TECHNICAL NOTE

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Rapid, Noninvasive Contraband Detection by Acoustic Response

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ABSTRACT: We present here a simple, inexpensive method for the rapid detection of concealed contraband materials. This method exploits the difference in acoustic response between a hollow, contraband-laden host and a solid object of the same type. We model the concealment as a damped resonator and contrast it with the unperturbed unit, which is solid and therefore exhibits less damping upon excitation. Next we present the laboratory results that confirmed the efficacy of the technique, prior to on-site deployment as part of a narcotics investigation. Finally, we summarize the results in situ and offer concluding comments.

KEYWORDS: engineering, contraband detection, acoustic response

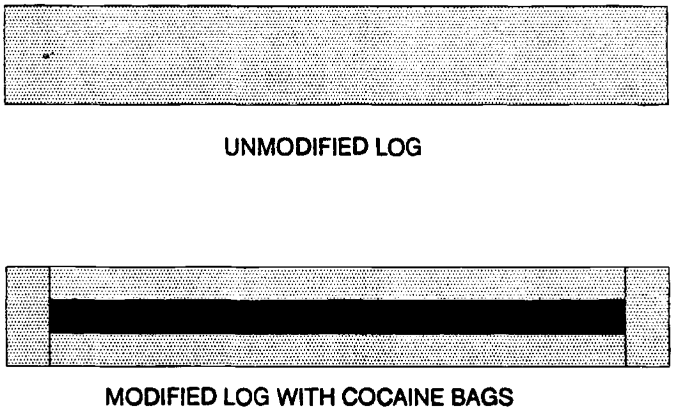

FIG. 1—*Solid log versus modified log.*

Some of the techniques now used operationally for the noninvasive detection of contraband secreted within hidden cavities include X-ray imaging (Transmission and Compton Backscatter), measurement of differences in dielectric constant, and canine olfactory response (sniffing). Mobile X-ray units are expensive and cumbersome to operate when the rapid imaging of large numbers of bulky containers is required. Dielectrometers are severely limited by the type and thickness of the concealment material. Trained dogs, though extremely sensitive, are becoming less effective against increasingly sophisticated forms of concealment.

The technique described herein was developed in support of a major narcotics investigation, where suspects were believed to be smuggling bags of cocaine concealed within wooden (mahogany) railroad ties. The concealment was effected by cutting a log across its width and then coring out the center. Bags of cocaine were then placed inside the hollow portion of the log. The two pieces were then rejoined and tar was used to cover the entire railroad tie (Fig. 1).

These compromised logs were being shipped into the United States among a much larger but externally indistinguishable shipment of unaltered ties. The problem facing law enforcement officials was how to rapidly and non-invasively detect the presence of cocaine in at least one of the transported ties, in order to effect an arrest of the subjects upon delivery of the shipment.

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The method employed in this instance consisted of exploiting the acoustic differences manifest in a hollow versus solid structure. This entailed striking the railroad tie with a hammer and simultaneously using an accelerometer as a sensor that is connected to a signal analyzer. The signal analyzer displays a trace of the acoustic energy derived from the hammer blow as a function of time. This is a more quantitative version of the "low tech" equivalent of merely listening to differences in pitch.

Our method models the acoustic response of solid and compromised logs as classic harmonic resonators. In the case of the hollowed units, the energy is increasingly damped by the introduction of lossy material. This energy damping is easily visible in the time domain. In addition, we hypothesize that anomalous modes of propagation are present due to the introduction of acoustic impedance mismatches between wood and a less dense medium, which are observable when analyzed in the frequency domain.

The method developed for this investigation may be useful in general, where the rapid detection of a specific, compromised host hidden among a cache of similar but unmodified structures is required. Furthermore, the effectiveness of this method would be independent of the concealed material in the cavity, and would be difficult to defeat due to the inherent loss of homogeneity and subsequent acoustic impedance mismatch, once the integrity of the host has been compromised through the hollowing procedure.

Theory

The theory of the classical harmonic oscillator is well known and forms the basis for the behavior of many of the vibratory phenomena that occur in nature. We refer the reader to references [*1*] and [*2*] where a brief introduction to the basic theory can be found. Similar descriptions can also be found in any physics text on vibrations and waves. We then begin by introducing the notion of damped harmonic motion, which we proffer as the theoretical model for the detection mechanism described herein.

Admissable solutions to differential equations describing damped harmonic motion are of the form of a decaying exponential,

$$c(0)\exp(-st), \tag{1}$$

where $C(0)$ is the initial amplitude, for any time $t > 0$. The decay constant s inherently manifests all of the loss mechanism of the wave's interaction with the medium.

Next, consider a solid rectangular block comprised of wood. A hammer striking against one end of the block will excite an acoustic pressure wave that propagates inside the block. This wave then reflects back and forth (through many different paths) till the energy in the wave completely dissipates, due to "internal friction." A block of wood that has been hollowed and filled with bags of low density contraband, will have lower density, less rigid, and highly dissipative air-contraband cavity contents (Fig. 1). The acoustic impedance mismatch that occurs at a wood/air iterface will necessarily affect the paths of energy propagation by effectively changing the interior cavity dimensions. The results are changes in vibratory modes that are observable when analyzed in the frequency domain.

The speed of sound in soft wood is equal to about 11,000 feet per second, nearly ten times that of the speed of sound in air at standard temperature and pressure (1089 ft/s).

The characteristic acoustic impedance Z, for an acoustic wave traveling in a medium is defined as the density of that medium d, multiplied by the velocity of sound in that medium v:

$$Z = d X v \tag{2}$$

As an example, we calculate the reflection coefficient for an acoustic wave traveling in wood and then hitting a wood/air interface. This will yield the fraction of energy reflected each time such an interface is encountered by the wave as it oscillates back and forth inside such a cavity.

The square of the reflection coefficient R for two media, indexed as (1) and (2), is defined as

$$R^2 = \left(\frac{Z(1) - Z(2)}{Z(1) + Z(2)}\right)^2 \tag{3}$$

We now examine the case of a wood/air interface. The act of coring out the central portion of the logs will necessarily introduce wood/air interfaces within the concealment, causing large fractions of the multipath-rich energy to be reflected. In addition, the huge acoustic impedance mismatch between wood and air (or wood and cocaine) is independent of the wavelength of the acoustic energy. The result is that even a thin air pocket will have a profound effect on propagation.

Let $Z(1)$ = acoustic impedance presented by wood. Using equation (2), where d (wood = yellow pine) = 30 lbs/cubic ft, v (wood) = 10,991 ft/s, we get $Z(1)$ = 329,730. 00 lbs/square ft-s. Let $Z(2)$ = acoustic impedance presented by air. Using (2) once more, d (air) = .0807 lbs/cubic ft, v (air) = 1089 ft/s, we get $Z(2)$ = 87.88 lbs/square ft-s. Substituting these values for $Z(1)$ and $Z(2)$ into (3) yields .99. This means that each time the wave encounters a transition from wood-to-air, 99% of the incident energy is reflected back from the interface. Conversely, only 1% of the remaining energy is transmitted for each traversal of a wood/air interface. This in effect, severely affects wave propagation within the cavity, which we claim results in the introduction of modes of propagation that otherwise are not supported in a completely solid resonator. Unlike fluid motion, solids support transverse acoustic waves or shear waves, in which the particles move at right angles to the direction of sound propagation. The acoustic response of a solid bar is complicated by those additional modes, that travel at different speeds.

Experimental Results

Figures 2 and 3 are characteristic of our experimental results. Figure 2 represents a time domain measurement of the acoustic response of an unmodified (solid) railroad tie made of yellow pine. The presence of cocaine was simulated using bags of sugar. A hammer was used to strike one end of the tie and an Etalon accelerometer, resonant at 50 kHz was hand-held on the same end for use as a transducer. A Hewlett Packard 3561 Dynamic Signal Analyzer measured the transient response of the acoustic energy (Fig. 4).

The frequency f of the principal mode of propagation in the undamped case is 1225 Hz corresponding to a reflection from the far end of a tie of length $v/2f$ = 4.49 ft where v is the velocity of

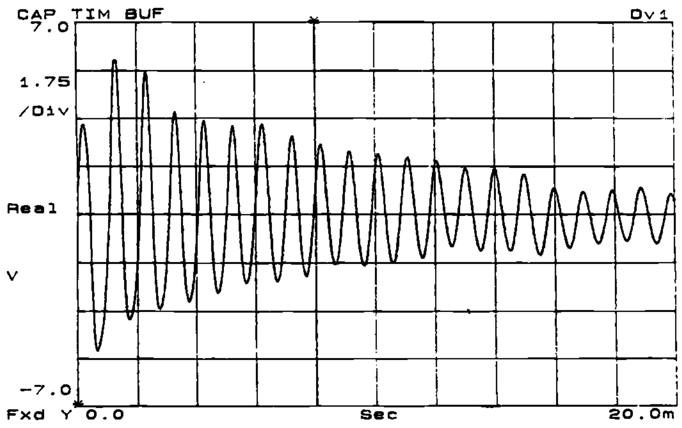

FIG. 2—*Unmodified tie, undamped structure.*

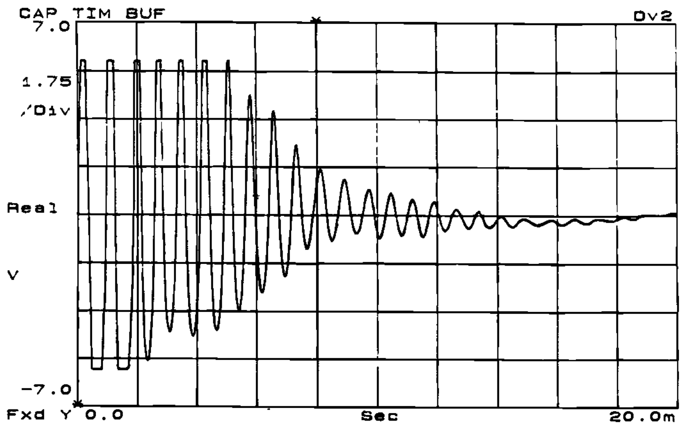

FIG. 3—*Modified tie, damped structure.*

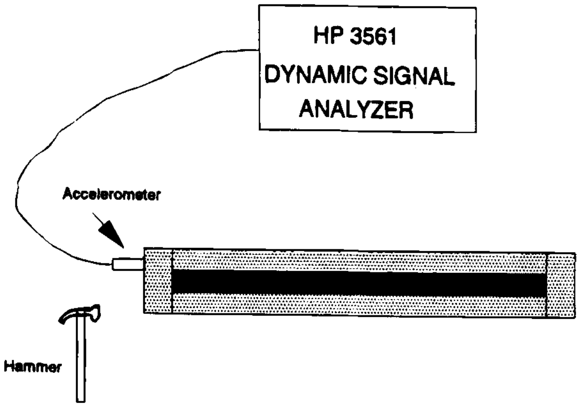

FIG. 4—*Instrumentation setup.*

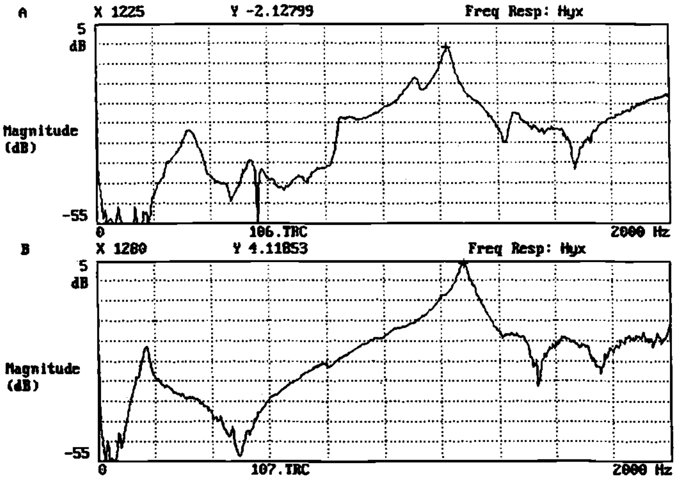

FIG. 5—(A) *Frequency response of unmodified tie;* (B) *frequency response of modified tie.*

sound in wood. The actual length of the laboratory ties was about six feet, indicating that the value used for the velocity of sound in generic wood may be too low when applied to computations for yellow pine in particular. The characteristic wave form is that of a sinusoid with a decaying exponential envelope.

The maximum amplitude is measured to be approximately 9.6 volts (an exact measurement is not available because of saturation of the electronics that produced the observed clipped signal). The time of propagation where the signal is at $1/e$ of its initial value is 11.1 msec.

Figure 3 represents a time domain response following hammer excitation of a railroad tie that was hollowed and then filled with bags of sugar. The maximum value is measured to be approximately 11.4 volts. In this case, the time in which the acoustic signal is at $1/e$ of its initial value is 3.1 msec. The difference in the value of the initial amplitude and its sustained high level from those seen in Fig. 2, is assumed to be due to the variation in applied force, which could not be accurately repeated. However, this method does not require a consistently applied impulse in order to be effective. In this instance, both plots showed an overload condition which would indicate a relatively severe hammer strike.

The faster rate of energy decay in Fig. 3 versus that in Fig. 2 shows the effect of absorption as the sound wave propagates through the lossy sugar/air medium. The time domain analysis of the acoustic response from the compromised units is clearly distinguishable from that of the solid pieces. These laboratory results motivated our optimism that this technique could be applicable to the case at hand. The hope was that this effect could be exploited operationally, in order to rapidly distinguish the compromised logs from the solid pieces of wood.

Frequency domain analysis was also considered as a method for detecting differences in acoustic response. Changes in modes of propagation and/or resonance might be an alternative method for void detection and was analyzed in this instance. Figure 5 shows the response in the frequency domain of the same impulse responses analyzed in Figs. 2 and 3, for the unmodified and modified ties, respectively. Frequency domain plots were computed from time domain measurements using a Fourier Transform routine.

A slight shift in the principal mode of propagation occurred from unmodified to modified ties, illustrated here by the presence of the cursor at the peak at 1225 Hz in the former instance and at 1280 Hz in the latter. Another consistent feature of the modified ties was a shift in the center frequency of a prominent peak in the lower portion of the spectrum. This was visible in Fig. 5*B*, manifest by the peak near 170 Hz. As indicated earlier, we hypothesize that the hollowing procedure followed by the insertion of material of a significantly different density than wood, results in changes in modes of wave propagation within the structure.

The acoustic response can also be analyzed in the frequency domain in order to quantify the damped oscillatory effect. The damping in any oscillatory system determines the relative amounts of energy dissipated versus the amount stored in its frequency components. The "Q" (quality) is a dimensionless parameter that indicates a quantitative measure of this. Specifically, the Q is defined as the average energy stored in a cycle divided by the average power dissipated in a cycle [*1*].

One alternative definition of Q is given by the following expression:

$$Q = w(0)\,/\Delta W \tag{4}$$

where $w(0)$ is the center frequency of oscillation (w = angular frequency = $2\pi f$) and ΔW is the bandwidth, measured as half-width at half amplitude. Thus if the ratio of these factors is large (indicating a high Q), the oscillator tends to "ring" longer after initial excitation than a correspondingly lower Q resonator. In frequency space, the difference between a high Q and low Q oscillator would be that the former is manifest as a narrow, sharp peak versus a broader, more rounded one. In the limit, an infinitely narrow peak in the frequency domain, representative of a system with an infinite Q, consists of a single frequency that is represented as a pure sine wave in the time domain.

The introduction of damping to an oscillatory system tends to broaden resonant peaks in the frequency domain. Thus the presence of the contraband in modified ties, which in Fig. 4 appears as a rapid decrease in signal amplitude in the time domain, should be revealed as a broadening of the spectral energy density in the frequency domain. This is equivalent to saying that the contraband effectively lowers the Q of the system. Figure 5 does not show this due to inadequate resolution bandwidth and thus prevents us from determining the Q directly from the plot.

However, an alternate definition of Q is given by the following expression [2],

$$Q = w/2s \tag{5}$$

The damping constant s is determined by the following procedure: Using the data from Fig. 2, we calculate the ratio of any two peak-to-peak amplitude measurements of the signal in the time domain. Since the oscillation envelope is a decaying exponential, we set that ratio equal to exp $(-t/T)$ where $1/T = s$ and t is the time in milliseconds between the two measured points. Solving for T in this instance we get 11.1 msec or s = 90.1/sec. Computing this value for the undamped case gives a Q value of 6.8. Following the same procedure and using Fig. 3 corresponding to the response of the damped resonator, we find T = 3.1 msec and from [14] the Q is computed to be approximately 2.

It is also possible to compute the Q from the time domain by counting the number of cycles of undamped frequency required to reduce the signal amplitude to $1/e$ of its original value [3]. We used this method to compute the Q for the resonators illustrated in Fig. 6 and these values are indicated below. Finally, we mention that instruments known as Q meters have been developed which can measure this parameter directly and therefore offers the possibility of automated instrumentation.

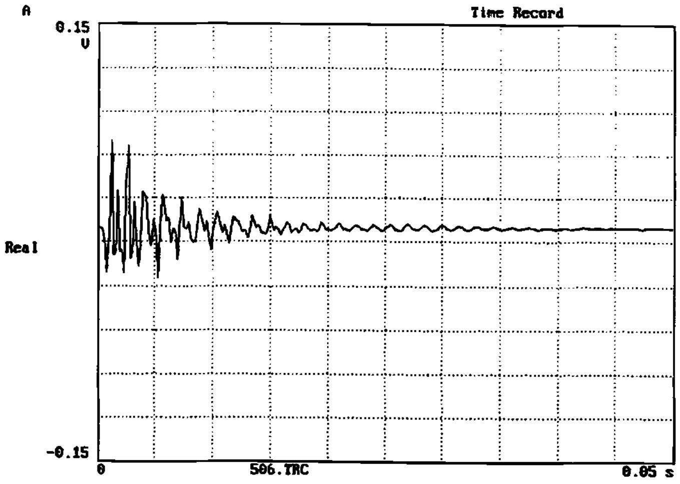

FIG. 7—*Contraband tie.*

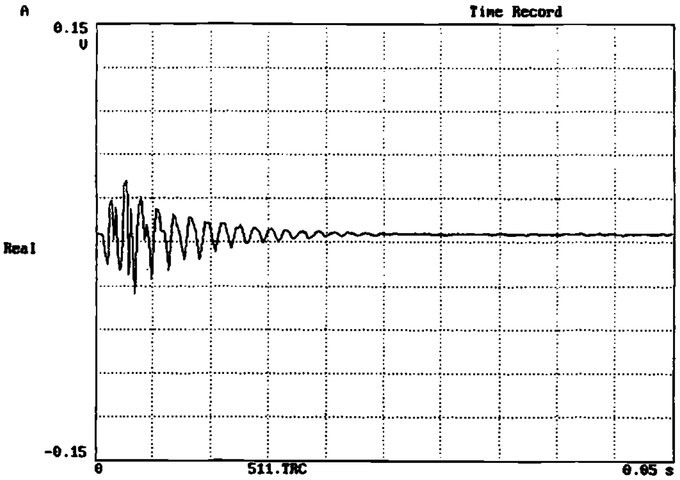

FIG. 8—*Contraband tie.*

In Situ Results

Following laboratory confirmation of this technique, on-site deployment commenced as part of the investigation. The same measuring equipment was used as in the proof-of-concept experiments, except for the use of a more portable, battery-operated signal analyzer and a different hammer. A shipment of eight foot long mahogany railroad ties, intercepted on the basis of source information, arrived at the warehouse on container trucks, stacked lengthwise in the vehicle. Access to both ends of the questioned ties was not possible without off-loading the shipment.

In some cases, measurements were made on ties that remained in the truck, and following off-loading in others. All measurements were performed only in the time domain. The accelerometer was hand-held, and placed against the exposed end of each railroad tie. Figure 6 typifies the acoustic response from solid and modified ties respectively. The calculated Q value for the undamped resonator in this case is approximately 9, and the value for the damped case is 3.

Figures 7 and 8 show the acoustic response for modified ties, both measured while still on the truck. The tie corresponding to Fig. 7 was positioned on top of the stack of ties in the truck while the tie corresponding to Fig. 8 bore the weight of five ties along its entire length. There appears to be little qualitative difference in the two responses, indicating that the technique was effective in identifying the contrabandladen ties without resorting to off-loading the entire shipment. Immediate identification of suspect ties was effected using this method, illustrated by Figs. 7 and 8, followed by positive confirmation using X-ray analysis and the results of an ion mobility spectrometer. Over 1500 kg of cocaine were seized in this shipment as part of this investigation.

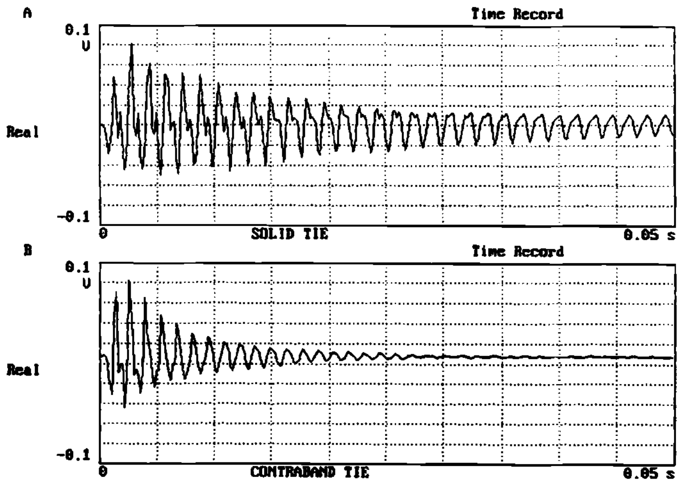

FIG. 6—*Typical responses from:* (A) *solid tie;* (B) *contraband tie.*

In total, 108 ties were tested and later confirmed using a portable transmission X-ray unit. In less than 1% of the total units measured did either a false positive or negative occur (that is, solid tie registering hollow or hollow tie registering solid). However, in 18% of all those tested, a definite status could not be determined at the time of measurement (11% uncertainty rate for hollow ties, 27% for solid ones). A number of factors might have contributed to this rate of ambiguity, owing in part to the exigencies dictated by an operational versus laboratory setting. These include variations in the applied force, where a light hammer tap might potentially negate the effects of damping (striking the log too hard, aside from saturating the detector, would not adversely affect the discrimination process, given the exponential rate of signal decay). Similarly, inconsistencies in the sensor coupling due to its hand-held method of attachment might have contributed to difficulties in exploiting the damped response, as well as naturally occurring cavities in otherwise solid pieces. Finally, variations in the cavity size and contraband content, in conjunction with the above variable parameters, might explain the lack of a clear delineation in acoustic response. Figure 9 summarizes the results of on-site measurements.

Conclusions

Modeling of solid and hollowed objects as resonators, which exhibit varying degrees of damping, is an exploitable phenomenon for the noninvasive detection of secreted material. Given a system model which includes damping as the principle physical mechanism, a broadband excitation source such as a hammer is effective in measuring the impulse response in real time [4]. This obviates the need for applying an oscillator and varying its frequency continuously since we are exciting the system with all frequencies simultaneously.

Initially, laboratory measurements were made using an accelerometer, mechanically excited in the ultrasonic regime (a continuous wave, varied over a 20–50 KHz range). We then looked for transmissive attenuation due to the impedance mismatch of the void. This proved ineffective due to the multipath propagation of the ultrasonic signal in the wood, as well as the random but seemingly ubiquitous presence of fissures and knots, which confounded consistent measurements.

Measurement of the questioned object's acoustic response using an impulse is effective for locating hidden cavities and/or revealing concealed contraband if a solid, uncompromised reference is available for comparison. Without such a standard, it may be difficult to assess the appropriate limits in frequency response.

However, this method appears useful where a rapid, and noninvasive discriminant is mandated. The simple means of implementation, coupled with a relatively minimal, off-the-shelf instrumentation requirement, make this technique immediately generalizable to a wide variety of solid objects.

Examination of the acoustic response has the added benefit of immediately interpretable data. Little or no training is required to apply this technique as it exists, since an eye-balled determination of decay rate is based solely on comparisons. A knowledge of the simplest functions of an oscilloscope is all that is technically required, and with some modest re-design efforts, a system could be packaged which would be entirely automated using a calibrated source.

In addition, our results indicate that effective on-site measurements can be made independent of the physical location or orientation of the host concealment, so long as a small area of the questioned object is accessible. Laboratory results suggest that analysis in the frequency domain may be effective as well, either through observed shifts in principle modes of propagation, or changes in resonance induced by the hollowing procedure. Furthermore, frequency domain analysis could potentially be used either as added confirmation of time domain measurements, or in various site-specific applications.

(NUMBER OF TIES SCREENED - 108)

# OF **SOLID** TIES THAT REGISTERED **SOLID**	32	#OF **HOLLOW** TIES THAT REGISTERED **SOLID** (FALSE NEGATIVE)	1
# OF **SOLID** TIES THAT REGISTERED **SUSPICIOUS**	12	# OF **HOLLOW** TIES THAT REGISTERED **SUSPICIOUS**	7
# OF **SOLID** TIES THAT REGISTERED **HOLLOW** (FALSE POSITIVE)	0	# OF **HOLLOW** TIES THAT REGISTERED **HOLLOW**	56

FIG. 9—*Field results of acoustic screening method.*

Acknowledgments

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