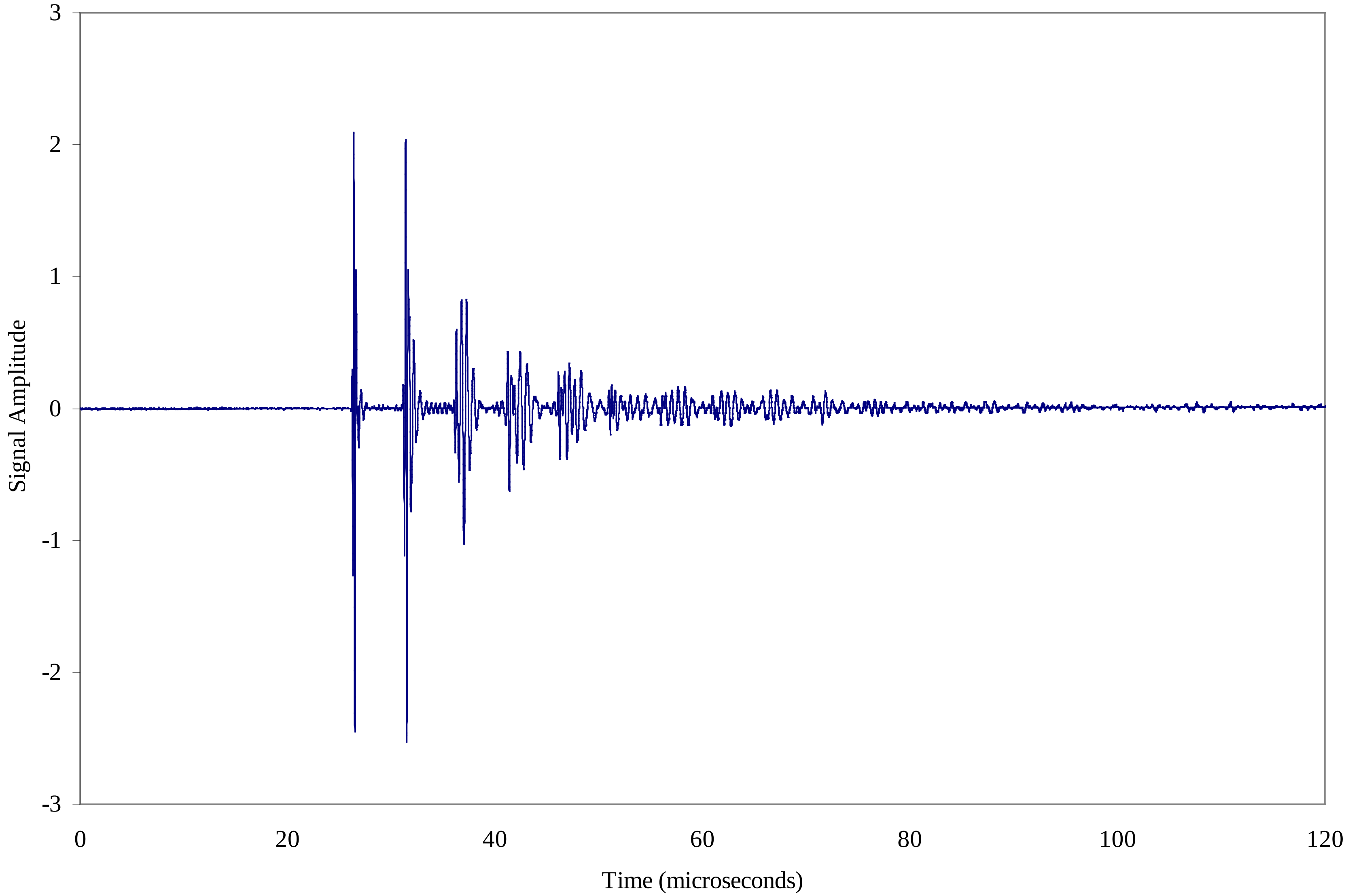

Figure A.26- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt M1 tested with 5 MHz probe frequency.

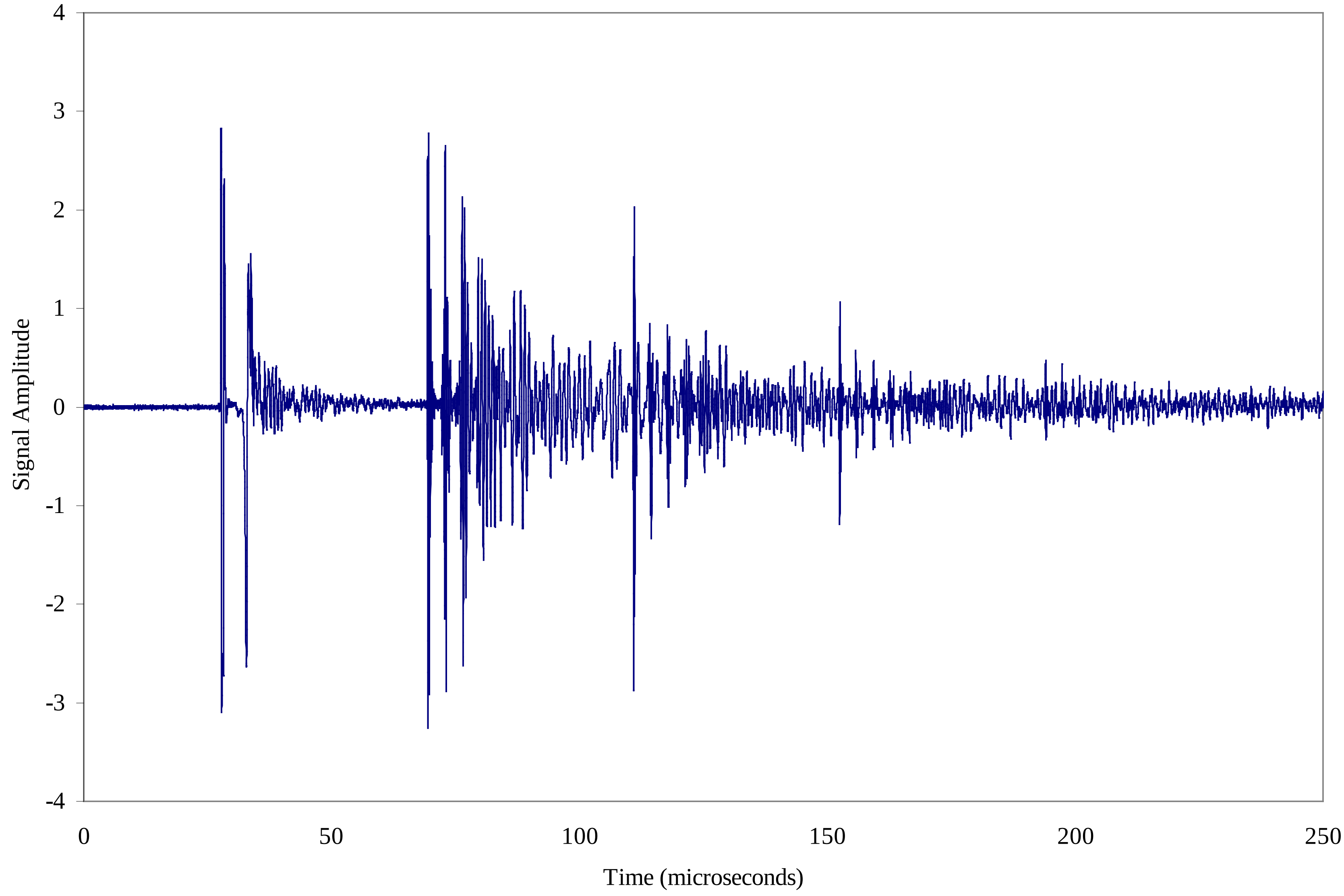

Figure A.27- Full time domain signal for ultrasonic pulse-echo inspection of bolt A1 tested with 10 MHz probe frequency.

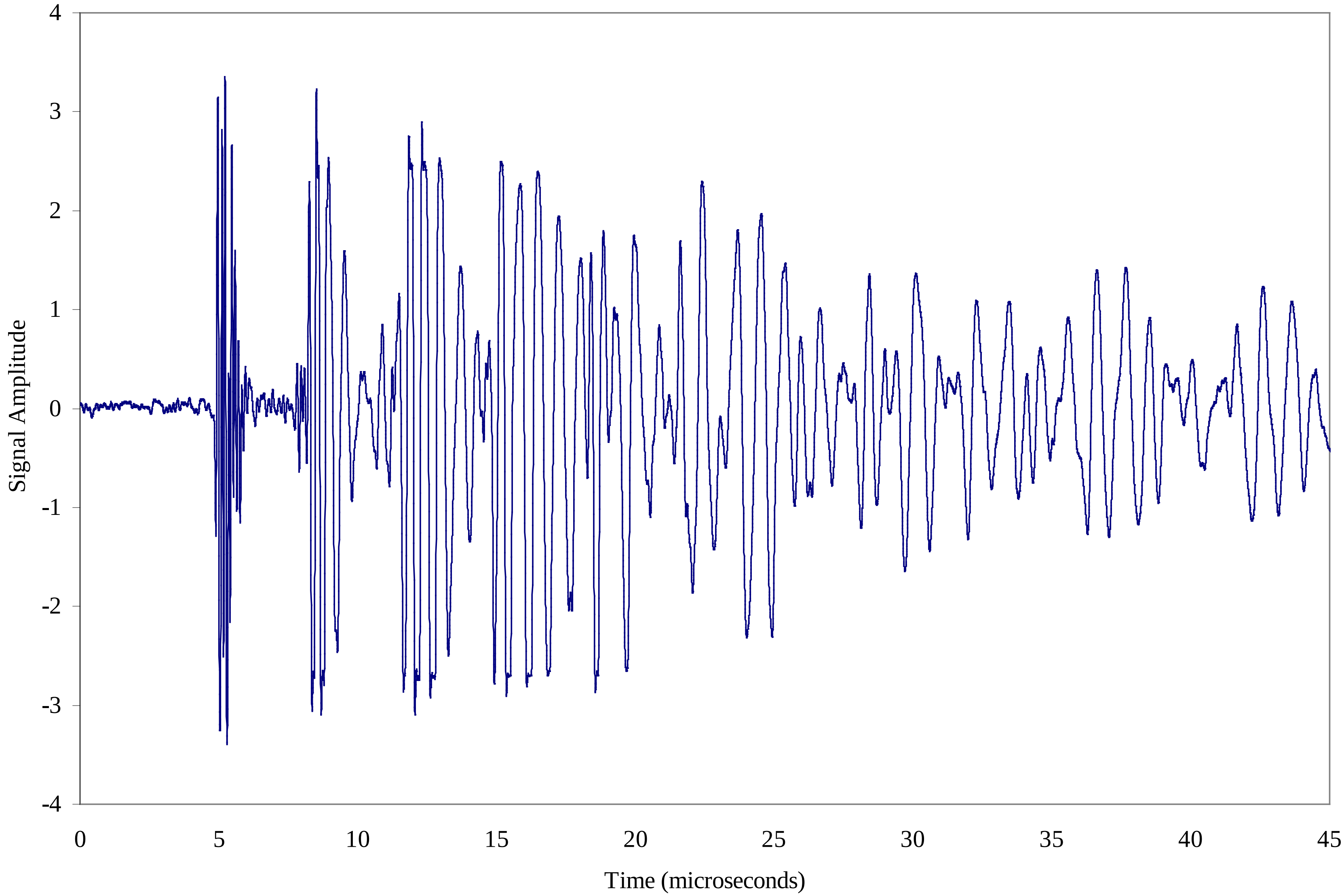

Figure A.28- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt A1 tested with 10 MHz probe frequency.

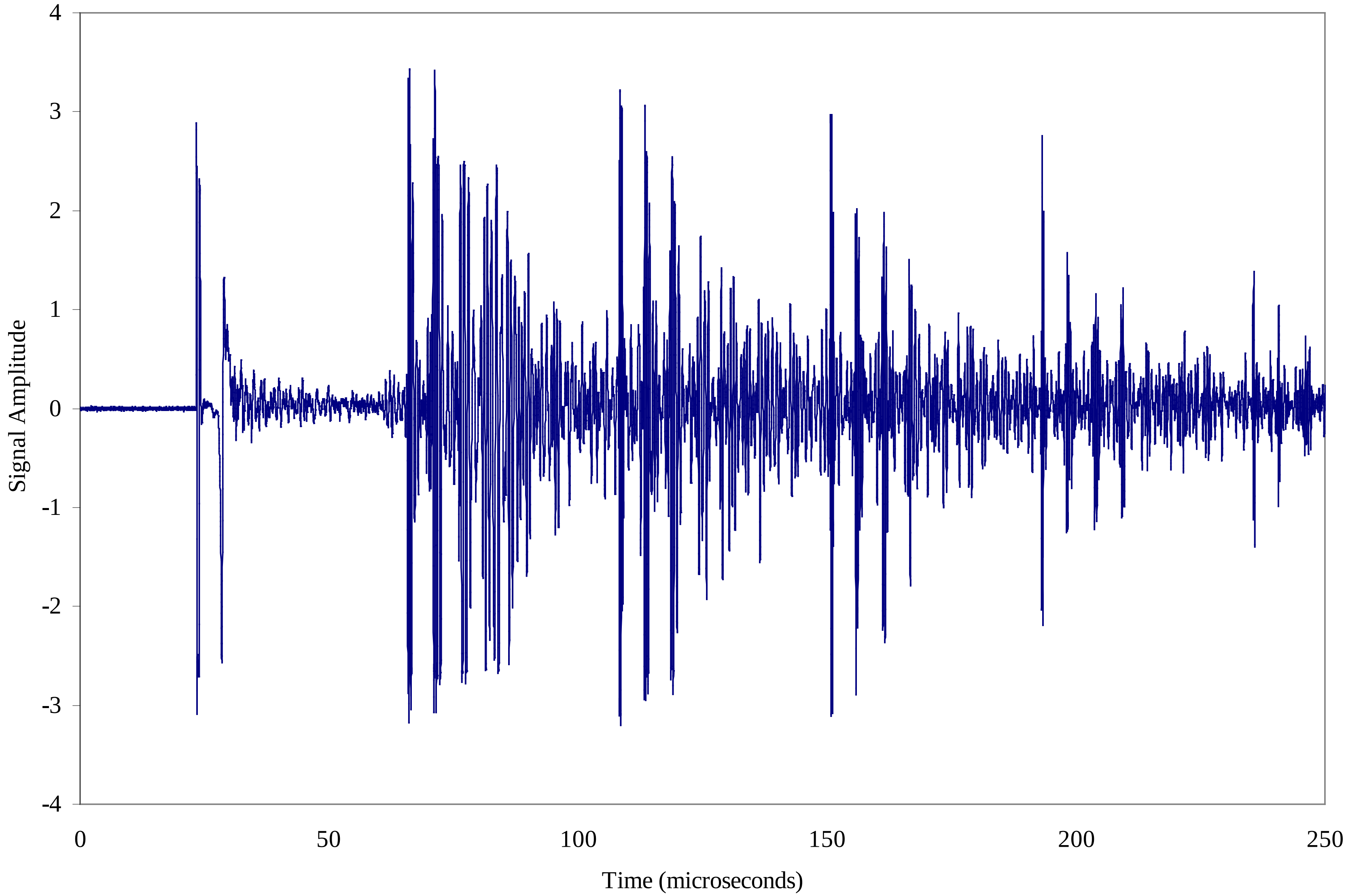

Figure A.29- Full time domain signal for ultrasonic pulse-echo inspection of bolt B1 tested with 10 MHz probe frequency.

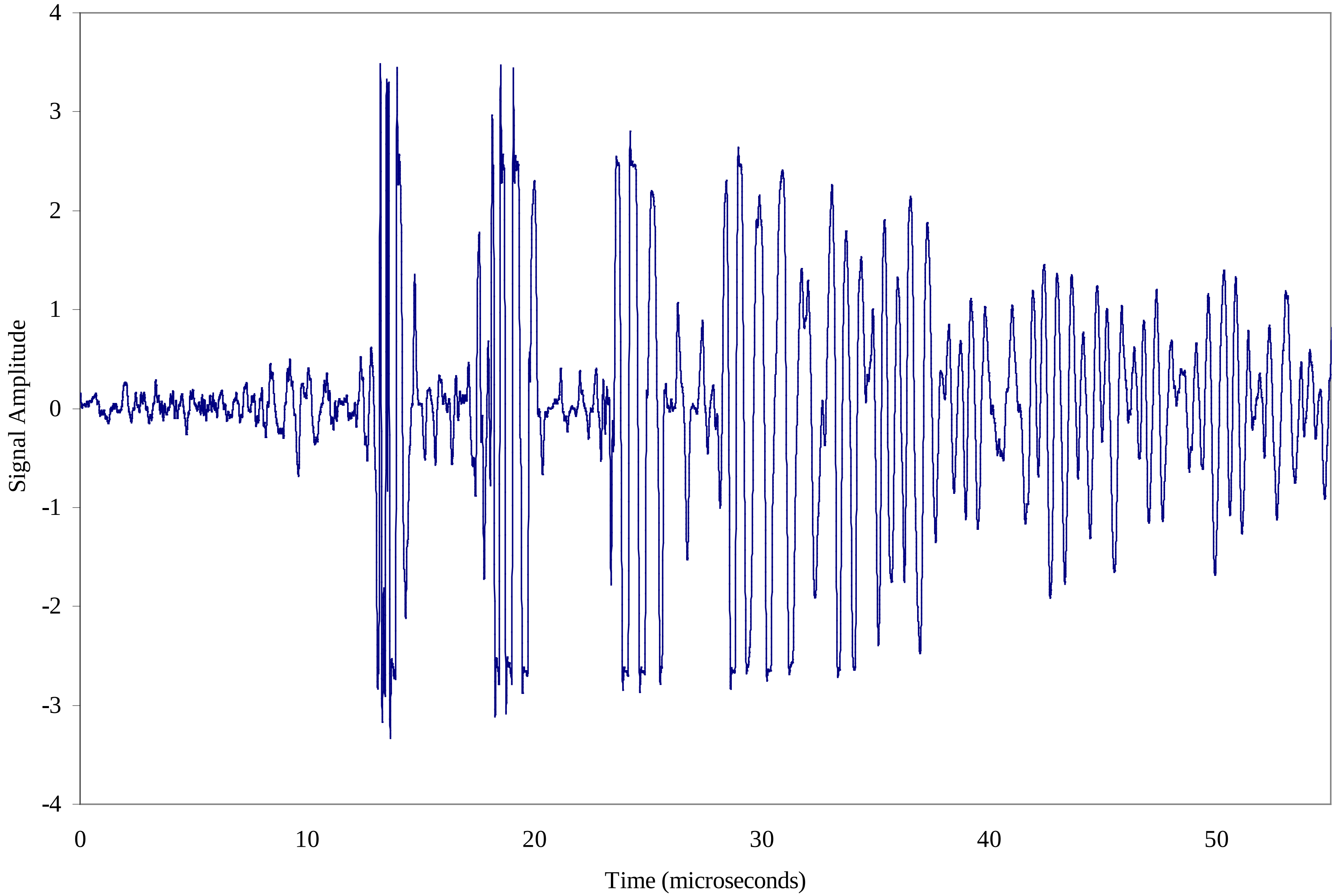

Figure A.30- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt B1 tested with 10 MHz probe frequency.

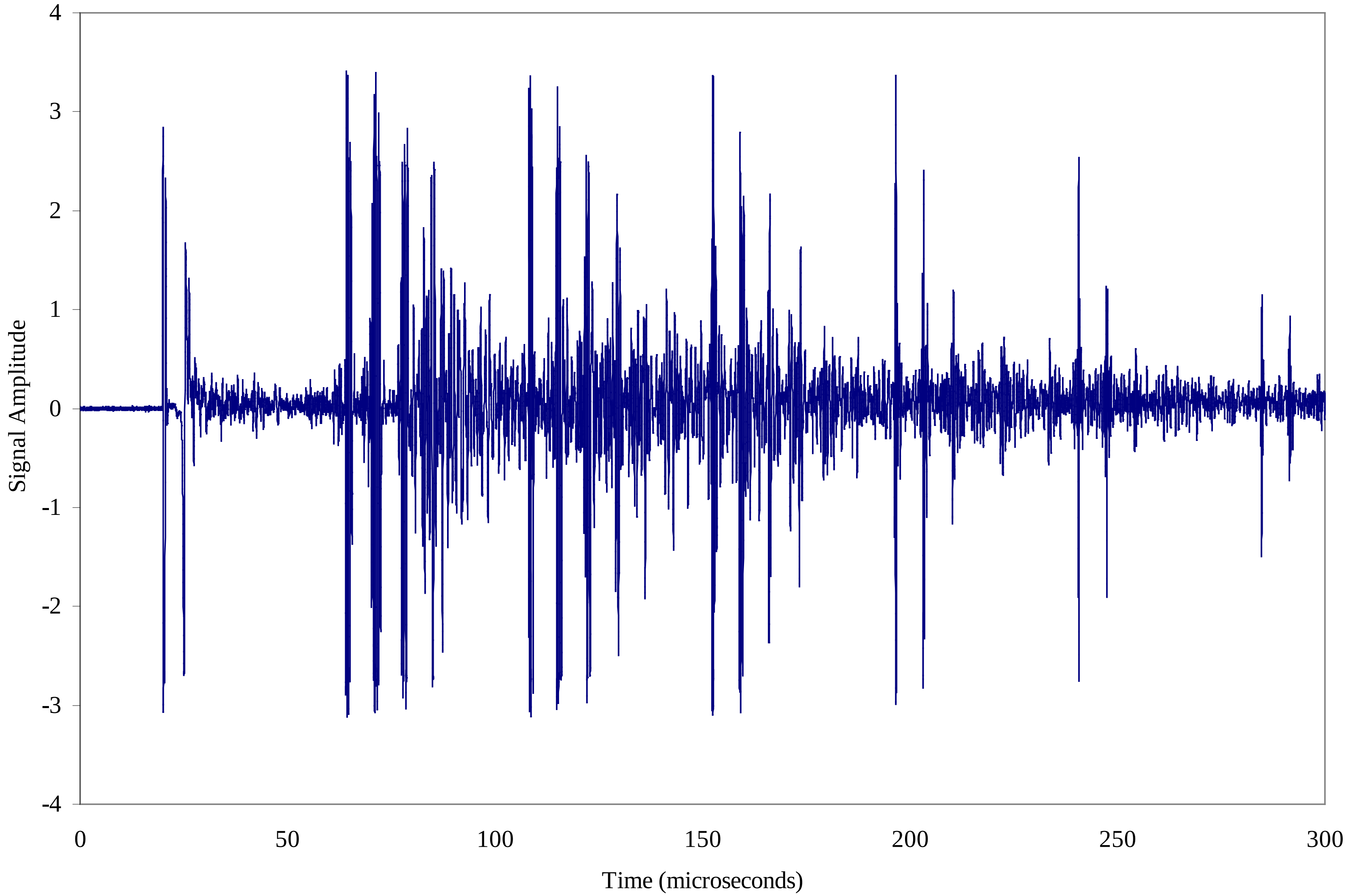

Figure A.31- Full time domain signal for ultrasonic pulse-echo inspection of bolt C1 tested with 10 MHz probe frequency.

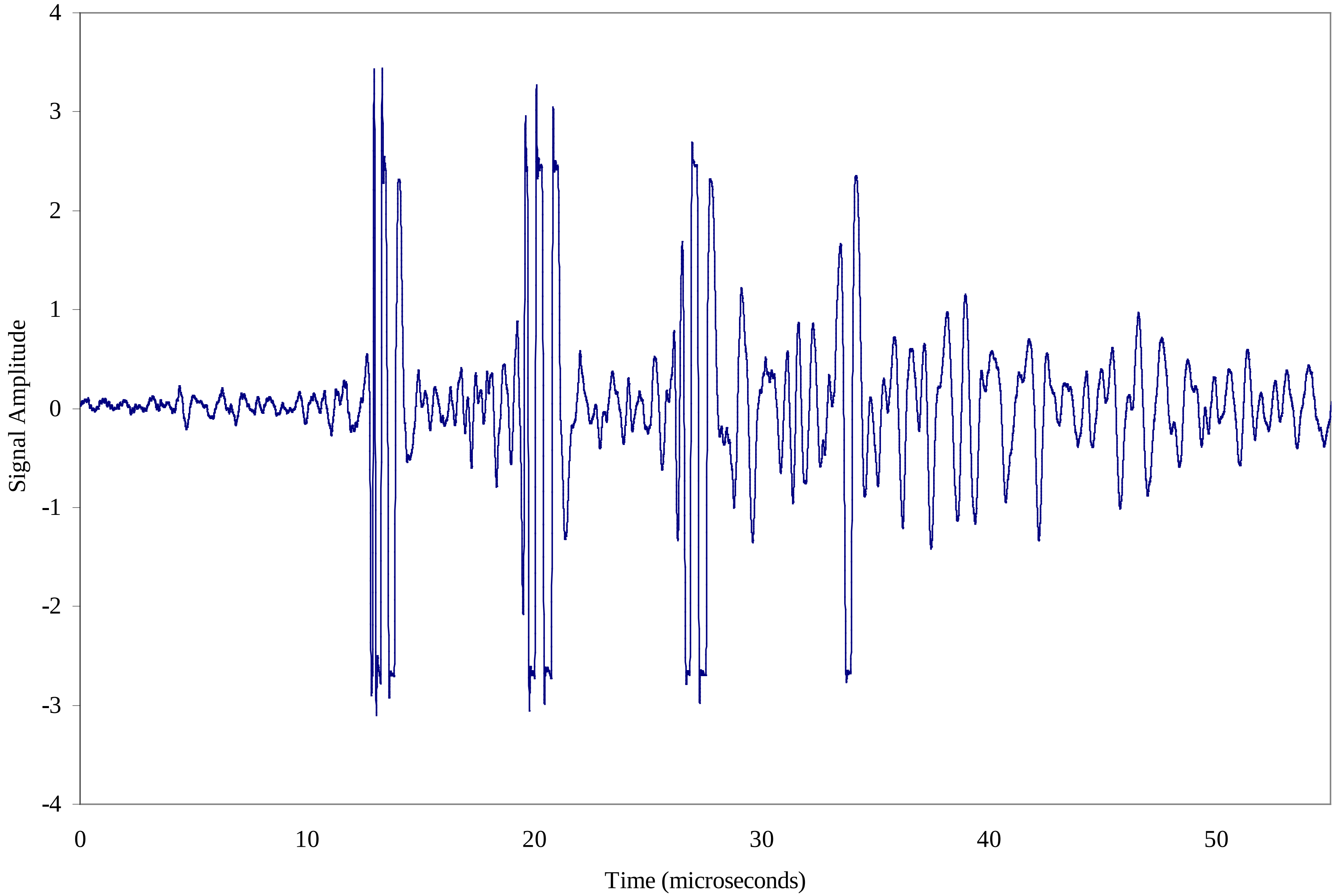

Figure A.32- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt C1 tested with 10 MHz probe frequency.

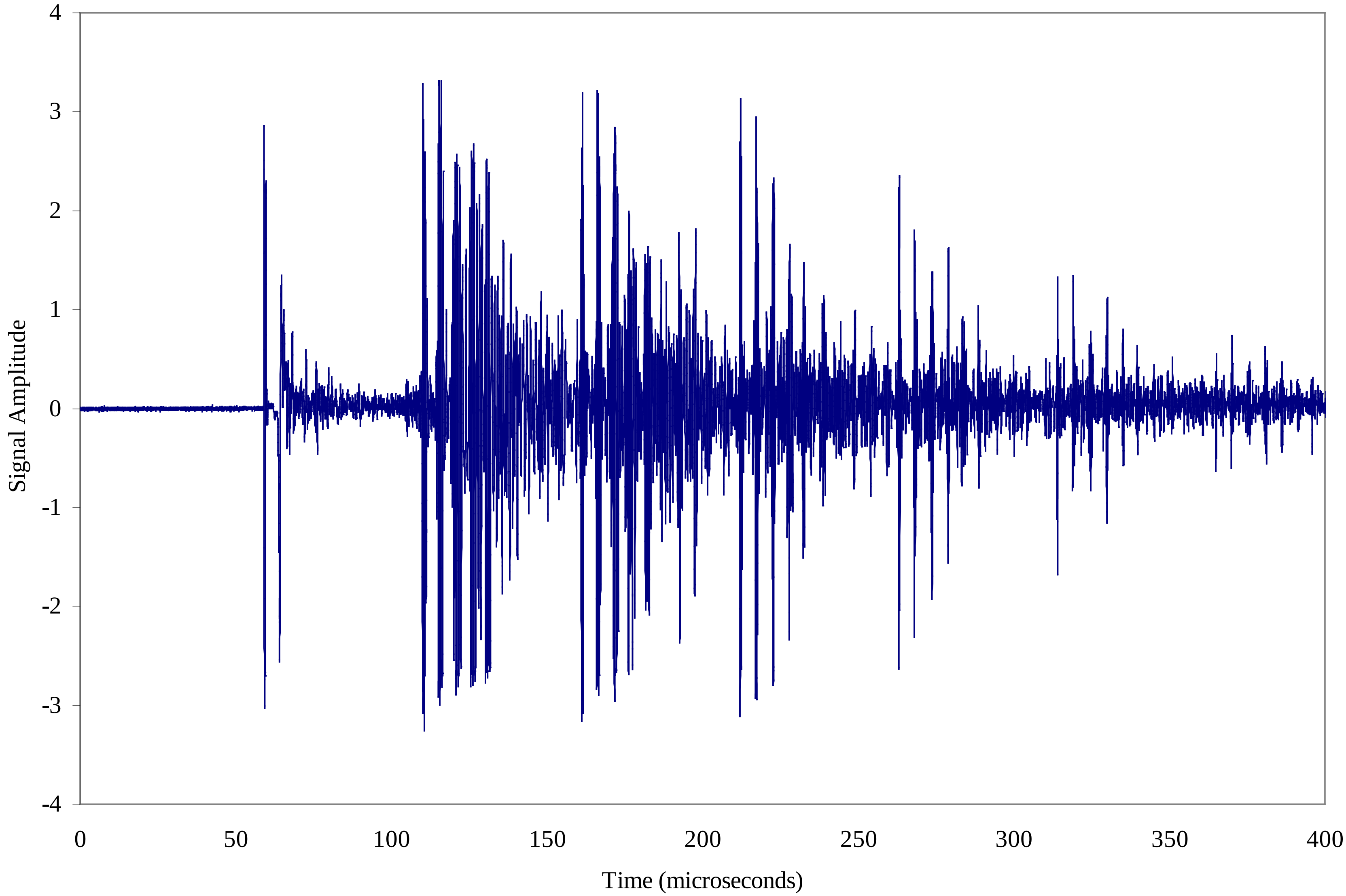

Figure A.33- Full time domain signal for ultrasonic pulse-echo inspection of bolt D1 tested with 10 MHz probe frequency.

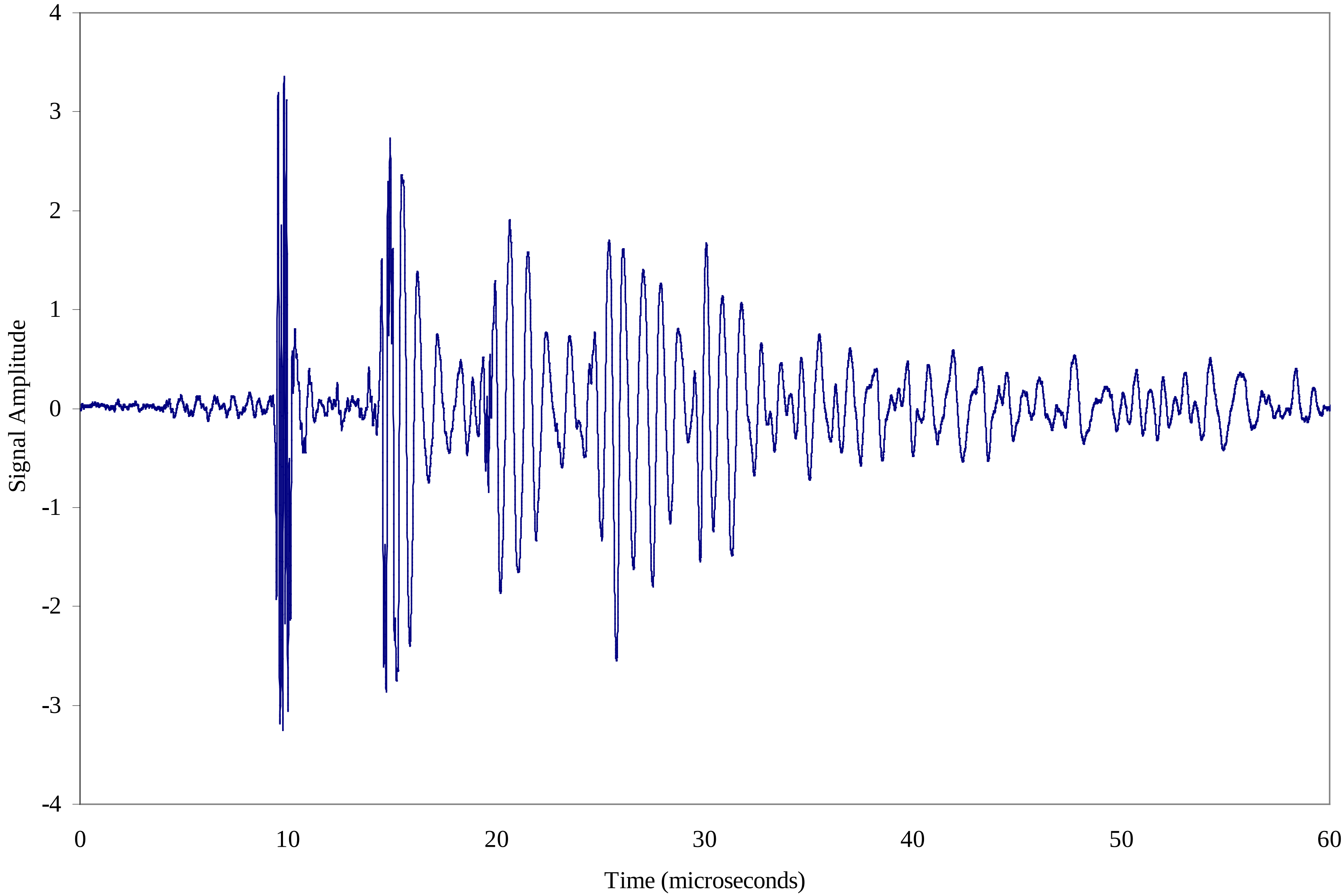

Figure A.34- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt D1 tested with 10 MHz probe frequency.

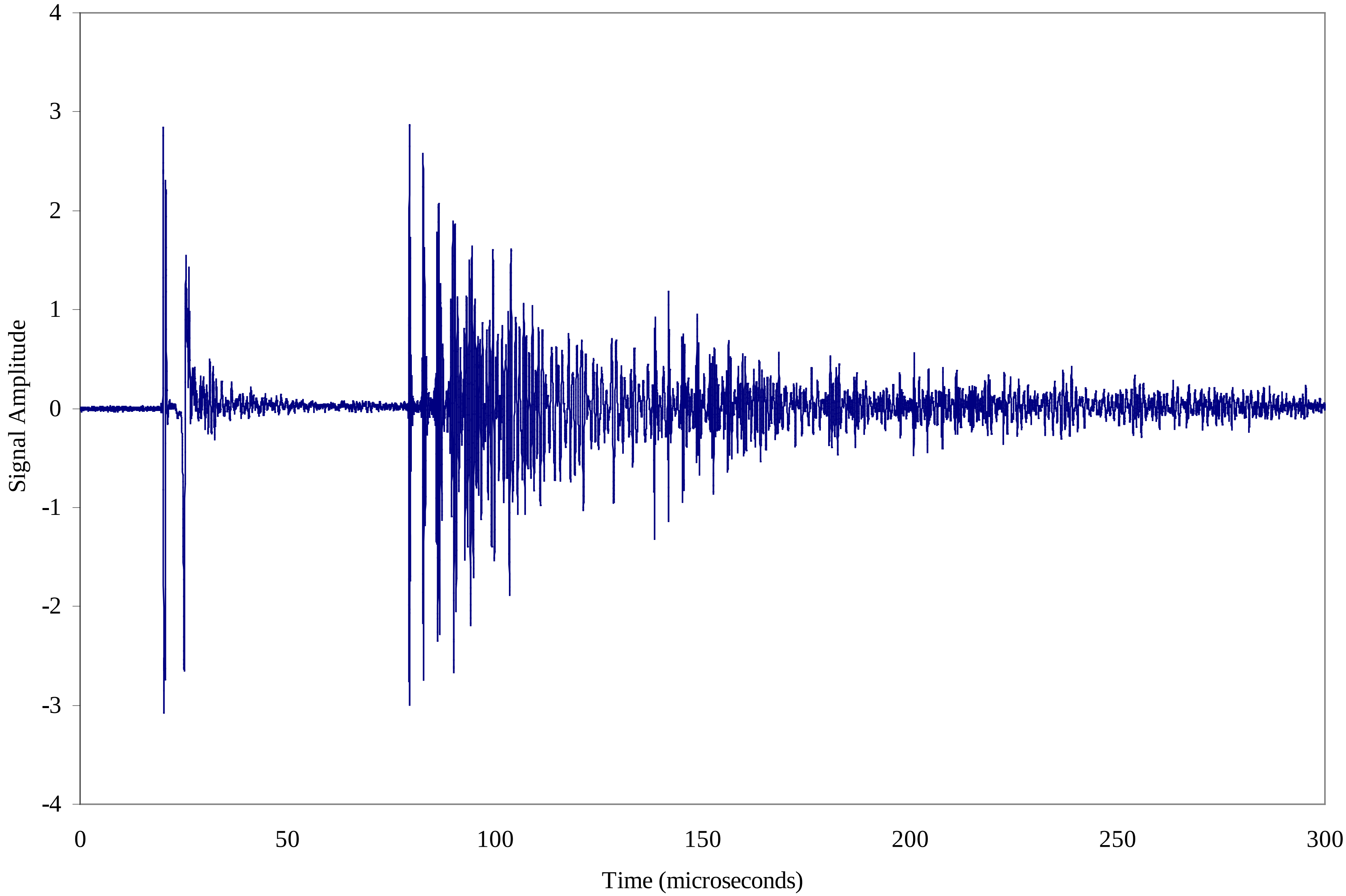

Figure A.35- Full time domain signal for ultrasonic pulse-echo inspection of bolt E1 tested with 10 MHz probe frequency.

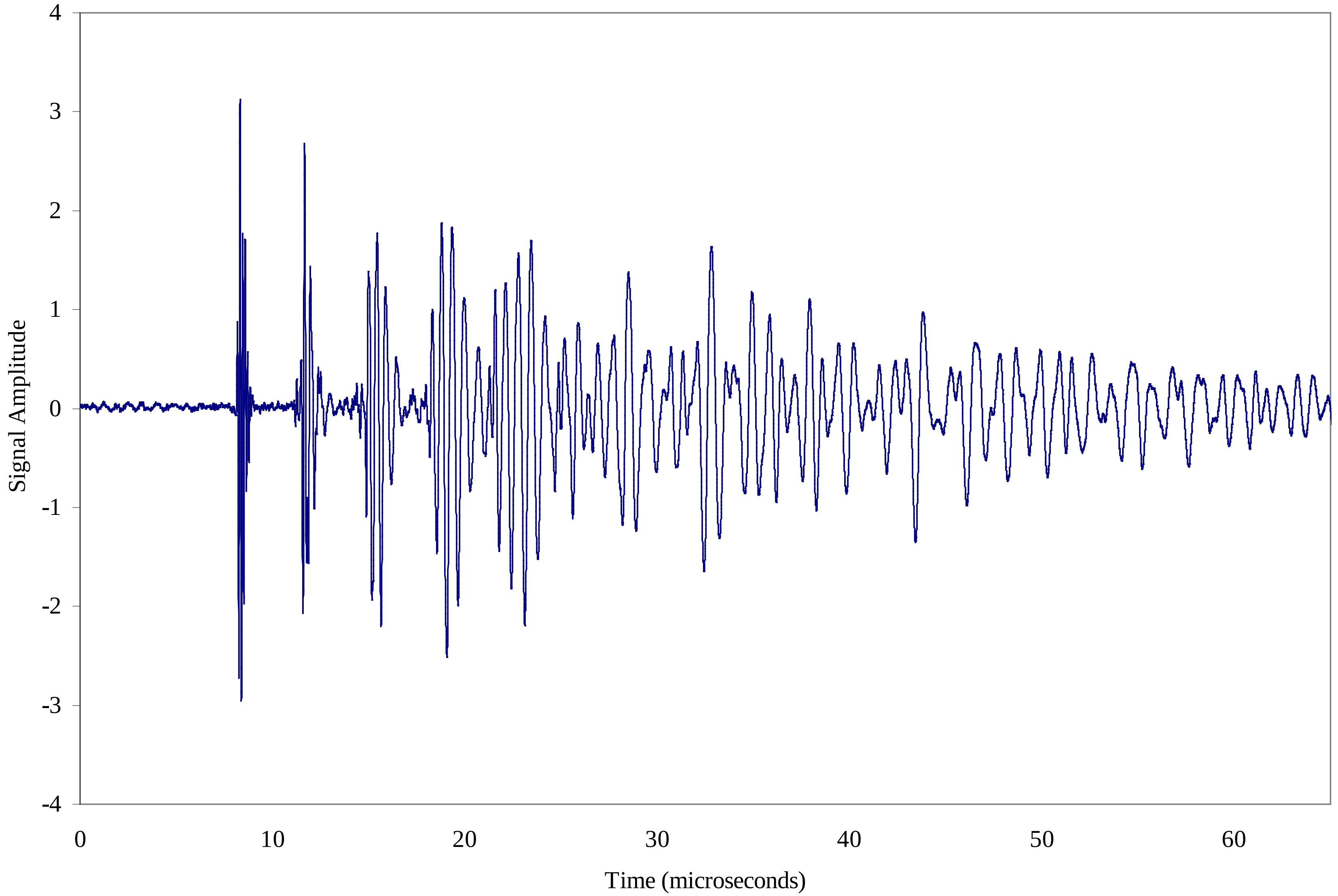

Figure A.36- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt E1 tested with 10 MHz probe frequency.

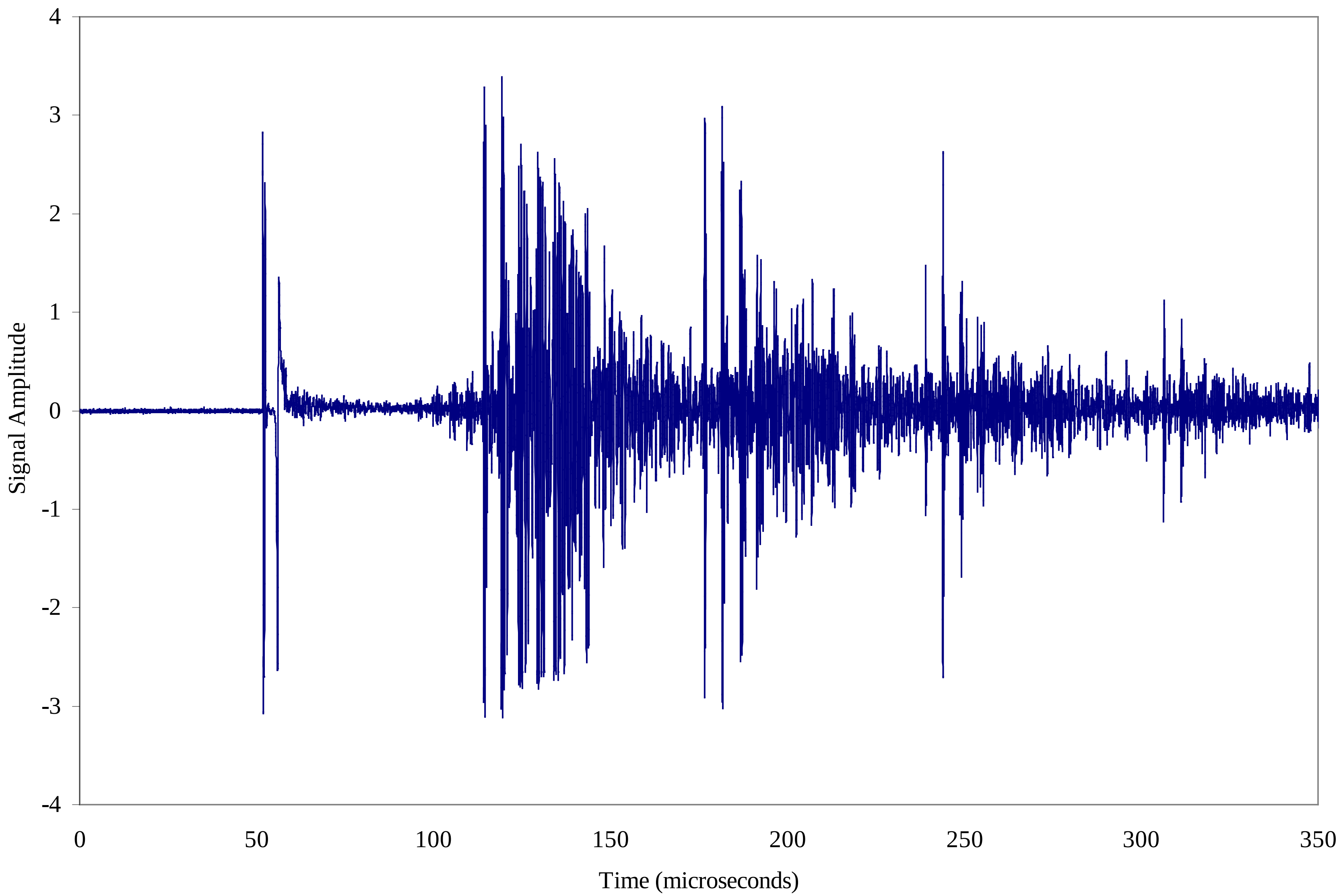

Figure A.37- Full time domain signal for ultrasonic pulse-echo inspection of bolt F1 tested with 10 MHz probe frequency.

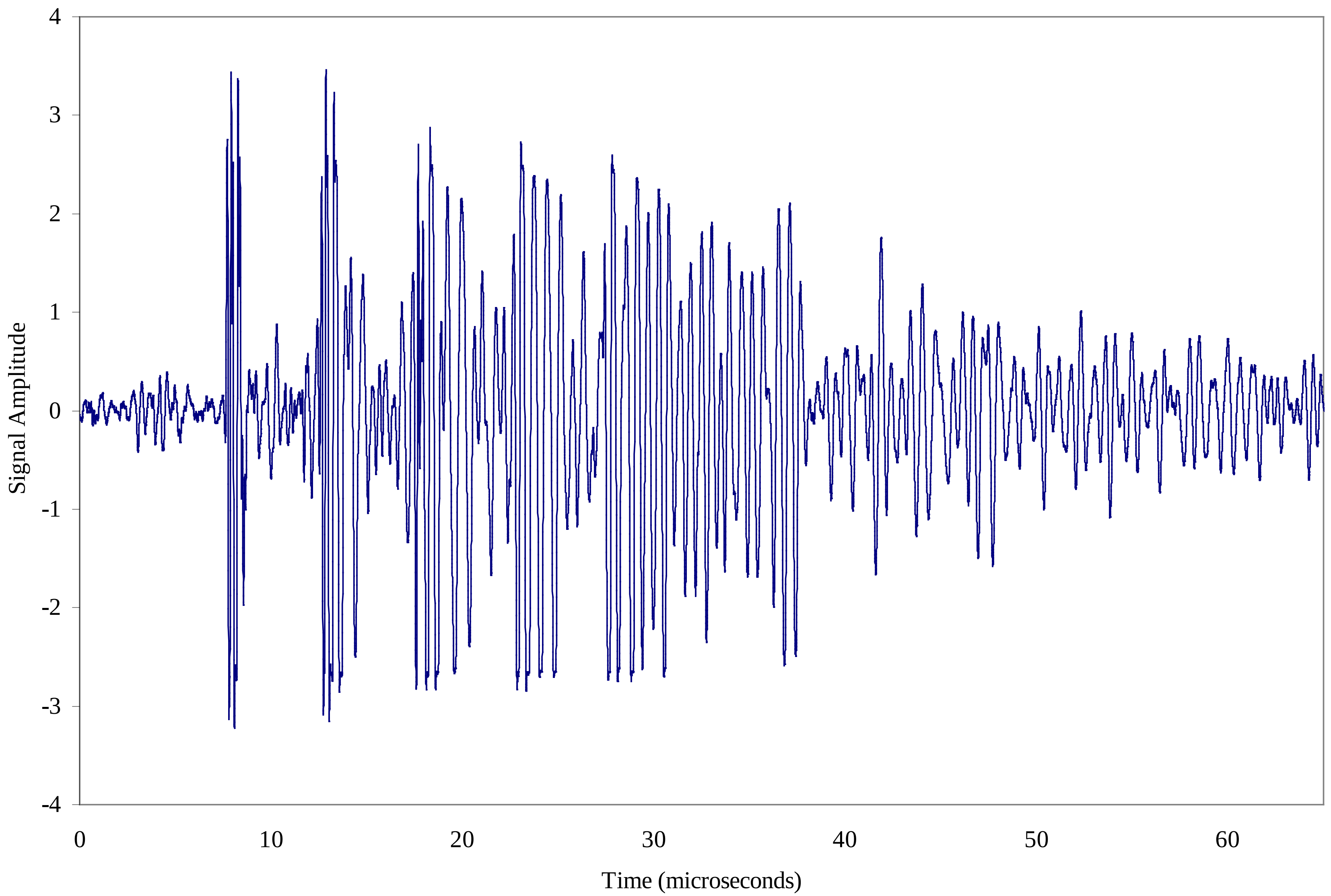

Figure A.38- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt F1 tested with 10 MHz probe frequency.

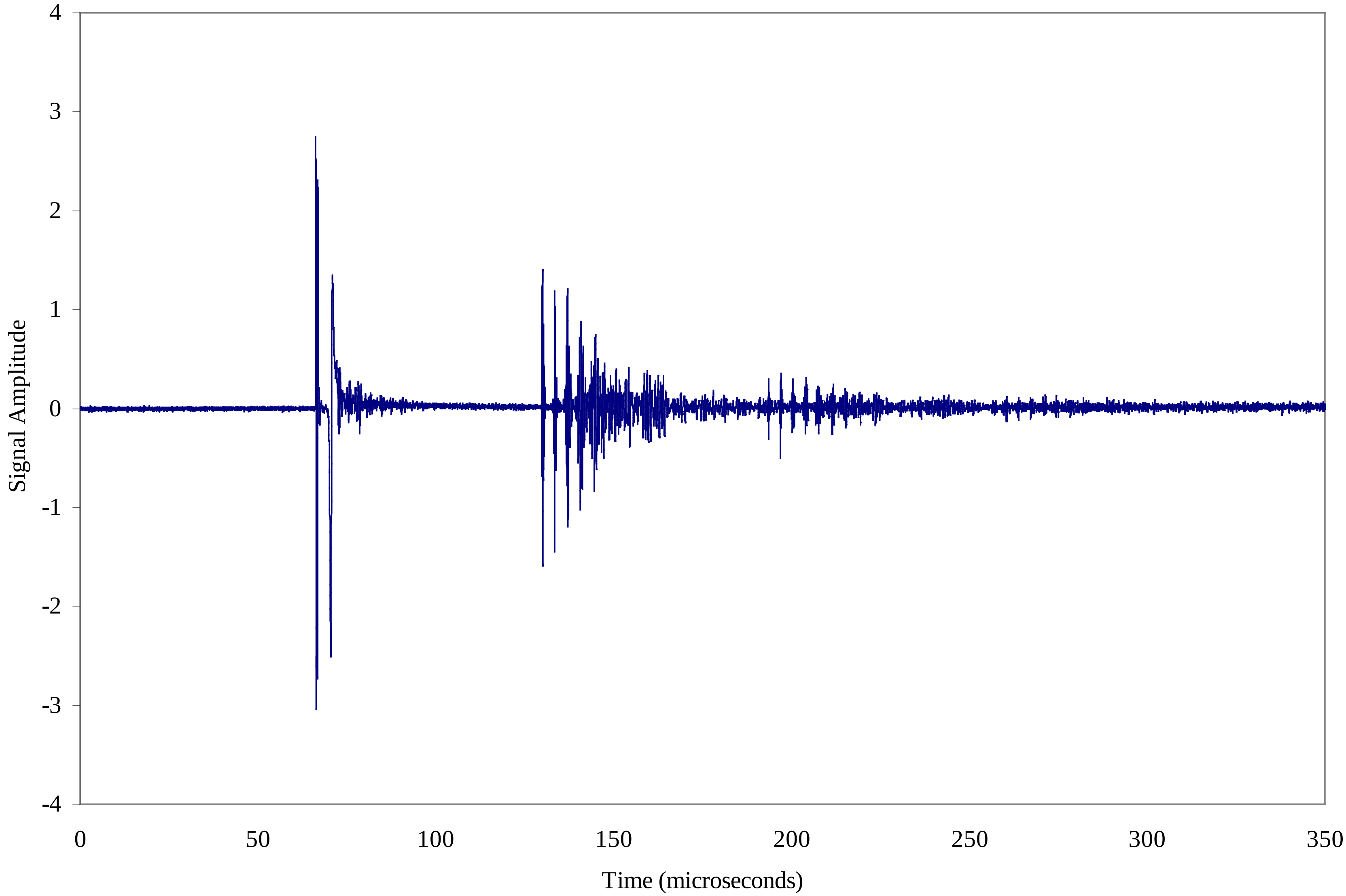

Figure A.39- Full time domain signal for ultrasonic pulse-echo inspection of bolt G1 tested with 10 MHz probe frequency.

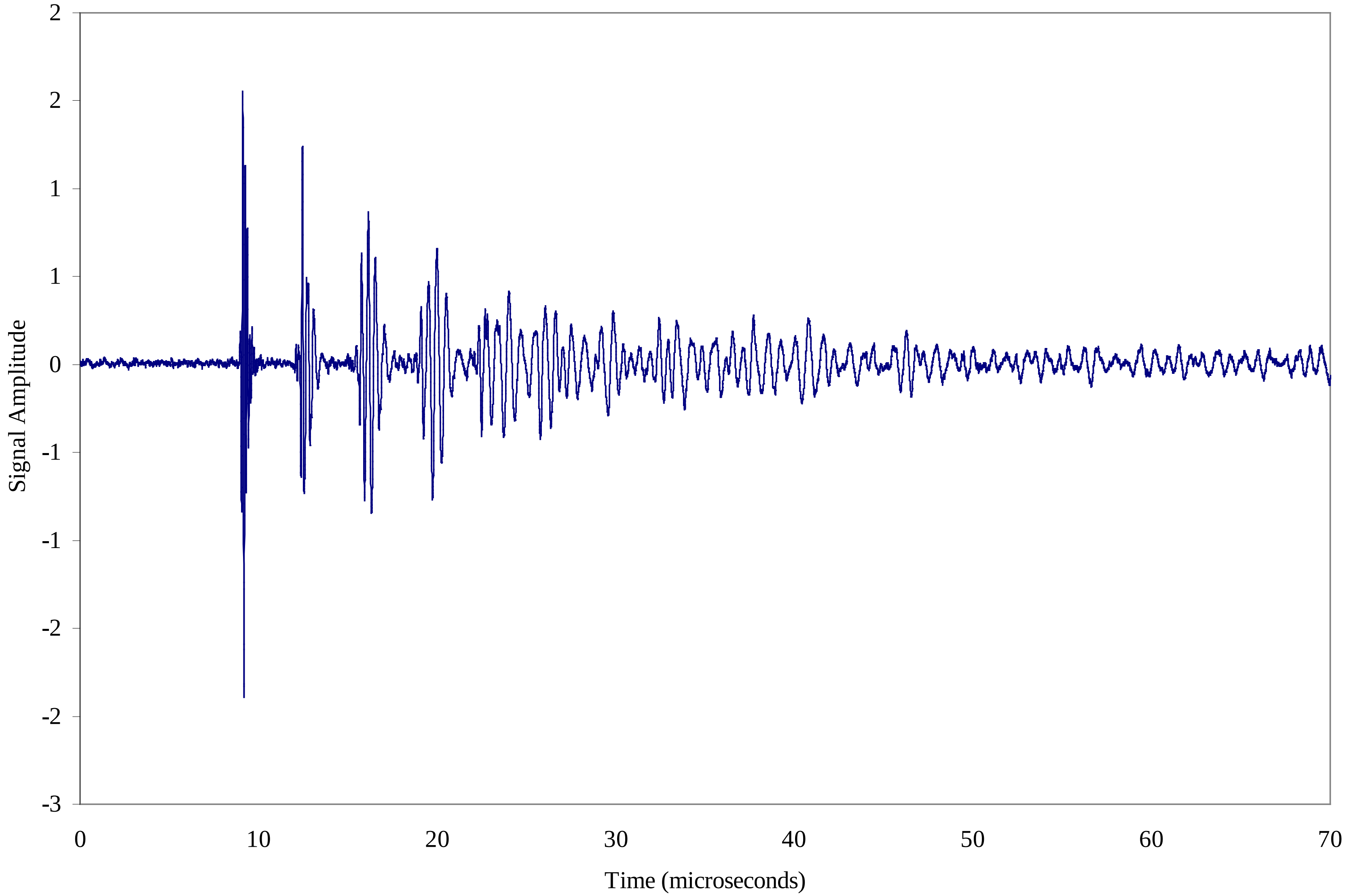

Figure A.40- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt G1 tested with 10 MHz probe frequency.

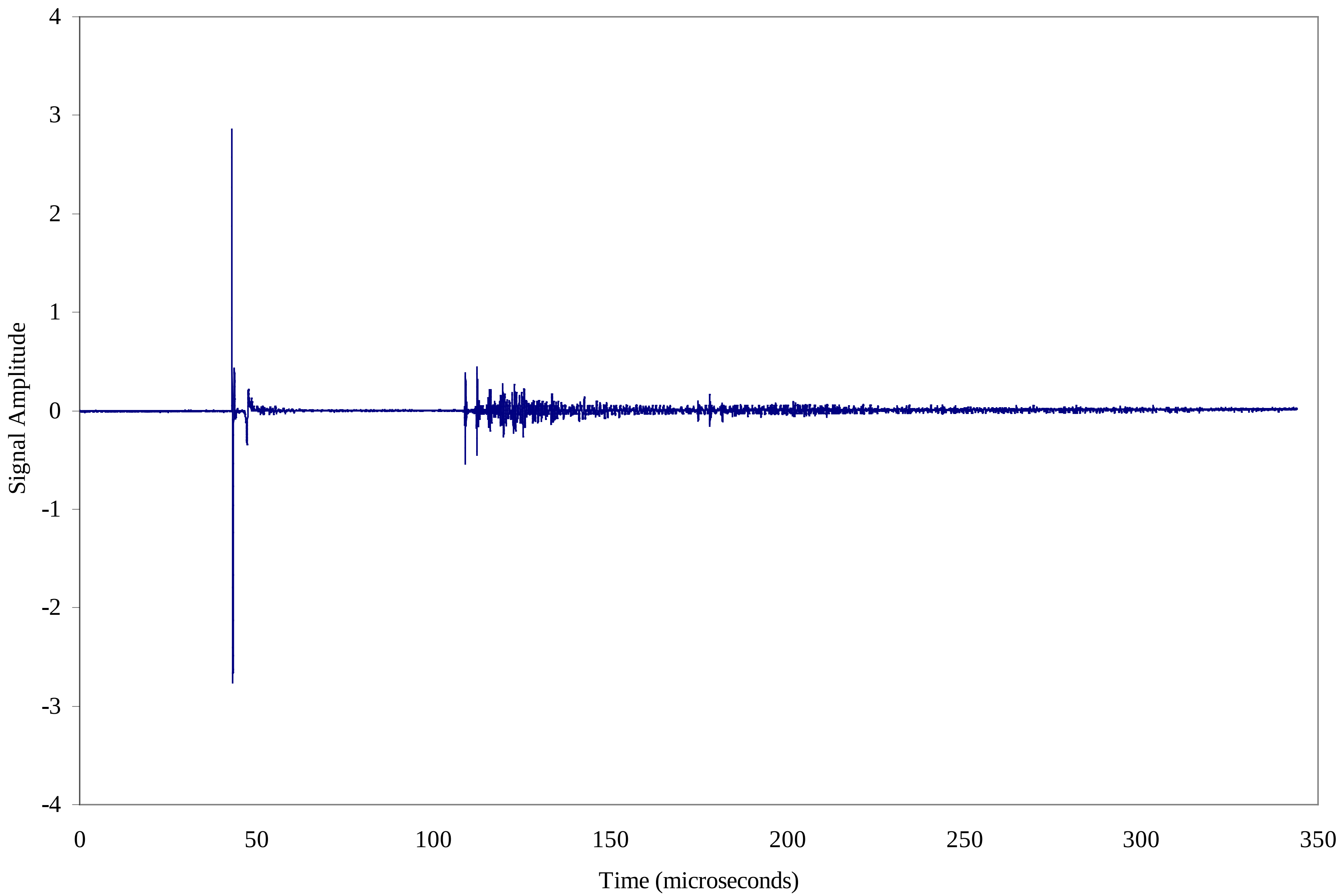

Figure A.41- Full time domain signal for ultrasonic pulse-echo inspection of bolt H1 tested with 10 MHz probe frequency.

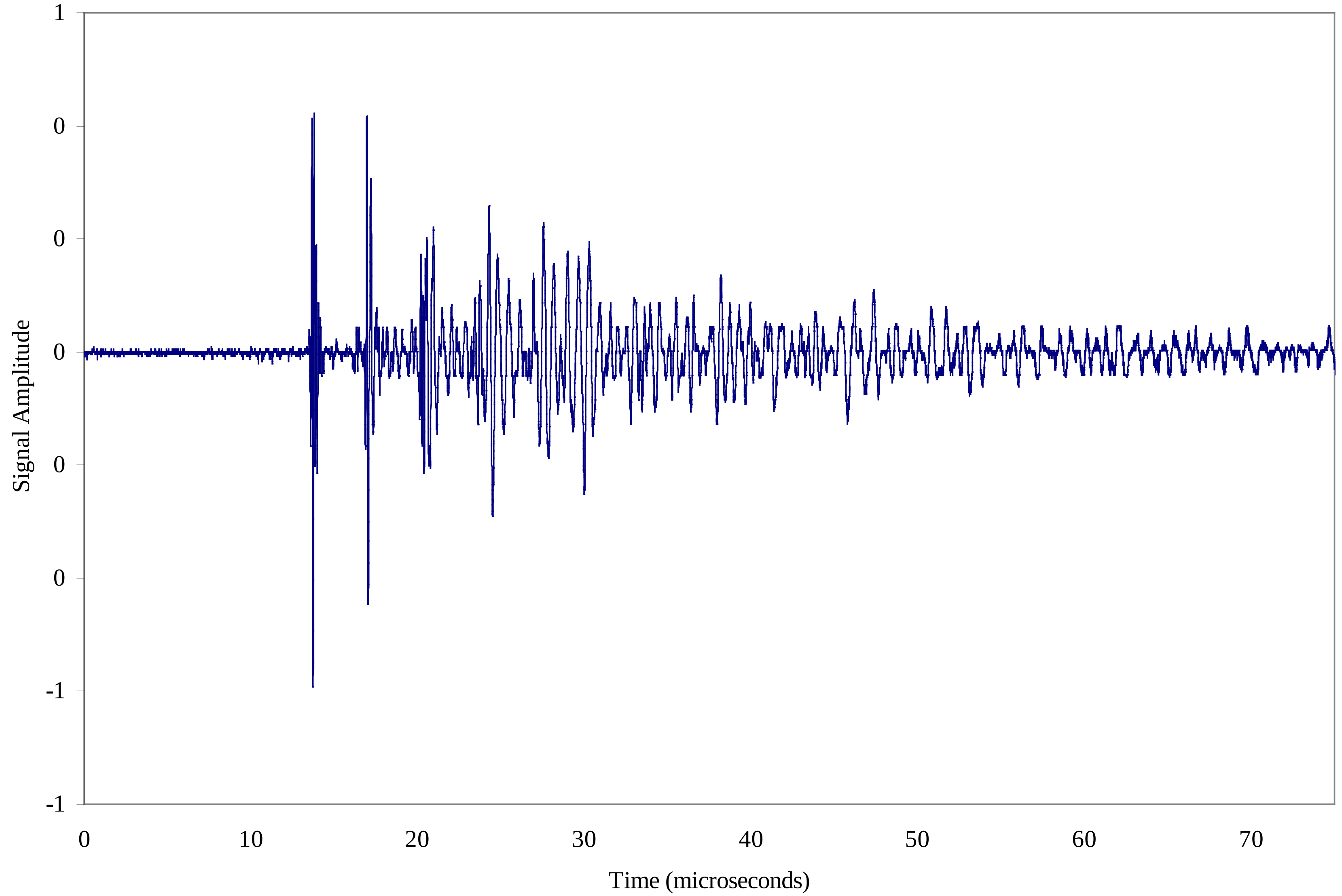

Figure A.42- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt H1 tested with 10 MHz probe frequency.

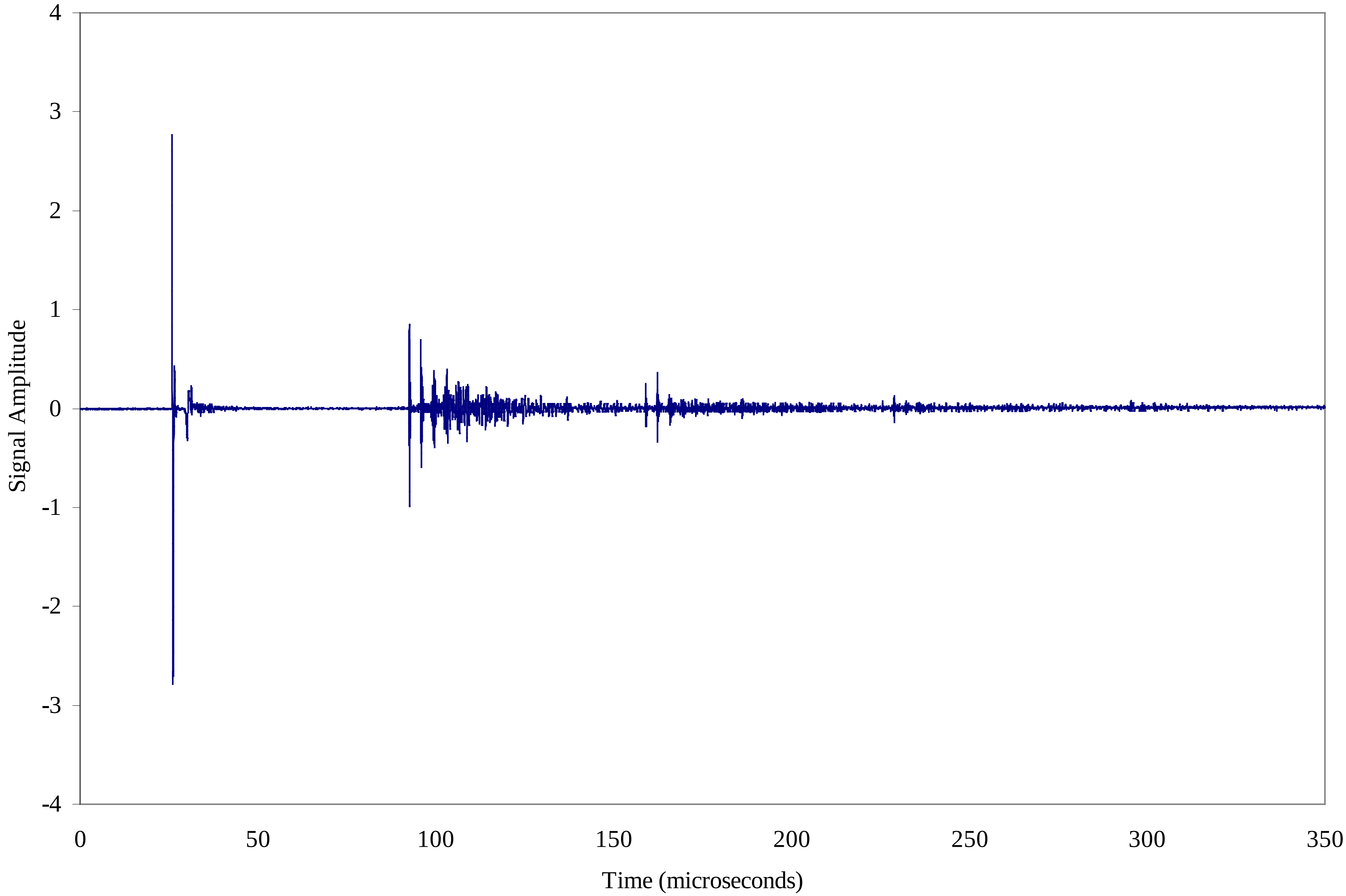

Figure A.43- Full time domain signal for ultrasonic pulse-echo inspection of bolt I1 tested with 10 MHz probe frequency.

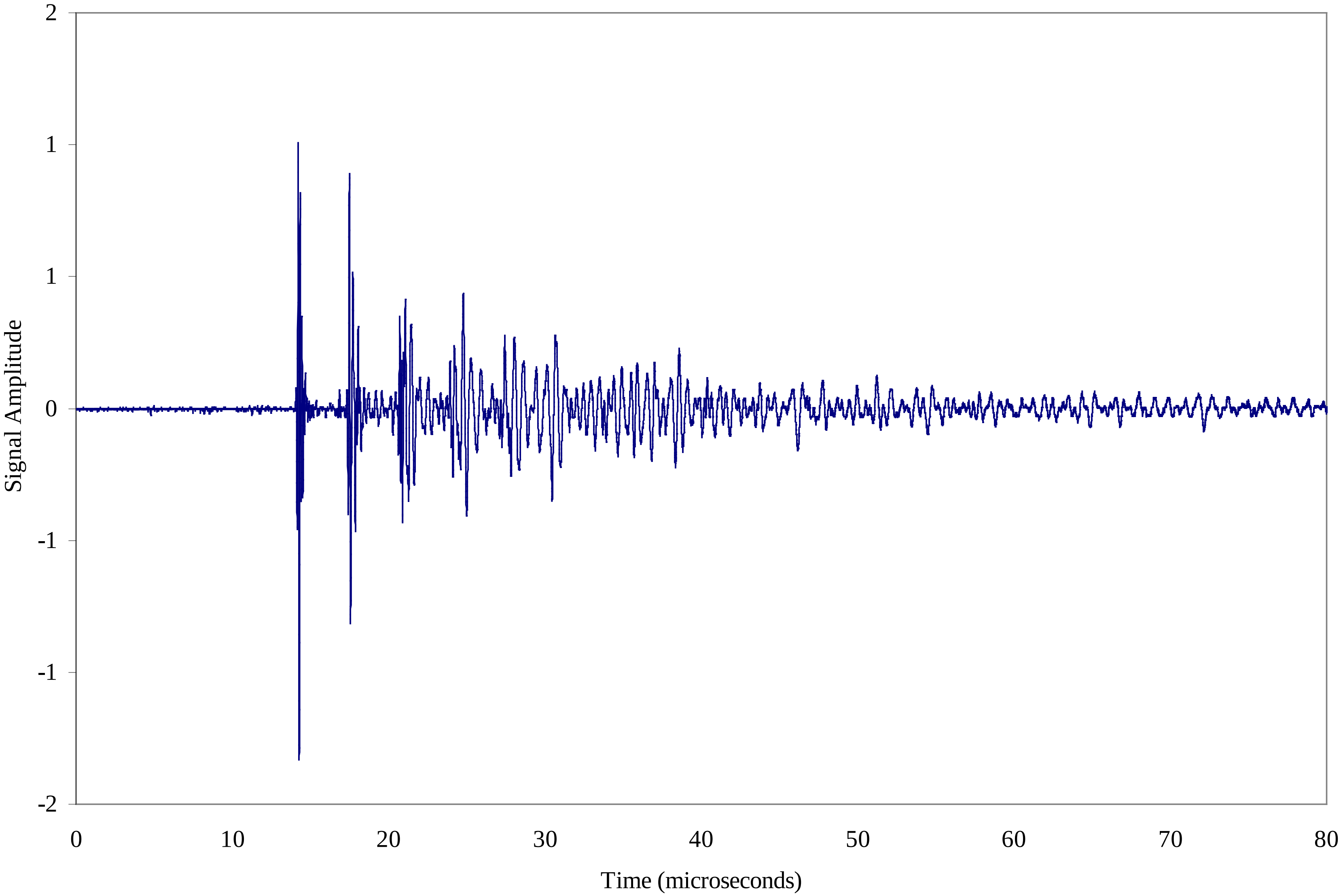

Figure A.44- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt I1 tested with 10 MHz probe frequency.

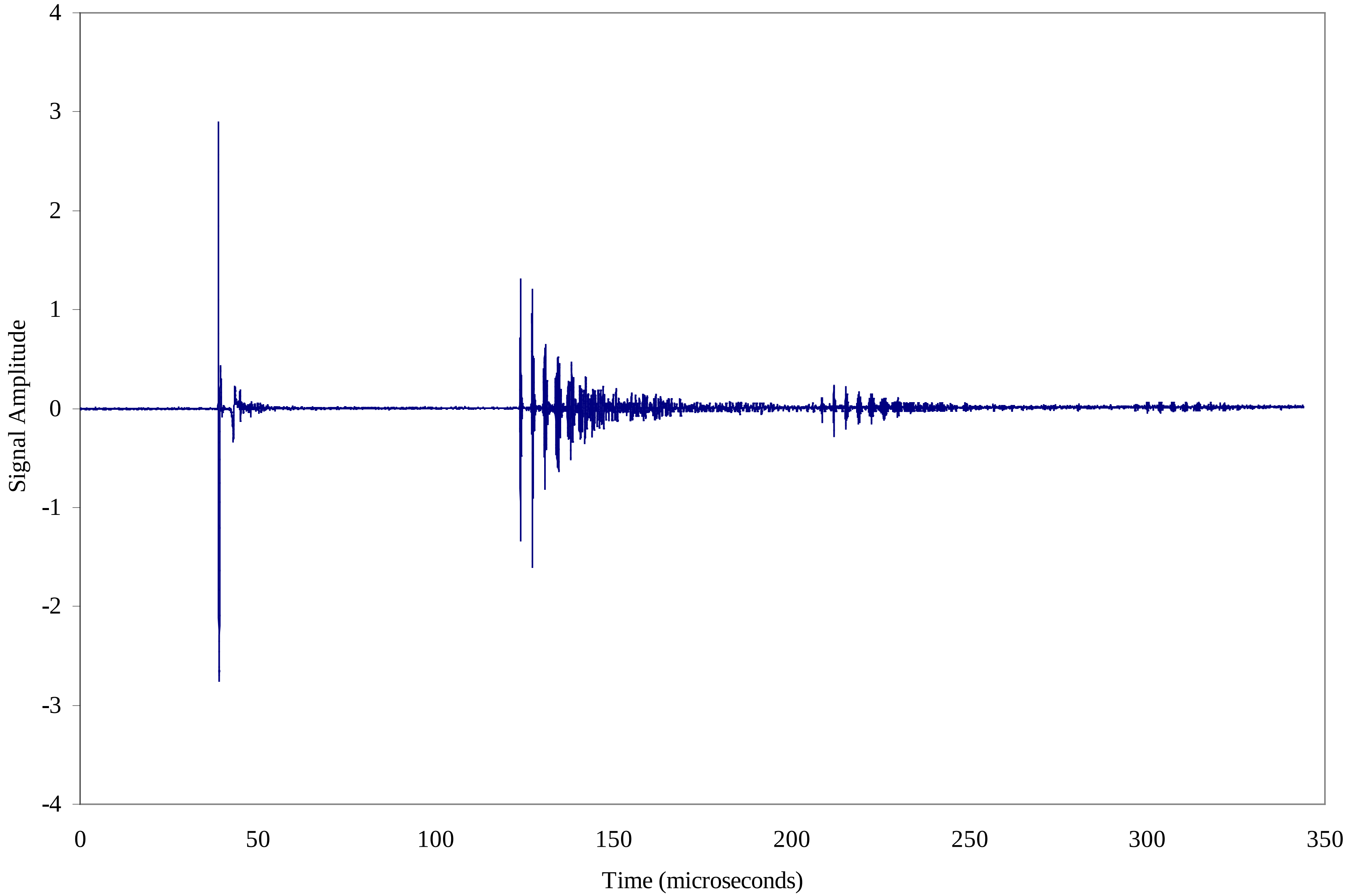

Figure A.45- Full time domain signal for ultrasonic pulse-echo inspection of bolt J1 tested with 10 MHz probe frequency.

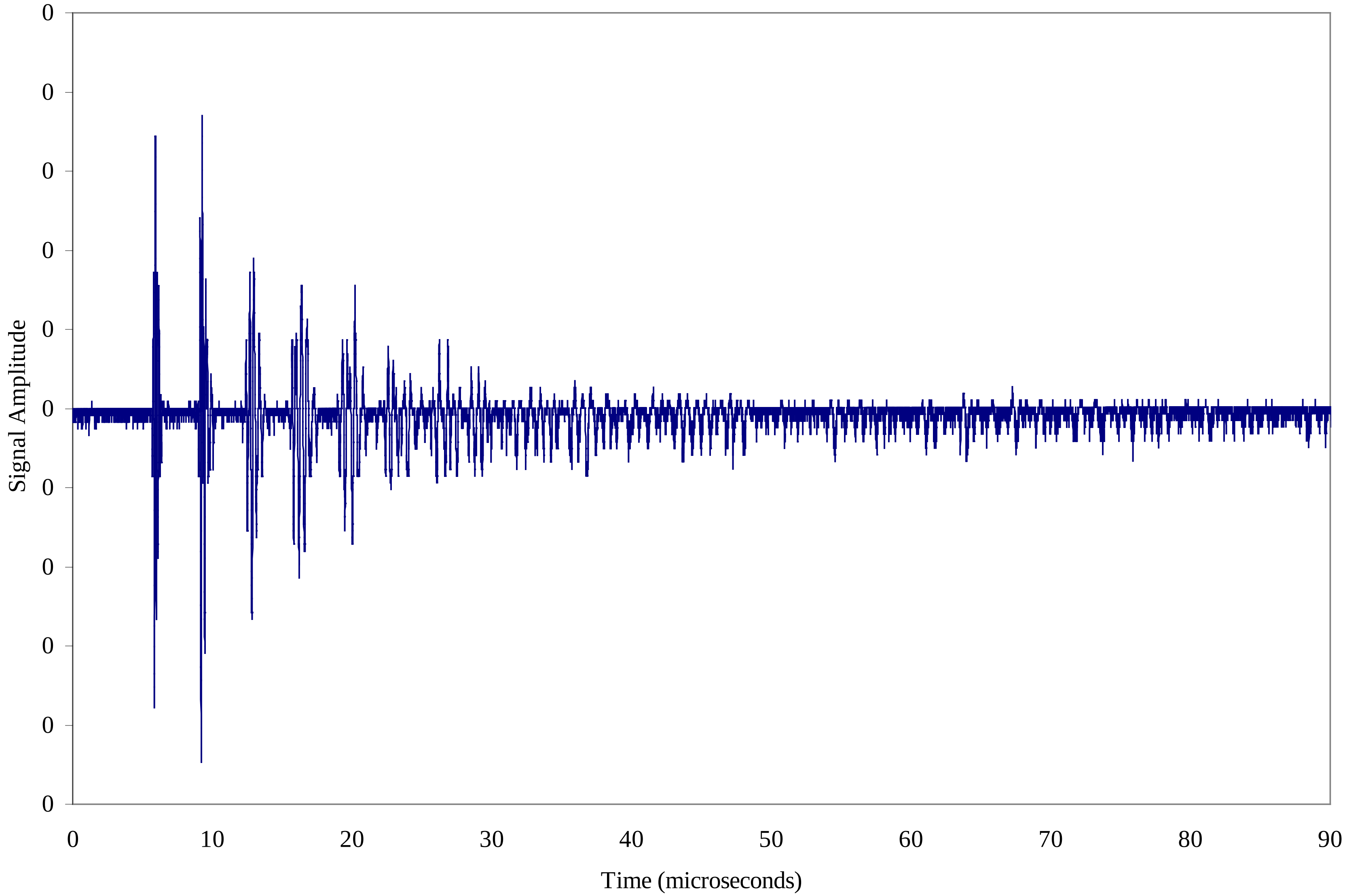

Figure A.46- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt J1 tested with 10 MHz probe frequency.

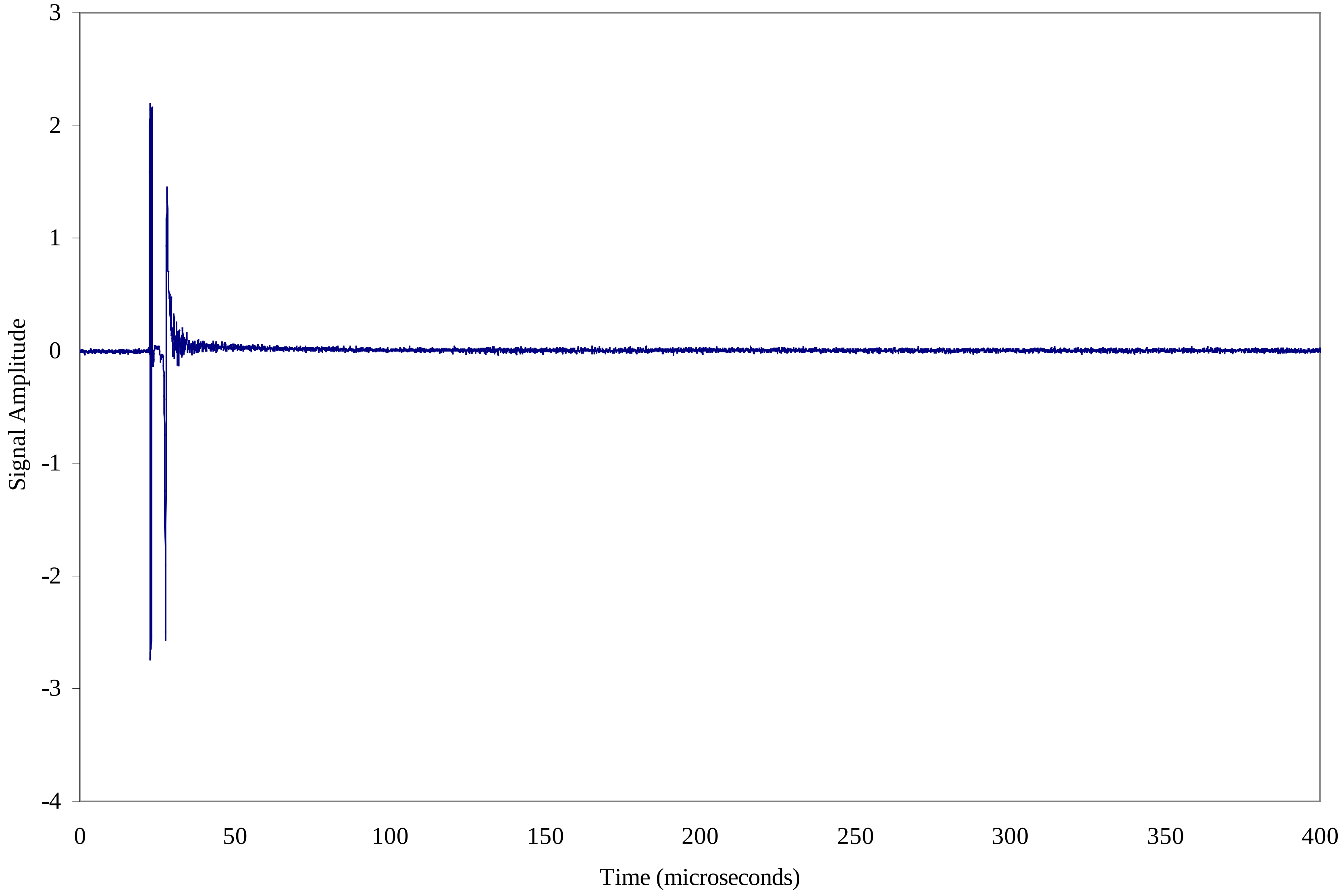

Figure A.47- Full time domain signal for ultrasonic pulse-echo inspection of bolt K1 tested with 10 MHz probe frequency.

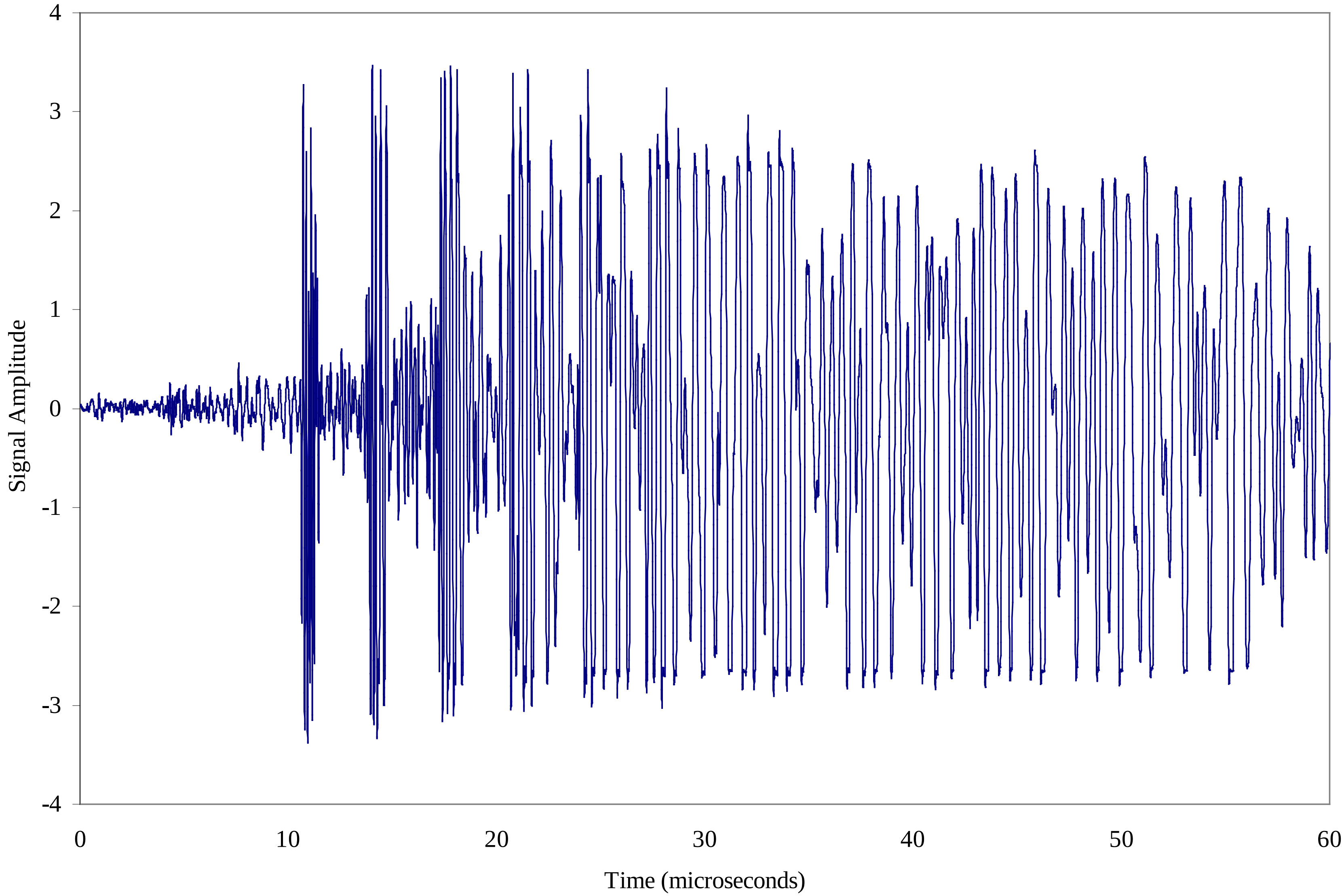

Figure A.48- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt K1 tested with 10 MHz probe frequency.

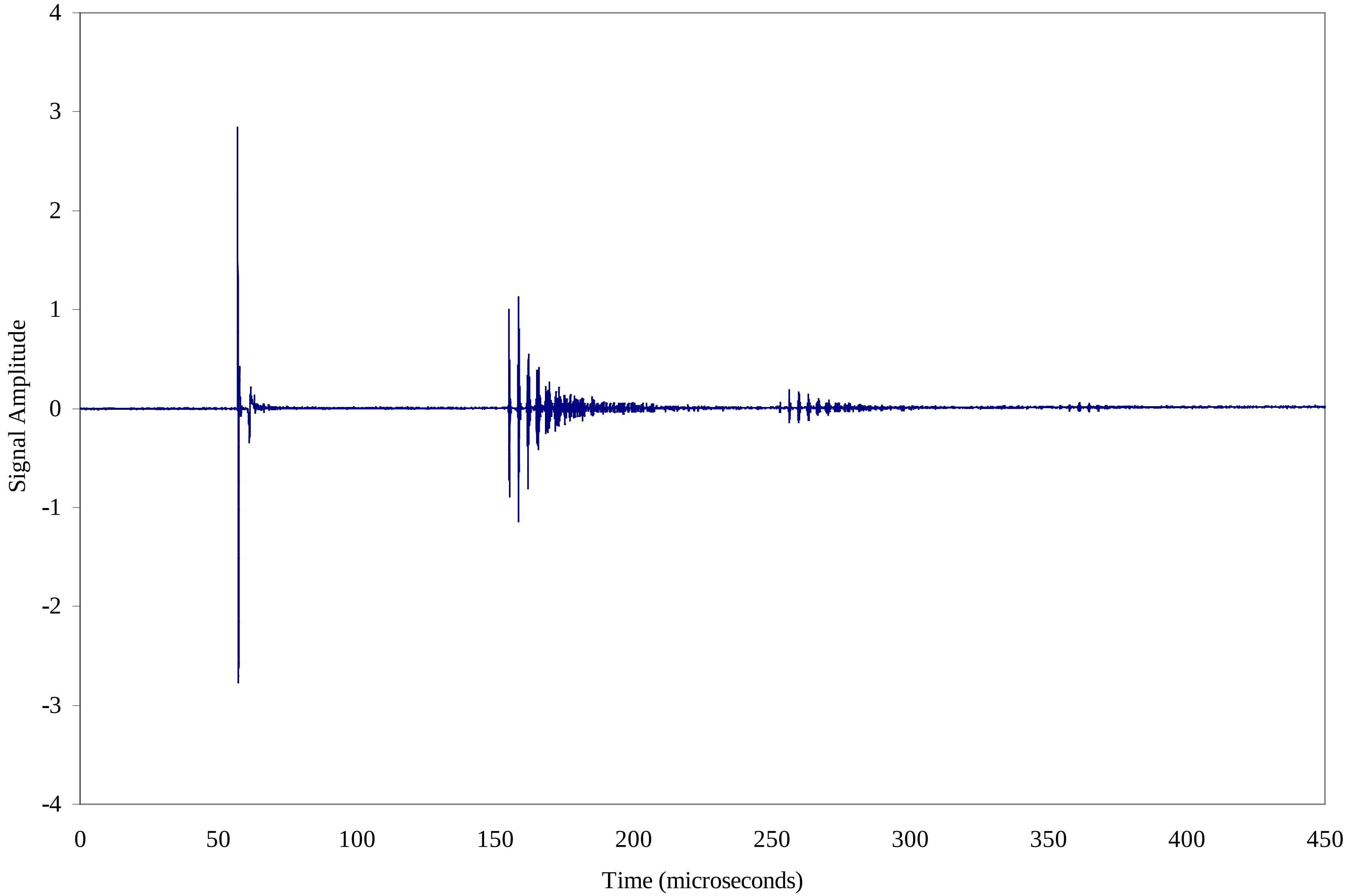

Figure A.49- Full time domain signal for ultrasonic pulse-echo inspection of bolt L1 tested with 10 MHz probe frequency.

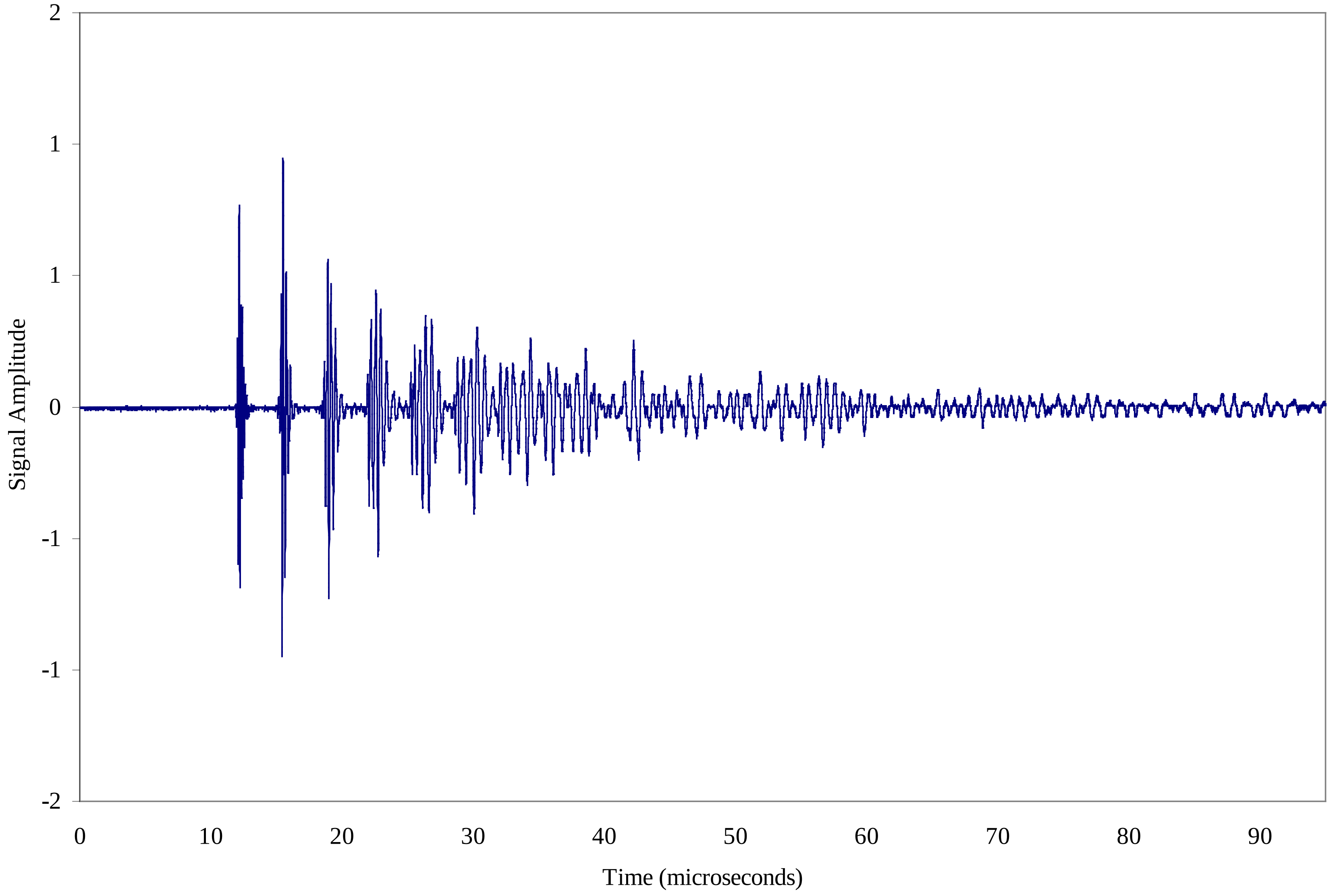

Figure A.50- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt L1 tested with 10 MHz probe frequency.

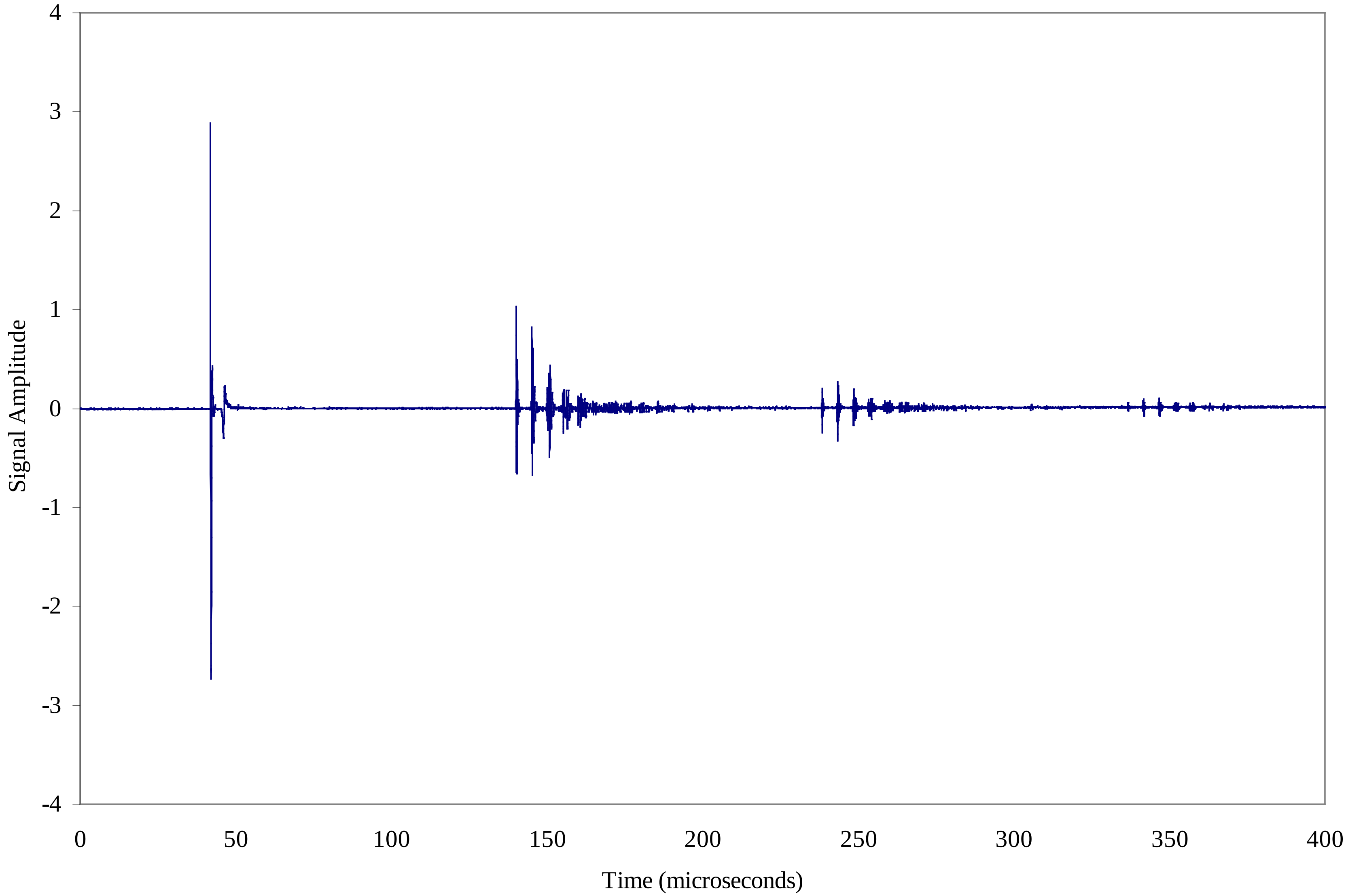

Figure A.51- Full time domain signal for ultrasonic pulse-echo inspection of bolt M1 tested with 10 MHz probe frequency.

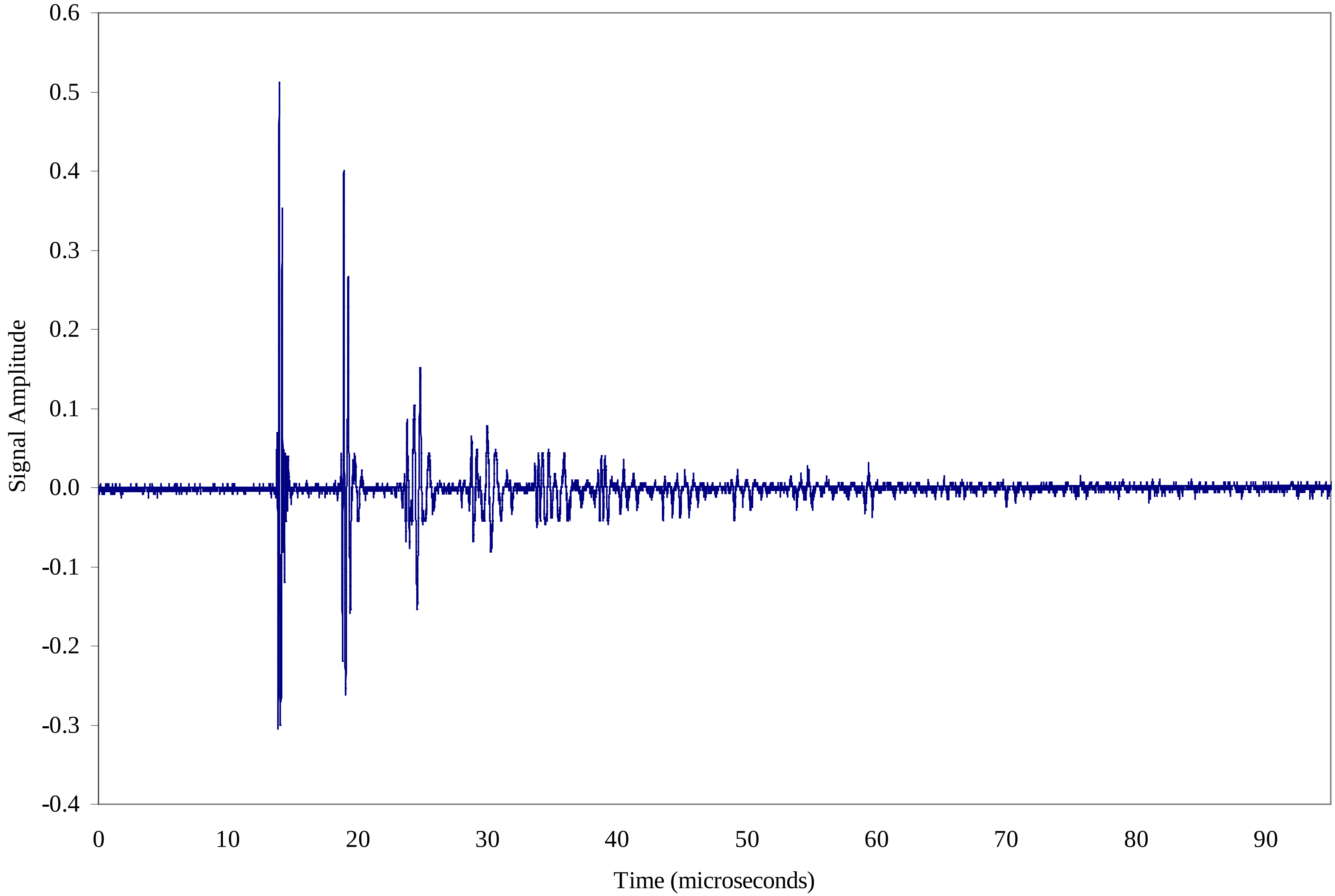

Figure A.52- First back echo and trailing echoes for ultrasonic pulse-echo inspection of bolt M1 tested with 10 MHz probe frequency.

APPENDIX B

ECHO PEAK FREQUENCY

Table B.1 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group A.

Bolt Group A Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	4.4			2.45			1.71		
2	4.4			2.45	2.94		1.71		
3	4.31			2.35	3.13		0.98		
4	4.31			2.74	3.13		1.76		
5	4.70			2.35			1.96		
6	4.40			2.45			1.71		
7	4.89			2.94			1.71		
8	4.70			2.35	3.13		1.96		
9	4.31			2.35			1.76		
10	4.40			2.45			1.96		
11	5.87			2.74	3.52	6.26	1.96		
12	4.31			2.35	3.13		1.96		
13	4.7			2.35	3.13		1.76		
14	4.31			2.35	3.13		1.96		
15	4.31	5.48		2.35	1.96		1.96		
16	4.89			2.45			1.71		
17	4.40			2.45	3.42		1.96		
18	4.70			2.74	3.13		1.96		
19	4.70	5.48		2.35	1.96	3.13	1.96		
20	4.70			2.35			1.96		
Average	4.60	5.48		2.47	3.00	4.70	1.82		
COV %	8.0	0		7.12	16.73	47.14	12.59		

Table B.2 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group A.

Bolt Group A Tested with 10 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	8.32			2.2			1.71		
2	8.32			2.45			1.71		
3	7.83			2.94	2.45		1.71		
4	8.32			2.45			1.71		
5	8.32			2.45			1.71		
6	8.32			2.94			0.489		
7	7.83			2.45			1.71		
8	8.32			2.45			1.71		
9	7.83			2.45			1.71		
10	8.32			2.45			1.96		
11	7.83			5.87	7.83		1.96		
12	8.32			4.89			1.96		
13	8.81	6.36	9.78	2.45			1.96		
14	7.83			2.45			1.96		
15	8.32			1.96			1.96		
16	7.83			2.45			1.96		
17	7.83			2.45			1.96		
18	8.32			2.45			1.96		
19	8.32			2.45			1.96		
20	8.32	3.91		2.45			1.71		
Average	8.17	5.14	9.78	2.76	5.14		1.78		
COV %	3.42	33.73		33.90	74.01		18.44		

Table B.3 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group B considering the outliers.

Bolt Group B Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	1.57	0.978	4.7	1.37			1.17		
2	1.63			1.63			1.3		
3	1.96			1.57			1.57		
4	1.57			1.57			1.57		
5	1.96			1.37			1.17		
6	1.57	2.35		1.37			1.17		
7	1.57			1.57			1.17		
8	1.63	2.28		1.63			1.3		
9	1.57			1.56			1.17		
10	1.57	2.35	5.87	1.57			1.37		
11	1.57			1.57			1.17		
12	1.57			1.57			1.17		
13	1.57	2.35		1.57			1.17		
14	1.96			1.37			1.17		
15	1.71	5.5	2.45	1.59			1.35		
16	1.57			1.37			1.17		
17	1.57			1.57			1.17		
18	1.96			1.56			1.17		
19	1.96			1.56			1.17		
20	1.96			1.57			1.17		
21	1.96			1.57			1.17		
22	1.96			1.37			1.17		
23	1.63			1.3			1.3		
24	1.57			1.37			1.17		
25	1.57			1.76	1.17		1.37		
26	1.57			1.57			1.17		
27	1.96	5.09		1.37			1.17		
28	1.57			1.56			1.17		
29	1.96			1.57			1.37		
30	1.57			1.57			1.37		

Table B.3 – Continued.

Bolt Group B Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
31	1.57			1.37			1.17		
32	1.57	2.35		1.57			1.17		
33	1.57			1.57			1.37		
34	1.96			1.76	1.17		1.17		
35	1.57			1.56			1.17		
36	1.96			1.56			1.57		
37	1.57			1.56			1.37		
38	1.96			1.57			1.17		
39	1.57			1.56			1.57		
40	1.63			1.63			1.3		
41	1.96			1.57			1.17		
42	1.57			1.57			1.17		
43	1.57			1.57			1.17		
44	1.96			1.57			1.37		
45	1.57			1.56	1.17		1.17		
46	6.19			1.63	6.19	6.52	1.3	6.52	
47	1.83	5.14		1.71			1.22		
48	1.96	5.22	8.48	1.63			1.3		
49	1.96			1.57			1.17		
50	1.63			1.63			1.3		
51	1.63	2.61		1.63			1.3		
52	1.63			1.3			1.3		
53	1.57			1.57			1.17		
54	1.63			1.63			1.3		
55	1.96			1.57			1.17		
56	1.96	8.61	4.7	1.57			1.17		
57	5.09			1.57			0.978		
58	1.57	2.74		1.76	1.17		1.37		
59	1.96			1.56	1.17		1.37	1.96	
60	1.57			1.57			1.17		
Average	2.138	4.864	6.59	1.587	2.425	6.52	1.2319	4.24	
COV %	57.188	50.178	40.559	5.428	103.505		7.991	76.047	

Table B.4 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group B ignoring the outliers.

Bolt Group B Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	1.57	0.978	4.7	1.37			1.17		
2	1.63			1.63			1.3		
3	1.96			1.57			1.57		
4	1.57			1.57			1.57		
5	1.96			1.37			1.17		
6	1.57	2.35		1.37			1.17		
7	1.57			1.57			1.17		
8	1.63	2.28		1.63			1.3		
9	1.57			1.56			1.17		
10	1.57	2.35	5.87	1.57			1.37		
11	1.57			1.57			1.17		
12	1.57			1.57			1.17		
13	1.57	2.35		1.57			1.17		
14	1.96			1.37			1.17		
15	1.71	5.5	2.45	1.59			1.35		
16	1.57			1.37			1.17		
17	1.57			1.57			1.17		
18	1.96			1.56			1.17		
19	1.96			1.56			1.17		
20	1.96			1.57			1.17		
21	1.96			1.57			1.17		
22	1.96			1.37			1.17		
23	1.63			1.3			1.3		
24	1.57			1.37			1.17		
25	1.57			1.76	1.17		1.37		
26	1.57			1.57			1.17		
27	1.96	5.09		1.37			1.17		
28	1.57			1.56			1.17		
29	1.96			1.57			1.37		
30	1.57			1.57			1.37		

Table B.4 – Continued.

Bolt Group B Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
31	1.57			1.37			1.17		
32	1.57	2.35		1.57			1.17		
33	1.57			1.57			1.37		
34	1.96			1.76	1.17		1.17		
35	1.57			1.56			1.17		
36	1.96			1.56			1.57		
37	1.57			1.56			1.37		
38	1.96			1.57			1.17		
39	1.57			1.56			1.57		
40	1.63			1.63			1.3		
41	1.96			1.57			1.17		
42	1.57			1.57			1.17		
43	1.57			1.57			1.17		
44	1.96			1.57			1.37		
45	1.57			1.56	1.17		1.17		
46				1.63	6.19	6.52	1.3	6.52	
47	1.83	5.14		1.71			1.22		
48	1.96	5.22	8.48	1.63			1.3		
49	1.96			1.57			1.17		
50	1.63			1.63			1.3		
51	1.63	2.61		1.63			1.3		
52	1.63			1.3			1.3		
53	1.57			1.57			1.17		
54	1.63			1.63			1.3		
55	1.96			1.57			1.17		
56	1.96	8.61	4.7	1.57			1.17		
57				1.57			0.978		
58	1.57	2.74		1.76	1.17		1.37		
59	1.96			1.56	1.17		1.37	1.96	
60	1.57			1.57			1.17		
Average	1.749	4.864	6.59	1.587	2.425	6.52	1.245	4.24	
COV %	10.440	50.178	40.559	5.428	103.50		6.454	76.047	

Table B.5 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group C.

Bolt Group C Tested with 5 MHz Probe Frequency									
Specimen	**Echo Peak Frequency (MHz)**								
	First Back			**1st Trailing**			**2nd Trailing**		
	1st Peak	**2nd Peak**	**3rd Peak**	**1st Peak**	**2nd Peak**	**3rd Peak**	**1st Peak**	**2nd Peak**	**3rd Peak**
1	3.42			1.47	3.91		0.978		
2	1.22			1.47			1.22		
3	1.47			0.978			1.22		
4	1.47			1.47	1.71		1.47		
5	1.47			1.22			1.47		
6	1.47			1.47			1.47		
7	1.22			1.47			1.47		
8	1.47			1.47			1.22		
9	1.47			1.47	2.44		1.47		
10	1.47			1.22	1.71		1.47		
11	1.47			1.47			1.47		
12	3.91			1.47	3.91	4.89	1.47		
13	1.47			1.22			1.22		
14	1.96			1.47			1.47		
15	1.96			1.47			1.22		
16	1.96			1.47			1.47		
17	1.47			1.22			1.47		
18	1.47			1.47			1.47		
19	2.94			1.47			1.47		
20	1.47	2.94		1.47	1.96		1.47		
Average	1.811	2.94		1.395	2.606	4.89	1.382		
COV %	40.900			10.145	40.057		10.529		

Table B.6 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group D.

Bolt Group D Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	1.96			1.71			1.22		
2	1.96			1.71			1.22		
3	1.96	4.89		1.71			1.47		
4	1.96	2.94		1.71			1.22		
5	1.96			1.71			1.22		
6	1.71	2.69		1.71			1.22		
7	1.71	2.69		1.71			1.22		
8	1.96	4.4		1.71			1.47		
9	1.96	4.4		1.71			1.22		
10	1.96			1.96			1.22		
11	1.96			1.71			1.47		
12	1.96			1.96			1.22		
13	1.96			1.71	1.22		1.22		
14	1.96	4.89		1.71			1.47		
15	1.96			1.71			1.22		
16	2.45	4.89		1.47			1.22		
17	1.96			1.71			1.47		
18	2.45	4.89		1.71			1.22		
19	1.96	4.4		1.47			1.22		
20	1.96	4.89		1.96			1.47		
Average	1.984	4.179		1.723	1.22		1.295		
COV %	8.909	22.246		7.279			9.076		

Table B.7 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group F.

Bolt Group F Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	3.13	1.96	5.09	1.37	2.35		1.37	1.96	
2	3.52	5.09	1.96	1.37	2.35		1.37	1.96	
3	3.13	4.7		1.96	2.35		1.37		
4	3.13	4.7		1.37	2.15		1.37	1.76	
5	3.13	1.96	5.09	1.57	2.35		1.37	1.96	
6	5.09			2.35	4.31	5.87	1.37		
7	4.7			4.7			1.37		
8	3.13	4.7	1.57	1.57	2.35		1.37	1.96	
9	3.13	1.96	5.09	2.35			1.17	1.96	
10	3.13	1.57	5.09	1.57	2.35		1.96		
11	3.13	3.52	4.7	1.57	2.35		1.37		
12	4.7			4.31			1.57	4.31	
13	2.35			1.37	1.96		1.56		
14	3.13	4.7		1.57	2.35		1.37		
15	3.52	1.96	5.09	1.37	2.15		1.17	1.96	
16	3.13	4.7	1.17	1.57	2.35		1.37		
17	3.13	1.96	5.09	1.37	2.15		1.37	1.96	
18	3.13	1.96	5.09	1.57	2.35		1.37		
19	3.13	4.31		1.57	2.35		1.17		
20	3.52	1.96	5.09	1.37	2.35		1.37		
Average	3.404	3.231	4.176	1.891	2.40706	5.87	1.389	2.1988	
COV %	19.447	43.436		49.863	20.923		12.103		

Table B.8 – The peak frequencies of the first back echo and associated first and second trailing echoes for bolt group M.

Bolt Group M Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1	5			2.16	3.91		1.74	1.96	
2	5.22			2.61	3.7		1.96	1.96	
3	5			2.61	3.48		1.74		
4	5.22			2.61	3.7	4.57	1.74	1.76	
5	4.78			2.61	3.48		1.74	1.96	
6	5			2.61	3.48	3.91	1.74		
7	4.78			2.61	3.48		1.74		
8	5			2.61	3.48		1.74	1.96	
9	4.78			2.61	3.48		1.74	1.96	
10	5			2.61	3.48	3.91	1.74		
11	4.78			2.61	3.91		1.74		
12	5			2.61			1.74	4.31	
13	5			2.61	3.48	3.91	1.74		
14	5			2.61	3.48		1.74		
15	5.22			2.61	3.48		1.96	1.96	
16	4.57			2.17	3.48	2.61	1.74		
17	4.57			2.39			1.74	1.96	
18	4.78			2.61			1.74		
19	4.78			2.61			1.74		
20	4.57			2.39	3.48	3.91	1.74		
Average	4.902			2.543	3.561	3.803	1.762	2.1988	
COV %	4.185			5.736	4.356	16.865	3.843		

Table B.9 – The peak frequencies of the first back echo and associated first and second trailing echoes for one bolt from each group tested with 5 MHz probe frequency.

One Bolt from Each Group Tested with 5 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1A	4.4			2.45			1.71		
1B	1.57	0.978	4.7	1.37			1.17		
1C	3.42			1.47	3.91		0.978		
1D	1.96			1.71			1.22		
1E	5.09			3.13	4.7		2.35		
1F	3.13	1.96	5.09	1.37	2.35		1.37	1.96	
1G	5.03			4.47	3.35		2.52		
1H	5.22			4.57			2.61	1.96	
1I	5.22			4.89			2.61		
1J	5.03			4.47			3.08		
1K	5.54			4.57	5.54		3.26	4.24	
1L	5.09			4.7			3.13		
1M	5			2.16	3.91		1.74		

Table B.10 – The peak frequencies of the first back echo and associated first and second trailing echoes for one bolt from each group tested with 10 MHz probe frequency.

One Bolt from Each Group Tested with 10 MHz Probe Frequency									
Specimen	Echo Peak Frequency (MHz)								
	First Back			1st Trailing			2nd Trailing		
	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak	1st Peak	2nd Peak	3rd Peak
1A	5			2.16	3.91		1.74	1.96	
1B	5.22			2.61	3.7		1.96	1.96	
1C	5			2.61	3.48		1.74		
1D	5.22			2.61	3.7	4.57	1.74	1.76	
1E	4.78			2.61	3.48		1.74	1.96	
1F	5			2.61	3.48	3.91	1.74		
1G	4.78			2.61	3.48		1.74		
1H	5			2.61	3.48		1.74	1.96	
1I	4.78			2.61	3.48		1.74	1.96	
1J	5			2.61	3.48	3.91	1.74		
1K	4.78			2.61	3.91		1.74		
1L	5			2.61			1.74	4.31	
1M	5			2.61	3.48	3.91	1.74		

APPENDIX C

THE CENTROID OF THE FIRST BACK ECHO AND ASSOCIATED FIRST AND SECOND TRAILING ECHOES

Table C.1 – The centroid of the first back echo and associated first and second trailing echoes for bolt groups A and C.

Centroid of First back Echo with its 1st and 2nd Trailing Echoes for Bolt Groups (sec)					
A (5 MHz)		A (10 MHz)		C (5 MHz)	
Specimen	**Centroid**	**Specimen**	**Centroid**	**Specimen**	**Centroid**
1	5.53E-06	1	5.28E-06	1	6.53E-06
2	5.15E-06	2	4.50E-06	2	8.62E-06
3	5.00E-06	3	5.18E-06	3	7.91E-06
4	4.86E-06	4	4.98E-06	4	7.99E-06
5	5.15E-06	5	5.14E-06	5	7.49E-06
6	4.83E-06	6	5.13E-06	6	7.68E-06
7	4.84E-06	7	5.03E-06	7	7.64E-06
8	5.11E-06	8	5.21E-06	8	7.97E-06
9	5.33E-06	9	5.00E-06	9	7.53E-06
10	4.95E-06	10	5.00E-06	10	7.60E-06
11	3.60E-06	11	3.28E-06	11	8.00E-06
12	5.13E-06	12	5.08E-06	12	5.86E-06
13	5.33E-06	13	4.98E-06	13	7.22E-06
14	4.78E-06	14	5.26E-06	14	7.54E-06
15	4.80E-06	15	4.95E-06	15	7.66E-06
16	5.00E-06	16	4.88E-06	16	8.13E-06
17	4.86E-06	17	5.14E-06	17	7.87E-06
18	4.89E-06	18	4.94E-06	18	7.90E-06
19	5.49E-06	19	5.09E-06	19	5.81E-06
20	5.13E-06	20	5.07E-06	20	7.55E-06
Average	4.988E-06	Average	4.956E-06	Average	7.525E-06
COV	7.94440235	COV	8.64763098	COV	9.38315741

Table C.2 – The centroid of the first back echo and associated first and second trailing echoes for bolt groups D, F, and M.

Centroid of First back Echo with its 1st and 2nd Trailing Echoes for Bolt Groups (sec)					
D (5 MHz)		F (5 MHz)		M (5 MHz)	
Specimen	**Centroid**	**Specimen**	**Centroid**	**Specimen**	**Centroid**
1	7.09E-06	1	7.24E-06	1	6.18E-06
2	7.21E-06	2	7.13E-06	2	6.14E-06
3	6.74E-06	3	6.96E-06	3	6.42E-06
4	7.20E-06	4	7.01E-06	4	6.25E-06
5	7.07E-06	5	7.07E-06	5	6.15E-06
6	7.23E-06	6	4.78E-06	6	6.25E-06
7	7.56E-06	7	6.24E-06	7	6.40E-06
8	6.81E-06	8	6.99E-06	8	6.07E-06
9	6.77E-06	9	7.09E-06	9	6.25E-06
10	7.17E-06	10	6.97E-06	10	6.31E-06
11	6.53E-06	11	7.11E-06	11	6.61E-06
12	6.89E-06	12	5.51E-06	12	6.12E-06
13	6.78E-06	13	6.53E-06	13	6.27E-06
14	6.74E-06	14	7.08E-06	14	6.80E-06
15	7.14E-06	15	6.99E-06	15	6.08E-06
16	7.08E-06	16	6.90E-06	16	7.42E-06
17	6.64E-06	17	7.00E-06	17	7.00E-06
18	6.68E-06	18	6.35E-06	18	6.72E-06
19	6.98E-06	19	6.89E-06	19	6.67E-06
20	6.64E-06	20	7.05E-06	20	7.12E-06
Average	6.95E-06	Average	6.74E-06	Average	6.46E-06
COV	3.809602	COV	9.12553	COV	5.923761

Table C.3 – The centroid of the first back echo and associated first and second trailing echoes for bolt group B.

Centroid of First back Echo with its 1st and 2nd Trailing Echoes for Bolt Groups (sec)					
B (5 MHz)		B (5 MHz)		B (5 MHz)	
Specimen	**Centroid**	**Specimen**	**Centroid**	**Specimen**	**Centroid**
1	4.92E-06	21	6.47E-06	41	6.61E-06
2	6.70E-06	22	6.32E-06	42	6.59E-06
3	6.58E-06	23	6.78E-06	43	6.55E-06
4	7.54E-06	24	6.78E-06	44	6.55E-06
5	6.45E-06	25	6.58E-06	45	6.45E-06
6	6.67E-06	26	6.74E-06	46	4.47E-06
7	6.45E-06	27	6.15E-06	47	5.70E-06
8	6.65E-06	28	6.93E-06	48	6.19E-06
9	6.56E-06	29	6.39E-06	49	6.62E-06
10	6.62E-06	30	6.48E-06	50	6.57E-06
11	6.48E-06	31	6.64E-06	51	6.65E-06
12	6.97E-06	32	6.75E-06	52	6.45E-06
13	6.75E-06	33	6.53E-06	53	6.88E-06
14	6.54E-06	34	6.58E-06	54	6.63E-06
15	5.96E-06	35	6.67E-06	55	6.36E-06
16	6.70E-06	36	6.43E-06	56	6.40E-06
17	6.54E-06	37	6.39E-06	57	6.00E-06
18	6.63E-06	38	6.91E-06	58	6.46E-06
19	6.65E-06	39	6.48E-06	59	6.52E-06
20	6.84E-06	40	6.48E-06	60	6.53E-06
				Average	6.4E-06
				COV	8.047

Table C.1 – The centroid of the first back echo and associated first and second trailing echoes for one bolt from each group.

Centroid of First back Echo with its 1st and 2nd Trailing Echoes for One Bolt from Each Groups (seconds)			
All (5 MHz)		All (10 MHz)	
Specimen	Centroid	Specimen	Centroid
1A	5.53E-06	1A	5.28E-06
1B	5.53E-06	1B	6.59E-06
1C	6.53E-06	1C	7.83E-06
1D	7.09E-06	1D	7.11E-06
1E	5.10E-06	1E	5.06E-06
1F	7.24E-06	1F	7.16E-06
1G	4.95E-06	1G	4.16E-06
1H	4.37E-06	1H	4.12E-06
1I	4.07E-06	1I	3.92E-06
1J	4.74E-06	1J	4.07E-06
1K	4.48E-06	1K	4.55E-06
1L	5.02E-06	1L	4.18E-06
1M	6.18E-06	1M	5.52E-06

APPENDIX D

THE AMPLITUDE RATIOS OF THE FIRST AND SECOND TRAILING ECHOES TO THE FIRST BACK ECHO

Table D.1 – Echo amplitude ratios for bolt groups A and C.

A	**Echo Amplitude Ratios**		**A**	**Echo Amplitude Ratios**		**C**	**Echo Amplitude Ratios**	
(5MHZ)	a_{1p}/a_{mp}	a_{2p}/a_{mp}	**(10MHZ)**	a_{1p}/a_{mp}	a_{2p}/a_{mp}	**(5MHZ)**	a_{1p}/a_{mp}	a_{2p}/a_{mp}
1	96.45	88.46	1	95.56	90.83	1	55.56	15.93
2	94.00	92.00	2	85.15	67.88	2	98.55	80.64
3	99.41	85.84	3	92.49	89.79	3	88.20	82.30
4	91.36	87.96	4	88.36	84.48	4	99.42	86.13
5	102.97	94.36	5	99.70	91.96	5	85.89	81.08
6	91.92	87.43	6	102.69	91.04	6	98.85	85.34
7	93.09	87.09	7	88.89	87.99	7	88.56	81.82
8	90.52	90.52	8	92.58	90.21	8	98.26	84.93
9	95.41	94.10	9	78.79	84.24	9	99.71	90.43
10	100.88	96.17	10	98.29	97.72	10	100.00	84.35
11	56.17	30.42	11	79.40	33.43	11	95.65	81.45
12	94.26	87.61	12	87.61	87.92	12	43.43	18.01
13	100.59	91.79	13	98.29	98.29	13	84.69	57.48
14	92.03	89.04	14	96.72	93.73	14	96.78	83.33
15	101.17	100.88	15	99.42	99.13	15	98.55	82.90
16	93.71	93.38	16	74.24	73.94	16	98.84	82.85
17	97.05	92.63	17	90.21	87.24	17	94.19	81.69
18	91.59	89.72	18	92.45	87.61	18	97.69	83.00
19	99.42	99.71	19	100.29	93.81	19	45.60	21.14
20	95.02	89.41	20	93.09	91.29	20	99.14	92.51
Average	93.85	88.43	Average	91.71	86.13	Average	88.38	72.86
COV %	10.01	15.71	COV %	8.28	16.38	COV %	19.95	32.66

Table D.2 – Echo amplitude ratios for bolt groups D, F, and M.

D	Echo Amplitude Ratios		F	Echo Amplitude Ratios		M	Echo Amplitude Ratios	
(5MHZ)	a_{1p}/a_{mp}	a_{2p}/a_{mp}	**(5MHZ)**	a_{1p}/a_{mp}	a_{2p}/a_{mp}	**(5MHZ)**	a_{1p}/a_{mp}	a_{2p}/a_{mp}
1	99.71	83.04	1	100.29	81.45	1	103.27	42.04
2	99.71	81.34	2	101.46	93.59	2	97.64	35.71
3	99.14	85.01	3	100.87	80.00	3	98.60	50.21
4	99.71	83.38	4	101.17	79.01	4	96.07	39.04
5	99.42	84.21	5	101.75	84.80	5	86.93	40.28
6	98.84	80.92	6	51.52	19.82	6	102.81	43.20
7	97.41	81.27	7	107.09	25.89	7	102.61	46.93
8	100.29	84.30	8	100.87	79.07	8	94.80	36.58
9	100.00	86.59	9	102.05	95.89	9	106.25	41.18
10	98.55	82.66	10	101.17	88.92	10	108.37	40.00
11	98.57	82.57	11	102.05	78.89	11	113.36	59.62
12	90.49	77.81	12	129.41	36.62	12	89.11	36.39
13	98.85	86.53	13	101.17	93.29	13	107.95	43.69
14	97.44	82.62	14	100.58	80.47	14	116.87	63.13
15	97.98	79.19	15	101.17	96.50	15	93.04	36.19
16	92.83	66.12	16	100.58	77.55	16	130.23	79.84
17	98.01	84.94	17	102.35	94.41	17	117.27	69.45
18	92.90	53.55	18	100.87	91.86	18	91.37	63.00
19	99.42	81.21	19	97.60	60.18	19	102.97	65.94
20	100.58	84.06	20	101.75	85.96	20	109.09	75.48
Average	97.99	80.57	Average	100.29	76.21	Average	103.43	50.40
COV %	2.72	9.32	COV %	12.81	29.23	COV %	10.12	27.76

Table D.3 – Echo amplitude ratios for bolt group B.

B	**Echo Amplitude Ratios**		**B**	**Echo Amplitude Ratios**		**B**	**Echo Amplitude Ratios**	
(5MHZ)	a_{1p}/a_{mp}	a_{2p}/a_{mp}	**(5MHZ)**	a_{1p}/a_{mp}	a_{2p}/a_{mp}	**(5MHZ)**	a_{1p}/a_{mp}	a_{2p}/a_{mp}
1	78.14	50.80	21	88.10	79.17	41	93.55	83.23
2	92.41	86.71	22	89.87	69.93	42	91.94	81.79
3	98.55	81.69	23	93.27	85.26	43	95.34	79.59
4	97.70	81.32	24	93.59	85.26	44	97.41	82.76
5	93.59	81.34	25	100.29	82.75	45	94.83	81.61
6	96.81	87.86	26	94.22	85.26	46	60.42	40.79
7	98.85	80.46	27	62.86	45.36	47	100.00	80.91
8	92.21	83.80	28	98.84	80.06	48	62.46	46.60
9	97.69	80.35	29	100.29	82.32	49	95.16	85.48
10	99.71	82.47	30	100.00	84.39	50	97.98	80.69
11	91.86	78.78	31	93.33	81.82	51	94.82	85.11
12	96.80	79.94	32	92.06	79.71	52	91.38	79.02
13	92.04	80.24	33	99.71	81.98	53	97.09	79.94
14	94.16	86.36	34	99.71	82.08	54	93.29	82.43
15	100.00	78.55	35	96.24	81.21	55	88.20	79.94
16	92.28	80.71	36	93.00	82.22	56	86.44	56.95
17	88.92	78.13	37	98.28	80.46	57	85.04	35.58
18	97.68	80.87	38	98.83	81.87	58	97.44	80.91
19	98.27	80.64	39	97.13	80.75	59	100.00	84.01
20	98.55	80.64	40	100.00	82.56	60	94.26	81.57
						Average	93.38	78.08
						COV %	9.00	14.34

Table D.4 – Echo amplitude ratios for one bolt from each group.

All (5MHZ)	Echo Amplitude Ratios		All (10MHZ)	Echo Amplitude Ratios	
	a_{1p}/a_{mp}	a_{2p}/a_{mp}		a_{1p}/a_{mp}	a_{2p}/a_{mp}
1A	96.45	88.46	1A	95.56	90.83
1B	78.14	50.80	1B	98.85	82.18
1C	55.56	15.93	1C	95.28	87.32
1D	99.71	83.04	1D	85.67	55.52
1E	108.61	95.90	1E	85.76	70.87
1F	100.29	81.45	1F	100.00	83.43
1G	184.91	129.25	1G	65.61	45.24
1H	103.64	89.39	1H	75.38	36.26
1I	135.83	58.00	1I	65.56	32.33
1J	184.08	180.82	1J	117.99	70.37
1K	102.97	102.08	1K	102.37	102.37
1L	266.67	266.67	1L	124.18	94.38
1M	103.27	42.04	1M	77.30	30.33

APPENDIX E

THE ACTUAL DIMENSIONS OF ALL BOLT GROUPS

Table E.1 – the actual dimensions for bolt groups A, C, and D.

A	Diameter	Length	C	Diameter	Length	D	Diameter	Length
1	0.51	4.82	1	1.00	5.13	1	0.75	5.92
2	0.50	4.82	2	1.00	5.15	2	0.75	5.92
3	0.50	4.83	3	0.99	5.16	3	0.75	5.90
4	0.51	4.84	4	1.00	5.15	4	0.75	5.92
5	0.51	4.85	5	1.00	5.13	5	0.75	5.91
6	0.51	4.84	6	1.00	5.15	6	0.75	5.94
7	0.50	4.83	7	1.00	5.11	7	0.76	5.92
8	0.51	4.82	8	1.01	5.16	8	0.75	5.90
9	0.51	4.84	9	1.00	5.16	9	0.75	5.92
10	0.51	4.83	10	1.00	5.15	10	0.75	5.93
11	0.50	4.85	11	1.02	5.16	11	0.76	5.92
12	0.50	4.84	12	1.00	5.14	12	0.75	5.92
13	0.50	4.84	13	0.99	5.13	13	0.75	5.94
14	0.51	4.83	14	1.00	5.15	14	0.75	5.92
15	0.51	4.82	15	1.00	5.14	15	0.76	5.93
16	0.51	4.85	16	1.00	5.12	16	0.76	5.93
17	0.51	4.82	17	0.99	5.15	17	0.75	5.92
18	0.51	4.84	18	1.01	5.13	18	0.75	5.91
19	0.50	4.84	19	1.00	5.17	19	0.75	5.94
20	0.51	4.83	20	1.01	5.13	20	0.75	5.92
Average	0.51	4.83	Average	1.00	5.14	Average	0.75	5.92
COV %	0.70	0.23	COV %	0.61	0.30	COV %	0.33	0.17

Table E.2 – the actual dimensions for bolt group B.

B	Diameter	Length	B	Diameter	Length	B	Diameter	Length
1	0.749	4.926	21	0.753	4.92	41	0.753	4.915
2	0.751	4.912	22	0.75	4.934	42	0.75	4.924
3	0.750	4.931	23	0.749	4.939	43	0.752	4.946
4	0.750	4.897	24	0.746	4.945	44	0.748	4.938
5	0.749	4.906	25	0.749	4.913	45	0.752	4.919
6	0.749	4.943	26	0.753	4.928	46	0.751	4.954
7	0.747	4.943	27	0.745	4.926	47	0.751	4.914
8	0.752	4.920	28	0.749	4.919	48	0.751	4.887
9	0.750	4.921	29	0.747	4.927	49	0.749	4.928
10	0.751	4.928	30	0.747	4.909	50	0.747	4.93
11	0.751	4.931	31	0.751	4.922	51	0.751	4.918
12	0.747	4.920	32	0.75	4.936	52	0.745	4.92
13	0.749	4.927	33	0.747	4.943	53	0.748	4.922
14	0.751	4.936	34	0.75	4.924	54	0.751	4.93
15	0.748	4.926	35	0.756	4.92	55	0.752	4.923
16	0.751	4.927	36	0.75	4.919	56	0.749	4.921
17	0.745	4.919	37	0.752	4.921	57	0.75	4.933
18	0.751	4.926	38	0.749	4.914	58	0.75	4.918
19	0.750	4.930	39	0.75	4.929	59	0.746	4.932
20	0.751	4.911	40	0.744	4.932	60	0.75	4.906
						Average	0.7496	4.924
						COV %	0.303115	0.239

Table E.3 – the actual dimensions for bolt groups E, F, and G.

E	Diameter	Length	F	Diameter	Length	G	Diameter	Length
1	0.501	6.867	1	0.746	7.262	1	0.503	7.380
2	0.503	6.841	2	0.744	7.271	2	0.502	7.373
3	0.501	6.841	3	0.746	7.264	3	0.502	7.384
4	0.503	6.838	4	0.745	7.266	4	0.500	7.356
5	0.506	6.844	5	0.743	7.344	5	0.503	7.390
6	0.500	6.858	6	0.743	7.217	6	0.502	7.379
7	0.503	6.859	7	0.745	7.327	7	0.504	7.393
8	0.501	6.862	8	0.743	7.279	8	0.501	7.384
9	0.504	6.849	9	0.744	7.326	9	0.500	7.386
10	0.505	6.849	10	0.749	7.271	10	0.500	7.368
11	0.502	6.837	11	0.749	7.326	11	0.509	7.383
12	0.505	6.856	12	0.745	7.327	12	0.503	7.378
13	0.503	6.847	13	0.744	7.336	13	0.502	7.415
14	0.501	6.865	14	0.742	7.334	14	0.506	7.374
15	0.505	6.841	15	0.746	7.335	15	0.504	7.368
16	0.502	6.843	16	0.746	7.277	16	0.501	7.400
17	0.499	6.847	17	0.742	7.332	17	0.503	7.377
18	0.502	6.847	18	0.745	7.346	18	0.503	7.382
19	0.504	6.838	19	0.742	7.345	19	0.505	7.375
20	0.502	6.841	20	0.742	7.330	20	0.501	7.378
Average	0.503	6.849	Average	0.745	7.306	Average	0.503	7.381
COV %	0.367	0.138	COV %	0.281	0.519	COV %	0.438	0.169

Table E.4 – the actual dimensions for bolt groups H, I, and J.

H	Diameter	Length	I	Diameter	Length	J	Diameter	Length
1	0.493	7.648	1	0.492	7.731	1	0.501	9.839
2	0.494	7.653	2	0.492	7.743	2	0.501	9.840
3	0.493	7.645	3	0.493	7.733	3	0.501	9.830
4	0.492	7.656	4	0.493	7.736	4	0.501	9.842
5	0.493	7.654	5	0.493	7.741	5	0.500	9.824
6	0.493	7.650	6	0.494	7.721	6	0.500	9.839
7	0.493	7.642	7	0.494	7.735	7	0.503	9.836
8	0.493	7.653	8	0.492	7.728	8	0.500	9.835
9	0.493	7.659	9	0.493	7.730	9	0.503	9.830
10	0.494	7.656	10	0.493	7.737	10	0.499	9.830
11	0.492	7.642	11	0.495	7.727	11	0.500	9.838
12	0.493	7.646	12	0.494	7.734	12	0.499	9.832
13	0.492	7.654	13	0.495	7.733	13	0.500	9.854
14	0.493	7.648	14	0.493	7.730	14	0.503	9.828
15	0.493	7.631	15	0.494	7.731	15	0.500	9.812
16	0.491	7.652	16	0.492	7.744	16	0.498	9.844
17	0.492	7.649	17	0.493	7.736	17	0.503	9.836
18	0.497	7.637	18	0.495	7.730	18	0.495	9.816
19	0.495	7.647	19	0.492	7.728	19	0.499	9.840
20	0.495	7.651	20	0.493	7.731	20	0.500	9.839
Average	0.493	7.649	Average	0.493	7.733	Average	0.500	9.834
COV %	0.268	0.089	COV %	0.207	0.072	COV %	0.384	0.097

Table E.5 – the actual dimensions for bolt groups K, L, and M.

K	Diameter	Length	L	Diameter	Length	M	Diameter	Length
1	0.500	10.835	1	0.500	11.364	1	0.748	11.413
2	0.500	10.828	2	0.500	11.364	2	0.750	11.408
3	0.500	10.845	3	0.502	11.375	3	0.747	11.400
4	0.500	10.840	4	0.502	11.380	4	0.750	11.408
5	0.510	10.840	5	0.503	11.379	5	0.749	11.402
6	0.500	10.848	6	0.501	11.391	6	0.750	11.416
7	0.501	10.843	7	0.499	11.375	7	0.751	11.402
8	0.500	10.857	8	0.499	11.385	8	0.747	11.410
9	0.503	10.856	9	0.497	11.372	9	0.746	11.404
10	0.500	10.833	10	0.500	11.383	10	0.749	11.400
11			11	0.501	11.389	11	0.744	11.400
12			12	0.499	11.383	12	0.752	11.423
13			13	0.500	11.356	13	0.749	11.404
14			14	0.499	11.384	14	0.758	11.410
15			15	0.502	11.356	15	0.753	11.415
16			16	0.499	11.380	16	0.748	11.397
17			17	0.499	11.364	17	0.751	11.396
18			18	0.499	11.395	18	0.745	11.412
19			19	0.499	11.369	19	0.746	11.407
20			20	0.499	11.354	20	0.749	11.400
Average	0.501	10.843	Average	0.500	11.375	Average	0.749	11.406
COV %	0.620	0.087	COV %	0.294	0.107	COV %	0.417	0.062