

IMPACT HAMMER TESTING OF MASONRY SEWERS

BY

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A thesis submitted for the Degree  
of  
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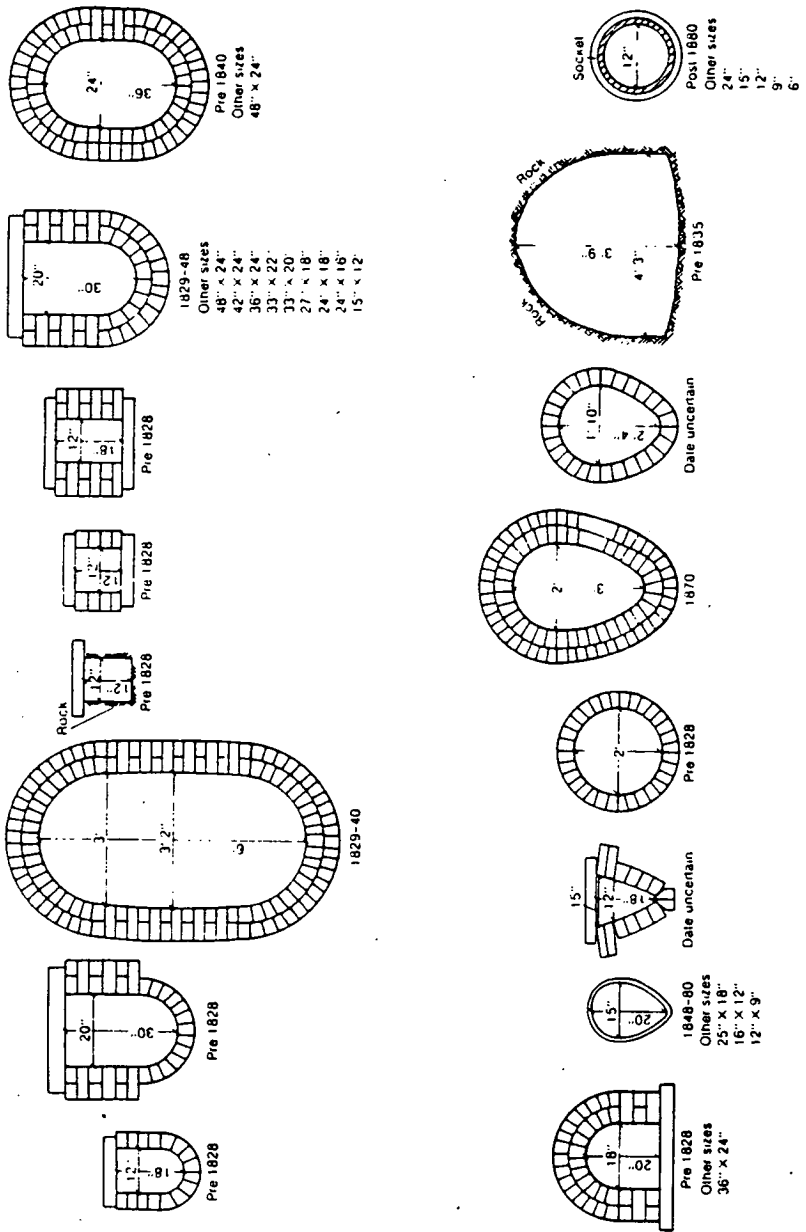


VOLUME 2

FIGURES AND PLATES

## CHAPTER 1

### INTRODUCTION



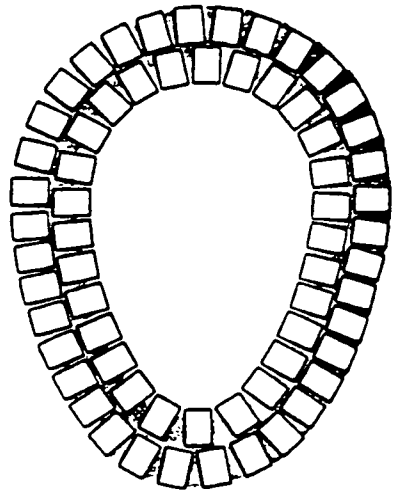
TYPICAL CROSS-SECTIONS OF EARLY SEWERS

FIGURE 1.1

(After Read, ref. 1)

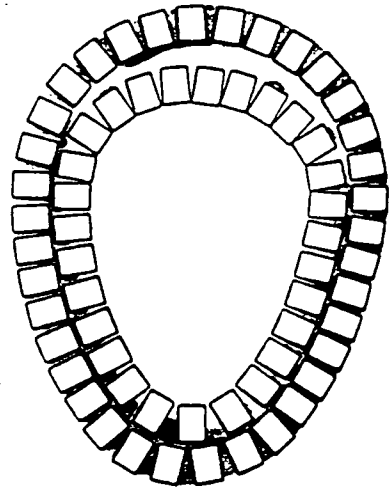
**STAGE 1**

Mortar is eroded or attacked chemically.  
*Visible defect: mortar loss.*



**STAGE 2**

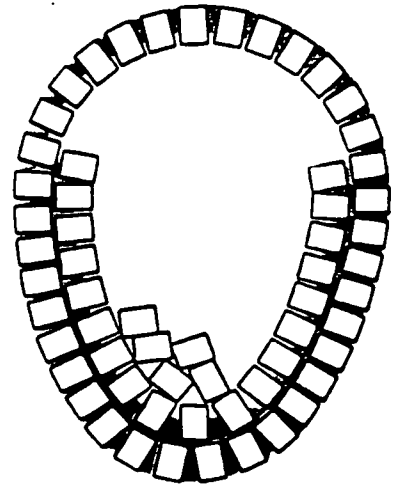
Loss of mortar between bricks allows joints to close causing inner ring of crown to "squat" and separate from outer ring.  
*Visible defects: total mortar loss, deformation of crown, displaced bricks.*



**STAGE 3**

Loss of compressive load on inner ring of bricks in crown allows bricks to be dislodged and fall causing progressive collapse of inner ring.  
*Visible defects: missing bricks, bricks in invert.*

NB: this mechanism may occur in single ring sewers where the ground "arches" above the sewer, as well as in multi-ring sewers.



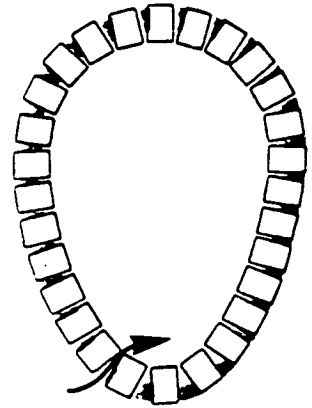
**FAILURE DUE TO LOSS OF BRICKS IN CROWN**

**FIGURE 1.2**

(After W.R.C., ref. 2)

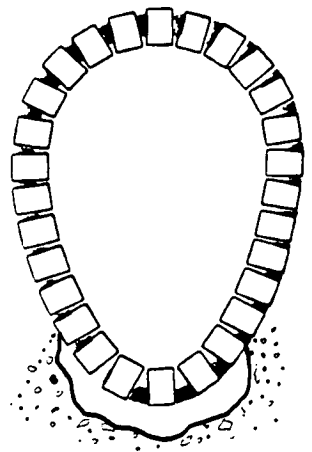
**STAGE 1**

Deterioration of mortar allows infiltration.  
*Visible defects:* mortar loss. Infiltration is rarely visible in the invert.



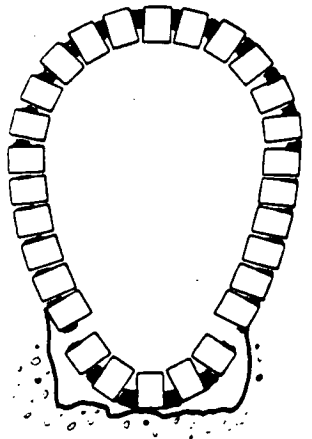
**STAGE 2**

Infiltration rate rises and brings in fine soil particles causing voids to form around sewer invert.  
*Visible defects:* mortar loss, sand in sewer, longitudinal crack may be visible near water level.



**STAGE 3**

Deterioration of mortar and loss of support beneath sewer allows invert section to drop into void. Sewer loses structural integrity and side walls may drop or may be held by mortar or friction.  
*Visible defects:* as above plus fracture around water line, dropped invert, displaced bricks in walls, deformation, loss of level.



**DROPPED INVERT MODE OF FAILURE**

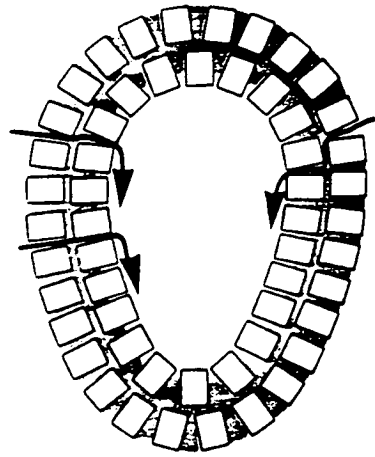
**FIGURE 1.3**

(After W.R.C., ref. 2)

**STAGE 1**

Mortar loss allows infiltration which begins to wash in fine soil.

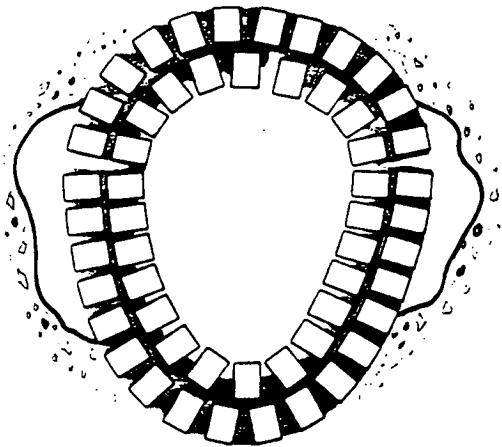
*Visible defects:* mortar loss, infiltration.



**STAGE 2**

Voids or zones of low compaction form outside sewer walls allowing the sewer to "spread" at springing level, causing crown to crack and drop.

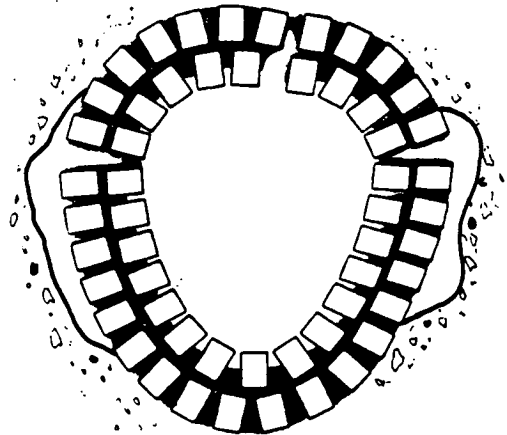
*Visible defects:* deformation, crack at crown.



**STAGE 3**

Mechanism proceeds and fracture forms at crown as the springings continue to spread. Sewer develops "heart" shape and crown eventually collapses.

*Visible defects:* deformation, heaving, fracture at crown.



**FAILURE DUE TO LOSS OF SIDE SUPPORT**

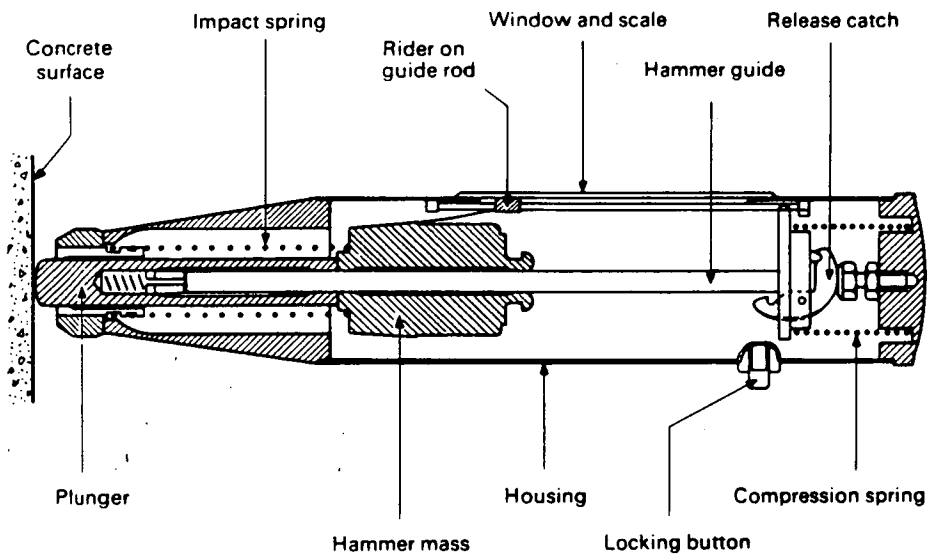
**FIGURE 1.4**

(After W.R.C., ref. 2)



## CHAPTER 2

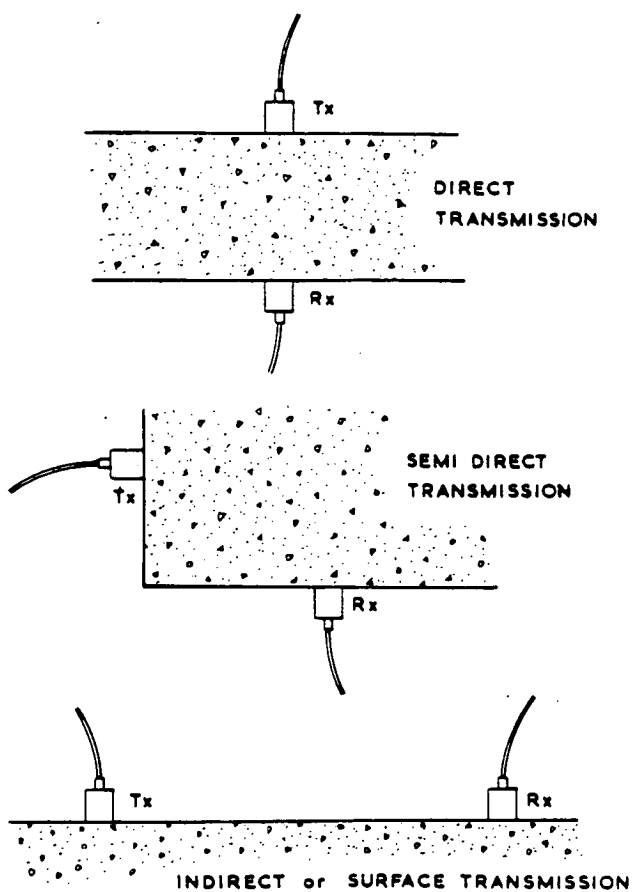
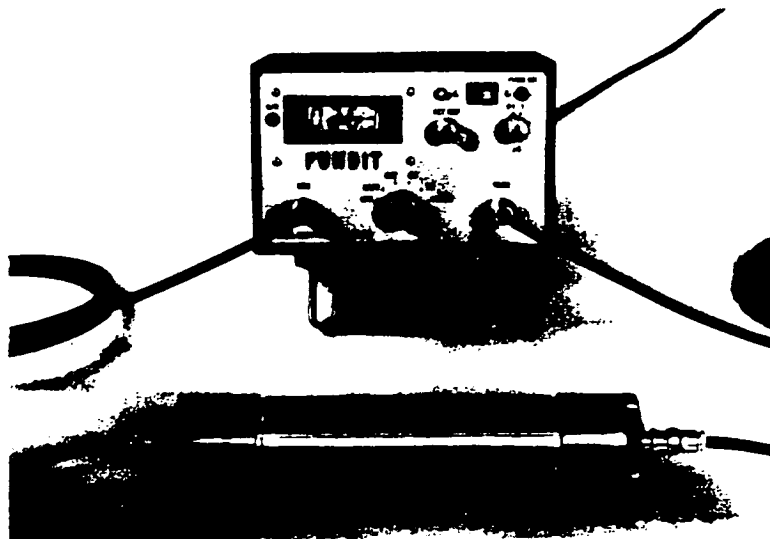
### NON-DESTRUCTIVE METHODS OF ASSESSING MASONRY STRUCTURES



**SCHMIDT REBOUND HAMMER**

**FIGURE 2.1**

(After Bungey, ref. 6)

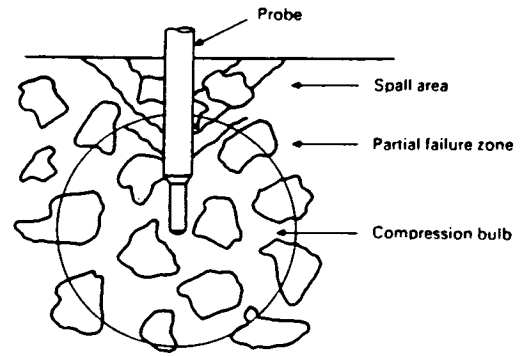
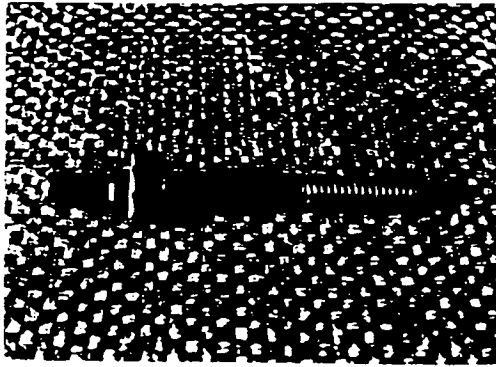


Methods of propagating ultrasonic pulses

## ULTRASONIC PULSE VELOCITY MEASUREMENT USING PUNDIT

FIGURE 2.2

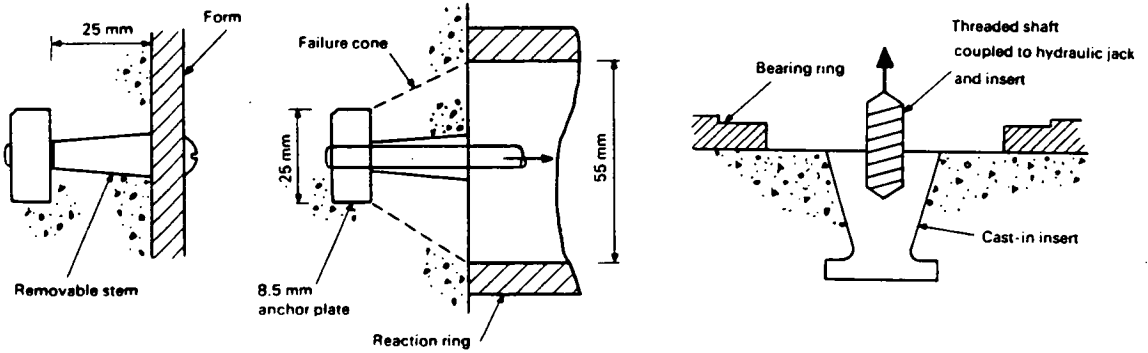
(After C.N.S., ref. 89)



WINDSOR PROBE TEST

FIGURE 2.3

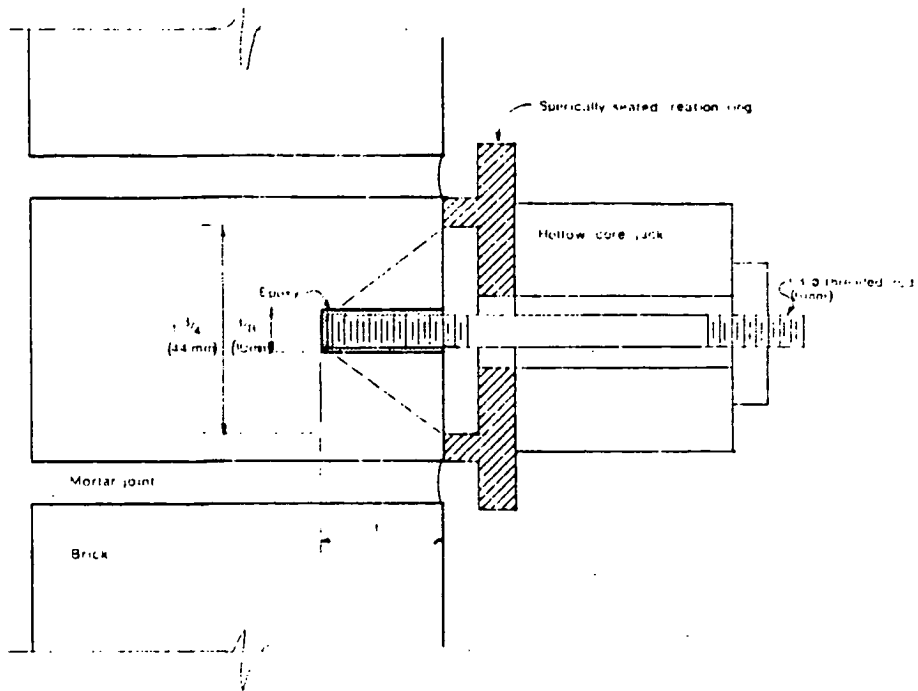
(After Bungey, ref. 6)



LOK-TEST INSERT AND "AMERICAN" INSERT

FIGURE 2.4

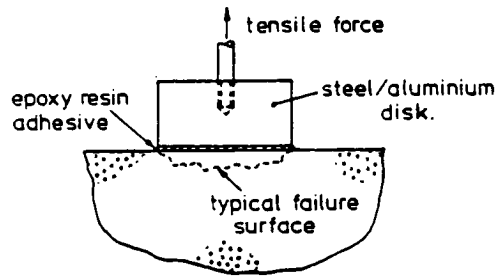
(After Bungey, ref. 6)



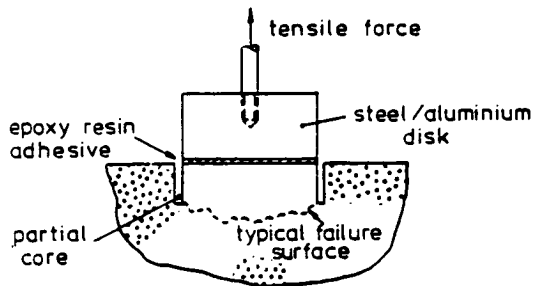
**PULL-OUT TEST (MASONRY)**

**FIGURE 2.5**

(After Noland et al, ref. 8)



(a) Arrangement for testing uncored specimens

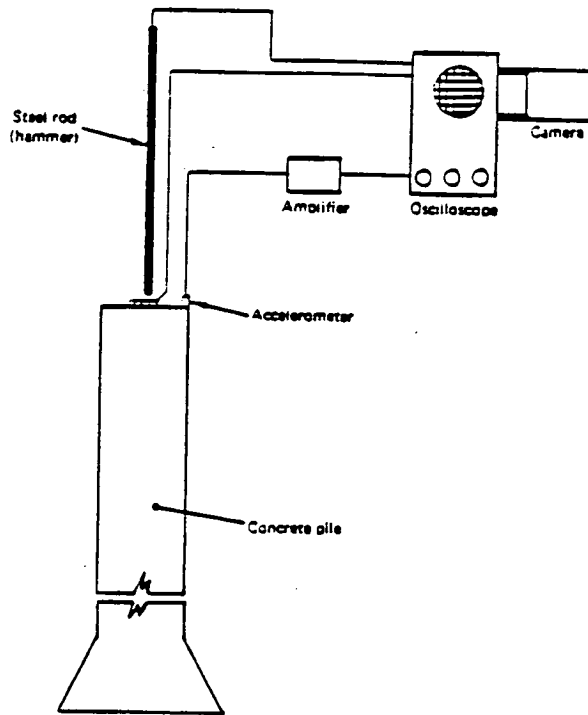


(b) Arrangement for testing partially cored specimens

**PULL-OFF TEST**

**FIGURE 2.6**

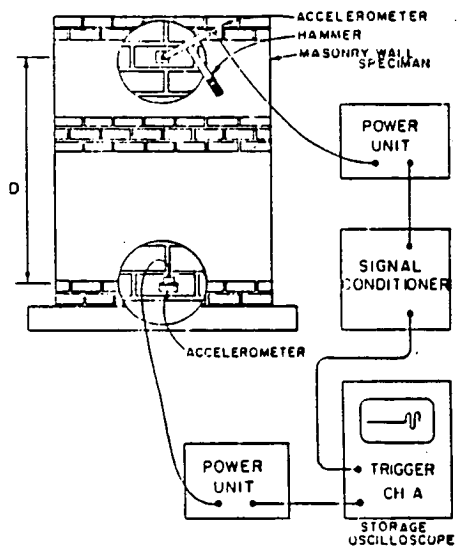
(After Long, ref. 19)



PULSE-ECHO METHOD

FIGURE 2.7

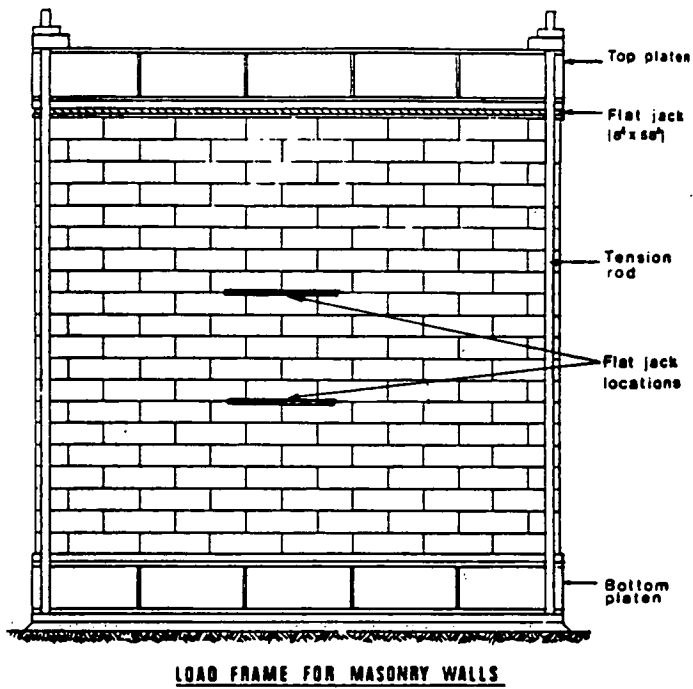
(After Steinbach & Vey, ref. 22)



MECHANICAL PULSE SYSTEM

FIGURE 2.8

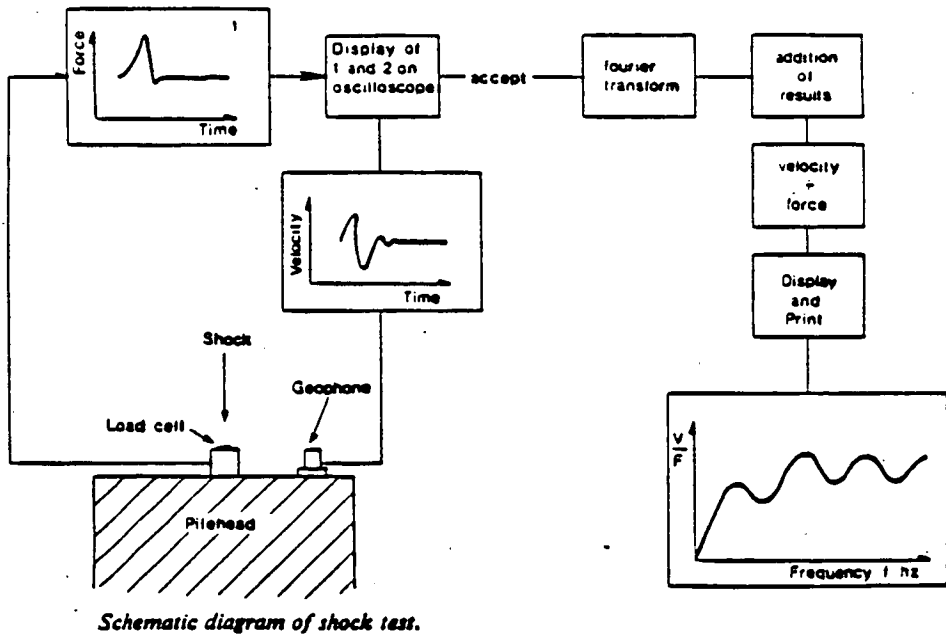
(After Noland et al, ref. 8)



**FLATJACK TEST**

FIGURE 2.9

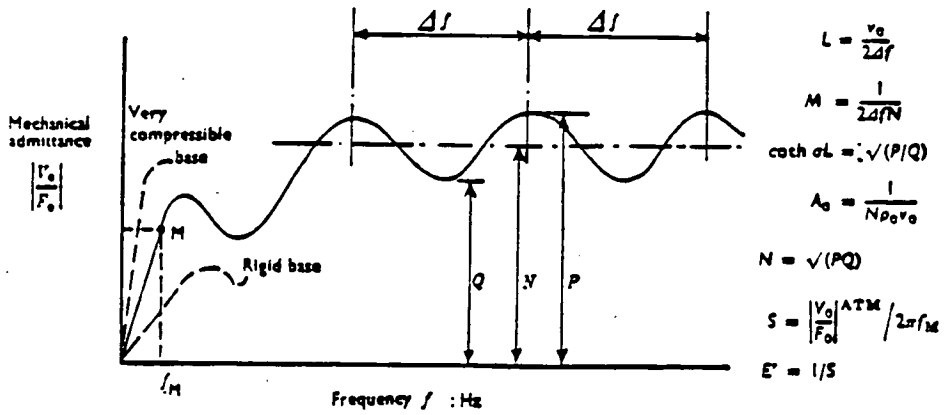
(After Rossi, ref. 26)



**IMPULSE SHOCK TEST**

FIGURE 2.10

(After Higgs & Robertson, ref. 37)

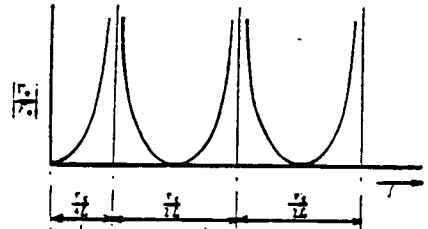


MECHANICAL ADMITTANCE RESPONSE CURVE FOR A CYLINDRICAL PILE

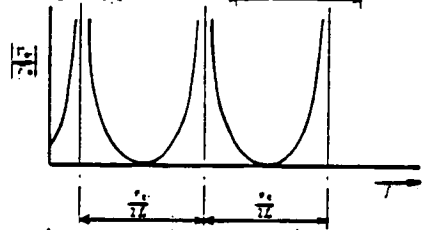
FIGURE 2.11

(After Davis & Dunn, ref. 23)

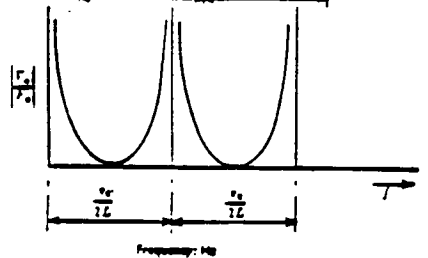
(a) rigid base



(b) intermediate elastic base



(c) infinitely compressible base



EFFECT OF BASE COMPRESSIBILITY ON RESONANCE FREQUENCY

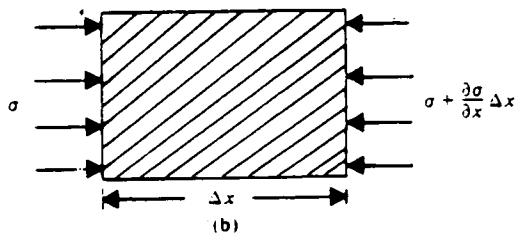
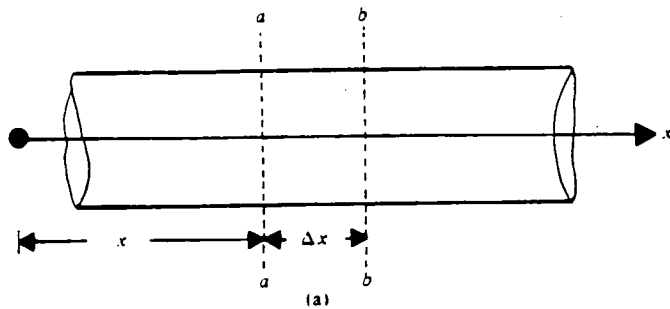
FIGURE 2.12

(After Davis & Dunn, ref. 23)



## CHAPTER 3

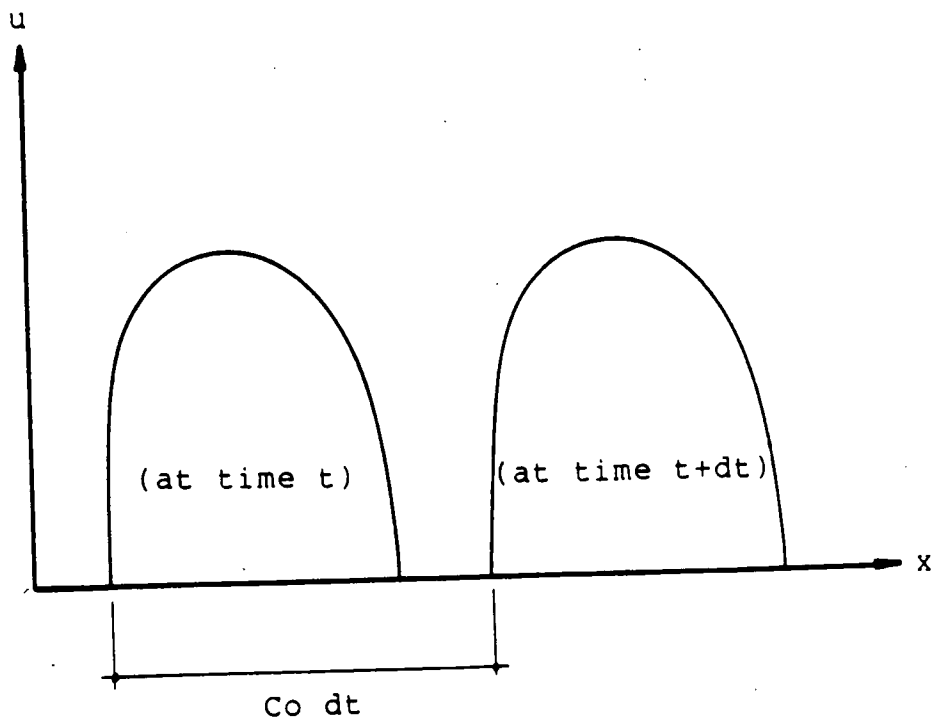
### WAVE PROPAGATION



LONGITUDINAL ELASTIC WAVES IN A ROD

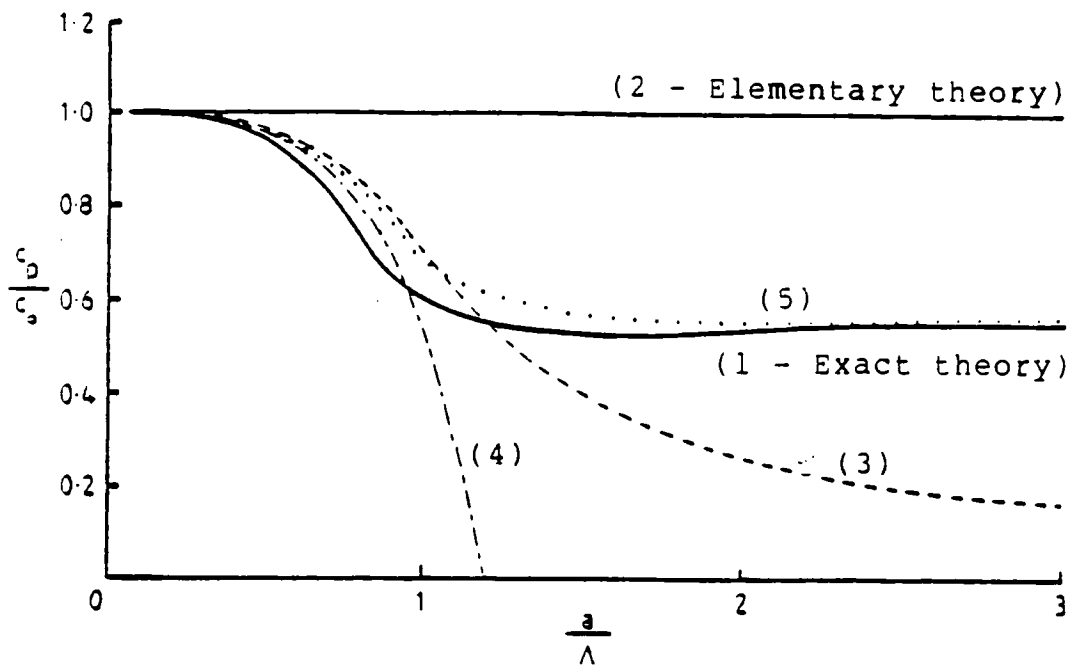
FIGURE 3.1

(after Das, ref. 59)



PROPAGATION OF A NON-DISPERSIVE STRESS WAVE

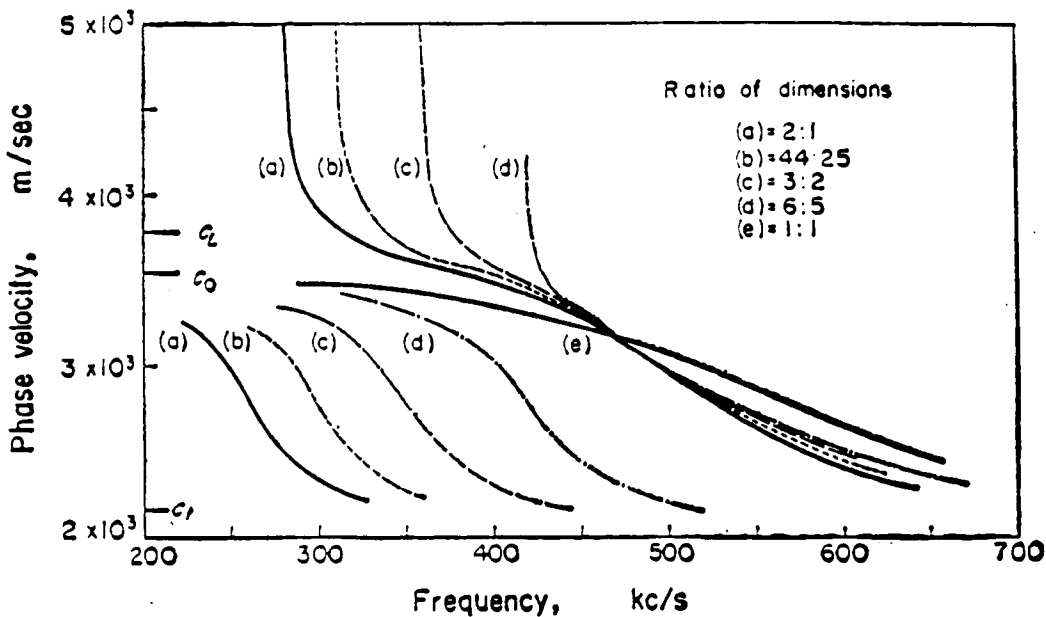
FIGURE 3.2



APPROXIMATE THEORIES OF LONGITUDINAL ELASTIC WAVES IN A CYLINDER

FIGURE 3.3

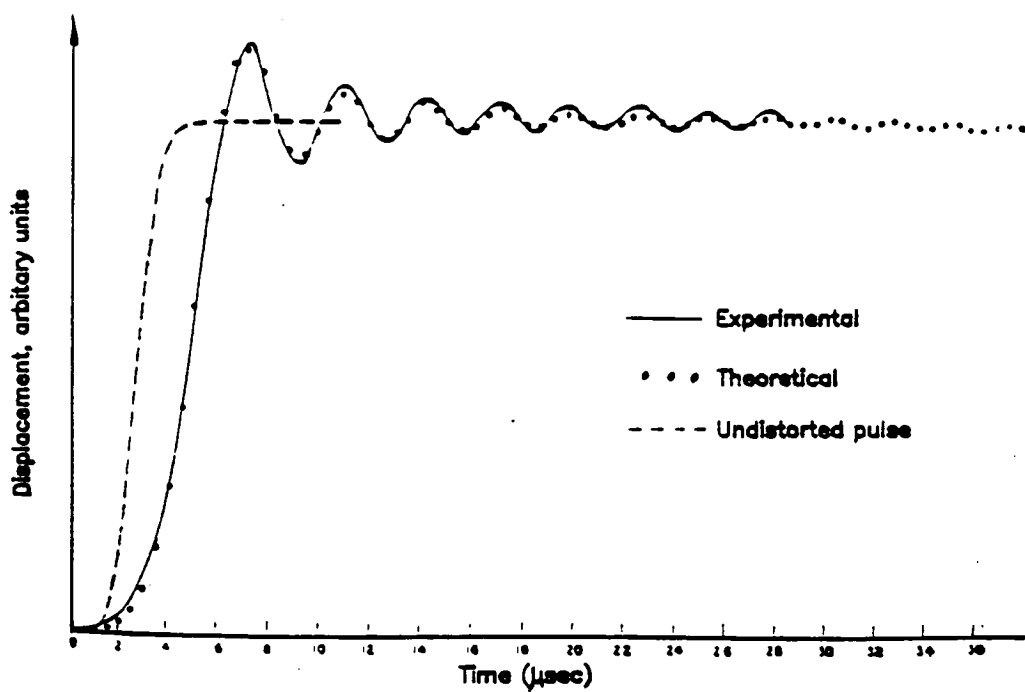
(after Redwood, ref. 40)



WAVE PROPAGATION IN RECTANGULAR RODS

FIGURE 3.4

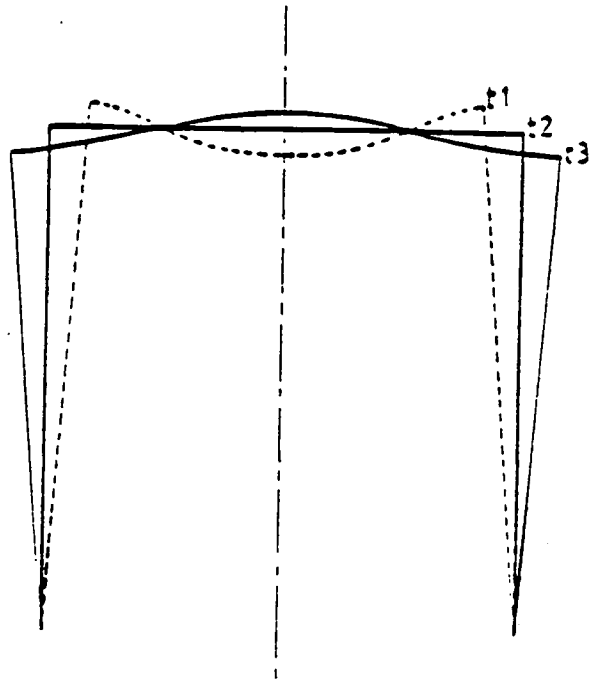
(after Morse, ref. 49)



PULSE DISTORTION IN A CYLINDRICAL ROD

FIGURE 3.5

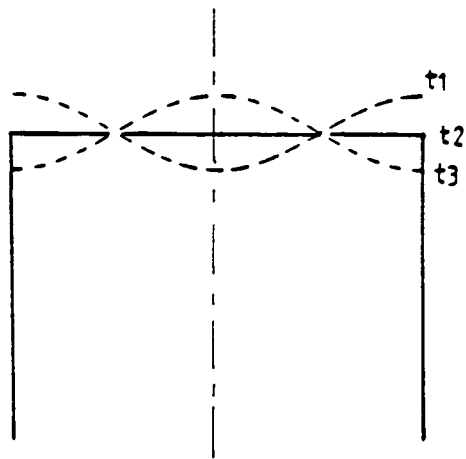
(after Hsieh and Kolsky, ref. 50)



END RESONANCES IN A CYLINDRICAL ROD

FIGURE 3.6

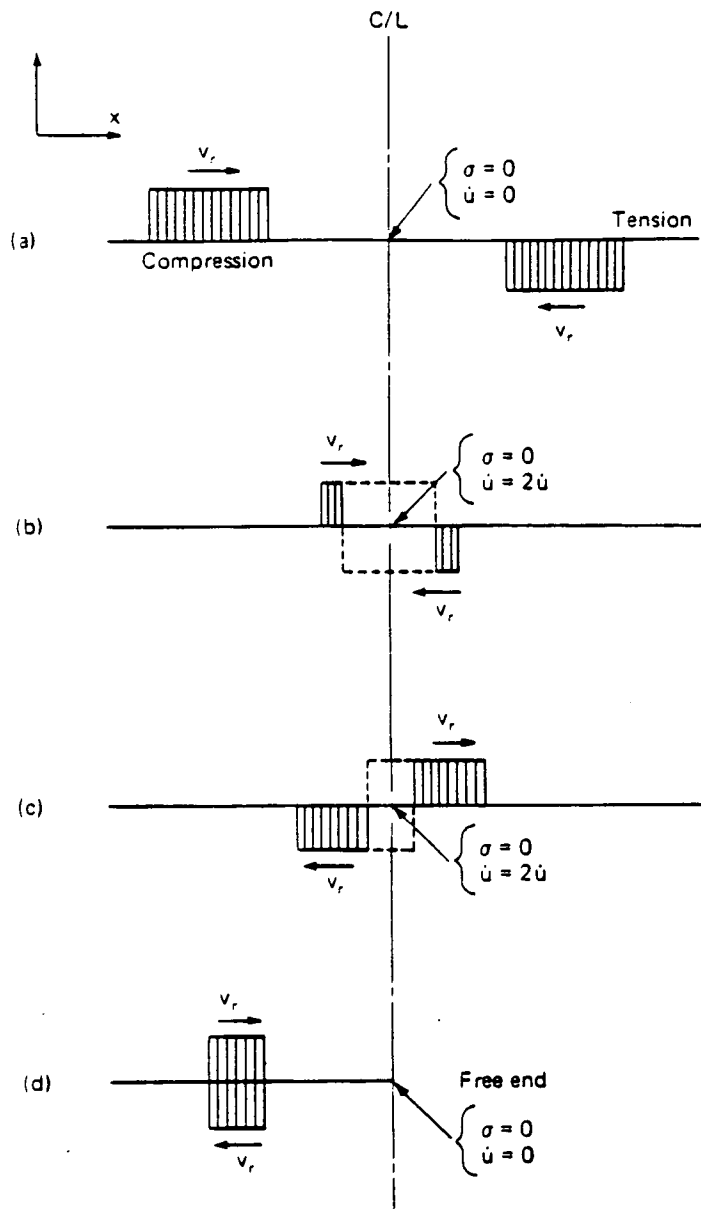
(after Oliver, ref. 52)



END RESONANCE MODE SHAPES IN A CYLINDRICAL ROD

FIGURE 3.7

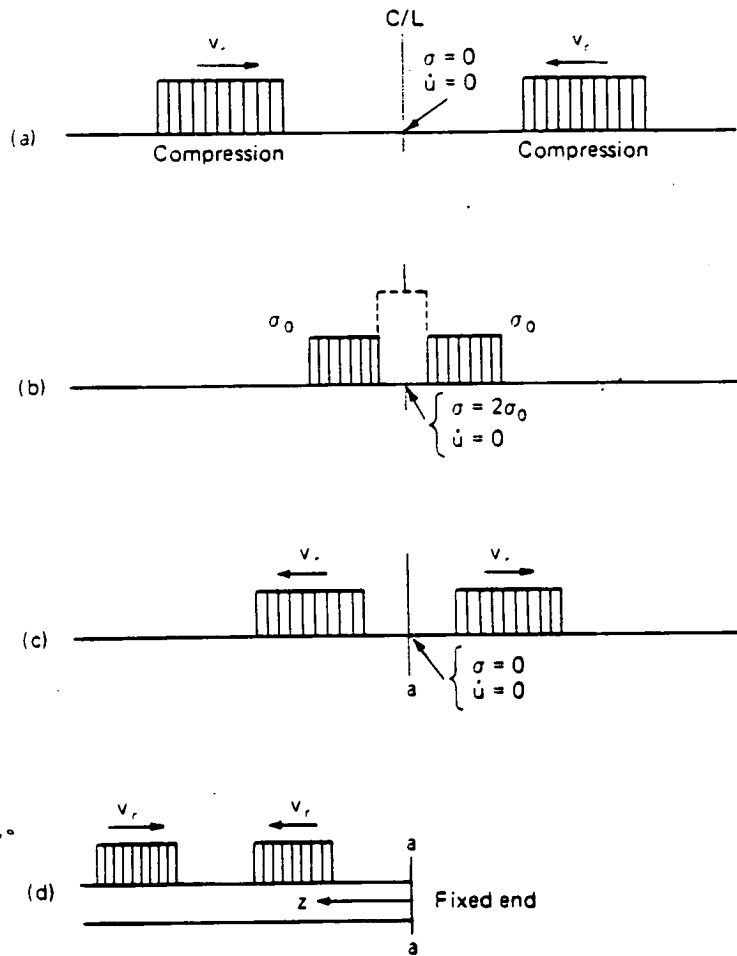
(after Chan, ref. 30)



ELASTIC WAVE PROPAGATION IN A BAR WITH FREE ENDS

FIGURE 3.8

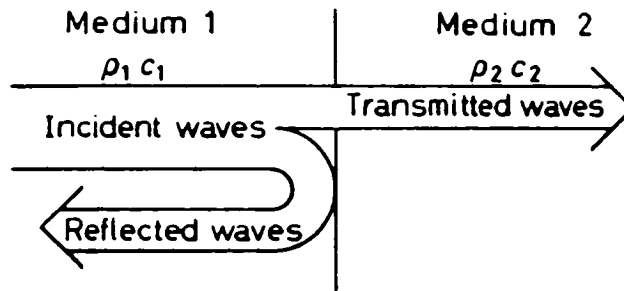
(after Prakash, ref. 58)



ELASTIC WAVE PROPAGATION IN A BAR WITH FIXED ENDS

FIGURE 3.9

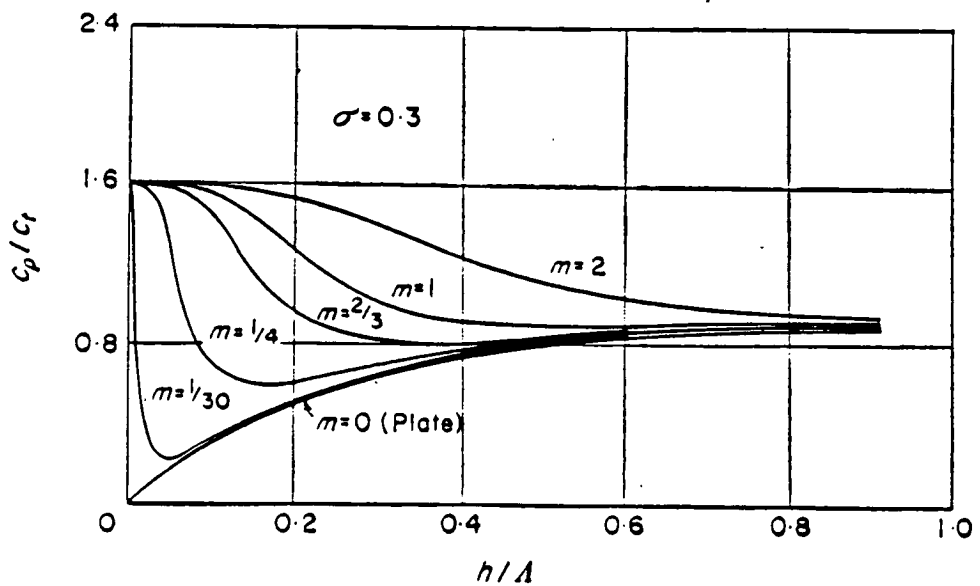
(after Prakash, ref. 58)



REFLECTION AND TRANSMISSION AT A MEDIUM BOUNDARY

FIGURE 3.10

(after Filipczynski, ref. 53)

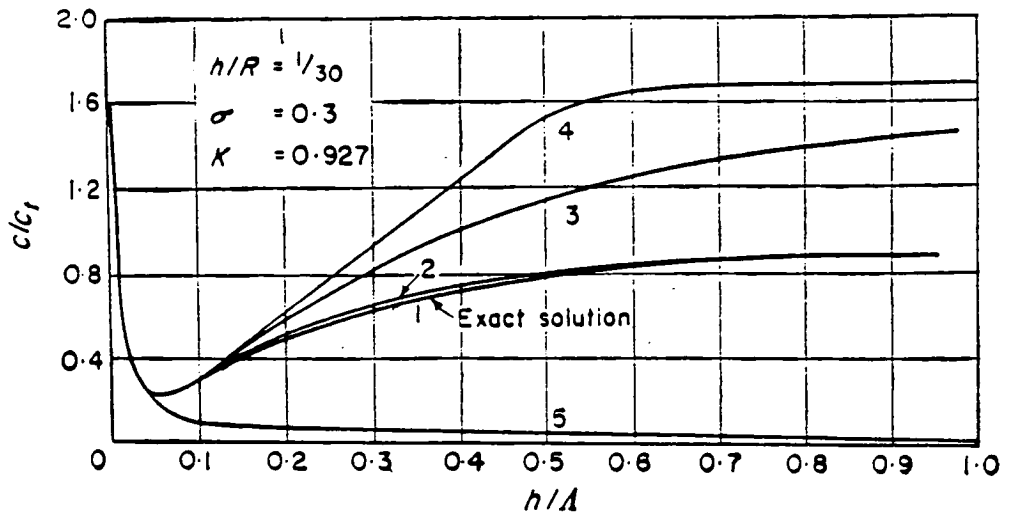


PHASE VELOCITY IN A CYLINDRICAL SHELL

FIGURE 3.11

(after Mirsky and Herrmann, ref. 55)

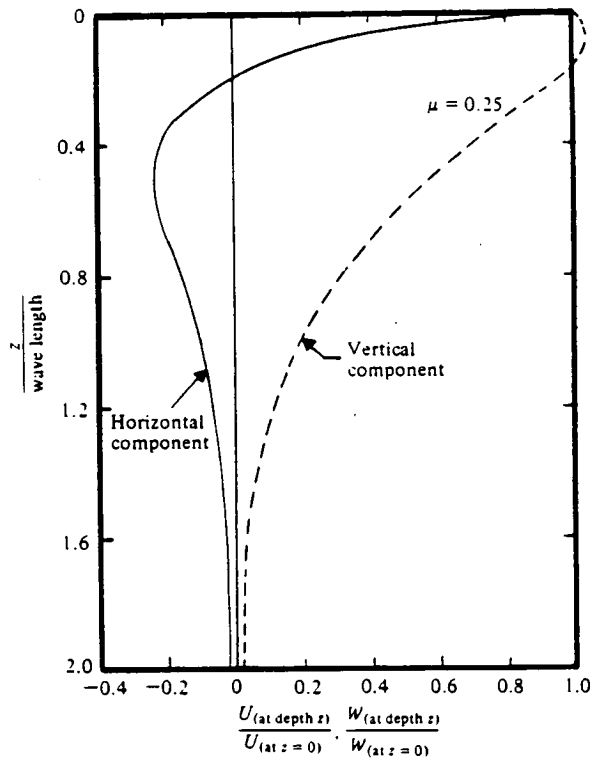




APPROXIMATE THEORY OF LONGITUDINAL WAVES IN A SHELL

FIGURE 3.12

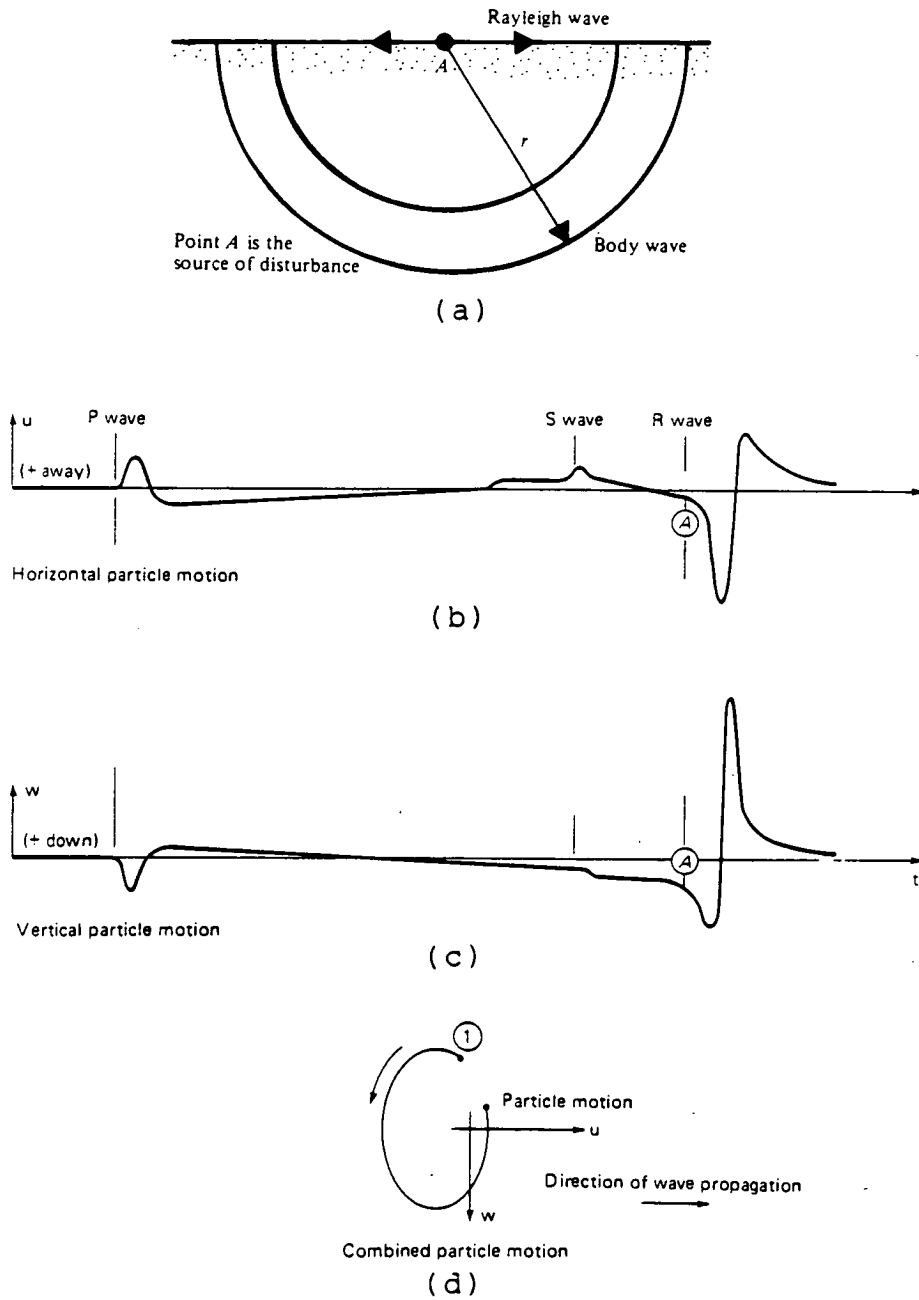
(after Herrmann and Mirsky, ref. 56)



VARIATION OF THE AMPLITUDE OF VIBRATION OF THE HORIZONTAL AND VERTICAL COMPONENTS OF RAYLEIGH WAVES WITH DEPTH

FIGURE 3.13

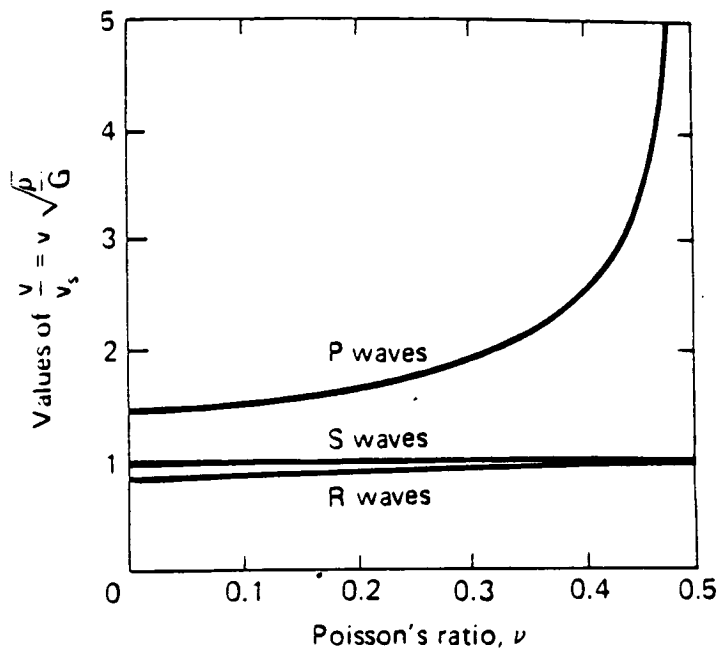
(after Das, ref. 59)



WAVE SYSTEM FROM SURFACE POINT SOURCE IN IDEAL MEDIUM

FIGURE 3.14

(after Woods, ref. 61)



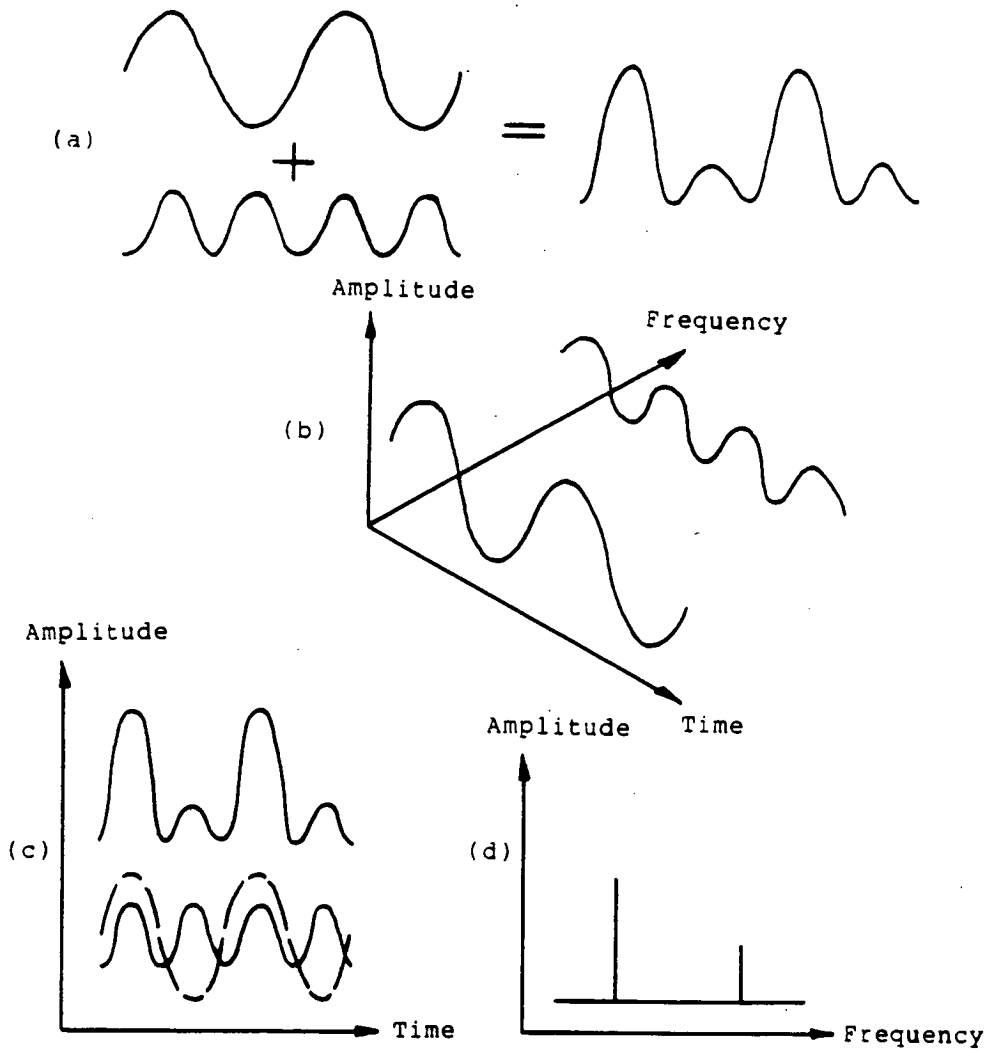
RELATIONSHIP BETWEEN POISSON'S RATIO AND VELOCITIES OF PROPAGATION OF COMPRESSION, SHEAR AND RAYLEIGH WAVES IN A SEMI-INFINITE ELASTIC MEDIUM

FIGURE 3.15

(after Richart, ref. 62)

## CHAPTER 4

### ANALYSIS AND PROCESSING OF SIGNALS IN TIME AND FREQUENCY DOMAINS



- (a) Waveform combination
- (b) Three dimensional coordinates showing time, frequency and amplitude
- (c) Time domain view
- (d) Frequency domain view

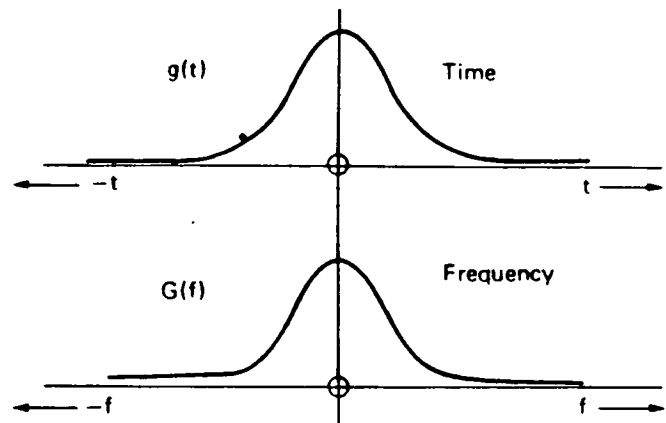
THE RELATIONSHIP BETWEEN THE TIME AND FREQUENCY DOMAINS

FIGURE 4.1

$$G(f) = \int_{-\infty}^{\infty} g(t)e^{-i 2\pi ft} dt$$

$$g(t) = \int_{-\infty}^{\infty} G(f)e^{i 2\pi ft} df$$

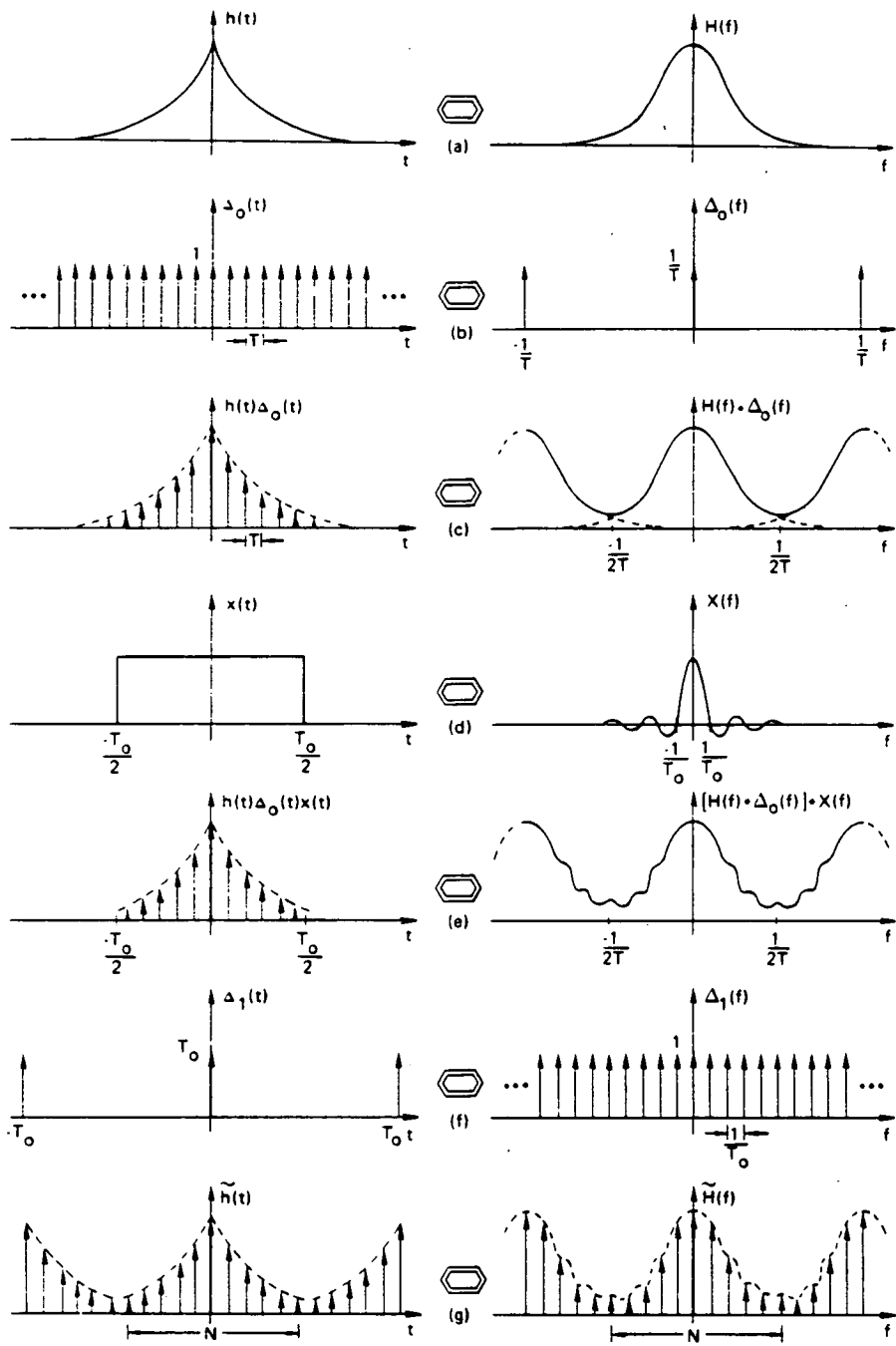
Infinite and continuous in  
time and frequency domains



## THE INTEGRAL TRANSFORM

FIGURE 4.2

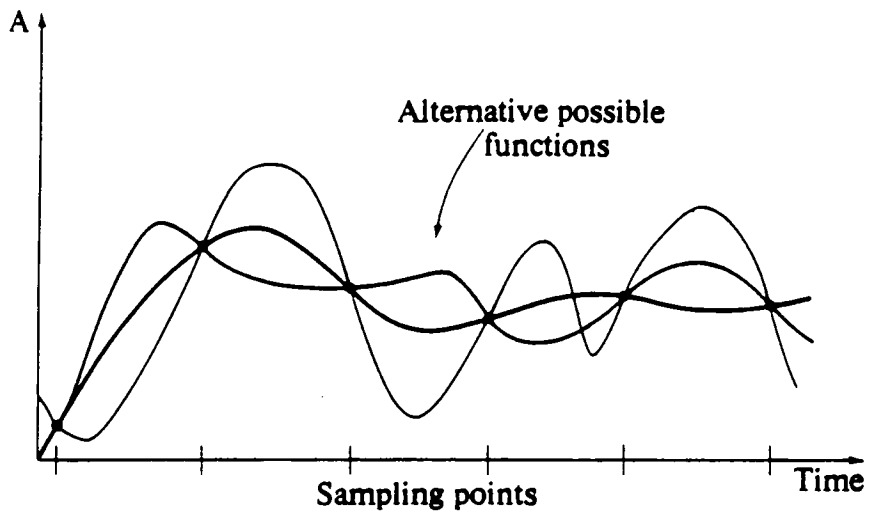
(after Thrane, ref. 64)



GRAPHICAL DEVELOPMENT OF THE DISCRETE FOURIER TRANSFORM

FIGURE 4.3

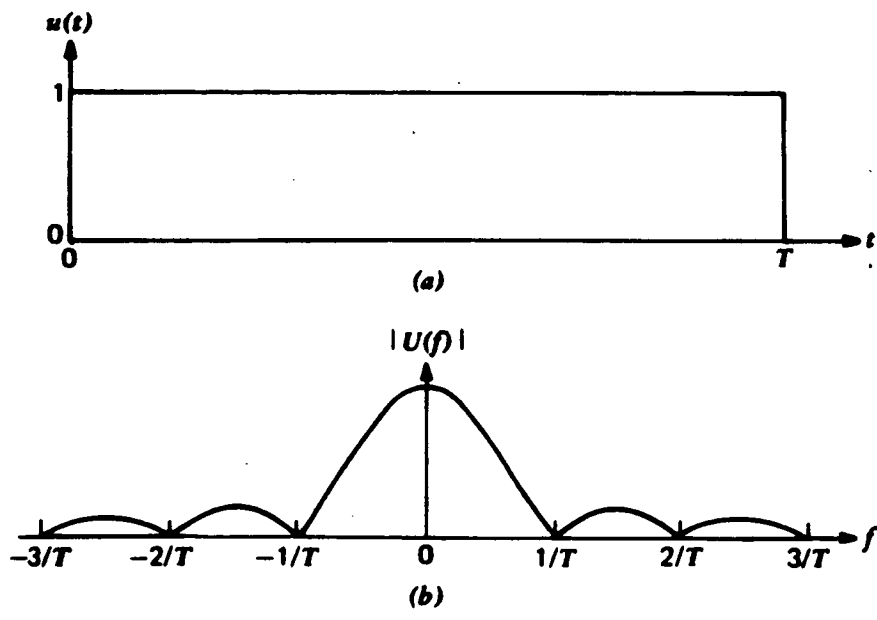
(after Brigham, ref. 63)



ALIASING

FIGURE 4.4

(after Beauchamp, ref. 65)

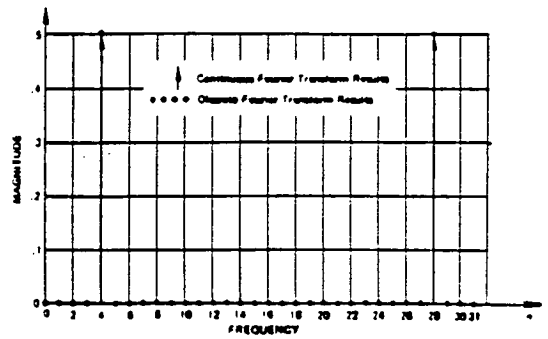
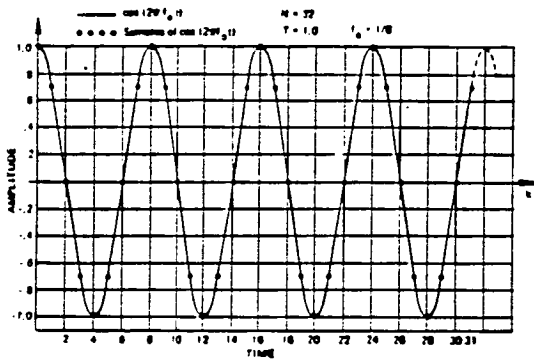


RECTANGULAR WEIGHTING FUNCTION

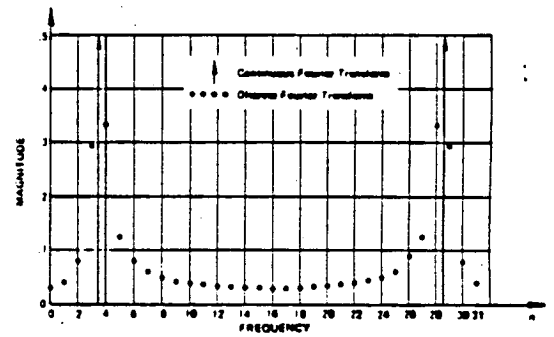
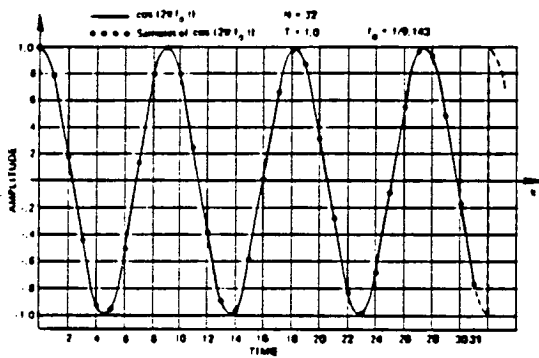
FIGURE 4.5

(after Bendat, ref. 74)





(a) Fourier transform of a cosine waveform:  
truncation interval equal to a multiple of the period.

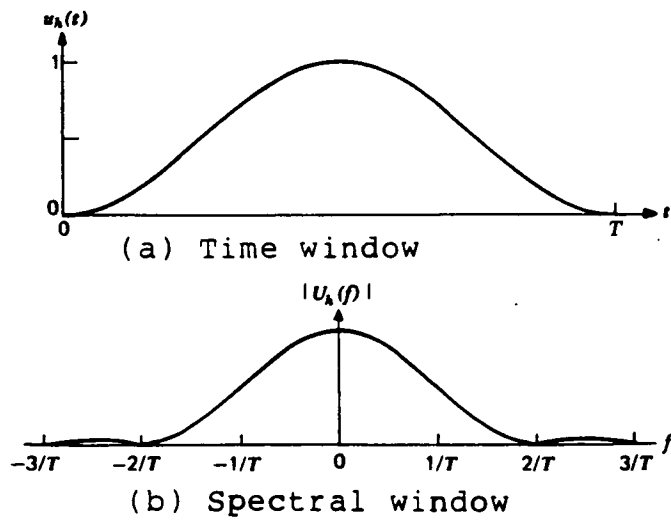


(b) Fourier transform of a cosine waveform:  
truncation interval not equal to a multiple of the period.

## LEAKAGE EFFECTS WITH THE RECTANGULAR WINDOW

FIGURE 4.6

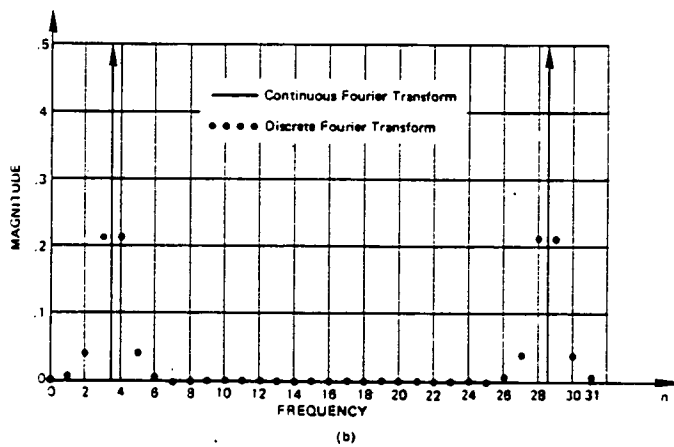
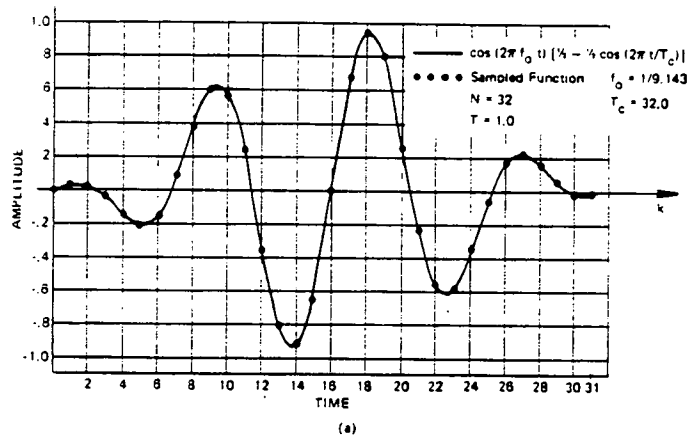
(after Brigham, ref. 63)



HANNING ANALYSIS WINDOW

FIGURE 4.7

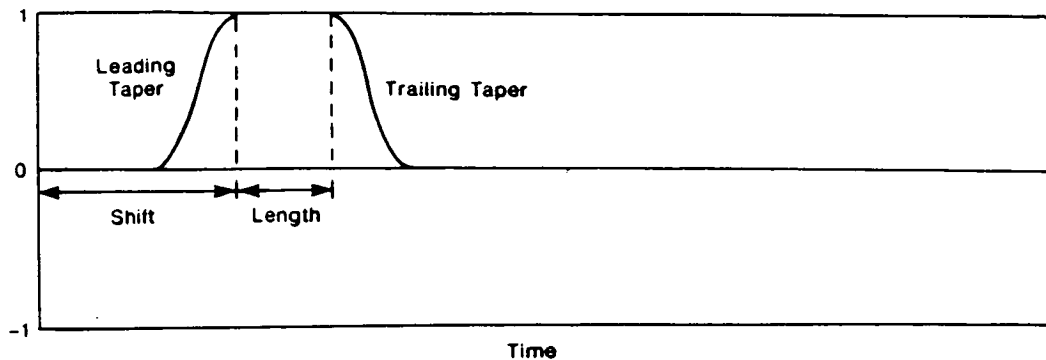
(after Bendat, ref. 74)



USE OF THE HANNING FUNCTION TO REDUCE LEAKAGE.

FIGURE 4.8

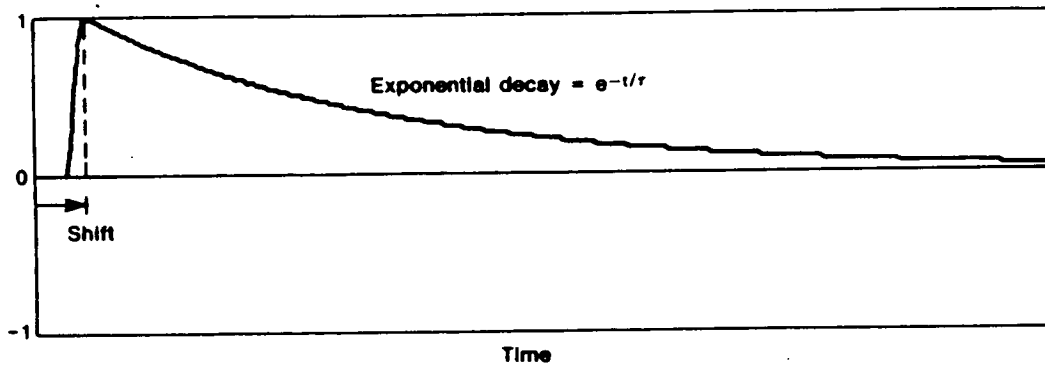
(after Brigham, ref. 63)



FORCE WINDOW

FIGURE 4.9

(after Sohaney, ref. 68)



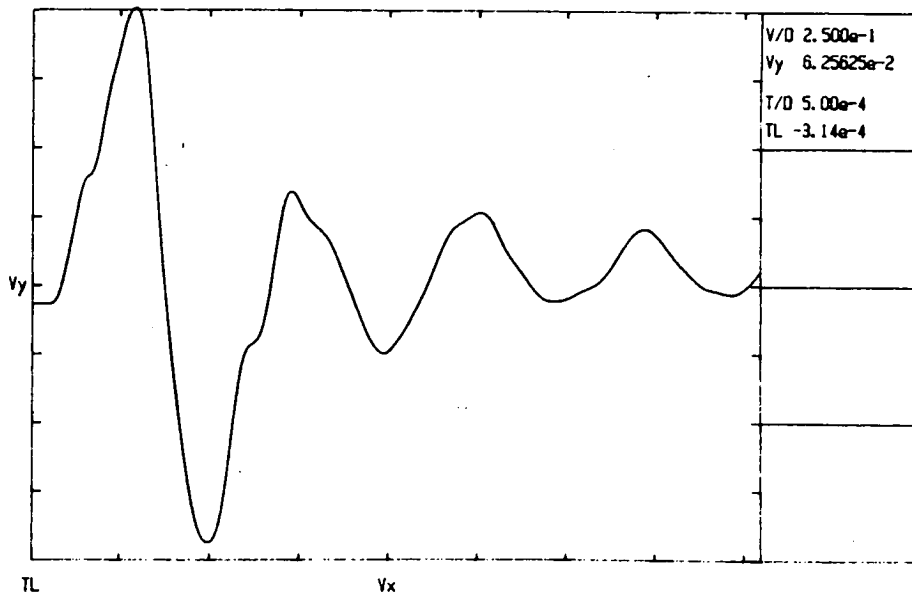
EXPONENTIAL WINDOW

FIGURE 4.10

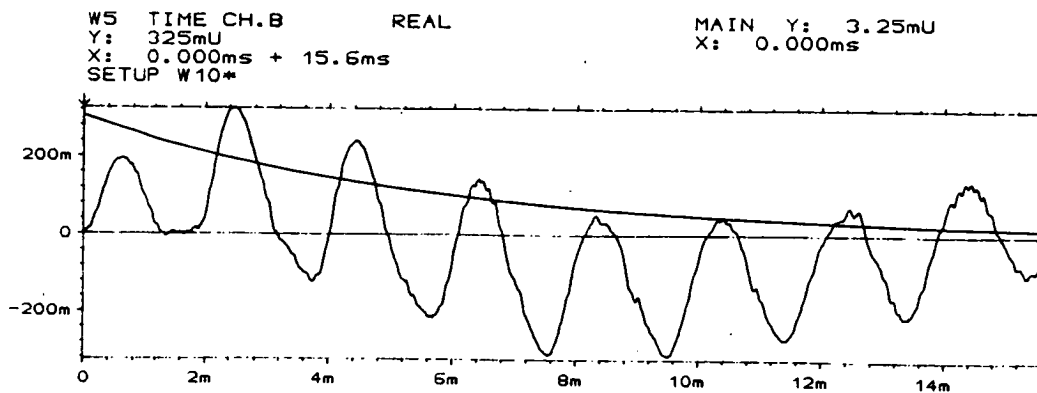
(after Sohaney, ref. 68)



(a) Polaroid records from analogue oscilloscope



(b) Plot from a digital oscilloscope



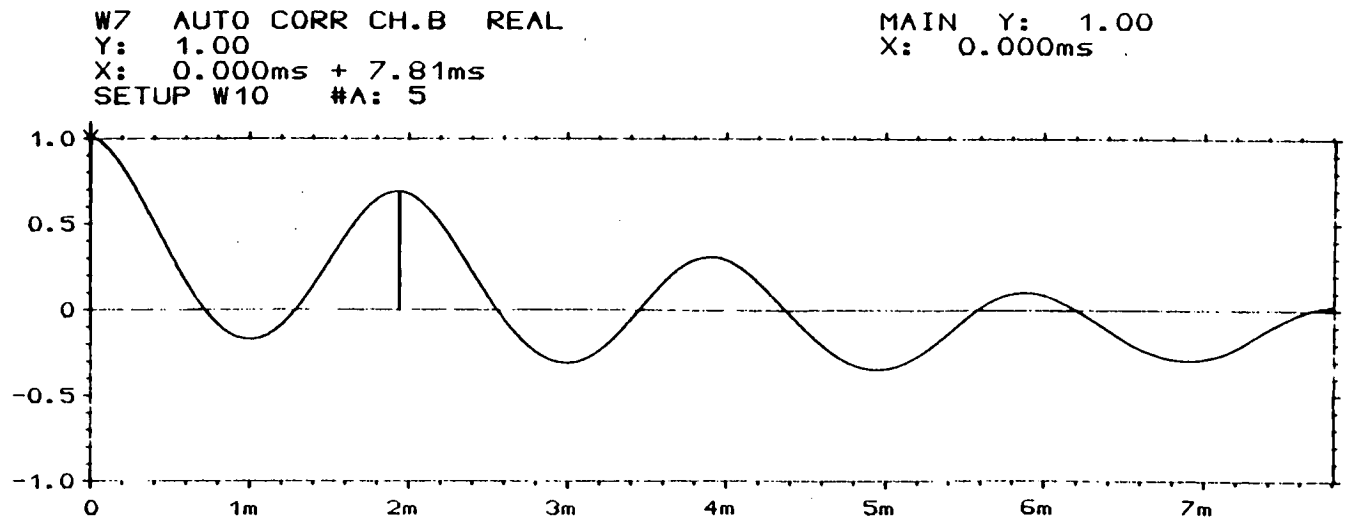
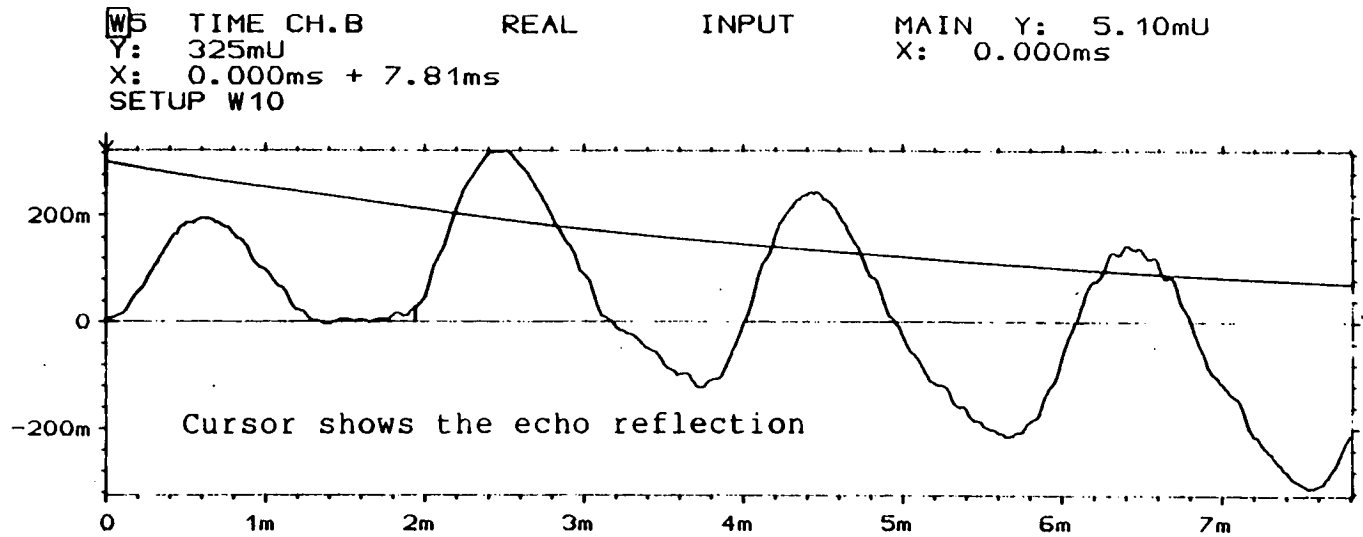
(c) Plots from a signal analyser

TYPICAL TIME HISTORY RECORDS

FIGURE 4.11

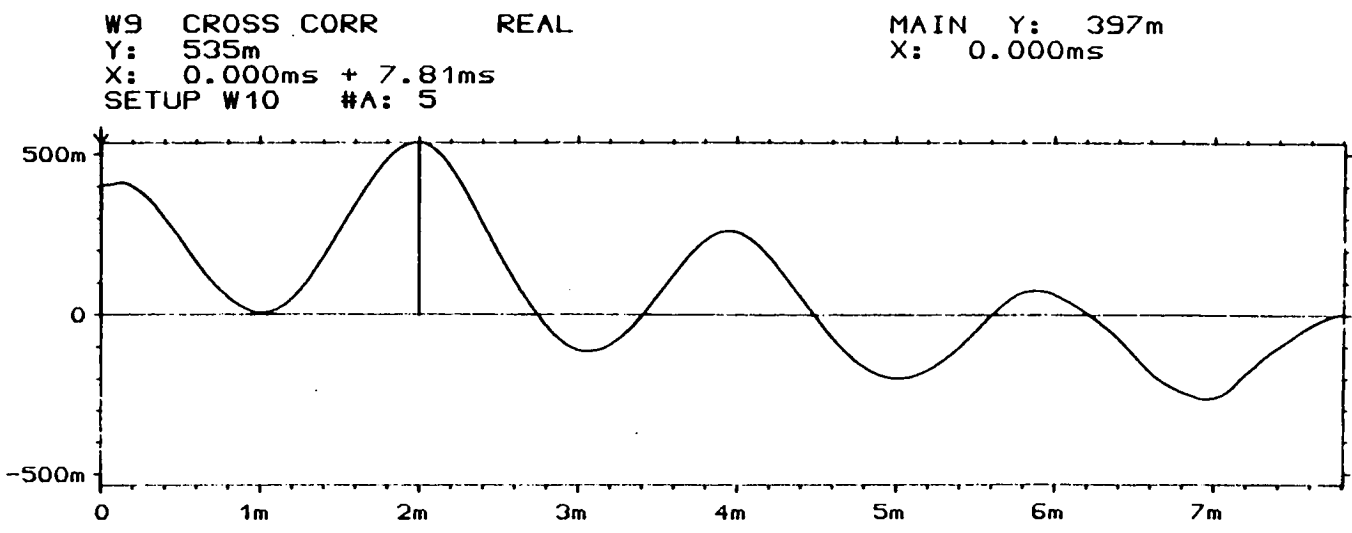
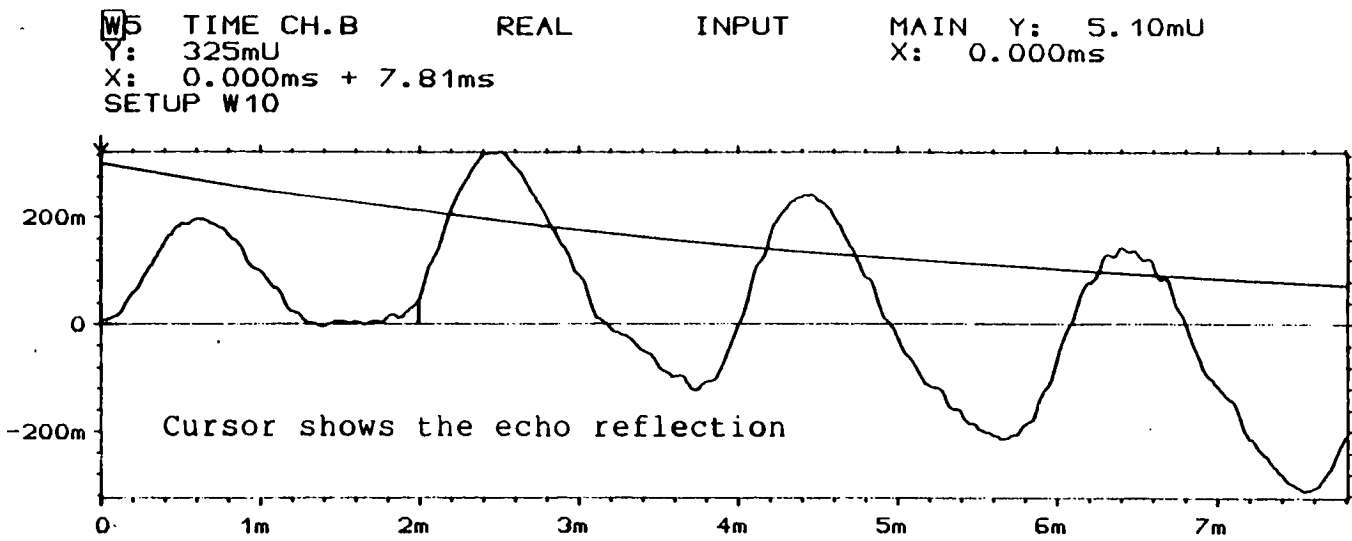
EXPERIMENTAL USE OF AUTO-CORRELATION TO DETECT AN ECHO

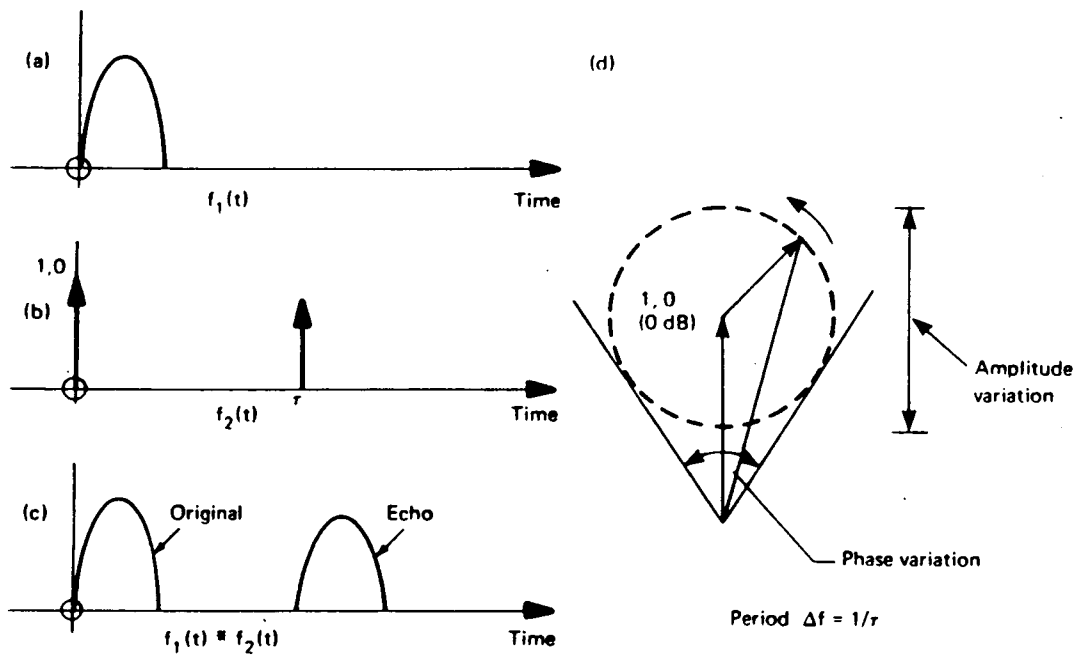
FIGURE 4.12



EXPERIMENTAL USE OF CROSS-CORRELATION TO DETECT AN ECHO

FIGURE 4.13





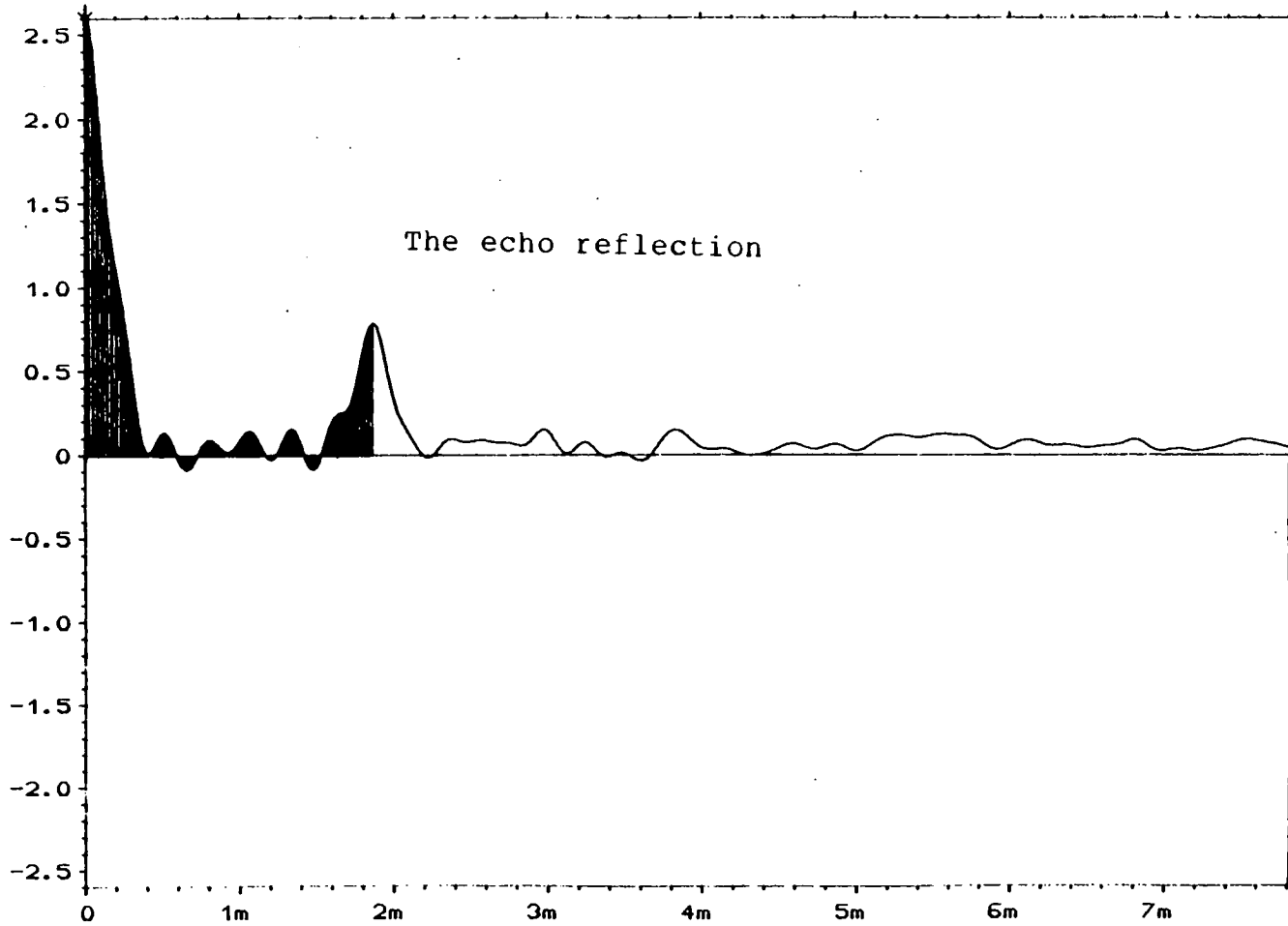
MODEL OF THE USE OF CEPSTRUM TO DETECT AN ECHO

FIGURE 4.14

(after Randall & Hee, ref. 72)

W2 CEPSTRUM CH.B REAL  
Y: 2.60dB  
X: 0.000ms + 7.81ms  
SETUP W10 #A: 5

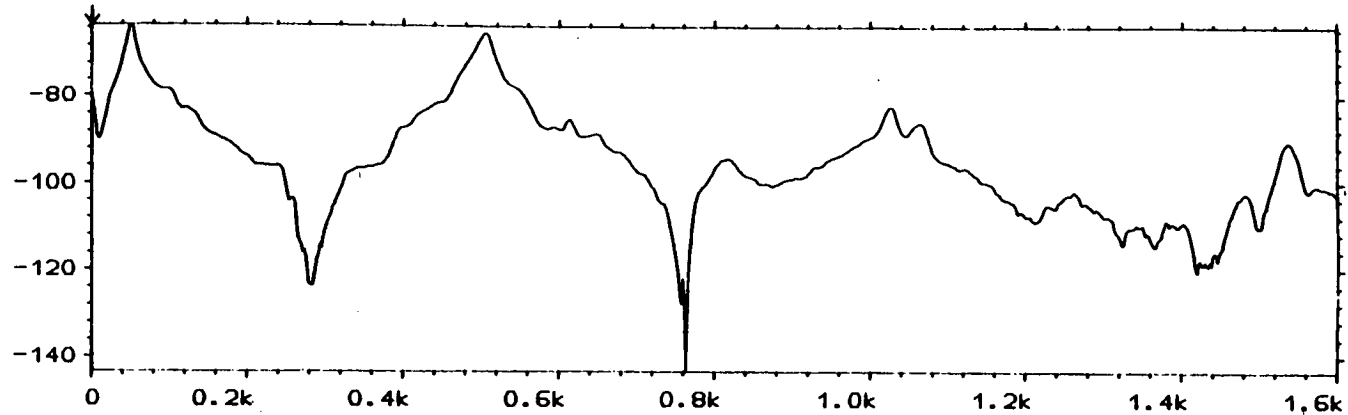
MAIN Y: -0.01dB  
X: 0.000ms  
SHORTPASS  
W: [124] [ ]



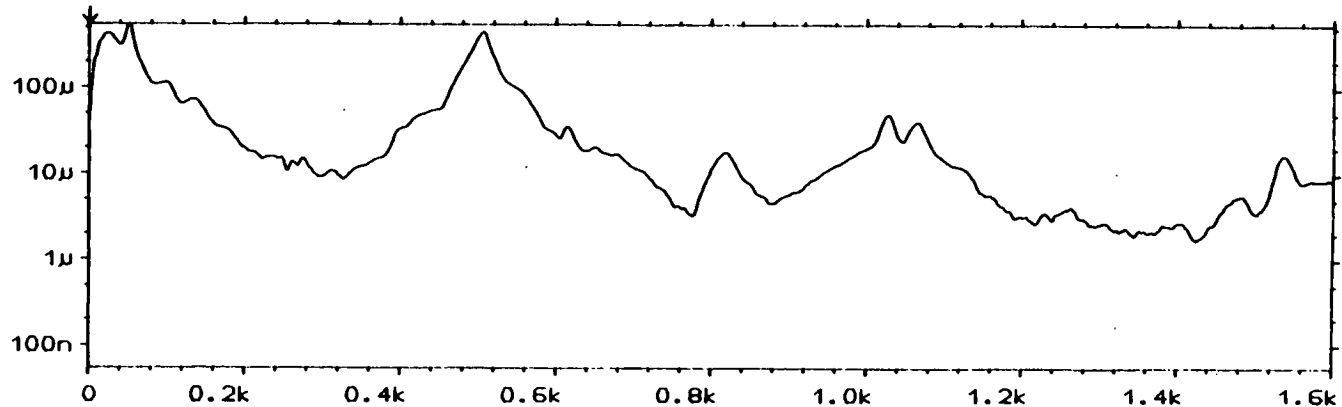
EXPERIMENTAL USE OF CEPSTRUM TO DETECT AN ECHO  
FIGURE 4.15



W1 INST SPEC CH.B MAG INPUT MAIN Y: -84.5dB  
Y: -63.4dB /1.00U RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN X: 0Hz  
SETUP 9



W6 AUTO SPEC CH.B MAIN Y: 29.5μU  
Y: 547μU RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN X: 0Hz  
SETUP 9 #A: 5

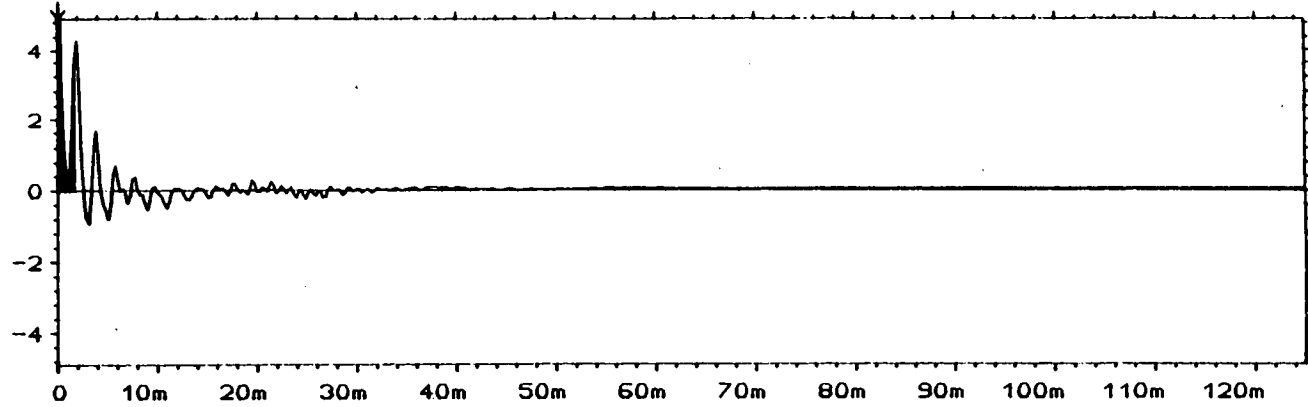


TYPICAL EXPERIMENTAL SPECTRA RECORDS

FIGURE 4.16

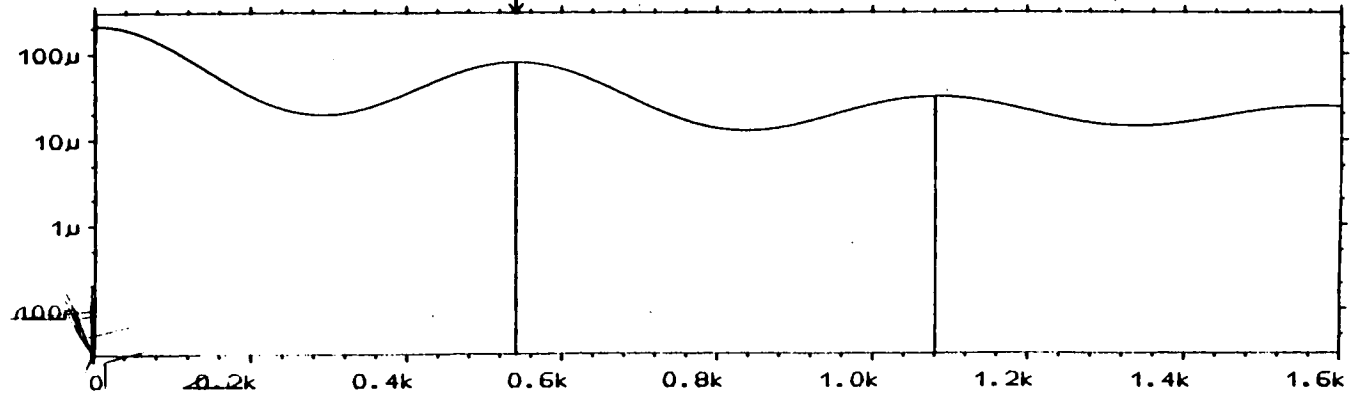
W2 CEPSTRUM CH.B REAL  
Y: 4.90dB  
X: 0.00ms + 125ms  
SETUP 9 #A: 5

MAIN Y: -0.02dB  
X: 0.00ms  
SHORTPASS  
W: 9 [ ]



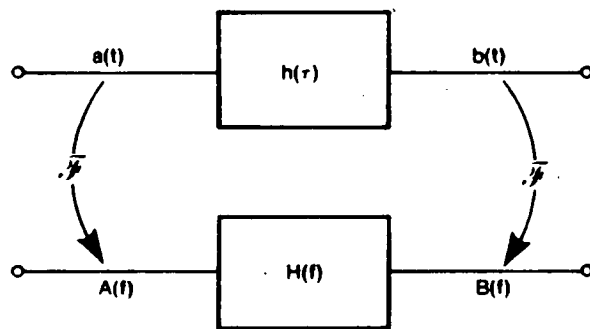
W4 LIFT SPEC CH.B  
Y: 299 $\mu$ U RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP 9 #A: 5

SIDB Y: 79.5 $\mu$ U  
X: 540Hz  
SHORTPASS  $\Delta$ X: 539.2500Hz  
W: 9



TYPICAL EXPERIMENTAL FILTERED SPECTRUM RECORD

FIGURE 4.17



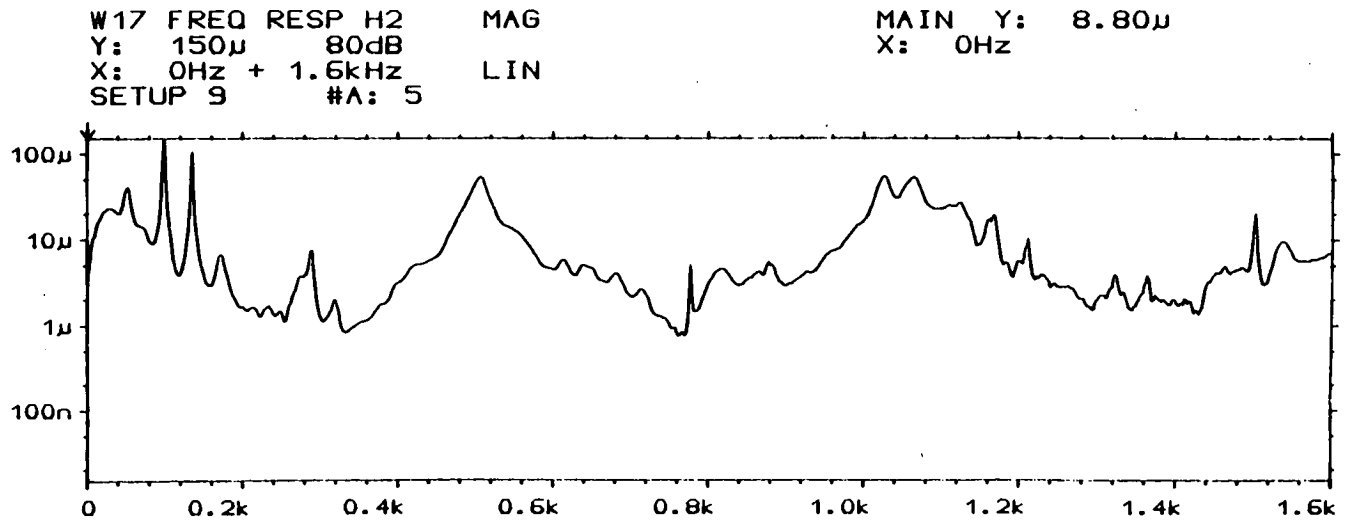
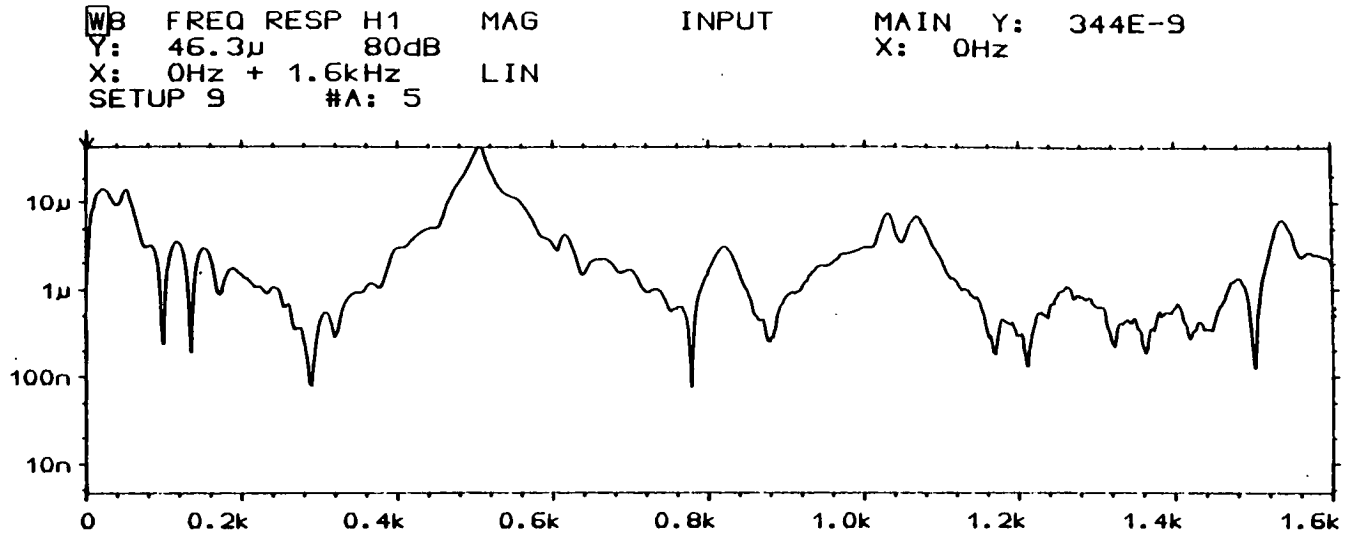
*System with input signal  $a(t)$  and output signal  $b(t)$ . The Fourier Transform of  $a(t)$  and  $b(t)$  are  $A(f)$  and  $B(f)$  respectively*

FIGURE 4.18

(after Herlufsen, ref. 75)

TYPICAL EXPERIMENTAL FREQUENCY RESPONSE FUNCTIONS

FIGURE 4.19

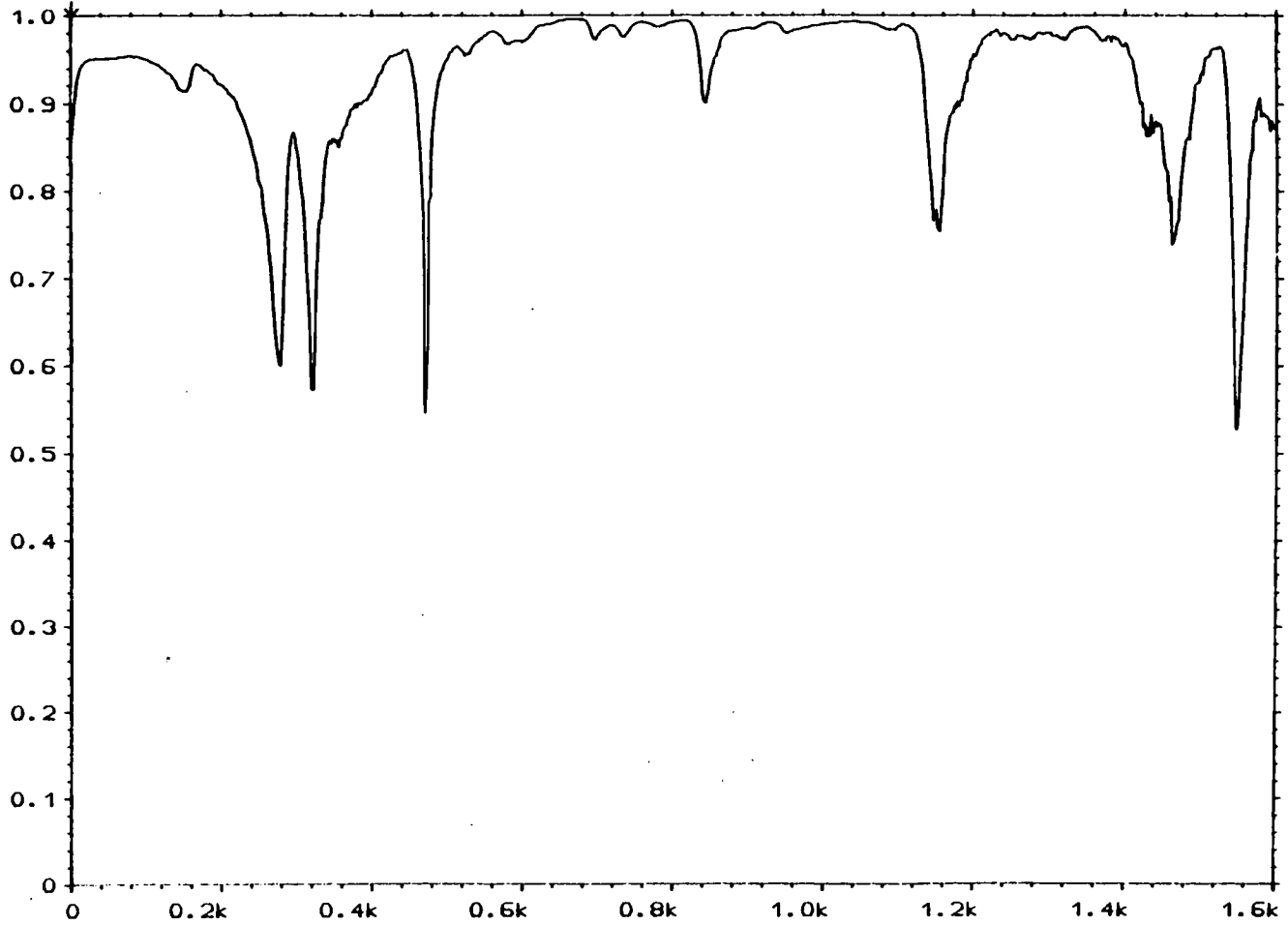


W20 COHERENCE  
Y: 1.00  
X: 0Hz + 1.6kHz  
SETUP W9 #A: 5

INPUT

MAIN Y: 834m  
X: 0Hz

LIN



TYPICAL EXPERIMENTAL COHERENCE FUNCTION

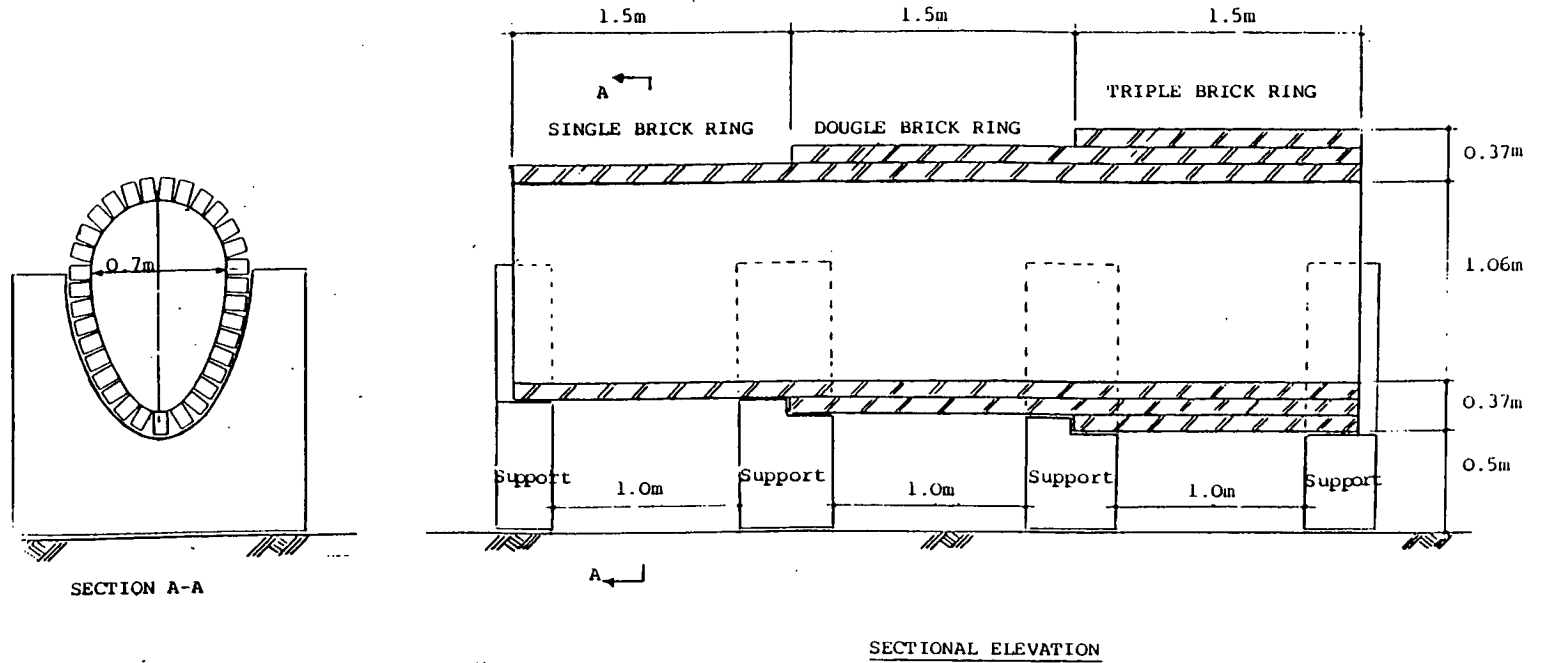
FIGURE 4.20

## CHAPTER 5

### EXPERIMENTAL PROGRAMME

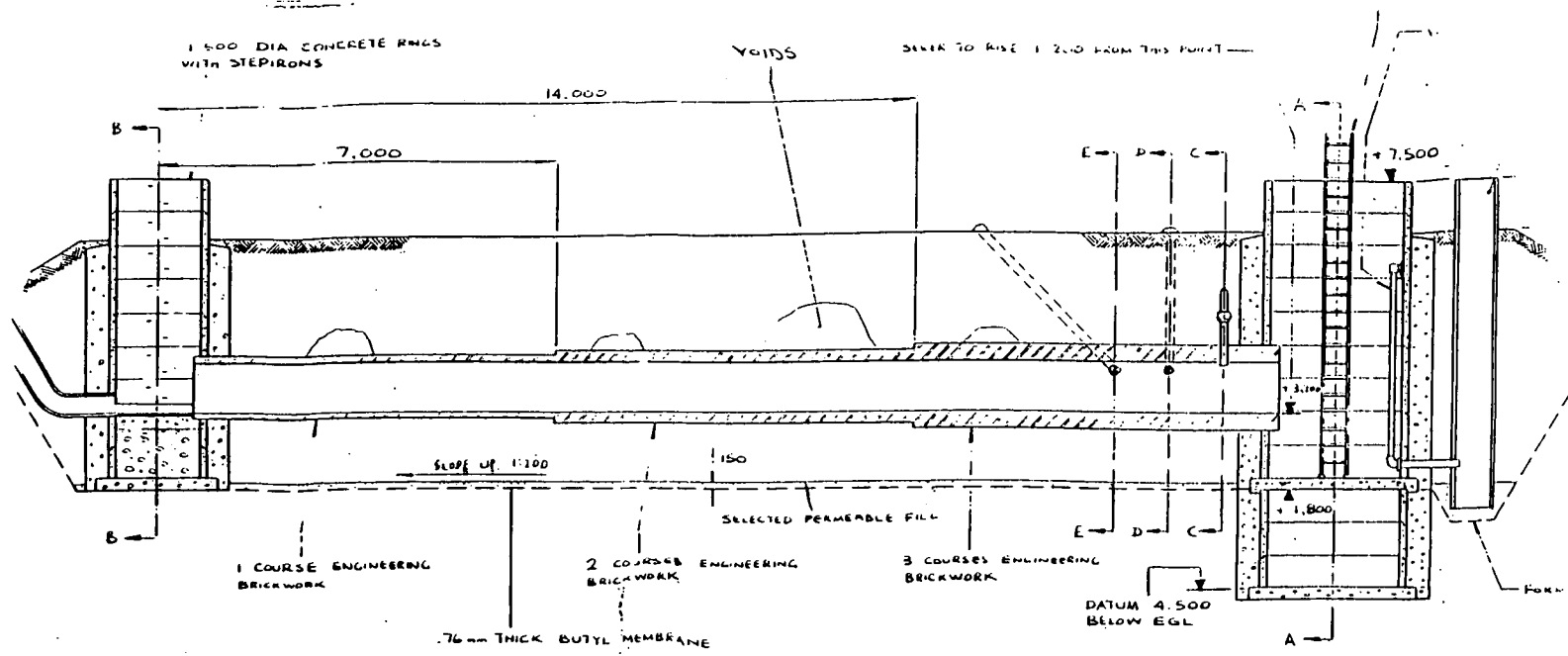
LABORATORY SEWER

FIGURE 5.1

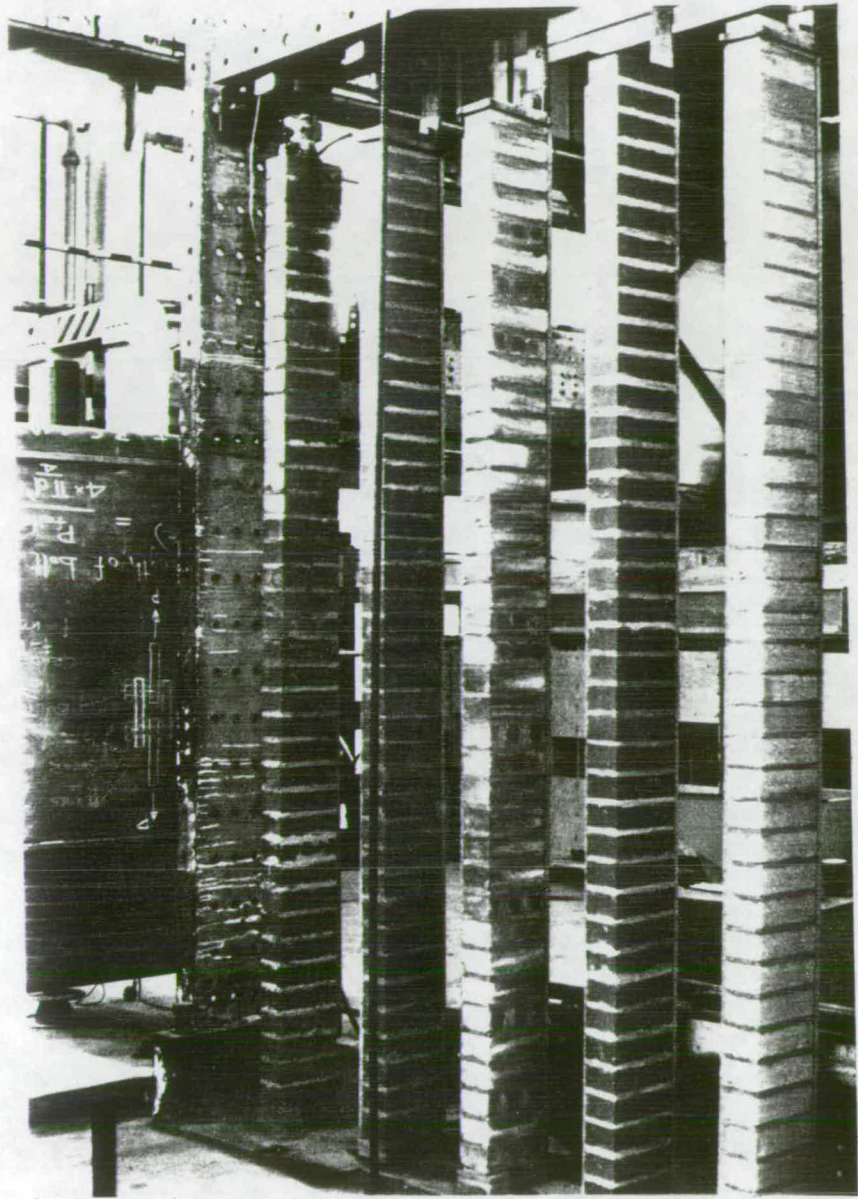


WROUGHTON SEWER

FIGURE 5.2

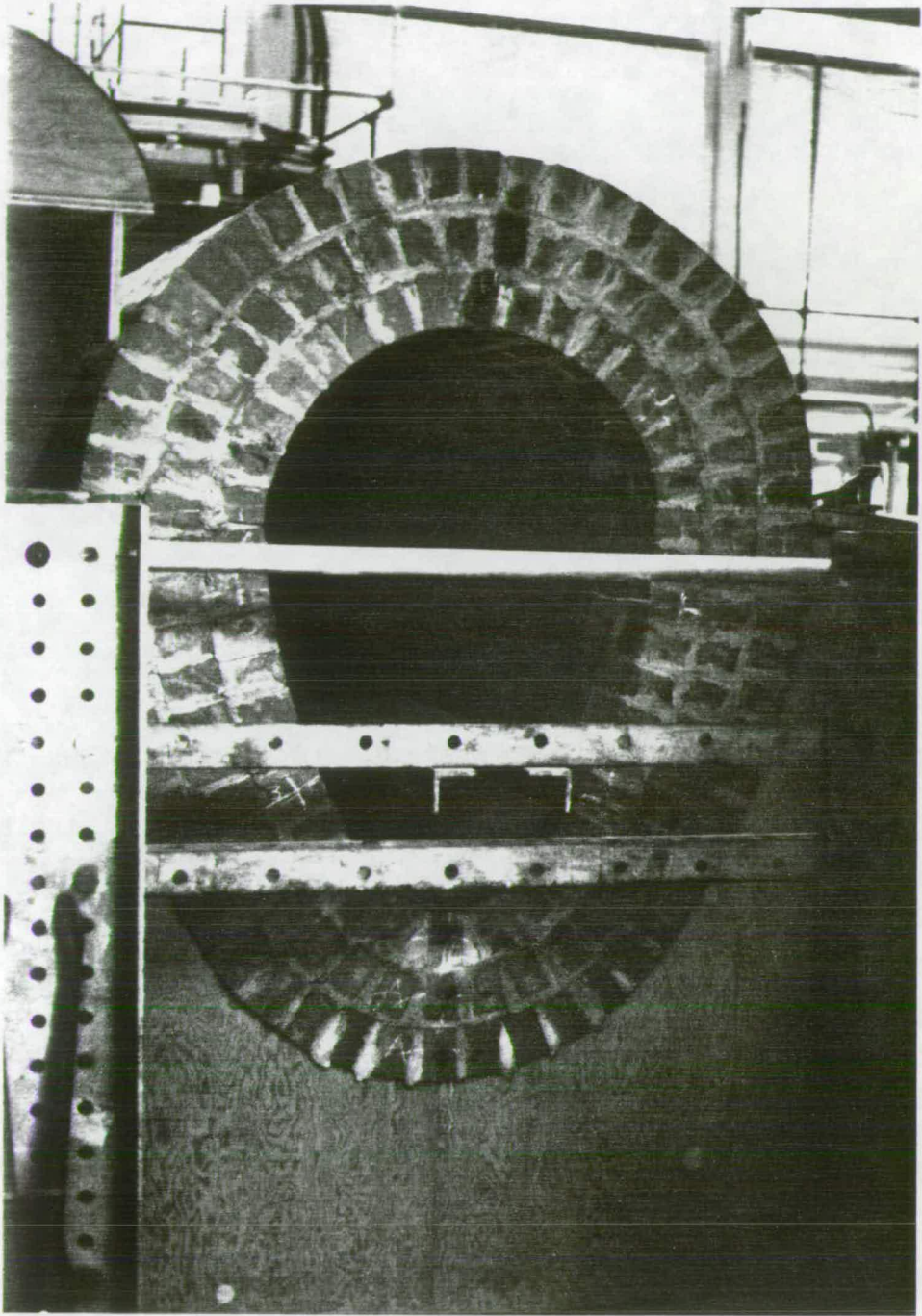






COLUMNS (GROUP 1)

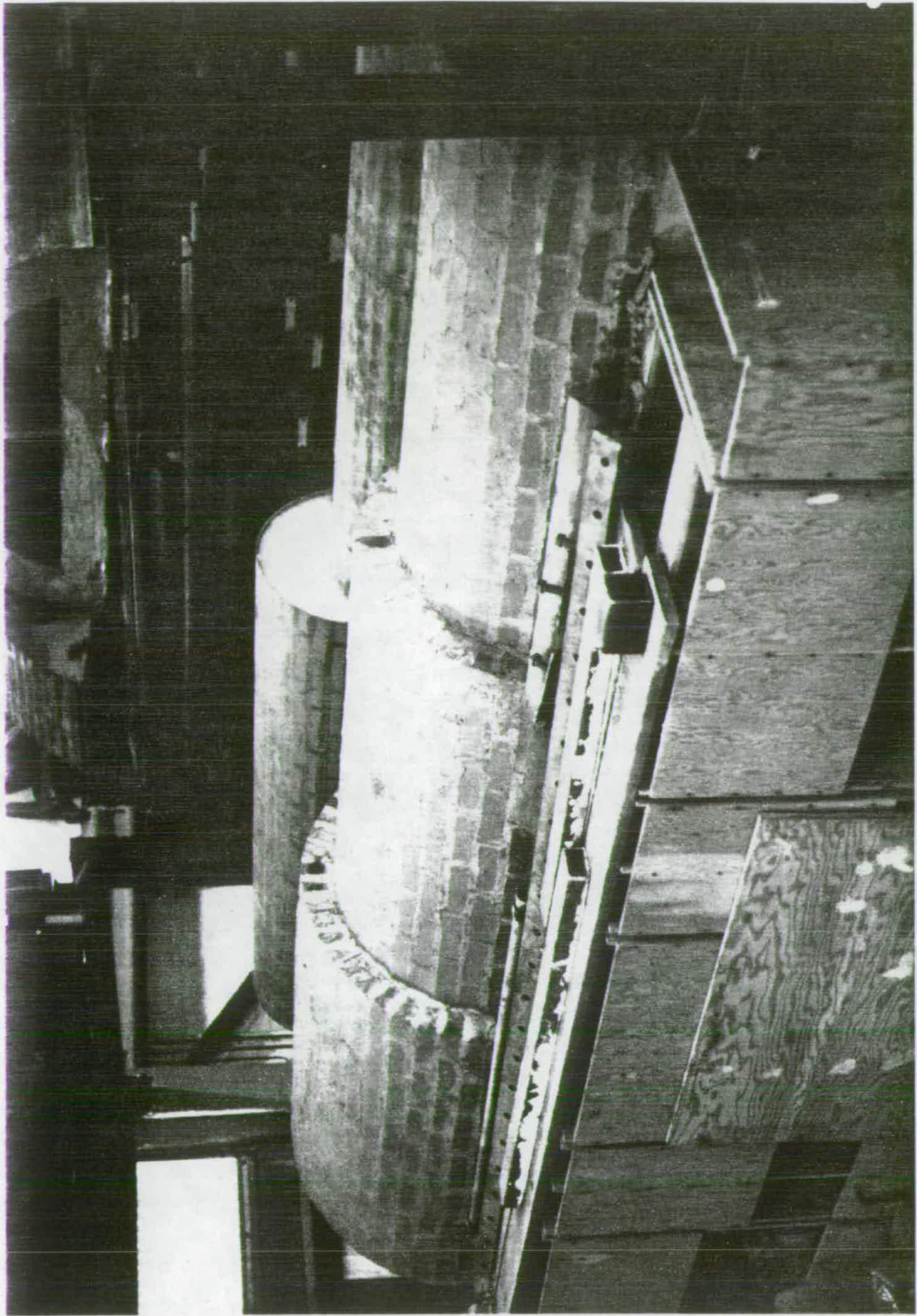
PLATE 5.1



LABORATORY SEWER

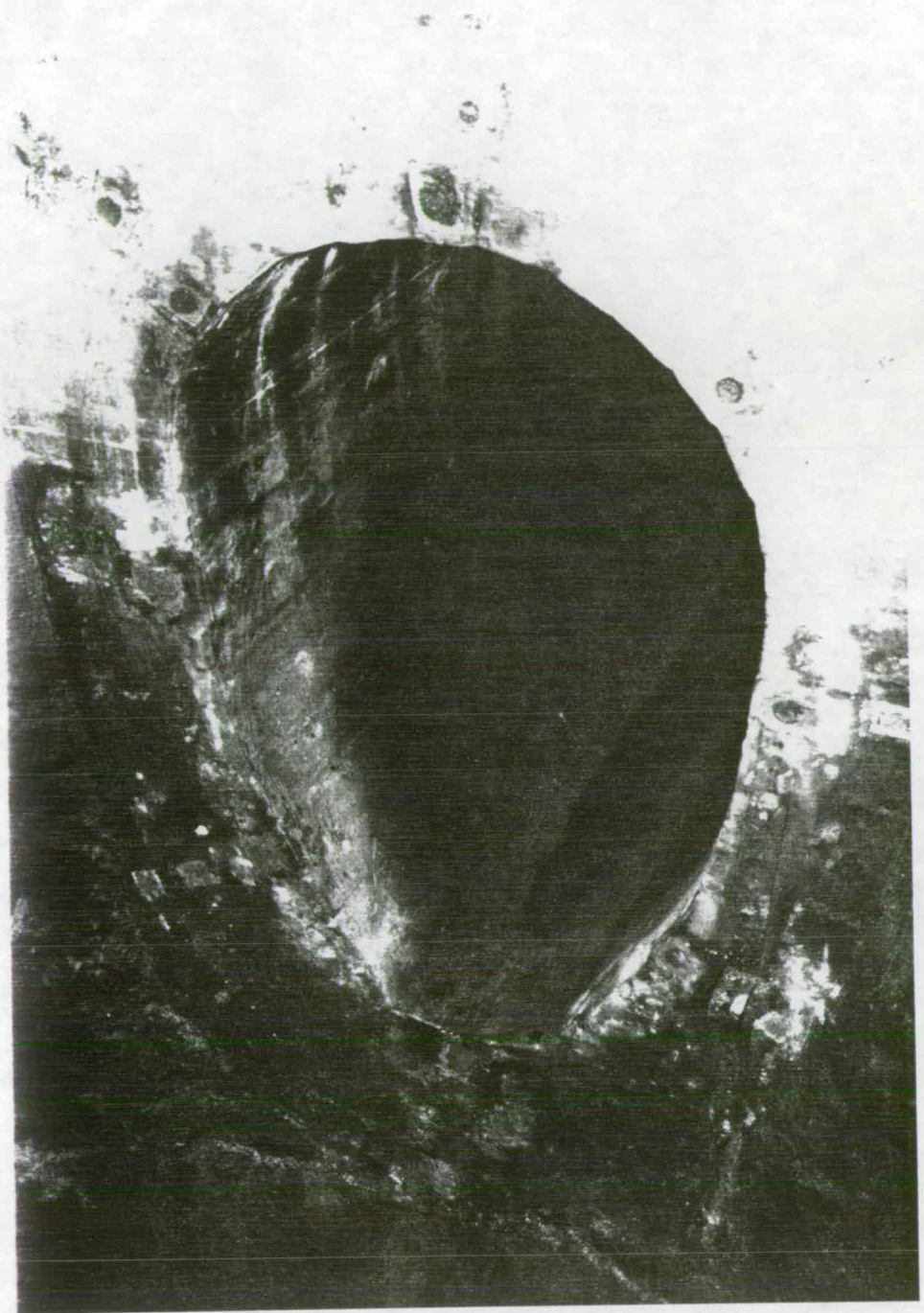
PLATE 5.2





LABORATORY SEWER

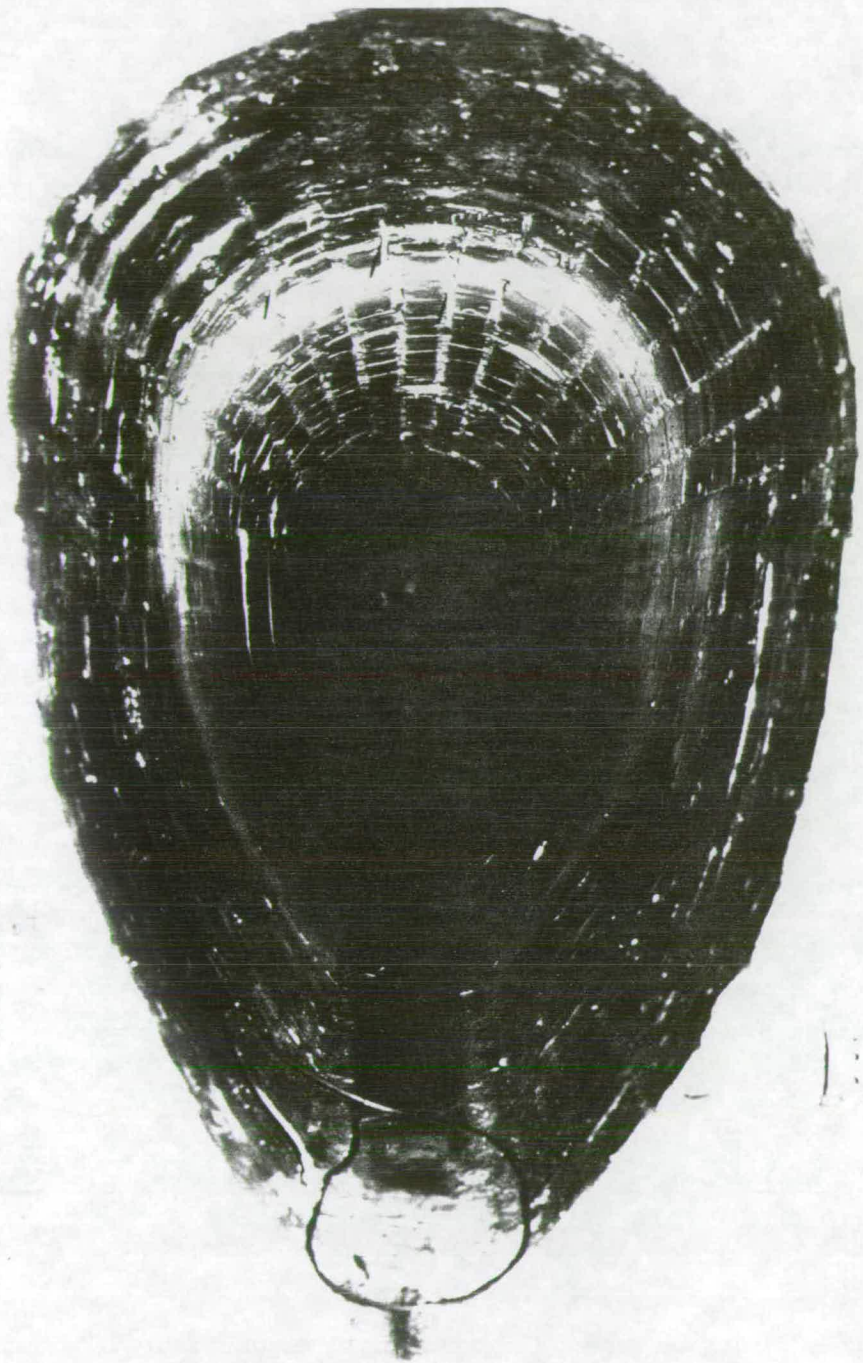
PLATE 5.3



WROUGHTON SEWER

PLATE 5.4



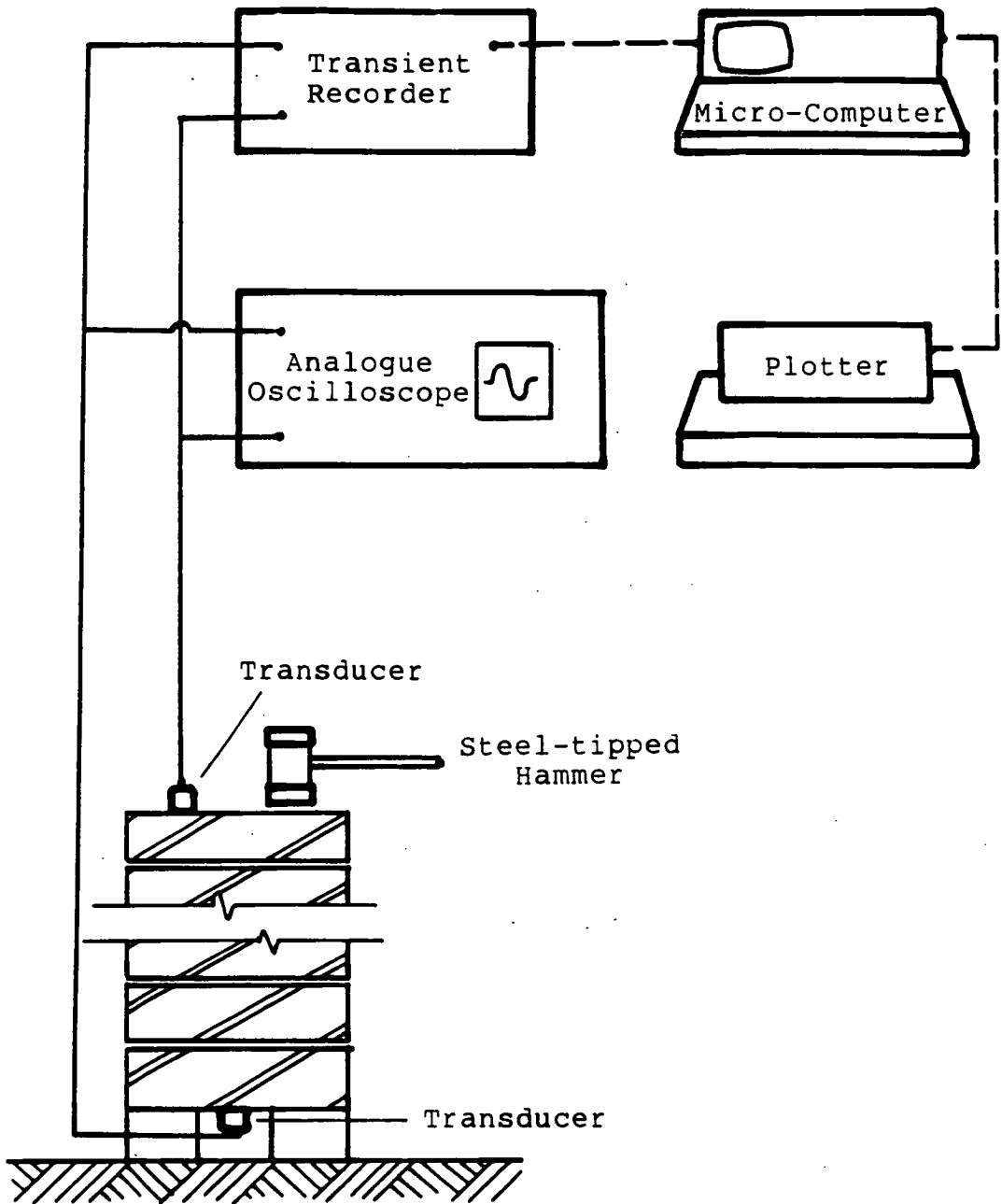


WROUGHTON SEWER

PLATE 5.5

CHAPTER 6

PRELIMINARY EXPERIMENTS  
AND  
INVESTIGATION OF EQUIPMENT

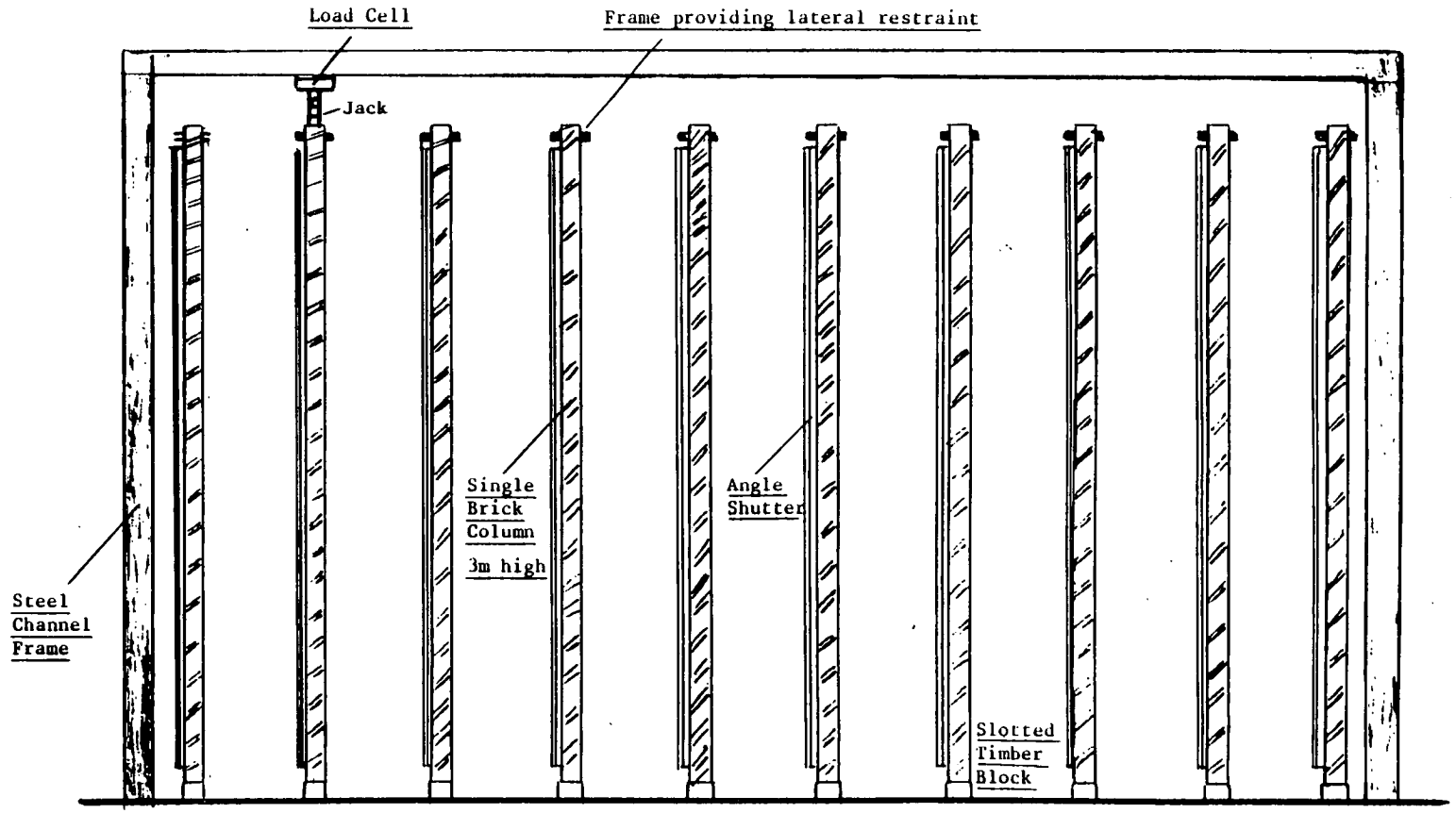


EQUIPMENT - PHASE A

FIGURE 6.1

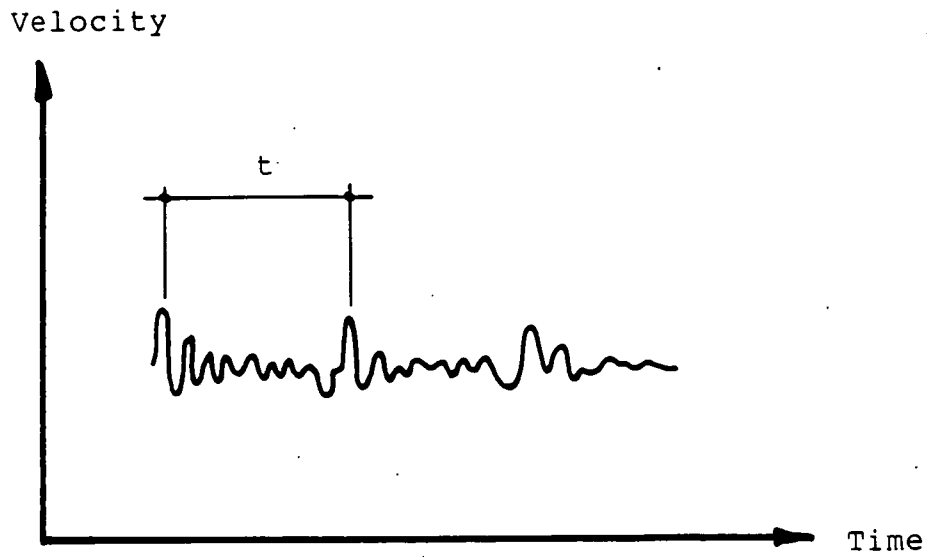
COLUMN TEST FRAME

FIGURE 6.2



Schematic Details of Column Test Rig

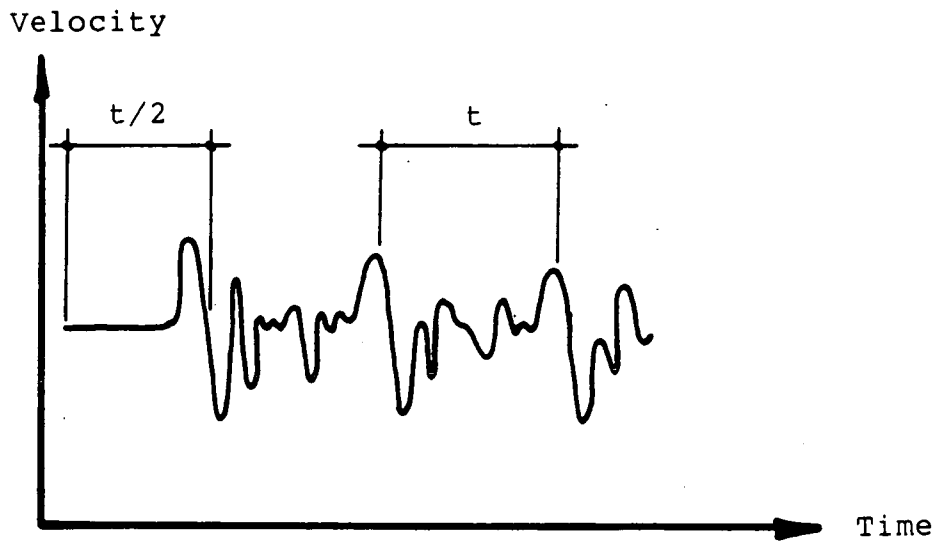




(a) Echo Method

Propagation time =  $t$

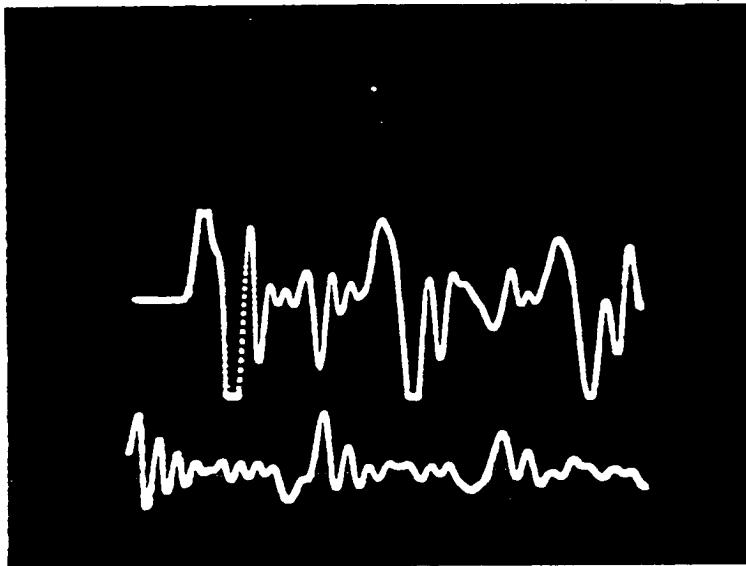
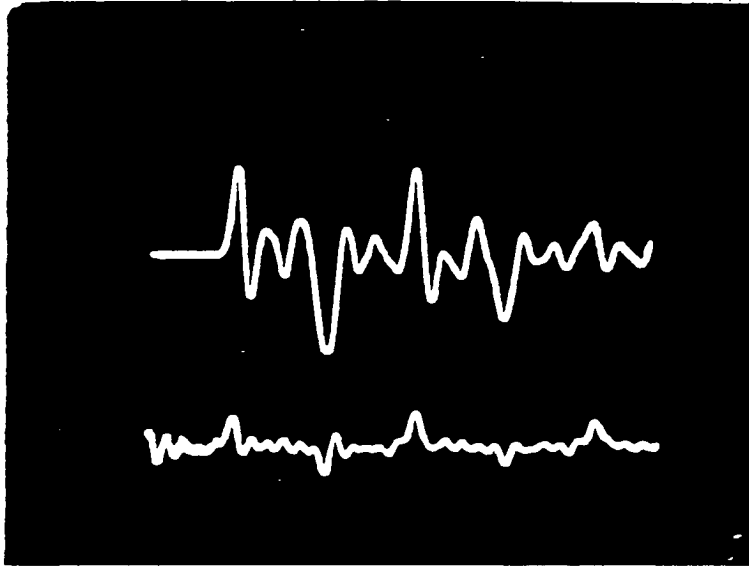
Transmission velocity = path length /  $t$



(b) Delay Echo Method

DETERMINATION OF PROPAGATION TIME USING PULSE METHODS

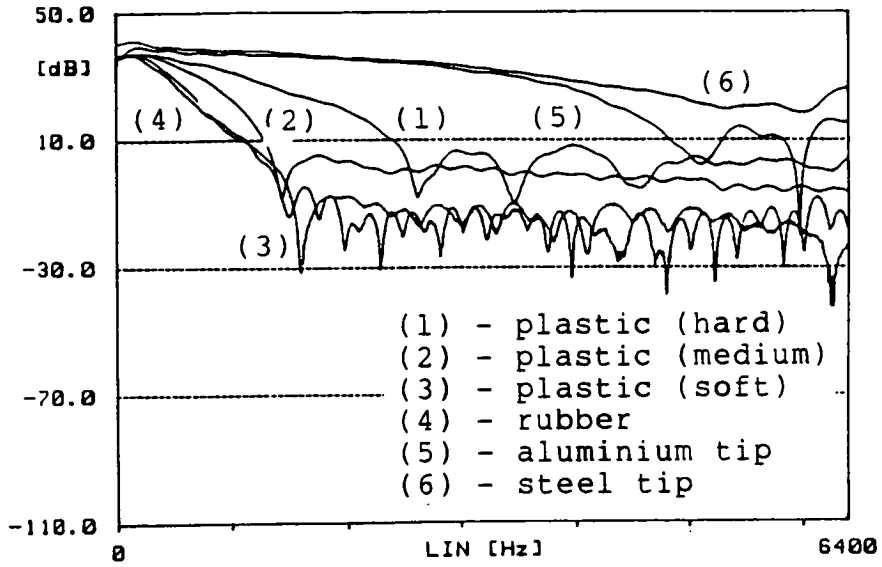
FIGURE 6.3



EQUIPMENT - PHASE A: TYPICAL TEST RESULTS

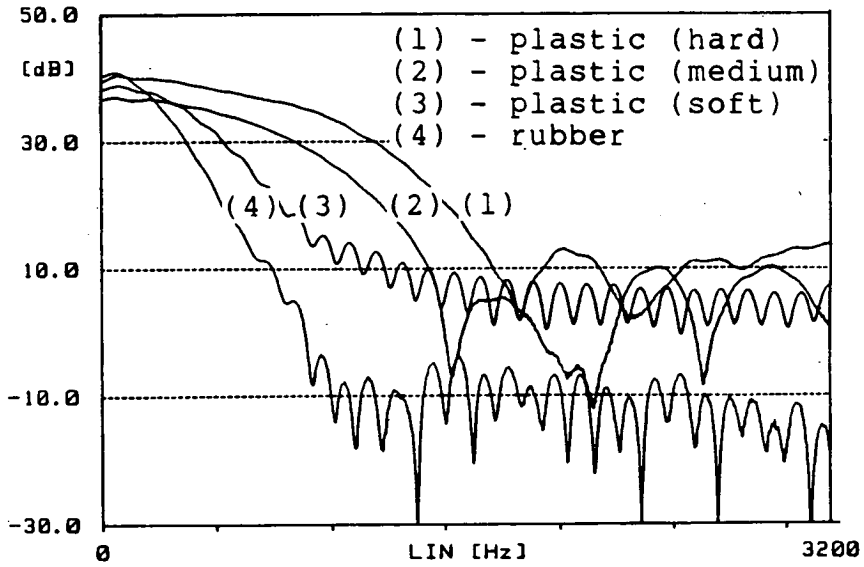
FIGURE 6.4

Auto Spec Ch.A PWR Lin Avg: 1



(a) 3 lb Hammer

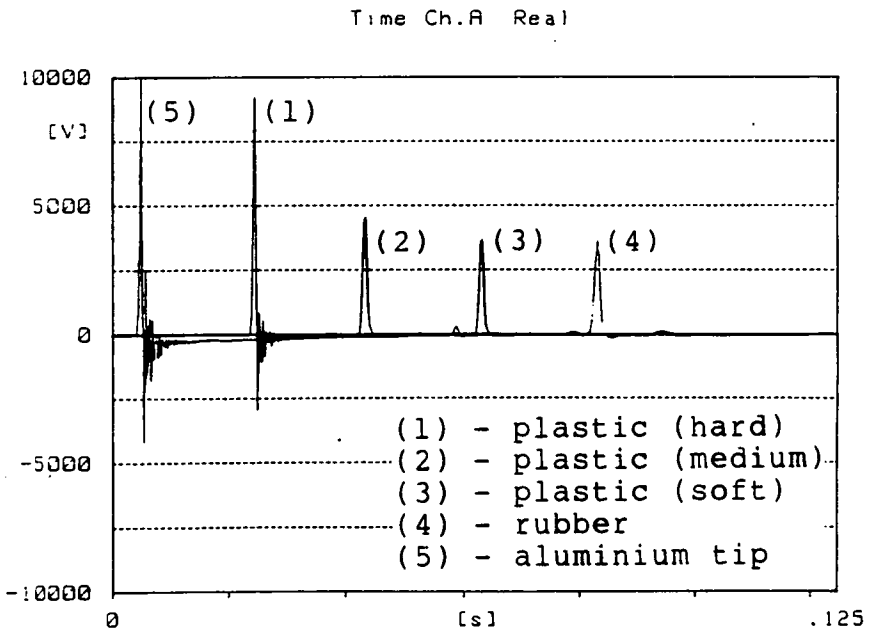
Auto Spec Ch.A PWR Lin Avg: 1



(b) 12 lb Hammer

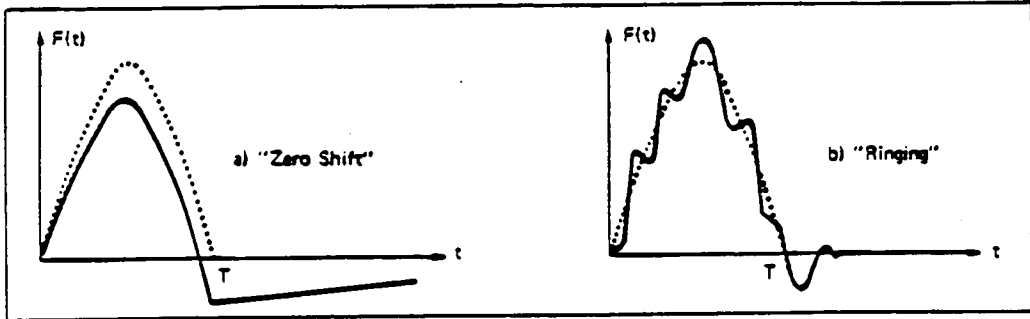
HAMMER FORCE AUTO SPECTRA

FIGURE 6.5



FORCE RECORDS - 3 LB HAMMER WITH DIFFERENT TIPS

FIGURE 6.6



*Vibration measurement system response to half sine wave pulse of length  $T$ .*

*a) "Zero Shift" limits the low-frequency response of the system.*

*b) "Ringing" limits the high frequency response of the system*

## ZERO SHIFT AND RINGING

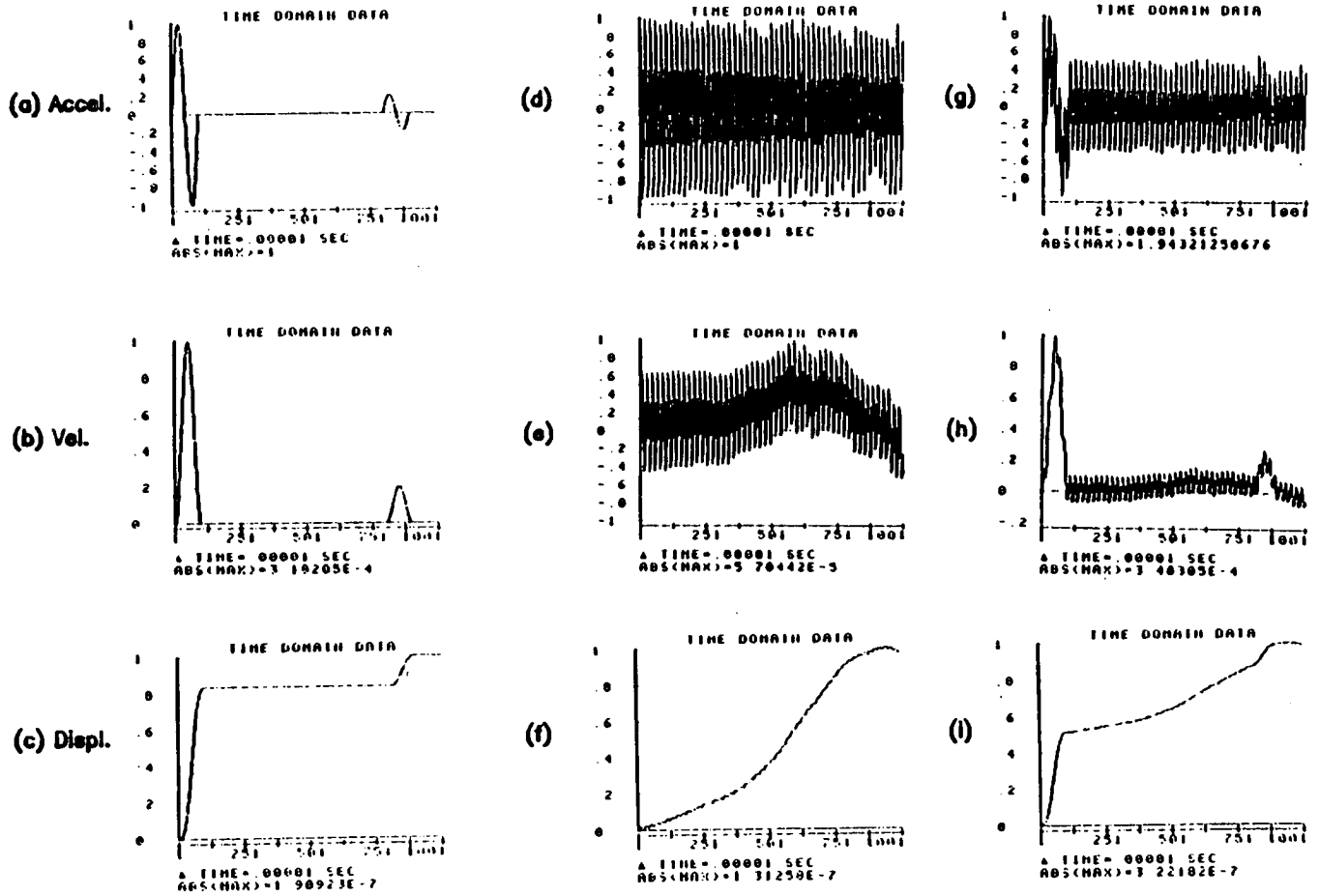
FIGURE 6.7

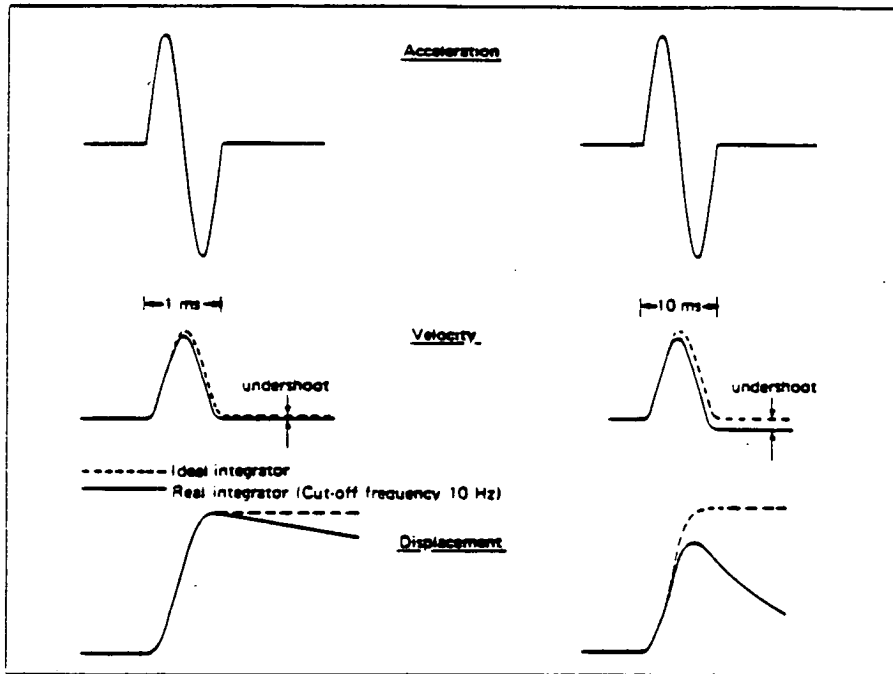
(after Broch, ref. 81)

USE OF INTEGRATION TO FILTER SURFACE WAVES

FIGURE 6.8

(after Chan, ref. 30)



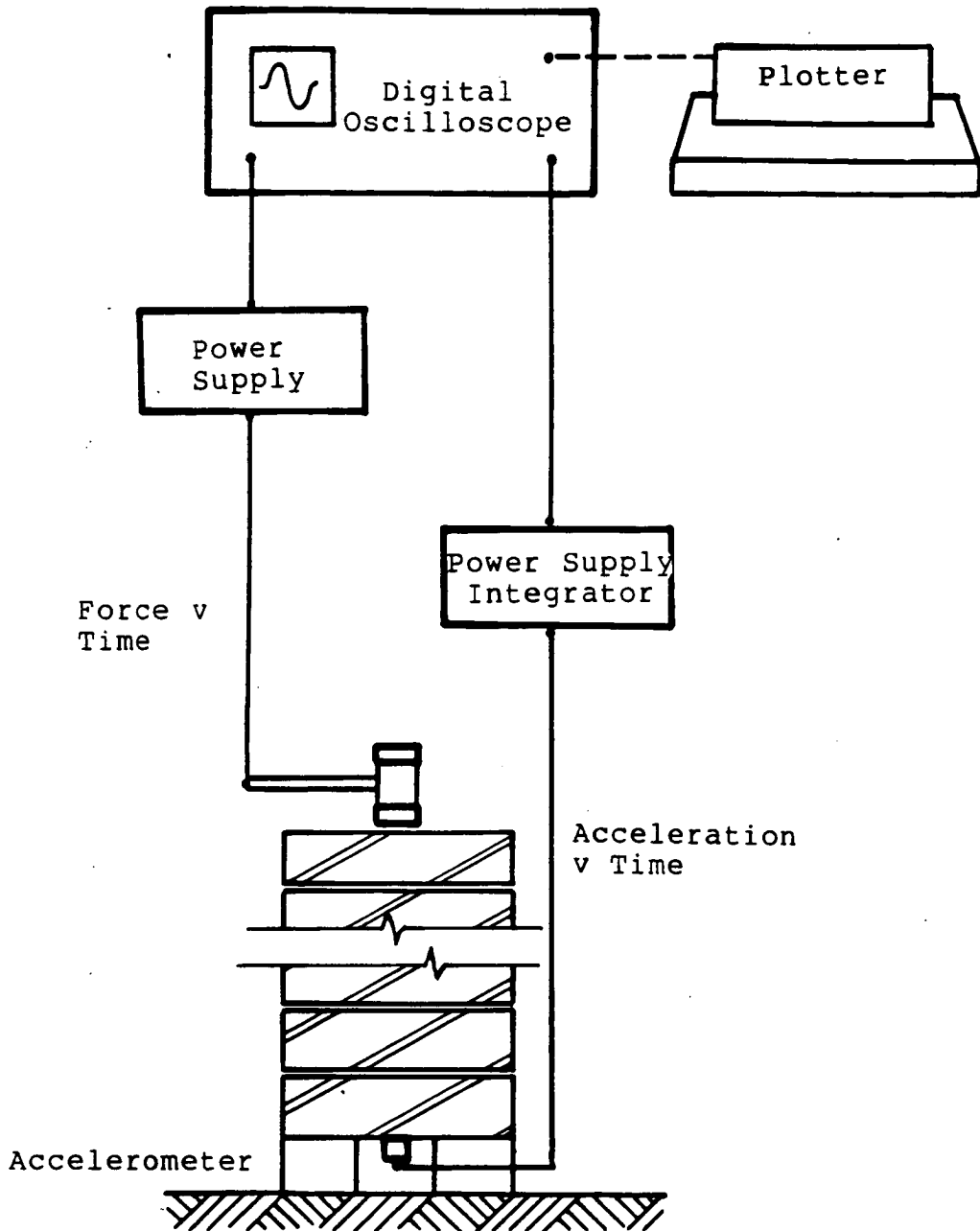


*Practical integration of 2 different length acceleration pulses to velocity and displacement using the same integration cutoff frequency*

Signal Distortion due to Integration - DC Shift

FIGURE 6.9

(after Broch, ref. 81)



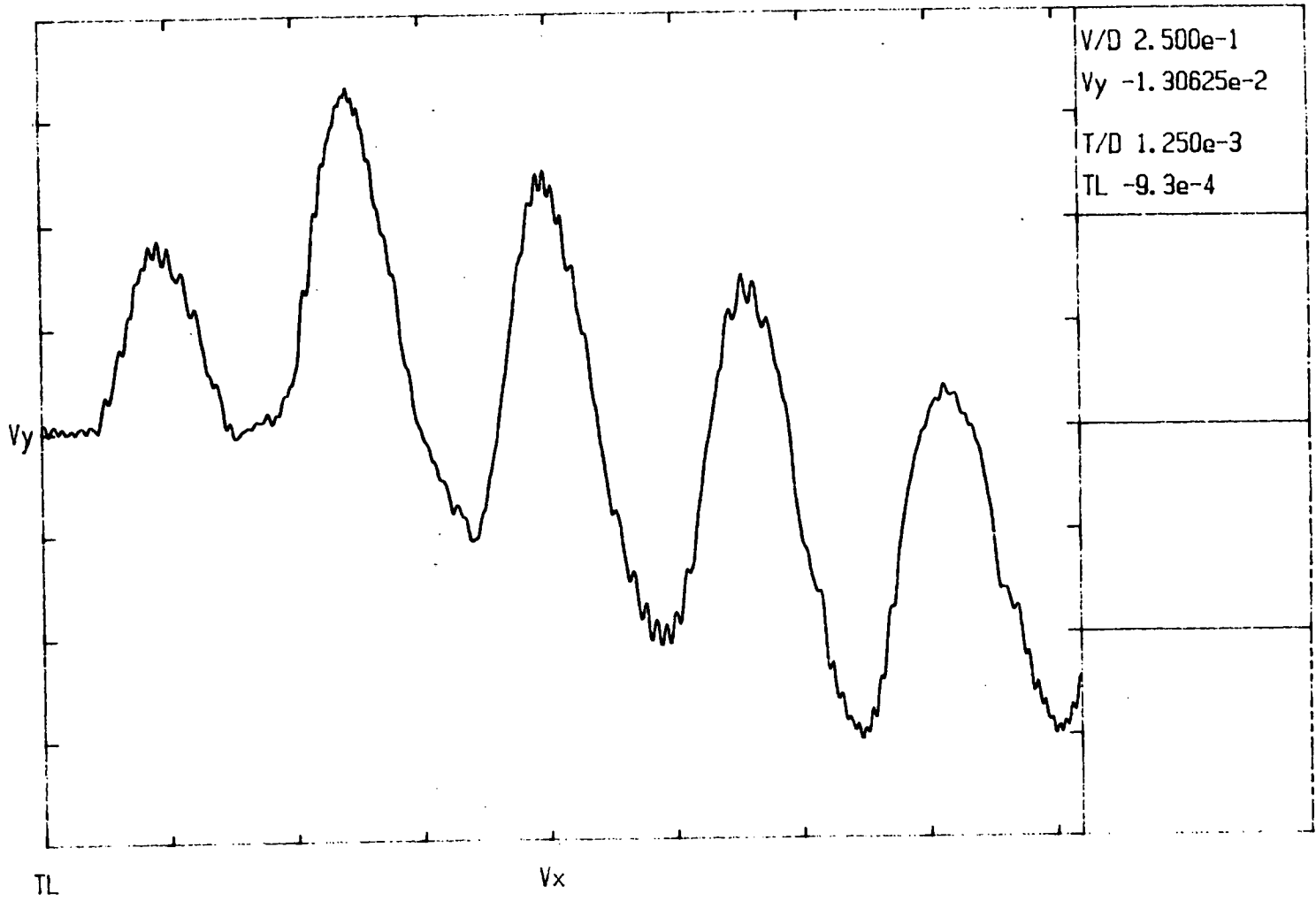
EQUIPMENT - PHASE B

FIGURE 6.10



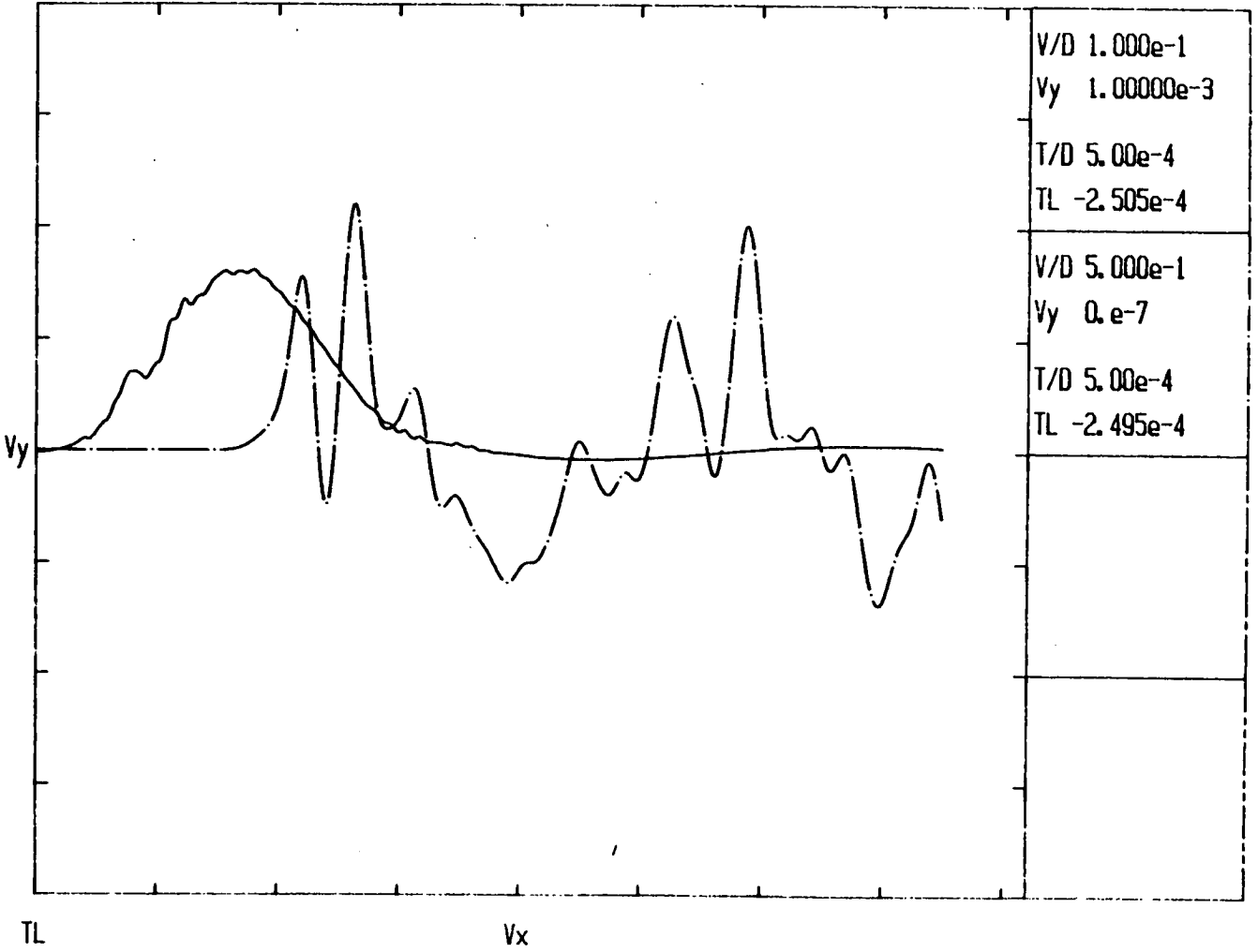
EQUIPMENT - PHASE B: TYPICAL ECHO METHOD RESULTS

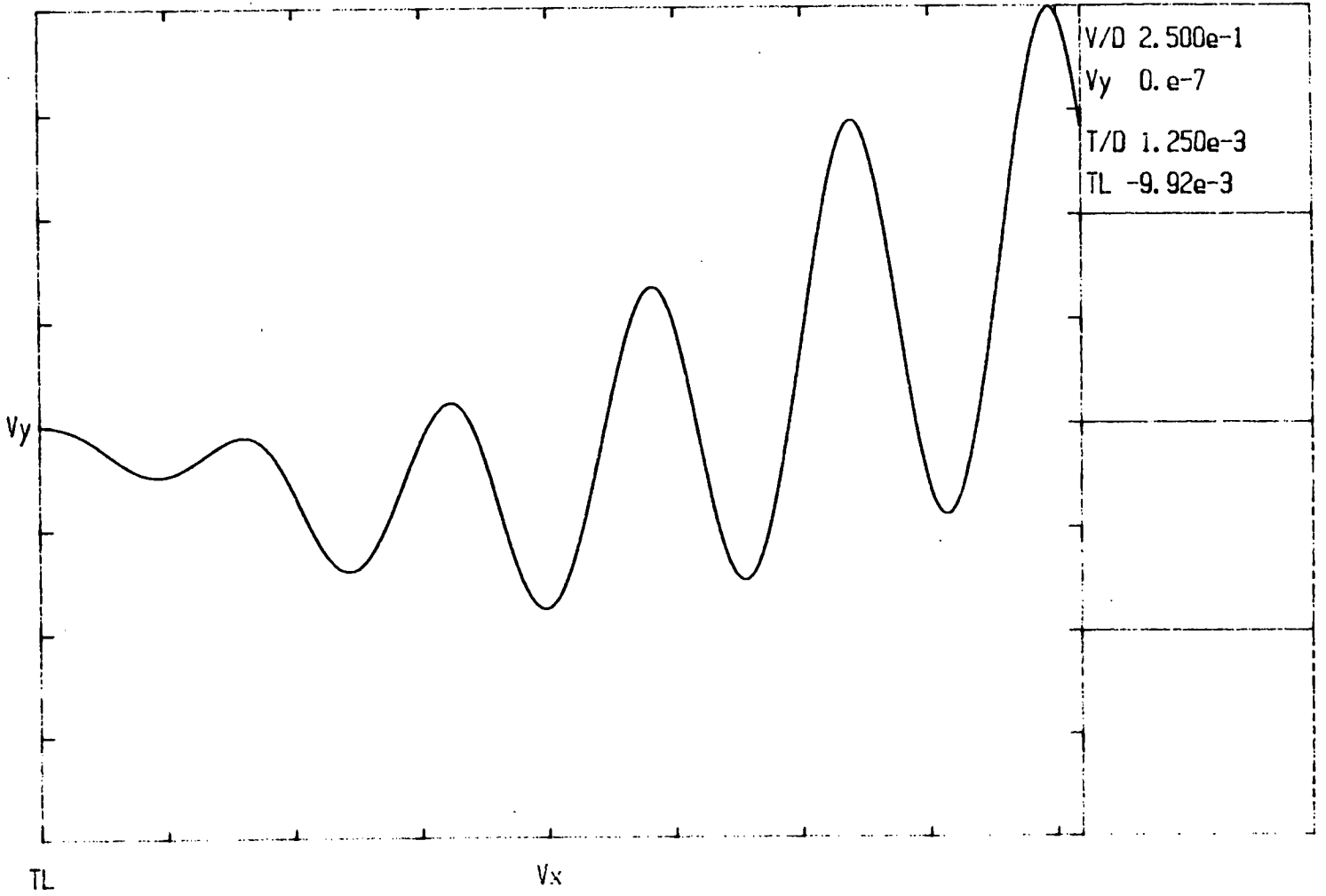
FIGURE 6.11



EQUIPMENT - PHASE B: TYPICAL DELAY METHOD RESULTS

FIGURE 6.12



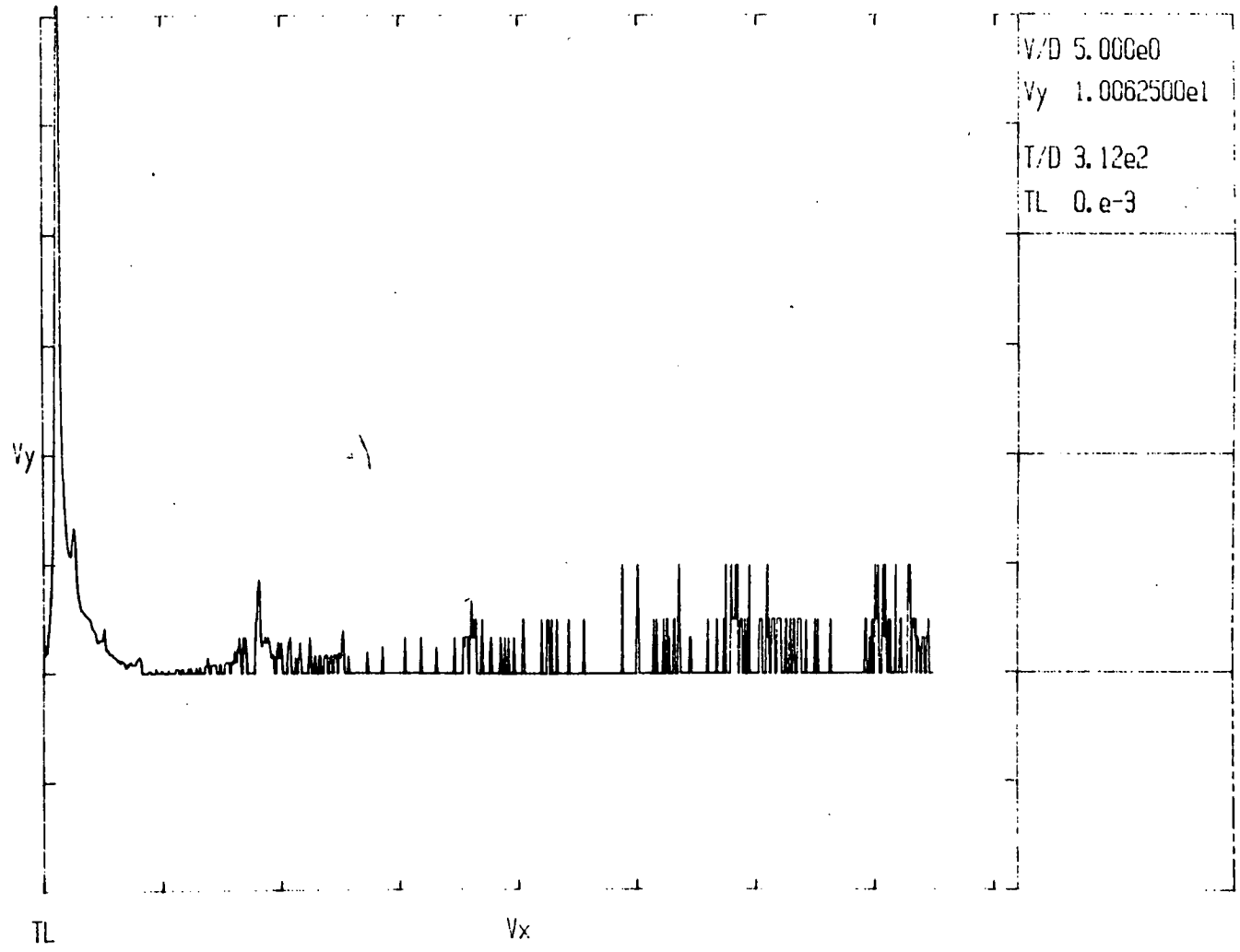


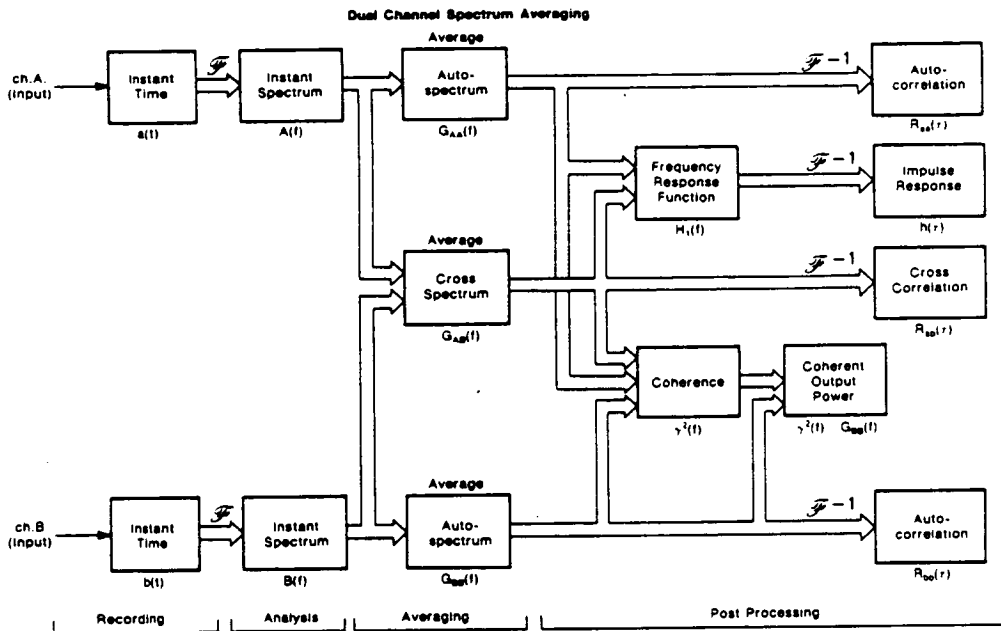
EQUIPMENT - PHASE B  
AUTO-CORRELATION FOR AN ECHO TEST

FIGURE 6.13

EQUIPMENT - PHASE B  
FREQUENCY RESPONSE FUNCTION FOR AN ECHO TEST

FIGURE 6.14



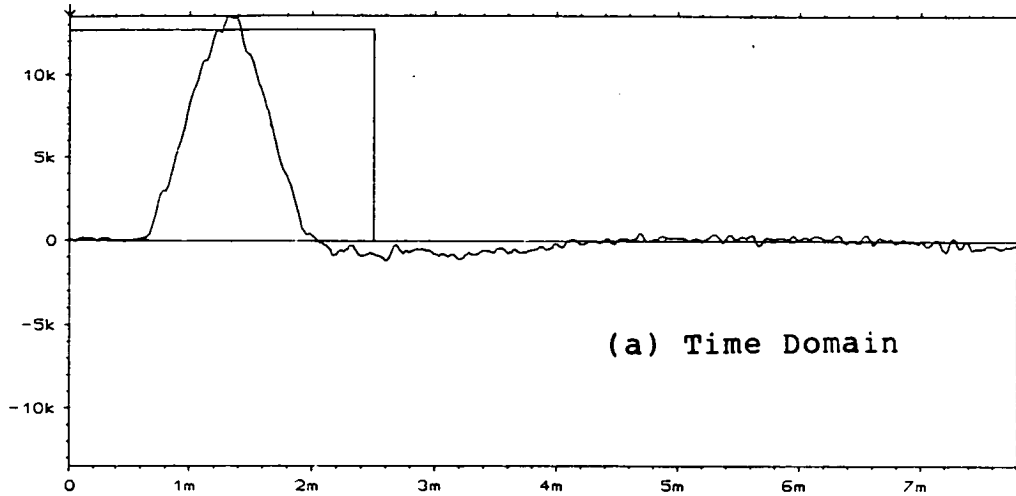


*Simplified block diagram of the analyzer in the dual channel spectrum averaging mode*

FIGURE 6.15

(after Herlufsen, ref. 75)

WD TIME CH.A REAL INPUT MAIN Y: 111U  
 Y: 13.5kU X: 0.000ms  
 X: 0.000ms + 7.81ms

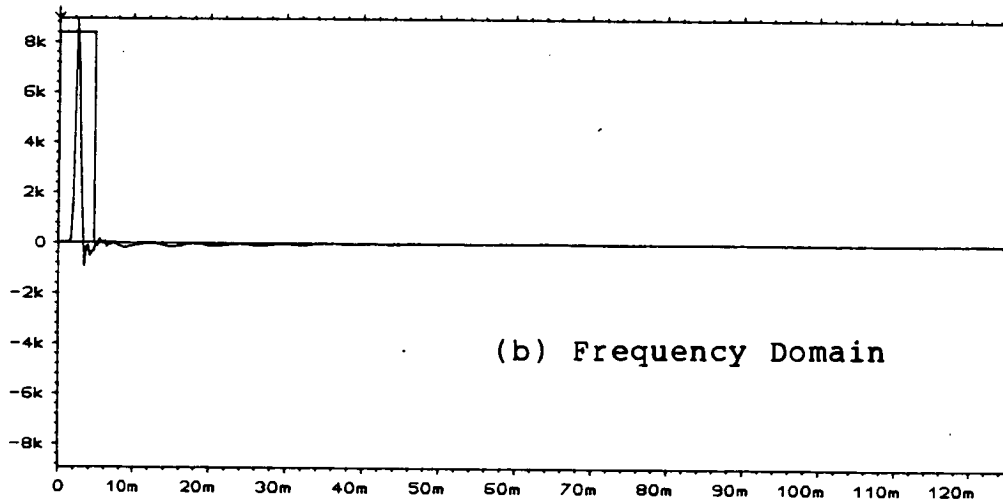


SETUP W10

MEASUREMENT: DUAL SPECTRUM AVERAGING  
 TRIGGER: CH.A +SLOPE LEVEL: +0.10 MAX INPUT  
 DELAY: TRIG→A: -1.007ms CH.A→B: 0.000ms  
 AVERAGING: LIN 5

FREQ SPAN: 25.6kHz ΔF: 32Hz T: 31.3ms ΔT: 15.3μs  
 CENTER FREQ: BASEBAND  
 WEIGHT CH.A: TRANSIENT SHIFT: 0.000ms LENGTH: 2.502ms  
 WEIGHT CH.B: EXPONENTIAL SHIFT: 0.000ms LENGTH: 20.004ms  
 CH.A: 6V + 3Hz DIR FILT: BOTH 92.0μV/N  
 CH.B: 6V + 3Hz DIR FILT: BOTH 31.6V/m/s  
 GENERATOR: DISABLED

WD TIME CH.A REAL INPUT MAIN Y: 9.95U  
 Y: 8.94kU X: 0.00ms  
 X: 0.00ms + 125ms



SETUP W9

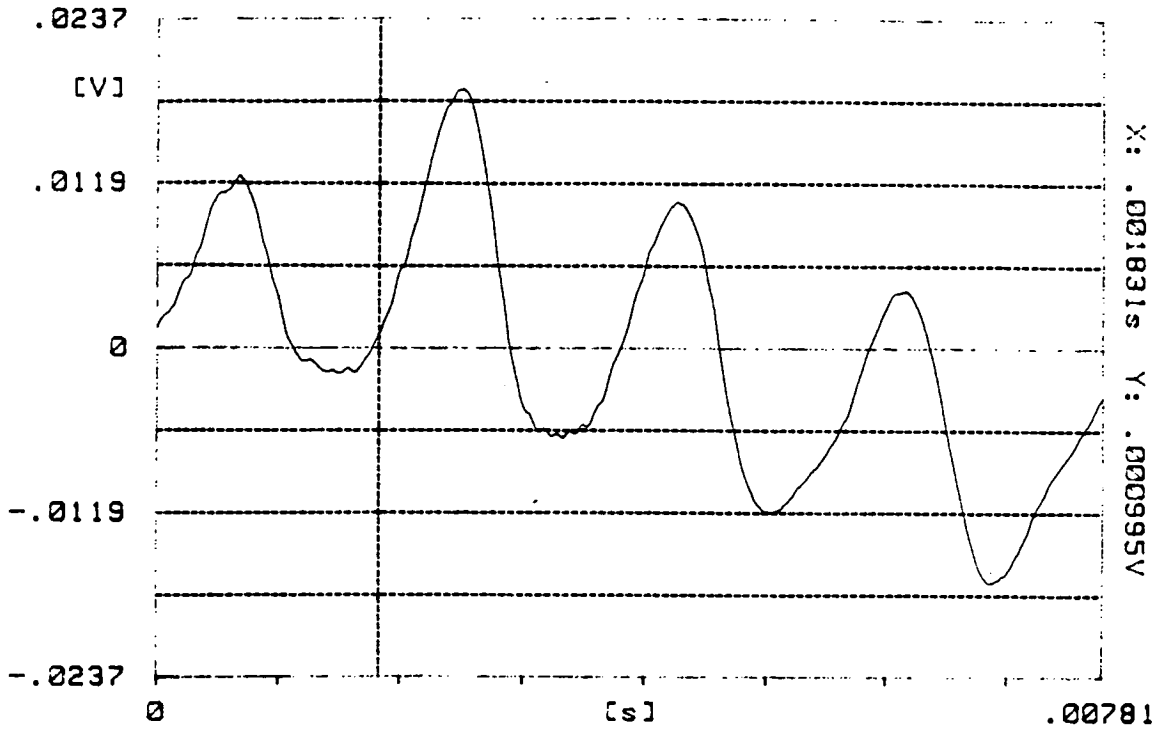
MEASUREMENT: DUAL SPECTRUM AVERAGING  
 TRIGGER: CH.A +SLOPE LEVEL: +0.10 MAX INPUT  
 DELAY: TRIG→A: -0.97ms CH.A→B: 0.00ms  
 AVERAGING: LIN 5

FREQ SPAN: 1.6kHz ΔF: 2Hz T: 500ms ΔT: 244μs  
 CENTER FREQ: BASEBAND  
 WEIGHT CH.A: TRANSIENT SHIFT: 0.00ms LENGTH: 4.63ms  
 WEIGHT CH.B: EXPONENTIAL SHIFT: 0.00ms LENGTH: 50.04ms  
 CH.A: 6V + 3Hz DIR FILT: BOTH 184μV/N  
 CH.B: 6V + 3Hz DIR FILT: BOTH 31.6V/m/s  
 GENERATOR: DISABLED

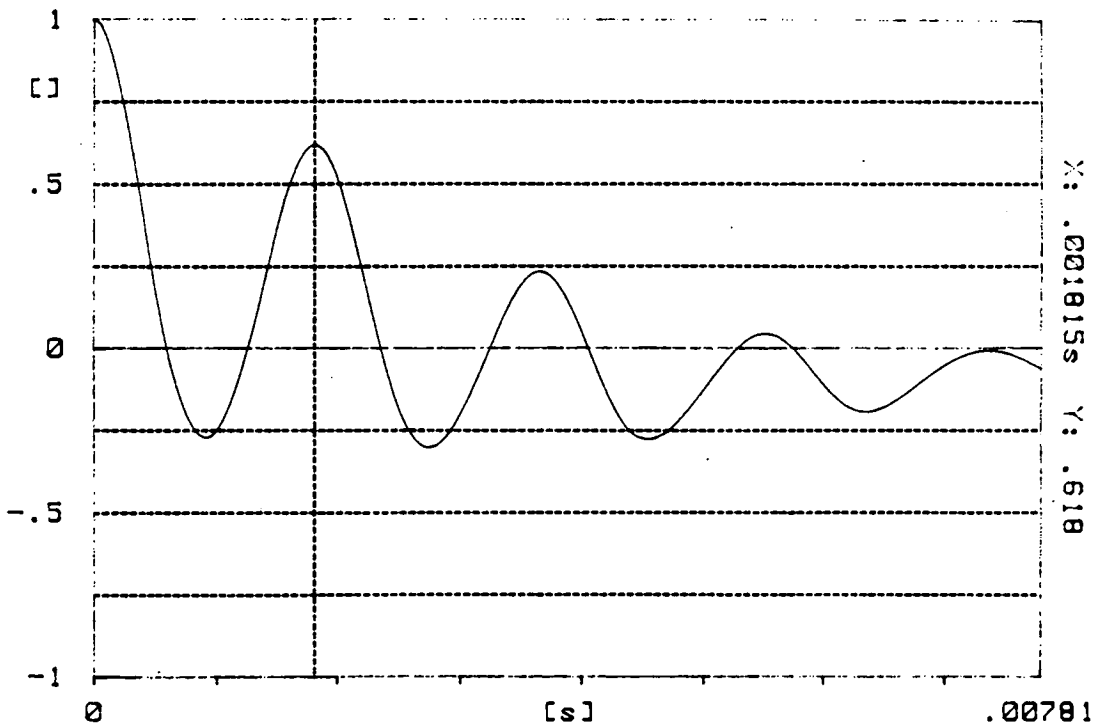
EQUIPMENT - PHASE D  
 TIME AND FREQUENCY MEASUREMENT SET-UPS

FIGURE 6.16

Time Ch.B Real  
W.R.C. COLUMN 1



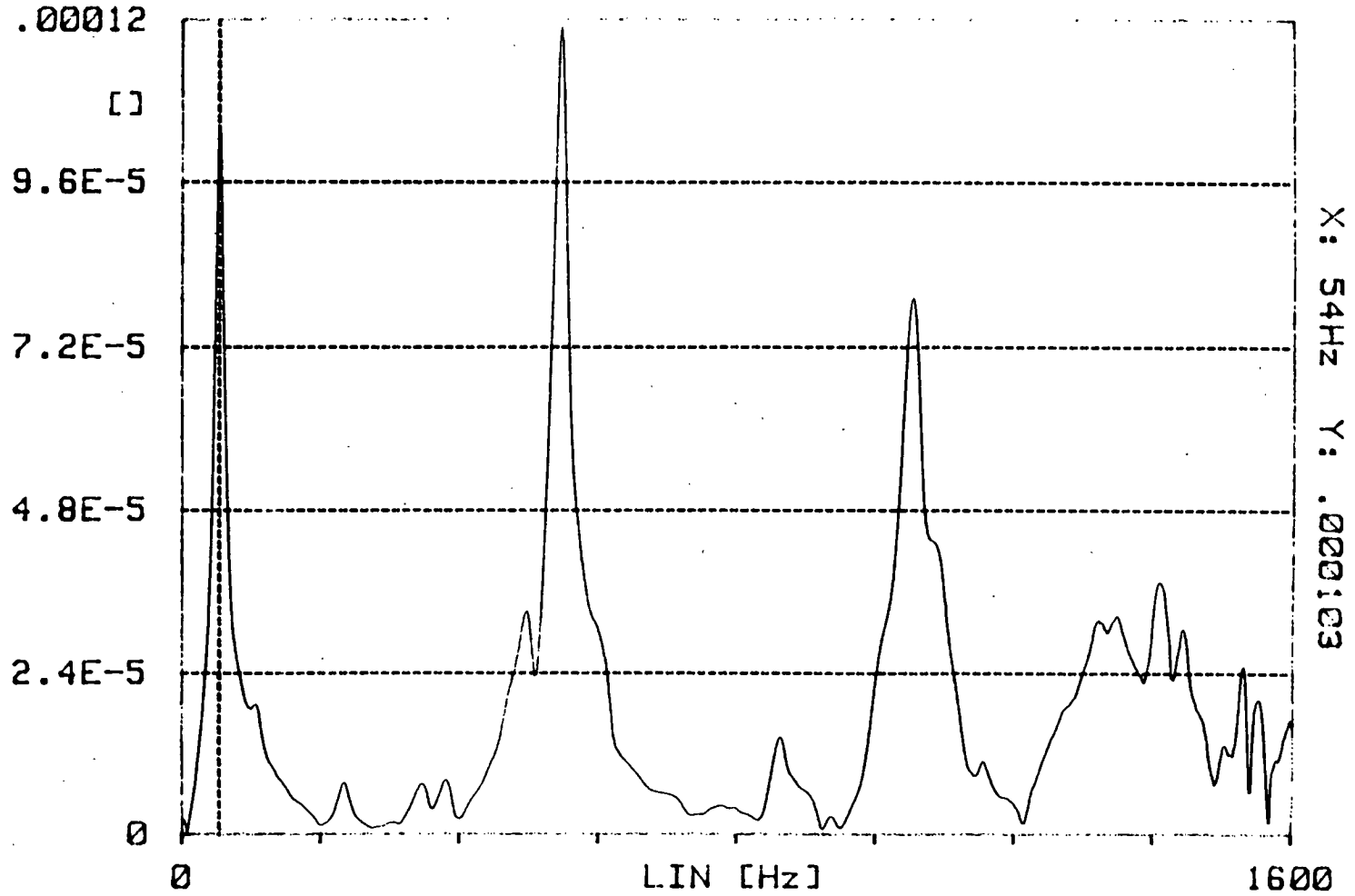
Auto Corr Ch.B Real Lin Avg: 20  
W.R.C. COLUMN 1



EQUIPMENT - PHASE D  
VELOCITY TIME RECORD AND AUTO-CORRELATION FUNCTION

FIGURE 6.17

Freq Resp H1 Mag Lin Avg: 19  
W.R.C. COLUMN 1

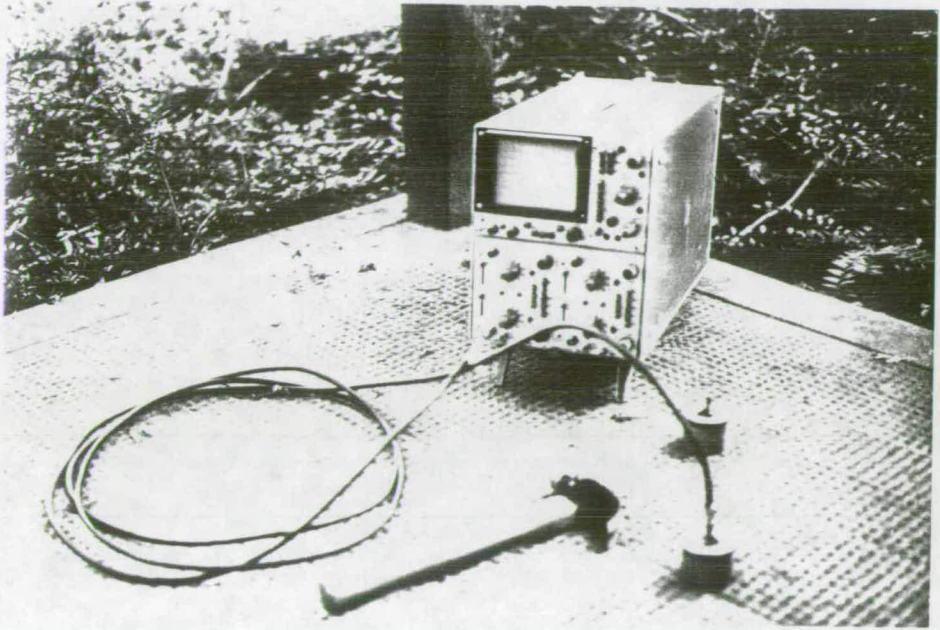


EQUIPMENT - PHASE D  
TYPICAL FREQUENCY RESPONSE FUNCTION

FIGURE 6.18

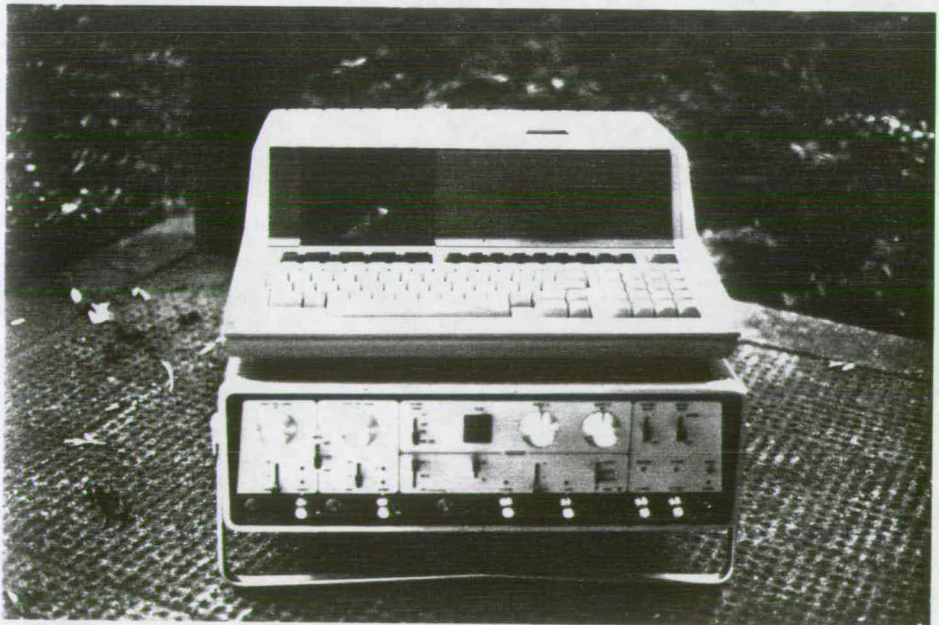
X: 54Hz Y: .000103





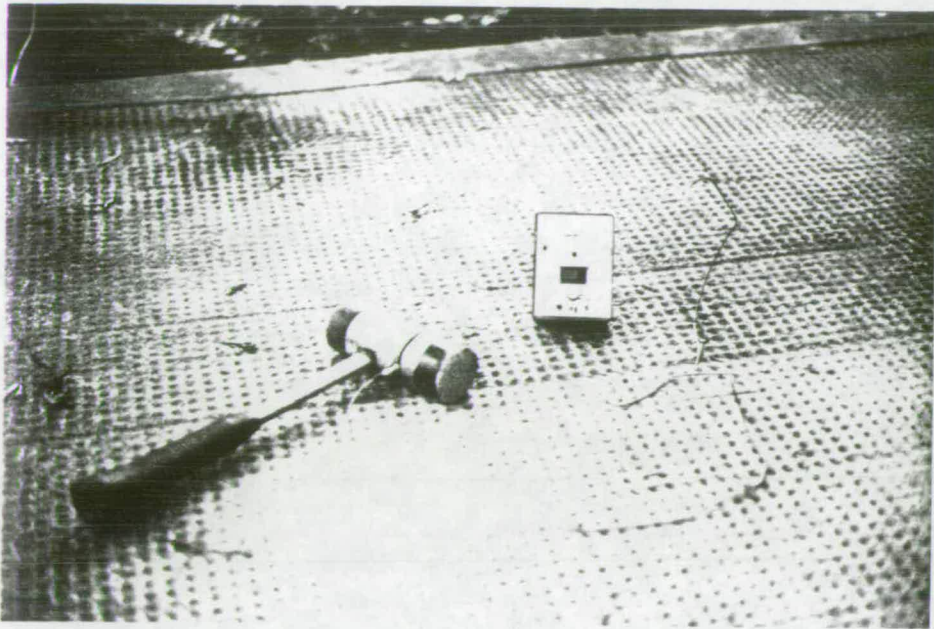
EQUIPMENT USED BY FEGEN

PLATE 6.1



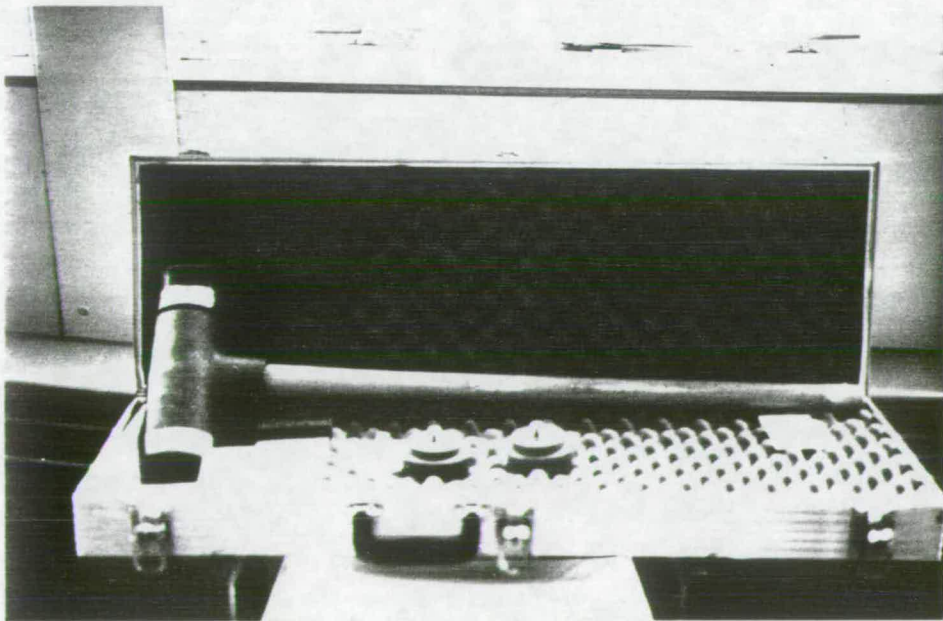
EQUIPMENT - PHASE A DEVELOPMENT

PLATE 6.2



3 lb INSTRUMENTED HAMMER

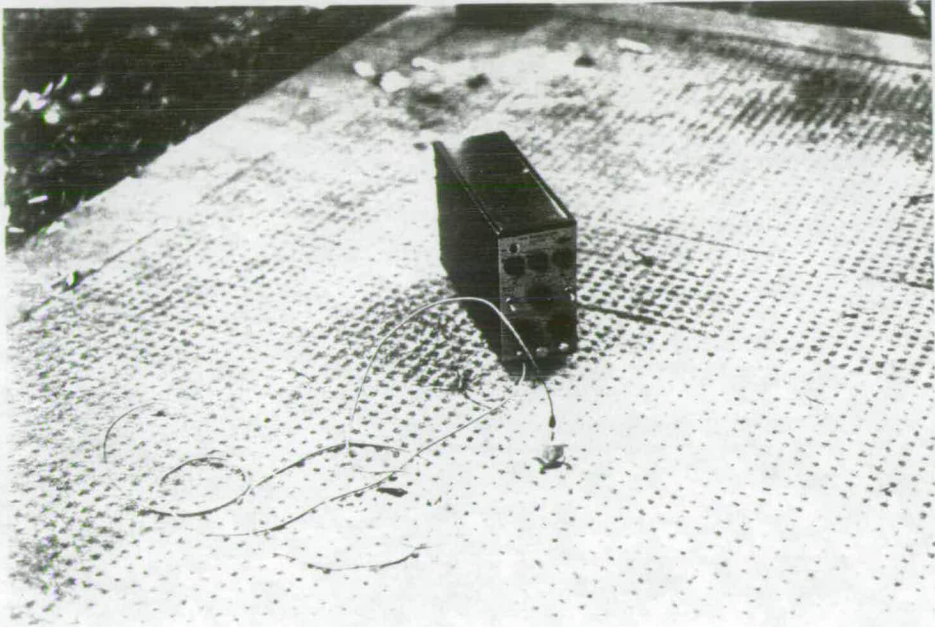
PLATE 6.3



12 lb INSTRUMENTED HAMMER

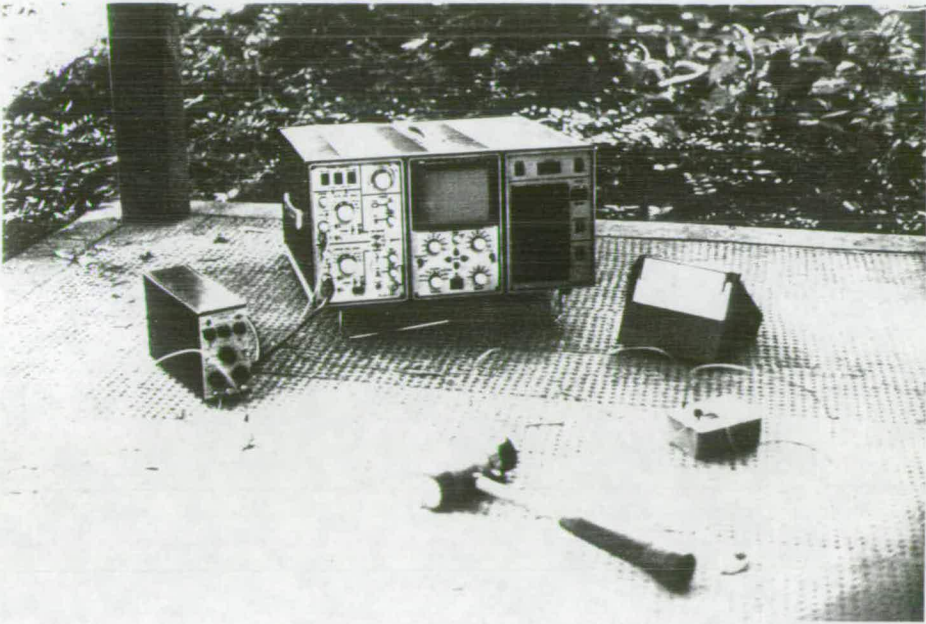
PLATE 6.4





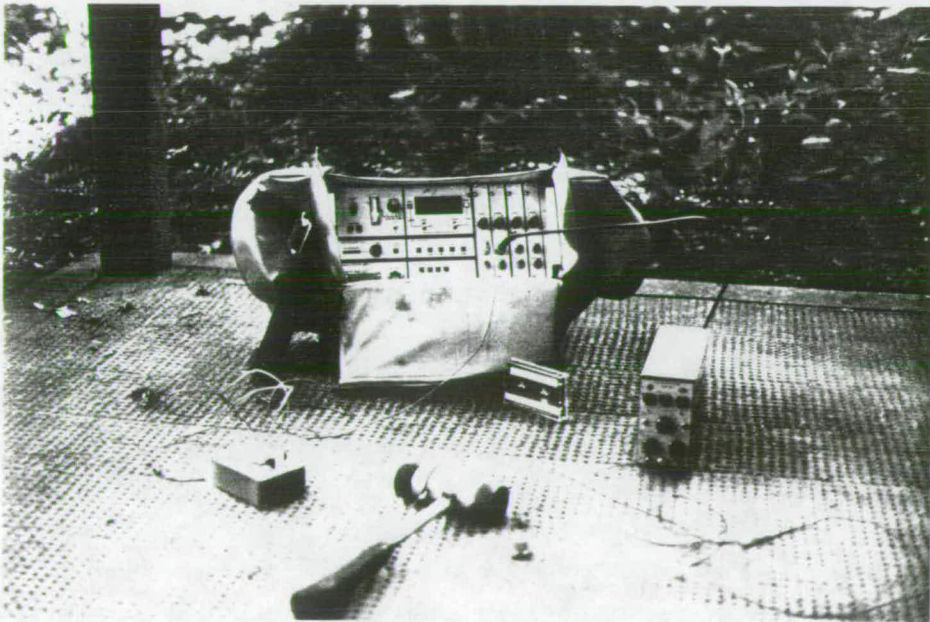
ACCELEROMETER AND CONDITIONING UNIT

PLATE 6.5



EQUIPMENT USED IN PHASE B EXPERIMENTS

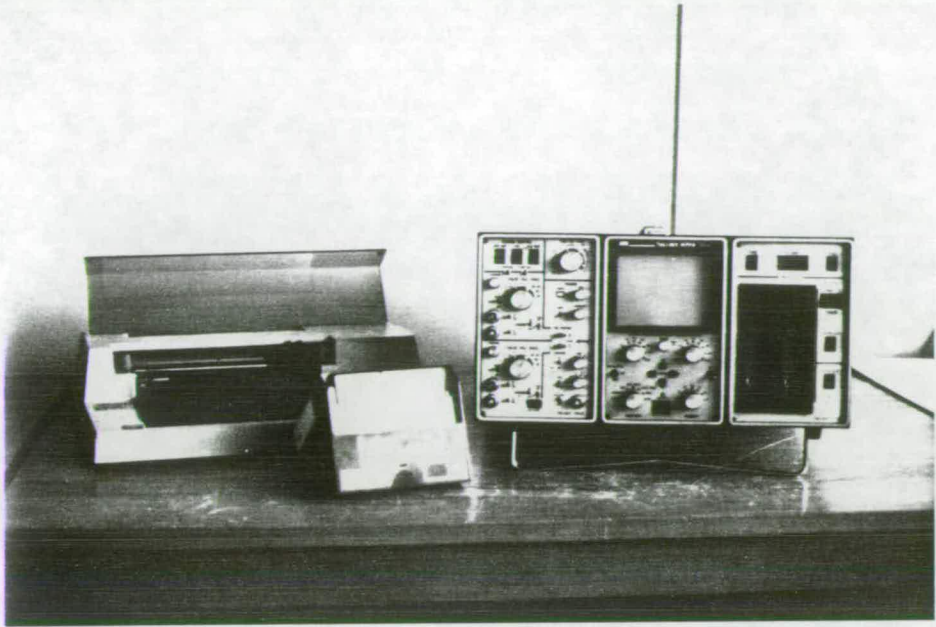
PLATE 6.6



MEASUREMENT EQUIPMENT IN PHASE D EXPERIMENTS

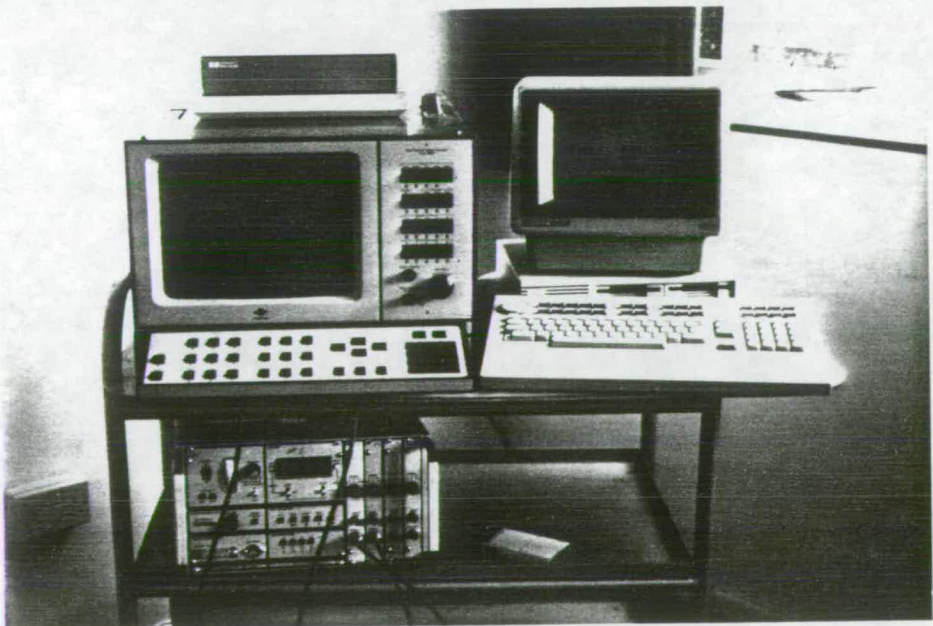
PLATE 6.7





ANALYSIS INSTRUMENTATION USED IN PHASE D

PLATE 6.8



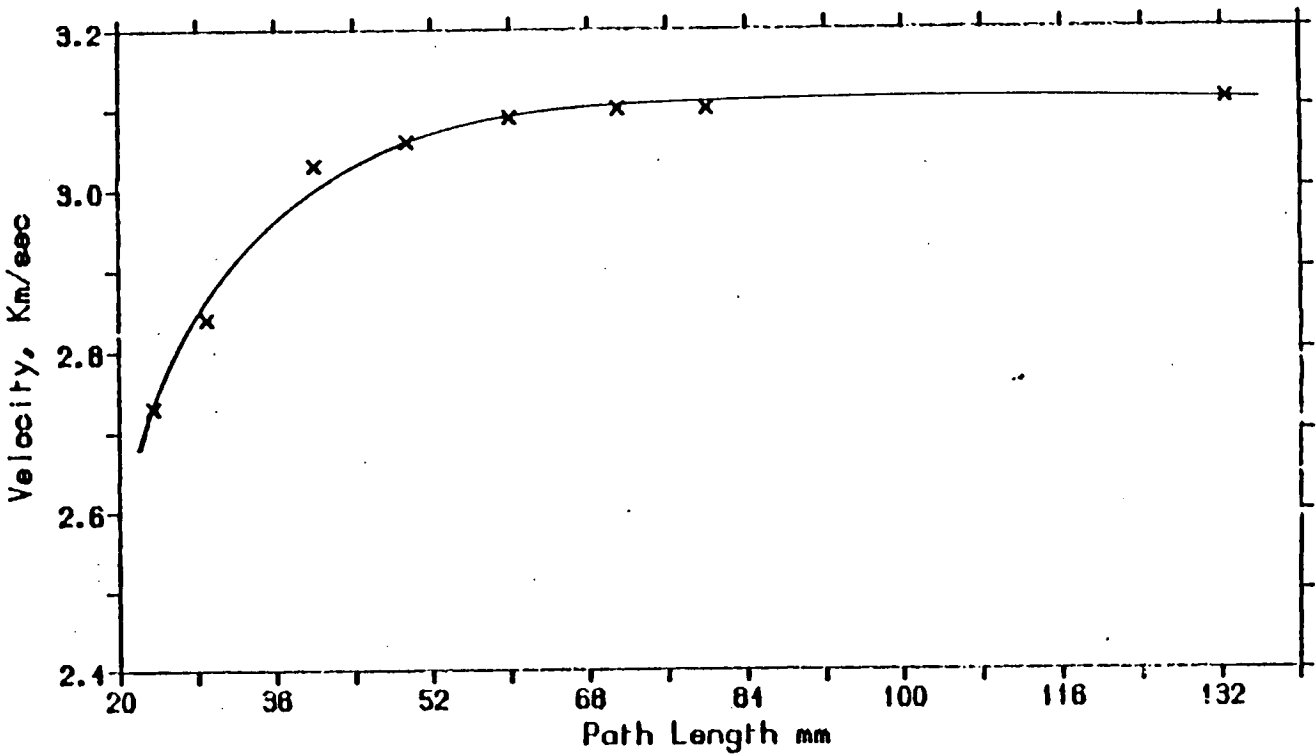
ANALYSIS INSTRUMENTATION USED IN PHASE D

PLATE 6.9

CHAPTER 7

COLUMNS

(ENHANCED SIGNAL PROCESSING AND ANALYSIS)

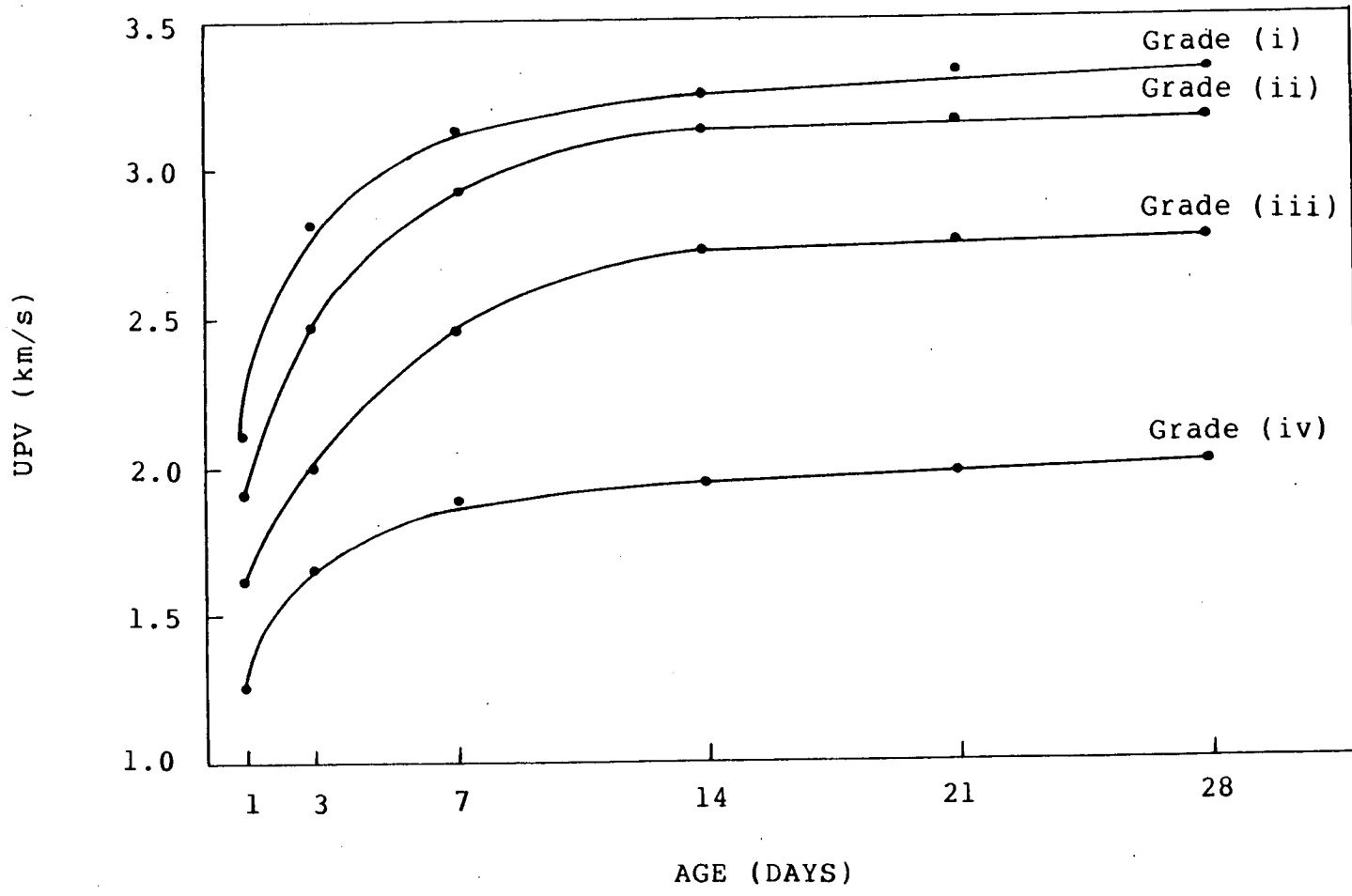


VARIATION OF UPV WITH MORTAR PATH LENGTH

FIGURE 7.1

(after Komeyli-Birjandi, ref. 4))

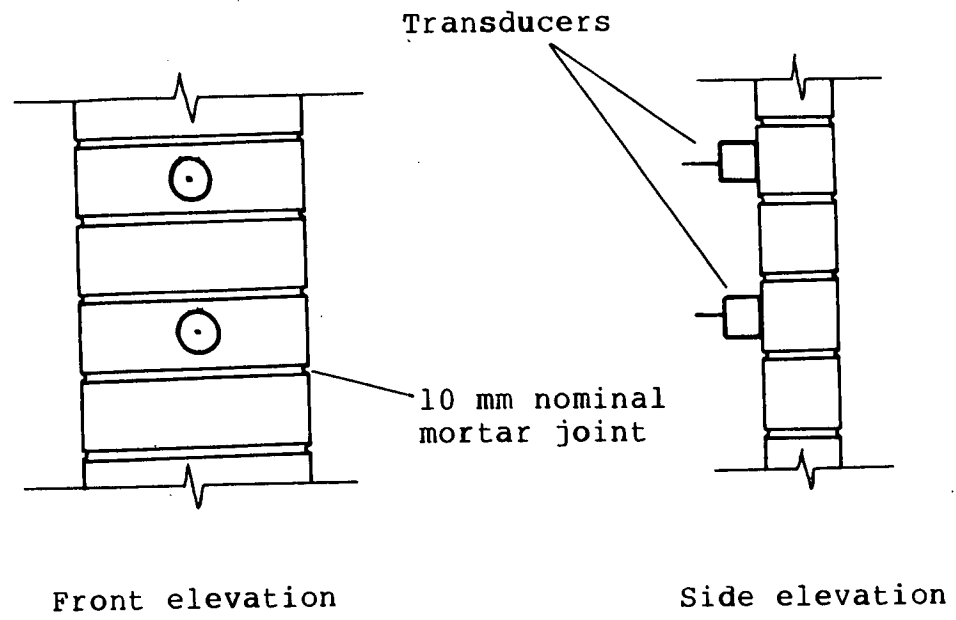
VARIATION OF UPV THROUGH MORTAR CUBES WITH AGE  
FIGURE 7.2





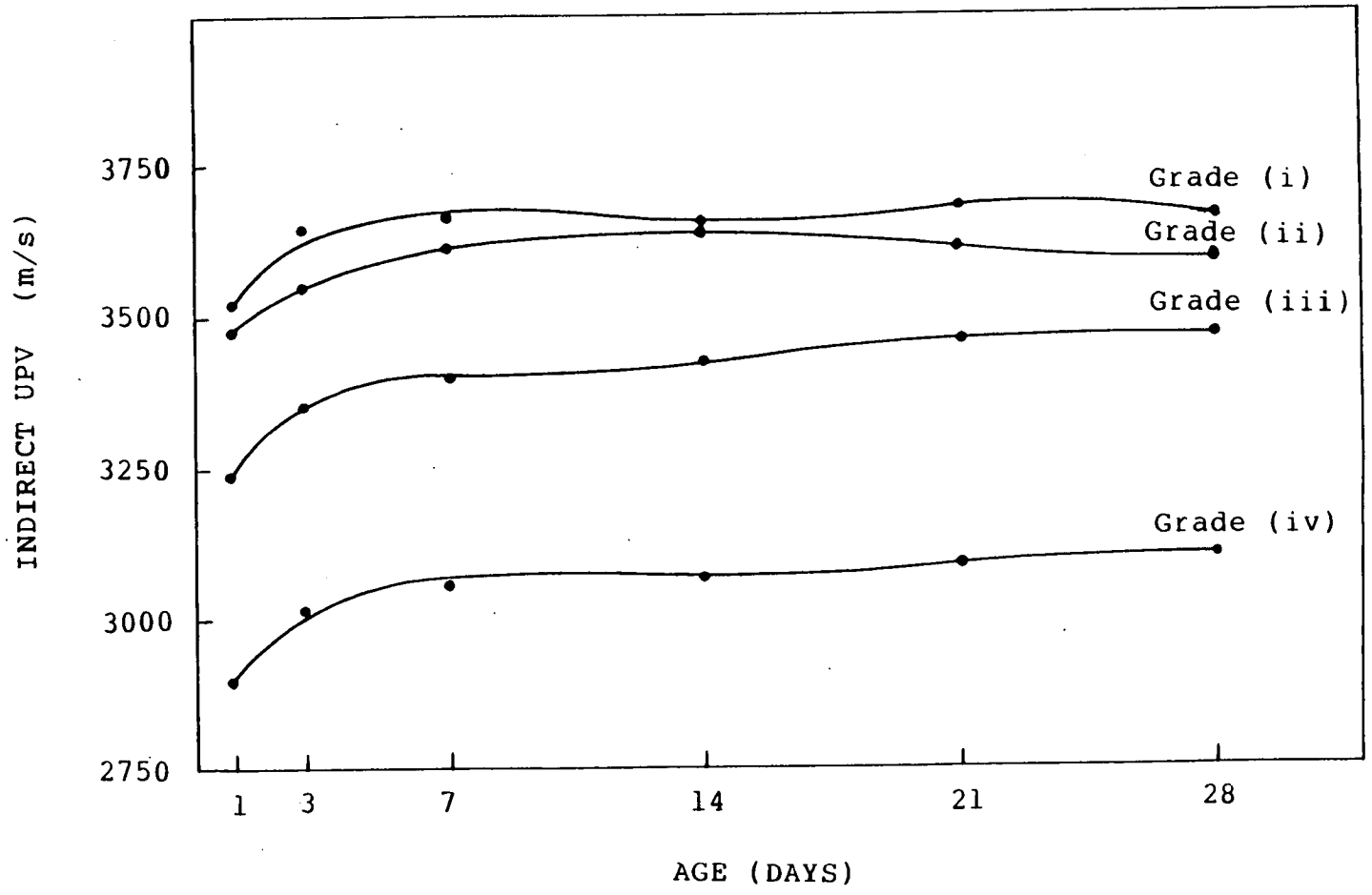
ARRANGEMENT FOR UPV TESTS ON COLUMNS

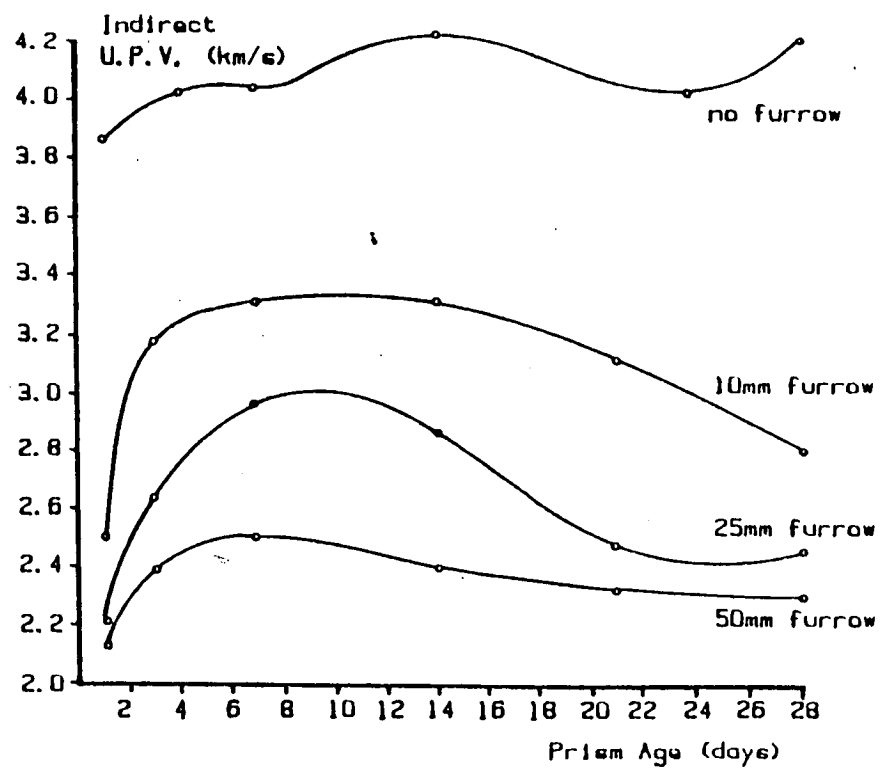
FIGURE 7.3



TYPICAL UPV TEST RESULT ON COLUMN MORTAR JOINTS  
EFFECT OF MORTAR STRENGTH

FIGURE 7.4



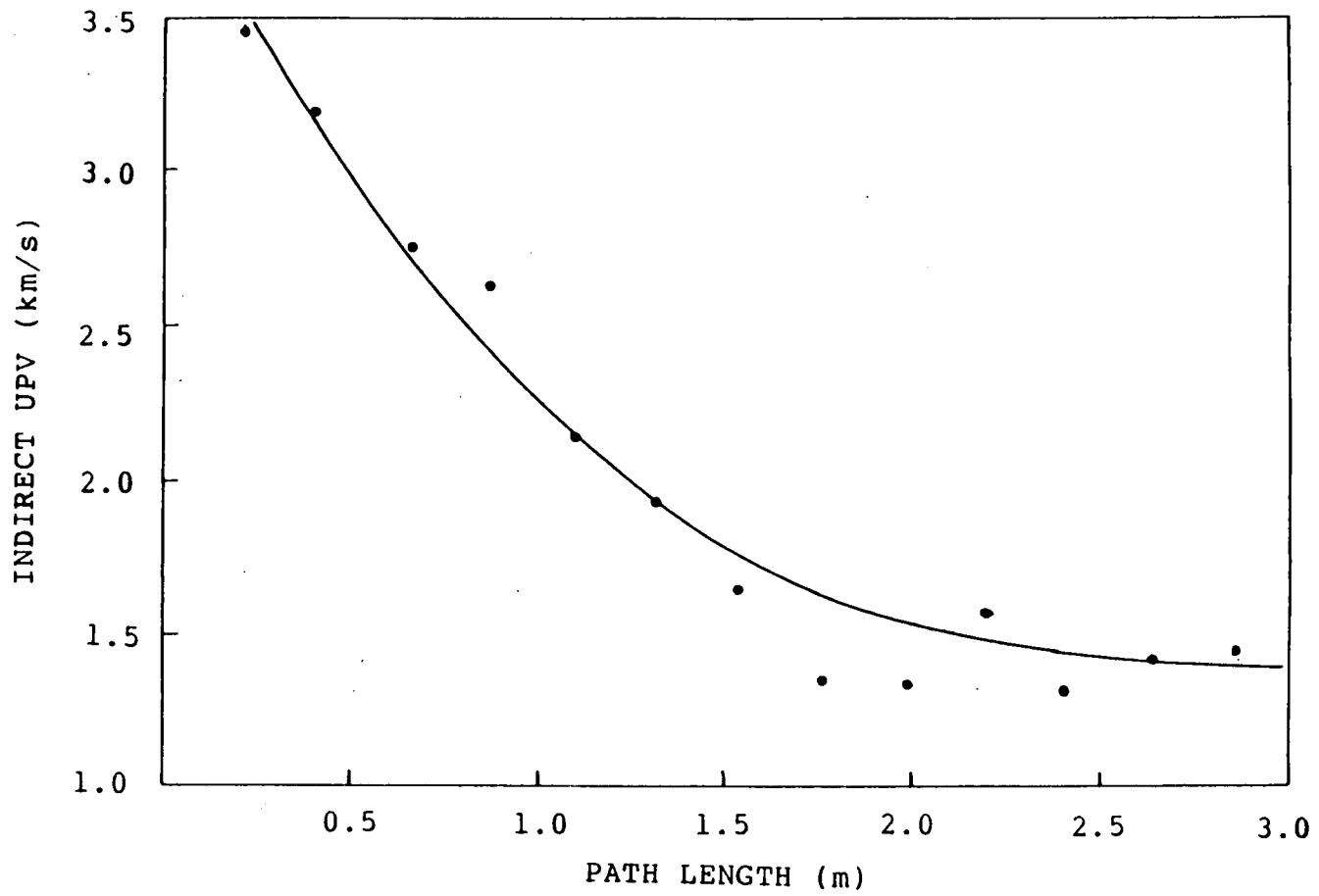


INFLUENCE OF FURROWED BED JOINTS

FIGURE 7.5

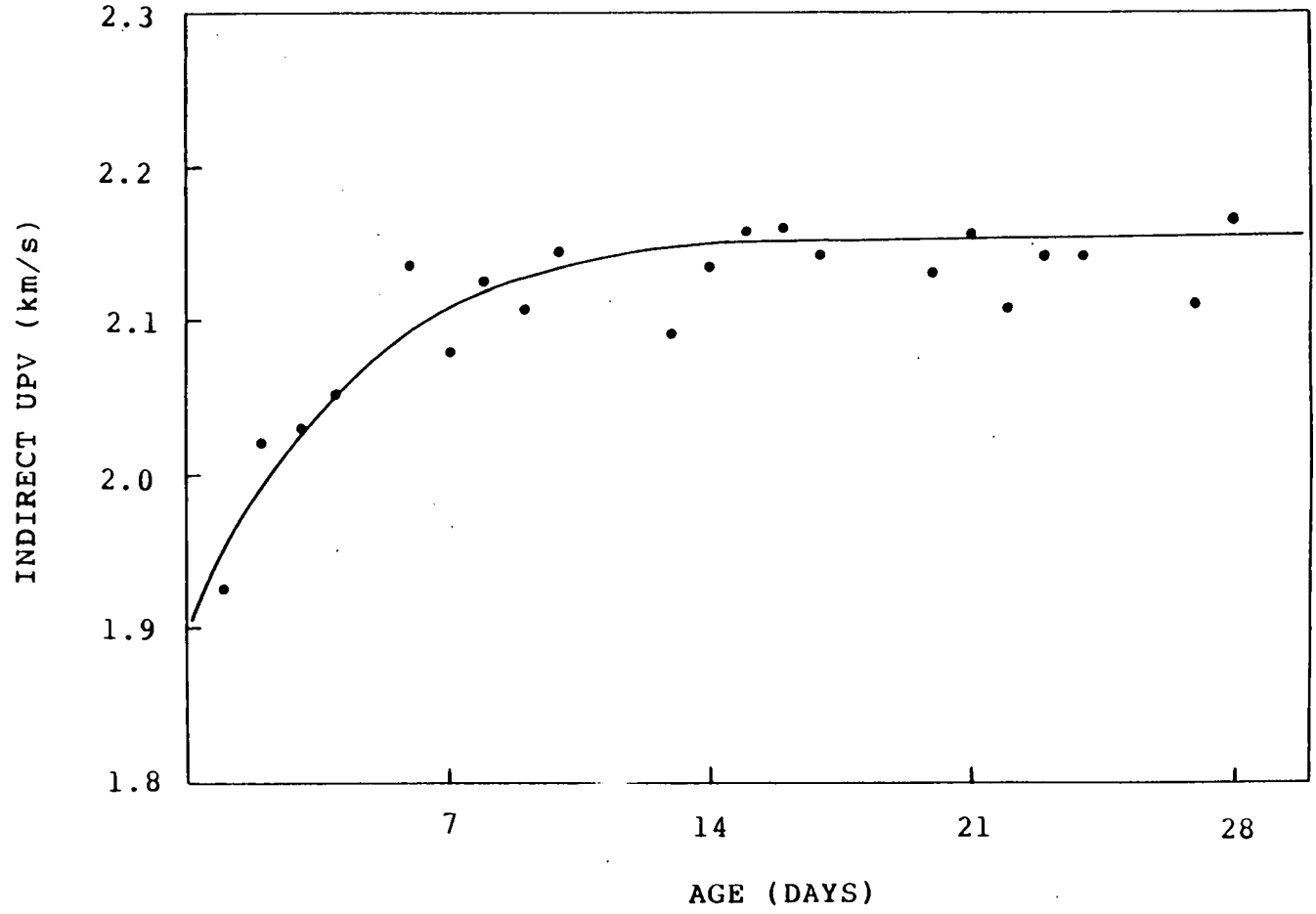
(after Hobbs, ref. 10)

VARIATION IN INDIRECT UPV WITH MASONRY PATH LENGTH  
FIGURE 7.6



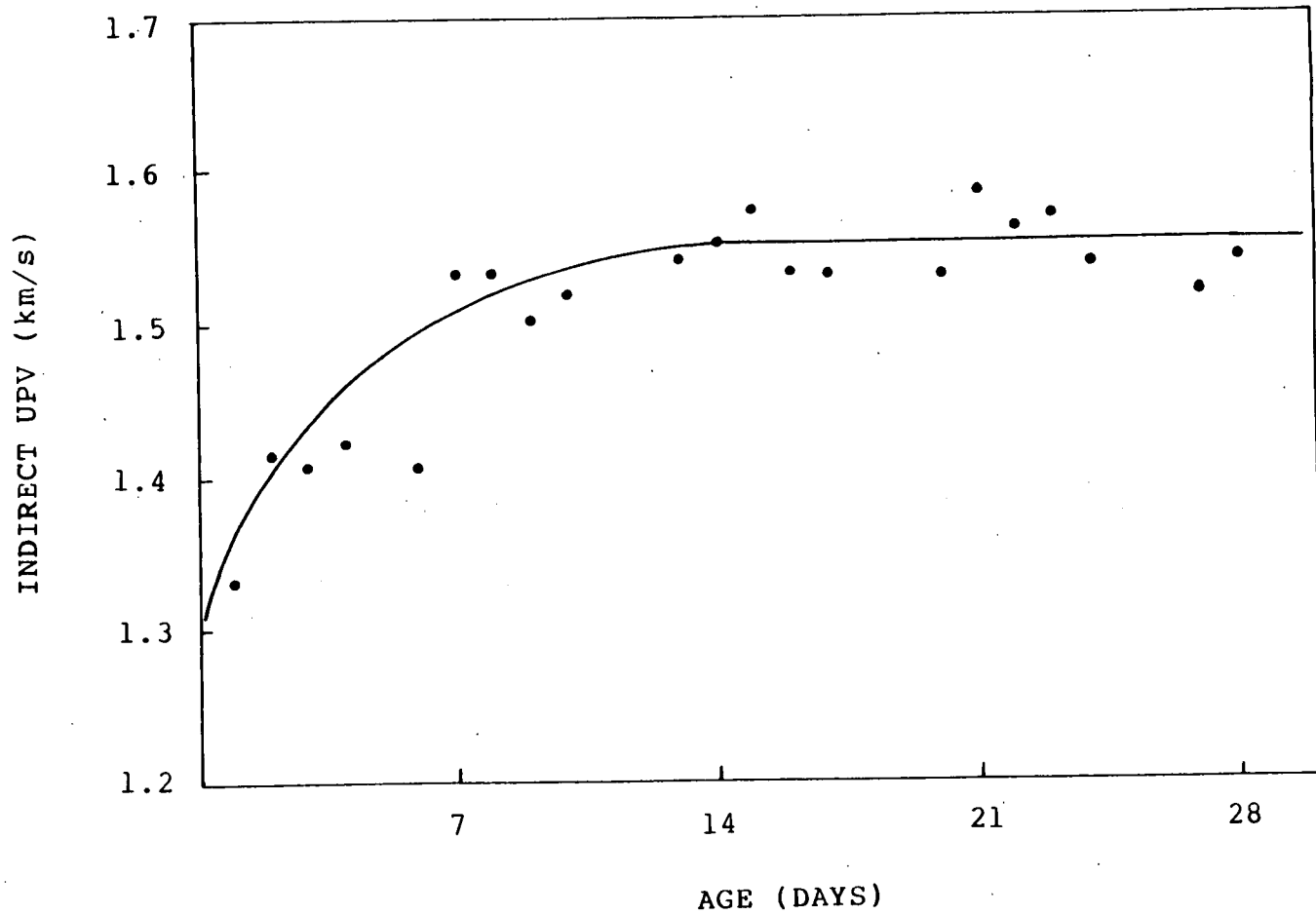
VARIATION OF INDIRECT UPV THROUGH MASONRY WITH AGE  
(1 m PATH LENGTH)

FIGURE 7.7



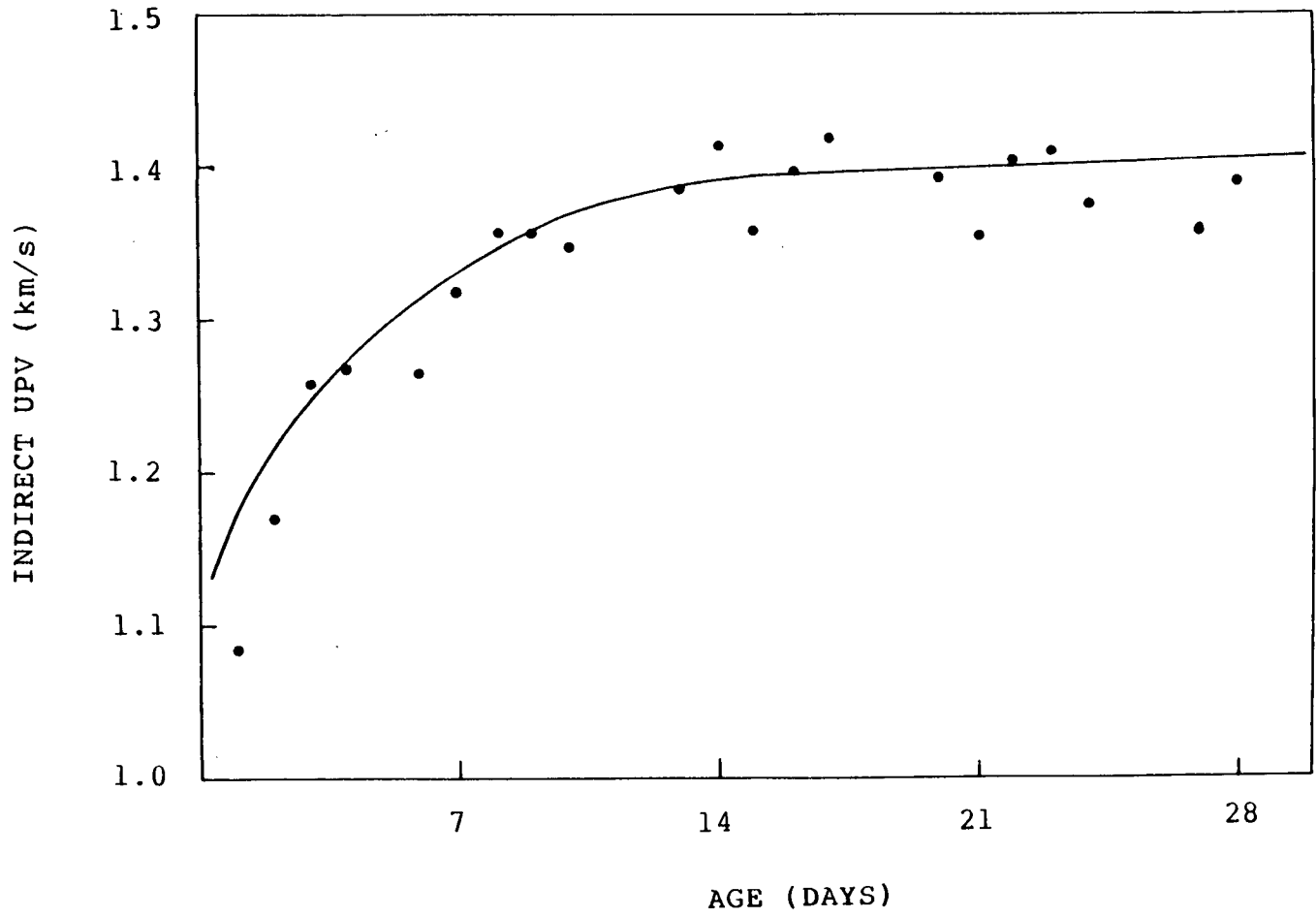
VARIATION OF INDIRECT UPV THROUGH MASONRY WITH AGE  
( 2 m PATH LENGTH )

FIGURE 7.8

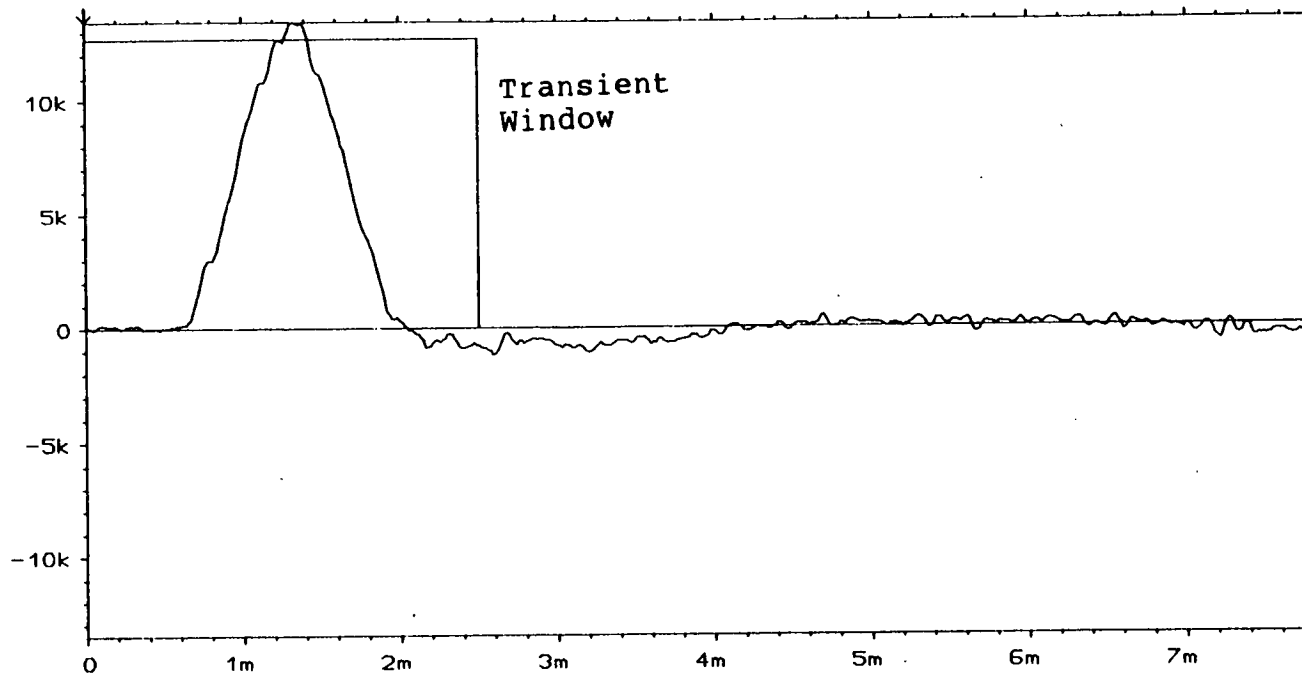


VARIATION OF INDIRECT UPV THROUGH MASONRY WITH AGE  
(3 M PATH LENGTH)

FIGURE 7.9



W3 TIME CH.A REAL INPUT MAIN Y: 111U  
 Y: 13.5kU X: 0.000ms  
 X: 0.000ms + 7.81ms



SETUP W10

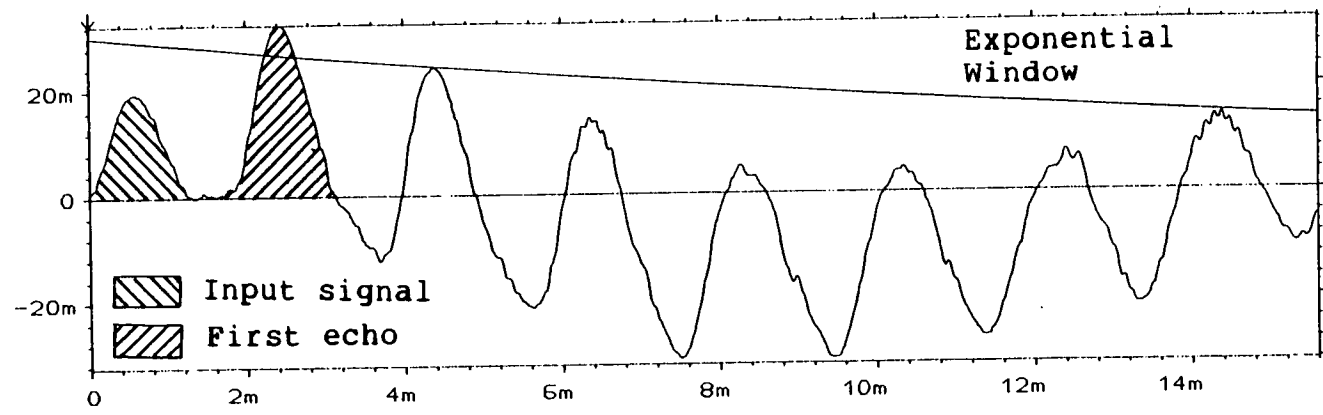
MEASUREMENT: DUAL SPECTRUM AVERAGING  
 TRIGGER: CH.A +SLOPE LEVEL: +0.10 MAX INPUT  
 DELAY: TRIG→A: -1.007ms CH.A→B: 0.000ms  
 AVERAGING: LIN 5

FREQ SPAN: 25.6kHz ΔF: 32Hz T: 31.3ms ΔT: 15.3μs  
 CENTER FREQ: BASEBAND  
 WEIGHT CH.A: TRANSIENT SHIFT: 0.000ms LENGTH: 2.502ms  
 WEIGHT CH.B: EXPONENTIAL SHIFT: 0.000ms LENGTH: 20.004ms  
 CH.A: 6V + 3Hz DIR FILT: BOTH 92.0μV/N  
 CH.B: 6V + 3Hz DIR FILT: BOTH 31.6V/m/s  
 GENERATOR: DISABLED

COLUMNS: TIME DOMAIN MEASUREMENT SET-UP  
 SHOWING HAMMER INPUT SIGNAL  
 FIGURE 7.10

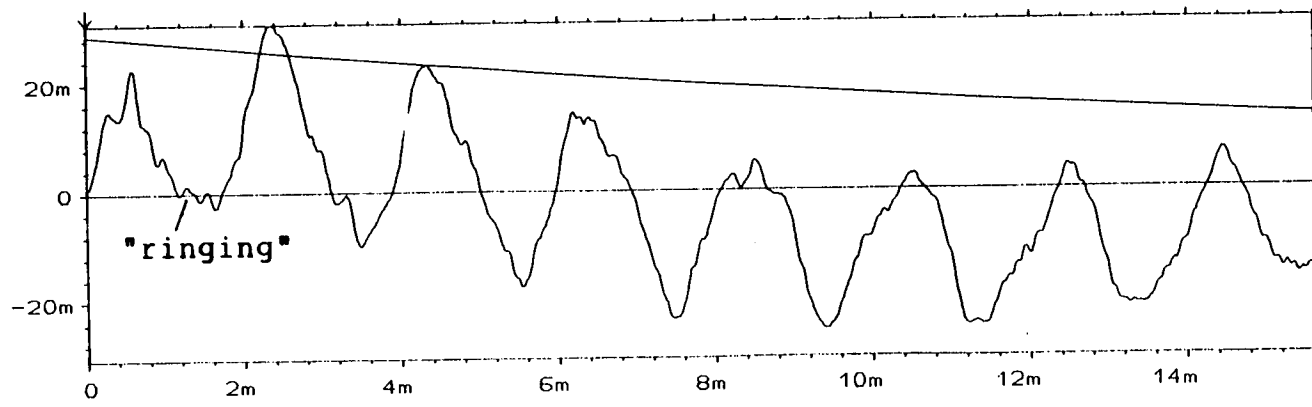


W5 TIME CH.B REAL STORED MAIN Y: 696 $\mu$ U  
Y: 32.3mU X: 0.000ms + 15.6ms  
SETUP S10\*



(a)  
Column 1

W5 TIME CH.B REAL MAIN Y: 974 $\mu$ U  
Y: 30.7mU X: 0.000ms + 15.6ms  
SETUP W10\*

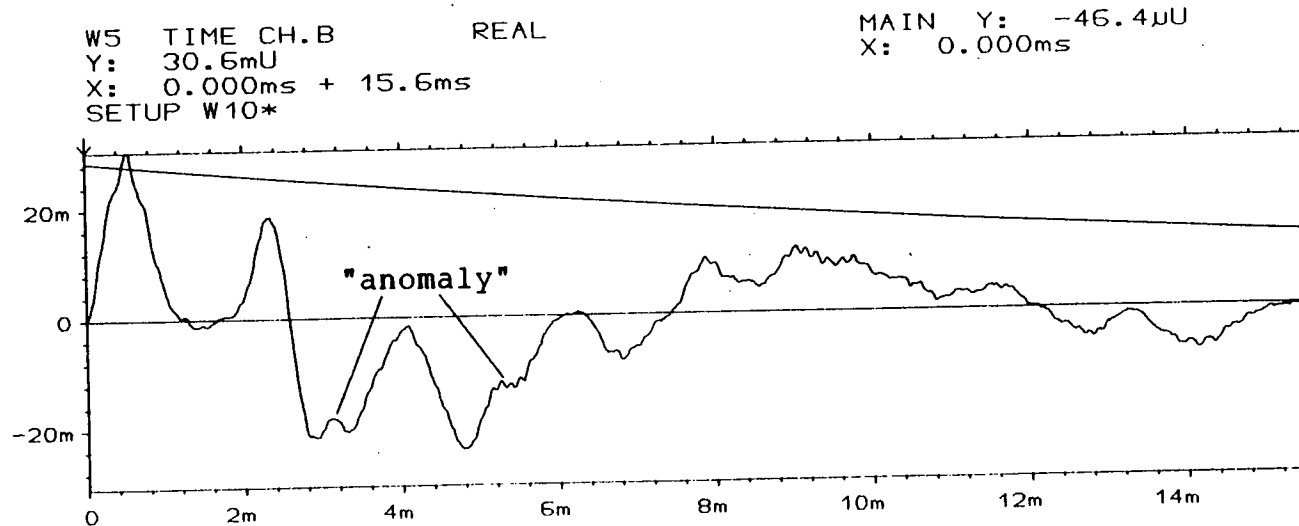
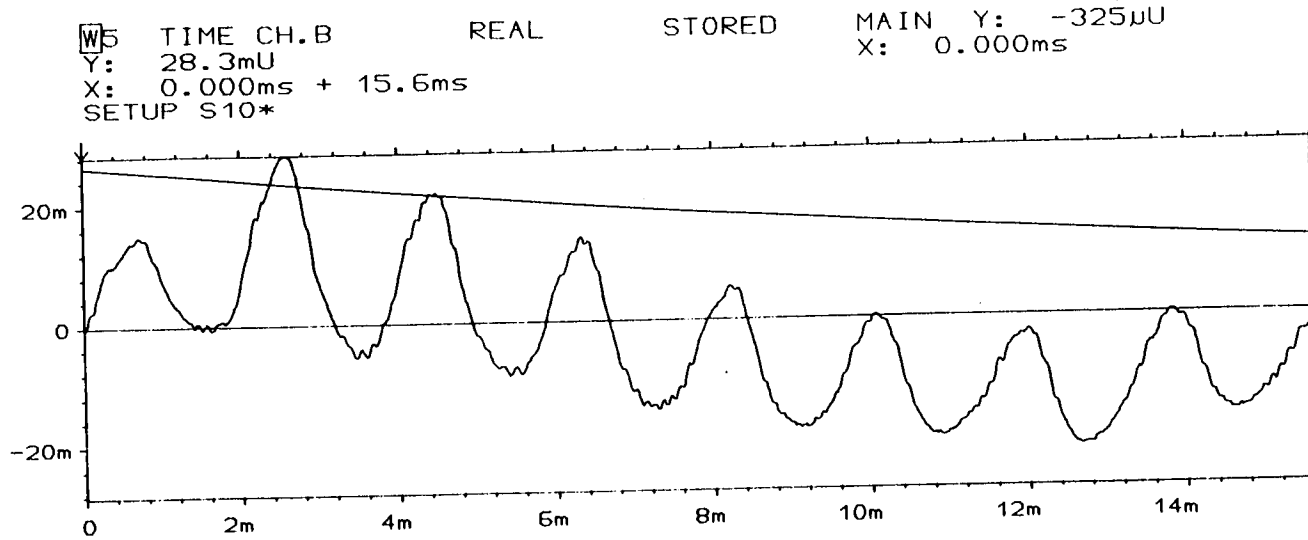


(b)  
Column 2

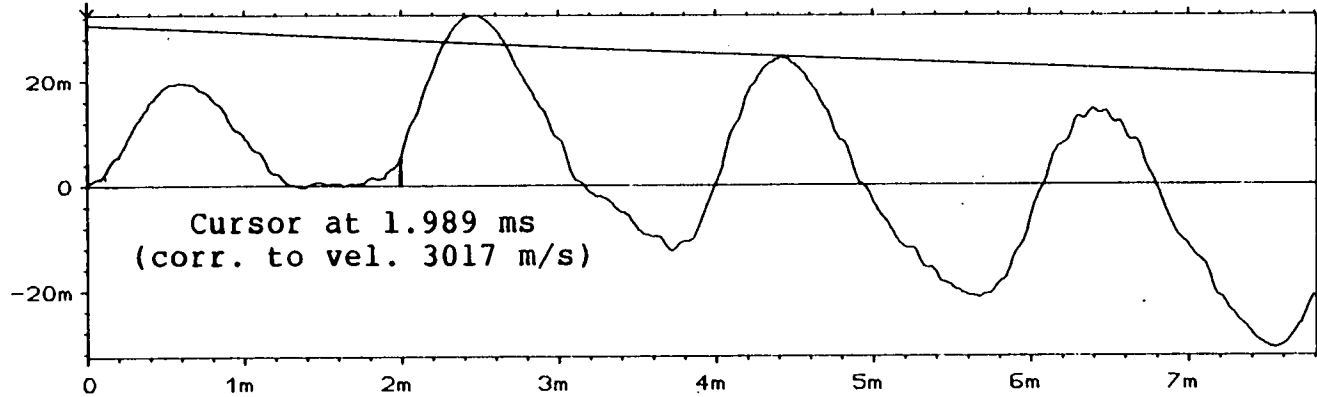
VELOCITY TIME RECORDS  
COLUMNS: NO DEFECTS  
FIGURE 7.11

VELOCITY TIME RECORDS  
COLUMNS: NO DEFECTS

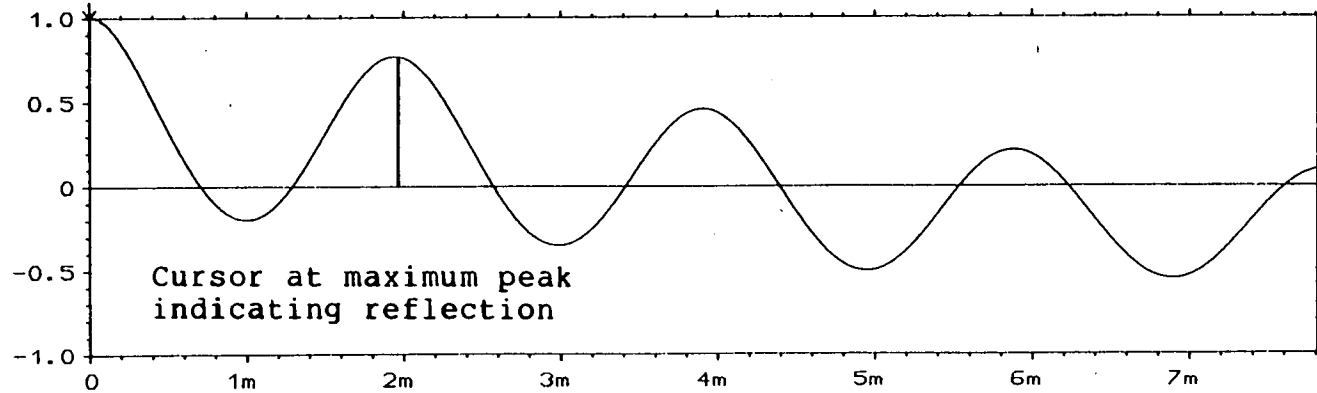
FIGURE 7.12



W5 TIME CH.B REAL INPUT MAIN Y: 557μU  
Y: 32.6mU  
X: 0.000ms + 7.81ms  
SETUP W10\*



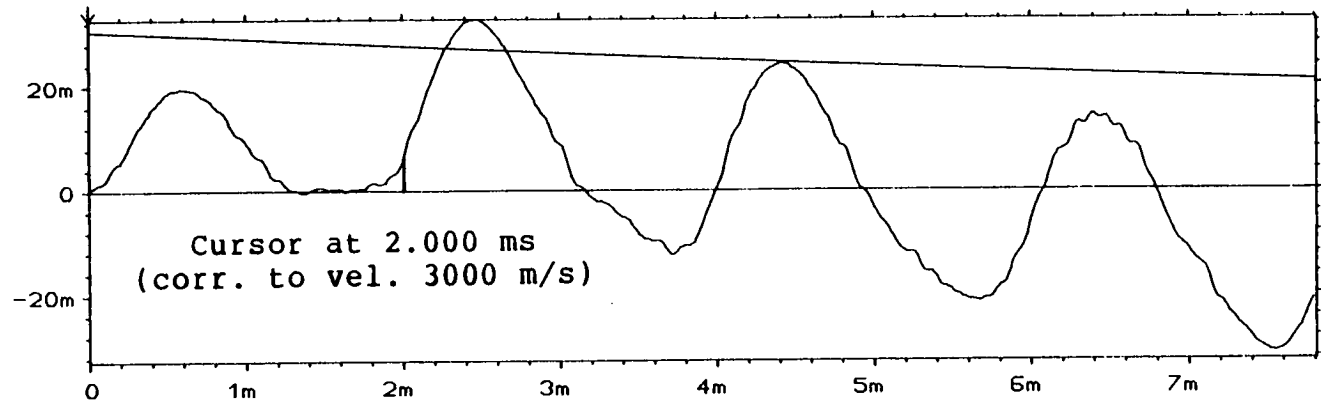
W7 AUTO CORR CH.B REAL MAIN Y: 1.00  
Y: 1.00  
X: 0.000ms + 7.81ms  
SETUP W10\* #A: 5



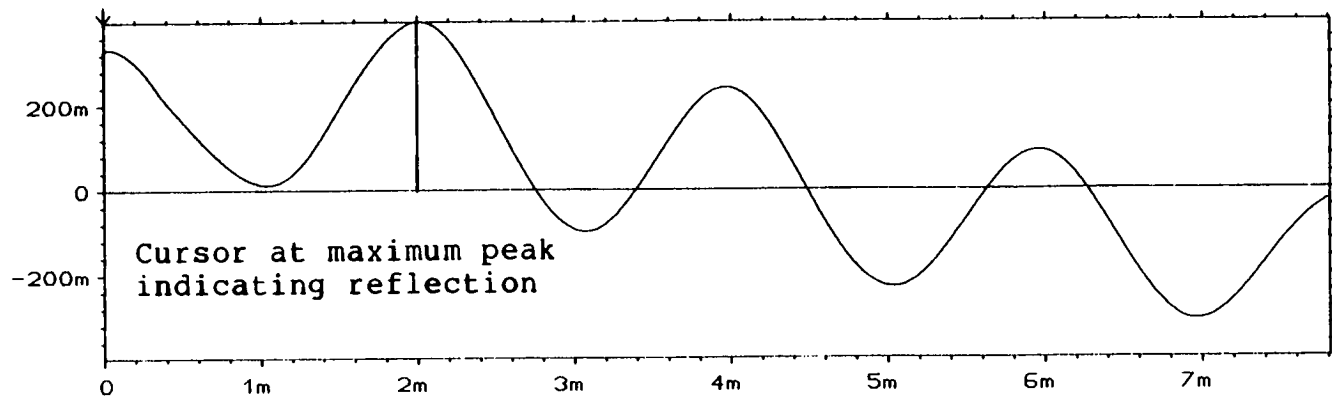
AUTO-CORRELATION FUNCTION  
COLUMN 1: NO DEFECT

FIGURE 7.13

W5 TIME CH.B REAL INPUT MAIN Y: 557μU  
Y: 32.6mU X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10\*



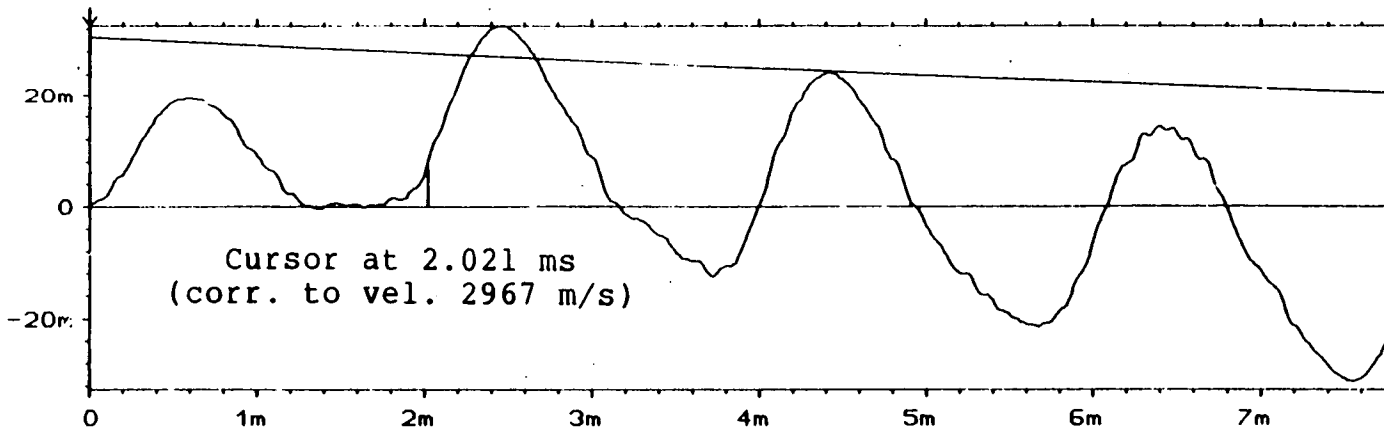
W9 CROSS CORR REAL MAIN Y: 328m  
Y: 398m X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10\* #A: 5



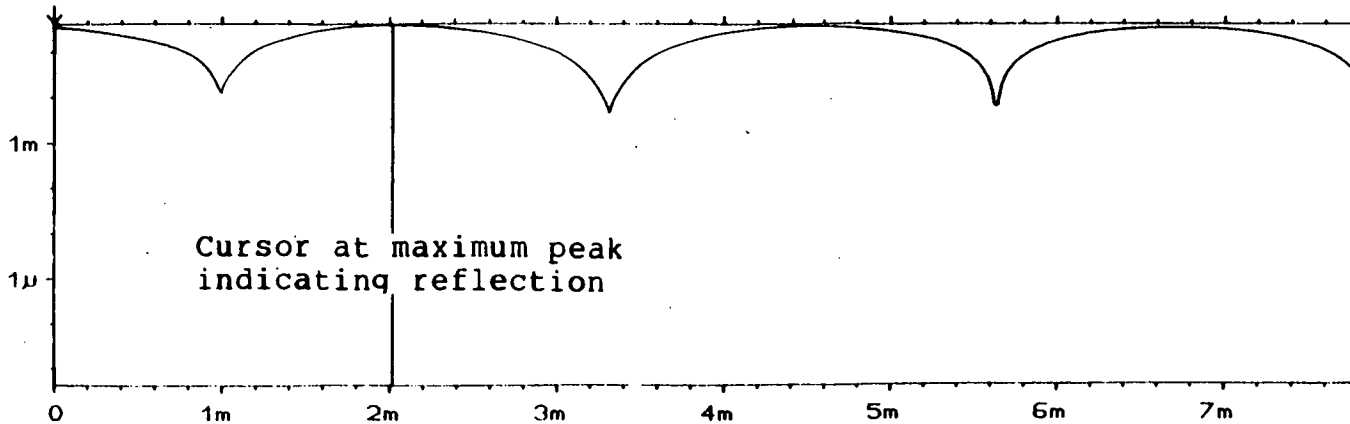
CROSS-CORRELATION (REAL) FUNCTION  
COLUMN 1: NO DEFECT

FIGURE 7.14

W5 TIME CH.B REAL INPUT MAIN Y: 557μU  
Y: 32.6mU X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10\*



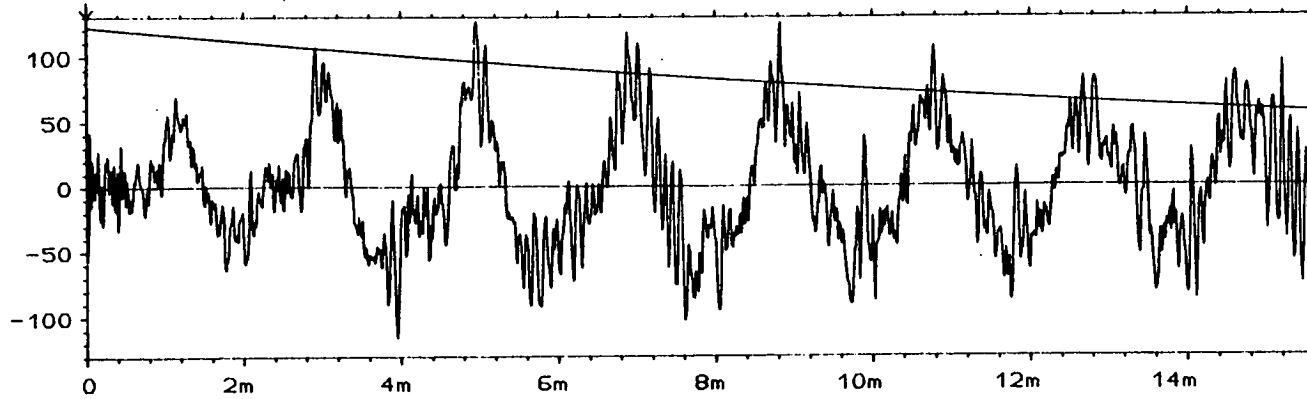
W9 CROSS CORR MAG MAIN Y: 346m  
Y: 424m 80dB X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10\* #A: 5



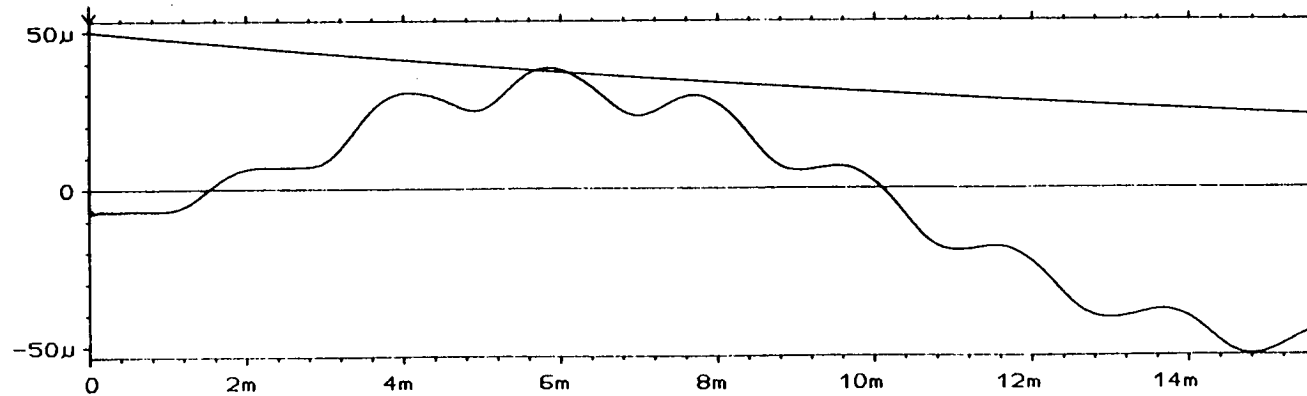
CROSS-CORRELATION (MAG.) FUNCTION  
COLUMN 1: NO DEFECT

FIGURE 7.15

W5 TIME CH.B REAL INPUT MAIN Y: 224U  
Y: 130U X: 0.000ms + 15.6ms  
SETUP W10



W5 TIME CH.B REAL MAIN Y: -7.08μU  
Y: 53.4μU X: 0.000ms + 15.6ms  
SETUP W10



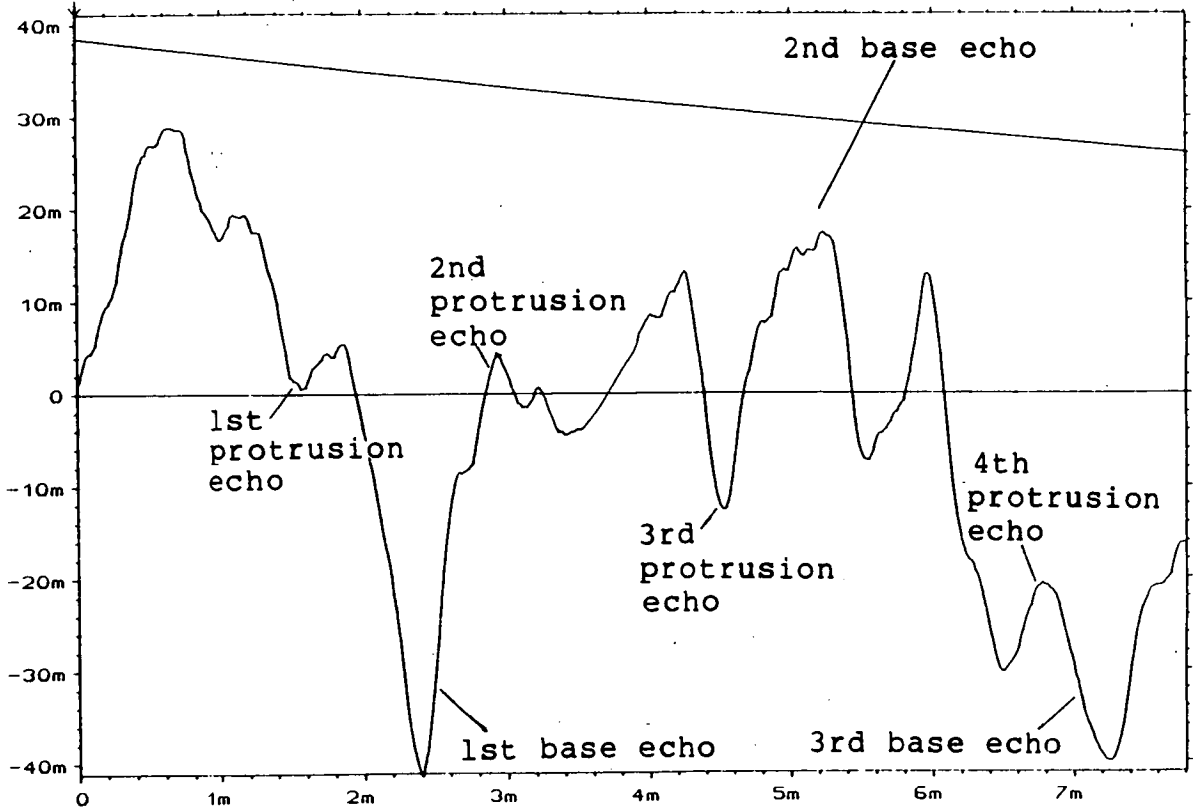
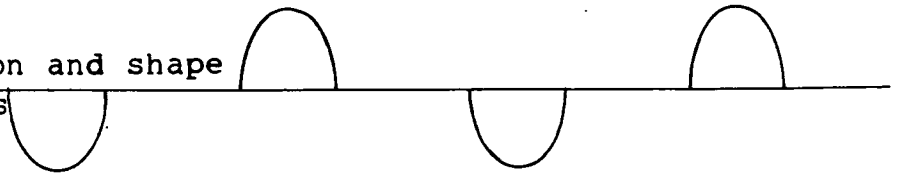
TYPICAL ACCELERATION AND DISPLACEMENT  
TIME RECORDS

FIGURE 7.16

W5 TIME CH.B REAL INPUT MAIN Y: 788μU  
Y: 41.1mU  
X: 0.000ms + 7.81ms  
SETUP W10\*

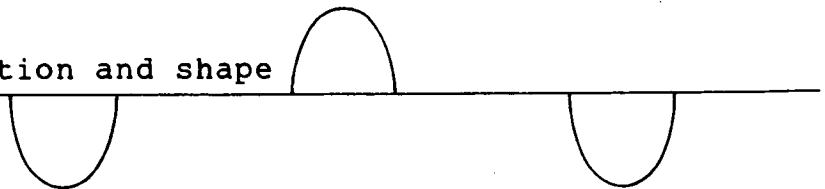
Predicted position and shape

Protrusion echoes



Predicted position and shape

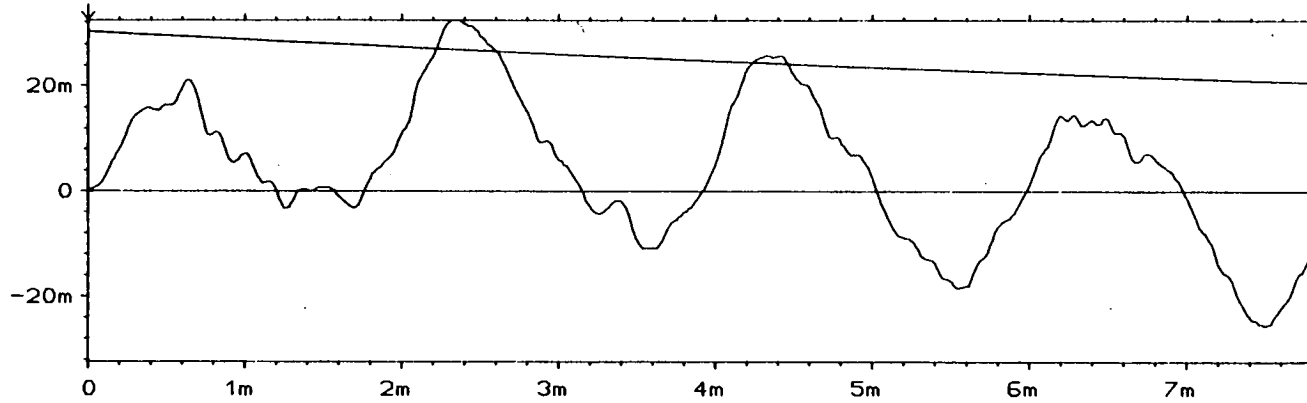
Base echoes



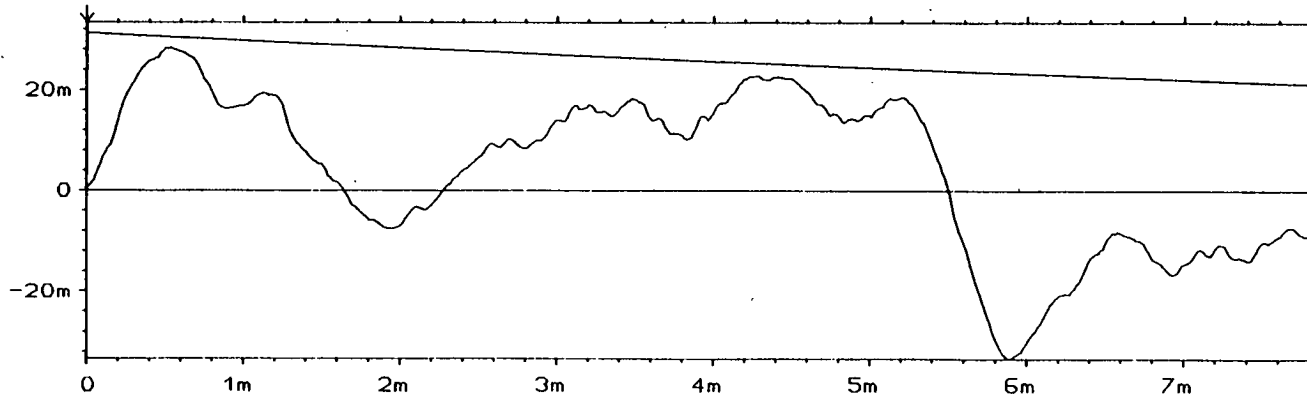
VELOCITY TIME RECORD  
COLUMN 1: FIXED BASE

FIGURE 7.17

W5 TIME CH.B REAL STORED MAIN Y: 232 $\mu$ U  
Y: 32.4mU X: 0.000ms + 7.81ms  
SETUP S10\*



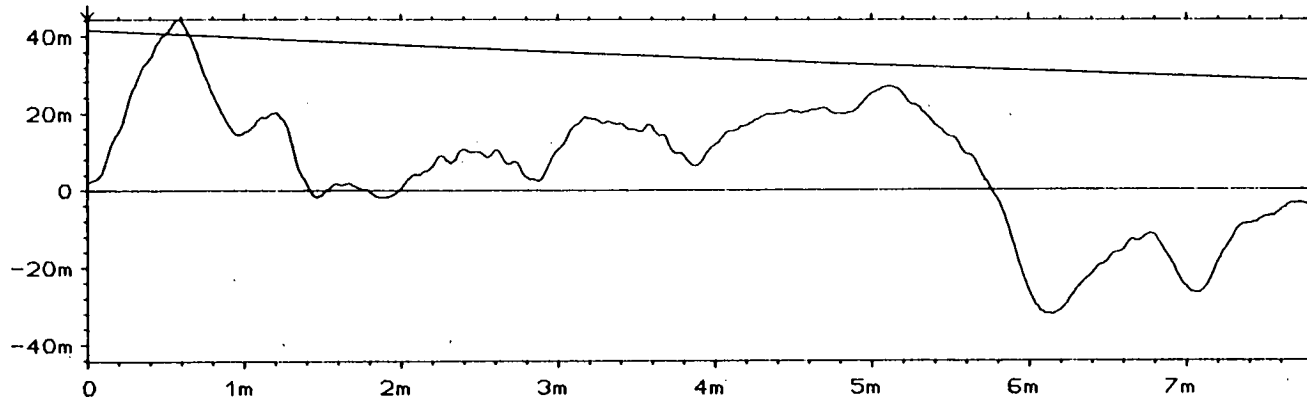
W5 TIME CH.B REAL MAIN Y: 510 $\mu$ U  
Y: 33.4mU X: 0.000ms + 7.81ms  
SETUP W10\*



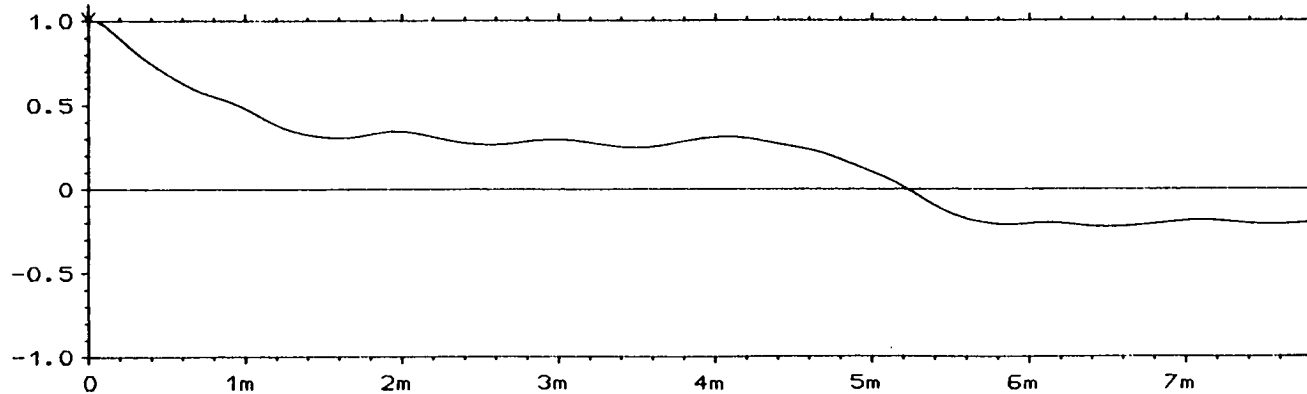
VELOCITY TIME RECORD  
COLUMN 2: MORTAR DEFECT  
FIGURE 7.18



W5 TIME CH.B REAL INPUT MAIN Y: 1.81mU  
Y: 44.3mU  
X: 0.000ms + 7.81ms  
SETUP W10



W7 AUTO CORR CH.B REAL MAIN Y: 1.00  
Y: 1.00  
X: 0.000ms + 7.81ms  
SETUP W10 #A: 5



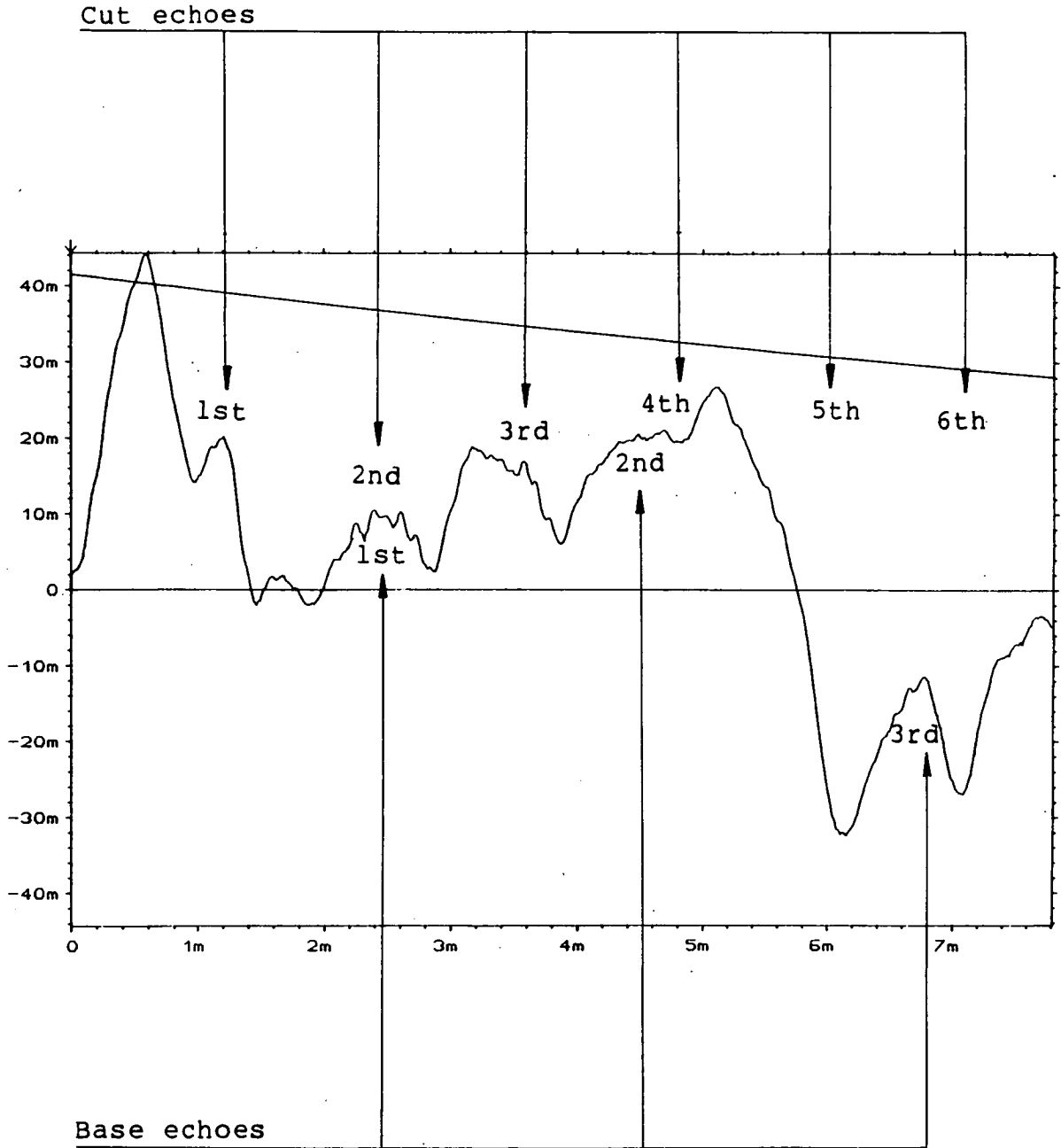
AUTO-CORRELATION AND VELOCITY TIME RECORD  
COLUMN 2: 50 & MORTAR DEFECT

FIGURE 7.19

W5 TIME CH.B REAL INPUT  
Y: 44.3mU  
X: 0.000ms + 7.81ms  
SETUP W10

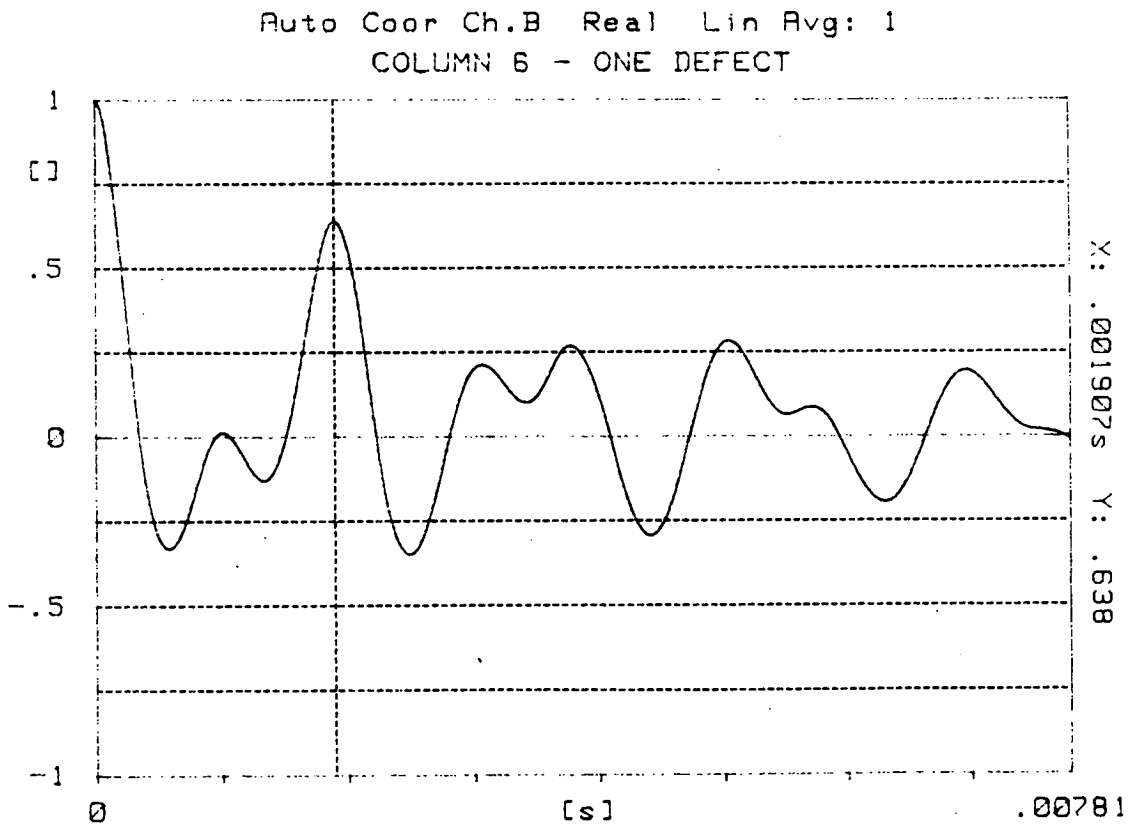
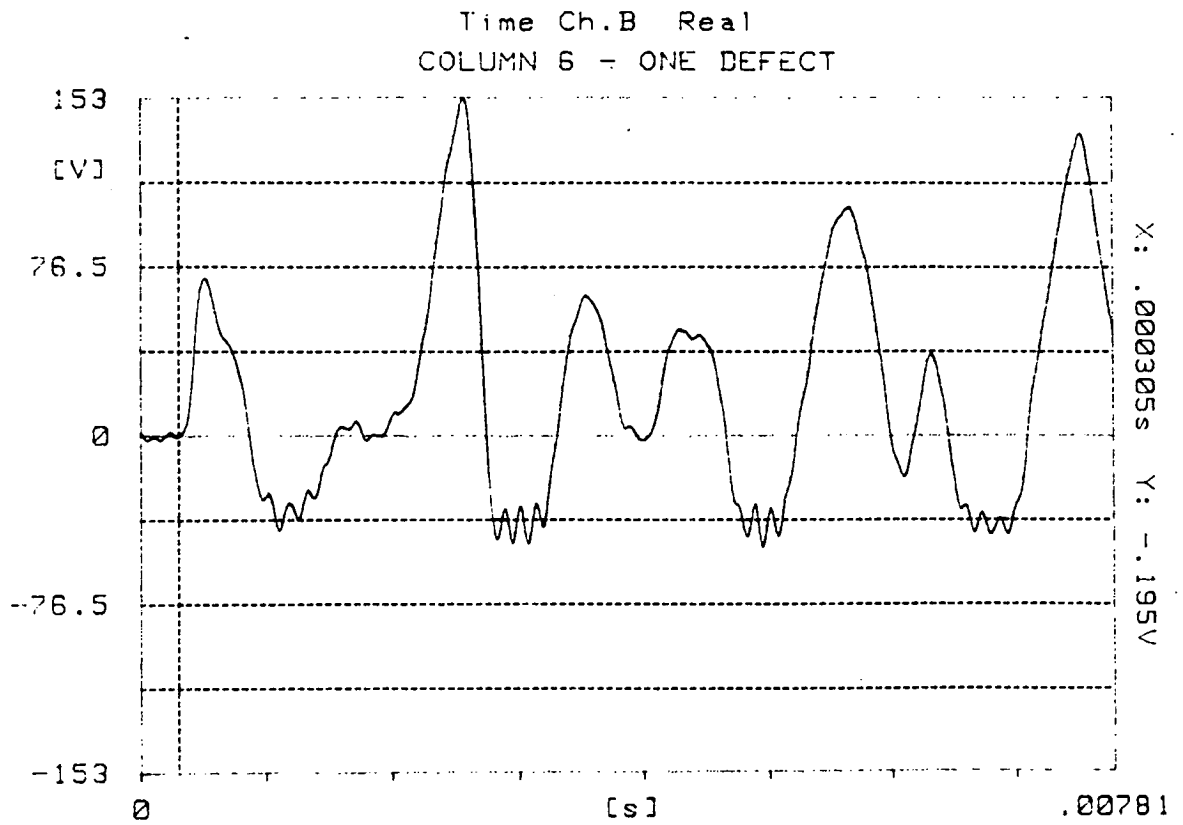
REAL INPUT

MAIN Y: 1.81mU  
X: 0.000ms



VELOCITY TIME RECORD  
COLUMN 2: 50 % MORTAR DEFECT

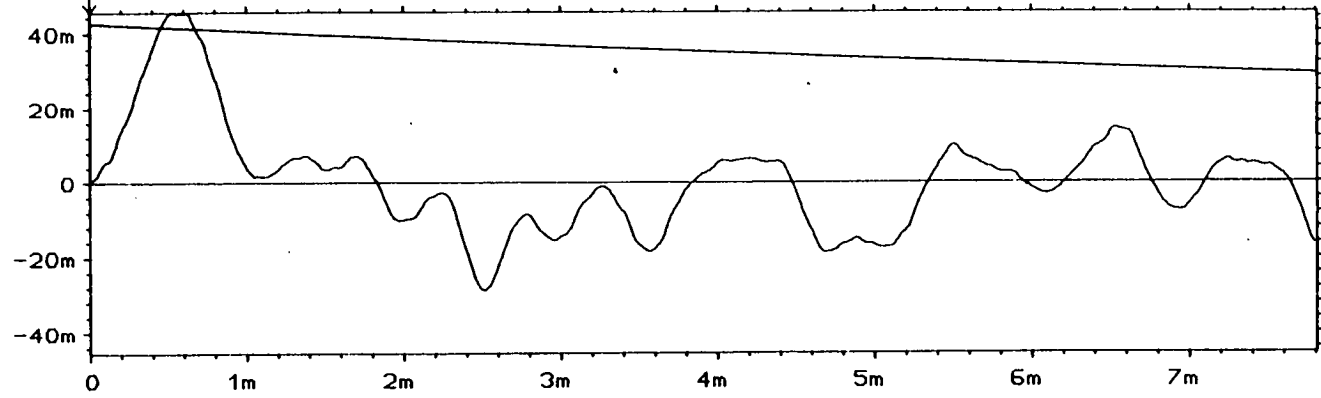
FIGURE 7.20



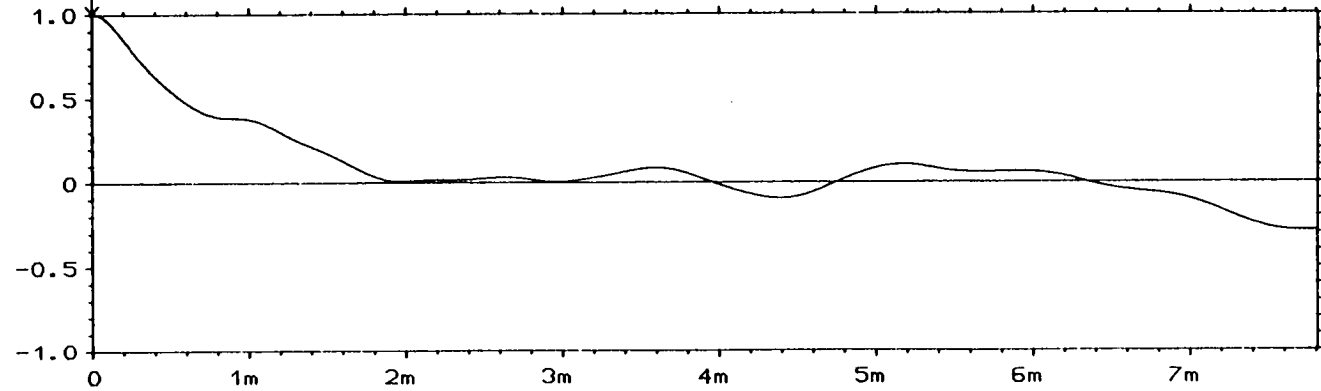
AUTO-CORRELATION AND VELOCITY TIME RECORD  
COLUMN: 15 & MORTAR DEFECT

FIGURE 7.21

W5 TIME CH.B REAL INPUT MAIN Y: 503μU  
Y: 45.4mU X: 0.000ms + 7.81ms  
SETUP W10



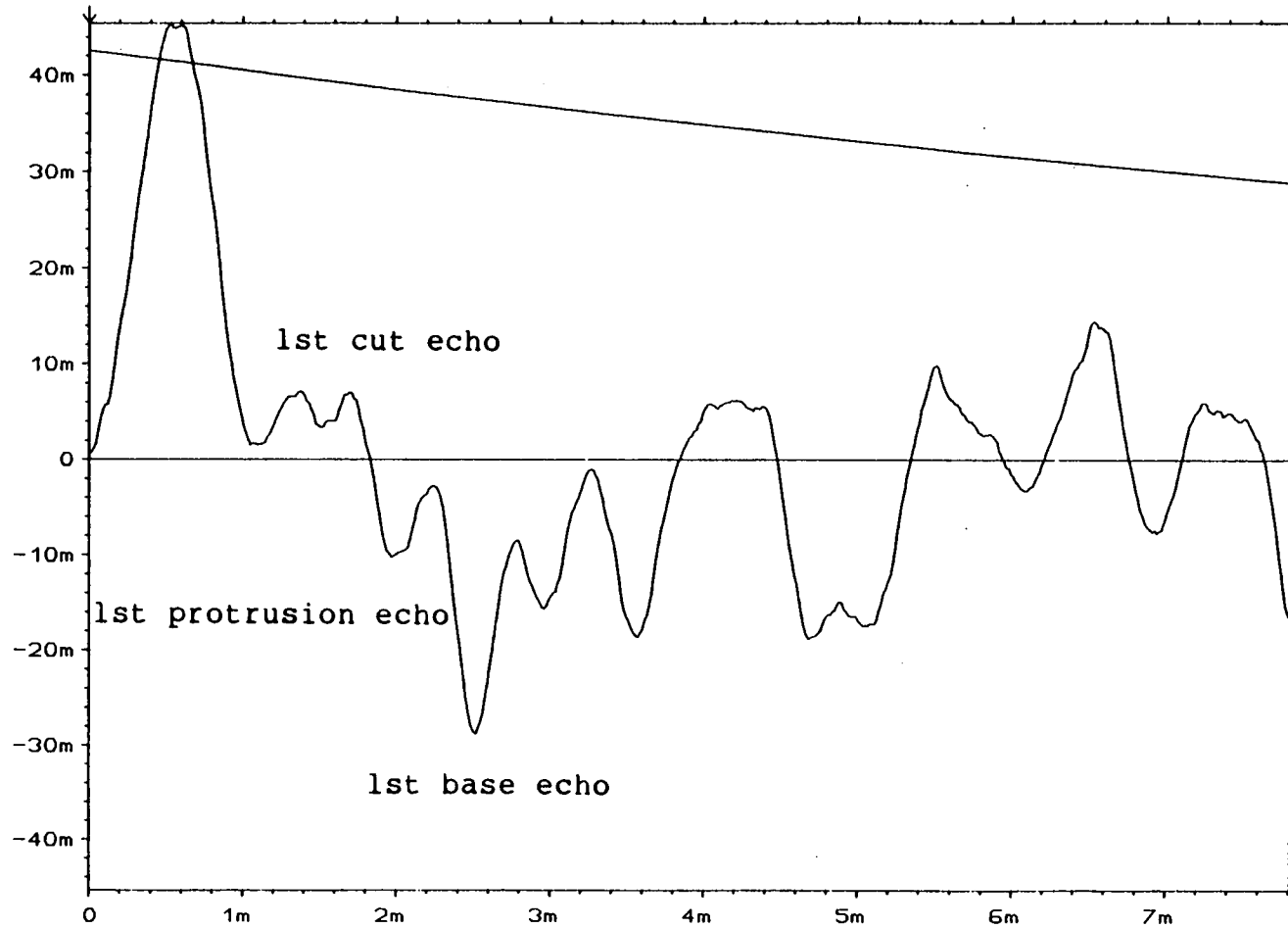
W7 AUTO CORR CH.B REAL MAIN Y: 1.00  
Y: 1.00 X: 0.000ms + 7.81ms  
SETUP W10 #A: 5



AUTO-CORRELATION AND VELOCITY TIME RECORD  
COLUMN 1: 50 & MORTAR DEFECT

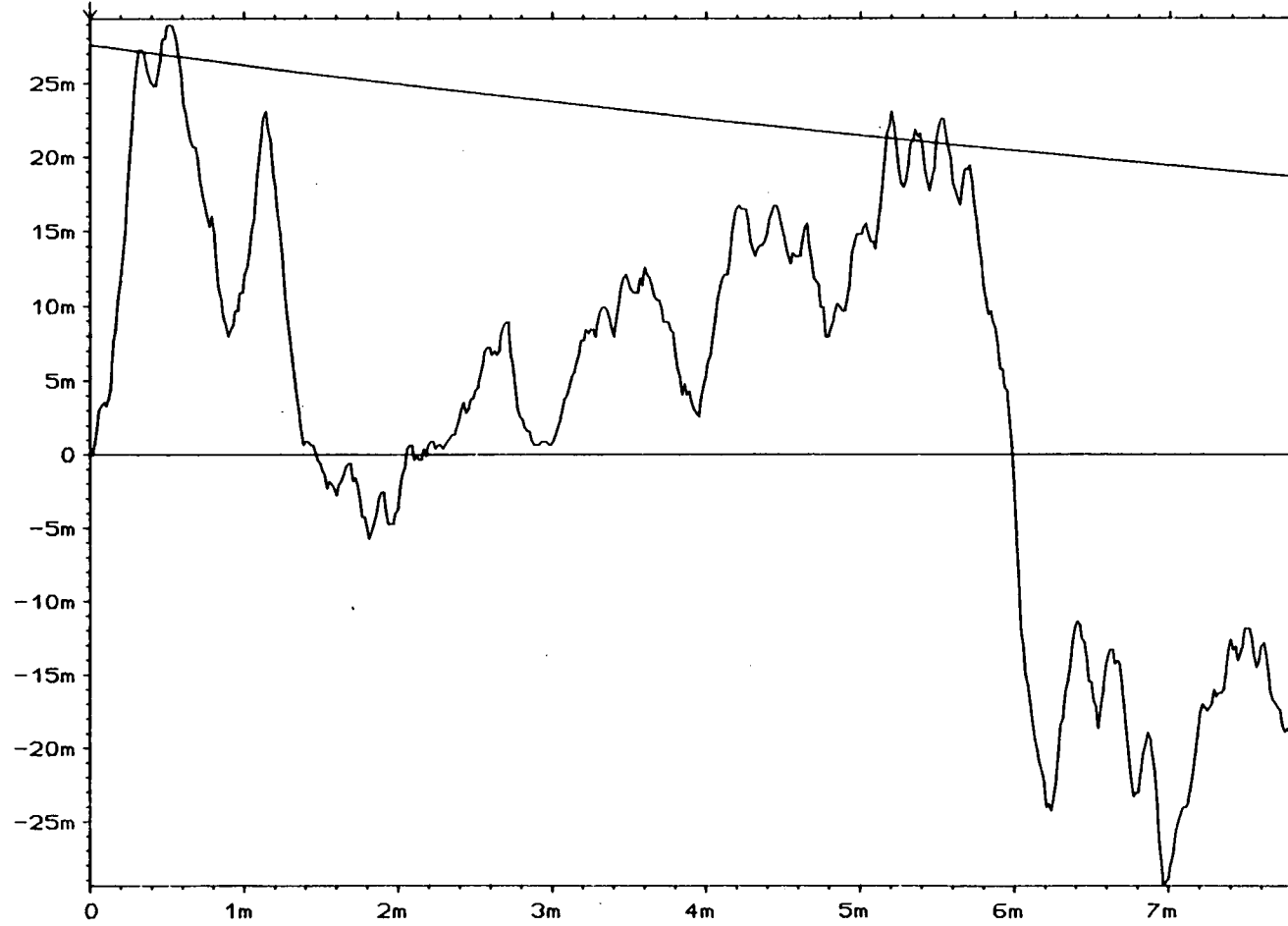
FIGURE 7.22

W5 TIME CH.B REAL INPUT MAIN Y: 603μU  
Y: 45.4mU X: 0.000ms + 7.81ms  
SETUP W10



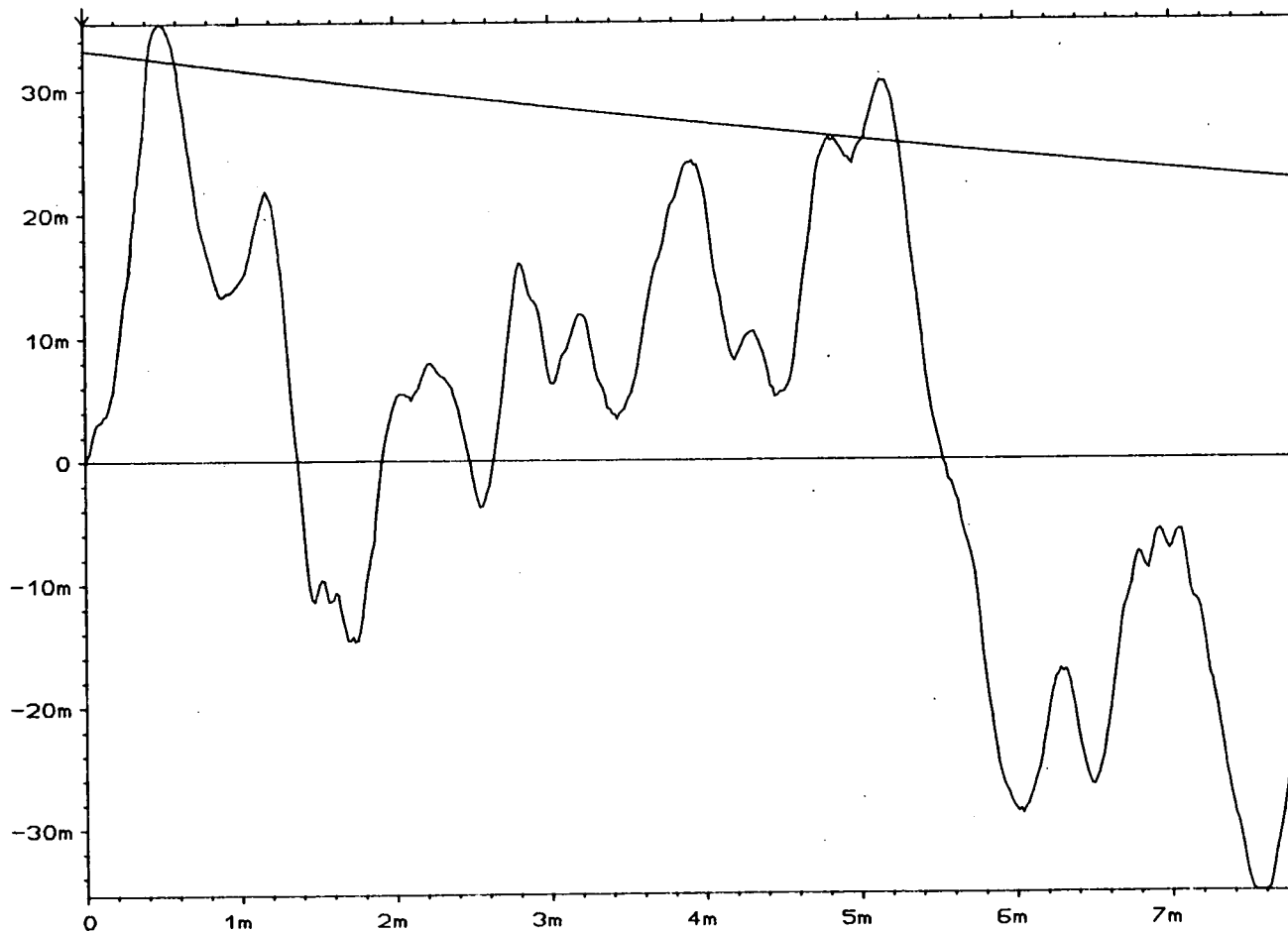
VELOCITY TIME RECORD  
COLUMN 1: 50 & MORTAR DEFECT  
FIGURE 7.23

W5 TIME CH.B REAL INPUT MAIN Y: 122μU  
Y: 29.4mU X: 0.000ms + 7.81ms  
SETUP W10\*



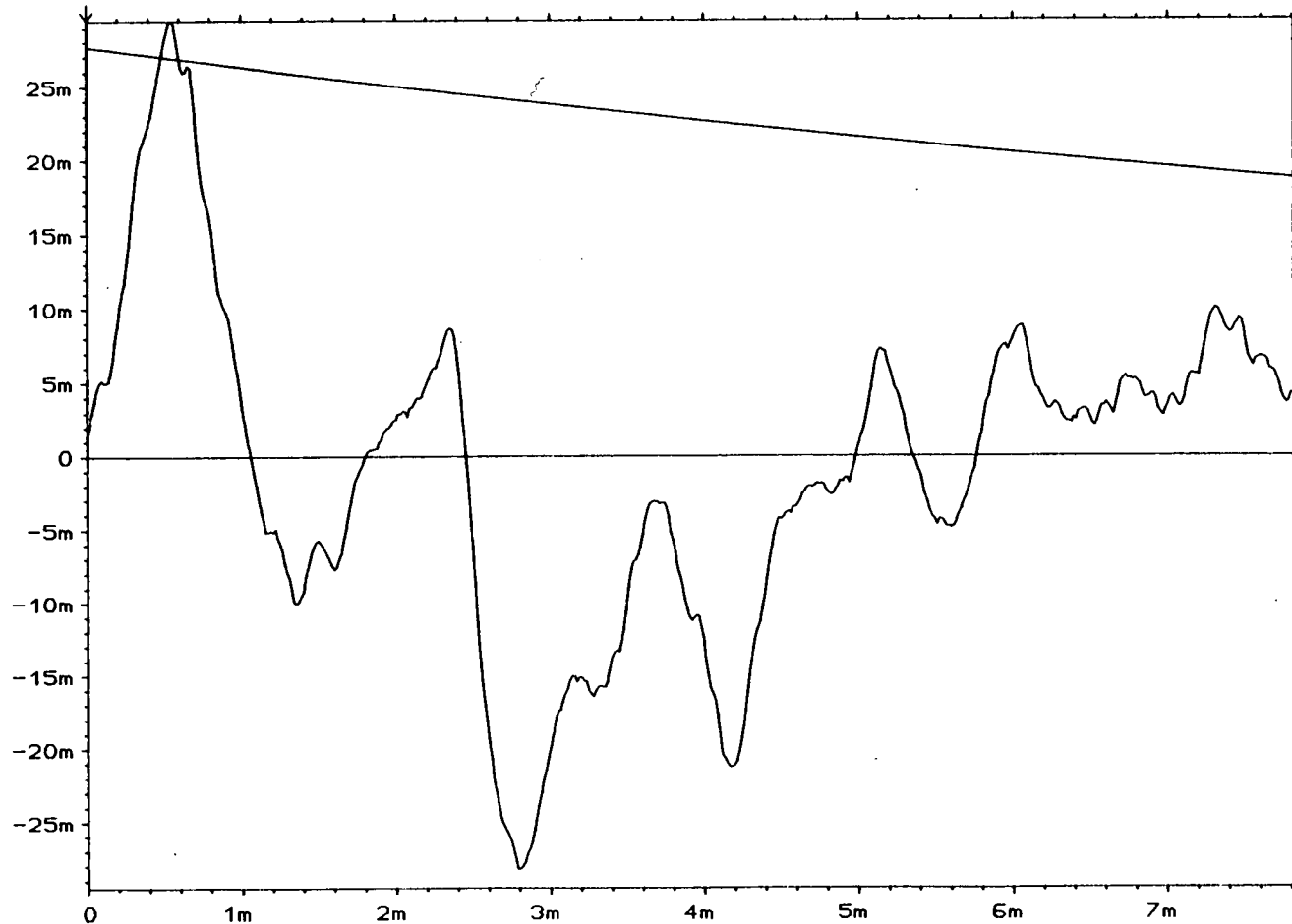
VELOCITY TIME RECORD  
COLUMN 2: 1st REPAIR  
FIGURE 7.24

W5 TIME CH.B REAL INPUT MAIN Y: -46.4μU  
Y: 35.4mU X: 0.000ms + 7.81ms  
SETUP W10\*



VELOCITY TIME RECORD  
COLUMN 2: 2nd REPAIR  
FIGURE 7.25

W5 TIME CH.B REAL INPUT MAIN Y: 1.25mU  
Y: 29.5mU X: 0.000ms + 7.81ms  
SETUP W10\*

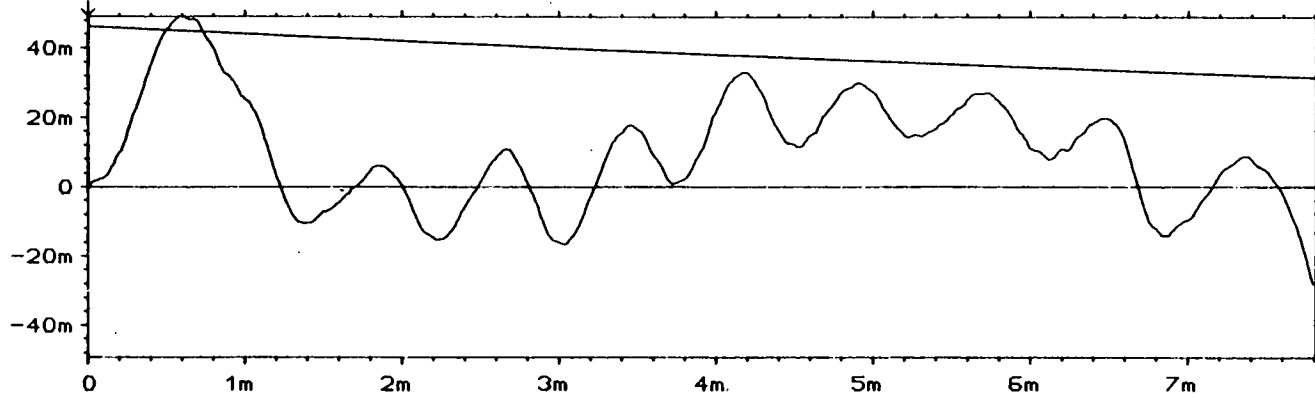


VELOCITY TIME RECORD  
COLUMN 1: REPAIR

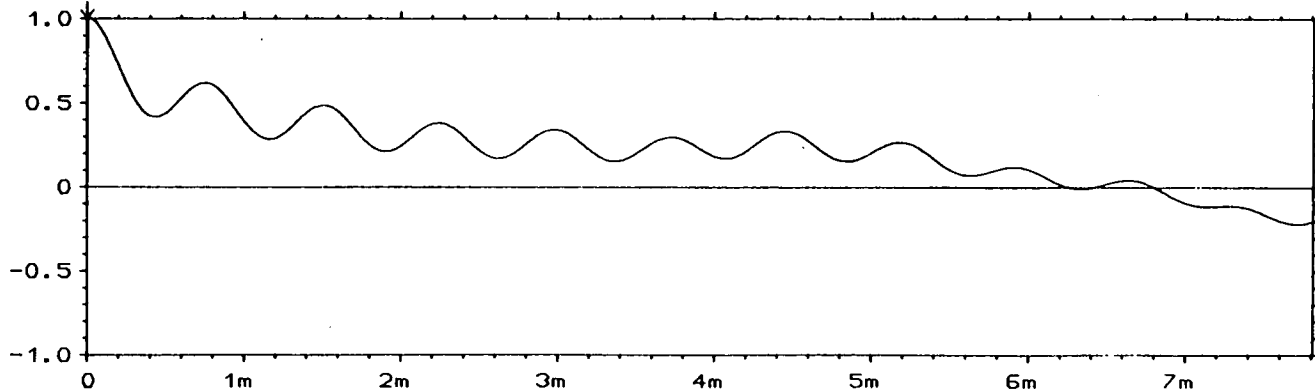
FIGURE 7.26



W5 TIME CH.B REAL INPUT MAIN Y: 742μU  
Y: 49.3mU X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10\*



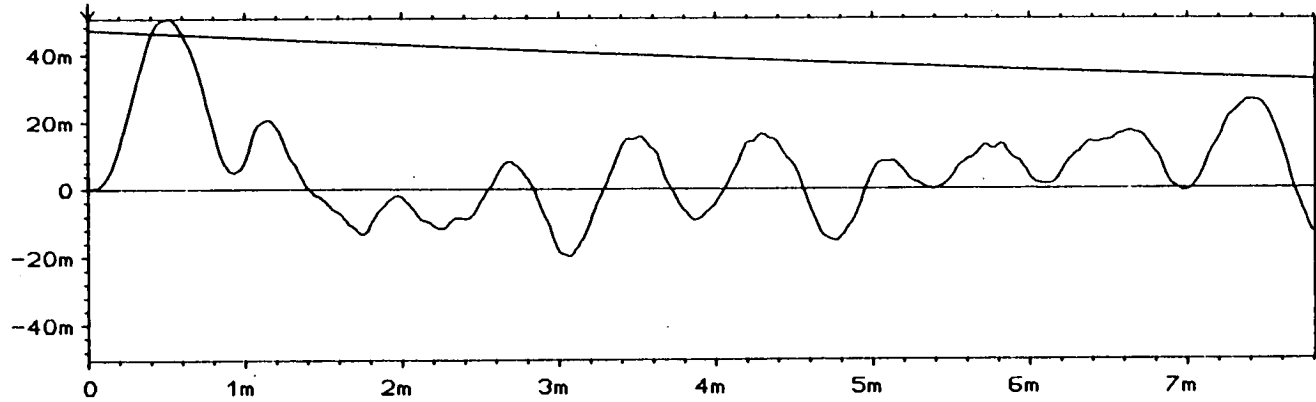
W7 AUTO CORR CH.B REAL MAIN Y: 1.00  
Y: 1.00 X: 0.000ms  
X: 0.000ms + 7.81ms #A: 5  
SETUP W10\*



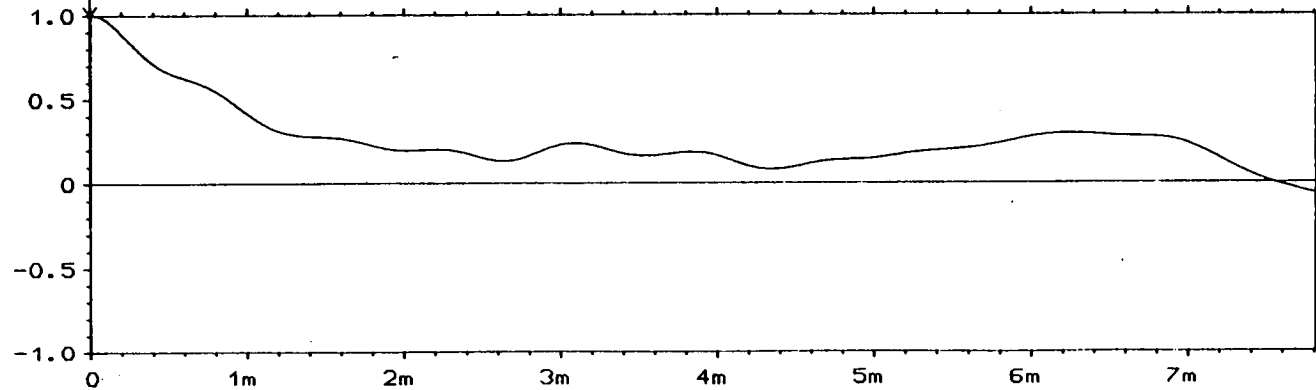
AUTO-CORRELATION AND VELOCITY TIME RECORD  
COLUMN 3: ONE BRICK DEFECT

FIGURE 7.27

W5 TIME CH.B REAL INPUT MAIN Y: 371μU  
Y: 50.4mU  
X: 0.000ms + 7.81ms  
SETUP W10\*



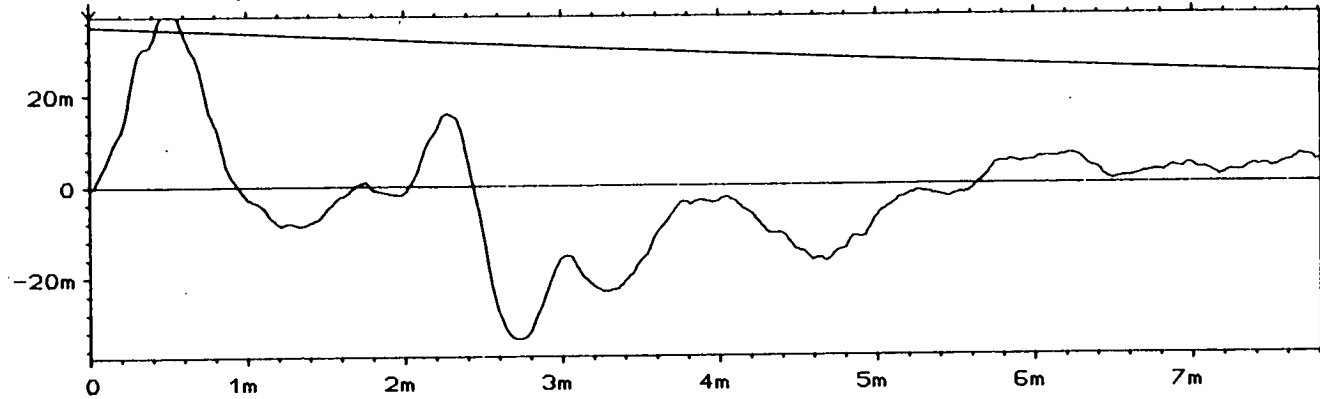
W7 AUTO CORR CH.B REAL MAIN Y: 1.00  
Y: 1.00  
X: 0.000ms + 7.81ms  
SETUP W10\* #A: 5



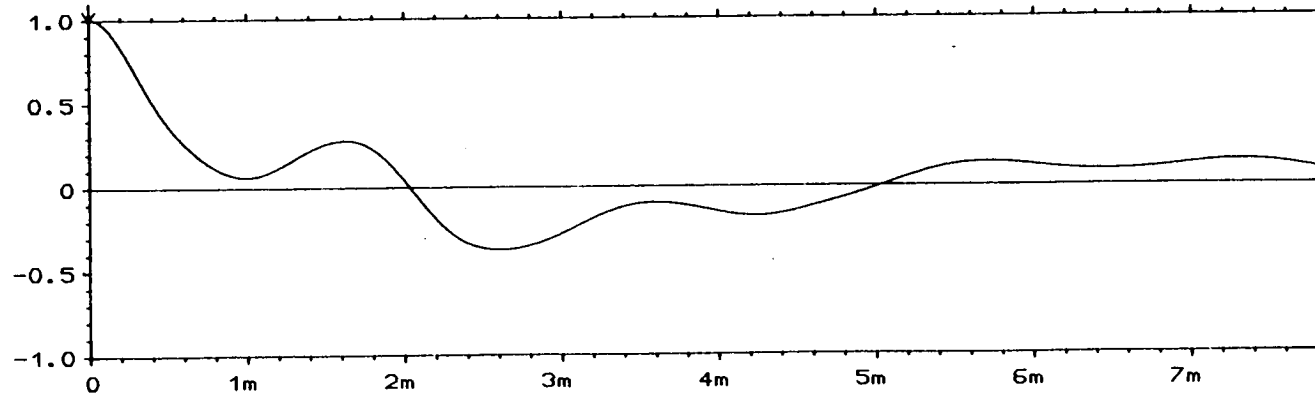
AUTO-CORRELATION AND VELOCITY TIME RECORD  
COLUMN 3: TWO BRICK DEFECTS

FIGURE 7.28

W5 TIME CH.B REAL INPUT MAIN Y: -556μU  
Y: 37.5mU X: 0.000ms + 7.81ms  
SETUP W10\*



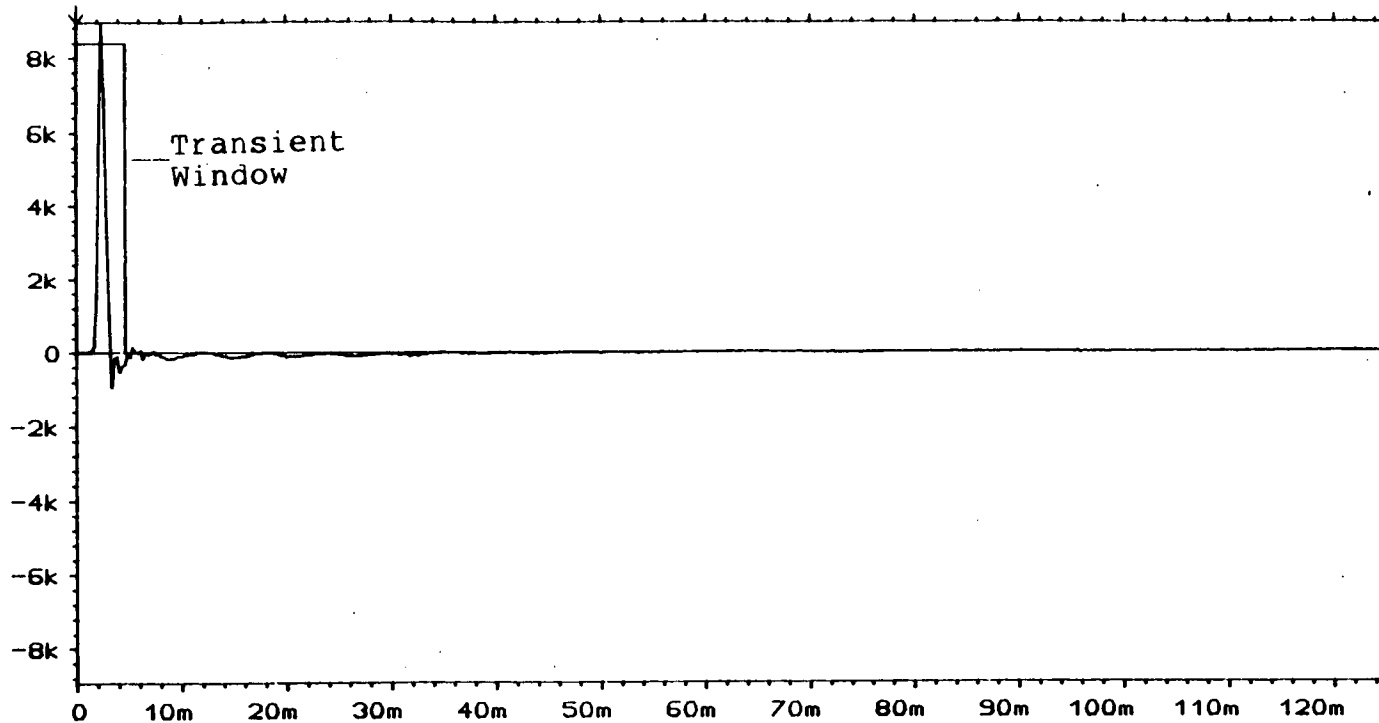
W7 AUTO CORR CH.B REAL MAIN Y: 1.00  
Y: 1.00 X: 0.000ms + 7.81ms  
SETUP W10\* #A: 5



AUTO-CORRELATION AND VELOCITY TIME RECORD  
COLUMN 4: DAMPED

FIGURE 7.29

W3 TIME CH.A REAL INPUT MAIN Y: 9.95U  
 Y: 8.94kU X: 0.00ms  
 X: 0.00ms + 125ms



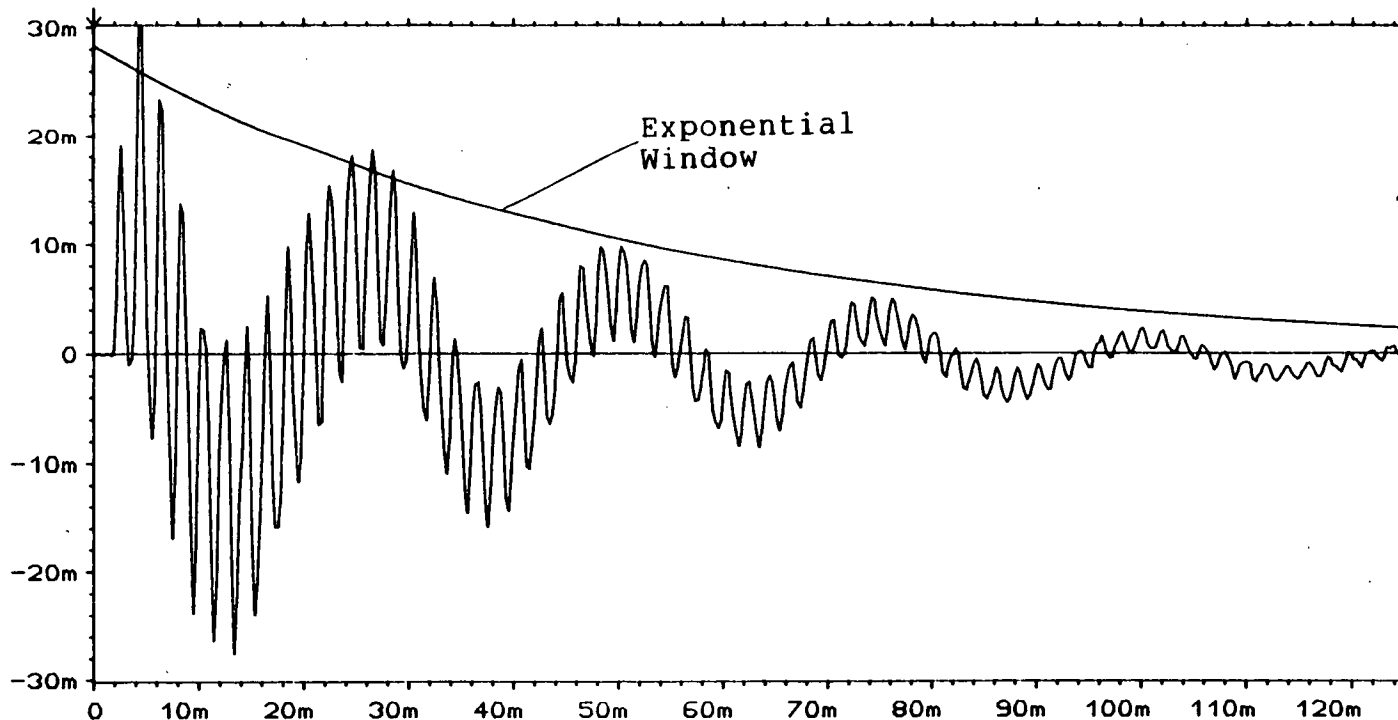
COLUMNS: FREQUENCY DOMAIN MEASUREMENT SET-UP  
 AND HAMMER INPUT SIGNAL

FIGURE 7.30

SETUP W9

MEASUREMENT:	DUAL SPECTRUM AVERAGING			
TRIGGER:	CH.A	+SLOPE	LEVEL: +0.10	MAX INPUT
DELAY:	TRIG→A: -0.97ms		CH.A→B: 0.00ms	
AVERAGING:	LIN	5		
FREQ SPAN:	1.6kHz	ΔF: 2Hz	T: 500ms	ΔT: 244μs
CENTER FREQ:	BASEBAND			
WEIGHT CH.A:	TRANSIENT	SHIFT: 0.00ms	LENGTH: 4.63ms	
WEIGHT CH.B:	EXPONENTIAL	SHIFT: 0.00ms	LENGTH: 50.04ms	
CH.A:	6V	+ 3Hz DIR	FILT: BOTH	184μV/N
CH.B:	6V	+ 3Hz DIR	FILT: BOTH	31.6V/m/s
GENERATOR:	DISABLED			

W5 TIME CH.B REAL INPUT MAIN Y: -58.0μU  
 Y: 30.2mU X: 0.00ms  
 X: 0.00ms + 125ms



COLUMNS: FREQUENCY DOMAIN MEASUREMENT SET-UP  
 AND VELOCITY TIME RECORD

FIGURE 7.31

SETUP W9

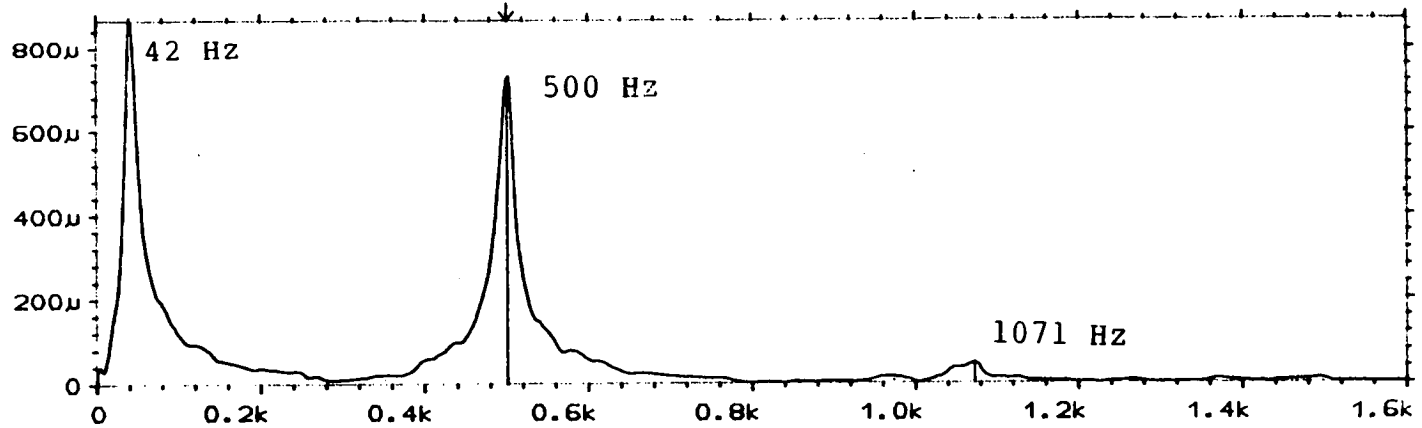
MEASUREMENT: DUAL SPECTRUM AVERAGING  
 TRIGGER: CH.A +SLOPE LEVEL: +0.10 MAX INPUT  
 DELAY: TRIG→A: -0.97ms CH.A→B: 0.00ms  
 AVERAGING: LIN 5

FREQ SPAN: 1.6kHz ΔF: 2Hz T: 500ms ΔT: 244μs  
 CENTER FREQ: BASEBAND  
 WEIGHT CH.A: TRANSIENT SHIFT: 0.00ms LENGTH: 4.63ms  
 WEIGHT CH.B: EXPONENTIAL SHIFT: 0.00ms LENGTH: 50.04ms  
 CH.A: 6V + 3Hz DIR FILT: BOTH 184μV/N  
 CH.B: 6V + 3Hz DIR FILT: BOTH 31.6V/m/s  
 GENERATOR: DISABLED

W3 INST SPEC CH.B MAG  
Y: 865 $\mu$ U RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9

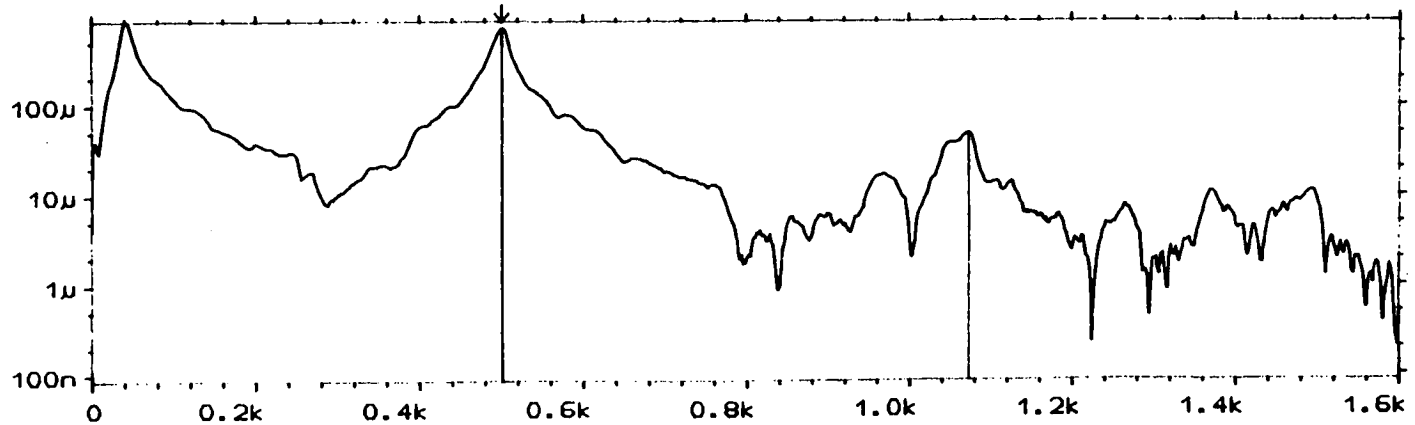
INPUT

SIDB Y: 721 $\mu$ U  
X: 500Hz  
 $\Delta$ X: 571.0625Hz



W8 INST SPEC CH.B MAG  
Y: 865 $\mu$ U RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9

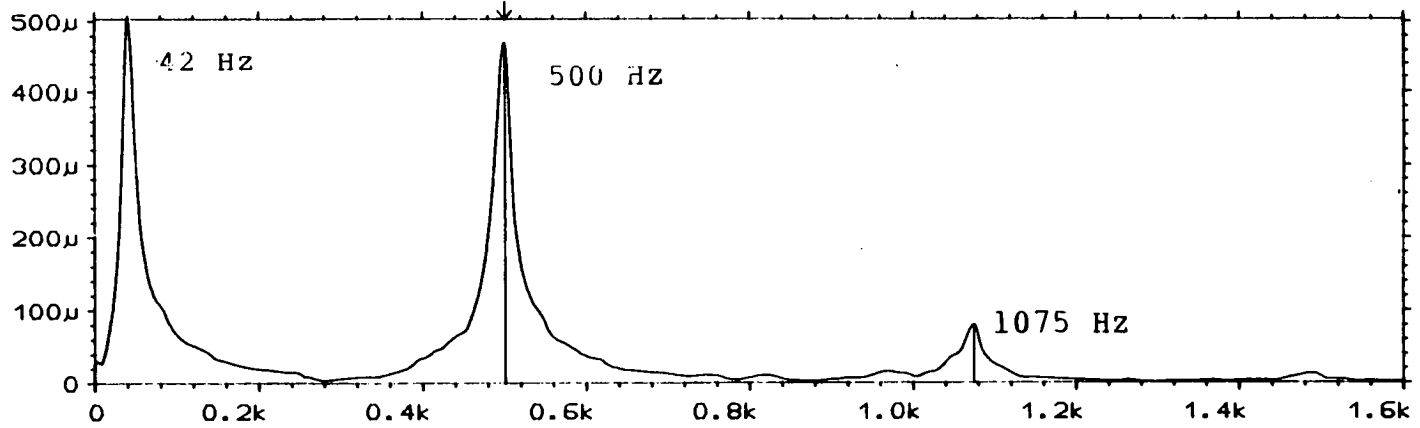
SIDB Y: 721 $\mu$ U  
X: 500Hz  
 $\Delta$ X: 571.0625Hz



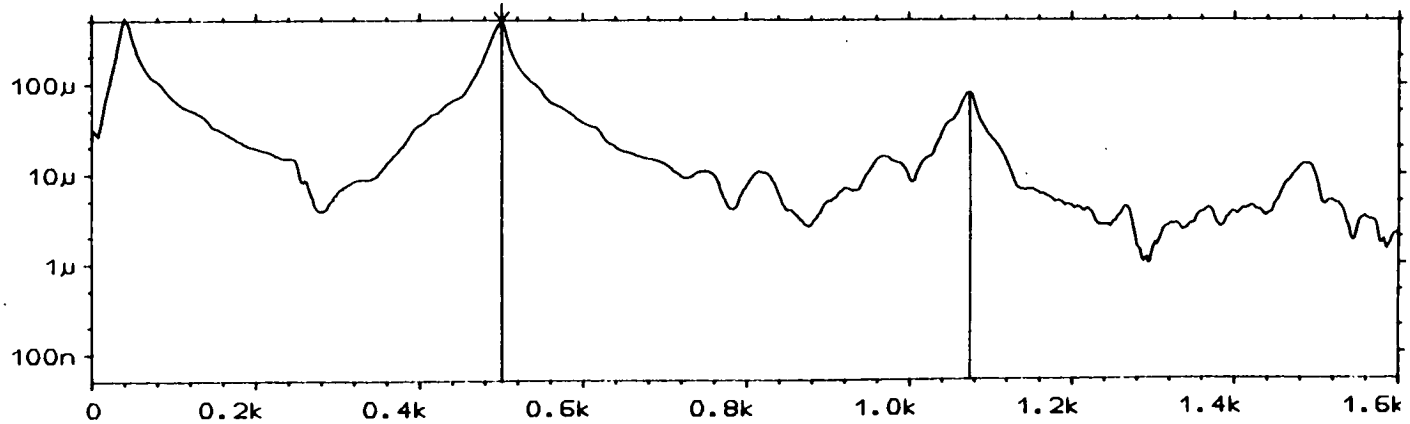
TYPICAL INSTANTANEOUS SPECTRUM  
COLUMN 2: NO DEFECTS

FIGURE 7.32

**W6** AUTO SPEC CH.B [ ] INPUT SIDB Y: 471 $\mu$ U  
 Y: 503 $\mu$ U RMS LIN X: 500Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 574.8750Hz  
 SETUP W9 #A: 5

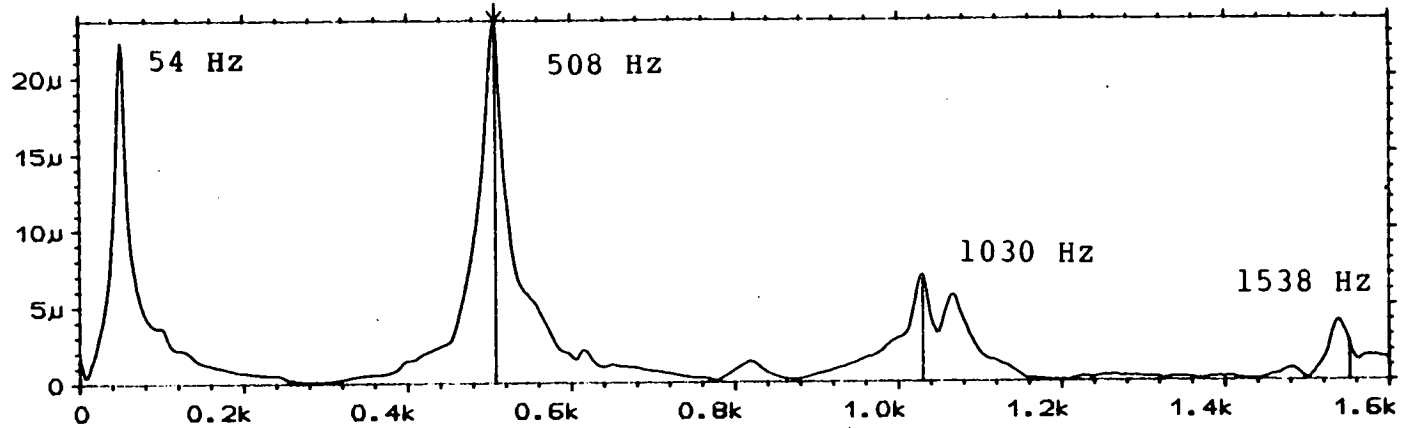


**W6** AUTO SPEC CH.B SIDB Y: 471 $\mu$ U  
 Y: 503 $\mu$ U RMS 80dB X: 500Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 574.8750Hz  
 SETUP W9 #A: 5

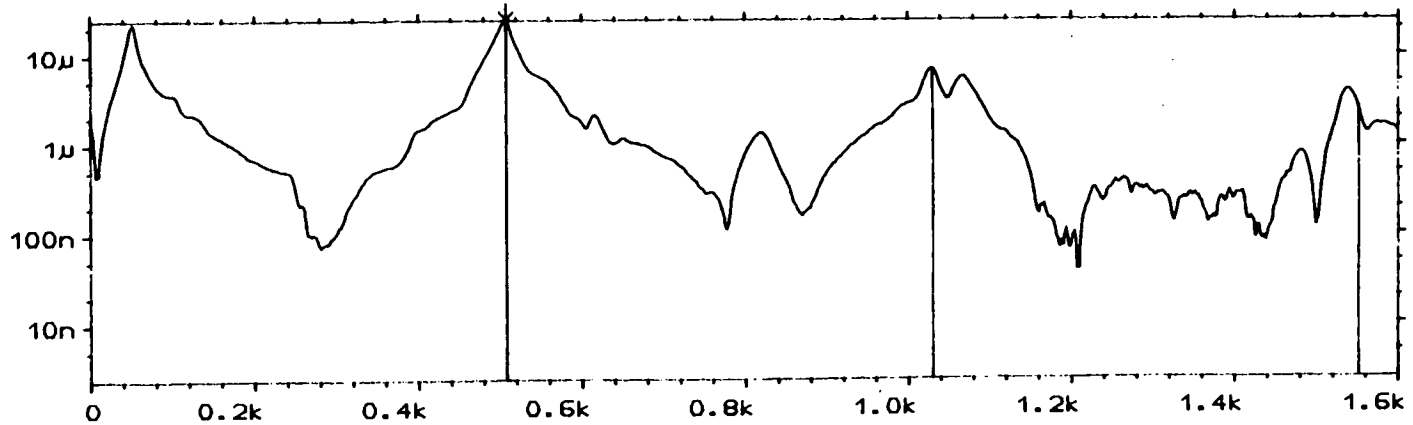


TYPICAL AUTO-SPECTRUM  
 COLUMN 2: NO DEFECTS  
 FIGURE 7.33

**W8** FREQ RESP H1 MAG INPUT SIDB Y: 23.6 $\mu$   
 Y: 23.8 $\mu$  LIN X: 508Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 521.8125Hz  
 SETUP W9 #A: 5



**W8** FREQ RESP H1 MAG SIDB Y: 23.6 $\mu$   
 Y: 24.4 $\mu$  80dB X: 508Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 521.8125Hz  
 SETUP W9 #A: 5

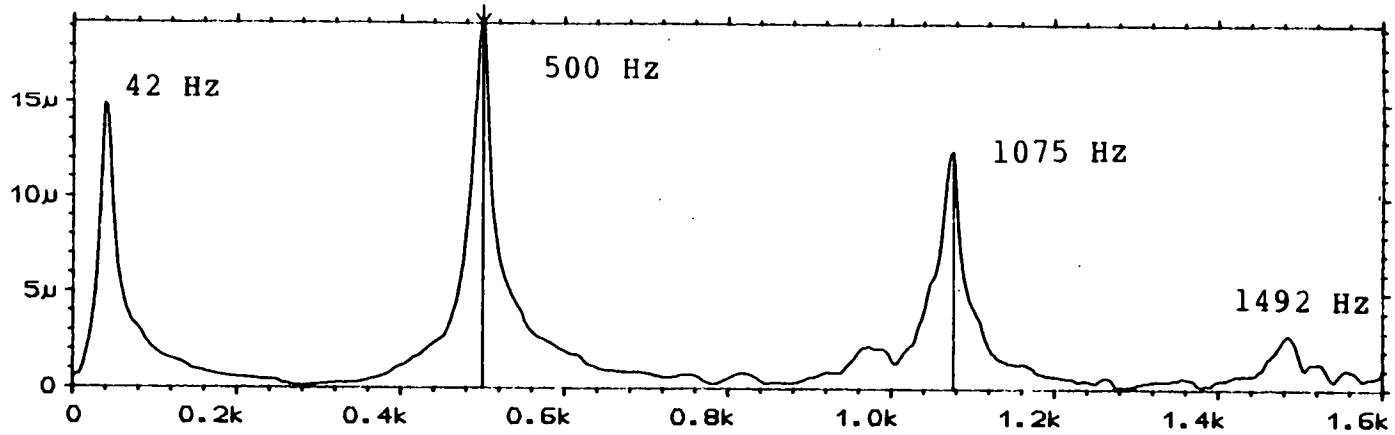


FREQUENCY RESPONSE FUNCTION  
 COLUMN 1: NO DEFECTS

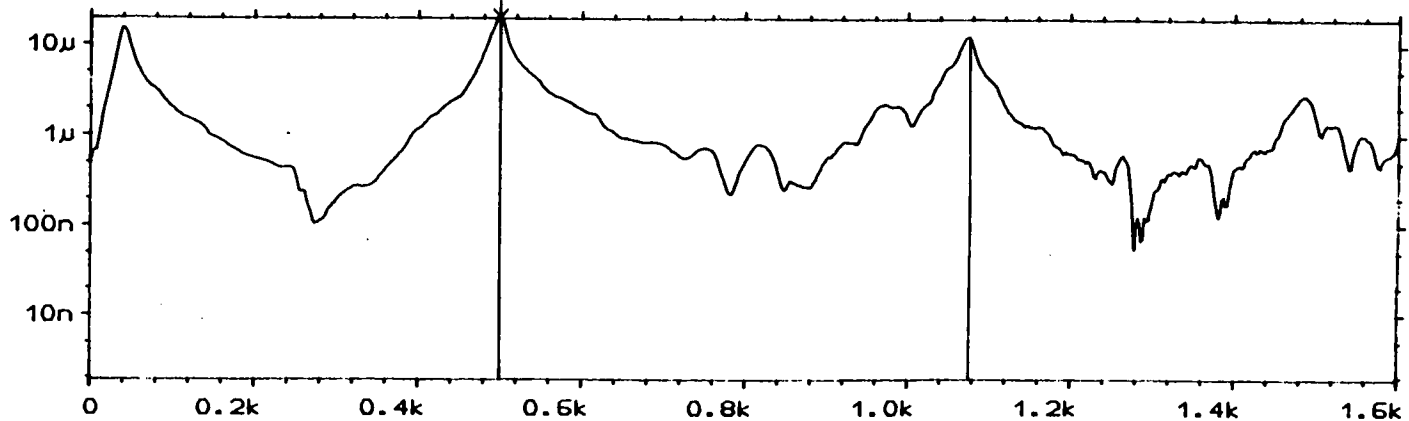
FIGURE 7.34



**WB** FREQ RESP H1 MAG INPUT SIDB Y: 19.2 $\mu$   
 Y: 19.2 $\mu$  LIN X: 500Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 575.0000Hz  
 SETUP W9 #A: 5



**W8** FREQ RESP H1 MAG SIDB Y: 19.2 $\mu$   
 Y: 19.2 $\mu$  80dB X: 500Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 575.0000Hz  
 SETUP W9 #A: 5

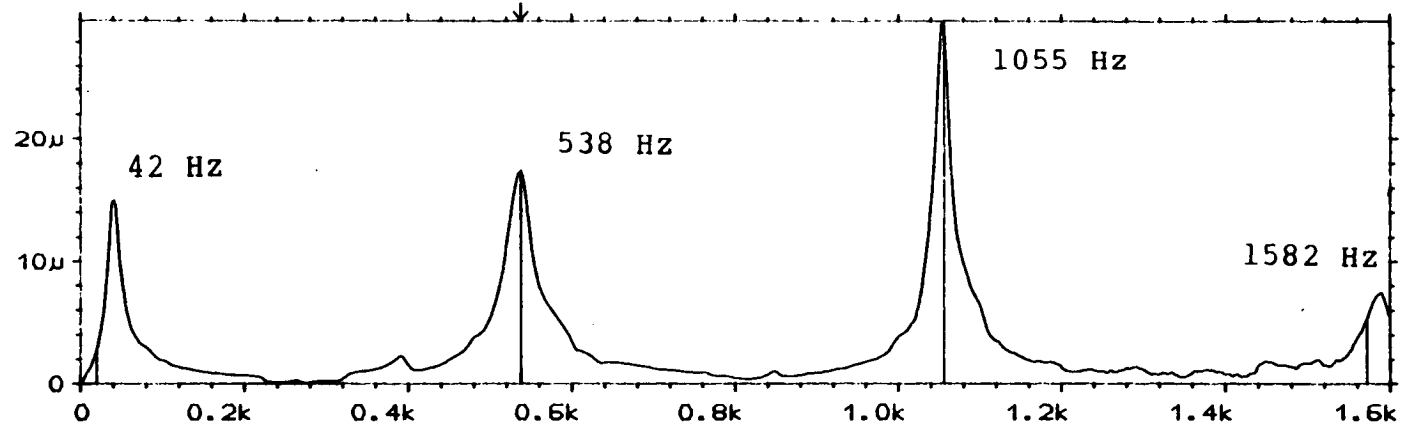


FREQUENCY RESPONSE FUNCTION  
 COLUMN 2: NO DEFECTS

FIGURE 7.35

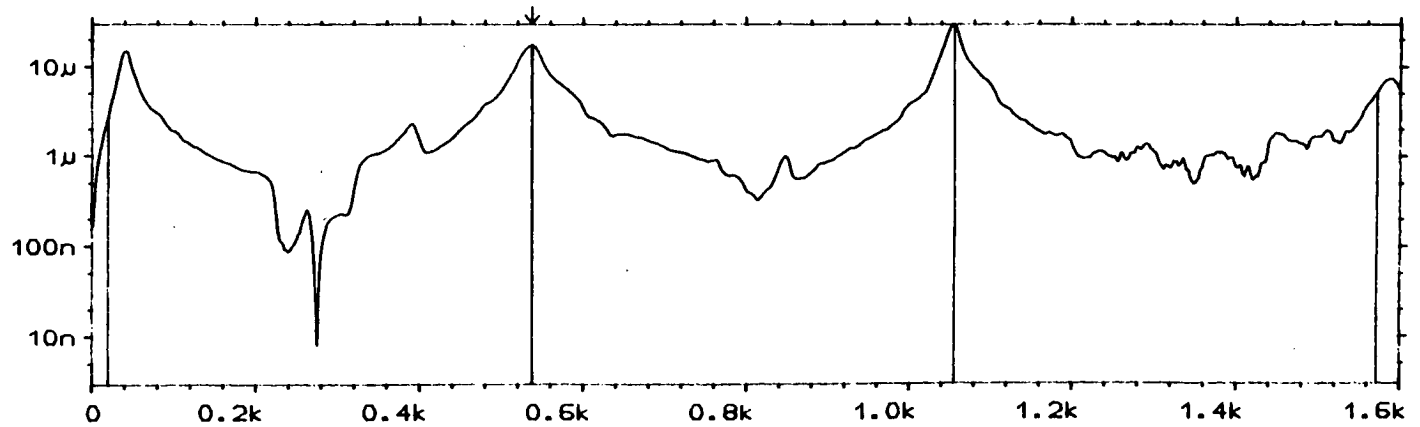
W8 FREQ RESP H1 MAG  
Y: 29.7 $\mu$  LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 17.3 $\mu$   
X: 538Hz  
 $\Delta$ X: 517.3750Hz



W8 FREQ RESP H1 MAG  
Y: 29.7 $\mu$  80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

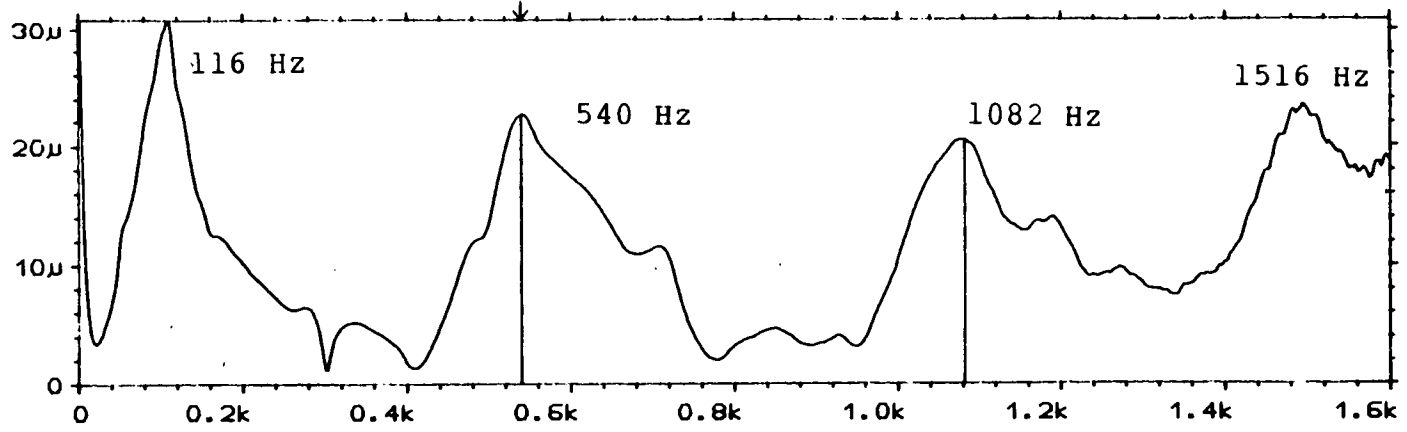
SIDB Y: 17.3 $\mu$   
X: 538Hz  
 $\Delta$ X: 517.3750Hz



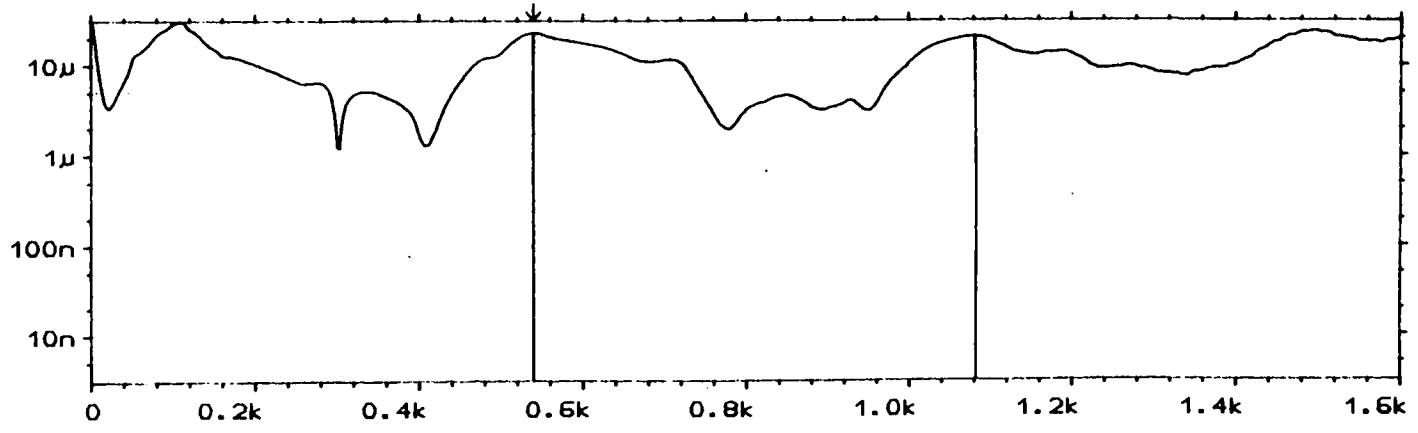
FREQUENCY RESPONSE FUNCTION  
COLUMN 3: NO DEFECTS

FIGURE 7.36

**W**B FREQ RESP H1 MAG INPUT SIDB Y: 22.6 $\mu$   
 Y: 30.8 $\mu$  LIN X: 540Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 541.1875Hz  
 SETUP W9 #A: 5

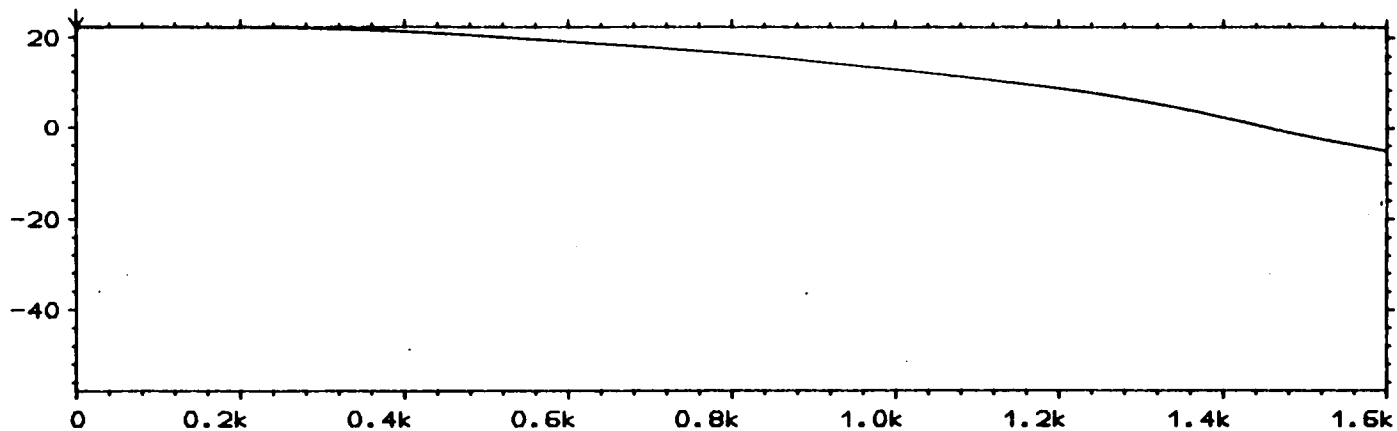


**W**B FREQ RESP H1 MAG SIDB Y: 22.6 $\mu$   
 Y: 30.8 $\mu$  80dB X: 540Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 541.1875Hz  
 SETUP W9 #A: 5

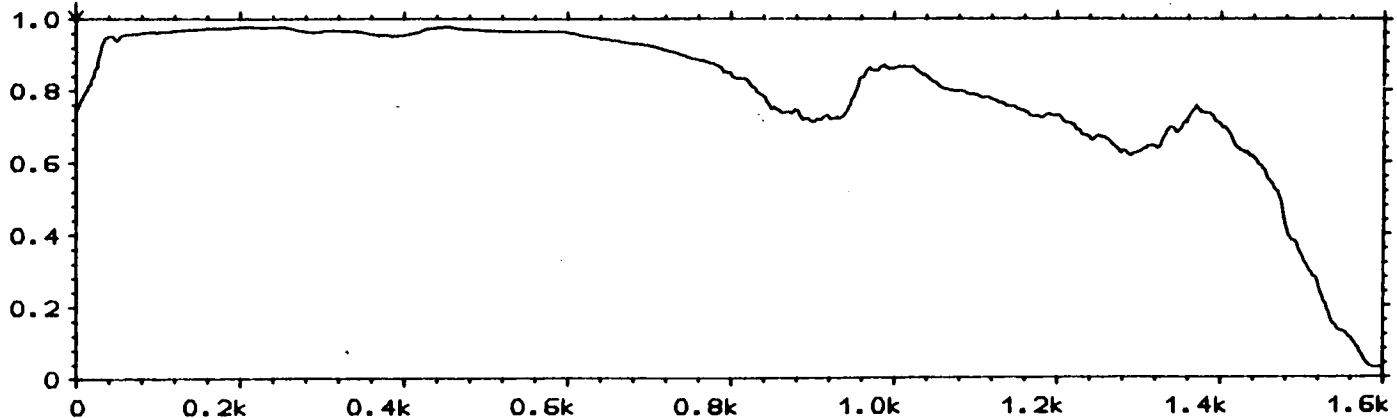


FREQUENCY RESPONSE FUNCTION  
 COLUMN 4: NO DEFECTS  
 FIGURE 7.37

W11 AUTO SPEC CH.A [ ] INPUT MAIN Y: 19.3dB  
Y: 22.3dB /1.00U RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5



20 COHERENCE MAIN Y: 747m  
Y: 1.00 X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

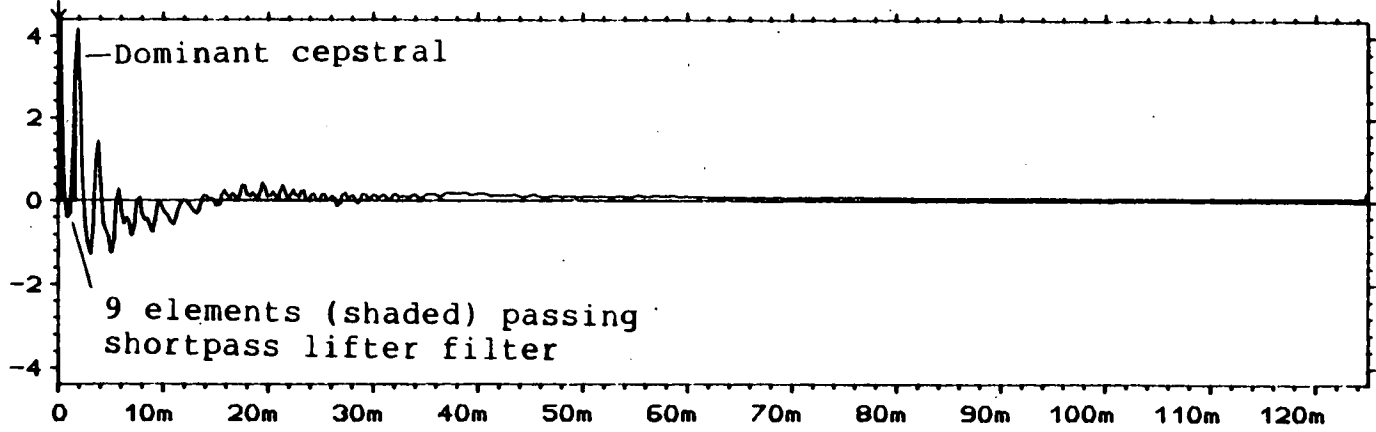


FORCE AUTO-SPECTRUM AND COHERENCE  
TYPICAL COLUMN

FIGURE 7.38

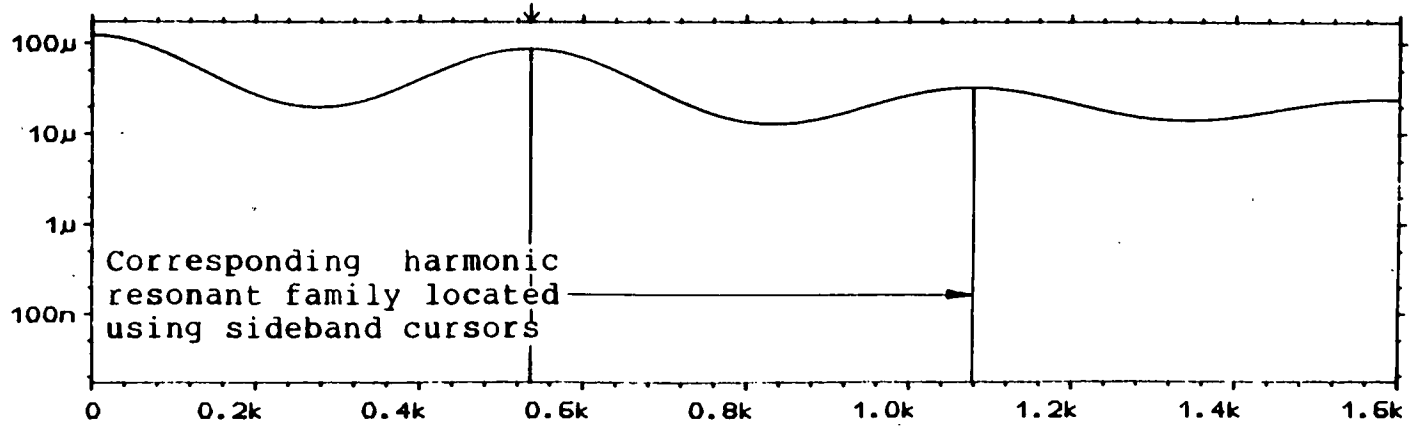
W2 CEPSTRUM CH.B REAL  
Y: 4.39dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.01dB  
X: 0.00ms  
SHORTPASS  
W: 9 [ ]



W4 LIFT SPEC CH.B  
Y: 173μU RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

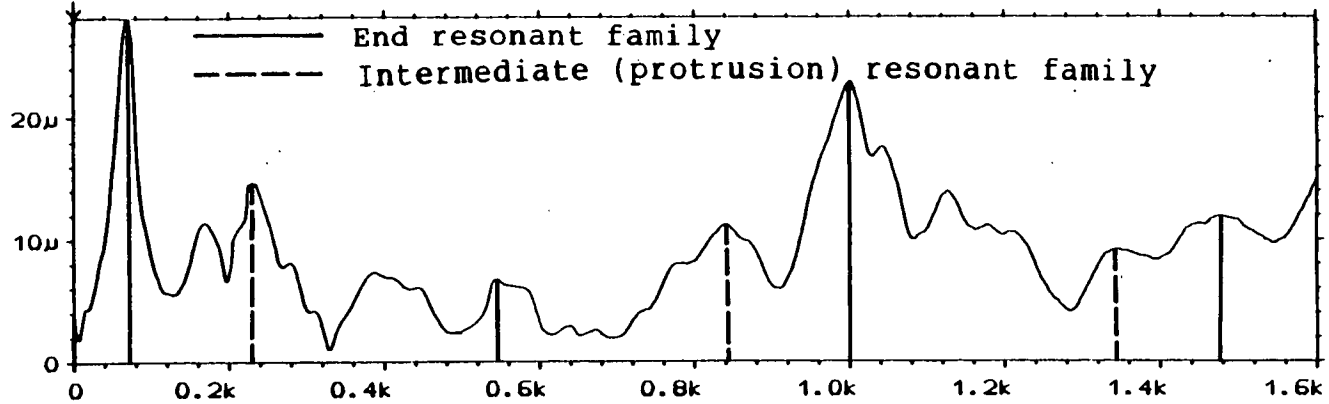
SIDB Y: 86.8μU  
X: 536Hz  
SHORTPASS ΔX: 542.1250Hz  
W: 9



CEPSTRUM AND LIFTERED SPECTRUM  
COLUMN 1: NO DEFECTS

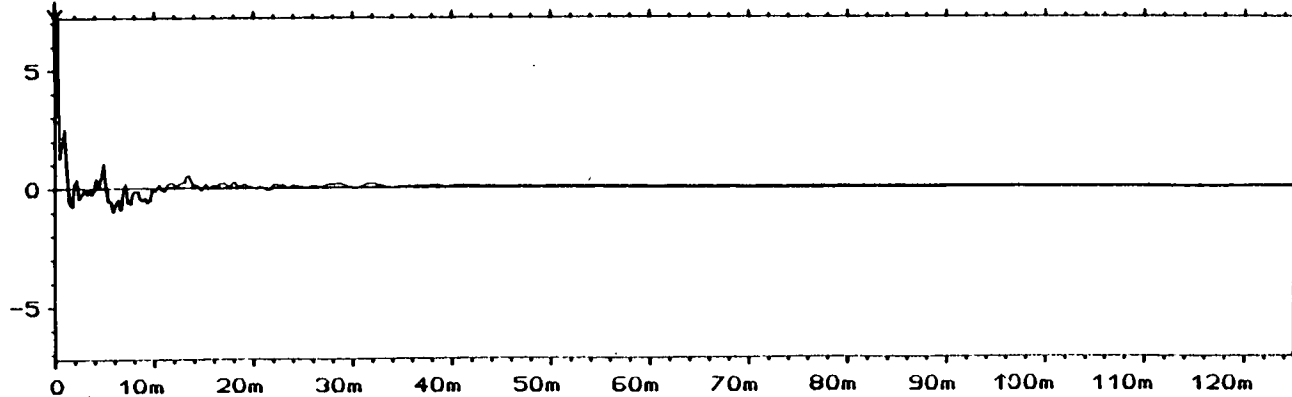
FIGURE 7.39

WB FREQ RESP H1 MAG INPUT SIDB Y: 3.48 $\mu$   
 Y: 28.3 $\mu$  LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 0.0000Hz  
 SETUP W9 #A: 5



(a)

W2 CEPSTRUM CH.B REAL MAIN Y: -0.01dB  
 Y: 7.21dB X: 0.00ms  
 X: 0.00ms + 125ms SHORTPASS  
 SETUP W9 #A: 5

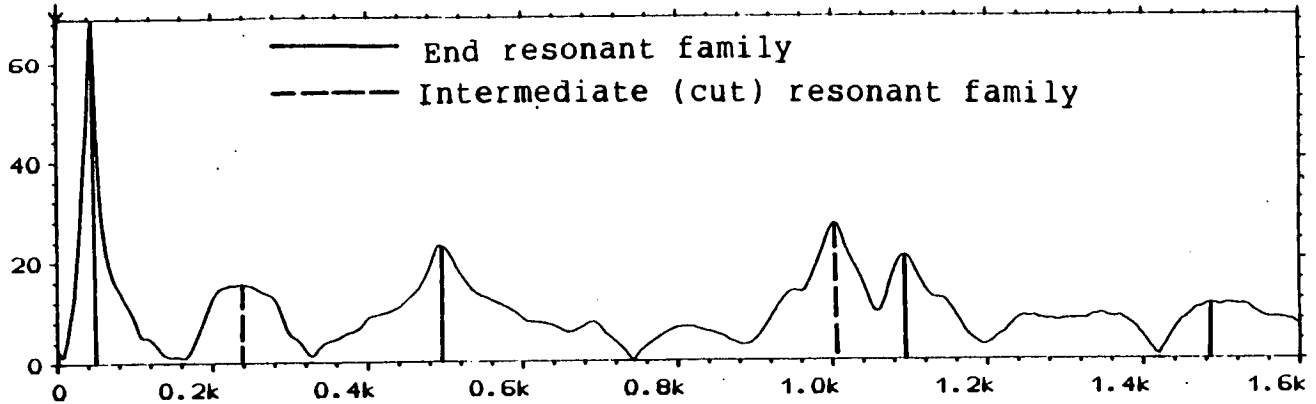


(b)

FREQUENCY RESPONSE FUNCTION AND CEPSTRUM  
 COLUMN 1: FIXED BASE

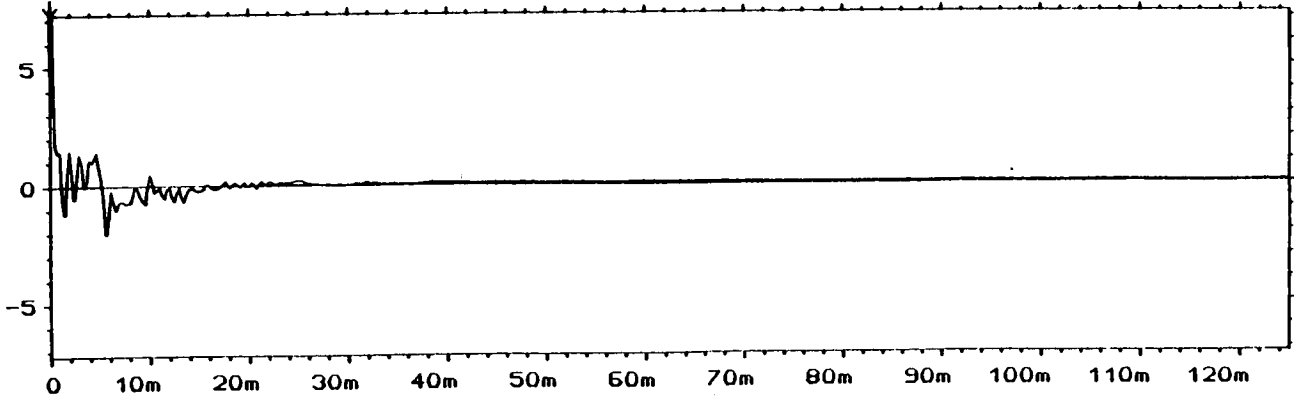
FIGURE 7.40

W1 FREQ RESP H1 MAG INPUT SIDB Y: 2.06  
 Y: 68.9 LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN ΔX: 0.0000Hz  
 SETUP W9 #A: 5



(a)

W2 CEPSTRUM CH.B REAL MAIN Y: -0.01dB  
 Y: 7.21dB X: 0.00ms  
 X: 0.00ms + 125ms SHORTPASS  
 SETUP W9 #A: 5

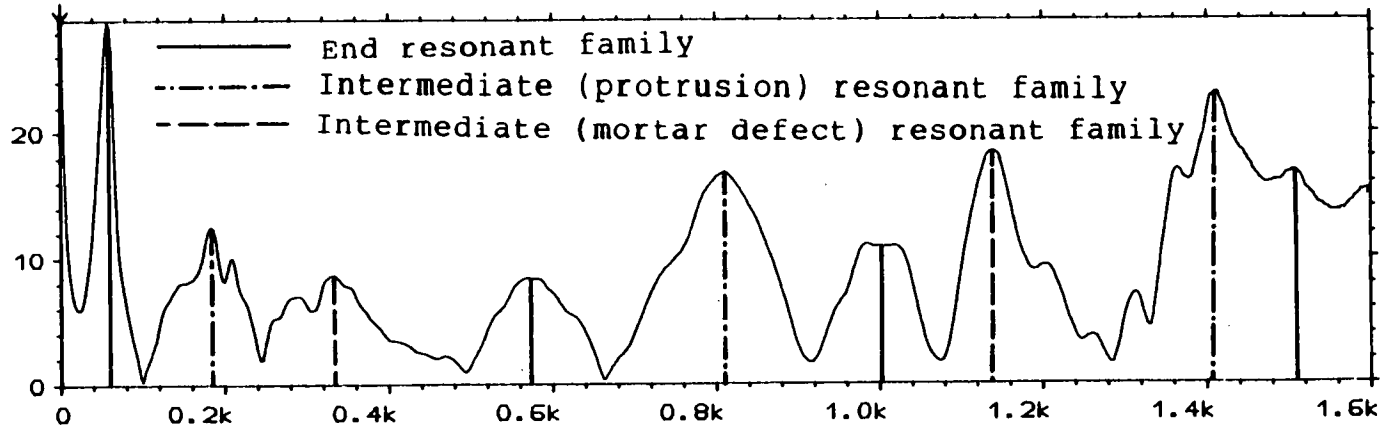


(b)

FREQUENCY RESPONSE FUNCTION AND CEPSTRUM  
 COLUMN 2: 50 & MORTAR DEFECT

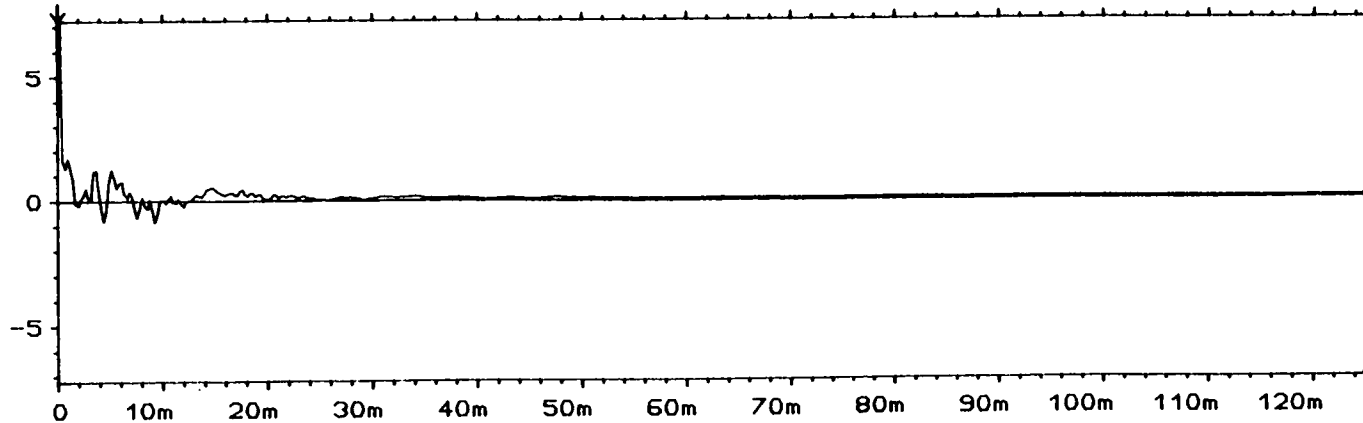
FIGURE 7.41

**W8** FREQ RESP H1 MAG INPUT SIDB Y: 29.5  
 Y: 29.0 LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN ΔX: 0.0000Hz  
 SETUP W9 #A: 5



(a)

**W2** CEPSTRUM CH.B REAL MAIN Y: 0.00dB  
 Y: 7.21dB X: 0.00ms  
 X: 0.00ms + 125ms SHORTPASS  
 SETUP W9 #A: 5



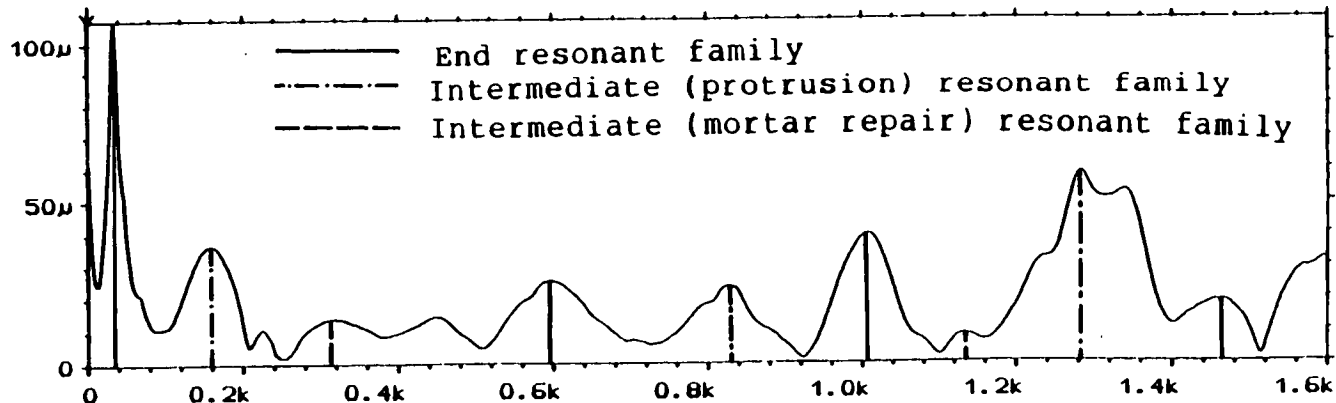
(b)

FREQUENCY RESPONSE FUNCTION AND CEPSTRUM  
 COLUMN 1: FIXED BASE AND 50 & MORTAR CUT  
 FIGURE 7.42



WB FREQ RESP H1 MAG  
Y: 107 $\mu$  LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 61.7 $\mu$   
X: 0Hz  
 $\Delta$ X: 0.0000Hz

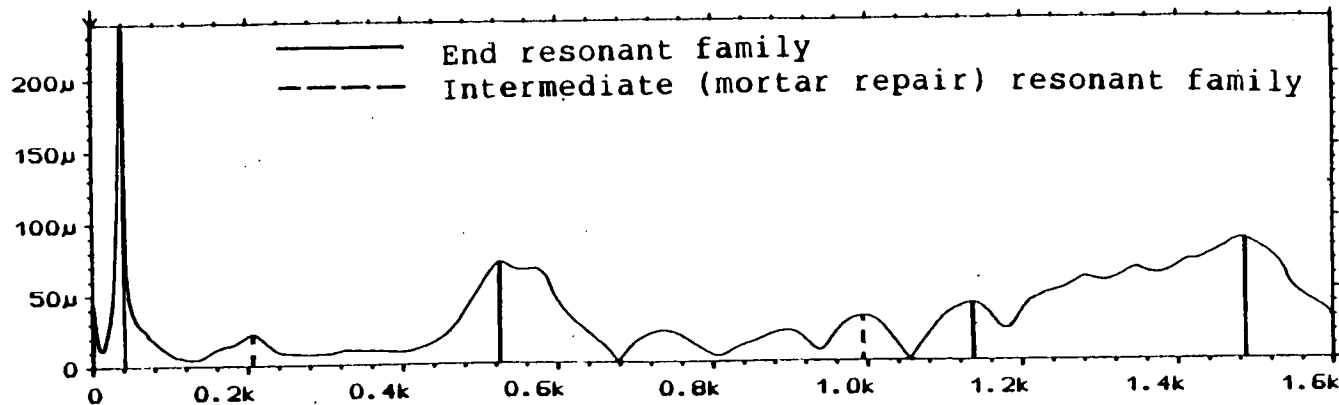


(a)

WB FREQ RESP H1 MAG  
Y: 239 $\mu$  LIN  
X: 0Hz + 1.6kHz LIN  
SETUP S9 #A: 5

STORED

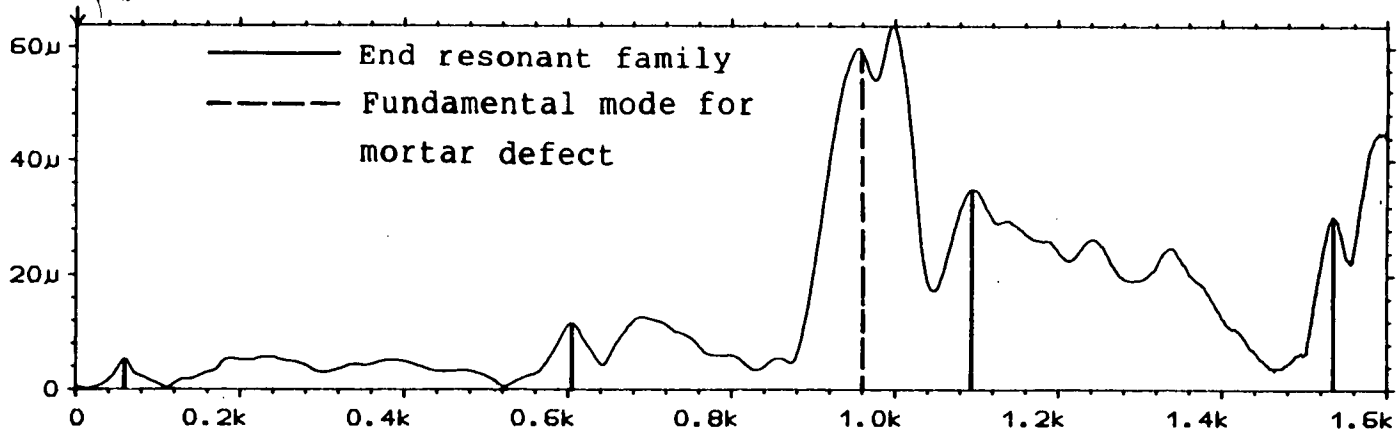
SIDB Y: 44.3 $\mu$   
X: 0Hz  
 $\Delta$ X: 0.0000Hz



(b)

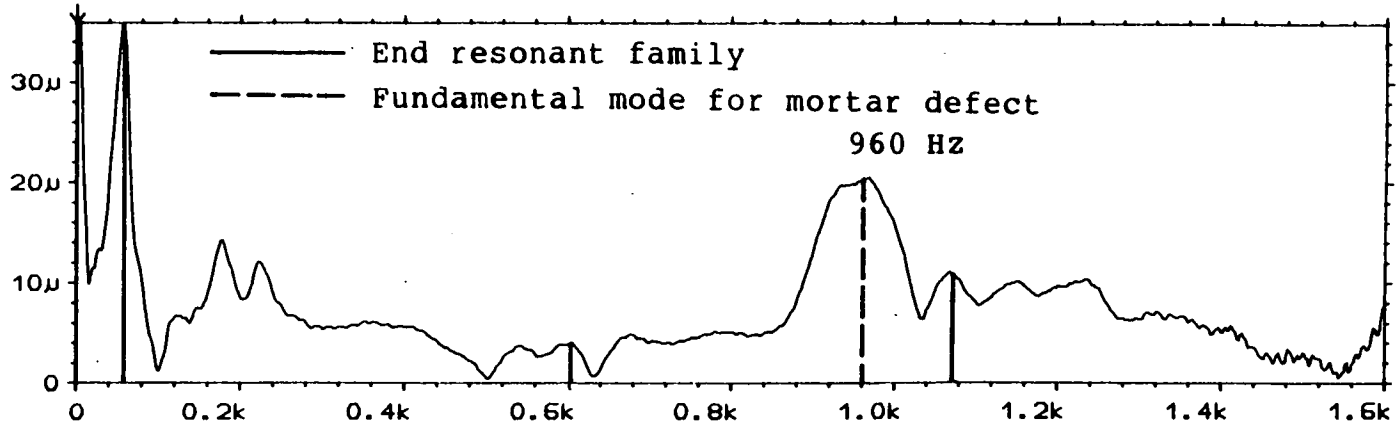
FIGURE 7.43  
FREQUENCY RESPONSE FUNCTIONS  
COLUMNS 1 AND 2: REPAIRS

W8 FREQ RESP H1 MAG STORED SIDB Y: 1.07 $\mu$   
 Y: 63.7 $\mu$  LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 0.0000Hz  
 SETUP S9 #A: 5



(a) One defect

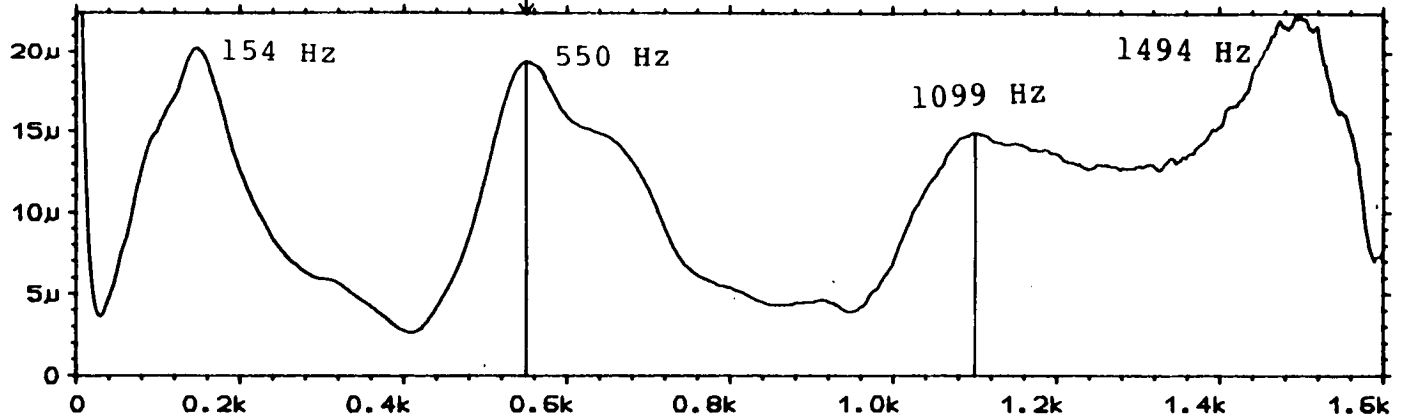
W8 FREQ RESP H1 MAG SIDB Y: 43.8 $\mu$   
 Y: 35.9 $\mu$  LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 0.0000Hz  
 SETUP W9 #A: 5



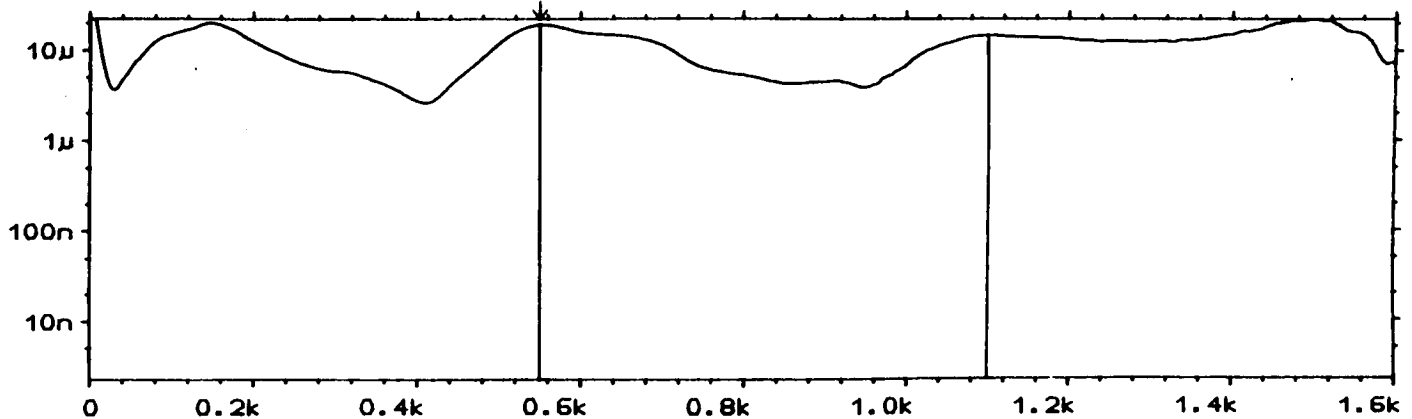
(b) Two defects

COLUMN 3: ONE AND TWO DEFECTS  
 FIGURE 7.44

**W8** FREQ RESP H1 MAG INPUT SIDB Y: 19.5 $\mu$   
 Y: 22.4 $\mu$  LIN X: 550Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 549.2500Hz  
 SETUP W9 #A: 5



**W8** FREQ RESP H1 MAG SIDB Y: 19.5 $\mu$   
 Y: 22.4 $\mu$  80dB X: 550Hz  
 X: 0Hz + 1.6kHz LIN  $\Delta$ X: 549.2500Hz  
 SETUP W9 #A: 5

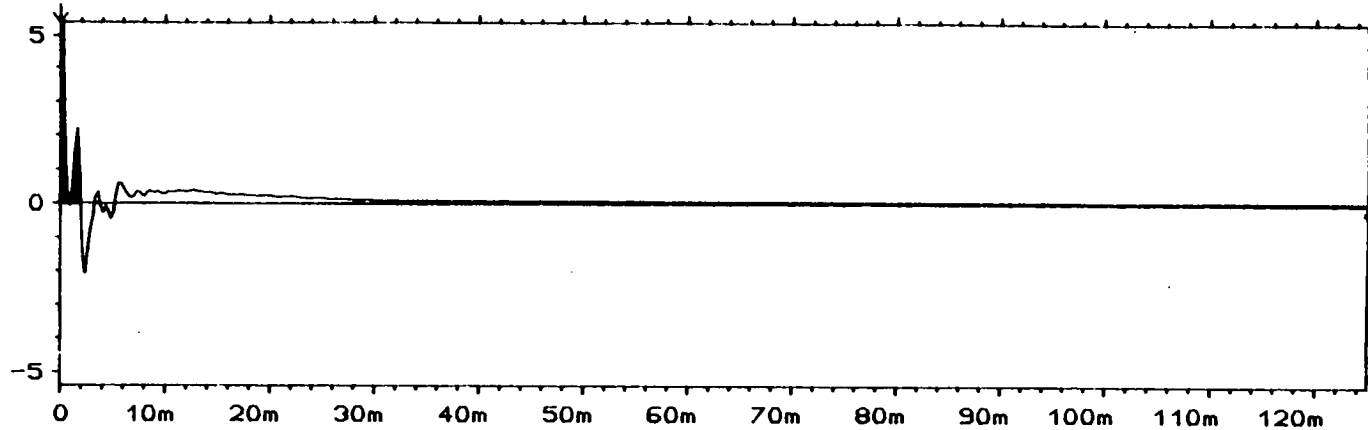


FREQUENCY RESPONSE FUNCTION  
 COLUMN 4: DAMPED  
 FIGURE 7.45

W2 CEPSTRUM CH.B REAL  
Y: 5.39dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: -0.01dB  
X: 0.00ms

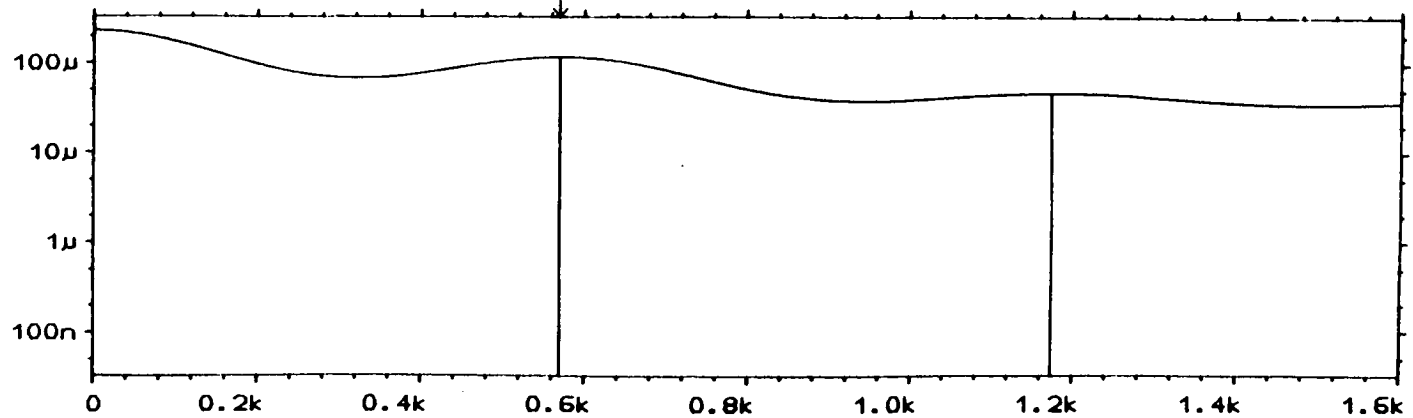
SHORTPASS  
W: 9 [ ]



W4 LIFT SPEC CH.B  
Y: 325 $\mu$ U RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

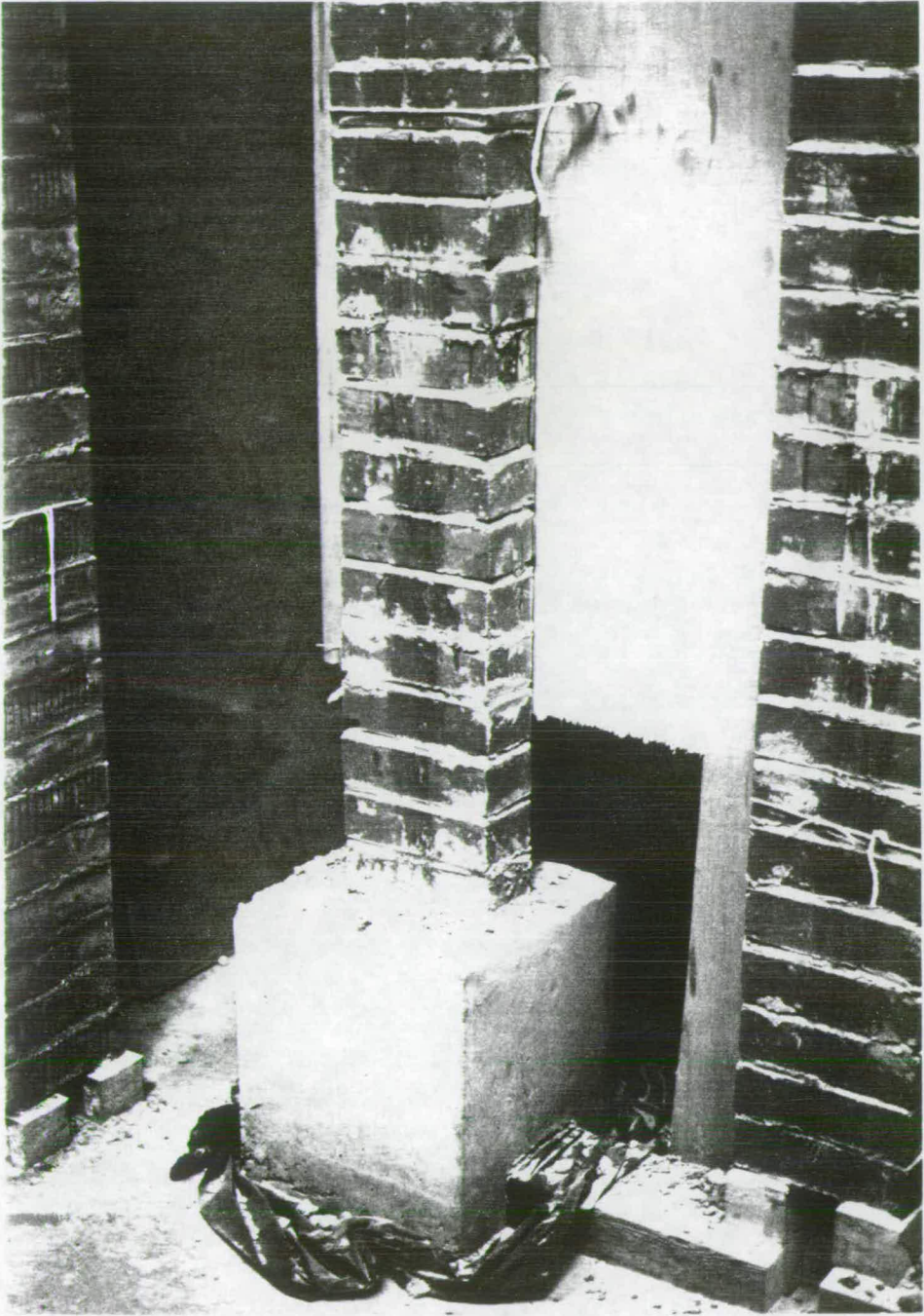
SIDB Y: 118 $\mu$ U  
X: 570Hz

SHORTPASS  $\Delta$ X: 604.6875Hz  
W: 9



CEPSTRUM AND LIFTED SPECTRUM  
COLUMN 4: DAMPED

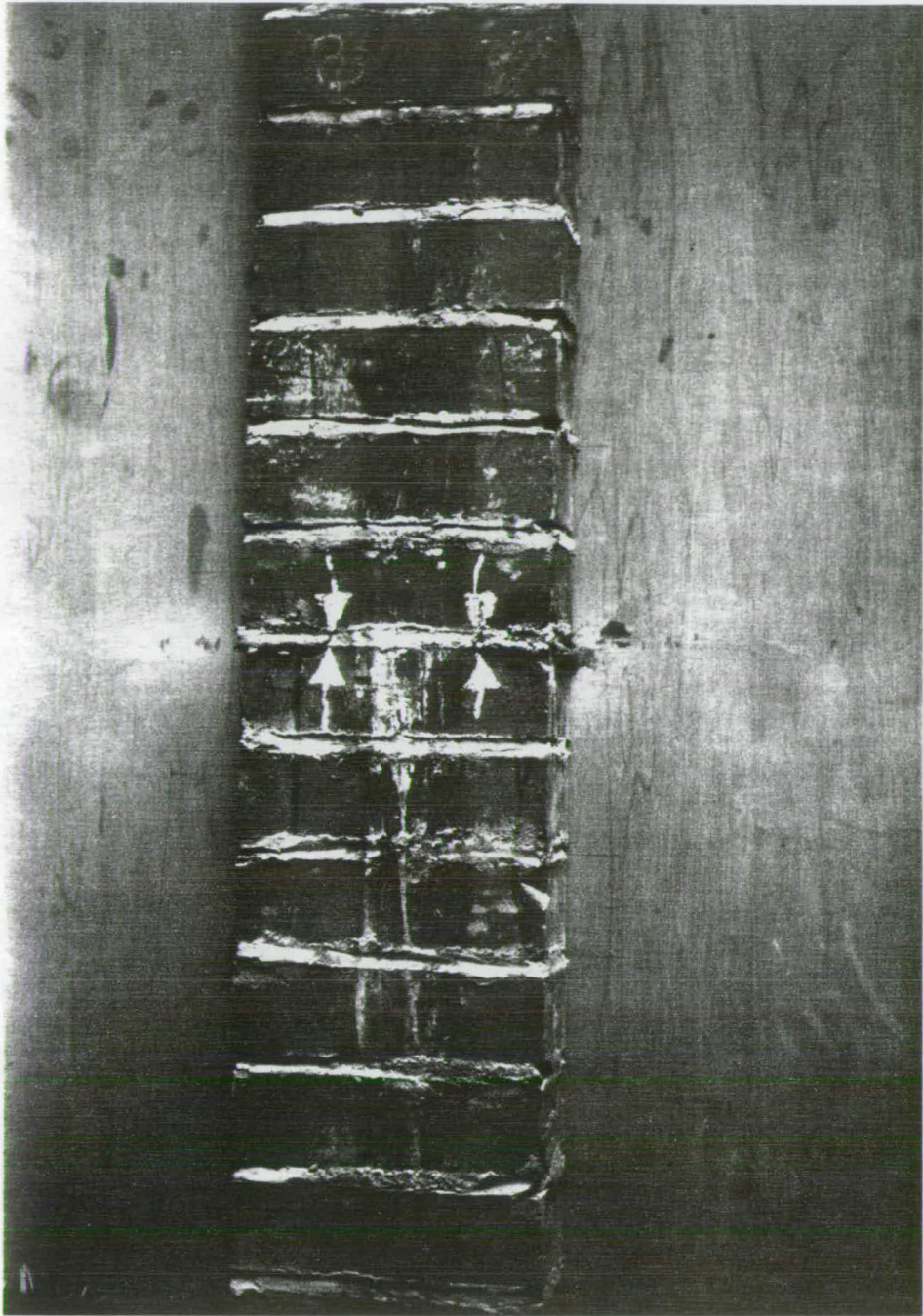
FIGURE 7.46



COLUMN 1: FIXED BASE

PLATE 7.1



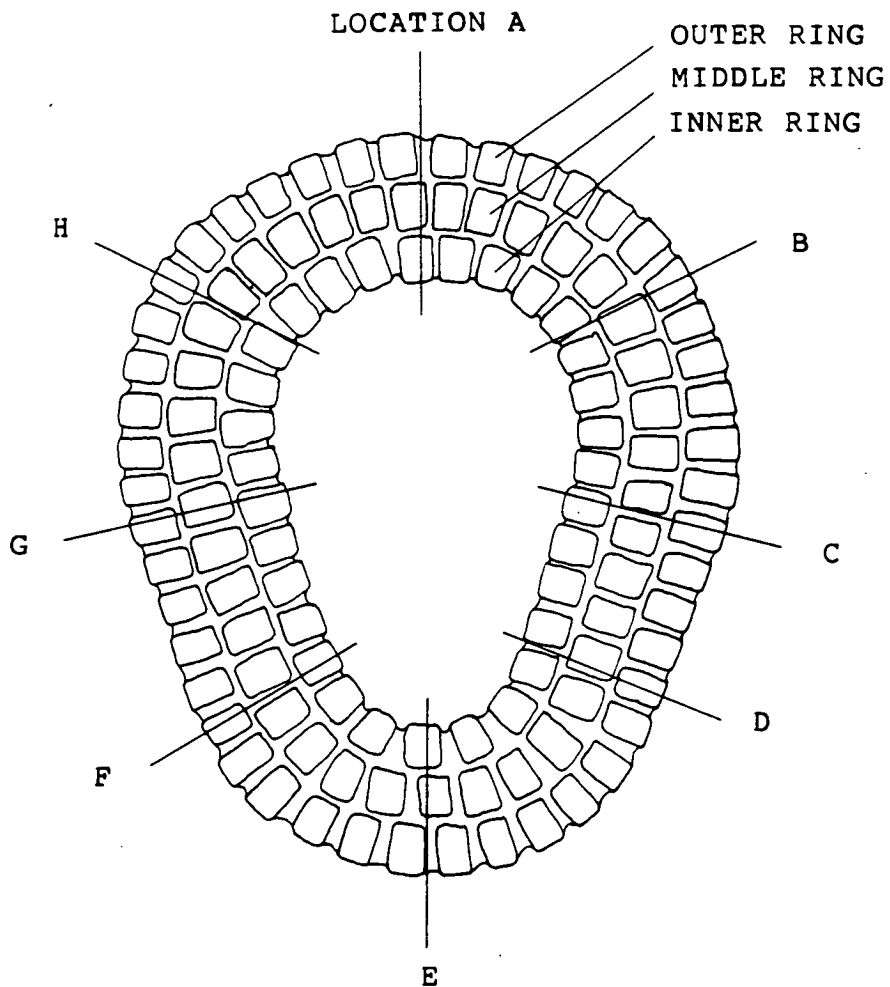


COLUMN 2: DEFECT IN MORTAR

PLATE 7.2

CHAPTER 8

LABORATORY SEWER TESTS



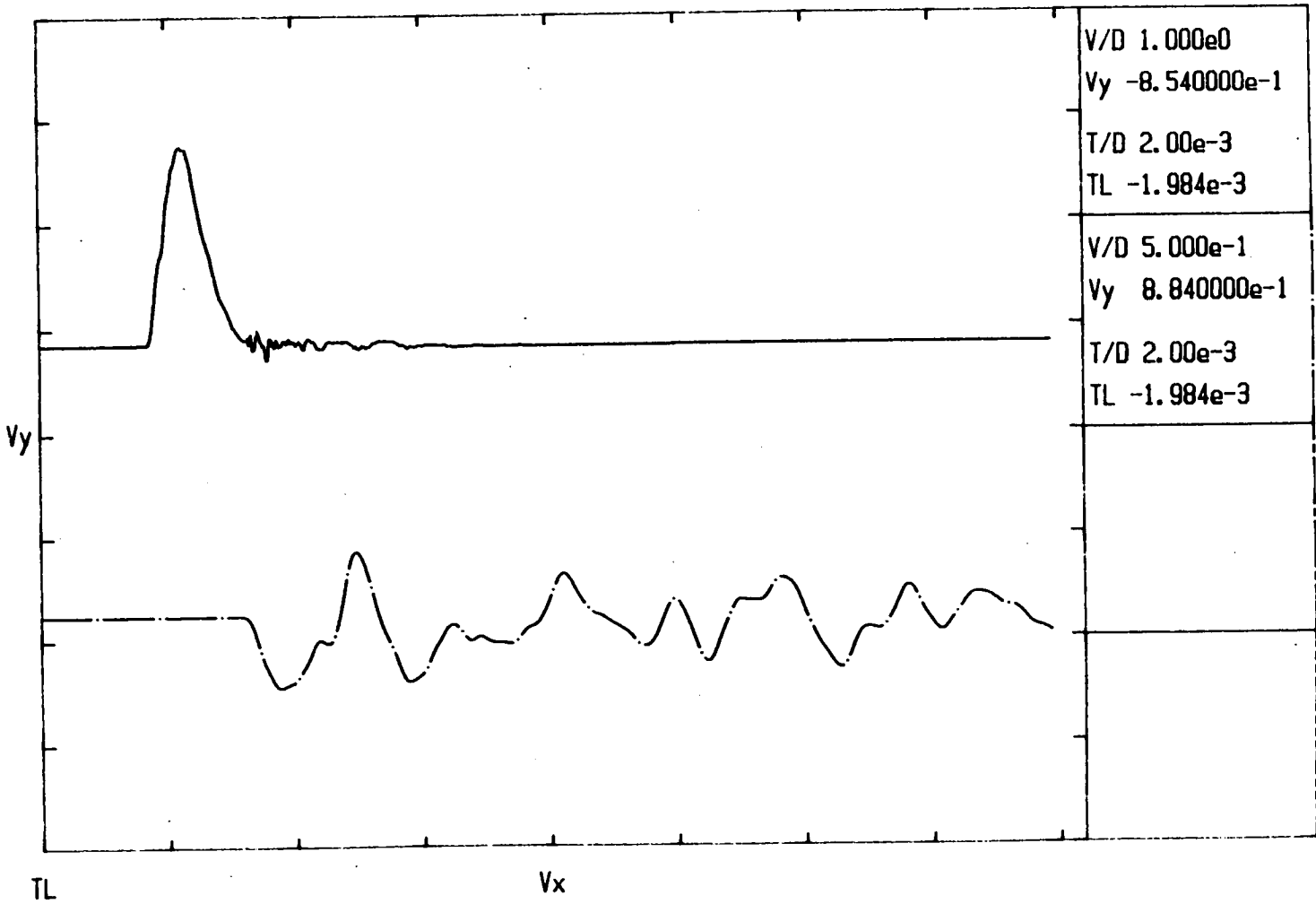
REFERENCE KEY  
SEWER CROSS-SECTION

FIGURE 8.1



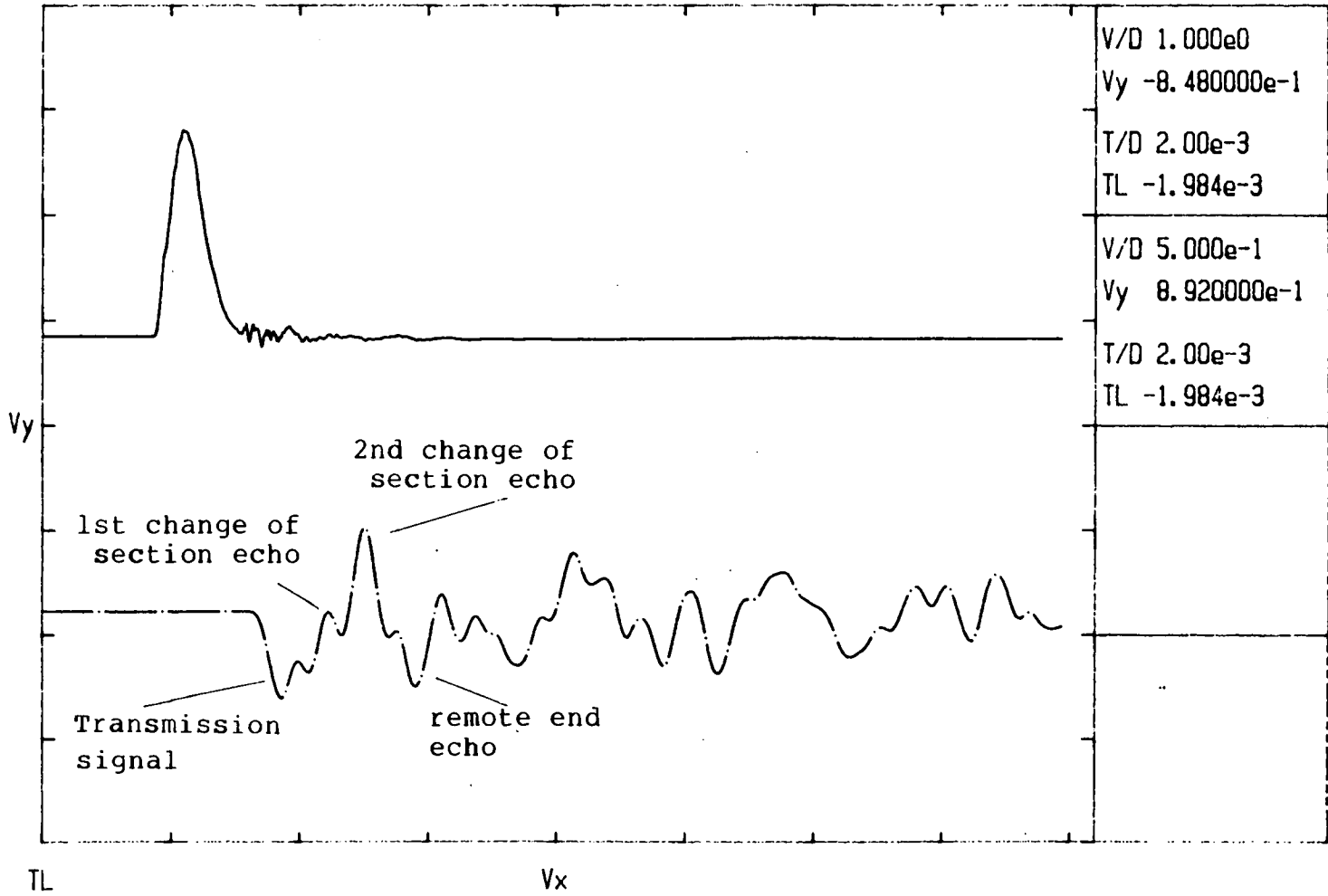
TYPICAL "DELAY" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 LABORATORY SEWER: 3 BRICK END TO 1 BRICK END

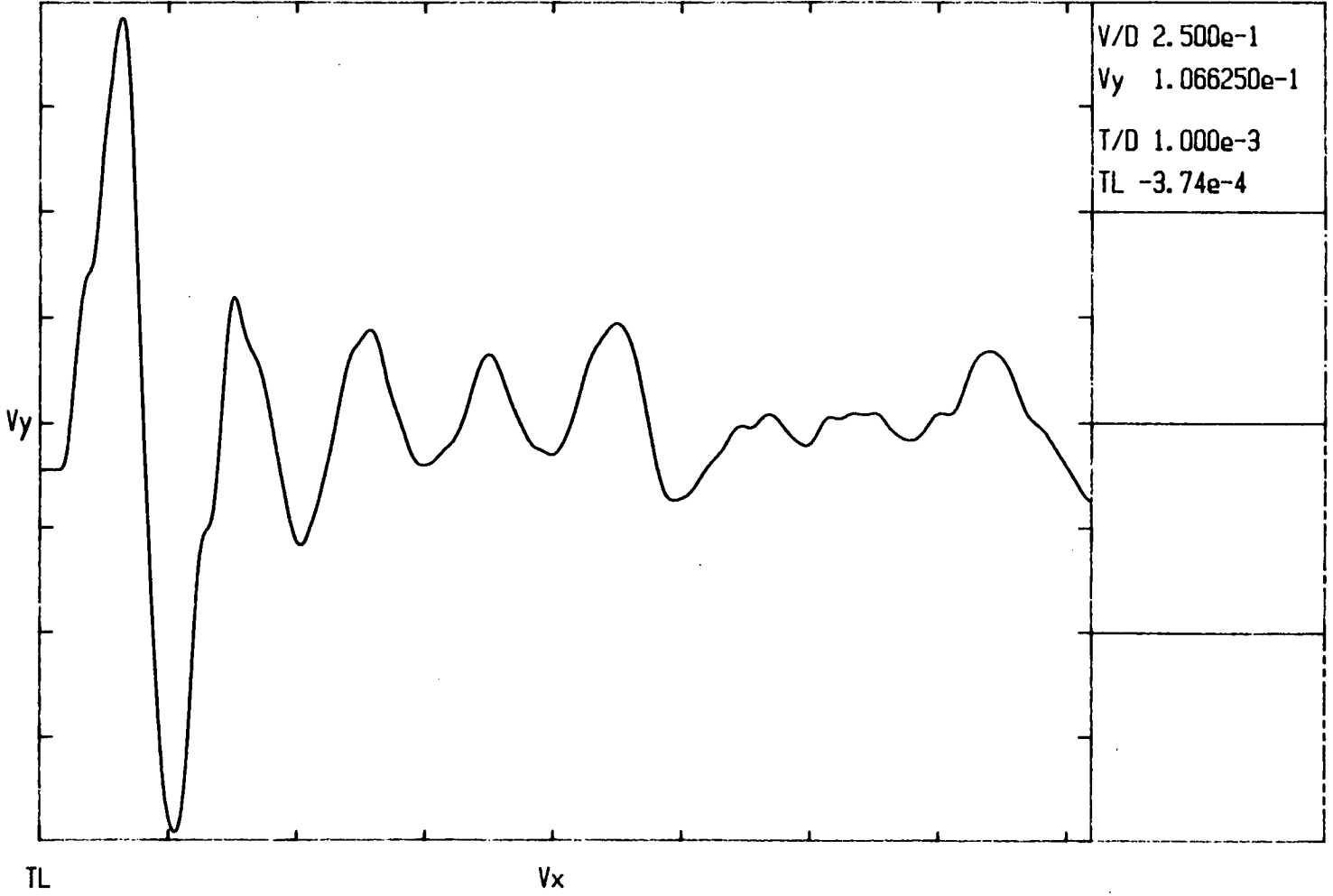
FIGURE 8.2



TYPICAL "DELAY" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 LABORATORY SEWER: 1 BRICK END TO 3 BRICK END

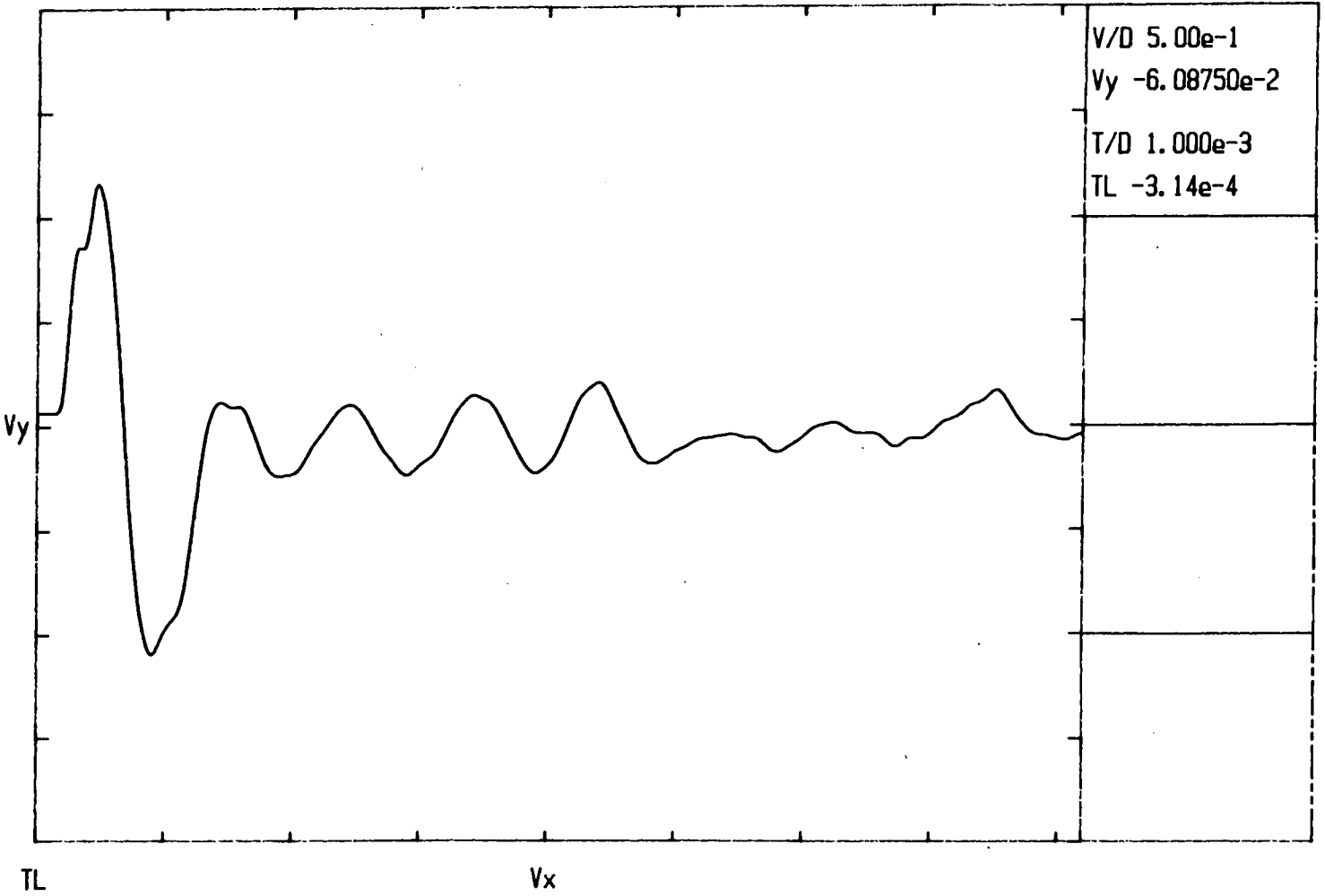
FIGURE 8.3





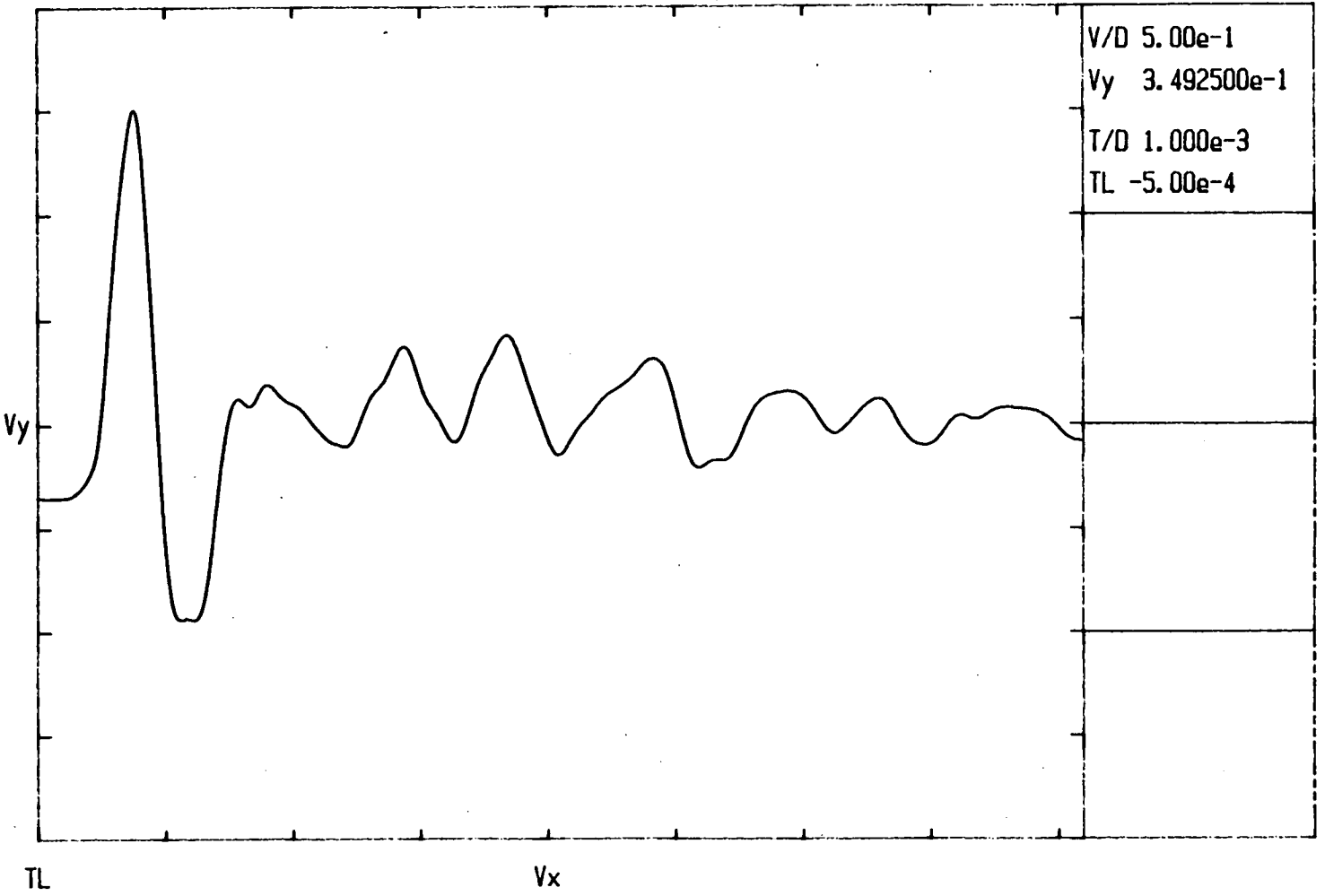
TYPICAL "ECHO" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 LABORATORY SEWER: 3 BRICK END (INNER) TO 1 BRICK END

FIGURE 8.4



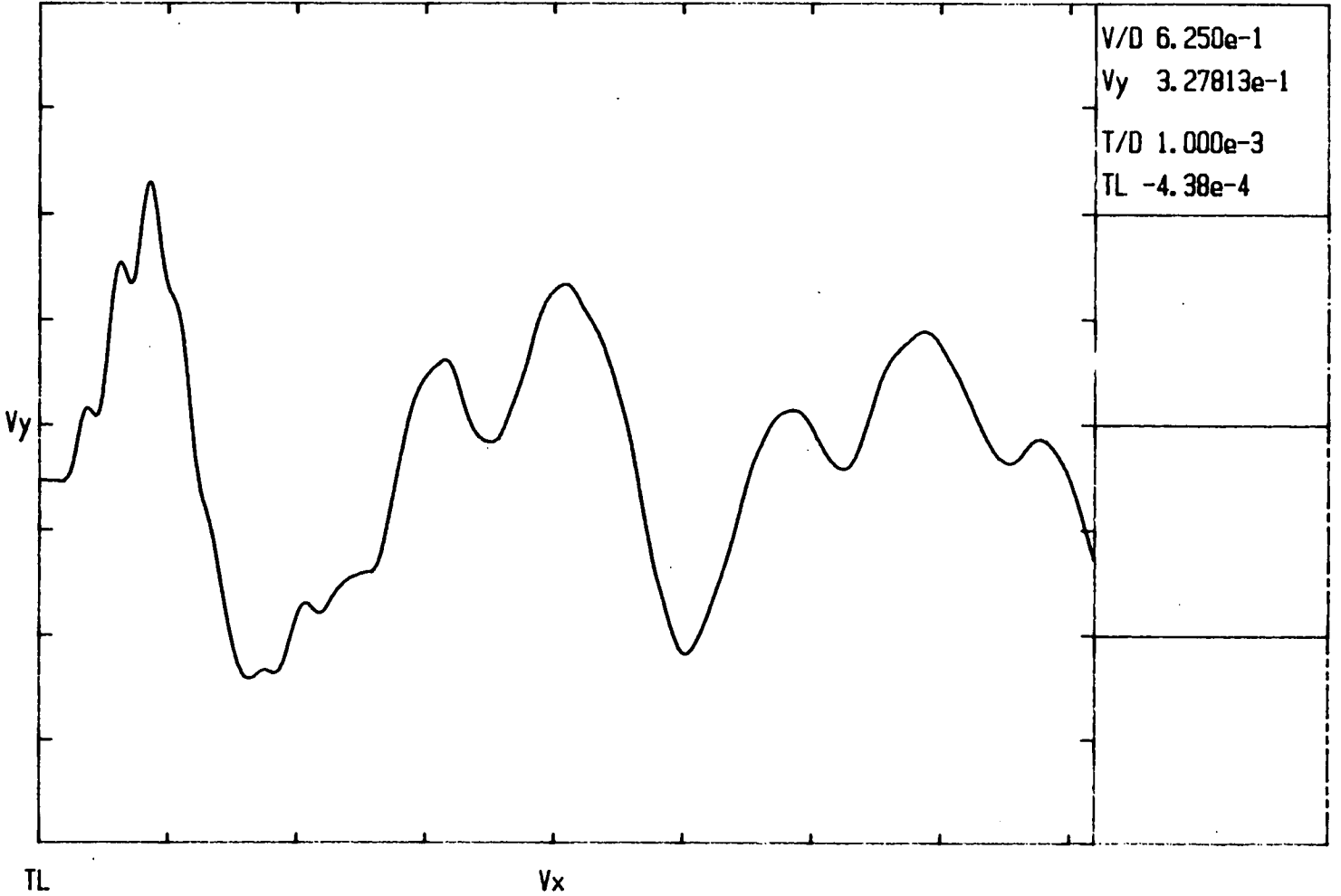
TYPICAL "ECHO" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 LABORATORY SEWER: 3 BRICK END (MIDDLE) TO 1 BRICK END

FIGURE 8.5



TYPICAL "ECHO" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 LABORATORY SEWER: 3 BRICK END (OUTER) TO 1 BRICK END

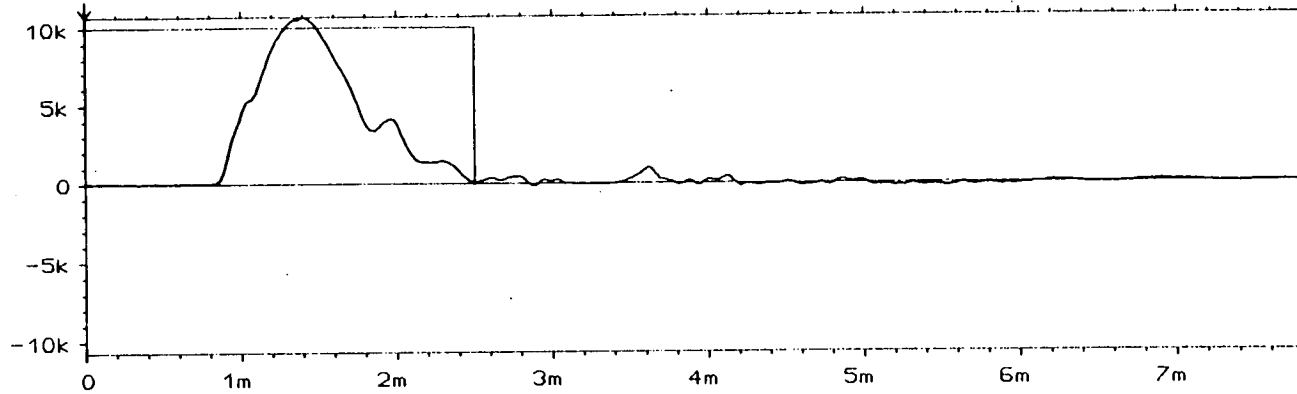
FIGURE 8.6



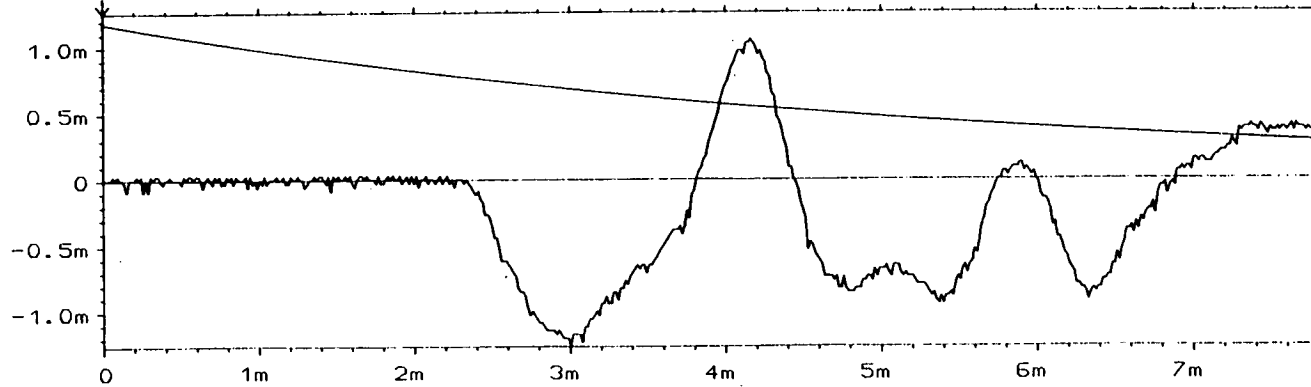
TYPICAL "ECHO" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 LABORATORY SEWER: 1 BRICK END TO 3 BRICK END

FIGURE 8.7

W3 TIME CH.A REAL INPUT MAIN Y: 15.9U  
Y: 10.7kU X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10



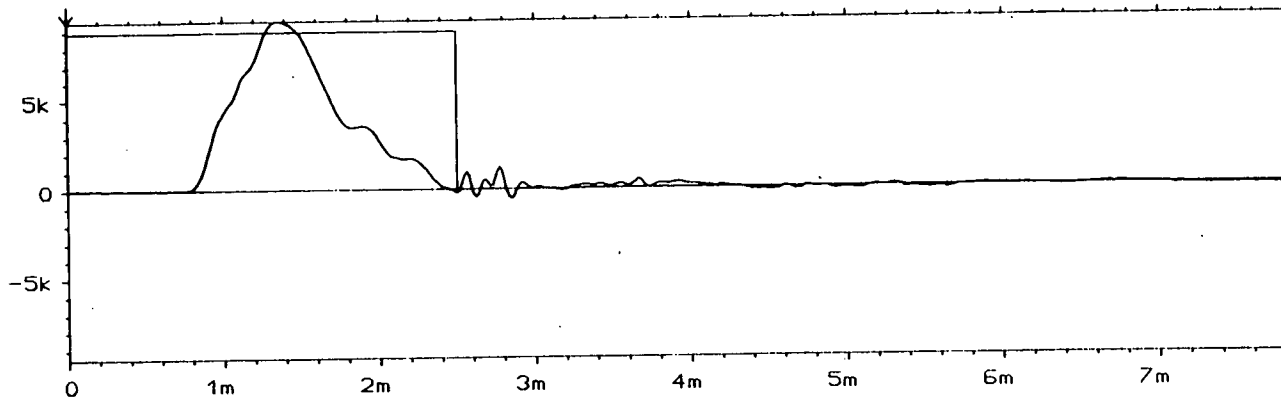
W5 TIME CH.B REAL MAIN Y: 28.0E-12U  
Y: 1.26mU X: 0.000ms  
X: 0.000ms + 7.81ms  
SETUP W10



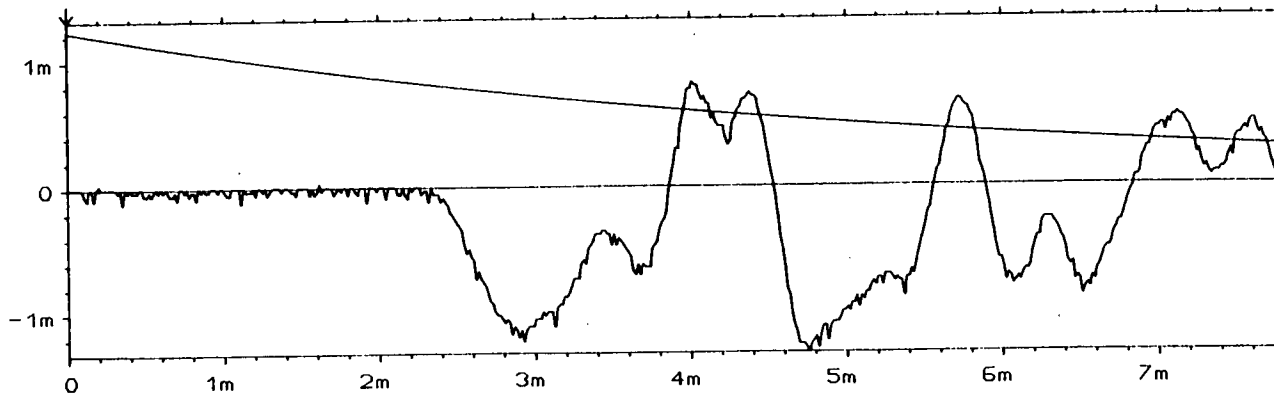
TYPICAL "DELAY" VELOCITY RECORD (SIGNAL ANALYSER)  
LABORATORY SEWER: 3 BRICK END TO 1 BRICK END

FIGURE 8.8

W3 TIME CH.A REAL INPUT MAIN Y: 15.9U  
Y: 9.52kU X: 0.000ms + 7.81ms  
SETUP W10



W5 TIME CH.B REAL MAIN Y: 28.0E-12U  
Y: 1.32mU X: 0.000ms + 7.81ms  
SETUP W10



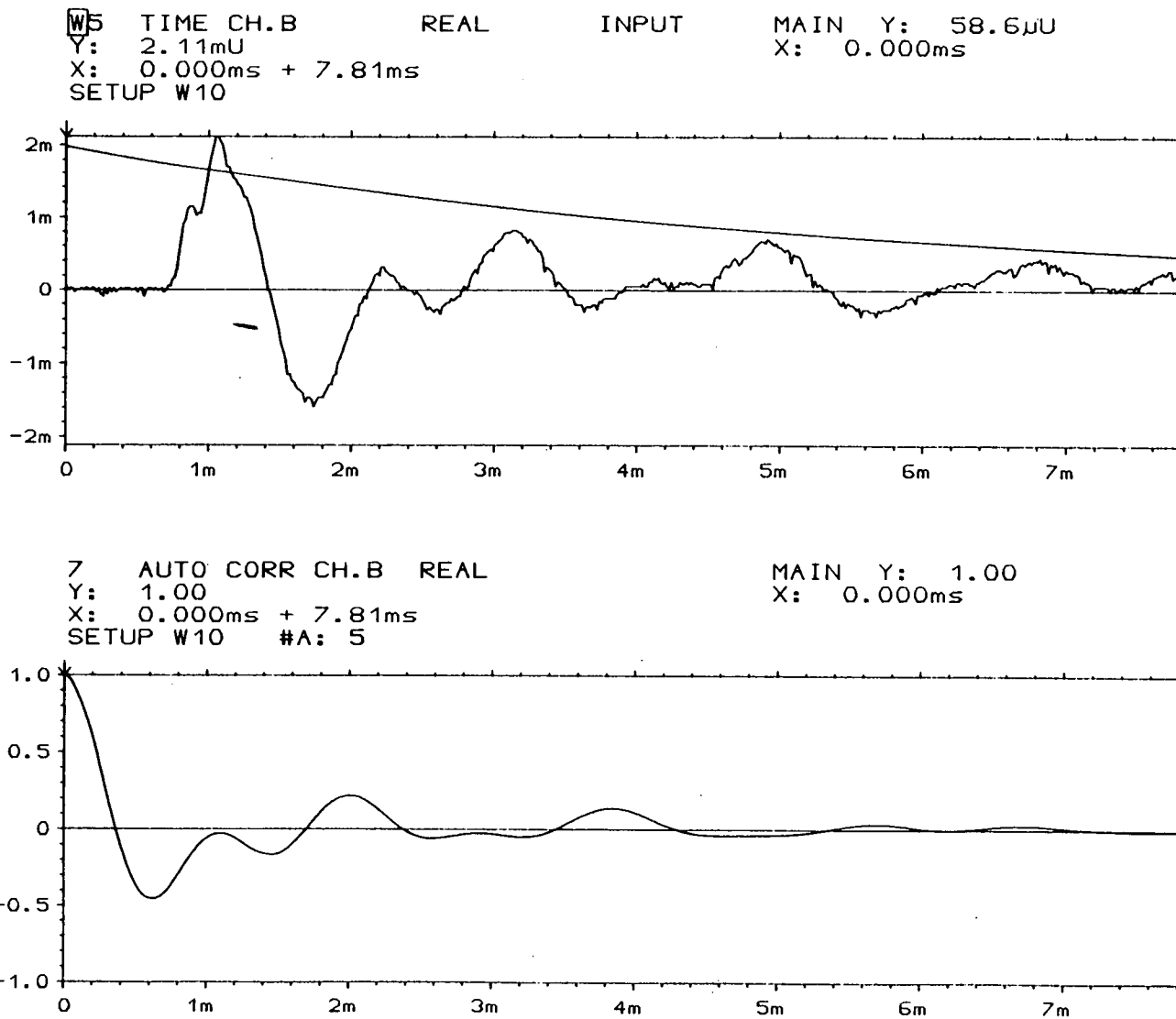
TYPICAL "DELAY" VELOCITY RECORD (SIGNAL ANALYSER)  
LABORATORY SEWER: 1 BRICK END TO 3 BRICK END

FIGURE 8.9



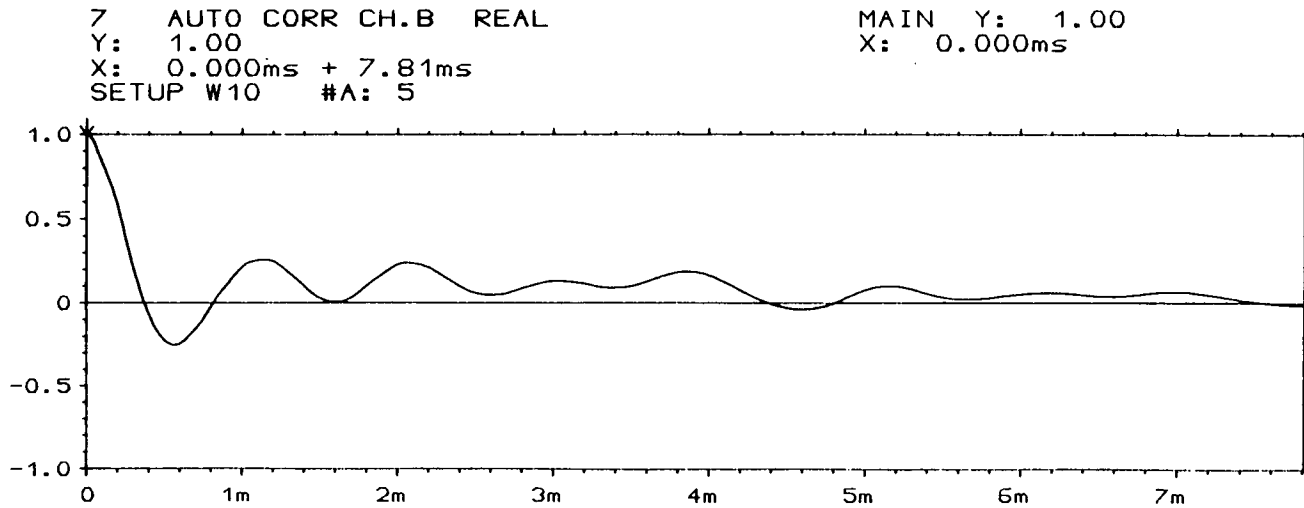
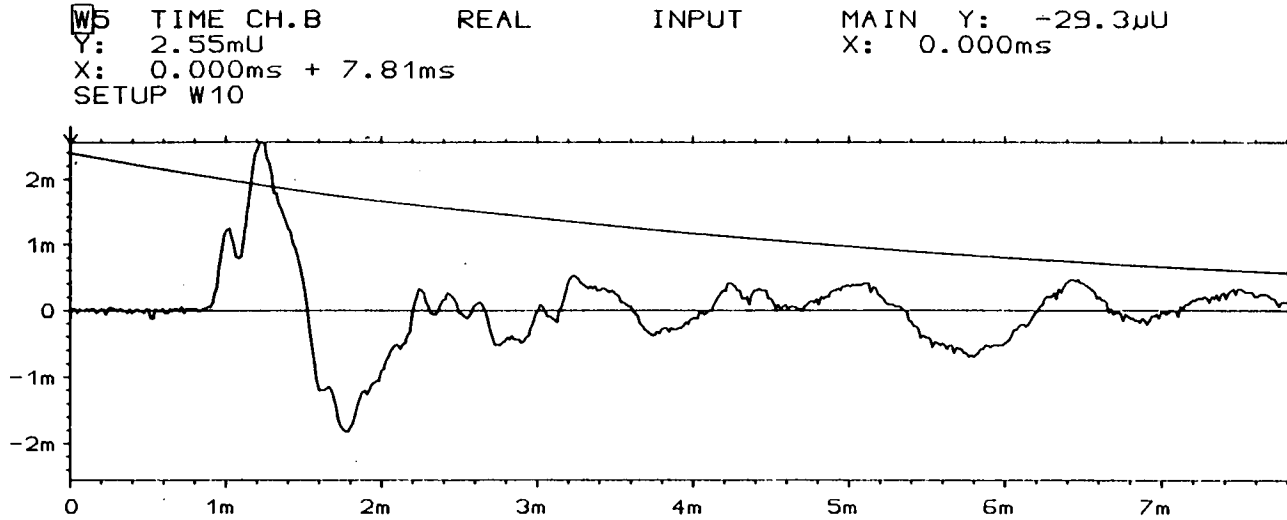
TYPICAL "ECHO" VEL. & AUTO-CORR. RECORD (SIGNAL ANALYSER)  
LABORATORY SEWER: 3 BRICK END (INNER) TO 1 BRICK END

FIGURE 8.10



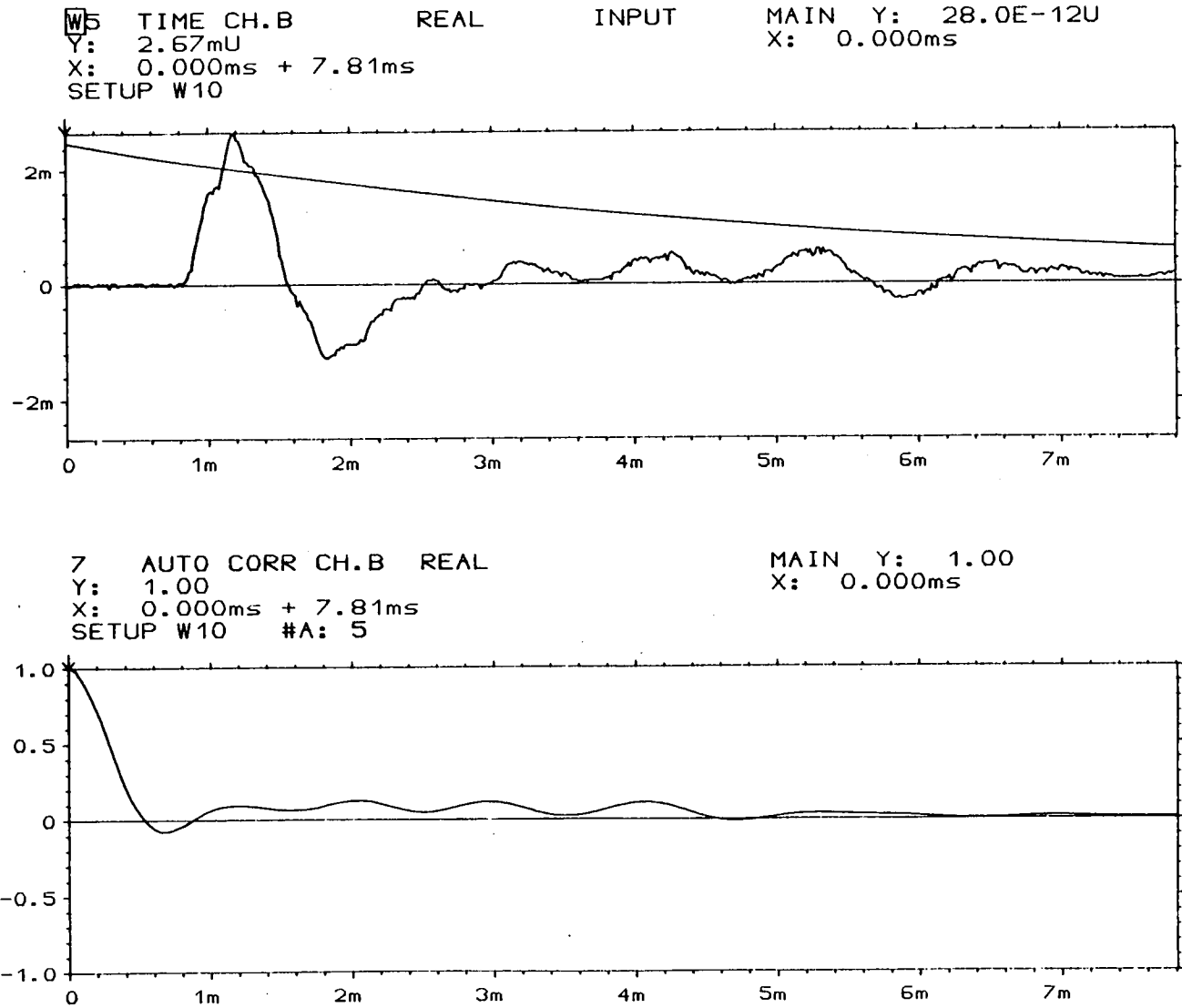
TYPICAL "ECHO" VEL. & AUTO-CORR. RECORD (SIGNAL ANALYSER)  
LABORATORY SEWER: 3 BRICK END (MIDDLE) TO 1 BRICK END

FIGURE 8.11



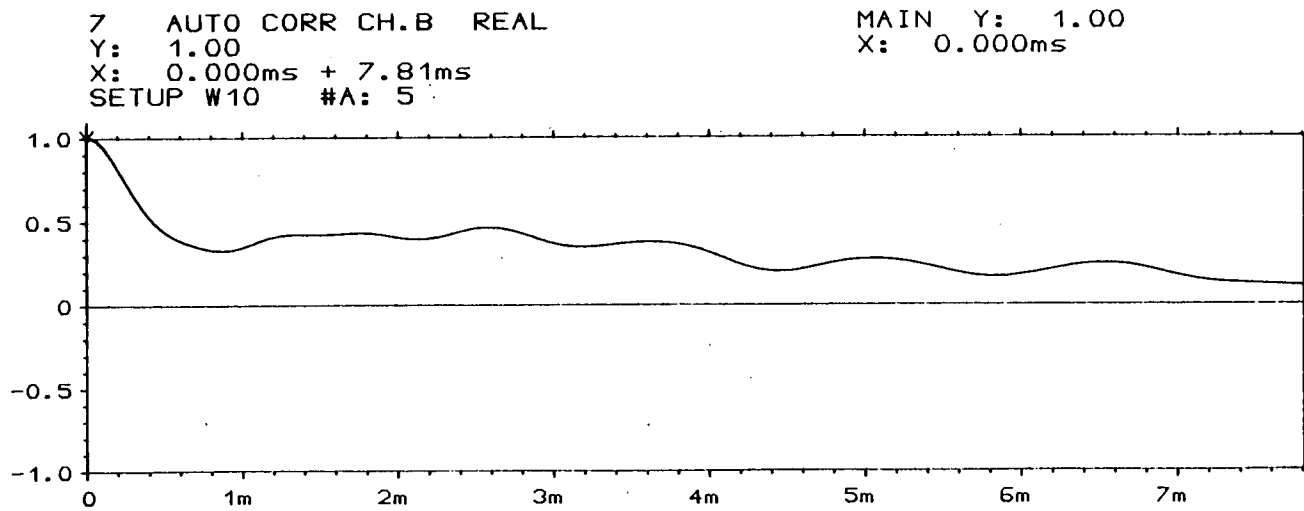
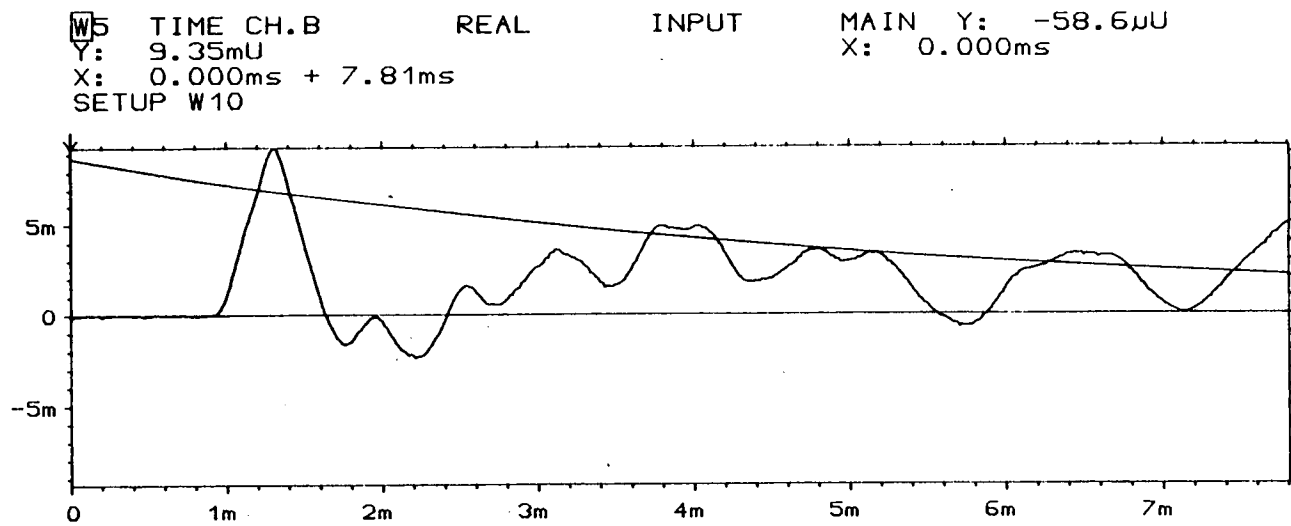
TYPICAL "ECHO" VEL. & AUTO-CORR RECORD (SIGNAL ANALYSER)  
LABORATORY SEWER: 3 BRICK END (OUTER) TO 1 BRICK END

FIGURE 8.12

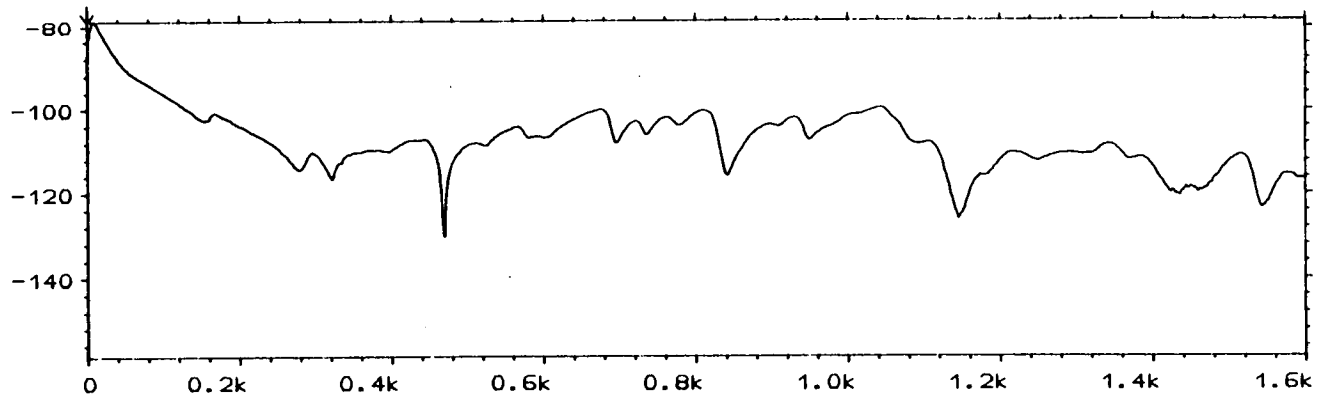


TYPICAL "ECHO" VEL. & AUTO-CORR. RECORD (SIGNAL ANALYSER)  
LABORATORY SEWER: 1 BRICK END TO 3 BRICK END

FIGURE 8.13

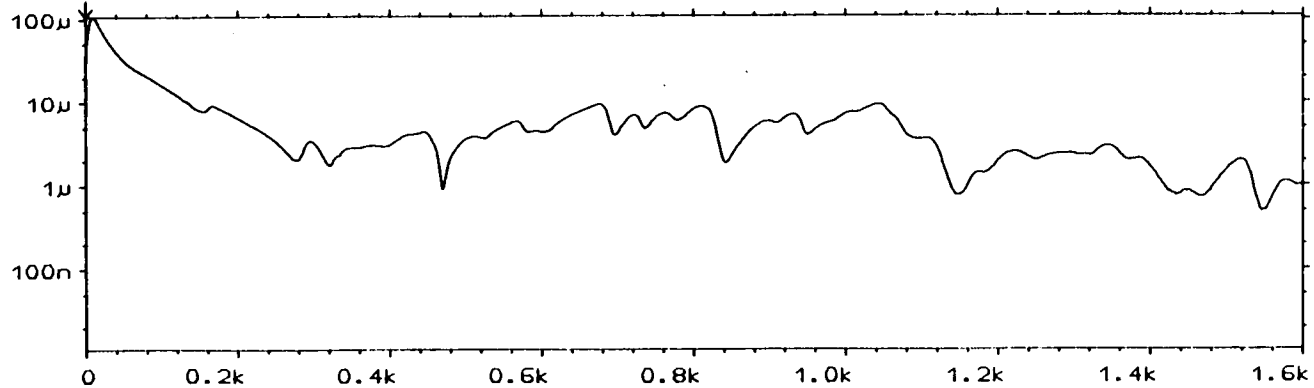


W1 INST SPEC CH.B MAG INPUT MAIN Y: -87.1dB  
Y: -78.5dB /1.00U RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9



W6 AUTO SPEC CH.B  
Y: 109μU RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

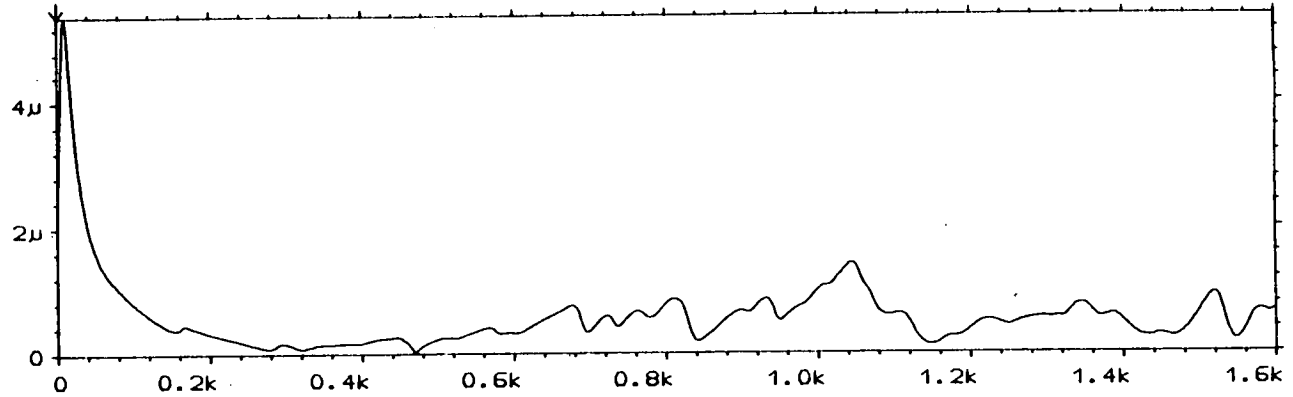
MAIN Y: 32.9μU  
X: 0Hz



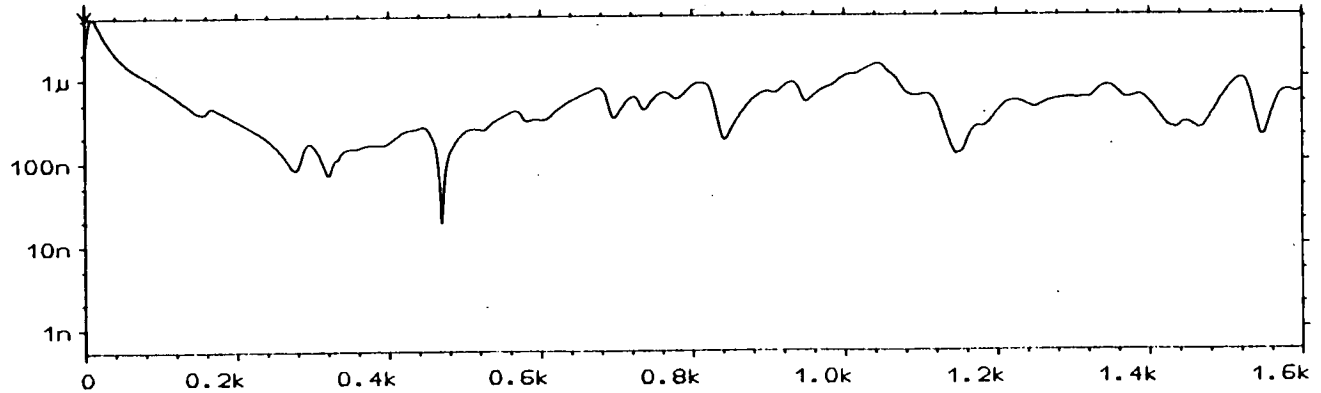
TYPICAL INSTANTANEOUS AND AUTOSPECTRA  
LABORATORY SEWER: 3 BRICK END

FIGURE 8.14

W8 FREQ RESP H1 MAG INPUT MAIN Y: 2.19 $\mu$   
 Y: 5.40 $\mu$  LIN X: OHZ  
 X: OHZ + 1.6kHz LIN  
 SETUP W9 #A: 5



W8 FREQ RESP H1 MAG MAIN Y: 2.19 $\mu$   
 Y: 5.40 $\mu$  80dB X: OHZ  
 X: OHZ + 1.6kHz LIN  
 SETUP W9 #A: 5

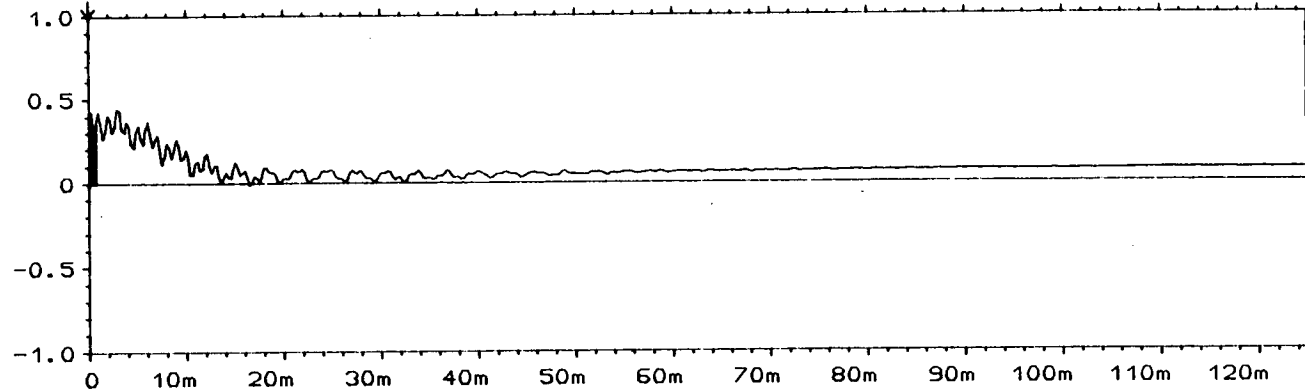


TYPICAL FREQUENCY RESPONSE FUNCTION  
 LABORATORY SEWER: 3 BRICK END

FIGURE 8.15

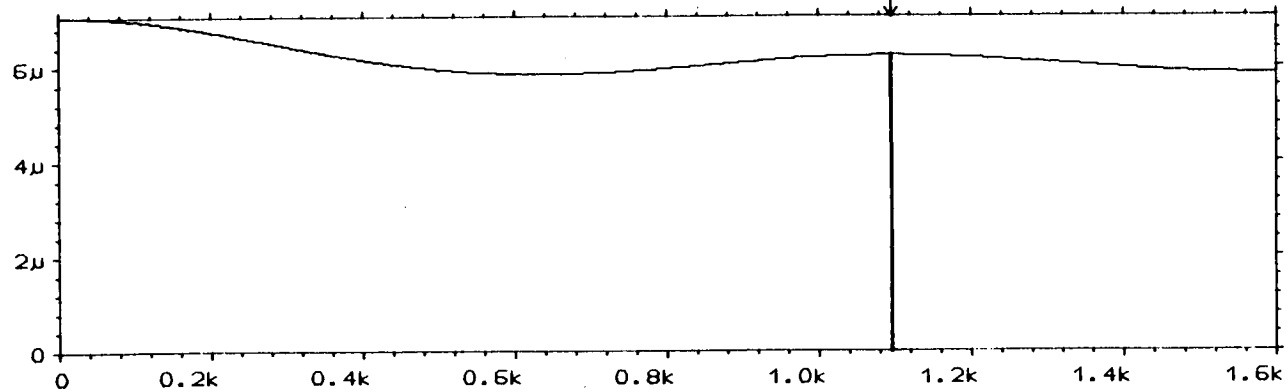
W2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: -0.01dB  
X: 0.00ms  
SHORTPASS  
W: 5 [ ]



W4 LIFT SPEC CH.B  
Y: 7.07μU RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 6.25μU  
X: 1096Hz  
SHORTPASS ΔX: 0.0000Hz  
W: 5

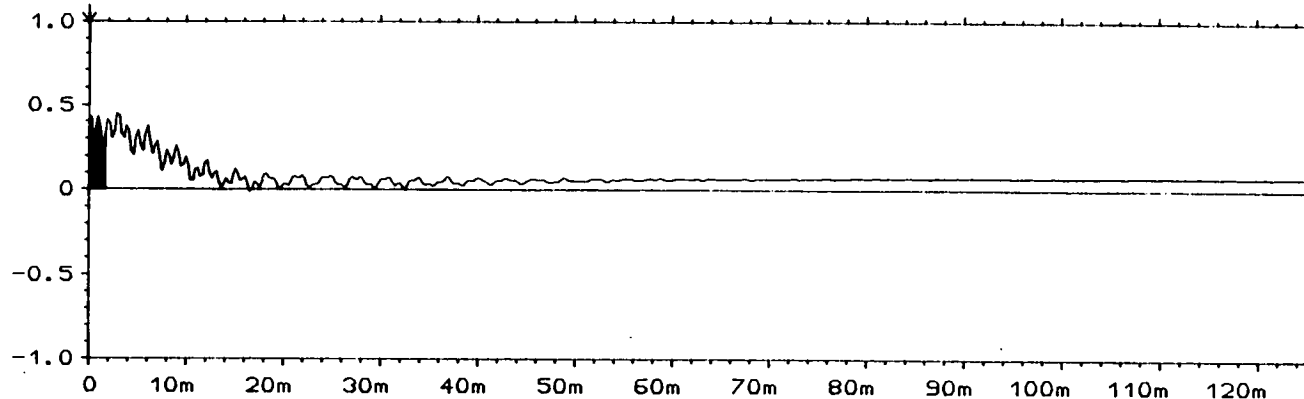


USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FIRST CHANGE OF CROSS-SECTION  
LABORATORY SEWER: 3 BRICK END

FIGURE 8.16

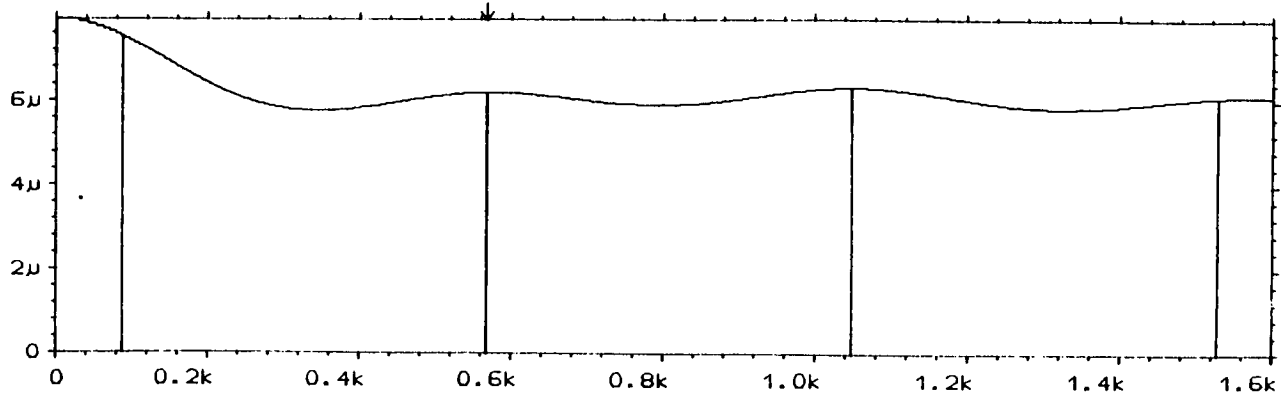
W2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: -0.01dB  
X: 0.00ms  
SHORTPASS  
W: 9 [ ]



W4 LIFT SPEC CH.B  
Y: 7.93μU RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 6.19μU  
X: 568Hz  
SHORTPASS ΔX: 480.3125Hz  
W: 9



USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE SECOND CHANGE OF CROSS-SECTION  
LABORATORY SEWER: 3 BRICK END

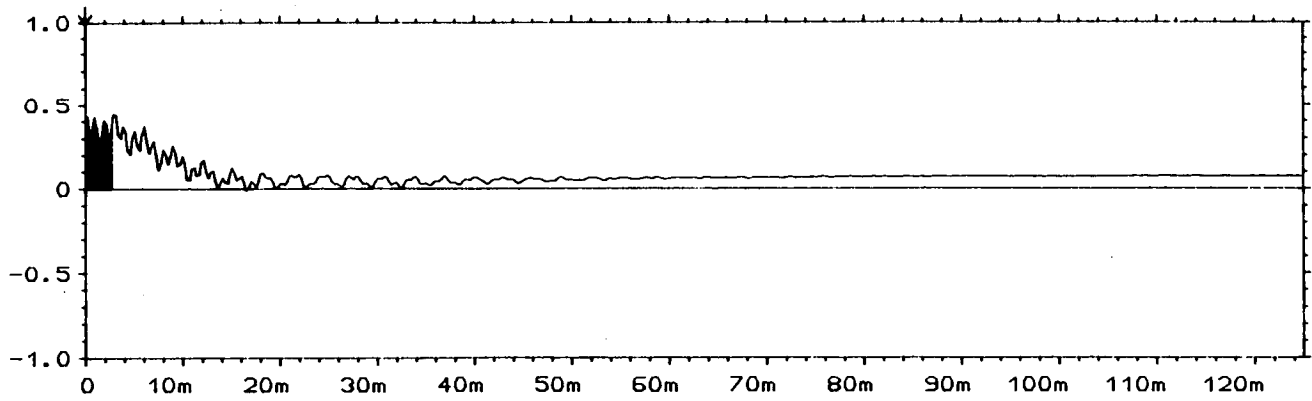
FIGURE 8.17



W2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: -0.01dB  
X: 0.00ms

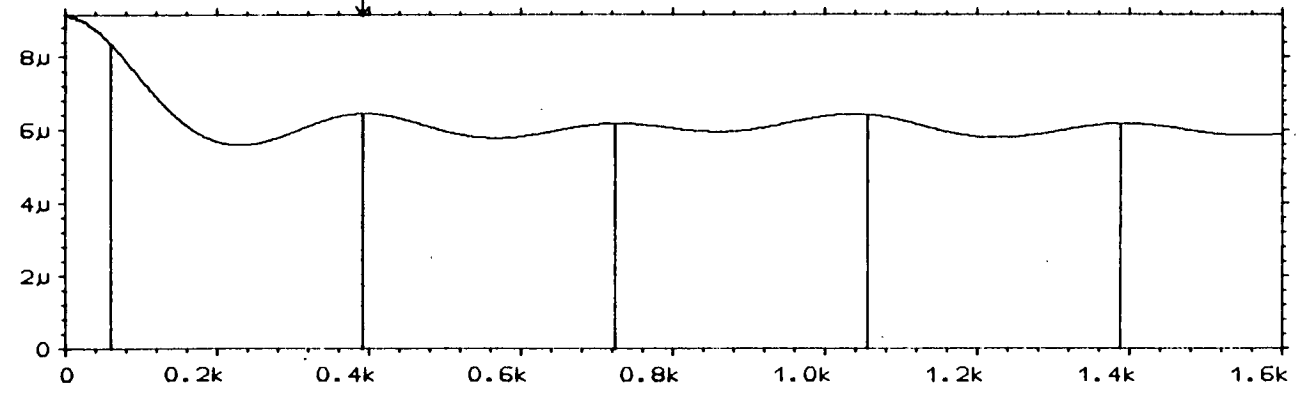
SHORTPASS  
W: 13 [ ]



W4 LIFT SPEC CH.B  
Y: 9.16μU RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 6.45μU  
X: 392Hz  
ΔX: 331.8750Hz

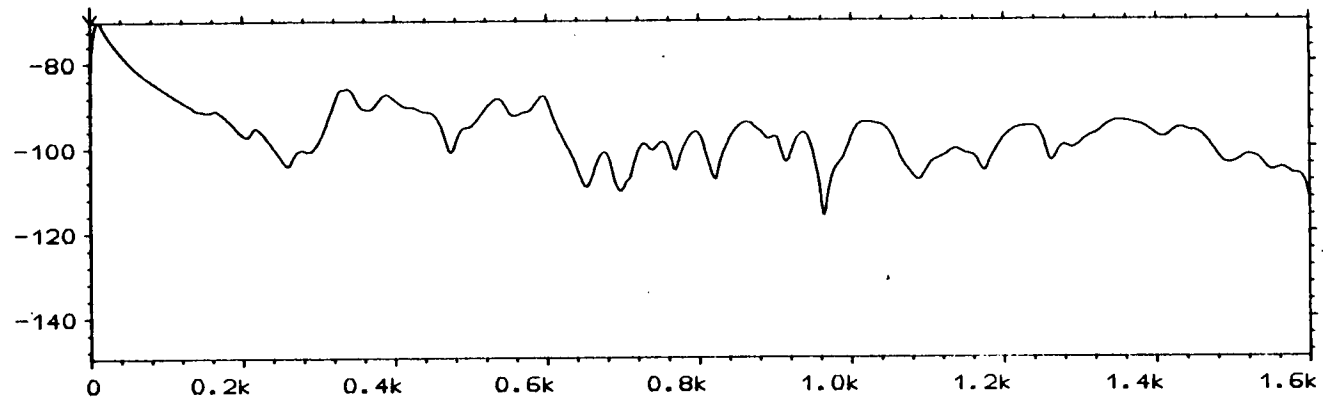
SHORTPASS  
W: 13



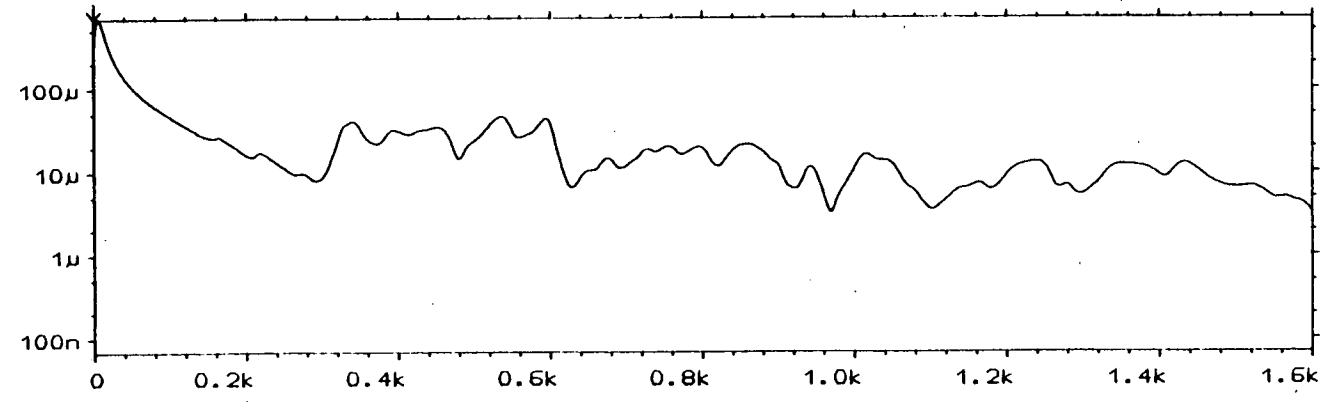
USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FAR END OF THE SEWER  
LABORATORY SEWER: 3 BRICK END

FIGURE 8.18

W1 INST SPEC CH.B MAG INPUT MAIN Y: -81.1dB  
Y: -69.6dB /1.00U RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9



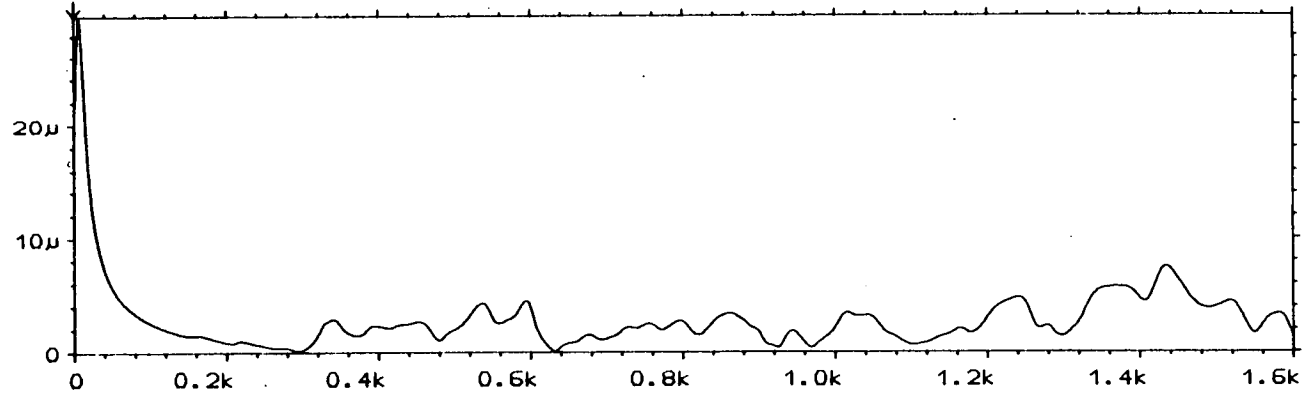
W6 AUTO SPEC CH.B MAIN Y: 331μU  
Y: 687μU RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5



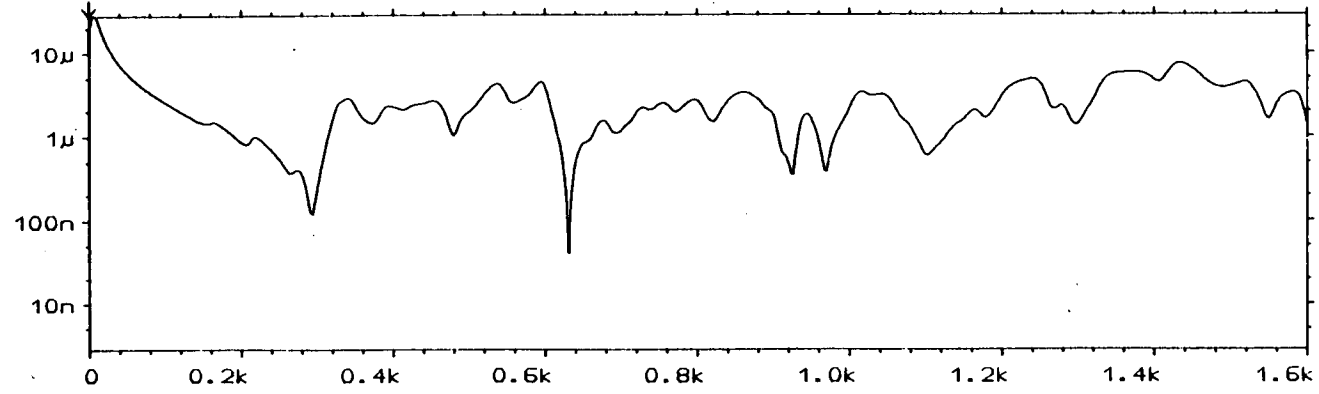
TYPICAL INSTANTANEOUS AND AUTOSPECTRA  
LABORATORY SEWER: 1 BRICK END

FIGURE 8.19

WB FREQ RESP H1 MAG INPUT MAIN Y: 19.4 $\mu$   
Y: 29.7 $\mu$  LIN X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5



W8 FREQ RESP H1 MAG MAIN Y: 19.4 $\mu$   
Y: 28.6 $\mu$  80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

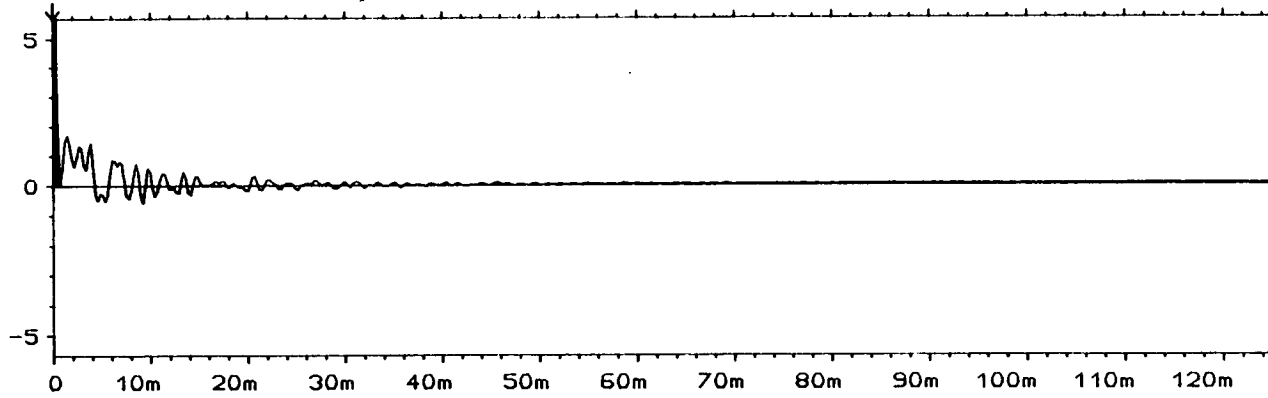


TYPICAL FREQUENCY RESPONSE FUNCTION  
LABORATORY SEWER: 1 BRICK END

FIGURE 8.20

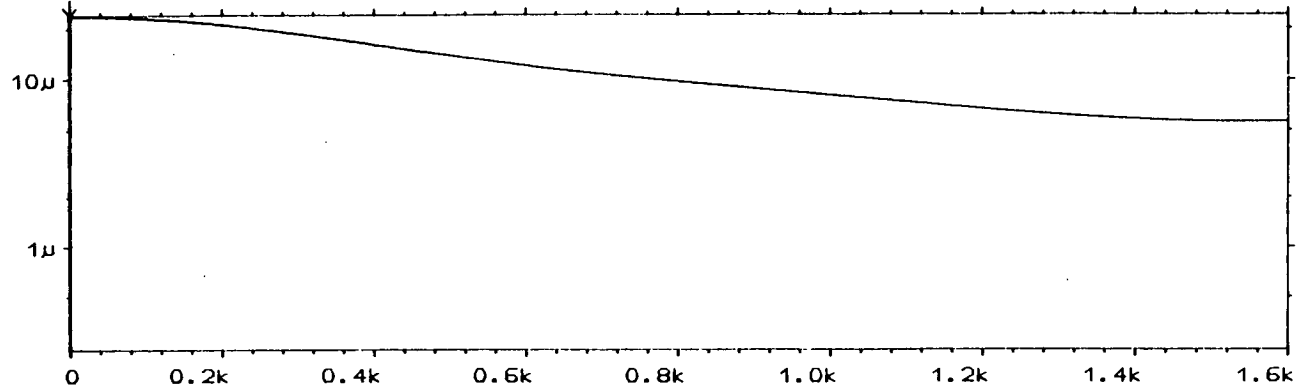
W2 CEPSTRUM CH.B REAL  
Y: 5.68dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: -0.01dB  
X: 0.00ms  
SHORTPASS  
W: 5 [ ]



W4 LIFT SPEC CH.B  
Y: 24.2 $\mu$ U RMS 40dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 33.6 $\mu$ U  
X: 0Hz  
SHORTPASS  $\Delta$ X: 0.0000Hz  
W: 5

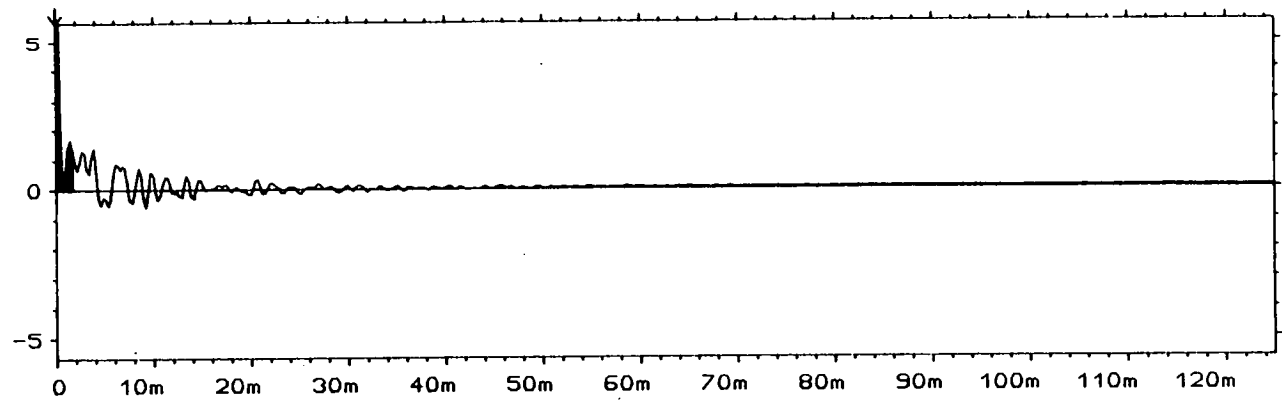


USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FIRST CHANGE OF CROSS-SECTION  
LABORATORY SEWER: 1 BRICK END

FIGURE 8.21

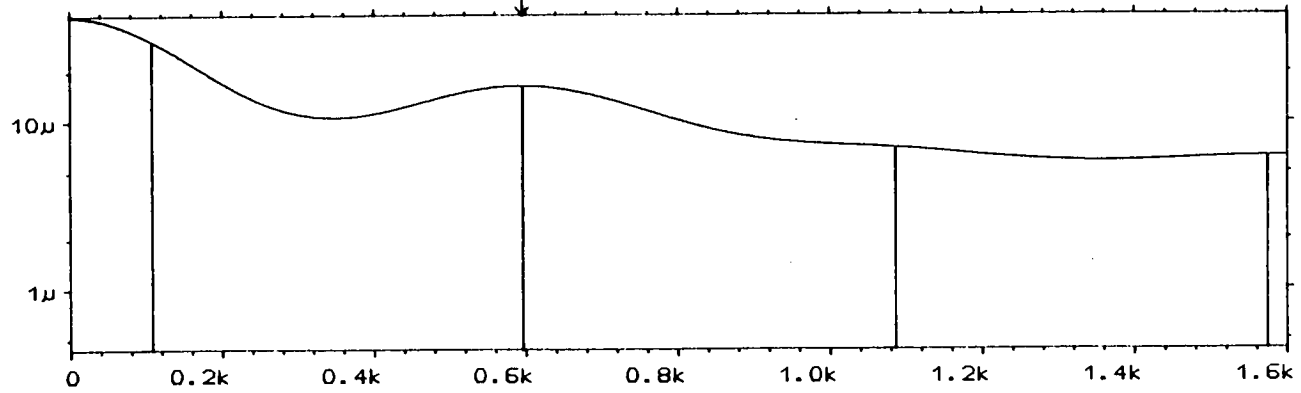
W2 CEPSTRUM CH.B REAL  
 Y: 5.68dB  
 X: 0.00ms + 125ms  
 SETUP W9 #A: 5

MAIN Y: -0.01dB  
 X: 0.00ms  
 SHORTPASS  
 W: 9 [ ]



W4 LIFT SPEC CH.B  
 Y: 43.7μU RMS 40dB  
 X: 0Hz + 1.6kHz LIN  
 SETUP W9 #A: 5

SIDB Y: 16.6μU  
 X: 596Hz  
 SHORTPASS ΔX: 489.0000Hz  
 W: 9

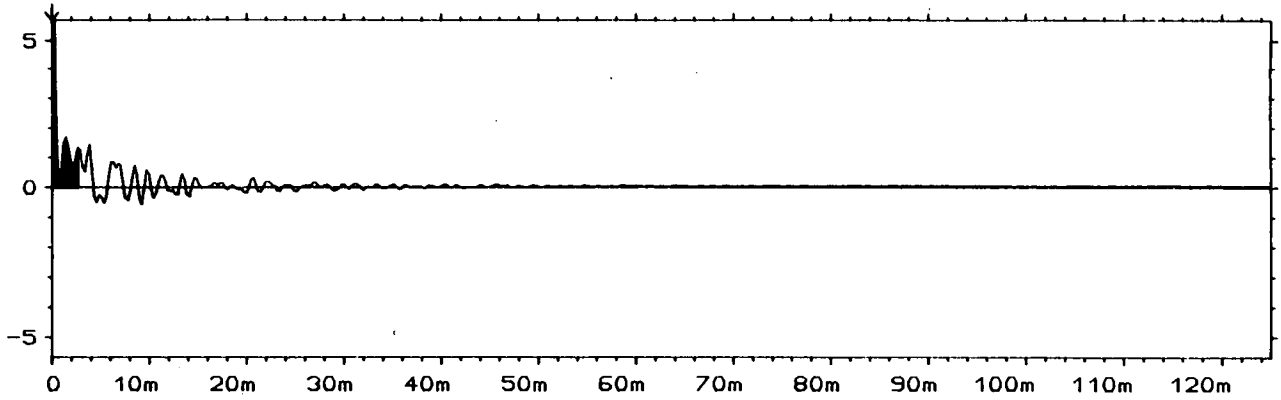


USING CEPSTRUM AND LIFTED SPECTRUM  
 TO LOCATE SECOND CHANGE OF CROSS-SECTION  
 LABORATORY SEWER: 1 BRICK END

FIGURE 8.22

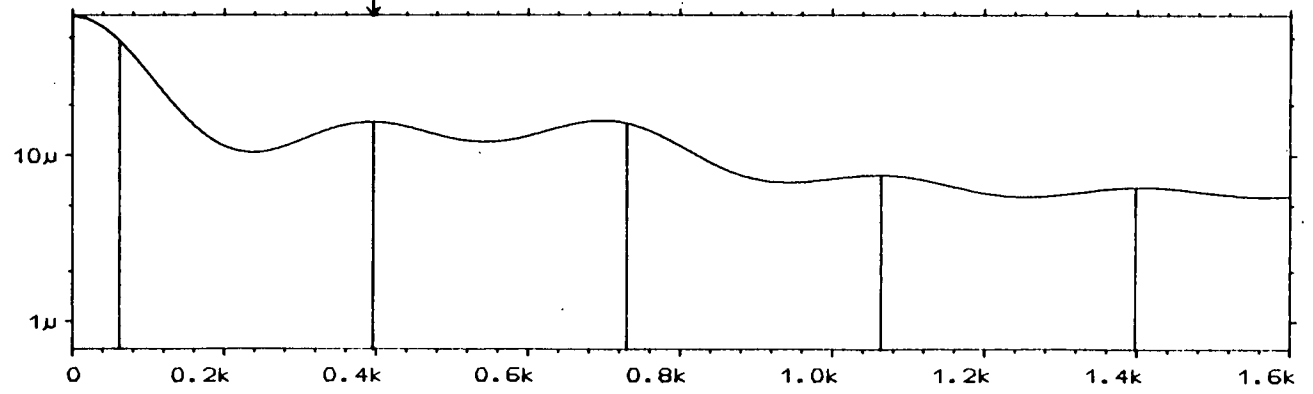
W2 CEPSTRUM CH.B REAL  
Y: 5.68dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: -0.01dB  
X: 0.00ms  
SHORTPASS  
W: 13 [ ]



W4 LIFT SPEC CH.B  
Y: 68.3μU RMS 40dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

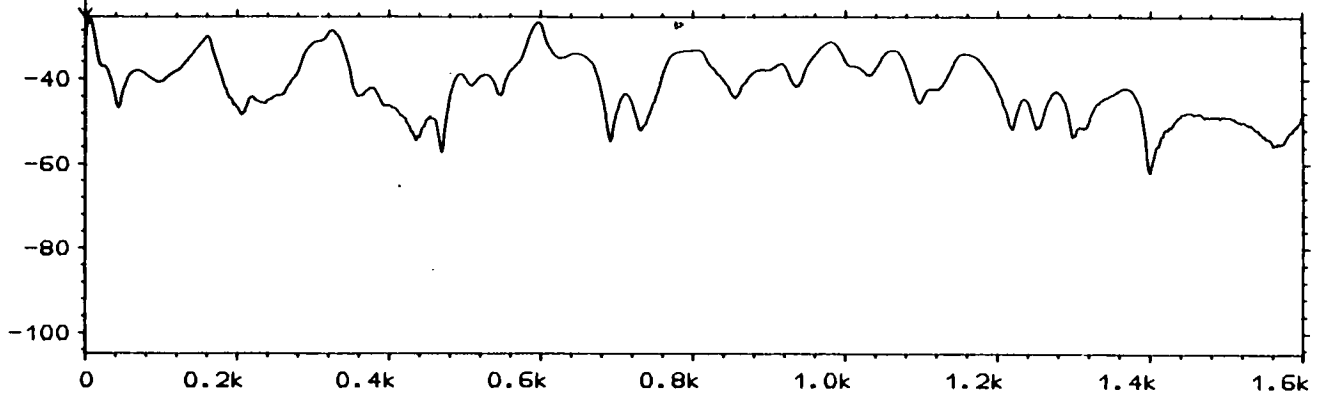
SIDB Y: 15.9μU  
X: 396Hz  
SHORTPASS ΔX: 333.8125Hz  
W: 13



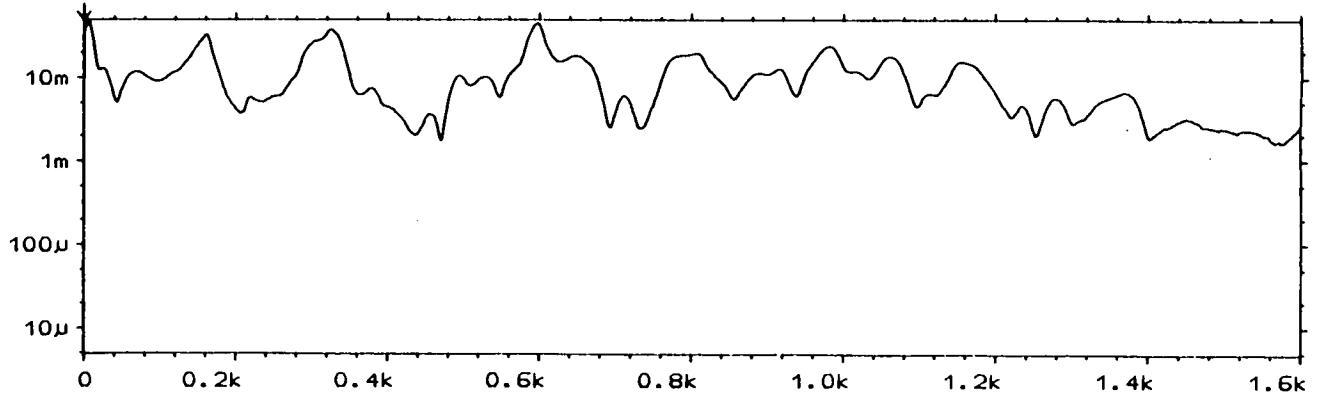
USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FAR END OF THE SEWER  
LABORATORY SEWER: 1 BRICK END

FIGURE 8.23

W1 INST SPEC CH.B MAG INPUT MAIN Y: -28.9dB  
Y: -24.9dB /1.00U RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9



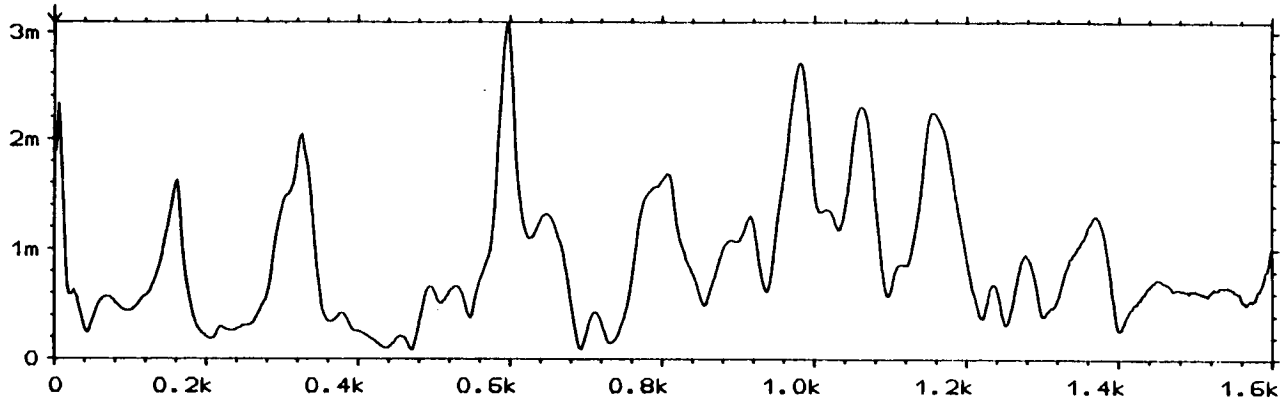
W6 AUTO SPEC CH.B  
Y: 49.0mU RMS 80dB MAIN Y: 31.9mU  
X: 0Hz + 1.6kHz LIN X: 0Hz  
SETUP W9 #A: 5



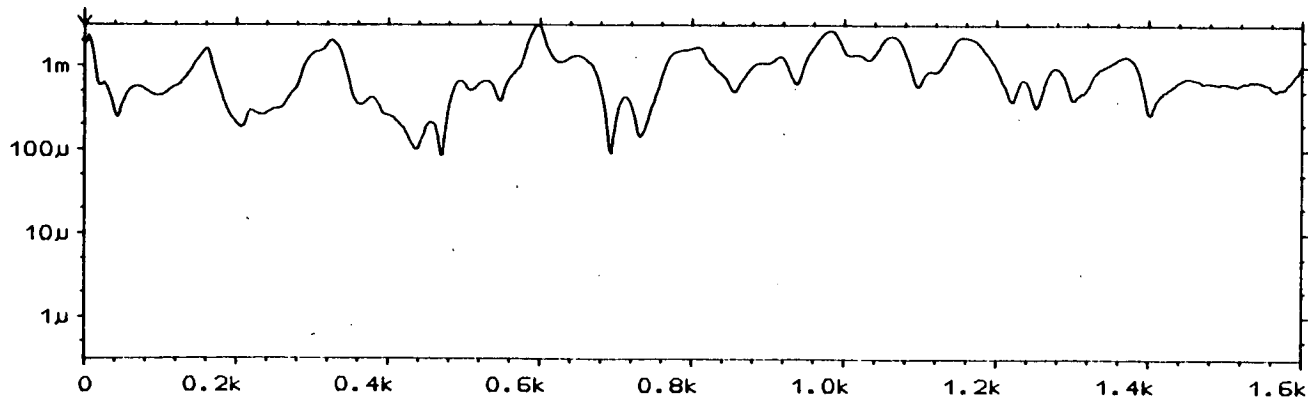
TYPICAL INSTANTANEOUS AND AUTOSPECTRA  
LABORATORY SEWER: HAMMER 3 BRICK END, ACCEL 1 BRICK END

FIGURE 8.24

**WB** FREQ RESP H1 MAG INPUT MAIN Y: 2.16m  
 Y: 3.09m LIN X: OHZ  
 X: OHZ + 1.6kHz LIN X: OHZ  
 SETUP W9 #A: 5



**WB** FREQ RESP H1 MAG MAIN Y: 2.16m  
 Y: 3.09m 80dB X: OHZ  
 X: OHZ + 1.6kHz LIN X: OHZ  
 SETUP W9 #A: 5



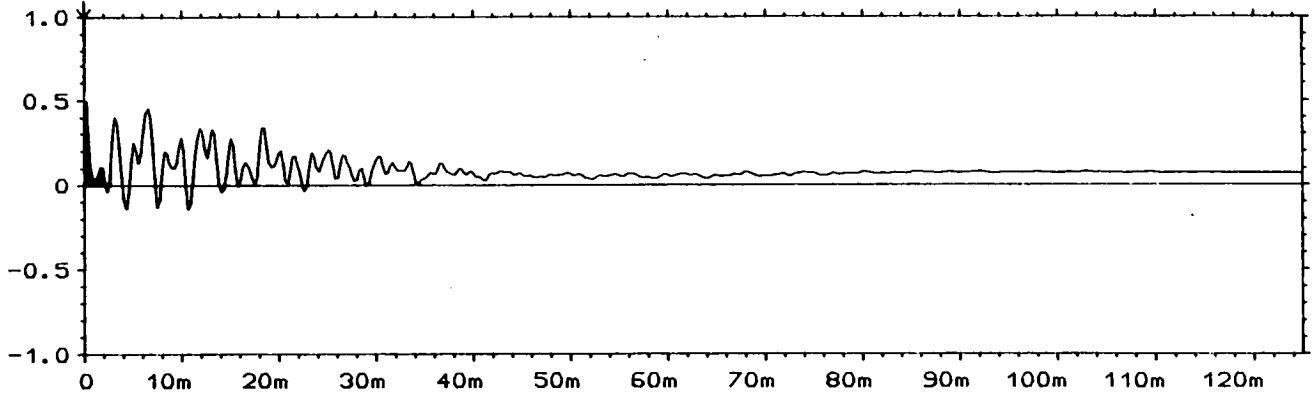
TYPICAL FREQUENCY RESPONSE FUNCTION  
 LABORATORY SEWER: HAMMER 3 BRICK END, ACCEL 1 BRICK END

FIGURE 8.25



USING CEPSTRUM AND FILTERED SPECTRUM  
 TO LOCATE FAR END OF THE SEWER  
 LABORATORY SEWER: HAMMER 3 BRICK END, ACCEL 1 BRICK END

2 CEPSTRUM CH.B REAL MAIN Y: 0.00dB  
 Y: 1.00dB X: 0.00ms  
 X: 0.00ms + 125ms SHORTPASS W: 13  
 SETUP W9 #A: 5 ELEM #: 0



W4 LIFT SPEC CH.B SIDB Y: 21.0mU  
 Y: 21.0mU RMS LIN X: 292Hz  
 X: 0Hz + 1.6kHz LIN SHORTPASS ΔX: 363.0000Hz  
 SETUP W9 #A: 5 W: 13 ELEM #: 146

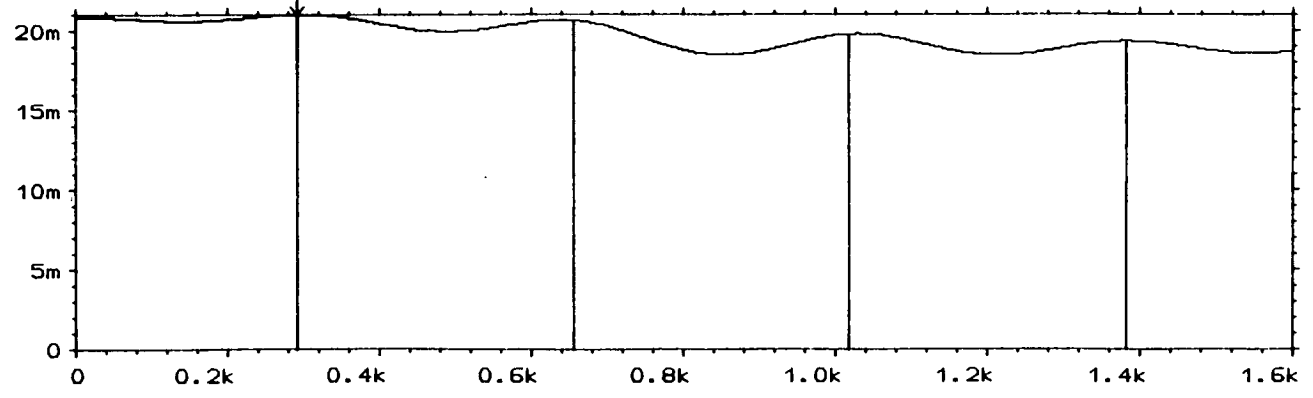
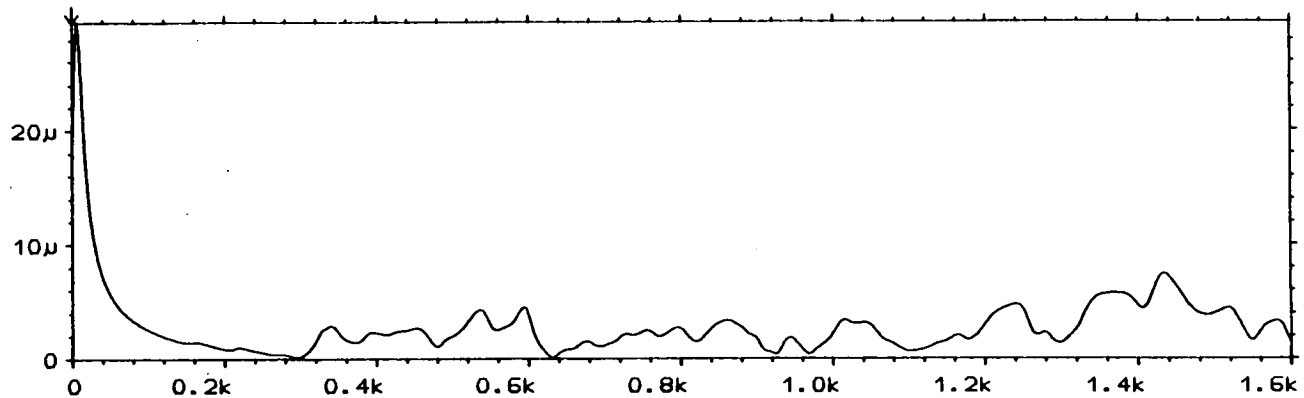
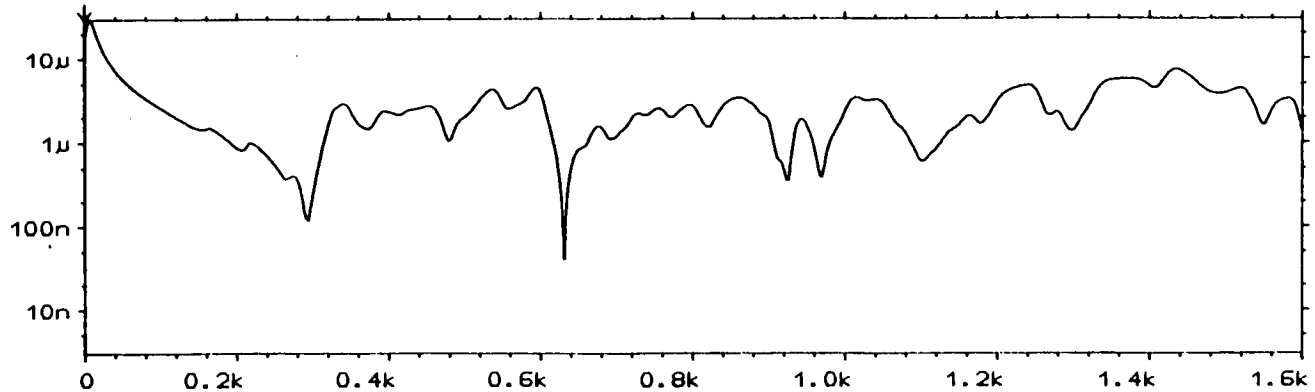


FIGURE 8.26

W8 FREQ RESP H1 MAG INPUT MAIN Y: 19.4μ  
 Y: 29.7μ LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN X: 0Hz  
 SETUP W9 #A: 5



W8 FREQ RESP H1 MAG MAIN Y: 19.4μ  
 Y: 29.7μ 80dB X: 0Hz  
 X: 0Hz + 1.6kHz LIN X: 0Hz  
 SETUP W9 #A: 5

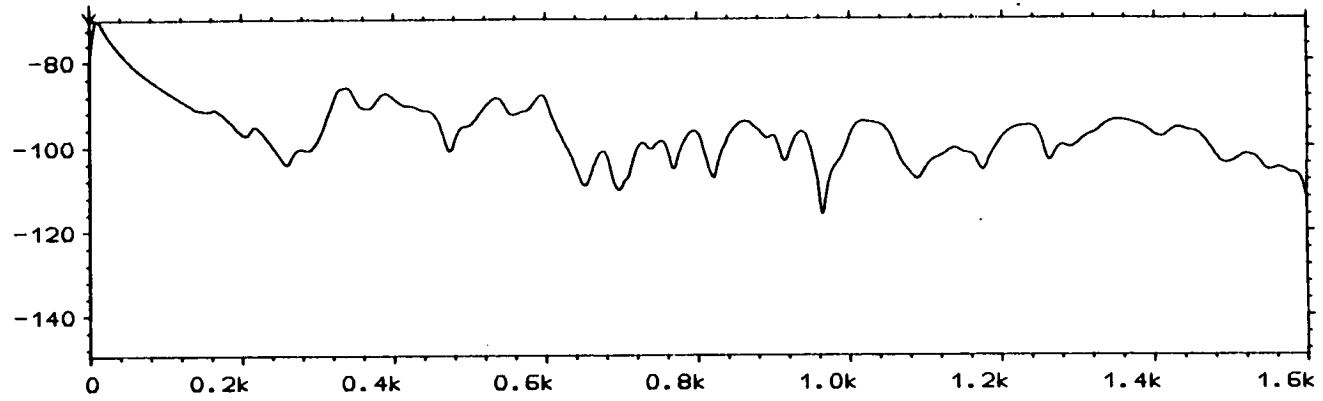


TYPICAL INSTANTANEOUS AND AUTOSPECTRA  
 LABORATORY SEWER: HAMMER 1 BRICK END, ACCEL 3 BRICK END

FIGURE 8.27

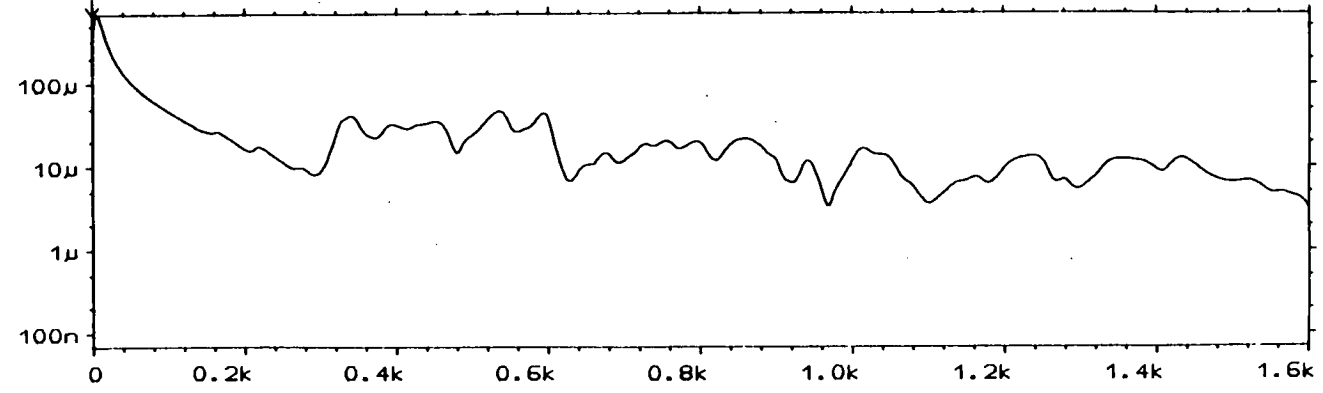
W1 INST SPEC CH.B MAG  
Y: -69.6dB /1.00U RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9

MAIN Y: -81.1dB  
X: 0Hz



W6 AUTO SPEC CH.B [ ] INPUT  
Y: 687μU RMS 80dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

MAIN Y: 331μU  
X: 0Hz

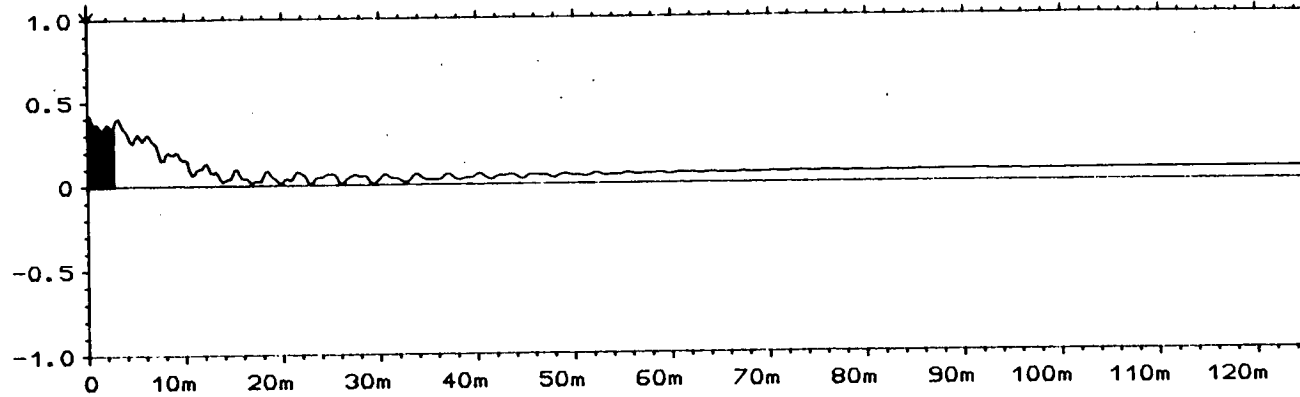


LABORATORY SEWER: HAMMER 1 BRICK END, ACCEL 3 BRICK END

FIGURE 8.28

LABORATORY SEWER: HAMMER 1 BRICK END, ACCEL 3 BRICK END  
USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FAR END OF THE SEWER

W2 CEPSTRUM CH.B REAL MAIN Y: -0.02dB  
Y: 1.00dB X: 0.00ms  
X: 0.00ms + 125ms SHORTPASS  
SETUP W9 #A: 5 W: 13 [ ]



W4 LIFT SPEC CH.B SIDB Y: 6.42μU  
Y: 9.09μU RMS LIN X: 396Hz  
X: 0Hz + 1.6kHz LIN SHORTPASS ΔX: 329.4375Hz  
SETUP W9 #A: 5 W: 13

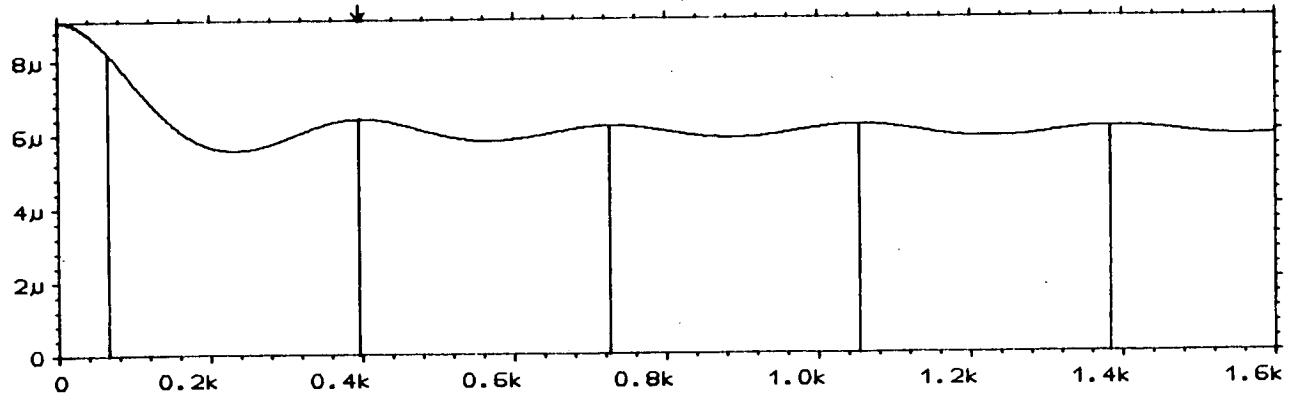
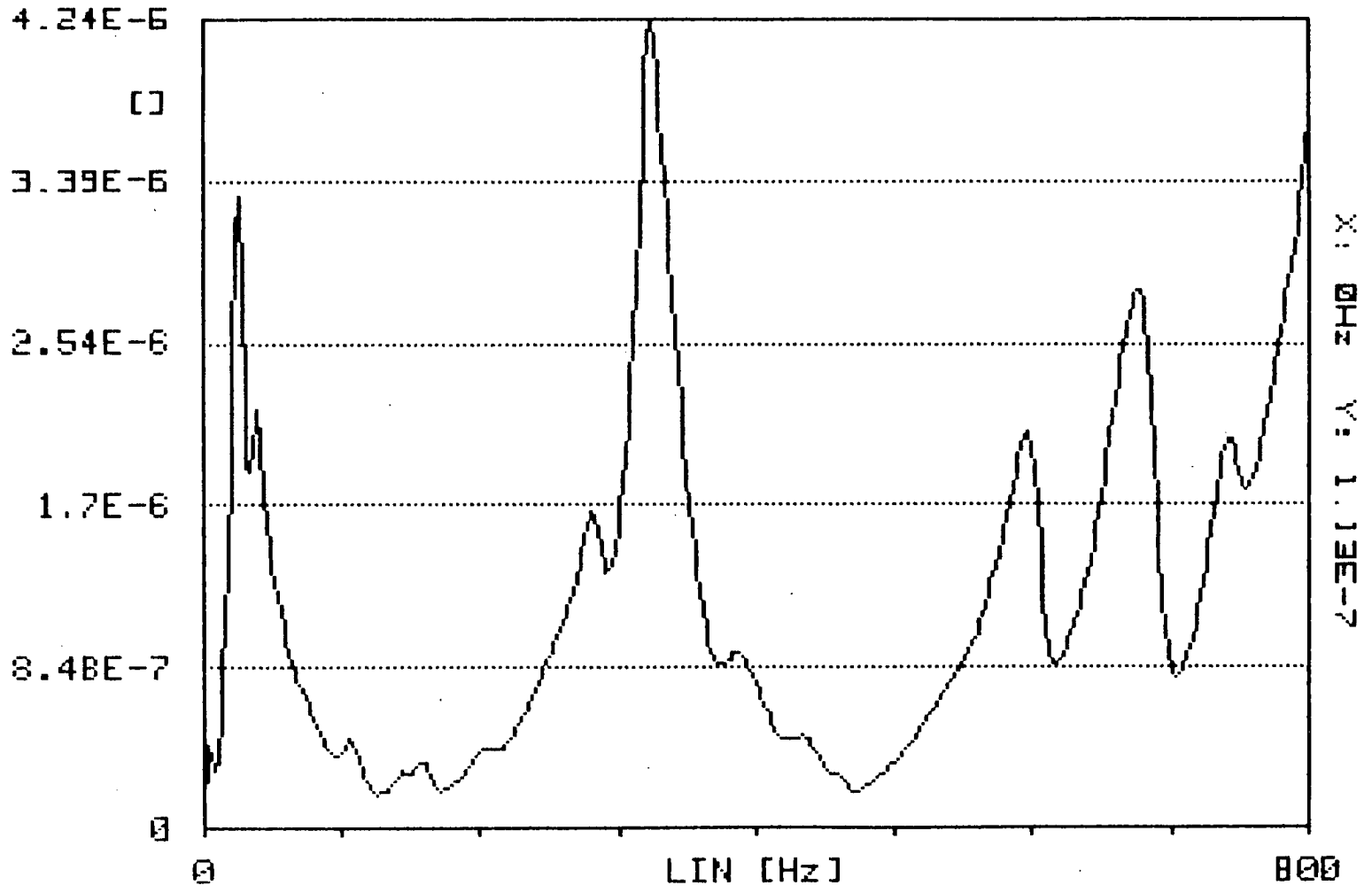


FIGURE 8.29

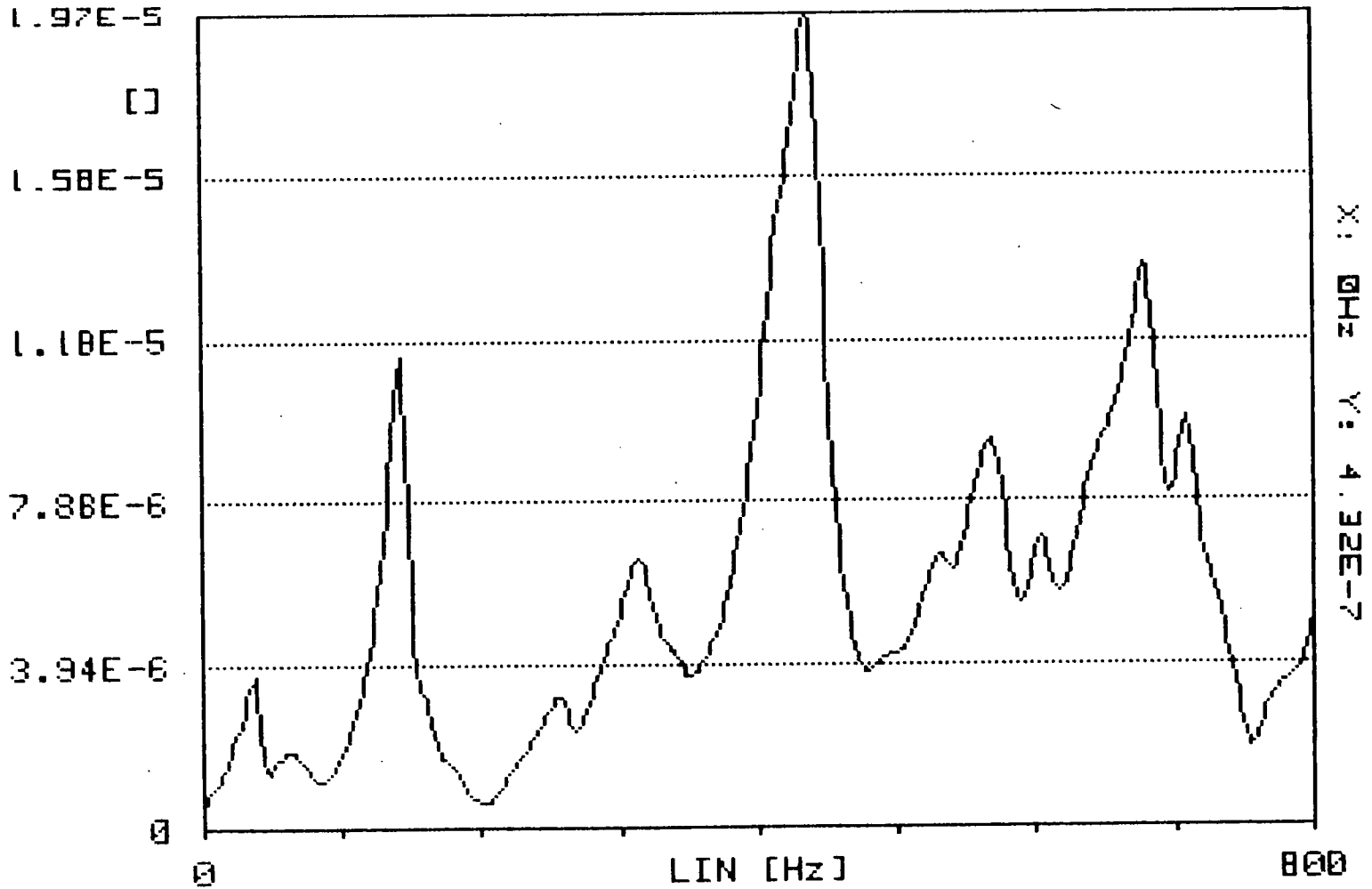
Freq Resp H1 Mag Lin Avg: 5



TYPICAL "NORMAL" FREQUENCY RESPONSE FUNCTION  
LABORATORY SEWER: SINGLE BRICK RING

FIGURE 8.30

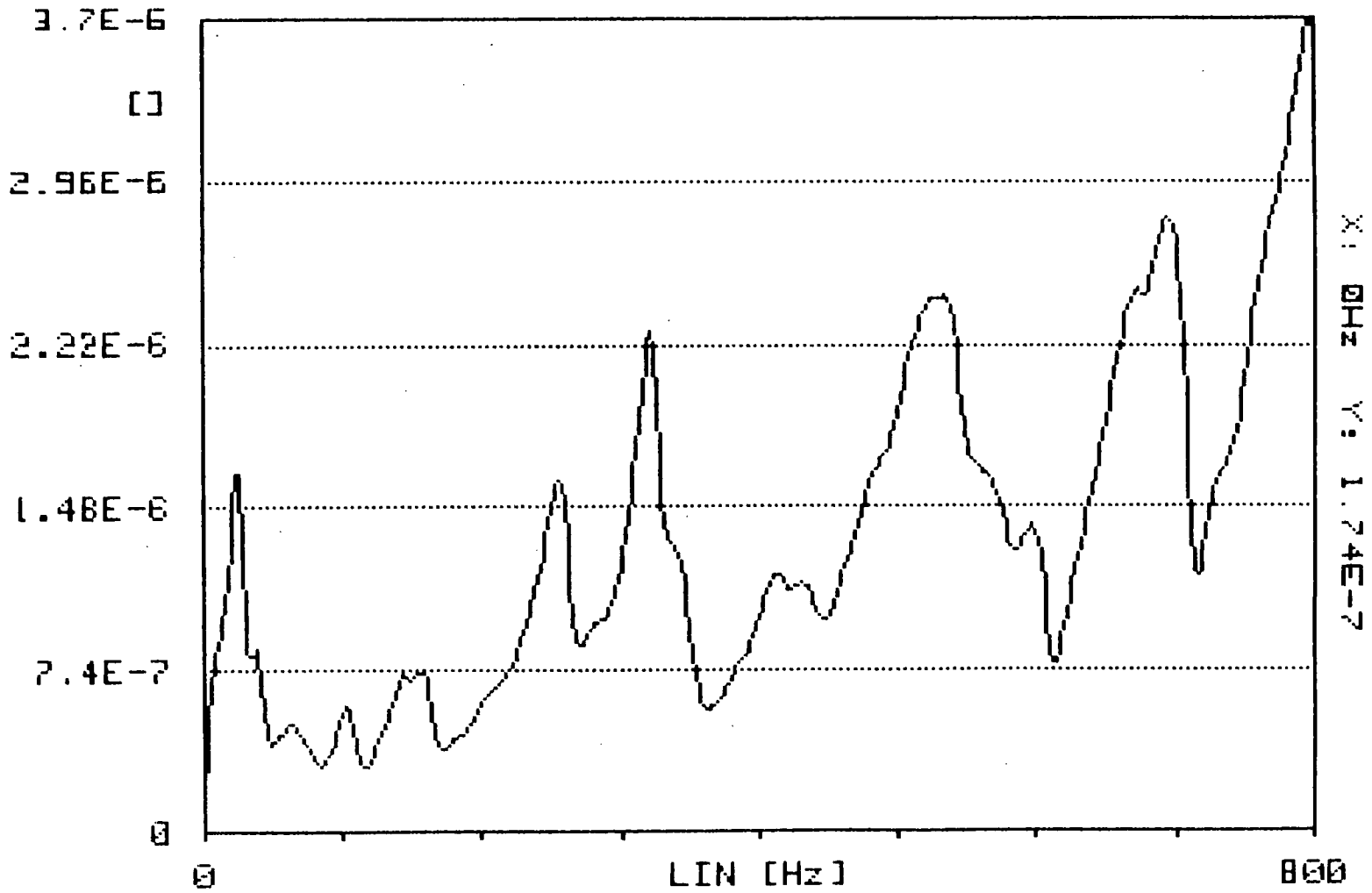
Freq Resp H1 Mag Lin Avg: 5



TYPICAL "NORMAL" FREQUENCY RESPONSE FUNCTION  
LABORATORY SEWER: DOUBLE BRICK RING

FIGURE 8.31

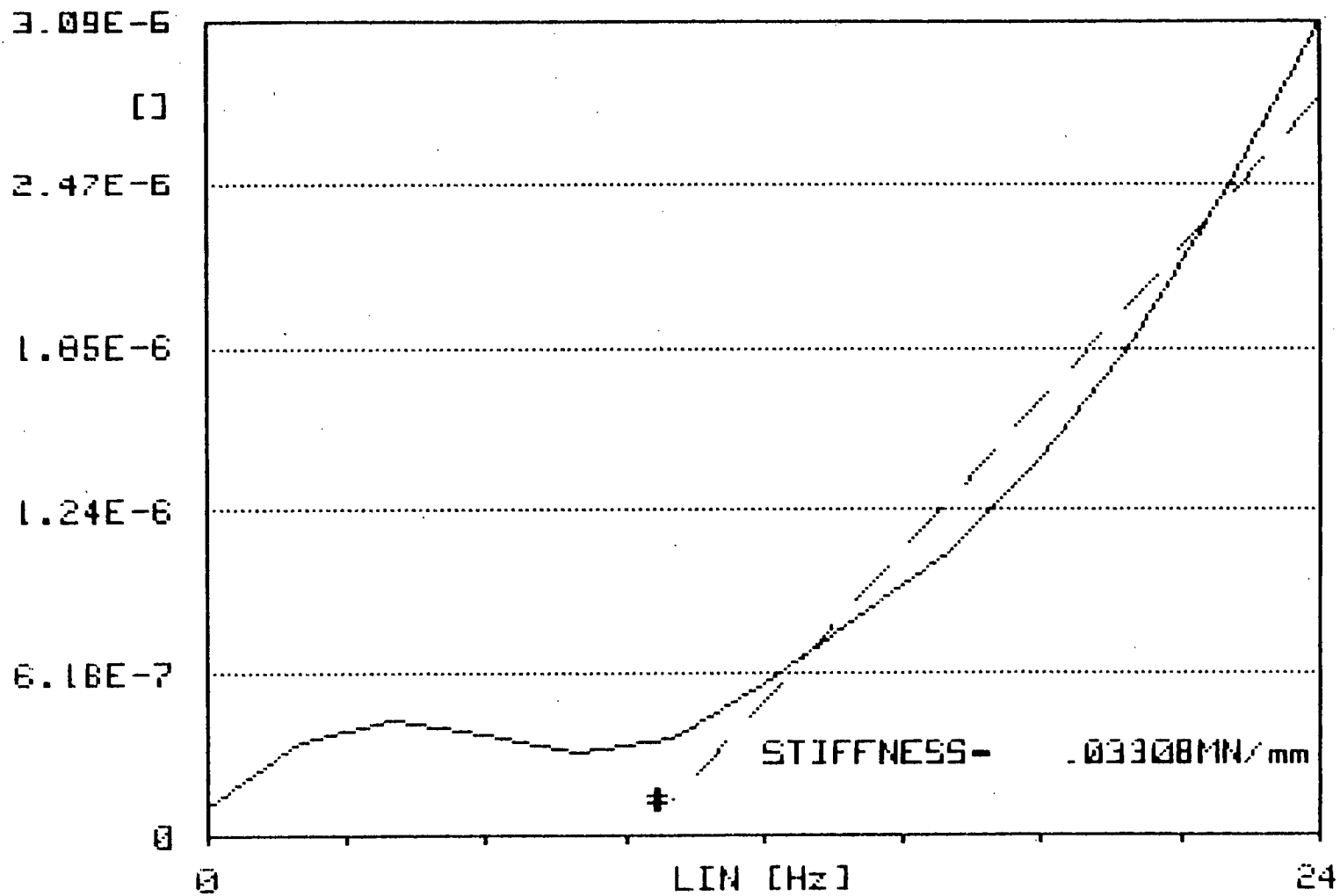
Freq Resp H1 Mag Lin Avg: 5



TYPICAL "NORMAL" FREQUENCY RESPONSE FUNCTION  
LABORATORY SEWER: TRIPLE BRICK RING

FIGURE 8.32

Freq Resp H1 Mag Lin Avg: 5

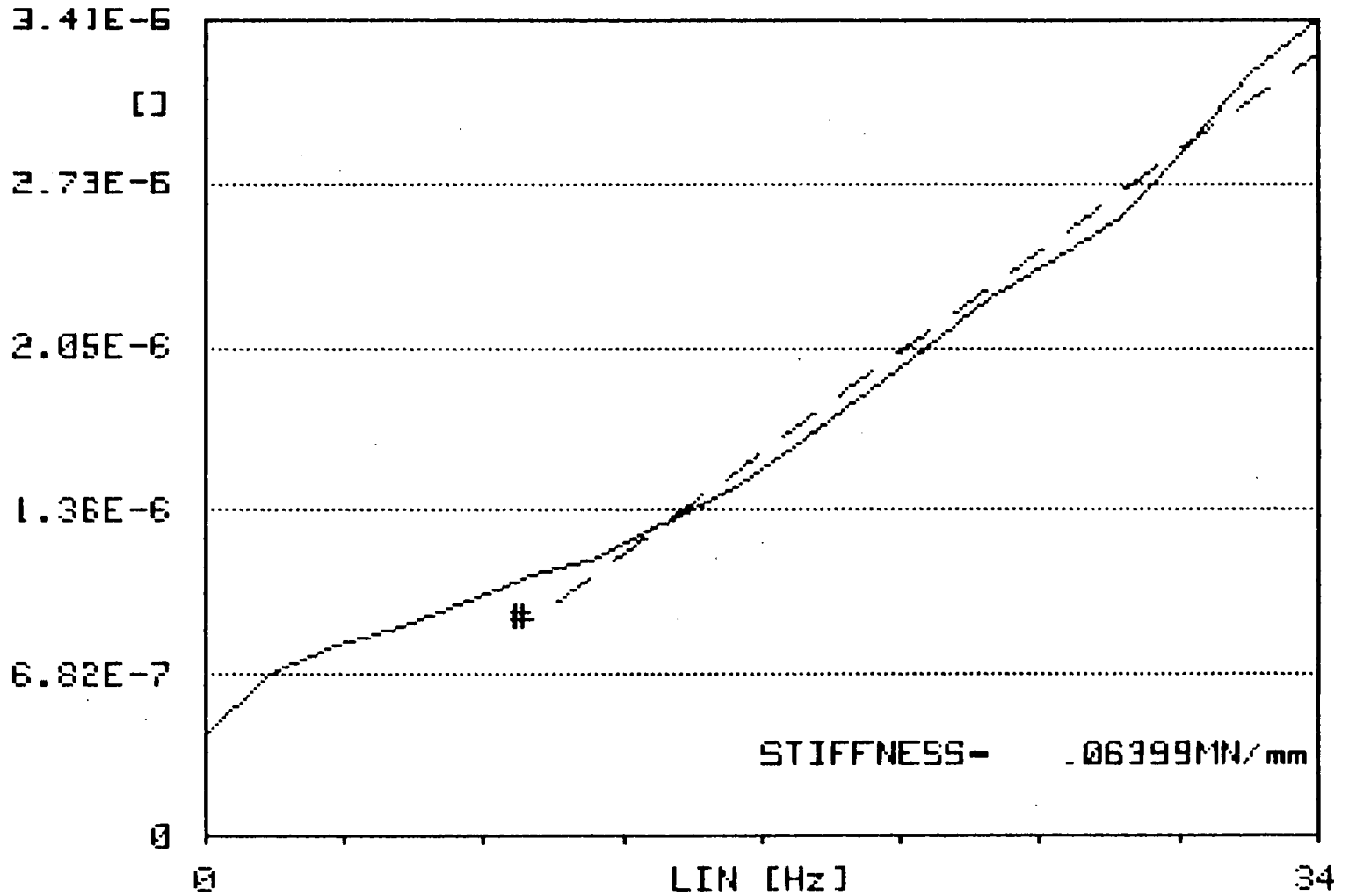


TYPICAL SEWER RING STIFFNESS  
LABORATORY SEWER: SINGLE BRICK RING

FIGURE 8.33

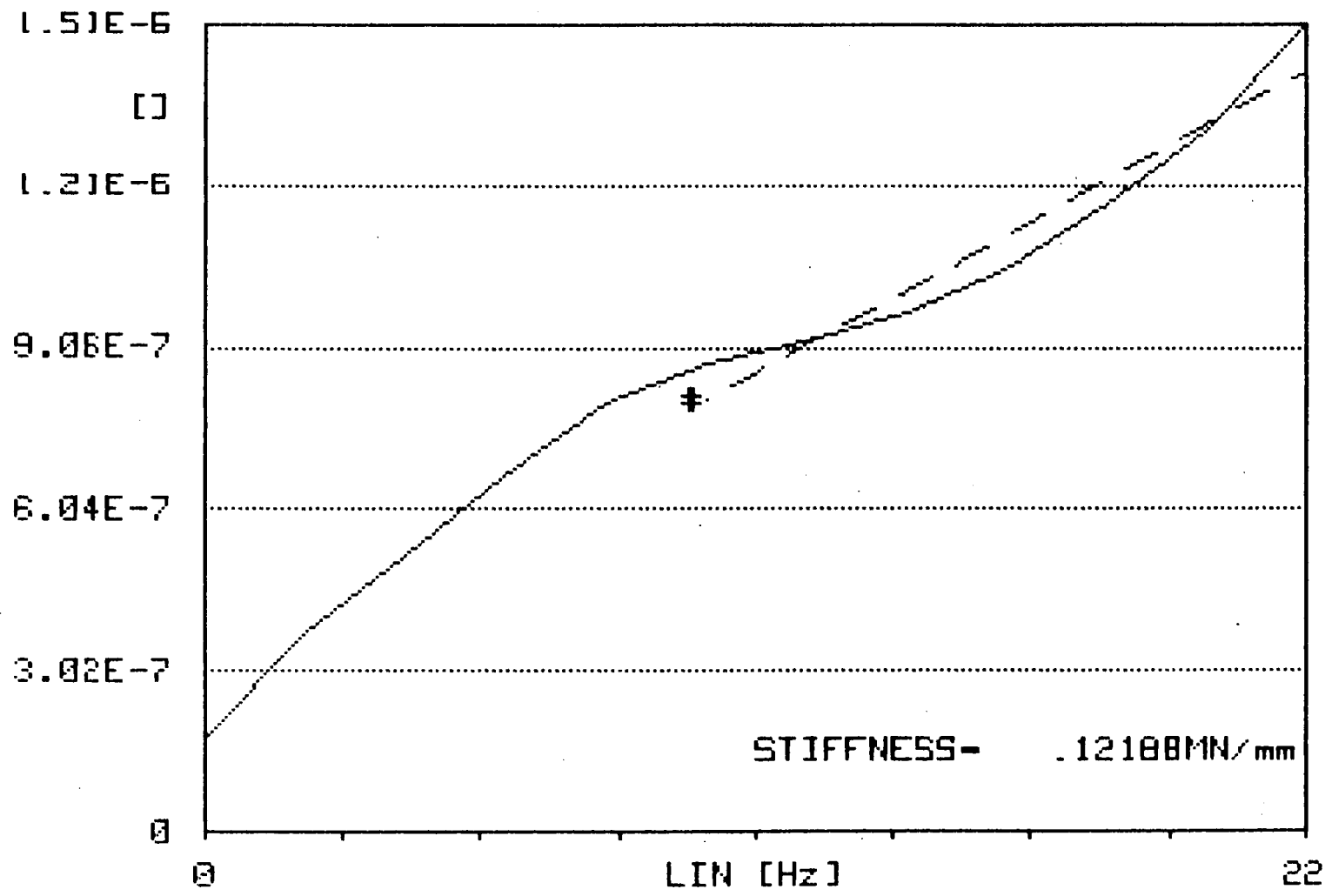


Freq Resp H1 Mag Lin Avg: 5



TYPICAL SEWER RING STIFFNESS  
LABORATORY SEWER: DOUBLE BRICK RING  
FIGURE 8.34

Freq Resp H1 Mag Lin Avg: 5



TYPICAL SEWER RING STIFFNESS  
LABORATORY SEWER: TRIPLE BRICK RING

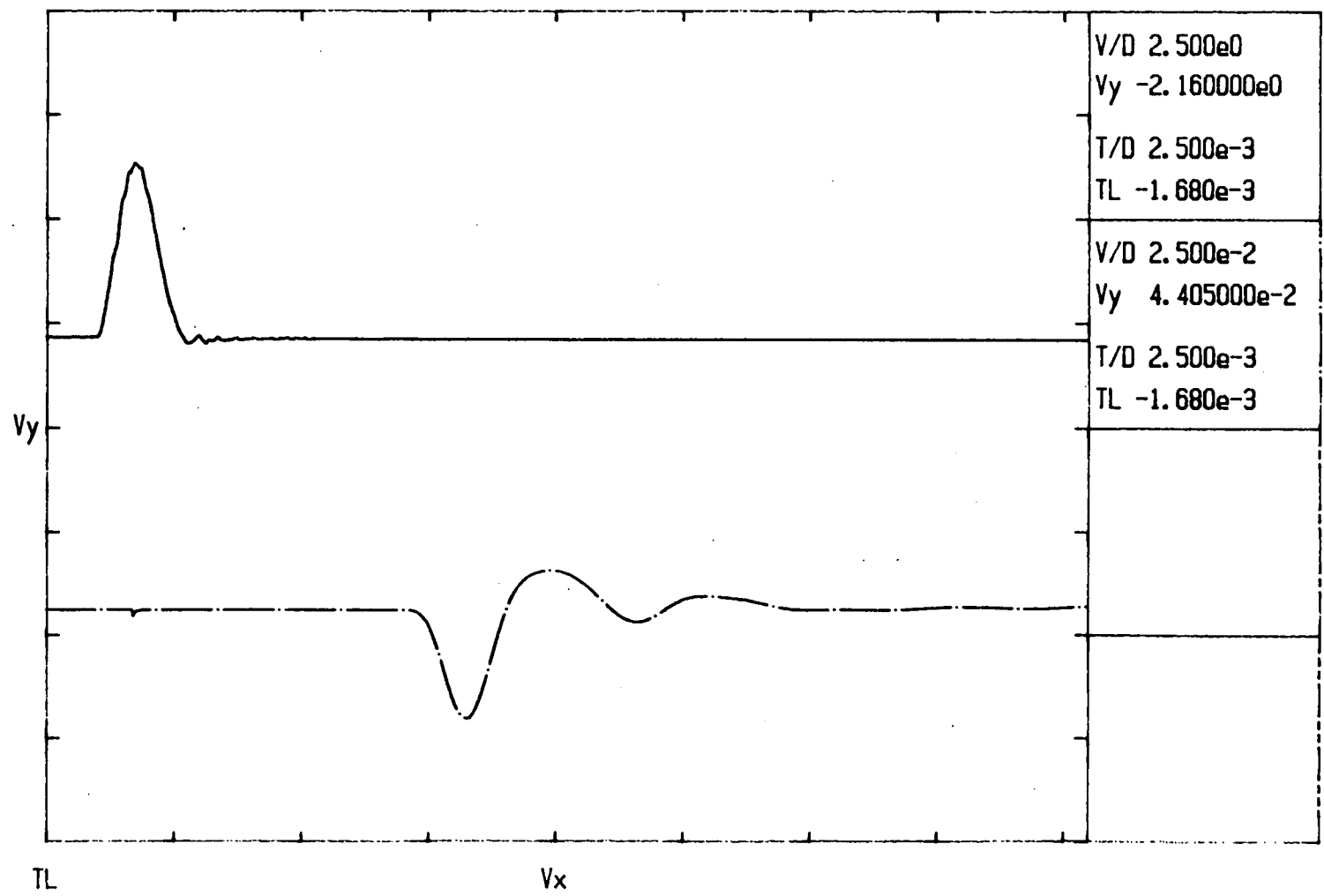
FIGURE 8.35

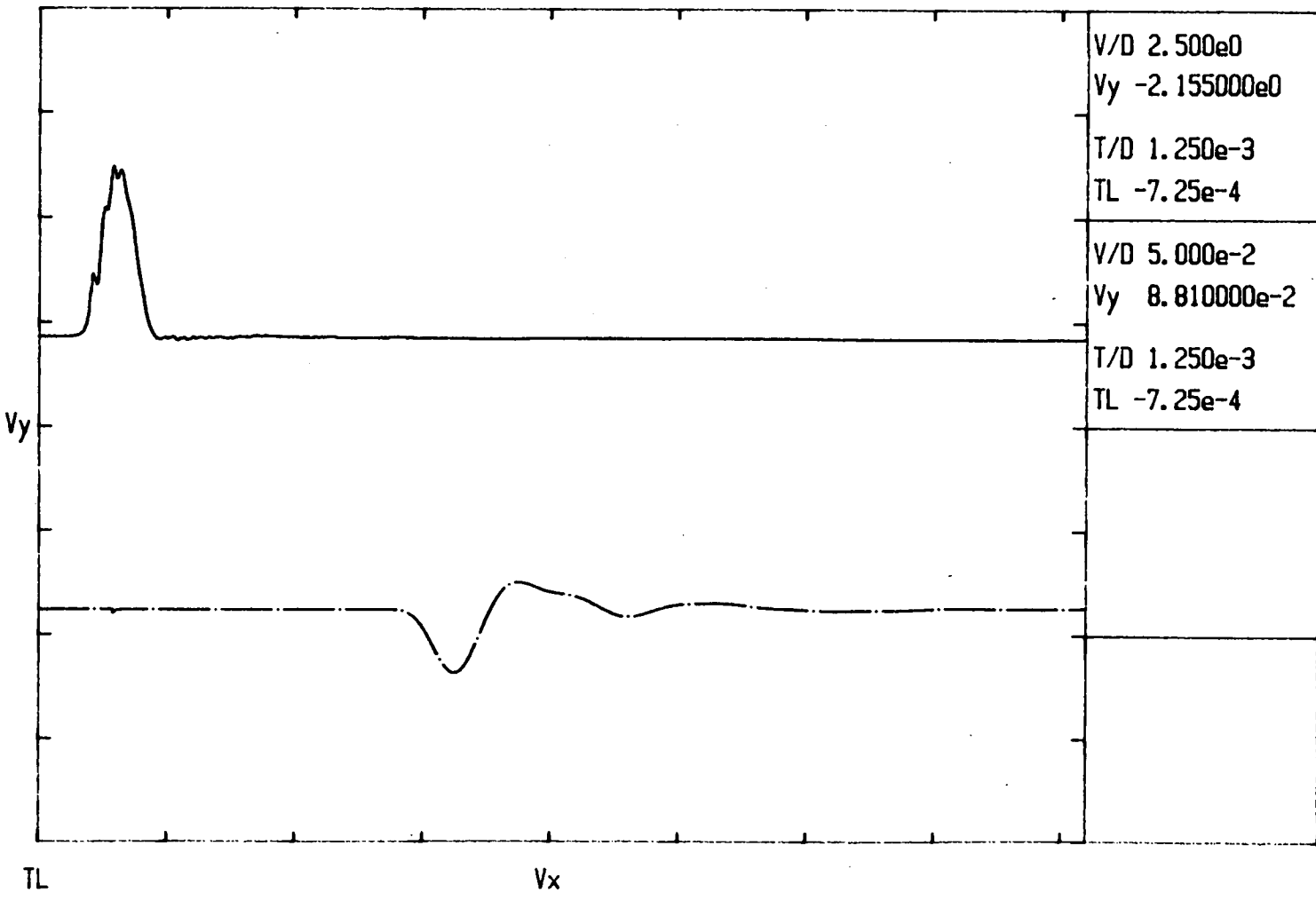
CHAPTER 9

FIELD SEWER TESTS

TYPICAL "DELAY" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 FIELD SEWER: 1 BRICK END TO 3 BRICK END

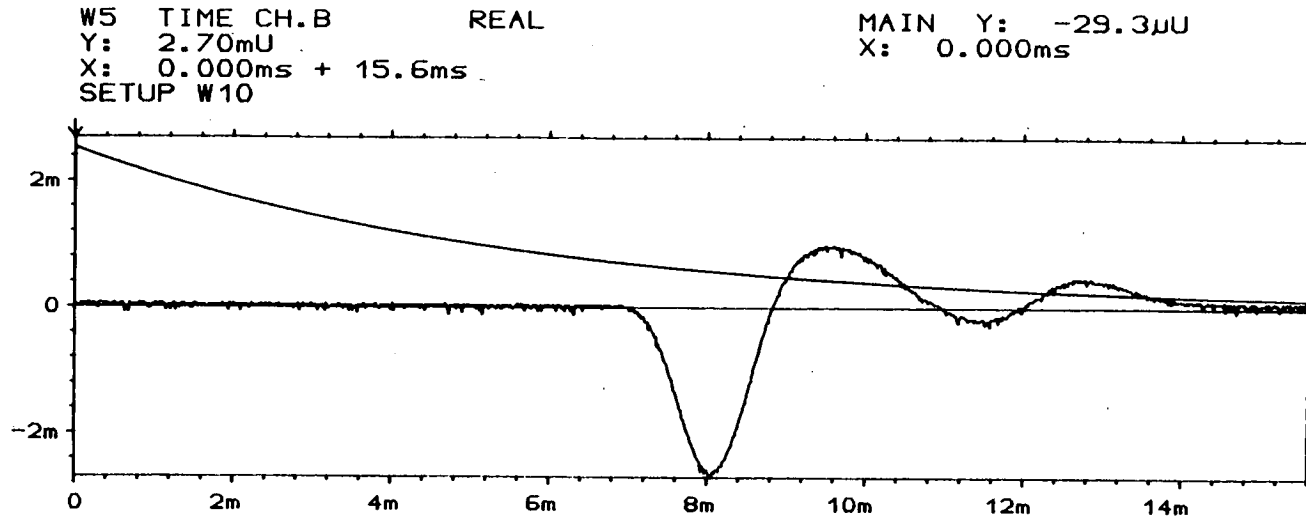
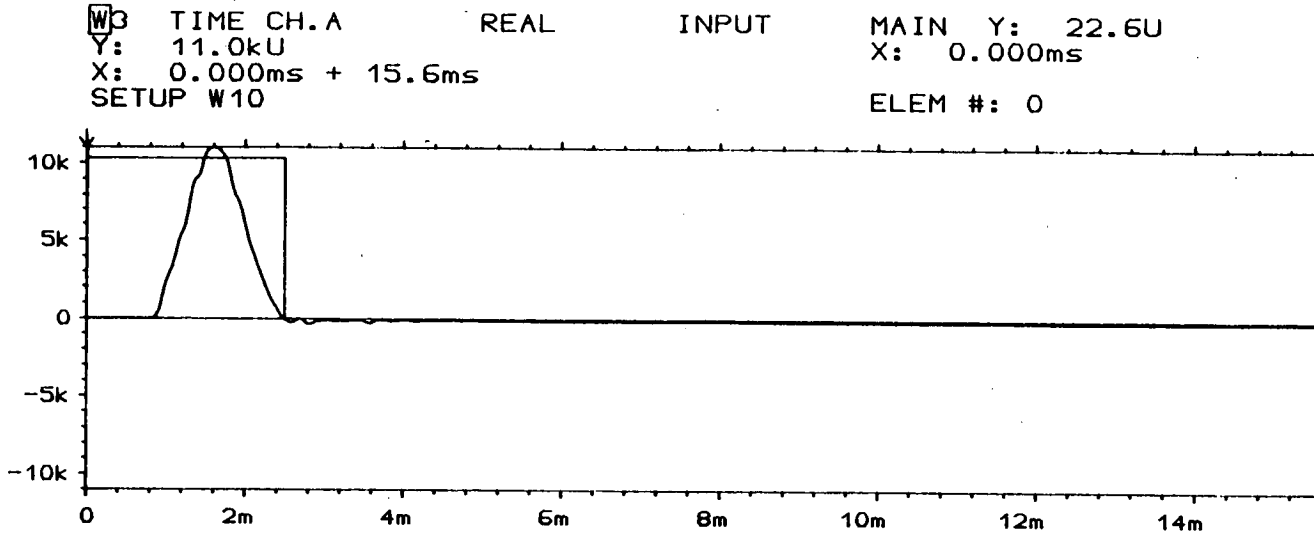
FIGURE 9.1





TYPICAL "DELAY" VELOCITY RECORD (DIGITAL OSCILLOSCOPE)  
 FIELD SEWER: 3 BRICK END TO 1 BRICK END

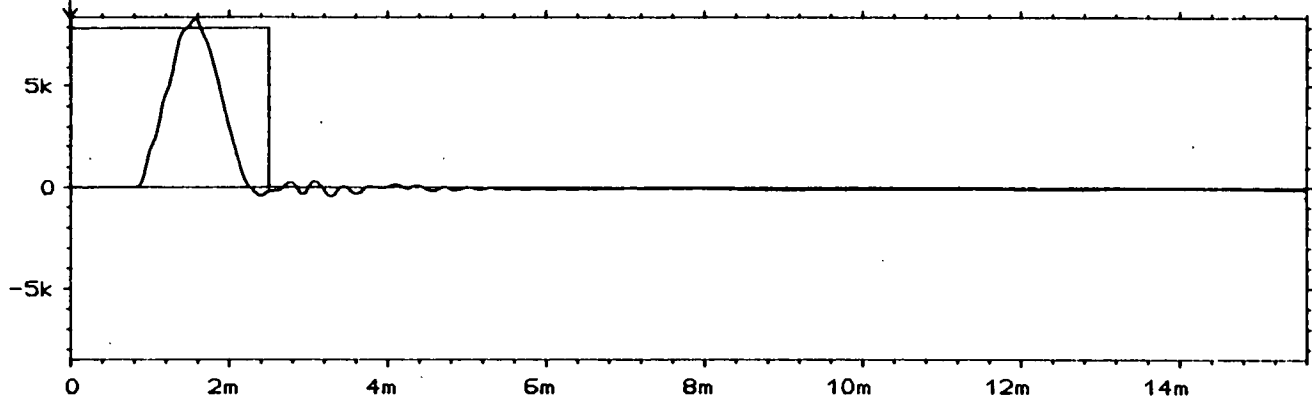
FIGURE 9.2



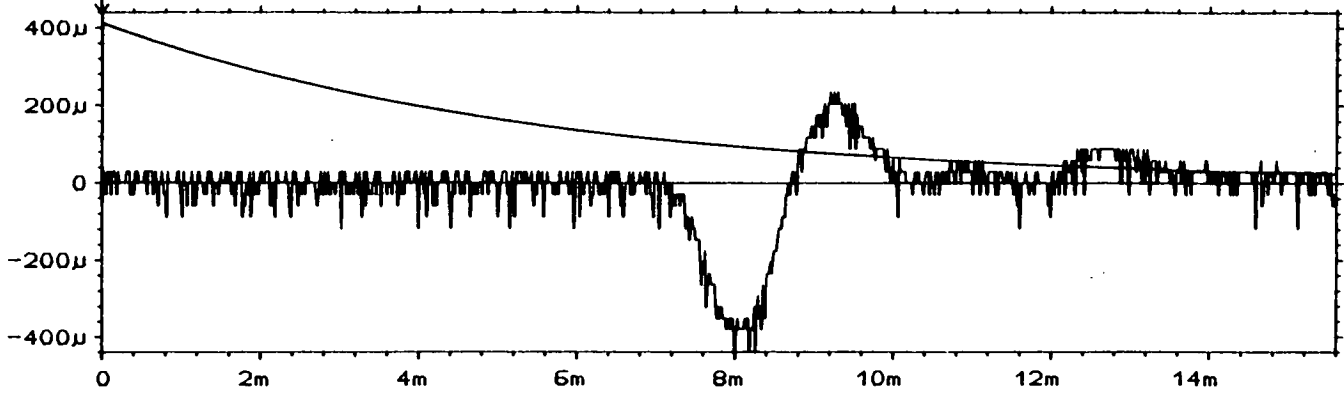
TYPICAL "DELAY" VELOCITY RECORD (SIGNAL ANALYSER)  
 FIELD SEWER: 1 BRICK END TO 3 BRICK END

FIGURE 9.3

W3 TIME CH.A REAL INPUT MAIN Y: 3.03U  
Y: 8.50kU X: 0.000ms  
X: 0.000ms + 15.6ms  
SETUP W10



W5 TIME CH.B REAL MAIN Y: -29.3μU  
Y: 440μU X: 0.000ms  
X: 0.000ms + 15.6ms  
SETUP W10

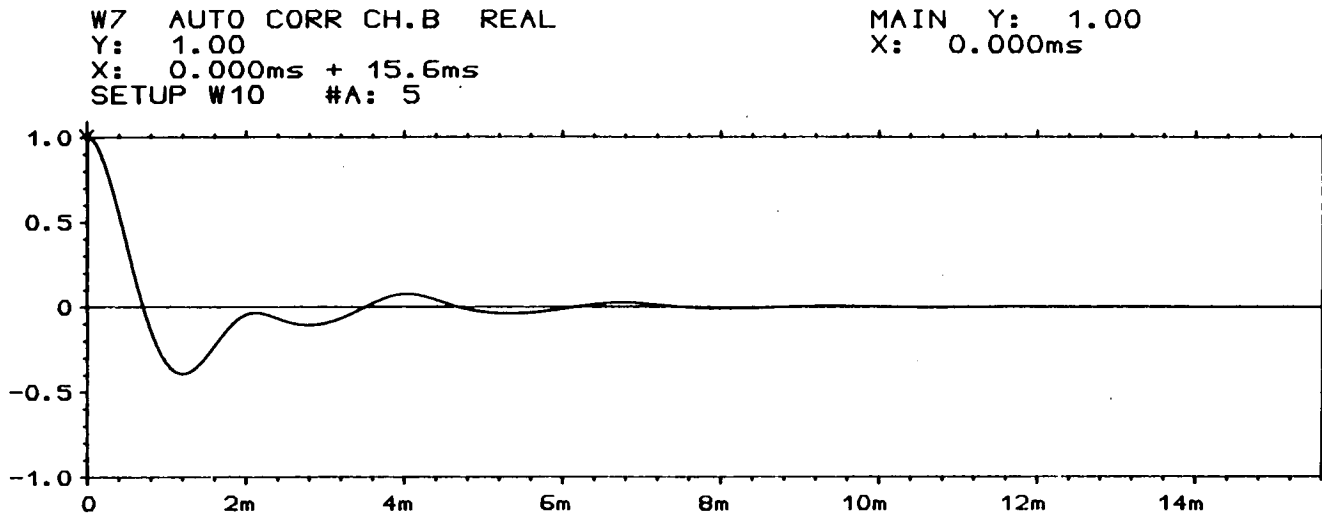
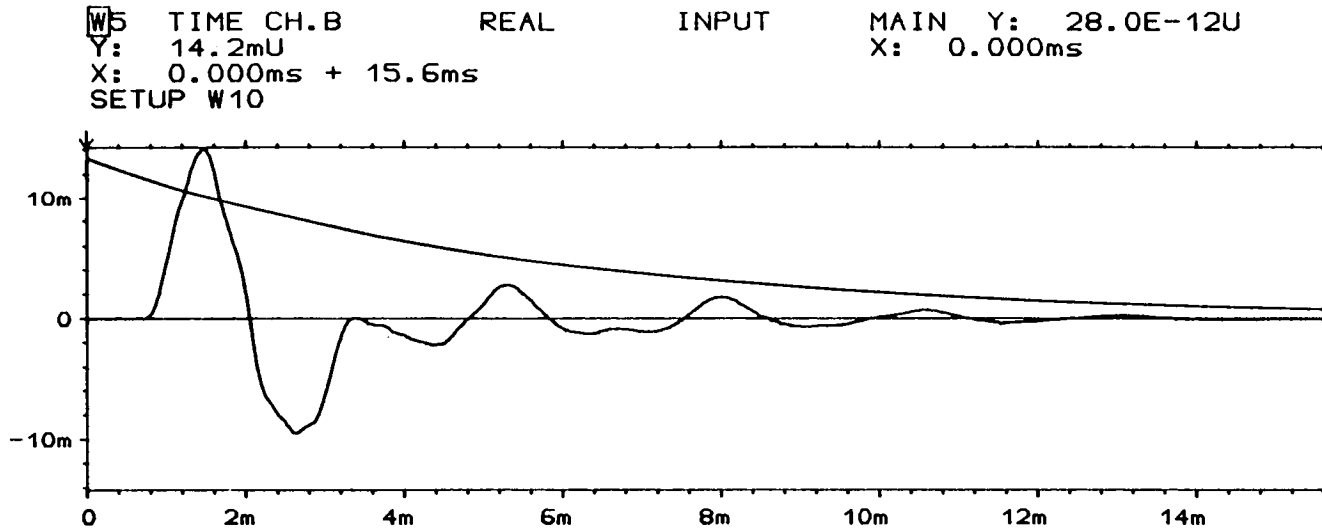


TYPICAL "DELAY" VELOCITY RECORD (SIGNAL ANALYSER)  
FIELD SEWER: 3 BRICK END TO 1 BRICK END

FIGURE 9.4

TYPICAL "ECHO" VEL. & AUTO-CORR. RECORD (SIGNAL ANALYSER)  
FIELD SEWER: 1 BRICK END TO 3 BRICK END

FIGURE 9.5

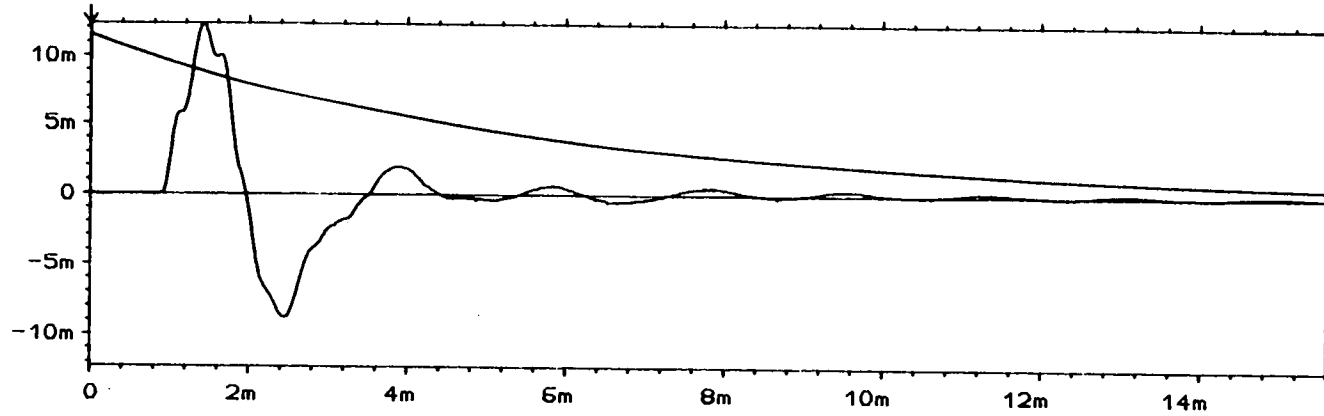




TYPICAL "ECHO" VEL. & AUTO-CORR. RECORD (SIGNAL ANALYSER)  
FIELD SEWER: 3 BRICK END (INNER) TO 1 BRICK END

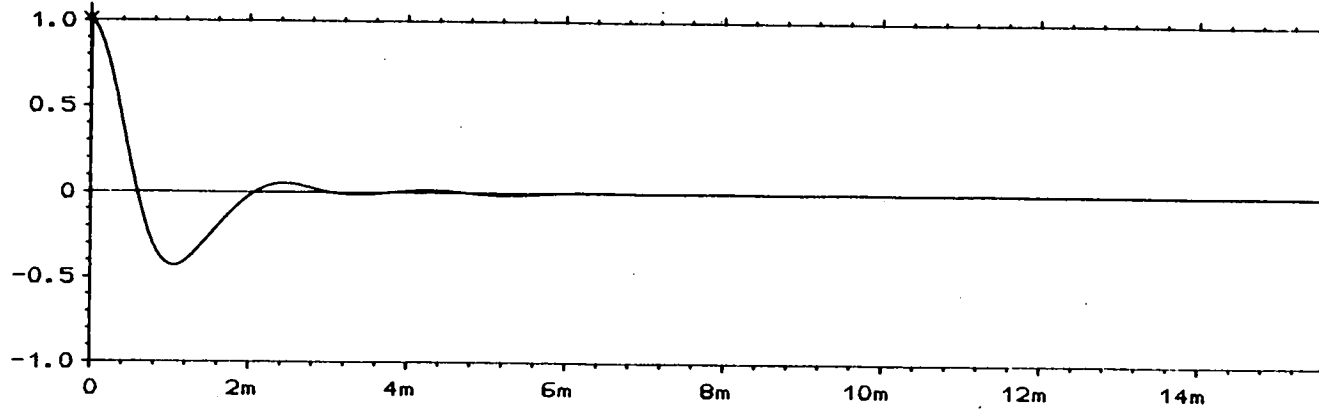
FIGURE 9.6

W5 TIME CH.B REAL INPUT MAIN Y: -14.7 $\mu$ U  
Y: 12.3mU  
X: 0.000ms + 15.6ms  
SETUP W10

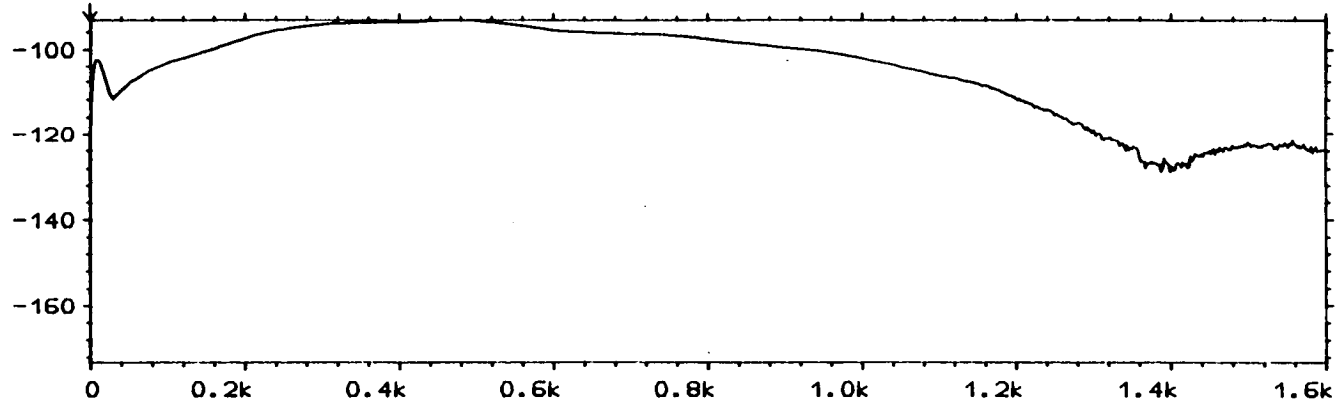


W7 AUTO CORR CH.B REAL  
Y: 1.00  
X: 0.000ms + 15.6ms  
SETUP W10 #A: 5

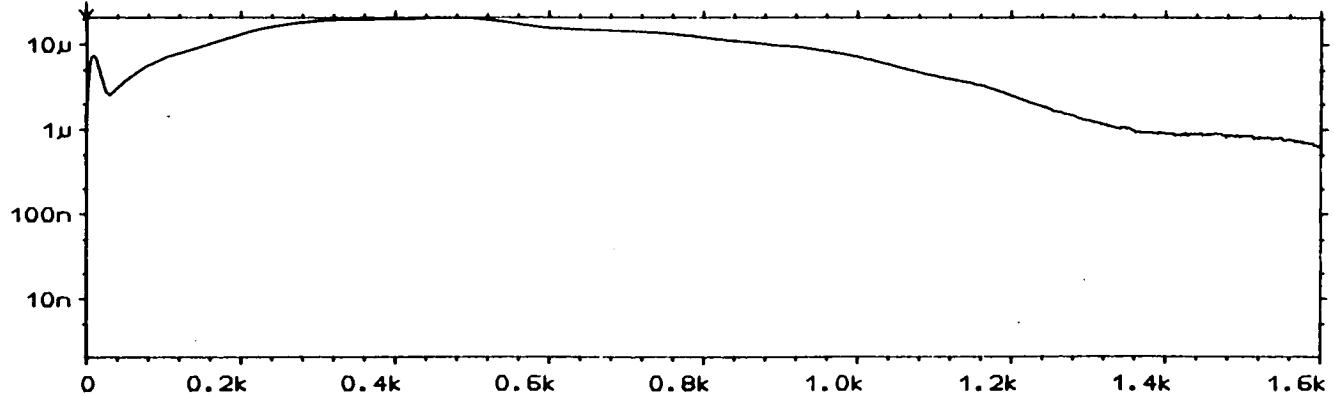
MAIN Y: 1.00  
X: 0.000ms



W1 INST SPEC CH.B MAG INPUT MAIN Y: -120.4dB  
 Y: -93.2dB /1.00U RMS 80dB X: 0Hz  
 X: 0Hz + 1.6kHz LIN  
 SETUP W9



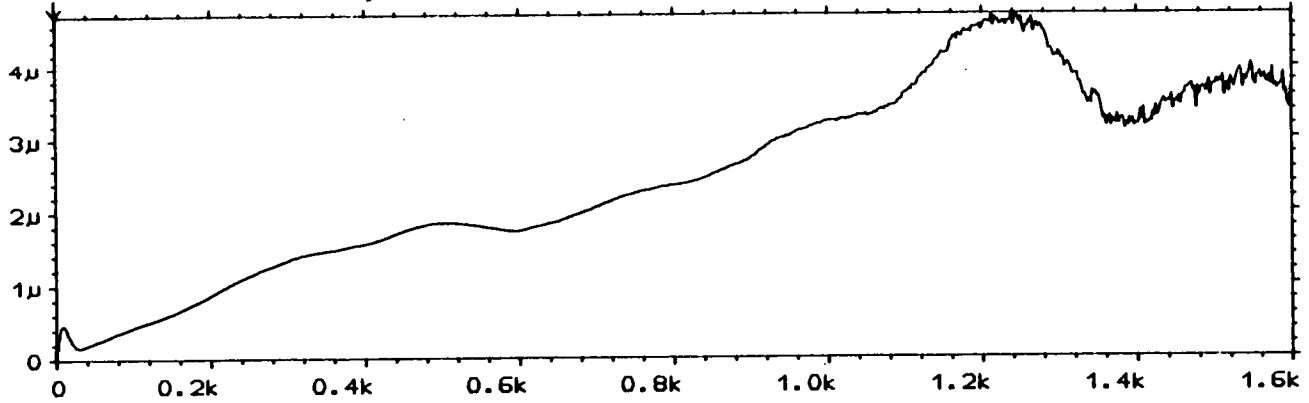
W6 AUTO SPEC CH.B MAIN Y: 1.46μU  
 Y: 20.7μU RMS 80dB X: 0Hz  
 X: 0Hz + 1.6kHz LIN  
 SETUP W9 #A: 5



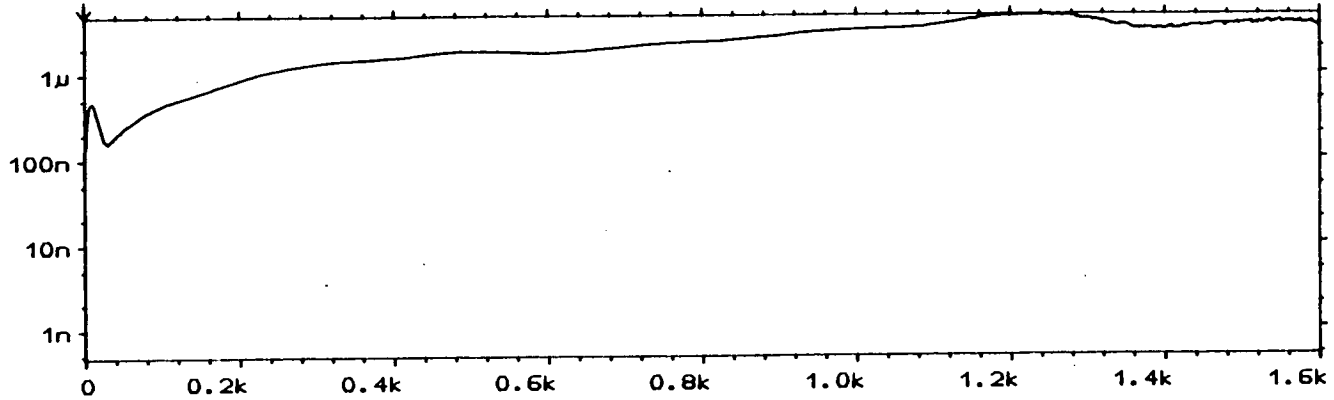
TYPICAL INSTANTANEOUS AND AUTOSPECTRA  
 FIELD SEWER: 3 BRICK END

FIGURE 9.7

W8 FREQ RESP H1 MAG INPUT MAIN Y: 128E-9  
Y: 4.75μ LIN X: 0Hz  
X: 0Hz + 1.6kHz LIN X: 0Hz  
SETUP W9 #A: 5



W8 FREQ RESP H1 MAG MAIN Y: 128E-9  
Y: 4.75μ 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN X: 0Hz  
SETUP W9 #A: 5

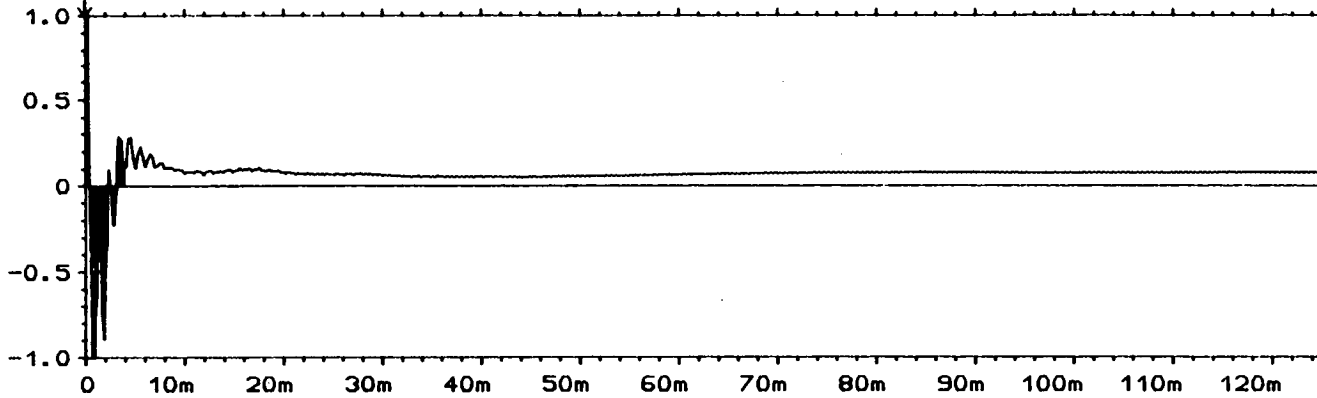


TYPICAL FREQUENCY RESPONSE FUNCTION  
FIELD SEWER: 3 BRICK END

FIGURE 9.8

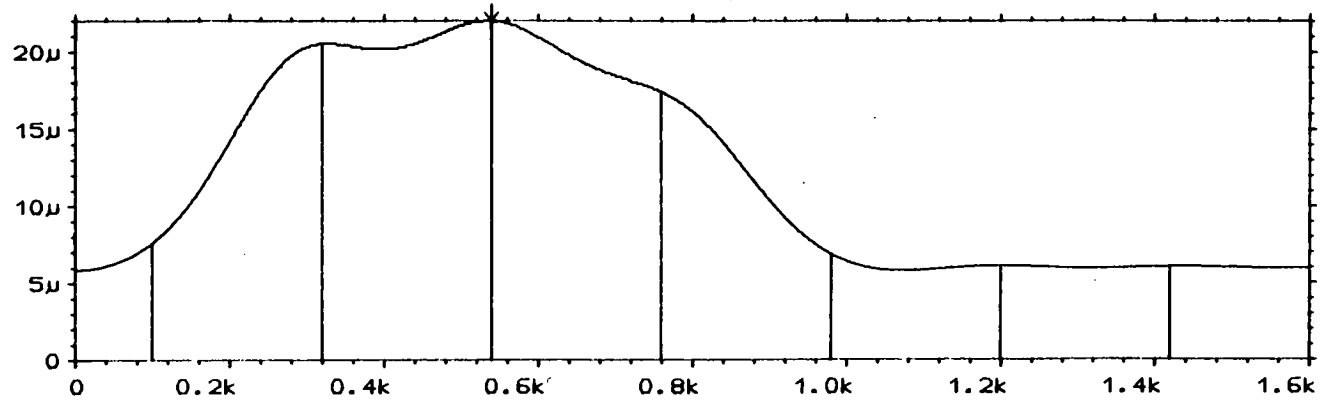
2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.00dB  
X: 0.00ms  
SHORTPASS  
W: 18 [ ]



W4 LIFT SPEC CH.B  
Y: 22.0μU RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 22.0μU  
X: 540Hz  
SHORTPASS ΔX: 220.0000Hz  
W: 18

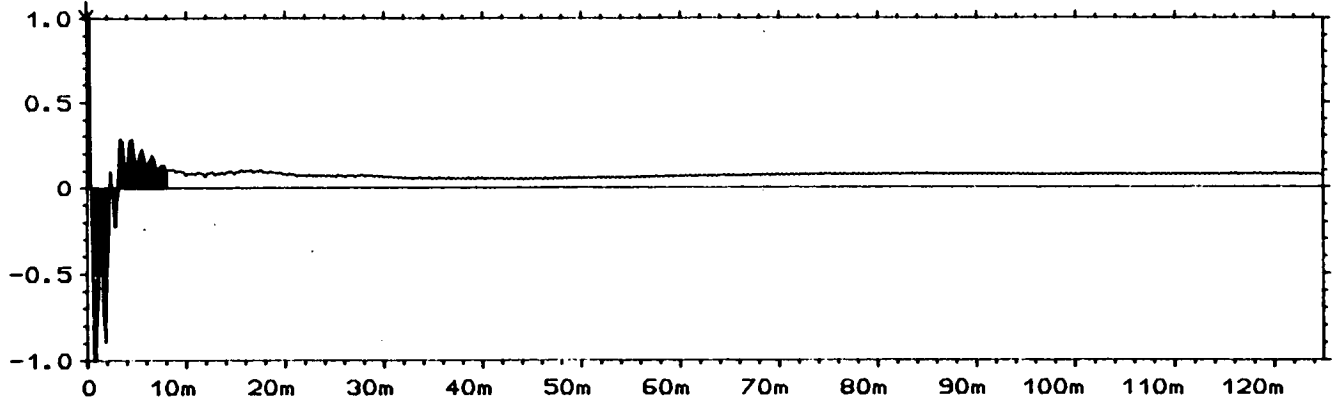


USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FIRST CHANGE OF CROSS-SECTION  
FIELD SEWER: 3 BRICK END

FIGURE 9.9

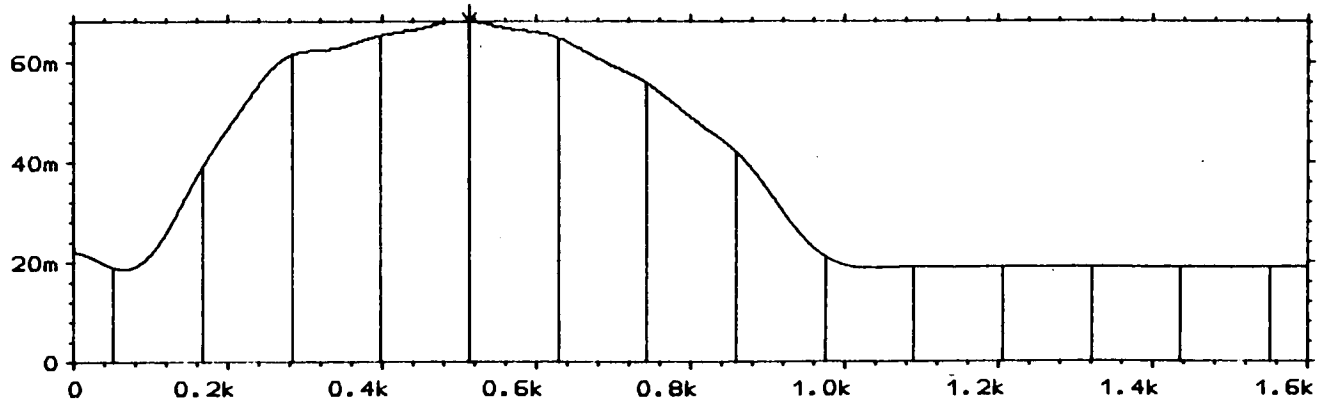
2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.00dB  
X: 0.00ms  
SHORTPASS  
W: 35 [ ]



W4 LIFT SPEC CH.B  
Y: 58.2mU RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 58.2mU  
X: 514Hz  
SHORTPASS ΔX: 115.3125Hz  
W: 35



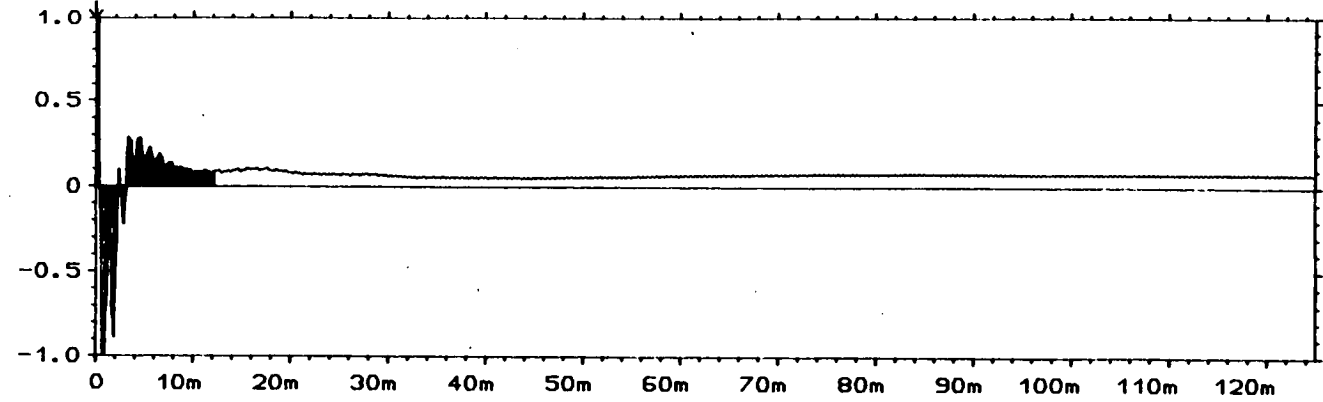
USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE SECOND CHANGE OF CROSS-SECTION  
FIELD SEWER: 3 BRICK END

FIGURE 9.10

2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.00dB  
X: 0.00ms

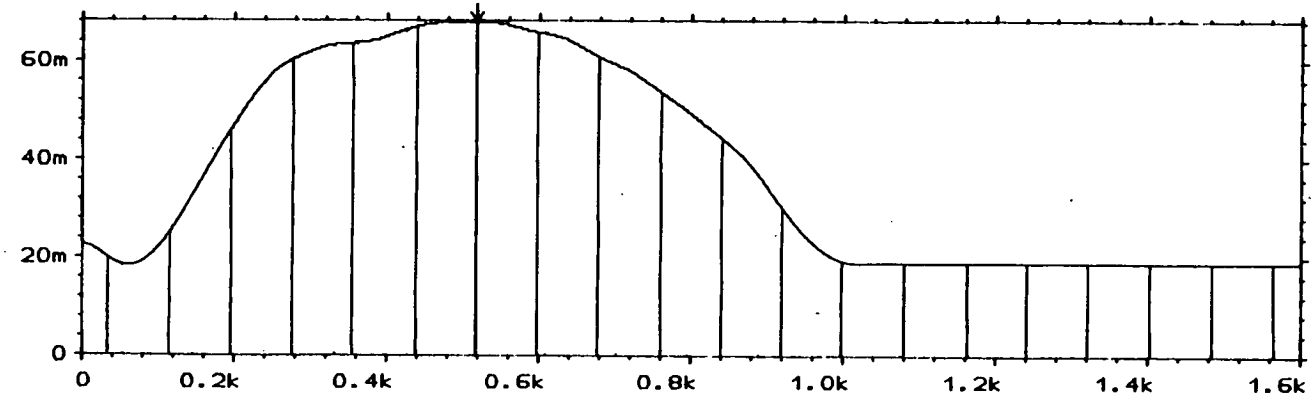
SHORTPASS  
W: 52 [ ]



W4 LIFT SPEC CH.B  
Y: 68.2mU RMS LIN  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 67.8mU  
X: 518Hz

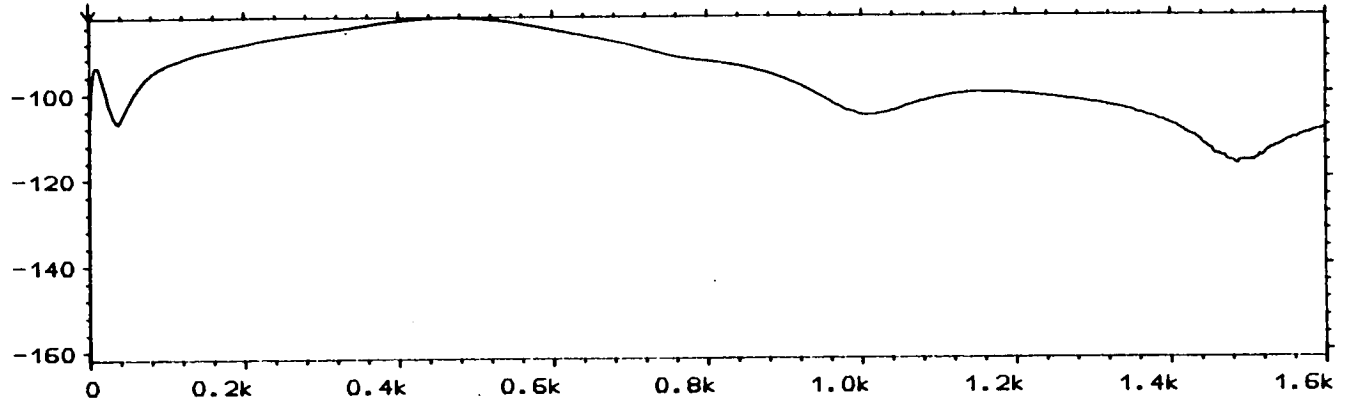
SHORTPASS ΔX: 80.5000Hz  
W: 52



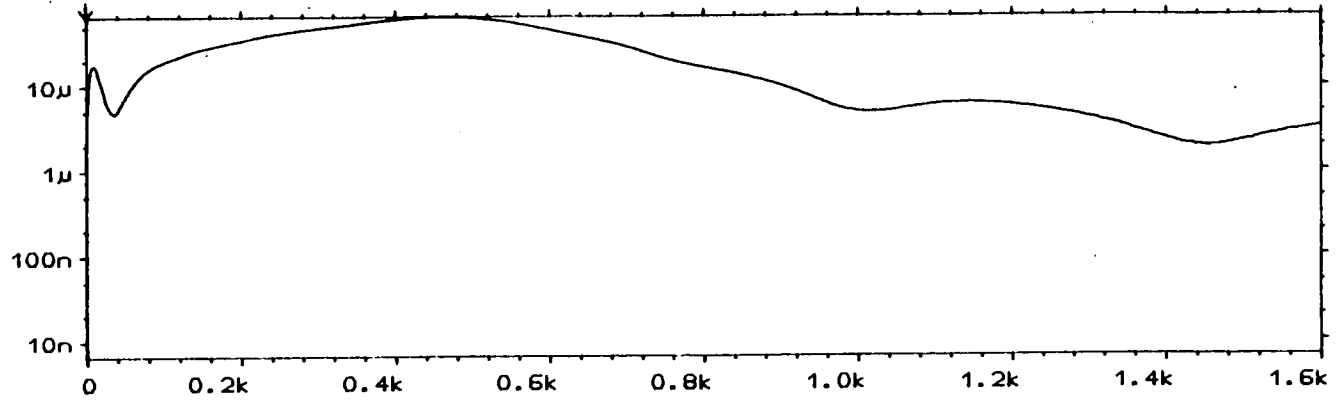
USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FAR END OF THE SEWER  
FIELD SEWER: 3 BRICK END

FIGURE 9.11

W1 INST SPEC CH.B MAG INPUT MAIN Y: -114.5dB  
Y: -81.8dB /1.00U RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN  
SETUP W9



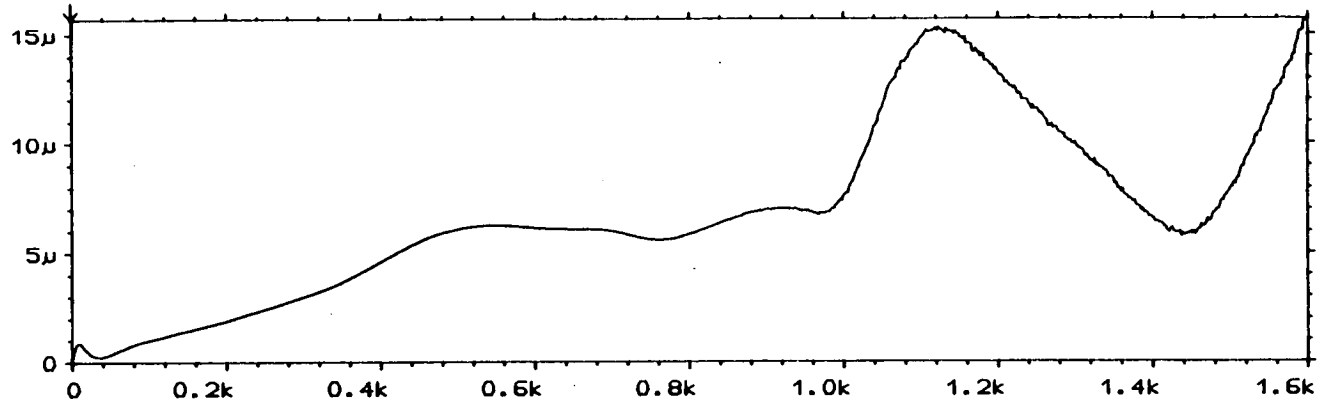
W6 AUTO SPEC CH.B MAIN Y: 1.48μU  
Y: 66.2μU RMS 80dB X: 0Hz  
X: 0Hz + 1.6kHz LIN #A: 5  
SETUP W9



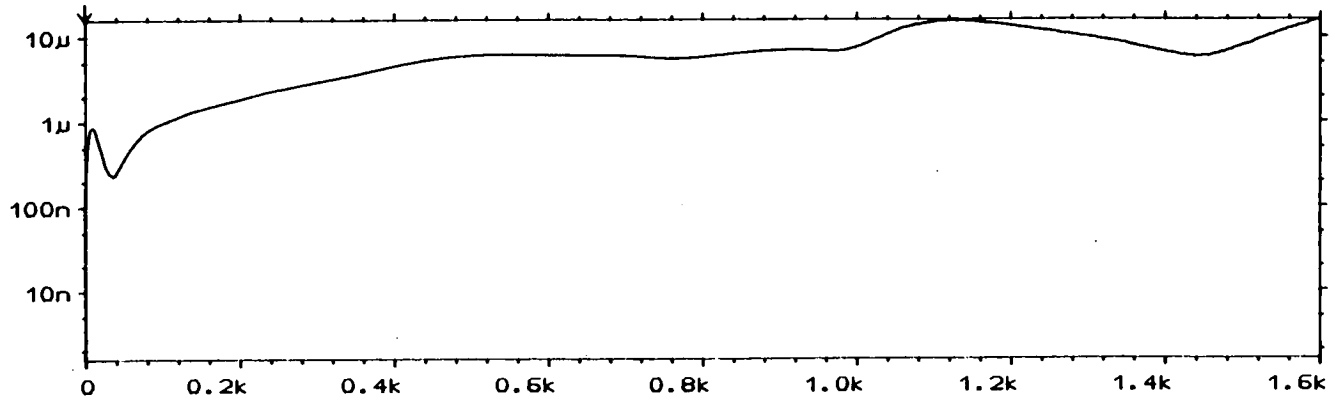
TYPICAL INSTANTANEOUS AND AUTOSPECTRA  
FIELD SEWER: 1 BRICK END

FIGURE 9.12

W8 FREQ RESP H1 MAG INPUT MAIN Y: 97.6E-9  
 Y: 15.8 $\mu$  LIN X: 0Hz  
 X: 0Hz + 1.6kHz LIN  
 SETUP W9 #A: 5



W8 FREQ RESP H1 MAG MAIN Y: 97.6E-9  
 Y: 15.8 $\mu$  80dB X: 0Hz  
 X: 0Hz + 1.6kHz LIN  
 SETUP W9 #A: 5



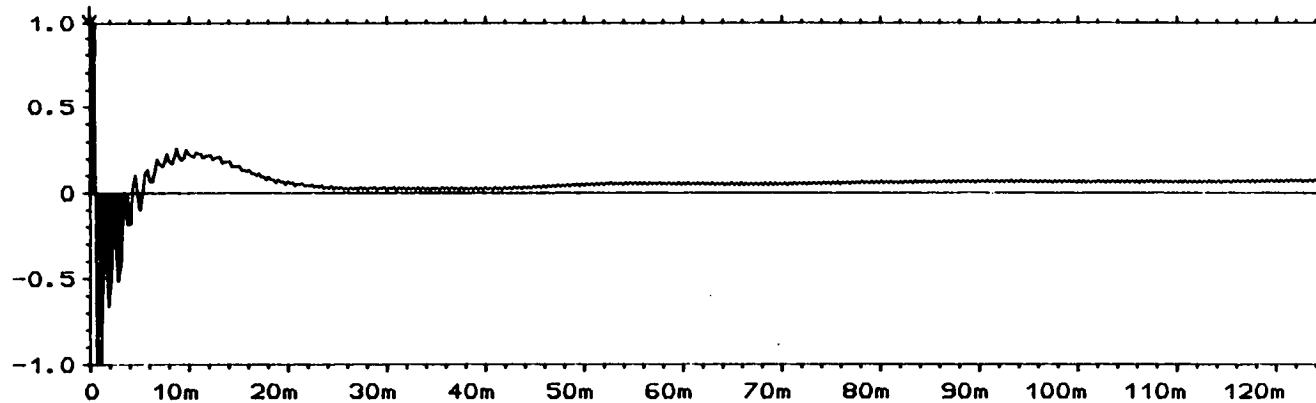
TYPICAL FREQUENCY RESPONSE FUNCTION  
 FIELD SEWER: 1 BRICK END

FIGURE 9.13



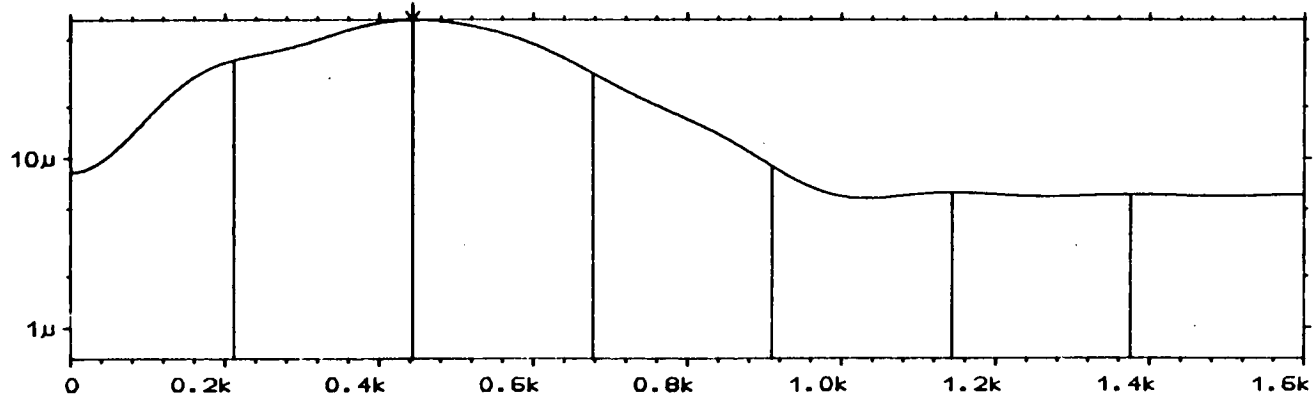
W2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.00dB  
X: 0.00ms  
SHORTPASS  
W: 18 [ ]



W4 LIFT SPEC CH.B  
Y: 65.7μU RMS 40dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 65.7μU  
X: 444Hz  
SHORTPASS ΔX: 233.0000Hz  
W: 18

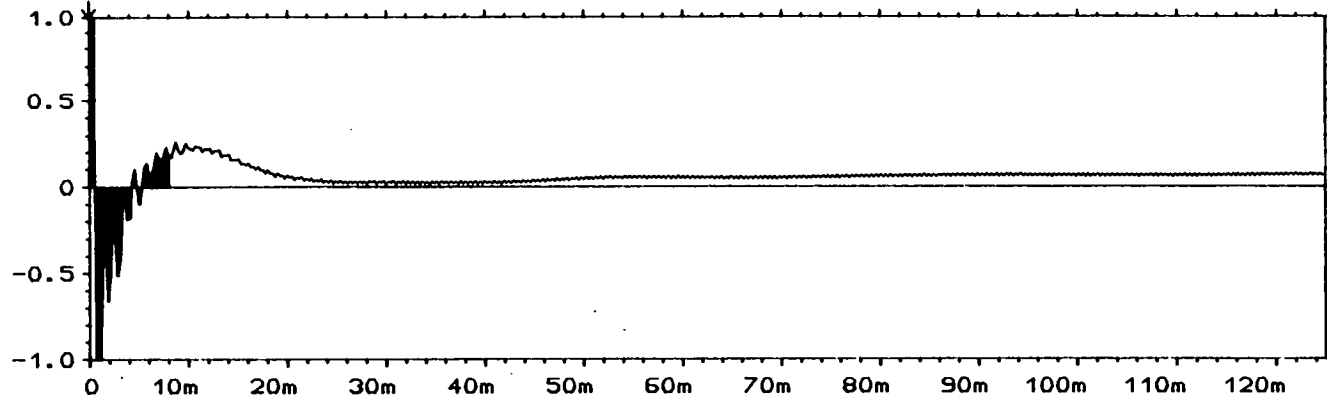


USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FIRST CHANGE OF CROSS-SECTION  
FIELD SEWER: 1 BRICK END

FIGURE 9.14

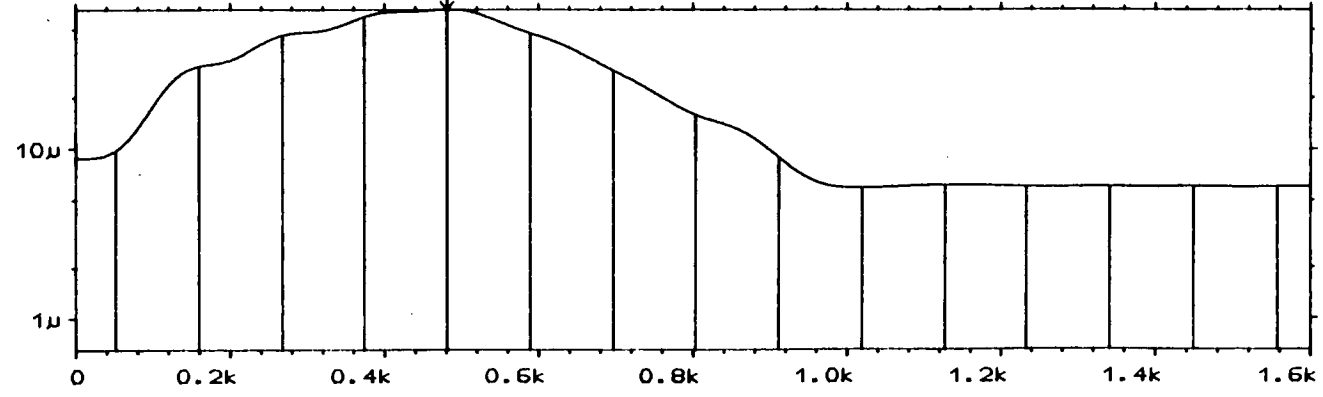
W2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.00dB  
X: 0.00ms  
SHORTPASS  
W: 35 [ ]



W4 LIFT SPEC CH.B  
Y: 65.3μU RMS 40dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

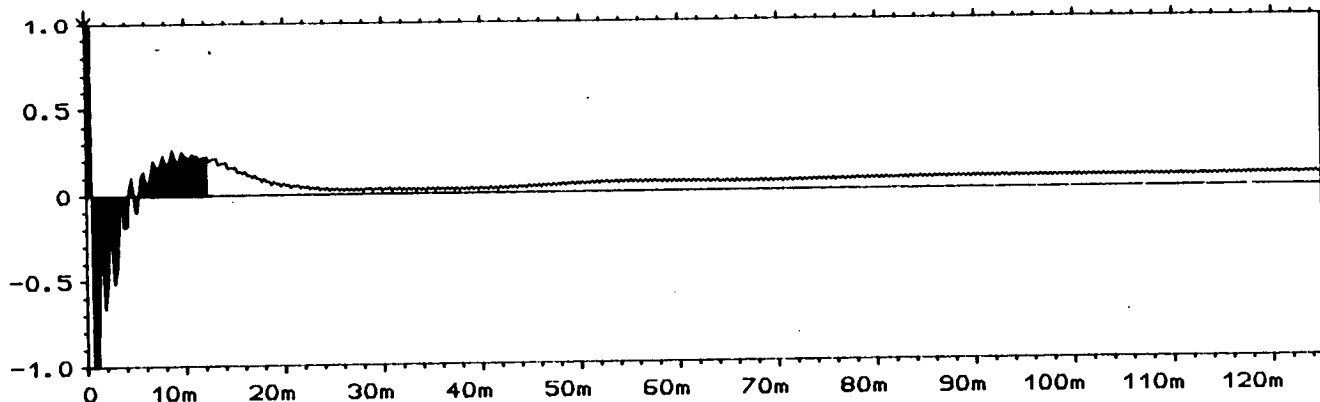
SIDB Y: 65.3μU  
X: 482Hz  
SHORTPASS ΔX: 107.5000Hz  
W: 35



USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE SECOND CHANGE OF CROSS-SECTION  
FIELD SEWER: 1 BRICK END  
FIGURE 9.15

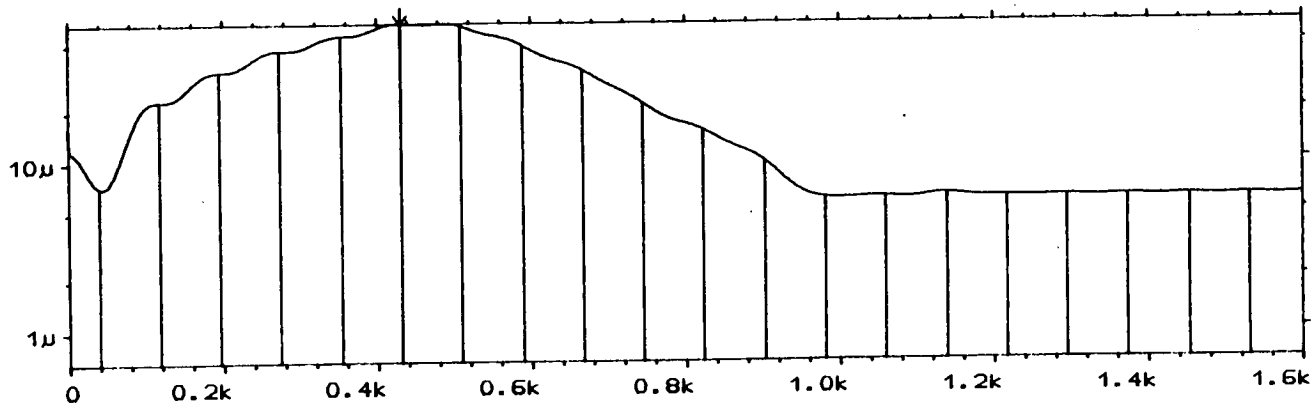
W2 CEPSTRUM CH.B REAL  
Y: 1.00dB  
X: 0.00ms + 125ms  
SETUP W9 #A: 5

MAIN Y: 0.00dB  
X: 0.00ms  
SHORTPASS  
W: 52 [ ]



W4 LIFT SPEC CH.B  
Y: 65.7μU RMS 40dB  
X: 0Hz + 1.6kHz LIN  
SETUP W9 #A: 5

SIDB Y: 65.7μU  
X: 432Hz  
SHORTPASS ΔX: 78.5625Hz  
W: 52



USING CEPSTRUM AND LIFTED SPECTRUM  
TO LOCATE FAR END OF THE SEWER  
FIELD SEWER: 1 BRICK END  
FIGURE 9.16