# A COMPARISON OF THE PERFORMANCE OF SEVERAL IMPACT ECHO TRANSDUCERS AND APPLICATION OF IMPACT ECHO NDT TO THE LINCOLN MEMORIAL IN WASHINGTON, D.C.

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**ABSTRACT**

The Impact Echo (IE) test method is an acoustic wave-based nondestructive method for evaluating conditions of concrete structures. The method is capable of evaluating material properties, locating cracks, determining thicknesses, etc, under the proper conditions. Recently, interest in the IE test method has been growing rapidly as both the amount of use and the capabilities of the method have increased. The development of commercially available IE test systems has allowed much greater use of the method, while the recent developments of scanning and other high-speed applications of the method have greatly increased the testing rates (by factors of up to 100 or more). In conjunction with the recent advances in the IE testing method,

there has been discussion within technical circles as to the relative performance and responses of several different acoustic transducers used as Impact Echo (IE) receivers. This paper presents a comparison of the responses of three popular transducers when used for IE testing, including a standard accelerometer and two displacement transducers currently used in commercial IE test systems. The Impact Echo method is applicable to testing a wide variety of structures. One recent application of the method was in the evaluation of the condition and as-built dimensions of the concrete members in the Lincoln Memorial in Washington, D.C. Included in this paper is a brief overview of this application of the IE test method.

## INTRODUCTION

The first part of this paper will present a brief summary of the Impact Echo (IE) method, and then will continue with the comparison of the performance of the three different transducers. The authors are not aware of any previous published comparison of these transducers for this application. The second part of this paper will present the application of the IE method to tests on the Lincoln Memorial. The IE method was used on this structure both to evaluate the current condition of concrete elements, and to measure as-built thicknesses of certain members.

## IMPACT ECHO METHOD DESCRIPTION

The IE test method and its applications have been described in detail in previous publications [1,2]. The IE method has traditionally been performed on a point-by-point basis by hitting the test surface at a given location with a small (90 grams (0.2 lb)) instrumented impulse hammer or impactor and recording the reflected wave energy with a displacement or accelerometer receiver mounted to the test surface adjacent to the impact location. Since the reflections are more easily identified in the frequency domain, the time domain test data of the impulse hammer (if measured) and receiver are processed by a dynamic signal analyzer for frequency domain analyses. For data collected with the impulse hammer and accelerometer, a transfer function (system output/input) is then computed between the hammer (input) and the receiver (output) as a function of frequency. If an impactor is used instead of an instrumented hammer, then just the linear displacement spectrum of the receiver signal is computed and displayed. Reflections, or “echoes”, of the compression wave energy are typically indicated by pronounced “echo” peaks in the transfer function or frequency spectrum test records. These peaks correspond to thickness or flaw depth resonant frequencies. If the velocity of the concrete is known or can be measured, then the depth of a reflector can be calculated from the echo peak frequency as depth equals velocity divided by twice the echo peak frequency.

## IMPACT ECHO TRANSDUCER COMPARISON

The comparison of IE transducers was done using three transducers which are currently, or have in the past, been used extensively for IE testing. The transducers tested include a PCB 303A02 accelerometer, a NIST-designed conical tip acoustic emission transducer (similar to that used by one current commercial IE testing system), and a proprietary displacement transducer designed and built by Olson Engineering for use in another commercially available IE test system. The relative performance of the three transducers was compared in several ways. First, tests were performed from the top of a standard 6x12 in cylinder (12 inches (30.5 cm) high and 6 inches (15.25 cm) in diameter), followed by tests on a nominally 5.5 inch (14.0 cm) thick slab-on-grade. For the cylinder, frequency spectra data were compared and are included herein. For the slab, both the relative time domain performance and the spectral responses of the transducer were compared. Note that the spectral response of the accelerometer was compared both as acceleration and after integration to displacement. The rationale behind the use of the cylinder as a test member is based on the typical response of a cylinder. Impact Echo tests on a cylinder produce a wideband set of very repeatable, predictable frequency peaks which are significantly different in relative amplitude for a displacement transducer compared to a velocity or acceleration transducer. Thus, testing on a cylinder shows most clearly the differences in expected response between the different transducer types over a wide range of frequencies. The time domain tests on the slab are presented to show the responses of the transducers on a more typical slab-like test member. Most IE tests are performed on slab-like structures such as these. Note that since the IE method uses only an analysis of spectra (or transfer function) data as its basis, the comparison of the spectral responses of various receivers is the best and most relevant comparison of their performance for IE testing. Time domain traces for some of the tests are presented in this paper in support of the spectral records and to provide an additional basis of comparison. Since the relative amplitude and frequency of spectral peaks comprise the valuable information of an IE test, all of the amplitude axes are relative voltage scales without rescaling to give standard units.

Cylinder Impact Echo Tests

The first data set presented is the spectral response of the NIST displacement transducer from an IE test on the end of the 6x12 cylinder. The cylinder has a measured IE-based velocity of 10,300 feet per second (3,380 m/s). Impacts were produced by a small hand-held impactor which produced impacts with a contact time of 50-60 microseconds. This corresponds to a maximum bandwidth of about 17-20 kHz. Note that all receiver data on the cylinder was taken with a wideband amplifier with only a 150 Hz high-pass filter.

The spectral response of the NIST transducer is seen in Fig. 1a. The very high amplitude, very low frequency peak seen (630 Hz) is from the low-frequency natural resonance of the NIST transducer assembly. The NIST transducer was placed on a strip of aluminum foil tape to provide the required electrical contact. The spectral data plot from this transducer is a plot of relative (un-scaled) displacement amplitude versus frequency. As seen in the figure, three relevant resonance peaks are evident. The largest peak is from the top-bottom resonance, with a frequency of 5.13 kHz. This corresponds to a measured thickness of 12.03 inches (30.6 cm). The remaining peaks in the response are higher-order resonances which could be predicted from the shape of the cylinder.

In Fig. 1b, the spectral response of the OLSON displacement transducer is presented. The OLSON transducer was pressed against the cylinder top by hand, and was dry-coupled (no couplant) to the surface. The primary resonance peak measured for the cylinder by this transducer is also 5.13 kHz, which again corresponds to a measured thickness of 12.03 inches (30.6 cm). This transducer also shows the low-frequency resonance of the transducer body at about 1000 Hz. Note that the response of this transducer is almost identical to that of the NIST transducer, other than the amplitudes of secondary resonances and body resonances. The small differences seen at higher frequencies are due to the different physical locations of the transducers on the cylinder top. Thus, it can be assumed that these two transducers are similar in performance for at least the frequency range of 6 to 15 kHz, which is the frequency range of the peaks evident in the spectra.

The unintegrated accelerometer response to an IE test on the same cylinder is presented in Fig. 1c. A PCB 303A02 accelerometer was used for this testing. The accelerometer was magnetically mounted to a grease-coupled washer on the top of the cylinder. Note that, in agreement with basic physics, the high-frequency peaks of the accelerometer spectra are much greater in relative amplitude than those of the two displacement transducers. Integrating the acceleration response (twice) will produce the equivalent displacement spectra as presented in Fig. 1d , and is done by dividing the amplitude of each spectral line by $(2*pi*frequency)^2$. This will effectively decrease the relative amplitude of the higher frequency components relative to the lower frequencies, and will result in a spectra similar to that of the displacement transducers. Note that for the acceleration spectra (Fig. 1c), the locations (frequencies) of the peaks are the same as those of the displacement spectra (Fig. 1d), but the relative amplitudes are different.

Slab Impact Echo Tests

The final sets of data presented are the time and spectral responses of an IE test on a nominally 5.5 inch (14.0 cm) thick slab-on-grade. Time domain data traces for these tests are presented in Figs. 2a, 2b, and 2c for the NIST and OLSON transducers, and the accelerometer, respectively. The data from these tests was collected with no filtering, and the impact source was a small impactor striking the surface. The three traces are from the three receivers responding to a similar impact at closely spaced locations on the slab. The primary echo frequency of the slab can be measured from the figures by measuring the time between adjacent major downward peaks. These downward peaks correspond to multiple reflections of the initial impact as it travels between the top and bottom of the slab. The frequency of these peaks corresponds to the 12.24 kHz peak which is the highest amplitude peak in the spectral responses (Fig. 3a, b). The minor differences in the two responses is most likely due to the different locations of the two transducers on the slab. The location differences will have a minor effect on the primary resonance response, as well as the response of the transducers to surface wave energy and other reflections. As seen in the figures, there are only minor differences between the first two responses (the two displacement transducers), while the accelerometer response is very different. The difference is due to two primary factors. The accelerometer has not been integrated to displacement, and the accelerometer does not have the low-frequency resonance from its structure that the two displacement transducers have. Note that the low frequency transducer structural resonance is normally filtered out for IE tests. This filtering sets the lower frequency limit response of the transducer for IE tests, which in turn sets a limit on the maximum thickness which can be measured in the IE test with a given transducer.

The frequency domain (spectral) responses of the IE tests on the slab are presented in Figs. 3a, 3b, 3c, and 3d. Included in this set are the responses of the NIST and OLSON displacement transducers, and the unintegrated and integrated responses of the accelerometer. Note that the NIST and OLSON responses are almost identical, and are similar to that of the integrated accelerometer. The unintegrated accelerometer spectra shows the same frequency peak for the floor slab as the others. This is due to the fact that integration changes relative amplitude of frequency peaks, but not the frequencies themselves. For a slab-like object, the IE spectral response has a single peak corresponding to the thickness of the slab. Integrating the response does not change this frequency, but may bring out details of shallow defects.

## APPLICATION OF THE IMPACT ECHO METHOD TO THE LINCOLN MEMORIAL

The Lincoln Memorial in Washington, D.C. is a historic structure of great significance in the United States. It has recently been the subject of projects to both document and rehabilitate the structure. The IE method was used in conjunction with other NDT methods for two different projects. The first of these was a condition survey of concrete portions of the memorial under the Raised Terrace and Approachway Slabs. The second project using NDT was a preliminary stone survey. This project was primarily a feasibility study of the use of NDT methods in characterizing the internal conditions of various stone members, primarily marble, in the memorial. In this section of the paper, a brief summary of the use of the IE method in each of these investigations is presented.

Impact Echo Method Used for Concrete Condition Evaluation

The IE method was used in this investigation primarily on the Raised Terrace surrounding the memorial and the Approachway Slab in front of the memorial. Each of these areas consists of elevated concrete slabs. The Raised Terrace has soil and grass on top of the slab, while the Approachway Slab has two concrete layers with a pedestrian walkway above. All IE tests were conducted from the slab bottoms looking upward.

***Raised Terrace***

The IE tests on the Raised Terrace were conducted on the south and southwest portions of the structure. Tests were conducted from the slab bottom after sounding and chipping of the concrete. There was significant areas of spalling present in the concrete prior to the chipping operation, and areas which were found to be obviously hollow during sounding were not tested with the IE method as they would simply have shown near-surface delamination conditions. Observed concrete conditions ranged from good to spalled to cracked concrete with exposed, corroded rebar and rust staining.

A total of 533 locations were tested in this part of the memorial with the IE method. The concrete of the Raised Terrace was found by the IE tests to range from 10 to 24 inches (25.4 to

61.0 cm) thick. Later coring at limited locations confirmed these results, showing thicknesses of 10 to 17 inches (25.4 to 43.2 cm) at the core locations. The IE tests varied by location within the Raised Terrace areas, with some sections showing mostly sound conditions and other sections showing a number of top and/or bottom discontinuities in the concrete. A sample record from a sound location on the Raised Terrace is presented in Fig. 4. This record was taken using an accelerometer as the transducer, with the spectra double-integrated to give displacement. Note the clear thickness echo at 6.2 kHz, corresponding to 10.8 inches (27.4 cm) in thickness. The clear backside echo and lack of any additional high frequency echoes indicate this location to be sound.

***Approachway Slab***

The IE tests on the Approachway Slab were conducted at various areas from the bottom of the slab. This slab was subject to daily washing on the top with significant leakage of water through the concrete. As a result, there were extensive "soda straws" and other calcite deposits below the concrete. Tests were again conducted from the slab bottom after sounding and chipping of the concrete. Observed concrete conditions for this area also ranged from good to spalled to cracked concrete with exposed, corroded rebar and rust staining.

A total of 231 locations were tested in this part of the memorial with the IE method. The concrete of the Approachway Slab consisted of two layers which were expected to be bonded together. Overall thickness of both layers was 15 to 17 inches (38.1 to 43.2 cm). The IE test results for this area showed generally sound conditions, with only 18% of the locations indicating open or closed discontinuities. Later coring at limited locations confirmed these results, showing thicknesses of 15 to 17 inches (38.1 to 43.2 cm) with some debonding between the upper and lower concrete layers at locations indicated by the IE test results. A sample record from a location with an open discontinuity (crack or interlayer debond) on the Approachway Slab is presented in Fig. 5. This record was again taken using an accelerometer as the trasnducer, with the spectra double-integrated to give displacement. Note the clear thickness echo at 11.2 kHz, corresponding to 6.5 inches (16.5 cm) in thickness. The lack of a backside echo (17 inches (43.2 cm) thickness expected) and the presence of the strong shallow reflector indicate this location to have an open crack or debond at 6.5 inches (16.5 cm) above the bottom of the slab. It should be noted that the depth of the reflector corresponds to the expected depth of the interface between concrete layers.

Impact Echo Method Used for Marble Block Condition Evaluation

The IE method was used in a second investigation on the Lincoln Memorial to evaluate the effectiveness of the method on massive marble blocks (stylobates) around the base of the structure The blocks were about 8 feet (2.6 m) long, 45 inches (1.2 m) wide, and 29 inches (0.8 m) deep. Many of the blocks appeared to have visible horizontal cracks or inclusions, but it was not known how deep these cracks extended or if they were simply surface flaws. IE tests were performed on selected stylobates with visible cracks and compared to those on sound areas. The test results showed that the IE method was effective for cracks parallel to the test surface, and was very effective in estimating the depth of the cracks on the horizontal plane when testing from above. Many of the appearent cracks were found to be shallow, likely from inclusions in the marble. The testing showed the IE method to be insensitive to cracks perpendicular to the test surface, unless the tests were conducted across the cracks, with the impact on the opposite side from the receiver.

## CONCLUSIONS

The testing performed provides a good comparison of the performance of the three transducers: the NIST-developed conical tip displacement transducer, the OLSON-developed scanning and fixed displacement transducer, and the PCB 303A02 accelerometer. As seen in both time domain and spectral response data traces, the OLSON transducer and the NIST transducer have nearly identical responses to IE-type excitations on concrete test surfaces. The accelerometer spectral response provides a very good comparison of the expected differences between a typical displacement response and a typical acceleration response. The Impact Echo method also proved to be a very effective tool in evaluating the condition of both concrete and rectangular stone members of the Lincoln Memorial, using an accelerometer as the transducer. The overall conclusion of this work is that all three transducers provide equally acceptable IE receiver performance, so long as the accelerometer response spectra is integrated to provide a displacement response plot. The author's wish to thank the National Park Service of the U.S. Department of Interior for permission to discuss the Lincoln Memorial data.

## REFERENCES

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2. Olson, L., Sack, D. and Phelps, G., "Sonic NDE of Bridges and Other Concrete Structures," National Science Foundation Conference on Nondestructive Evaluation of Civil Structures, University of Colorado at Boulder (1992).

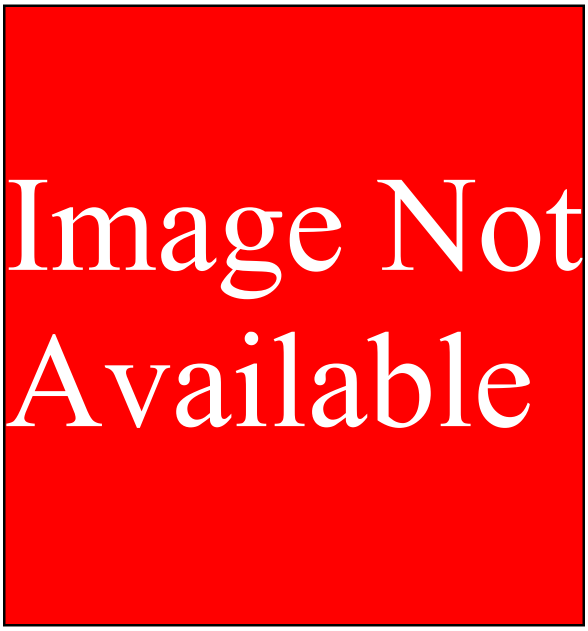


Fig. 1a  NIST Transducer Spectral Response on Cylinder

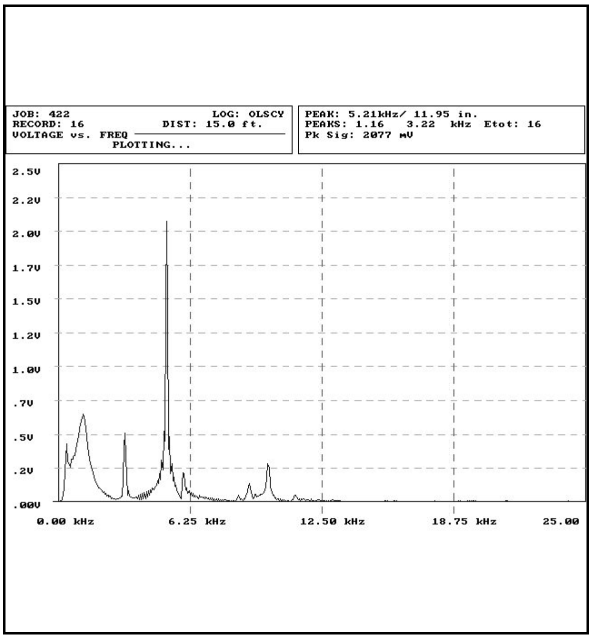


Fig. 1b Olson Displacement Transducer Spectral Response on Cylinder

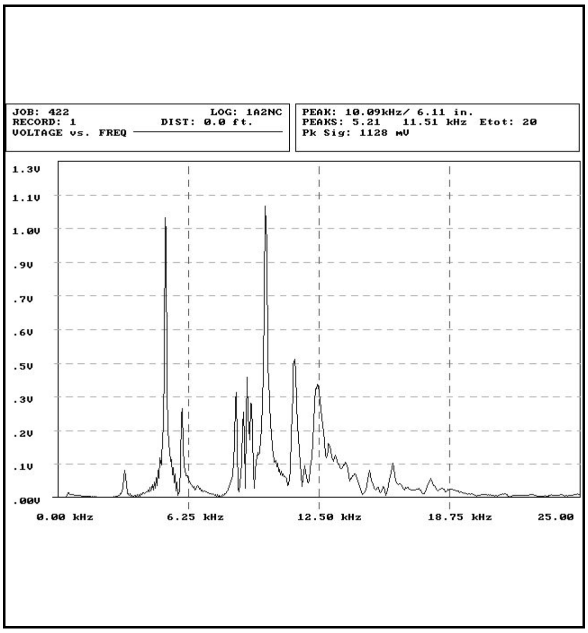


Fig. 1c Accelerometer Spectral Response on Cylinder, Unintegrated

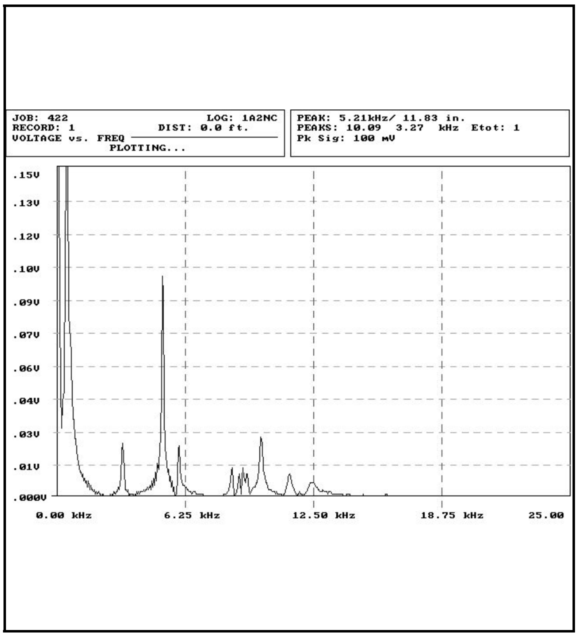


Fig. 1d Accelerometer Spectral Response on Cylinder, Integrated to Displacement

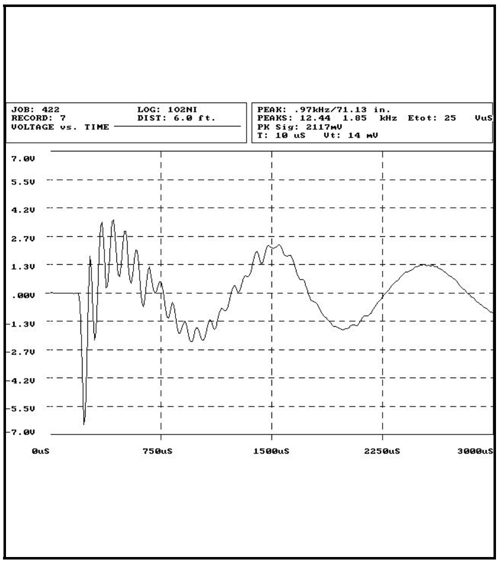


Fig. 2a NIST Displacement Transducer Time Response on a Slab

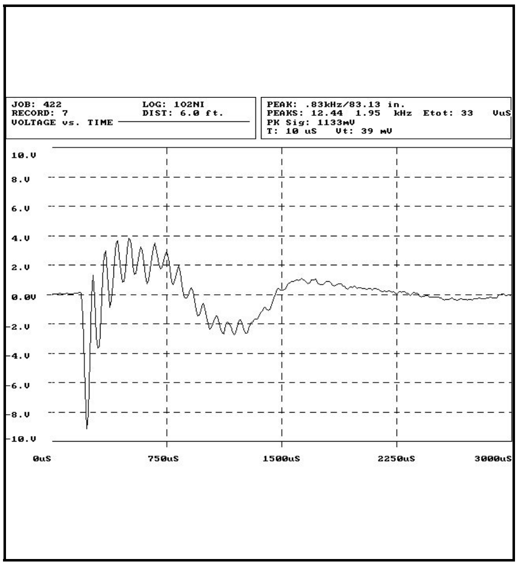


Fig. 2b Olson Displacement Transducer Time Response on a Slab

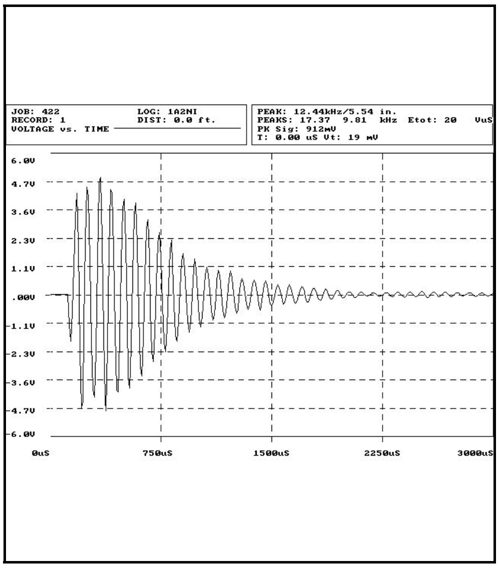


Fig. 2c Accelerometer Time Response on a Slab

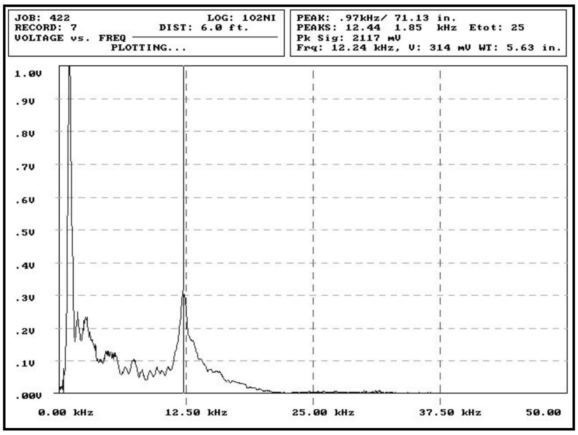


Fig. 3a NIST Displacement Transducer Spectral Response on a Slab

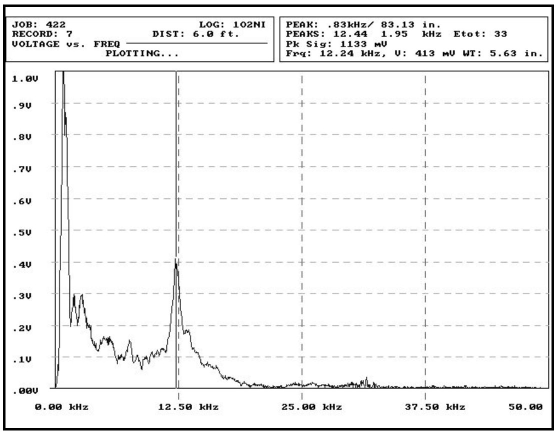


Fig. 3b OLSON Displacement Transducer Spectral Response on a Slab

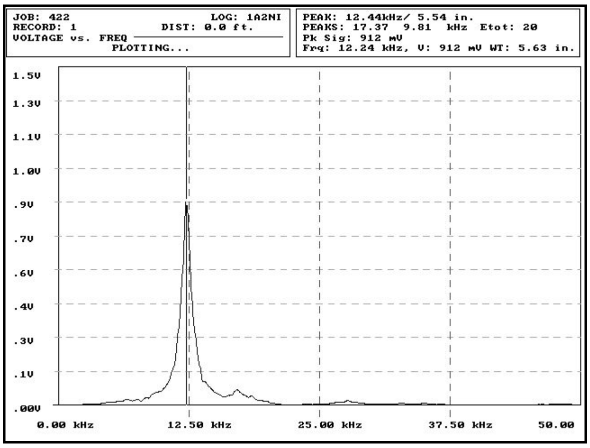


Fig. 3c Accelerometer Spectral Response on a Slab, Unintegrated

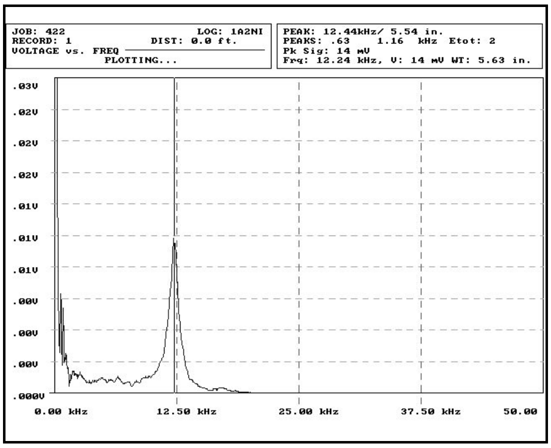


Fig. 3d Accelerometer Spectral Response on a Slab, Integrated to Displacement

Fig. 4 Impact Echo Test Record, Sound Concrete Conditions

Fig. 5 Impact Echo Test Record, Cracked/Debonded Conditions