

Building Research Establishment Note

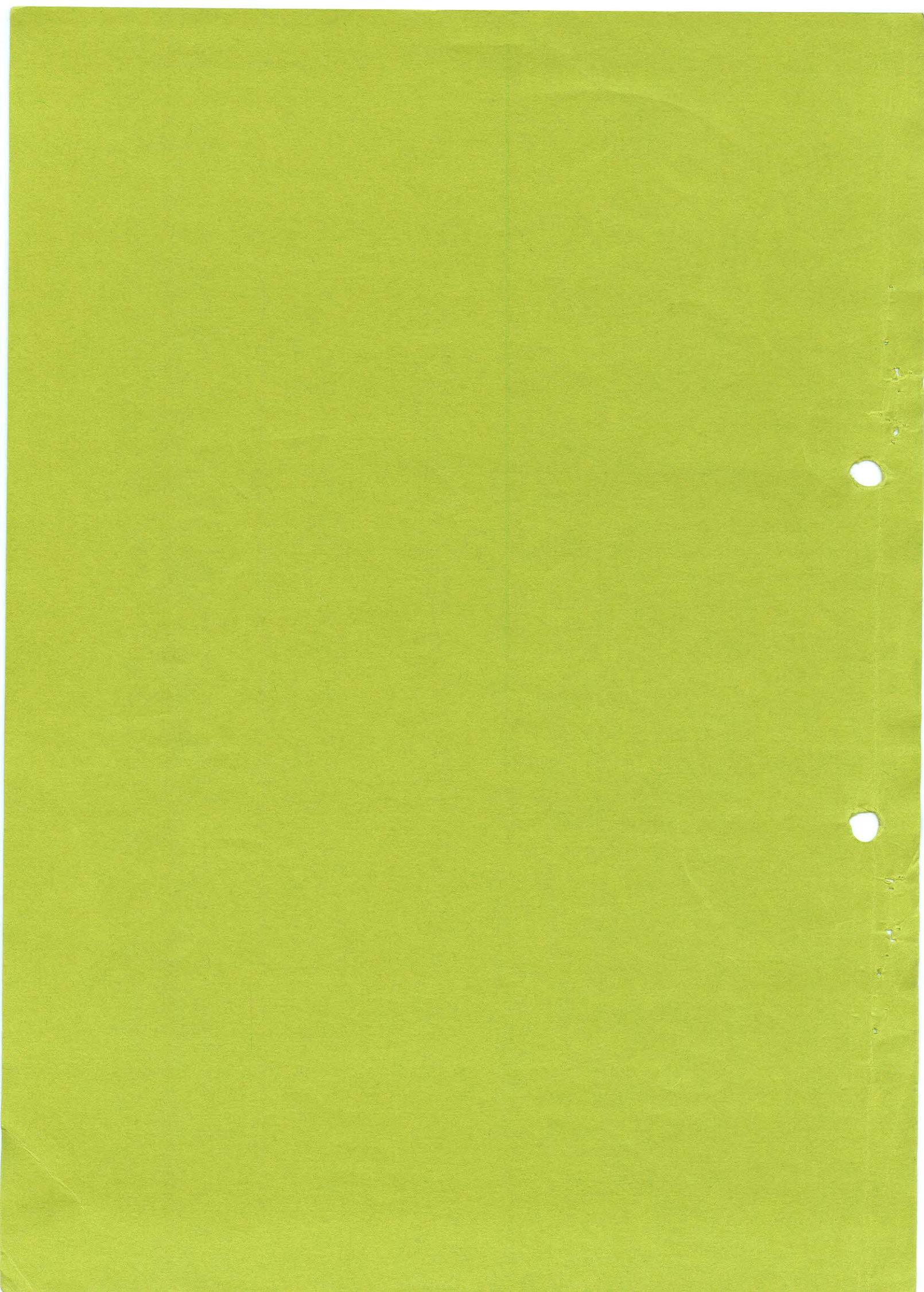
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Vibration tests at South Stoneham House
Southampton University

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Building Research Station



DEPARTMENT OF THE ENVIRONMENT

BUILDING RESEARCH ESTABLISHMENT

NOTE No. N54/84

VIBRATION TESTS AT SOUTH STONEHAM HOUSE
SOUTHAMPTON UNIVERSITY

by

A.P.JEARY, M.BEAK, B.R.ELLIS and J.D.LITTLER

1.SUMMARY

Artificially induced vibrations were used to vibrate South Stoneham House -a hall of residence at Southampton University-so as to ascertain the dynamic properties of the building.

The results from the study are presented here and are used in conjunction with the Engineering Sciences Data Unit, Item 76001, (guide to the evaluation of dynamic response), to compare the actual and the predicted behaviour.

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2. INTRODUCTION

As part of a continuing study of the dynamic behaviour of full-scale structures, a series of induced vibration tests was conducted at South Stoneham House, at the University of Southampton. The tests comprised a study of the dynamic properties of the building and of the response of human volunteers to various levels of vibration. This note is concerned only with the dynamic properties of the building.

The building is a 16 storey shear wall construction with light-weight concrete cladding. The building is founded on a deep concrete raft and is sited on alluvial deposits. It is 44.6 metres tall and 17 by 15 metres in plan. Figure 1 is a schematic of the structure.

3. THE TESTS

The response of the building to induced vibration and to wind excitation was monitored. In the induced vibration tests four vibrators of the BRE system were used, and were positioned on the 15th floor as shown in Figure 1. Accelerometers were used for transducing motion. This type of testing and its' rationale are discussed below.

A record of the response of the building to wind was taken on the night of 8th/9th January 1981.

4. THE VIBRATOR SYSTEM

Previous experience with vibration tests on tall buildings led to an identification of the need for a purpose built eccentric mass vibrator system, and accordingly, in 1976, the BRE let a contract to Bristol University to design and build a system which would meet a stringent specification. The prototype system was completed in December 1977 and the full system was operational by August 1978. Up to the date of these tests the system has been used to test eight buildings and four dams. The results from this work have been published elsewhere (refs 1 and 2).

The vibrator system comprises four exciters, each of which has its' own 'slave' control unit, driven by a master unit which controls the whole system. The frequency required is clocked from a crystal oscillator which is precise to one part in a million. The use of servo control techniques allows the frequency of the vibrators to be controlled to a 0.001 Hz. precision. Operation is possible up to a maximum of 20 Hz.

The exciters each consist essentially of two sets of contra rotating weights to which may be added further weights, thereby allowing the force to be varied. The force produced in this way has been calibrated using a load cell and is well within the 3 per cent of the original specification. With the maximum number of weights attached a force of nearly one tonne peak to peak is achieved at one

Hertz. The servo control system allows each unit to be run either in phase or anti-phase to the master control demand, and is accurate to 0.06 radians. The exciters are mounted on rings of steel designed so that each unit may be rotated to any desired orientation in the horizontal plane.

Certain safety features have been incorporated into the design. For example, to avoid accidental over-excitation, a conscious effort, on the part of the operator, is needed to exceed certain frequency limits.

5. THE RATIONALE FOR THE TESTING

It is assumed that the dynamic response of a structure can be described by the superposition of a series of similar equations, each of which describes the behaviour of a single mode of vibration. This technique is currently popular and forms the basis for most dynamic design methods. However, it will be shown that the model is inadequate in certain cases.

The modal superposition method describes the modal response X_r , for mode r , in the following way:

$$\ddot{X}_r + 4\pi^2 f_r^2 \zeta_r \dot{X}_r + 4\pi^2 f_r^2 X_r = \frac{F_r}{M_r} \quad (1)$$

Where f_r is the natural frequency, ζ_r is the modal damping ratio, M_r is the modal mass and F_r is the modal force.

If the mode shape ($\phi(x,y,z)$) is normalised to a value of 1 at the largest displacement, then Lagrange's equation can be used to show that:

$$M_r = \int_0^H \int_0^B \int_0^L m(x,y,z) \phi^2(x,y,z) dx, dy, dz \quad (2)$$

Where L , B , and H are the length, breadth and height of the building and $m(x,y,z)$ is the mass of that volume defined by dx, dy, dz . It is often assumed that x and y are constants and so the equation reduces to:

$$M_r = \int_0^H m(z) \phi^2(z) dz \quad (3)$$

where $m(z)$ is the mass/ unit height of the building

Measurements of M_r and of mode shape then allow the total mass of the structure to be calculated.

Thus the measurement of natural frequency, damping ratio, and mode shape defines all the necessary dynamic parameters, based on linear visco-elastic theory, since the modal mass can be calculated using equation 3, once f_r , z_r and X_r have been measured for a particular value of F_r .

The induced vibration testing conducted by the BRE seeks to define these parameters by selecting the following test sequence:

1. Choose an orientation for the vibrator, increment the frequency sequentially and produce a response/frequency curve. (normally this chosen orientation is in-line with the geometry of the structure).
2. Select a frequency of resonance (defined by a peak response in (1)) and set the vibrators to operate at this frequency.
3. At this resonance frequency, monitor the directional response (for translational modes) by incrementally rotating an accelerometer in the horizontal sense. Establish the direction of minimum response.
4. Set the vibrators to a direction which is orthogonal to this direction of minimum response, and increment the frequency of the vibrators through the range 0.1 to 10 Hz., taking measurements in the horizontal sense, of vibration amplitudes at each frequency for one reference position in the building. In the jargon of vibration testing this process is known as 'frequency sweeping'.
5. Repeat step 4 for the orthogonal set of modes.
6. Repeat step 4 for the torsional set of modes. This may involve setting the vibrators at opposite sides of the building to operate in a anti-phase.
7. Set the vibrators to a frequency of resonance, take an accelerometer to various locations throughout the building in turn, and measure the vibration amplitude and phase at each position.
8. Repeat (7) for each mode of vibration in turn.
9. Tune the vibrators to a frequency of resonance, and monitor the the decay of oscillation which results when the vibrators are suddenly turned off.
10. Repeat (9) for each mode of vibration in turn

11. Repeat (10) at various amplitudes of interest.

Wherever possible, recordings of the response of the structure to wind excitation should be obtained.

In order to obtain acceptable statistical estimates of natural frequency and damping ratio it is necessary to use stationary samples of data. It has been found that for buildings with long time constants ($T = 2$ frzr) it is uncommon to obtain stationary samples from sequential data and ensemble averaging techniques have to be used. The methodology for this type of analysis has been detailed previously (references 3 and 4).

In fact, in these tests steps 1 to 3 were omitted, and the vibrators were aligned with the geometry of the building.

6. RESULTS

With the vibrators oriented appropriately for examining the response in the X-X modes(for orientation see fig. 1), the frequency of excitation was incremented. Figure 2 shows the results of this test. The procedure was repeated for the Y-Y and the torsional modes and the results from these tests are shown in Figs.3 and 4 respectively.

The modes of vibration identified in the frequency incrementing tests were then examined in detail. Figure 5 shows the results of the investigation of the variation of maximum displacement with height (mode shapes) for each of the resonances discovered. The apparent mode at 4.5 Hz. in the Y-Y direction was investigated, but was found to be "non-classical". For this reason it is not included in figure 5.

A search for the torsional centre of the building was made and the measurements are shown in Figure 6. This shows that the centre of torsion is located inside the lift shaft.

With the vibrators oriented to excite the fundamental mode in the X-X direction a check was made on the directionality. Figure 7 shows, somewhat surprisingly, that the principal direction for the X-X1 mode is some 10 degrees out-of-line with the geometrical axes of the building. Whilst no direct measurement was made in the Y-Y orientation, it can be assumed that these modes are at 90 degrees (geometrically) to the X-X modes.

Adjustments to the number of weights on each vibrator allowed tests to be conducted at various amplitudes. Table 1 lists the principal results obtained in these tests. Decays of oscillation were recorded for each of the resonances and are depicted in Figures 8 to 25. Additionally, the decay of oscillation for the X-X1 mode was studied in rather more detail than is usual by continuing the recording of the decay until the vibration amplitude was too small to distinguish from the background noise level.

Figures 26 to 28 show these extended decays of oscillation. The plots show the damping level to decrease with decreasing amplitude and that at small amplitudes the values tend to a constant value over large amplitude ranges. A disturbing feature of these plots (from the point of view of understanding the damping behaviour) is the non-repeatability of the result. A particular decay seems to be a function of the largest amplitude obtained as well as a function of the instantaneous amplitude. It is well to point out, though, that this effect is relatively small. The relationship of damping value against frequency squared is shown in fig.29, and, as can be seen, the form of the relationship is in broad agreement with the linear relationship found for other structures.

The response of the building to wind excitation was monitored on the night of the 8th/9th of January between 3 p.m. and 4 a.m.. At these times the velocity of the wind was monitored at roof level from an anemometer operated by Southampton University. The velocity of the prevailing wind during this time varied between 2.1 and 4.1 metres/sec.. The response of the building was recorded on magnetic tape and was returned to the laboratory for subsequent spectral analysis. Figs. 30 and 31 show the results of this analysis in the two major axes of the building. The data were then used as a basis for comparison of the measured response with that predicted by the ESDU 76001 guide to the evaluation of the response of structures to wind excitation.

7. THE RESPONSE OF THE BUILDING TO WIND LOADING

Appendix 1 gives the results of the calculations for the response of South Stoneham House to that wind which, on average, will occur only once in fifty years. The calculations are based on the ESDU 76001 method.

As can be seen the predictions are for the case of the wind which actually occurred. There is a difference of a factor of 20 between the measured and predicted response. It should be borne in mind that this is for a light wind, and the following factors may affect this result:

- (i) The proximity of the anemometer to the building will tend to give underestimates of the wind speed. (At Sheffield an anemometer 6 m. above roof level had to be corrected by 25% to give a true wind speed unaffected by the influence of the building)
- (ii) This type of anemometer, operating at low speeds tends to give erroneous readings because of the time constant of the device itself.

For the ESDU 76001 method to predict a response of that which was measured for this building, it is necessary for the wind speed used to be in the region of 15 metres/sec.. This is clearly so much larger than the measurement as to be indicative of a significant difference between the real response and that predicted by the ESDU 76001 guide, for this building under the conditions of measurement.

8. DISCUSSION

There are some aspects of the behaviour of South Stoneham House that are worthy of comment. The first concerns the damping behaviour. Long records were taken after the vibrators were suddenly switched off, and, as can be seen from figs 8 and 26 to 28 the value of damping at first decreases with decreasing amplitude but later, at very small amplitudes it tends to remain at a constant value.

The second point of interest is that the modal directionality is shifted by almost 10 degrees from the geometric axes of the building. This fact and the fact that the torsional centre is shifted by 2 metres from the centre of geometry, show that the response to wind excitation, as calculated theoretically, should have some corrections for these factors.

The mass of the building is calculated from these tests as approximately 4.5 Mtonnes and the modal stiffness is around 100 MN/m (calculated in both of the major axes). Both these figures are somewhat low for this type of structure.

The last item worthy of special mention is that shown in table 2. The natural frequencies of the building were monitored for small changes during the test period. The changes noted were up to two hundredths of a Hertz for the two fundamental translation modes, and up to five hundredths of a Hertz for the fundamental torsional mode. These frequency changes bear no obvious correlation with physical occurrences external to the building (i.e. either the temperature or tidal water height changes). The changes monitored do, however serve to show the range of change possible in such a building in normal conditions.

9. ACKNOWLEDGEMENT

The authors are grateful to the University of Southampton for the provision of help and facilities during the testing, also for the provision of working drawings of the building.

10. REFERENCES

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3. JEARY A.P.: The dynamic behaviour of the Arts Tower, University of Sheffield, and its implications for wind loading and occupant reaction. BRE CP48/78. 1978

4. JEARY A.P.: Temporal requirements for the analysis of random data. BRE N87/83. 1983.

TABLE 1 SUMMARY OF MODAL INFORMATION

MODE	FORCE N p-p	FREQ. Hz.	ACCN. g p-p (x10E-2)	AMP. mm. p-p	DAMPING % crit.	Mr MKg	Kr MN/m
XX1 <i>15m</i>	14582	1.305	1.836	2.68	2.40	1.568	105.4
	11766	1.305	1.491	2.18	2.34	1.595	107.2
	9086	1.315	1.164	1.67	2.29	1.618	110.4
	6226	1.315	0.818	1.18	2.28	1.576	107.6
	3398	1.321	0.455	0.65	2.23	1.582	109.0
YY1 <i>17m</i>	15146	1.330	1.891	2.66	2.75	1.379	96.3
	12313	1.335	1.600	2.23	2.56	1.425	100.3
	9435	1.340	1.236	1.71	2.44	1.483	105.1
	6466	1.340	0.909	1.26	2.48	1.357	96.2
	3523	1.345	0.498	0.68	2.38	1.417	101.2
	535	1.350	0.080	0.11	2.10	1.497	107.7
XX2	85335	6.62	1.930	0.11	4.49	—	—
YY2	51030	6.75	1.020	0.06	5.80	—	—

TORSIONAL RESPONSE

	TORQUE Nm p-p	FREQ. Hz.	ANG DISP. rads. x 10E-4	DAMPING % crit.	Ir Kg mE2 x 10E8	Kr Nm/rad. x 10E8
01	186728	1.830	2.08	1.66	1.96	2.04
	152318	1.840	1.75	1.68	1.86	1.93
	117106	1.850	1.35	1.67	1.84	1.92
	81121	1.860	0.97	1.53	1.92	2.00
	44579	1.875	0.56	1.28	2.15	2.24
	7011	1.915	0.09	—	—	—
02	505462	5.81	0.117	3.11	4.17	—

TABLE 2 VARIATION OF NATURAL FREQUENCIES WITH TIME

MODE XXI	MODE YYI	MODE OI
Freq. Date Time Vib	Freq. Date Time Vib	Freq. Date Time Vib
1.335 2/1 12:30 2-5	1.330 3/1 15:30 4-5	1.87 3/1 09:30 4-2
1.335 2/1 3-5	1.335 4-4	1.83 10:00 4-5
1.315 2/1 4-5	1.34 4-3	1.84 4-4
	1.34 4-2	1.85 4-3
	1.345 4-1	1.86 4-2
	1.35 4-0	1.875 4-1
1.315 4/1 17:00 4-5		1.915 4-0
		1.82 13:40 4-5
1.315 5/1 08:45 4-5	1.33 4/1 08:45 4-5	1.82 14:30 4-5
	1.335 3-5	
1.315 6/1 16:30 4-3	1.33 2-5	
1.305 4-5	1.34 1-5	
1.305 4-4		
1.315 4-2		
1.321 4-1	1.33 5/1 10:10 4-5	
1.315 7/1 11:20 4-3		
1.315 13:20 4-3		
1.315 14:25 4-3		
1.315 16:35 4-3		
1.310 17:20 4-5		
1.310 8/1 08:45 4-5		
1.315 08:55 4-3		
1.315 11:30 4-3		
1.325 11:35 4-3		
1.330 13:25 4-3		
1.327 16:25 4-3		
1.315 16:30 4-3		
1.310 19:40 4-5		

'vibs' readings refer to the number of vibrators and the number of sets of weights used on each one.

APPENDIX 1 ESDU 76001 PARAMETER VALUES AND CALCULATIONS

Basic wind speed = 3.6 m/s. (measured at roof level)

$$z_0 = 0.4$$

$$\bar{c} = 0.25$$

~

$$Z = 1/2(H-d) = 22 \text{ m.}$$

$$\bar{V}_H = 3.6 \text{ m/s}$$

$$H = 44.6 \text{ m.}$$

$$W = 17.0 \text{ m.}$$

$$n_l = 1.35 \text{ Hz.}$$

$$\gamma_l = 2.1 \%$$

$$m_l = 1.5 \times 10^6 \text{ Kg}$$

$$\frac{x}{L}_u = 78$$

$$\tilde{n}_x = \frac{n_l \frac{x}{L}_u}{\bar{V}_z} = 29.25$$

$$\frac{y}{L}_u = 34$$

$$\tilde{n}_y = \frac{n_l \frac{y}{L}_u}{\bar{V}_z} = 12.8$$

$$\frac{z}{L}_u = 27$$

$$\tilde{n}_z = \frac{n_l \frac{z}{L}_u}{\bar{V}_z} = 10.1$$

$$\frac{n_W}{\frac{y}{L}_u} = 0.675$$

$$\frac{n_H}{\frac{z}{L}_u} = 2.23$$

$$I_u = 0.191$$

$$\phi_{uu} = 0.0118$$

$$B(n)^2 = 2.25$$

$$\frac{J_H^2}{H} = 0.021$$

$$\frac{J_W^2}{W} = 0.05$$

$$F_1 = 0.5 p_C \frac{\bar{V}^2}{D_z} W_H / (2 \bar{C} + 2)$$

$$= 2417.3$$

$$nS(n) = 4 J_H^2 \times J_W^2 \times \frac{F_l^2}{u} \times \phi_{uu} \times I_u^2 \times B(n)$$

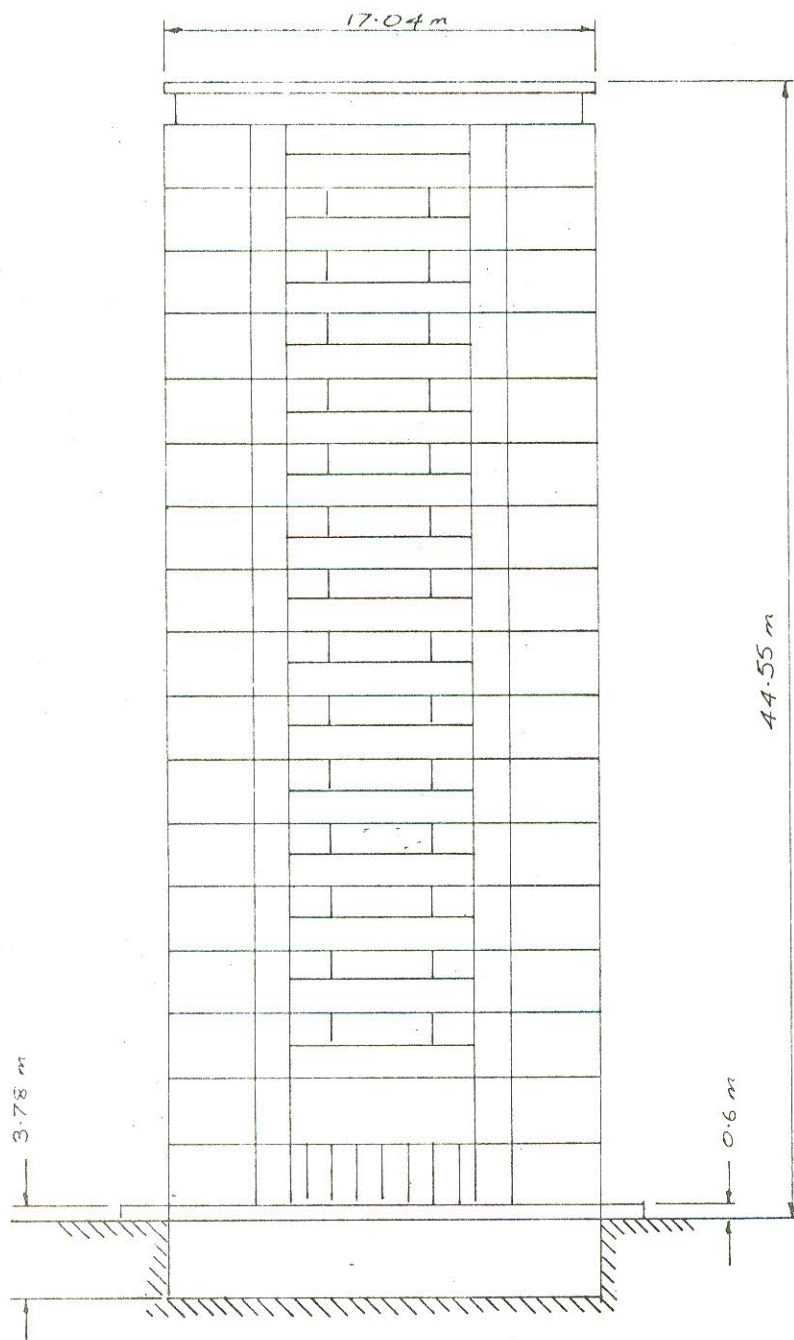
$$= 124.45$$

$$g_D = 2 \log_e (n T)_1 + \frac{0.577}{2 \log_e (n T)_1} = 4.26$$

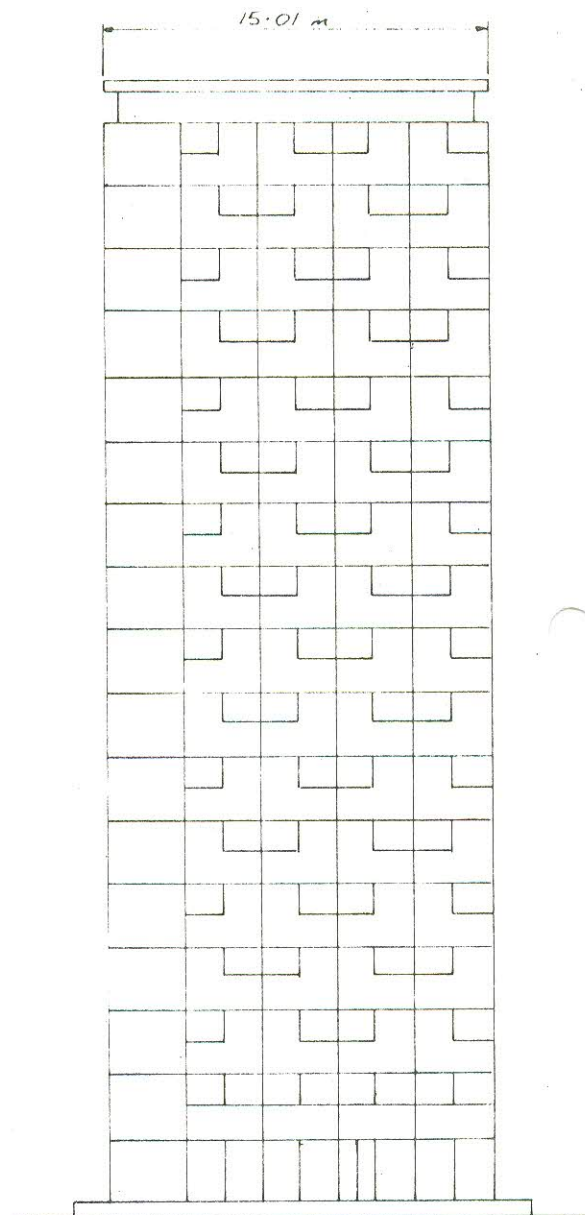
$$\ddot{x}_{\max} = g_D \sqrt{\frac{\pi nS(n)}{4 \times \xi}} \cdot \frac{u}{m} \quad \text{m/s}^2 = 193.8 \times 10E-6$$

$$= 19.75 \times 10E-6 \text{ g} \quad \text{or} \quad 0.0027 \text{ mm. pk.}$$

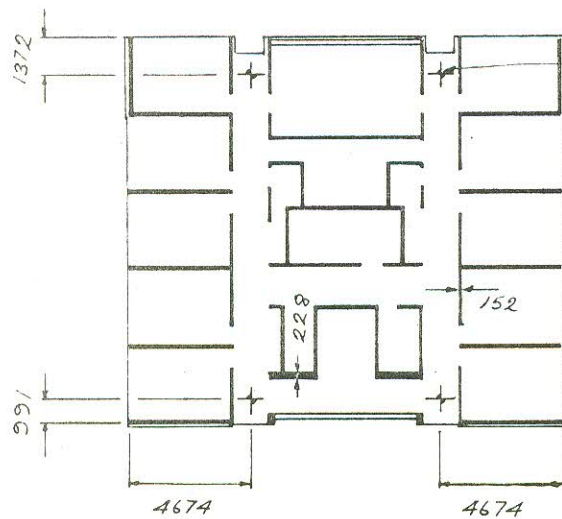
measured response at this time was 0.056 mm. pk.



NORTH ELEVATION



EAST ELEVATION

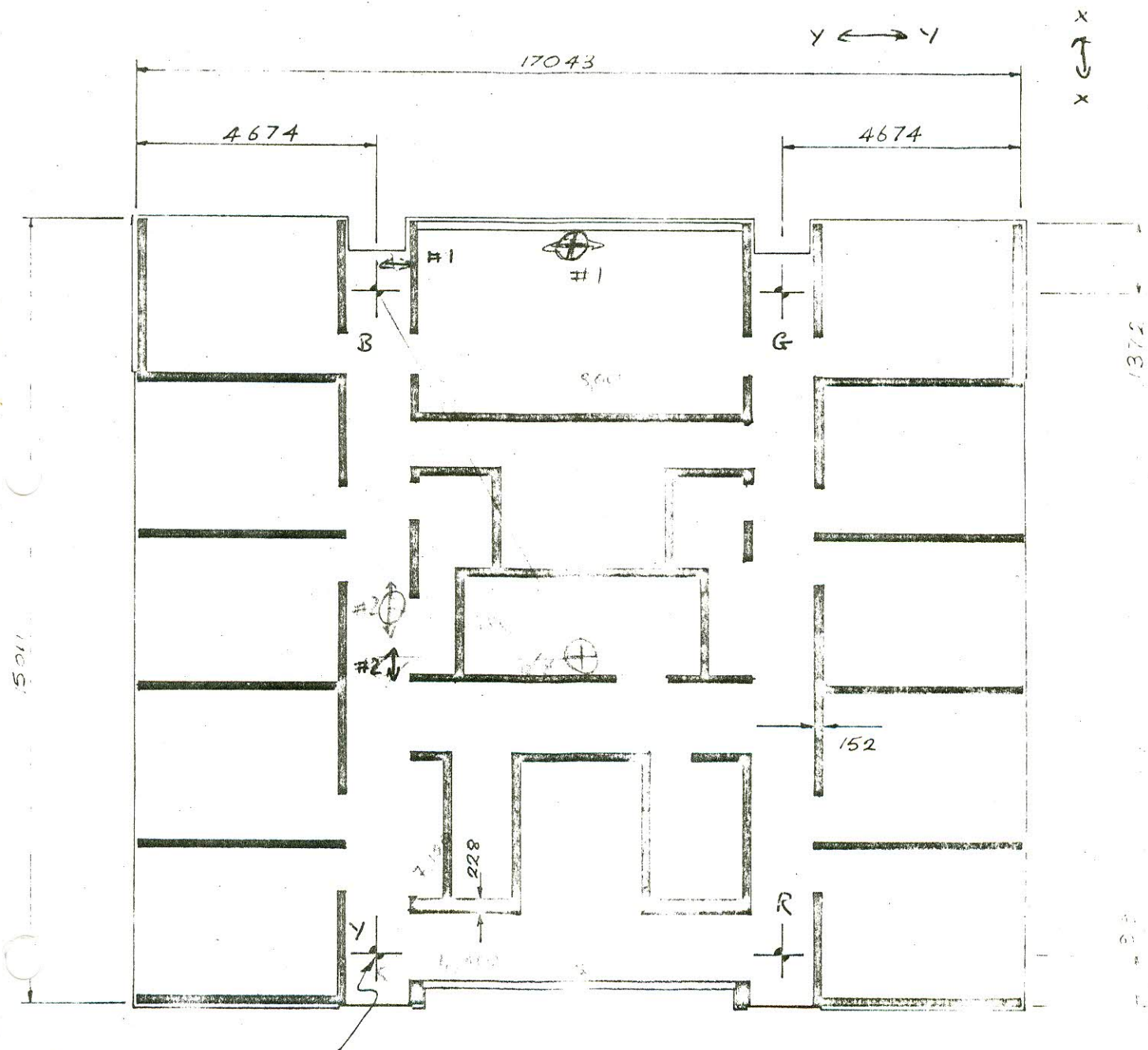


TYPICAL FLOOR PLAN (15th)

POSITION OF VIBRATORS
ON 15th FLOOR



SOUTH STONEHAM HOUSE



POSITION OF VIBRATORS ON 15TH FLOOR

0 1 2 3 4 5 10m

TYPICAL FLOOR PLAN (15TH)

⊕ Centre of torsion

FIG 2 SOUTH STONEHAM FREQUENCY SWEEP

X-X DIRECTION

Frequency range

Vibrations

0.9 - 2.5

no. sets

2.5 - 3.6

4-3

3.5 - 6.7

4-1

6.0 - 10.0

4-1/2

Max 169.69 $\times 10^6$ mm/Newton
at 1.33 Hz

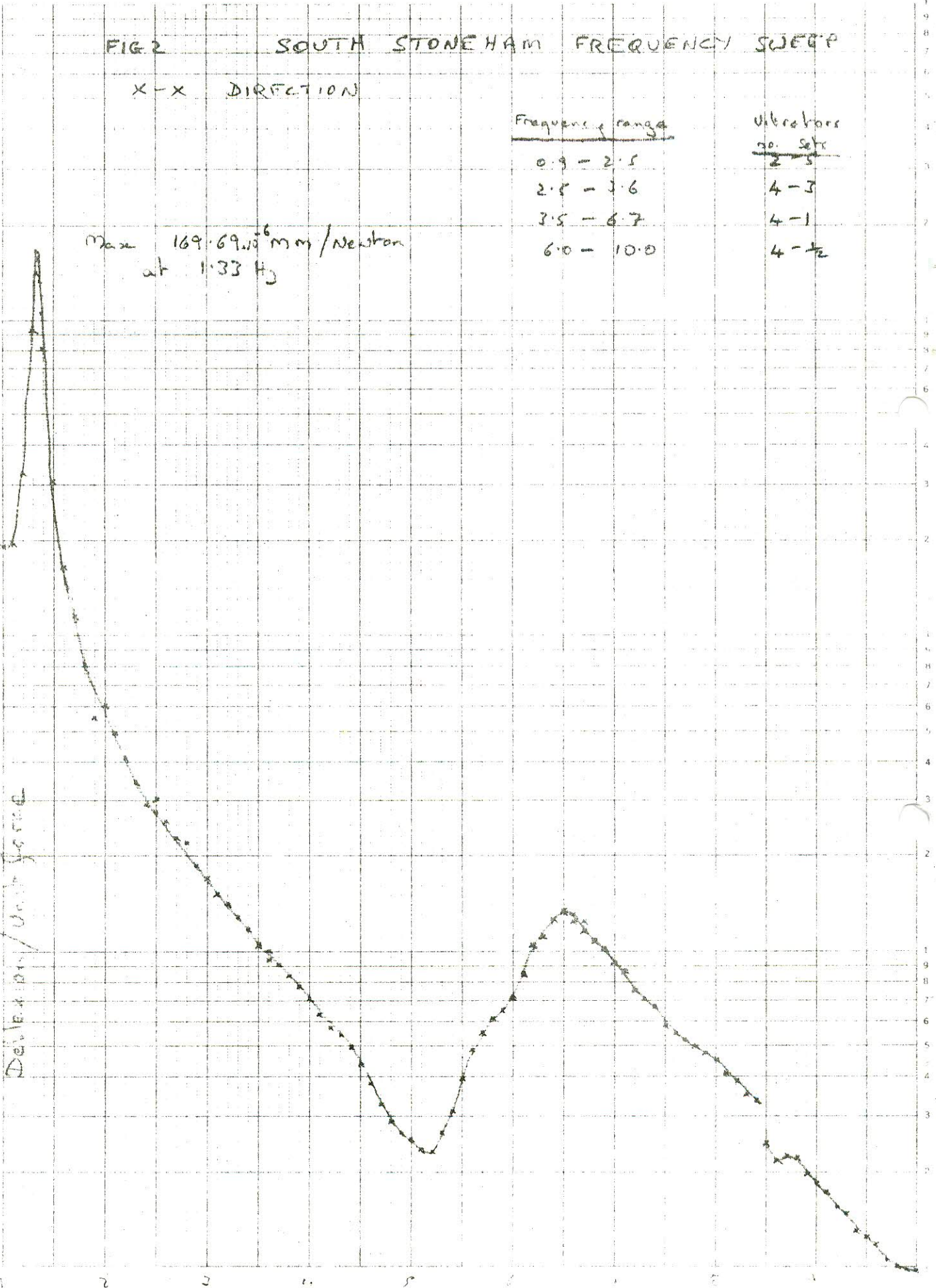
mm
Newton

log 4 Cycles x 2 mm and cm

Graph Data Ref 5542

WELL

Deflection/Unit Force



(Hz)

FIG 3

SOUTH STONHAM

FREQUENCY SWEEP

Y-Y DIRECTION

P100
No. 100

Mass $18.14 \cdot 10^{-5}$ m.m./Newton

Frequency 1-10

Vibrates

1-3

4-5

3-5.5

4-1

5.8-10

4-1/2

Log 4 Cycles x 2 mm and cm

Graph Data Ref. 5542

CHALL
WELL

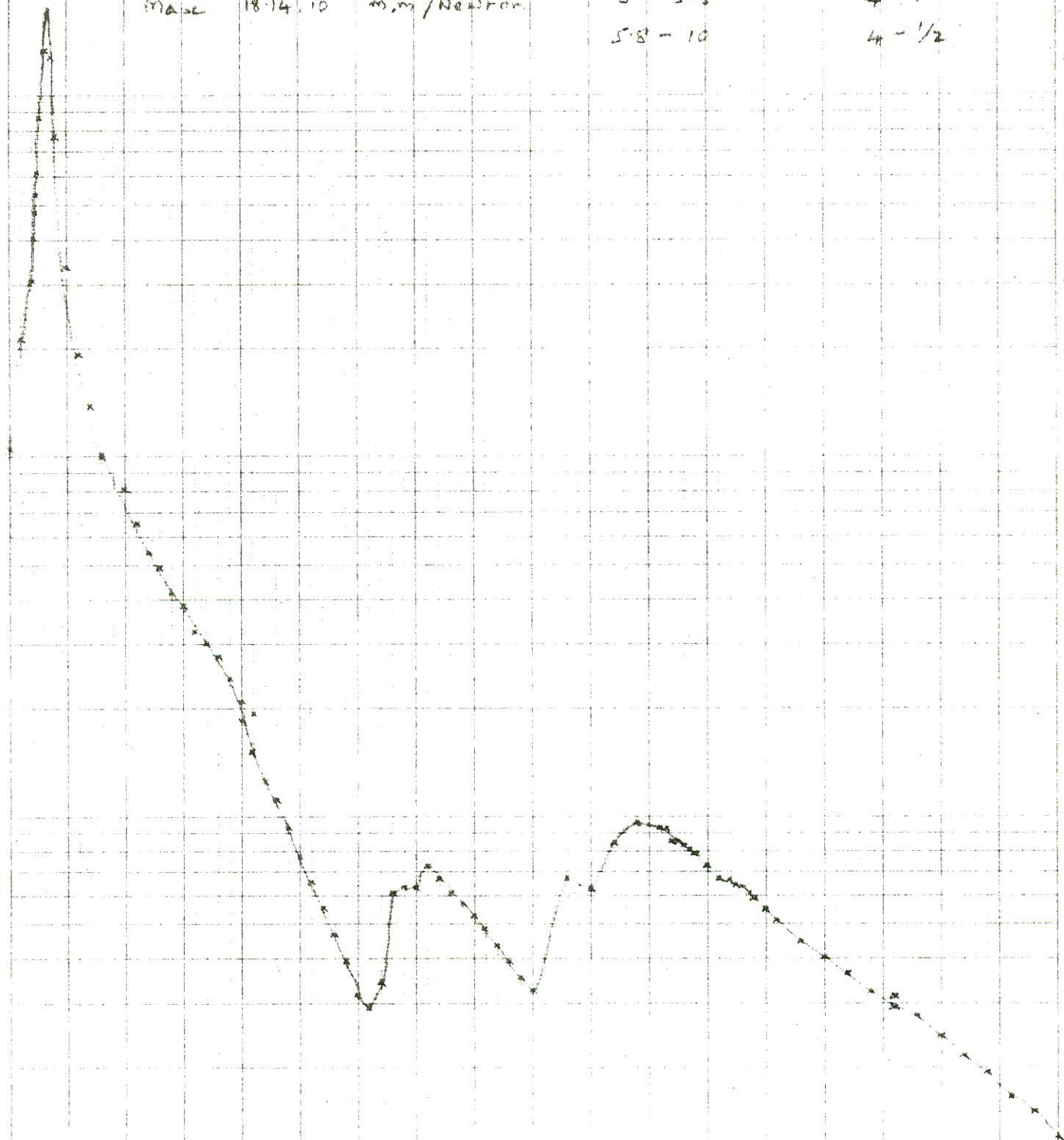


FIG 4 SOUTH STONEHAM FREQUENCY SWEEP
TORSION

Frequency Range

Vibrators

1 - 2.0

4-5

82V Anti

1.8 - 4.6

4-2

82V Anti

4.4 - 8.8

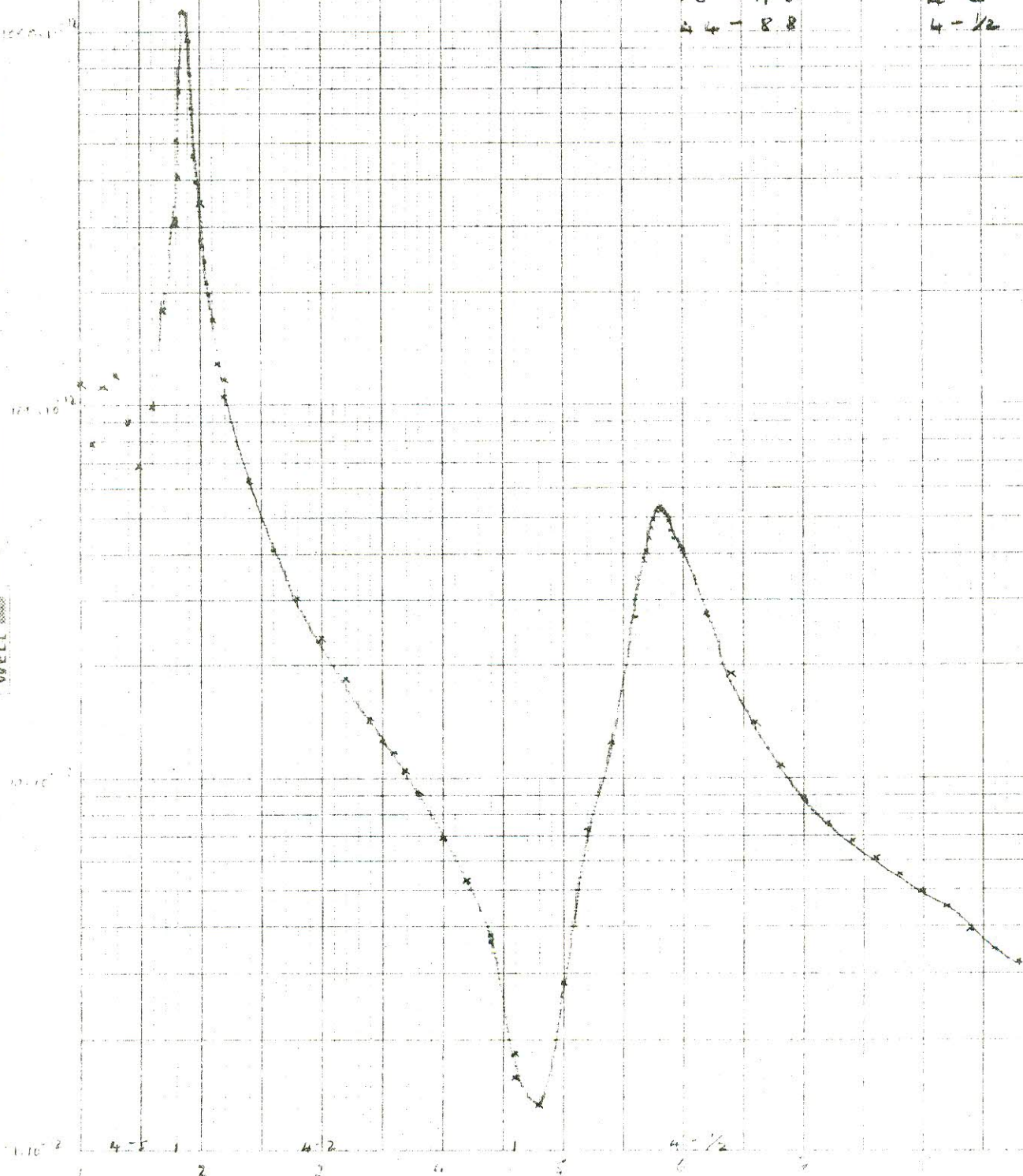
4-1/2

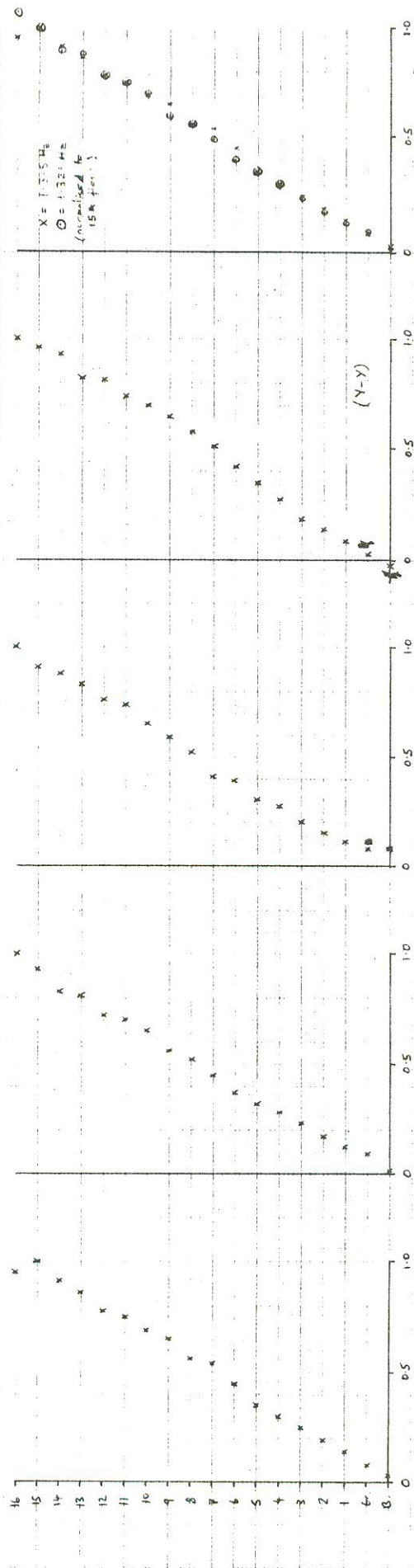
82V Anti

Log 4 Cycles x 2 mm and cm

Graph Data Ref. 5542

WELL



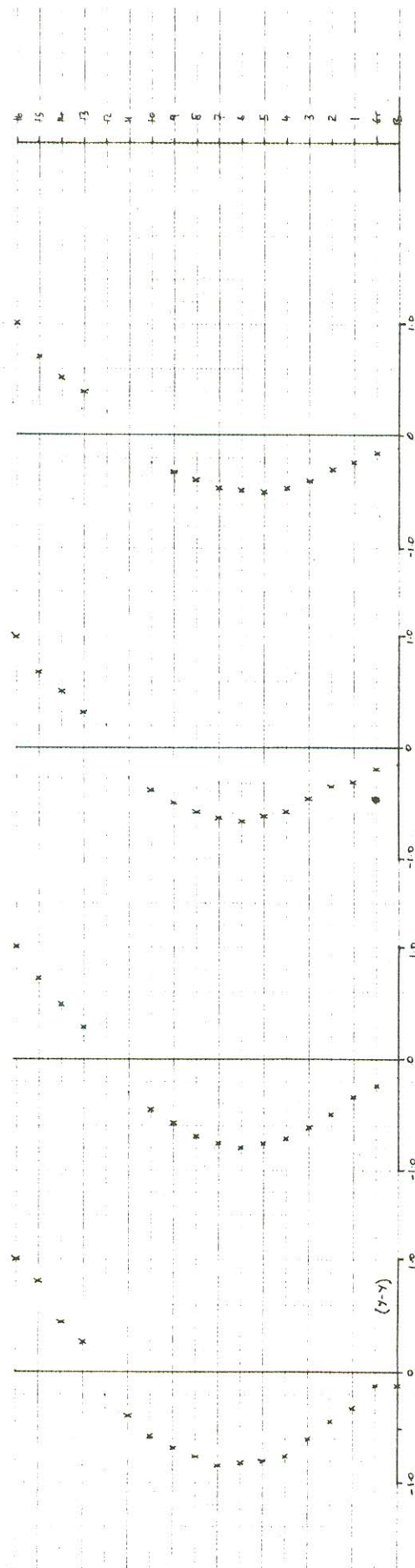


$X - X_1$

$Y - Y_1$, 1.33 Hz
(4 Vib, 5 wt)

$X - X_1$, 1.321 Hz
(4 Vib, 1 wt)

$X - X_1$, 1.315 Hz
(4 Vib, 5 wt)



Q_2 , 5.81 Hz
(4 Vib, 1 wt)

$X - X_2$, 6.62 Hz
(4 Vib, 1 wt)

$Y - Y_2$, 6.75 Hz
(4 Vib, 5 wt)

$Y - Y_2$, 7.30 Hz
(4 Vib, 5 wt)

$F = 2.5$

FIG-6

Centre of torsion

Normalised model shape displacements
at top floor level

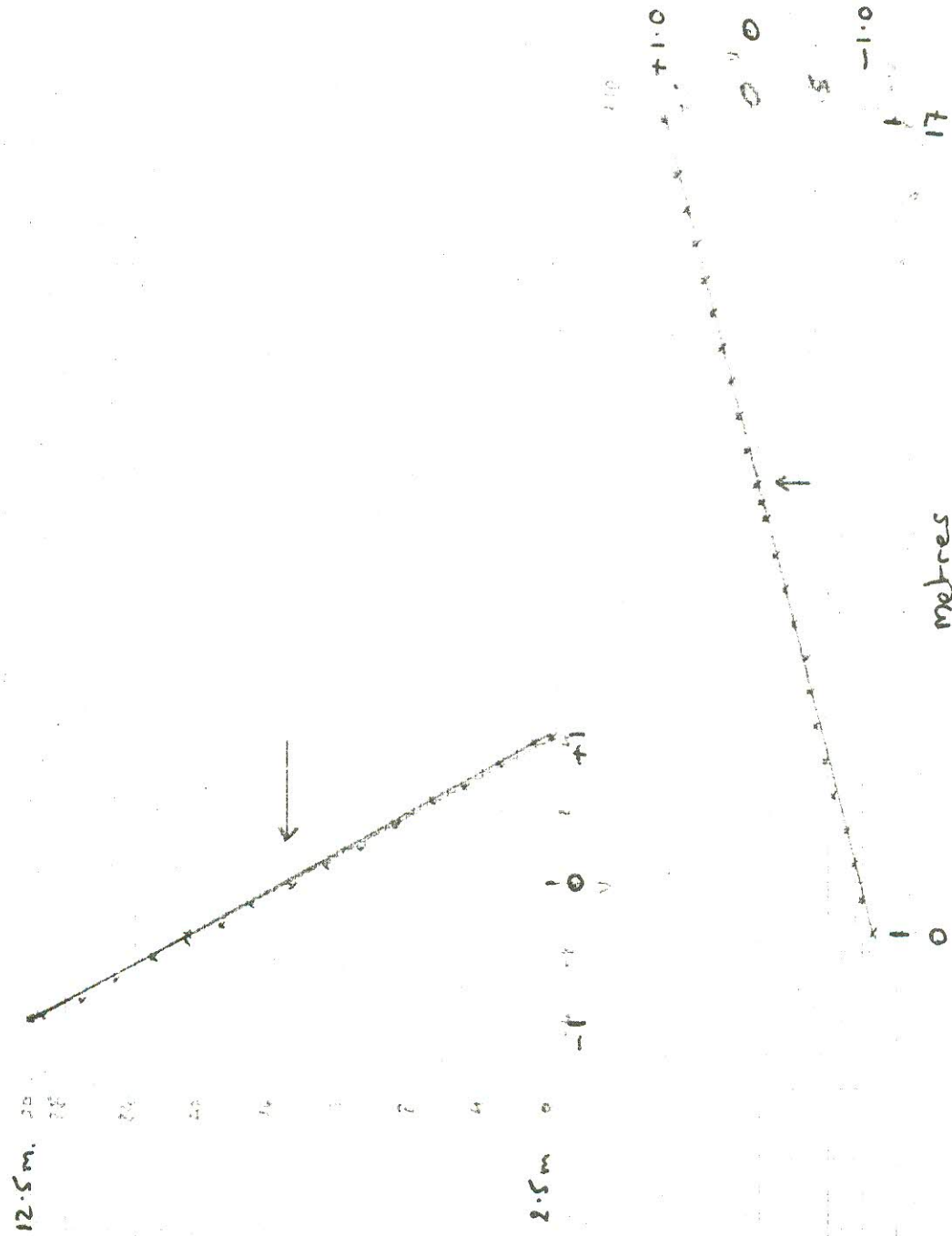


FIG 7 DODGE DIRECTION SEARCH

4 VIBS 5075 1315 HZ

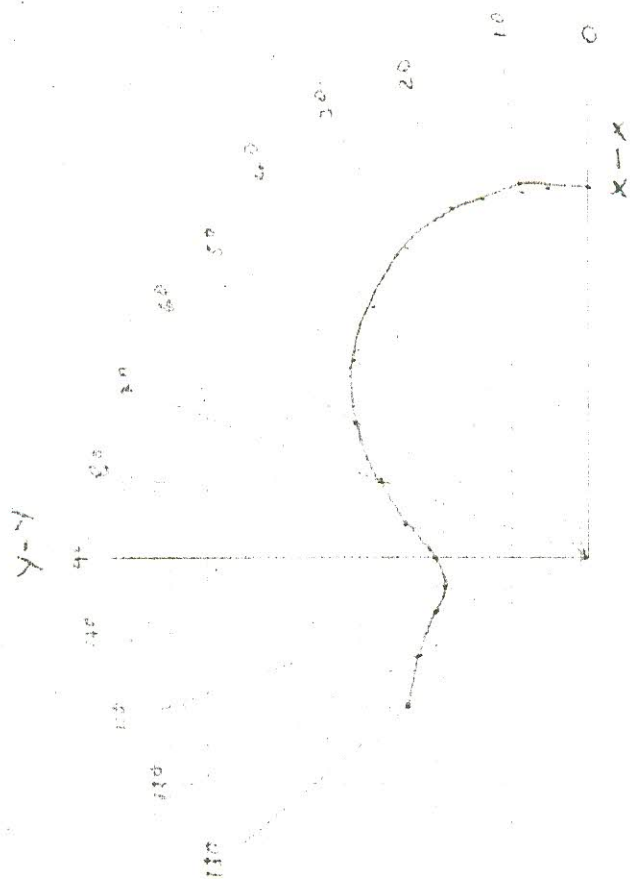


FIG 2

Decay from 4-5 at 16.40 on 6/1/81

Acc #2 X-X Dim

MODE XX1

2.68 mm X
P-P

2.65%

1.17 mm

2.36%

0.302 mm

1.74%

1.34%

1.37%

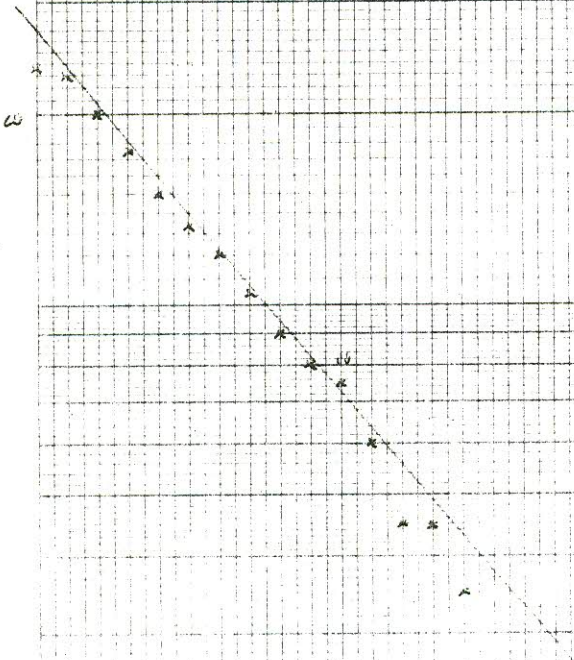
FIG 9

1.25 Hz V-Y

4-0

2/1/81

17.40



$$\xi = 2.1\%$$

31-7

4-1

4/1/82

17-20

$$\xi = 2.38\%$$

FIG 11

1-24 Hg

Y-Y

4-2

3/1/81

16.50

$$\xi = 2.48\%$$

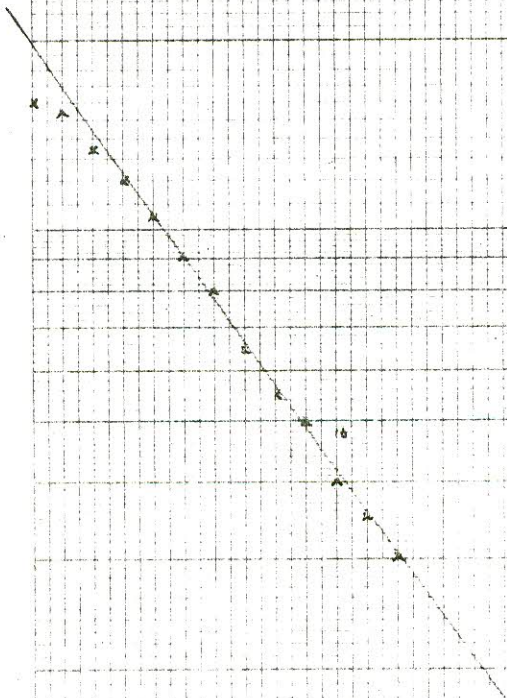


FIG 12

1.34 Hz

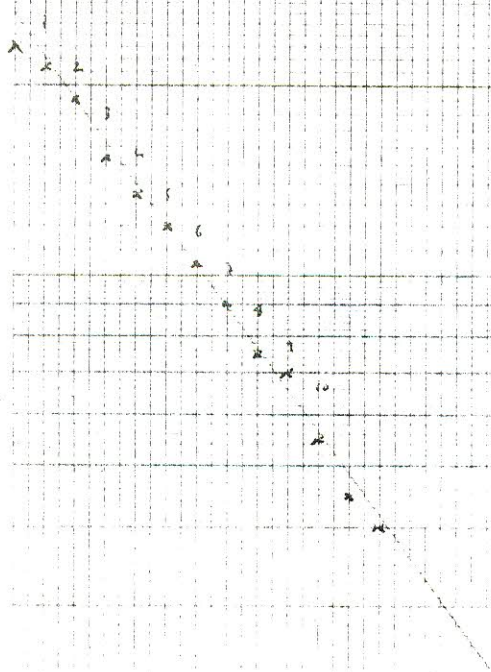
4-3

Y-Y

3/1/81

16.30

$$\xi = 2.44 \%$$



3/1/81 16 16

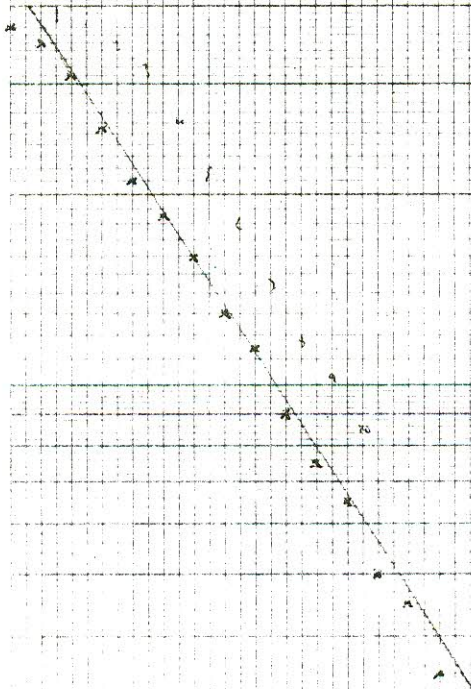
$$\xi = 2.56\%$$

FIG 14

1.32 H₂ 7-7

4-5

3/1/81 16.00



$$\xi = 2.75\%$$

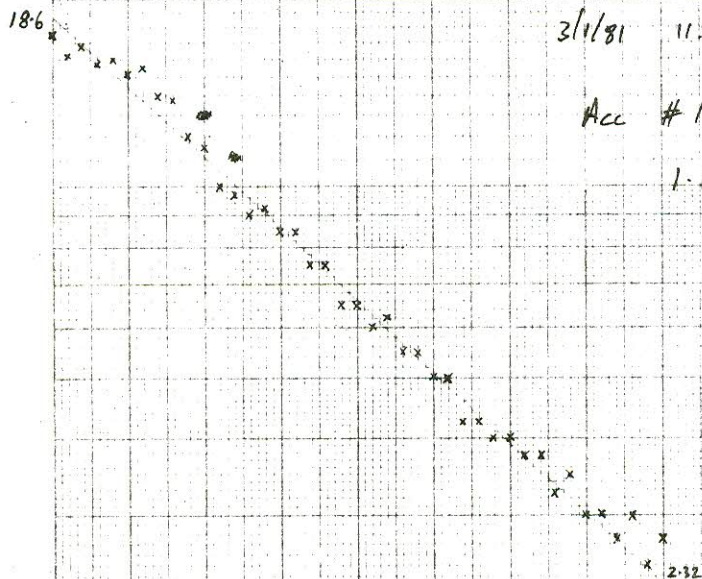
FIG 15 1.83 Hz B & Y antiphase.

4 uibs, 5 uib.

3/1/81 11:14

Acc #1

1.66%



1.84 Hz B & Y antiphase

4 uibs, 4 uib uib.

3/1/81 11:29

Acc #1

1.68%

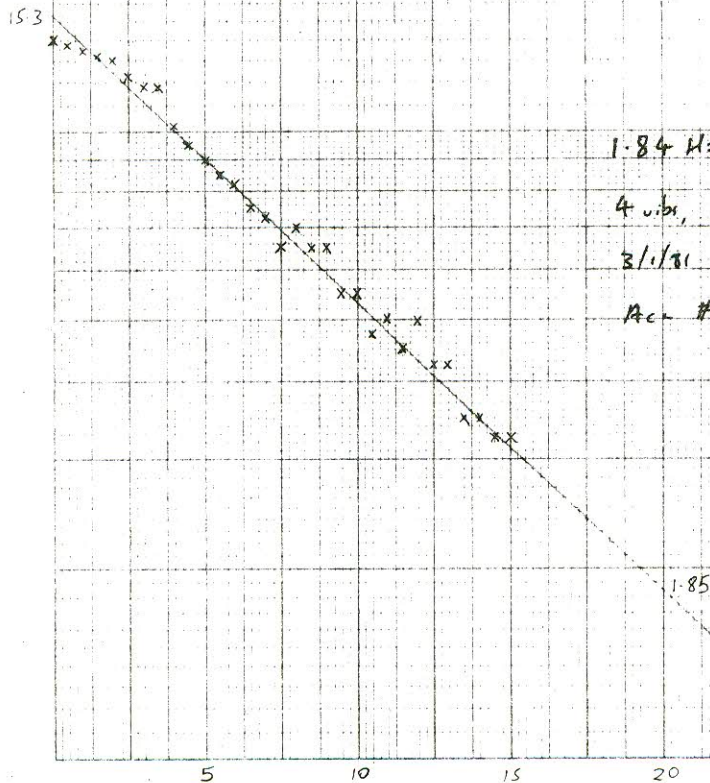


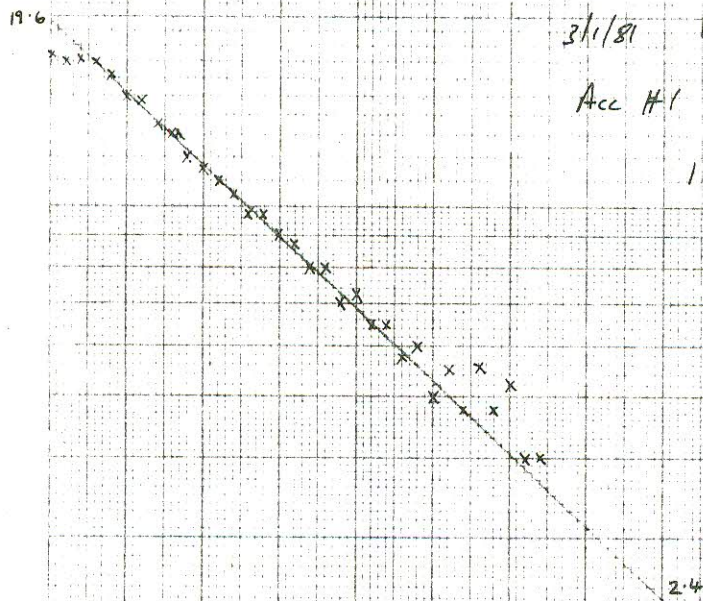
FIG 16 1.85 Hz B & Y antiphase.

4 vibr, 3 sets wts.

31/1/81 11:45

Acc H1

1.67%



1.86 Hz B & Y antiphase

4 vibr, 2 sets wts.

31/1/81 12:01

1.53%

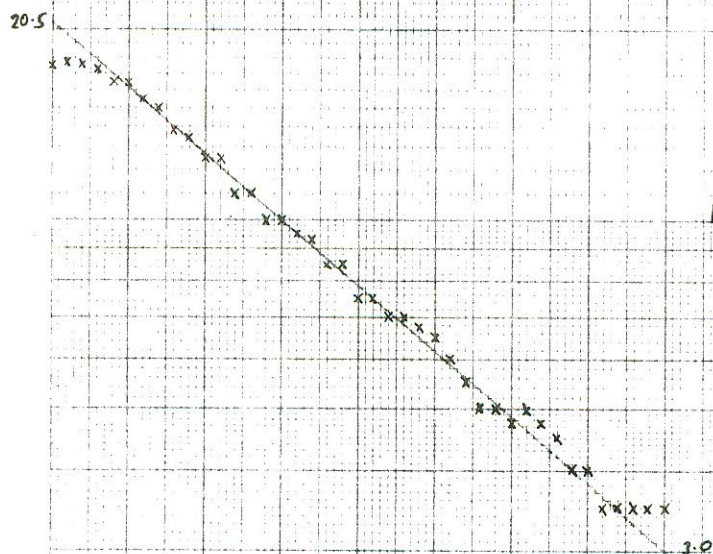


FIG 17 6.62 Hz

4 Vib, 1 set w/b

5/1/81 19:00

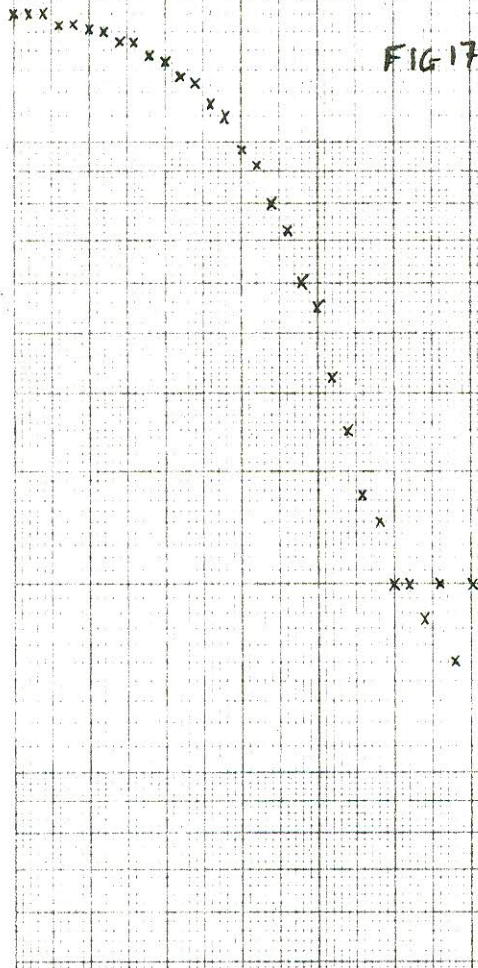


FIG 18

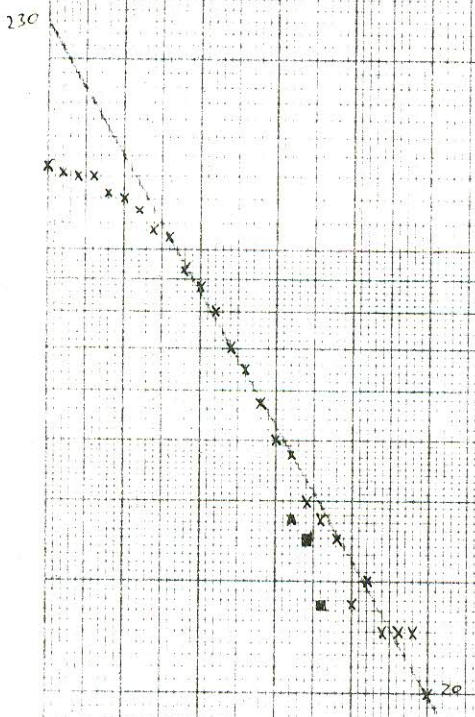
5.83 Hz

4 vibs, 1/2 set wts.

3/1/81 09:30

(X-X?)

3.11%



5.83 Hz

4 vibs, 1/2 set wts

3/1/81 09:30

(Y-Y?)

2.76%

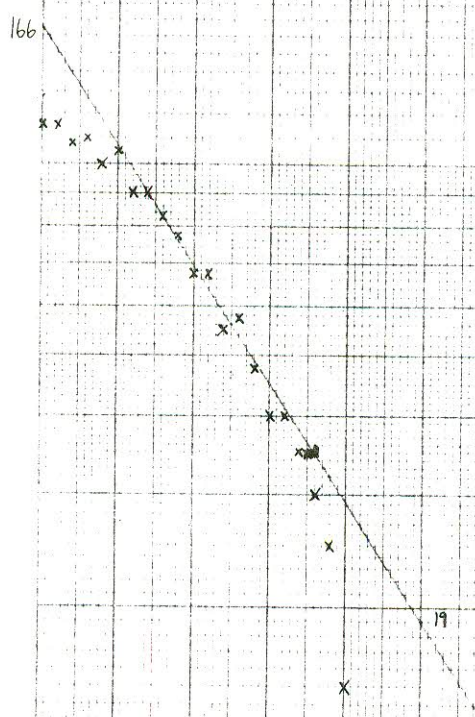


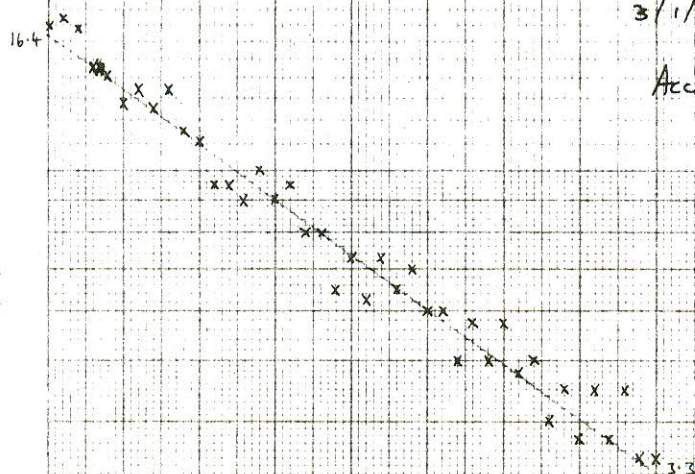
FIG-19 1.875 Hz B & Y antiphase

4 vibr, 1 sat wtr

3/1/81 12:15

Acc #1

1.28%



5.81 Hz B & Y antiphase

vibr in x-x dir

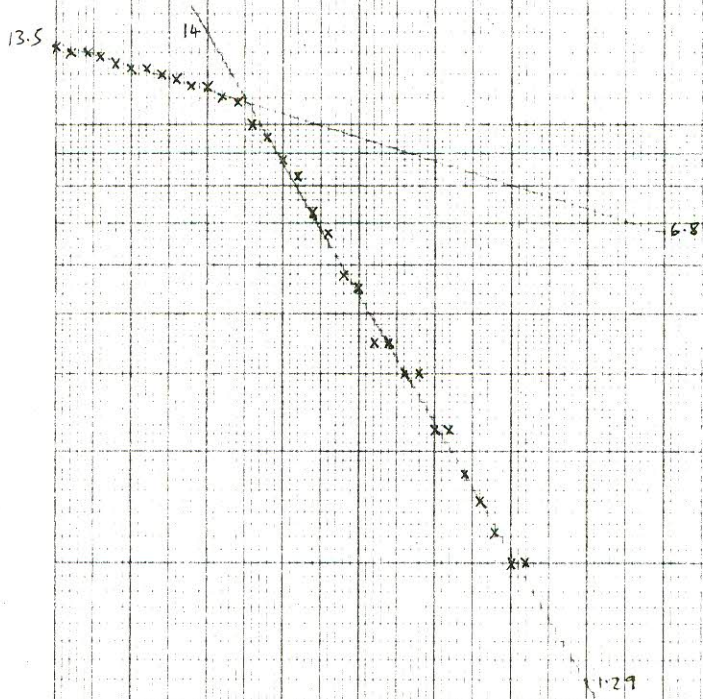
4 vibr, 1 sat wtr

6/1/81 19:20

0.55%

Ken

3.04%



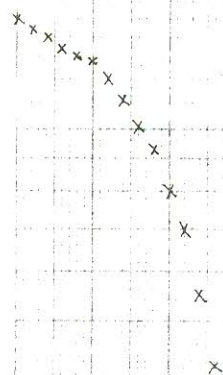
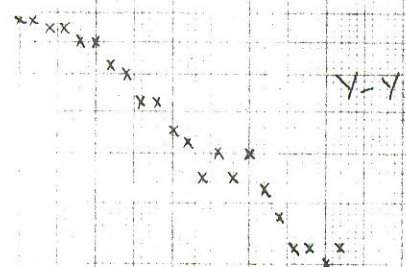
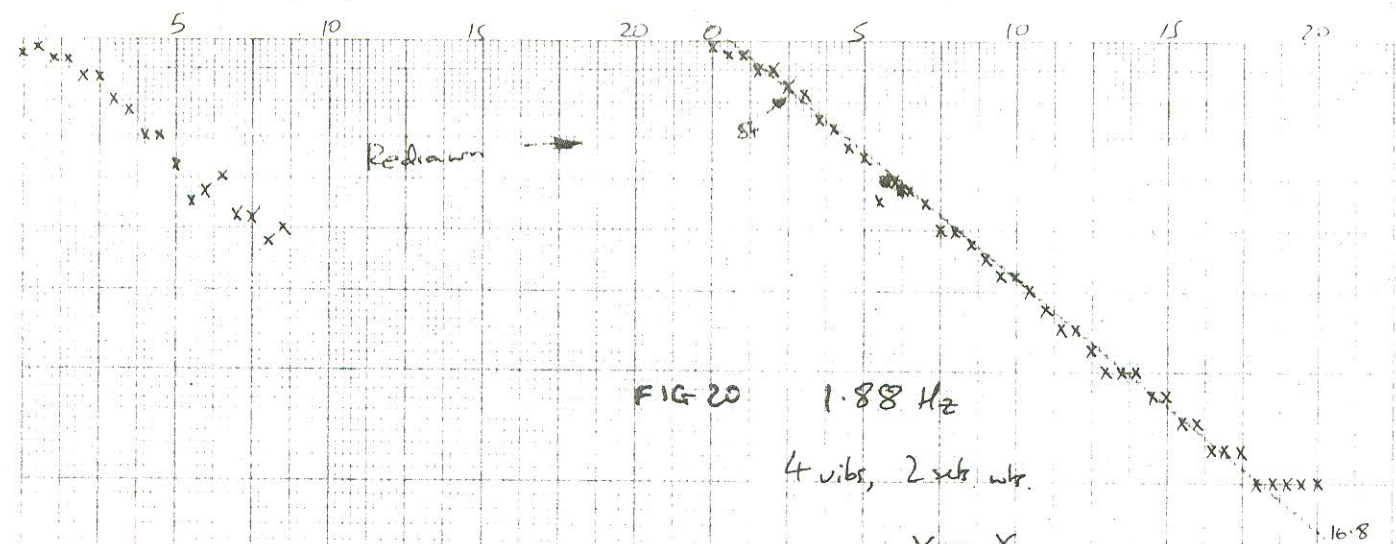


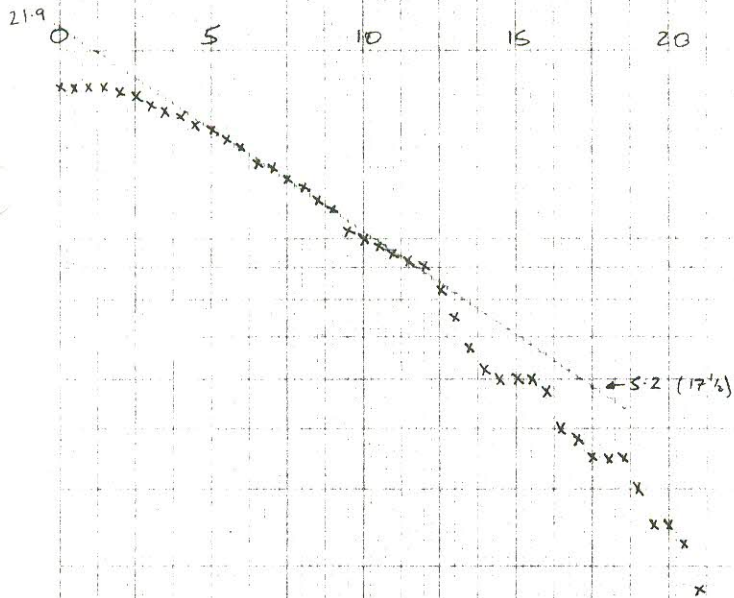
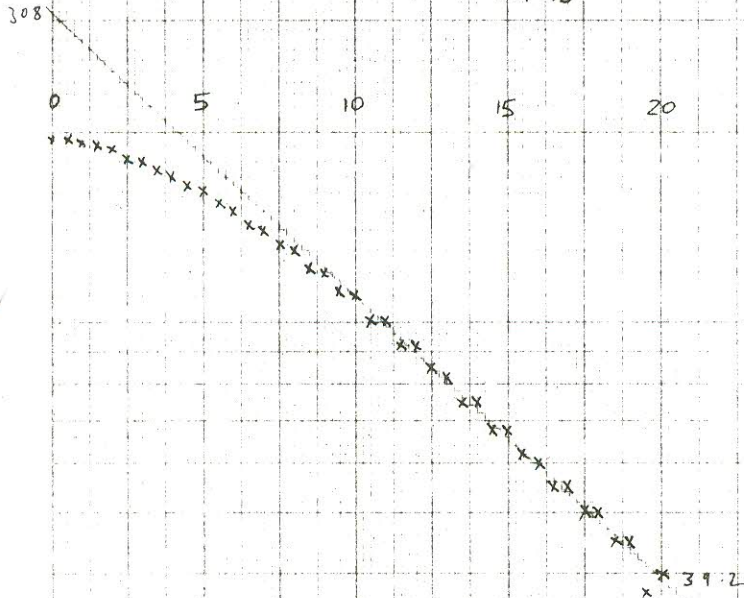
FIG 21

3vibs. 5 sets wt.

1.335 Hz - Y-Y

2/1/81 15:54

1.64 %



4 vibs, 5 sets wt

1.315 Hz - Y-Y

(2/1/81)

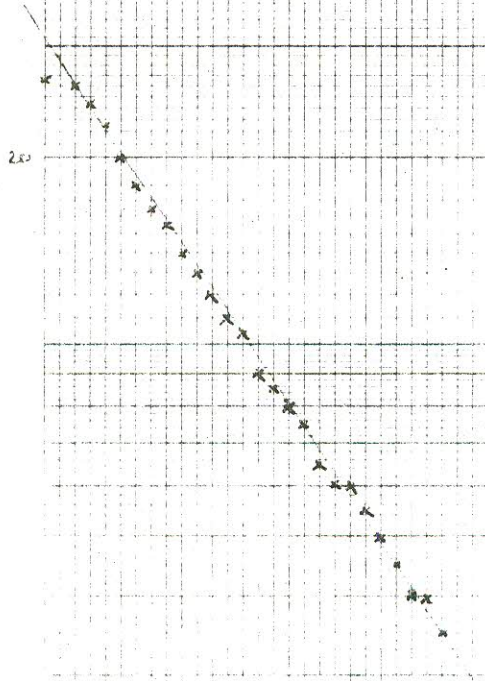
1.31 %

FIG 22 Y & R vibrators 5 sets at each

1.325 Hz

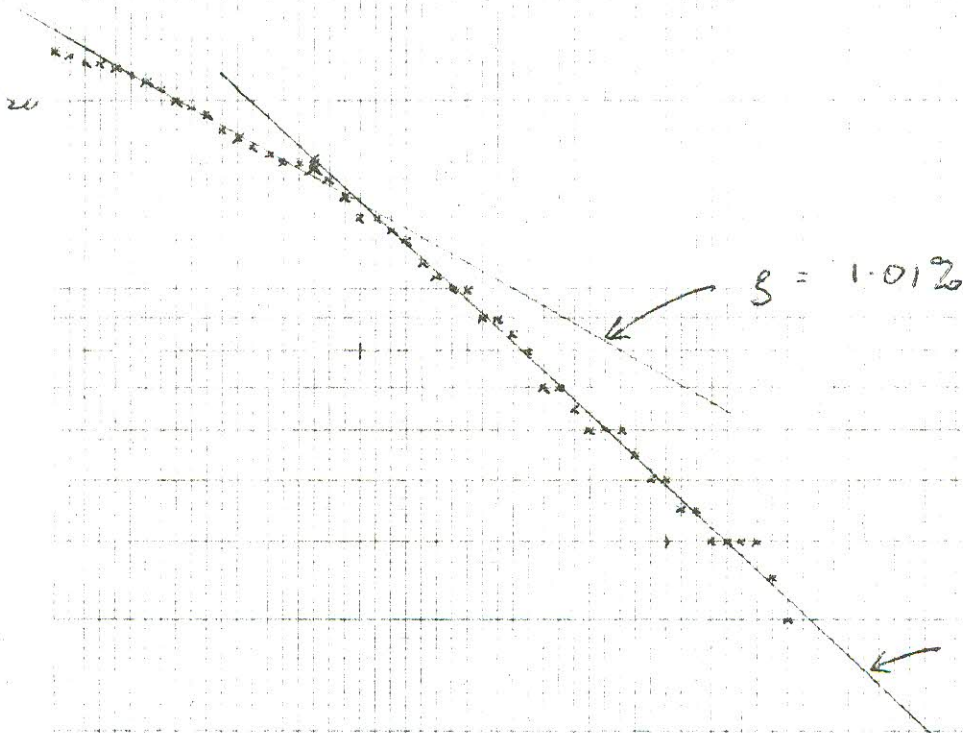
2/1/81

X-X Direction



$$\xi = 2.72\%$$

Y-Y Direction



$$\xi = 1.01\%$$

$$\xi = 1.65\%$$

14.8

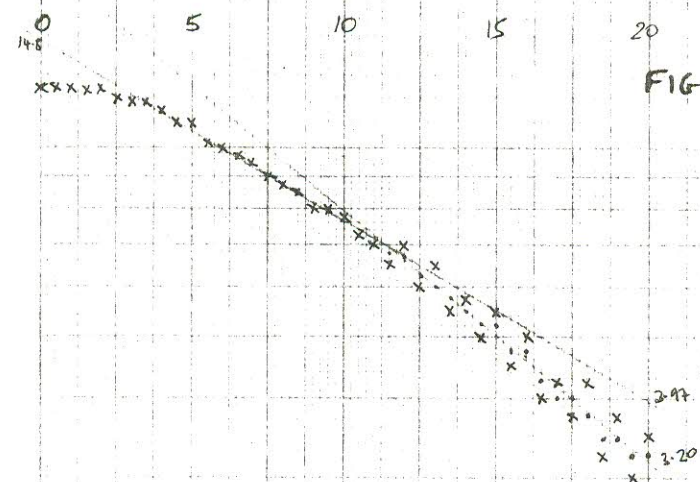


FIG 23

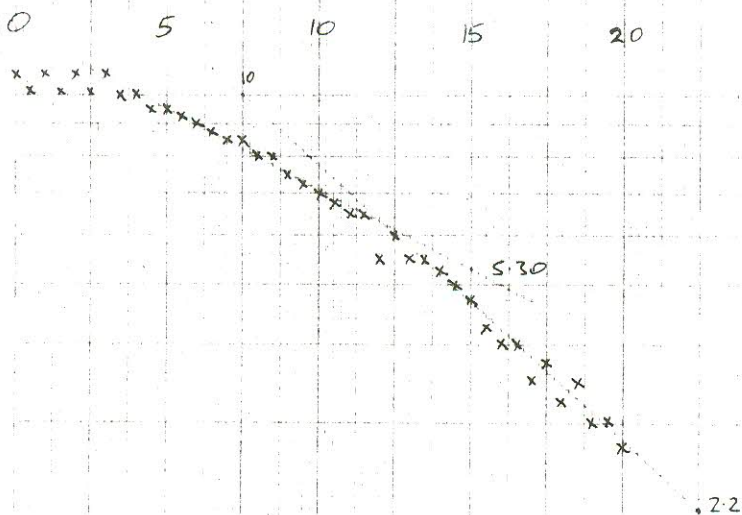
4 vibs, 2 sets wks

1.34 Hz - X-X

3/1/81 16:50

1.05% then 1.45%

12.80



4 vibs, 1 set wks

1.345 Hz - X-X

3/1/81 17:20

0.94% then 1.61%

(X-X₂)

4 uibs, 1/2 set wts.

6.62 Hz - X-X

base rate

19.00.

5/1/81

4.49%

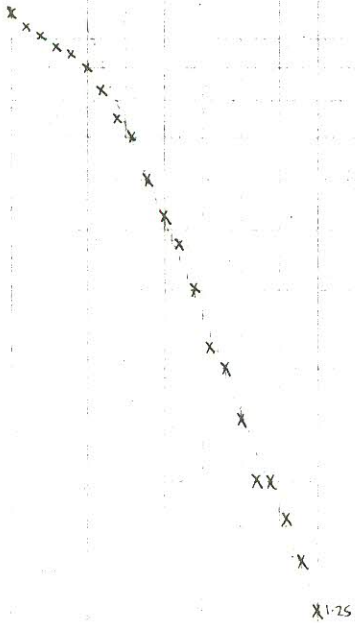
FIG 24

21.01

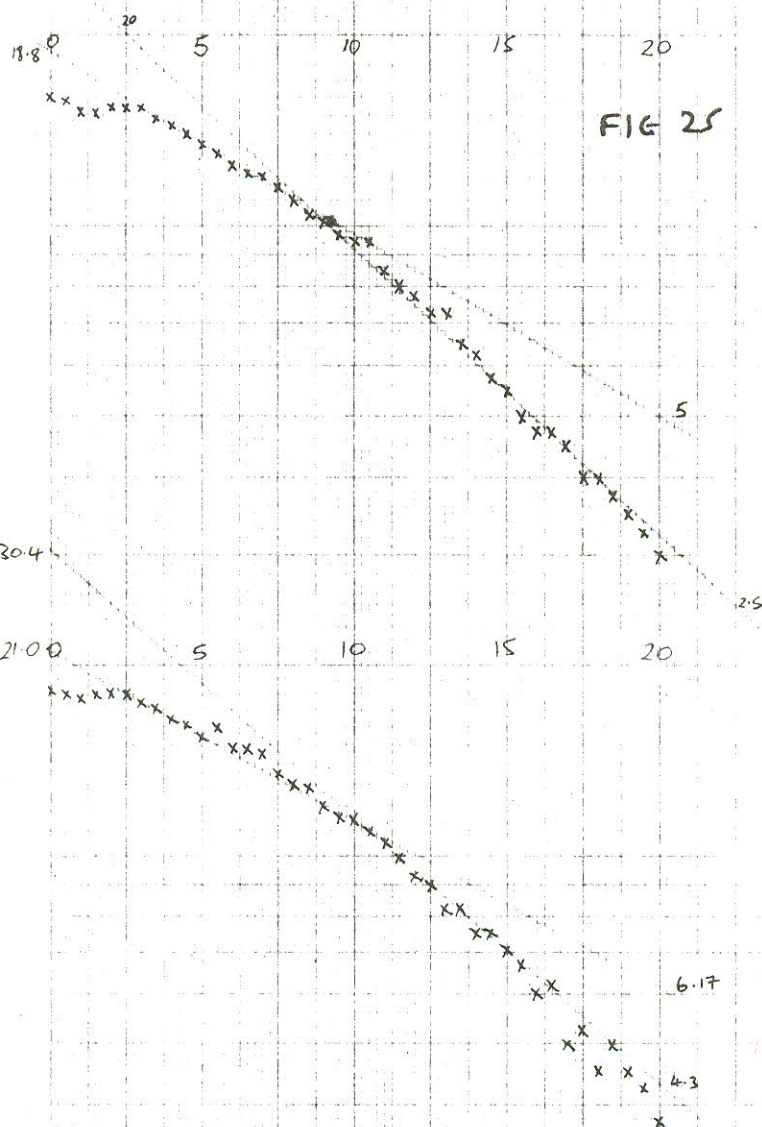
0

5

10



X1-25



4 vibs, 5 sub wts

6/1/81 16:40

1.310 Hz - Y-Y

1.05% then

1.65%

4 vibs, 3 sub wts

6/1/81 16:20

1.315 Hz - Y-Y

0.97% then

1.56%

FIG 26

4 vib, 4 wh wh.

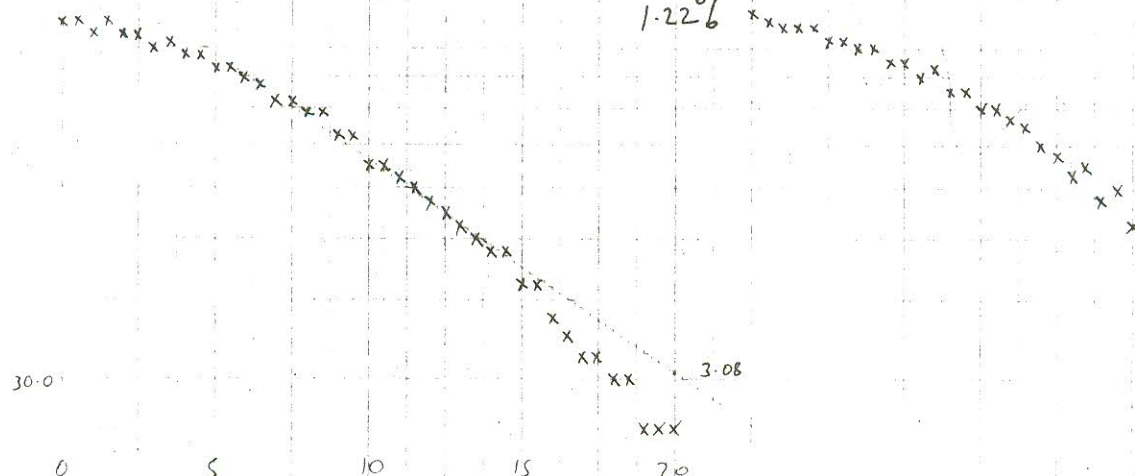
6/1/81 17.00.

1.305 Hz - Y-Y

(Redrawn)

1430 S 10 15 20 0 S 10 15 20.

1.22%



4 vib, 2 sets wh.

6/1/81 17:17

1.315 Hz - Y-Y.

1.63%

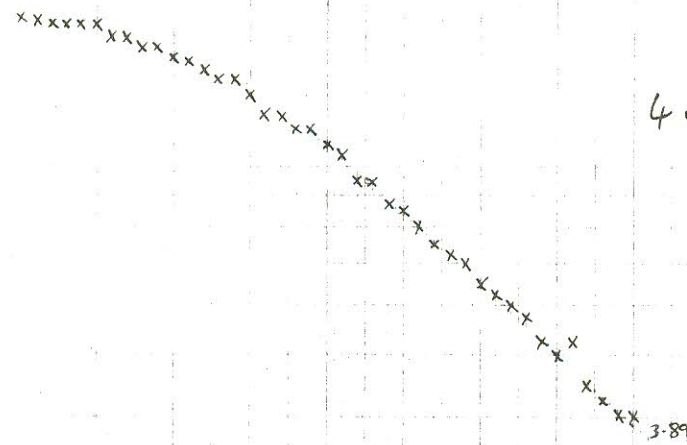


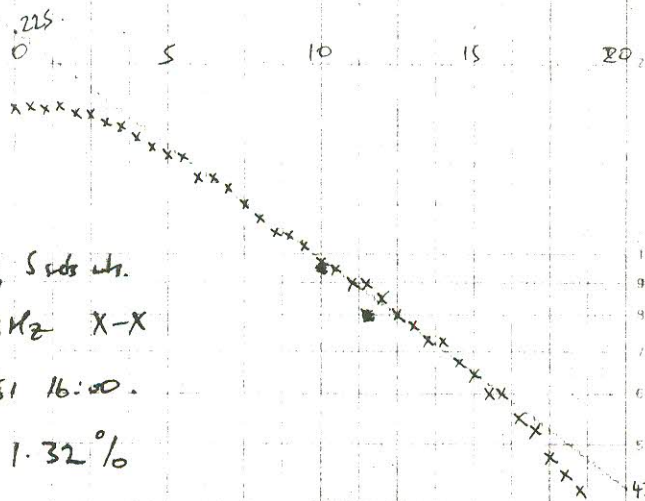
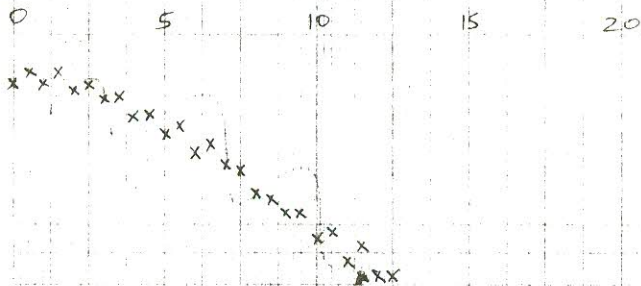
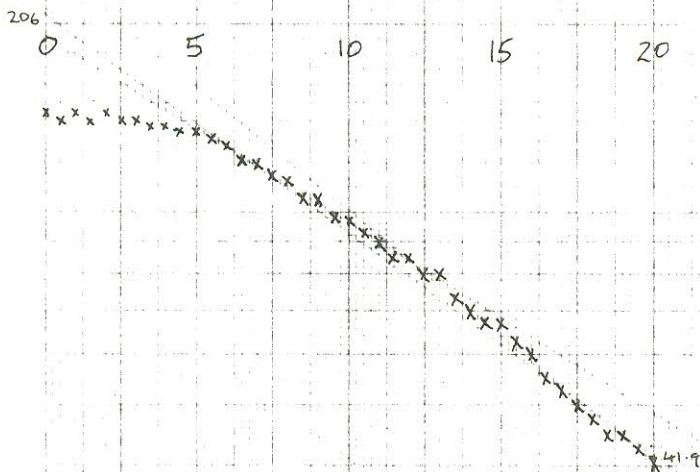
FIG 27

1.0.6, 2. sets wts

1.33 Hz X-X

5/1/81 12:30.

1.27%



Quik, 5 sets wts.

1.33 Hz X-X

3/1/81 16:00.

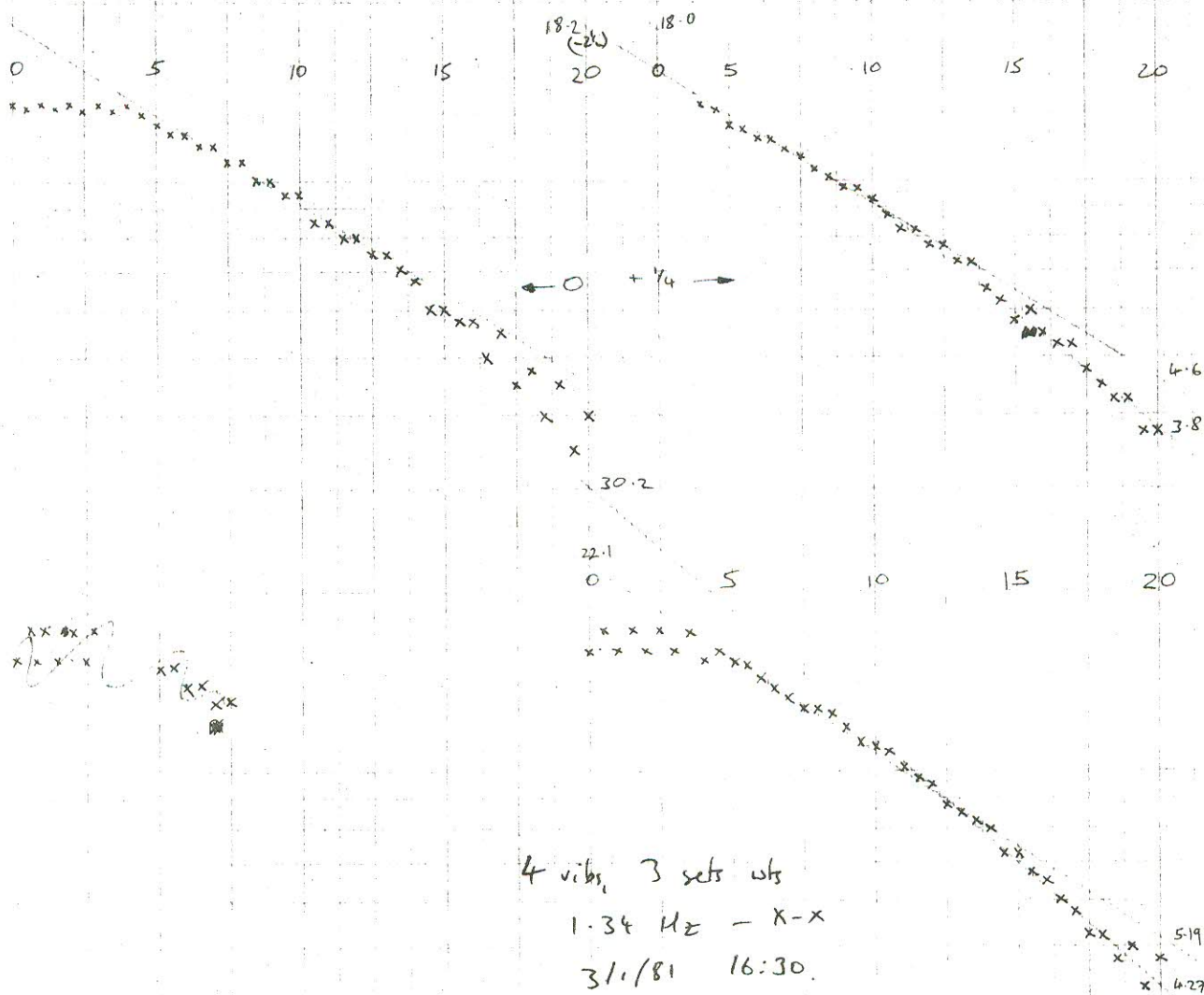
1.32%

FIG 28 4 vibs, 4 sets wts

1.335 Hz - X-X

3/1/81 16:16

0.97% then 1.24%



4 vibs, 3 sets wts

1.34 Hz - X-X

3/1/81 16:30.

1.15% then 1.56%.

FIG 29

1.315 Hz

4 vibs, 2 subs chr.

6/1/81

17/17

X-X

2.28%

12.9

1.02

FIG 30

(1.310 Hz)

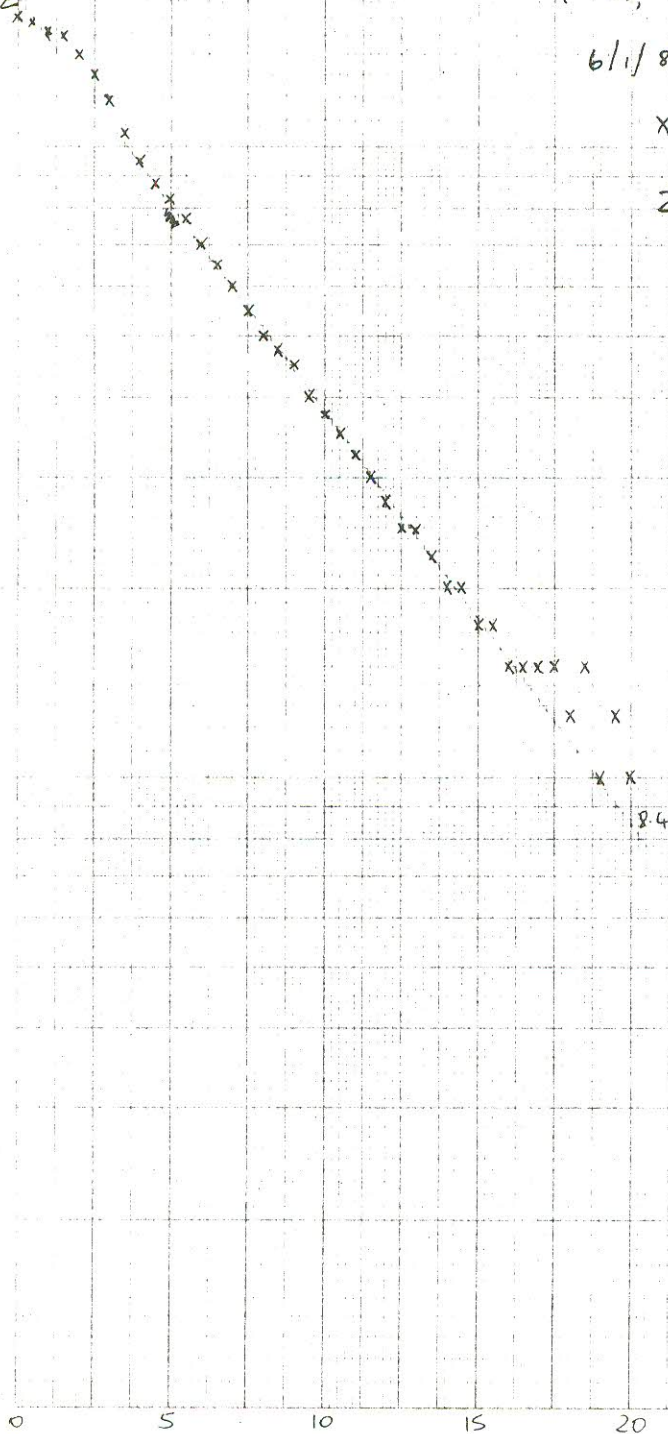
4 vibr, 5 sets wts

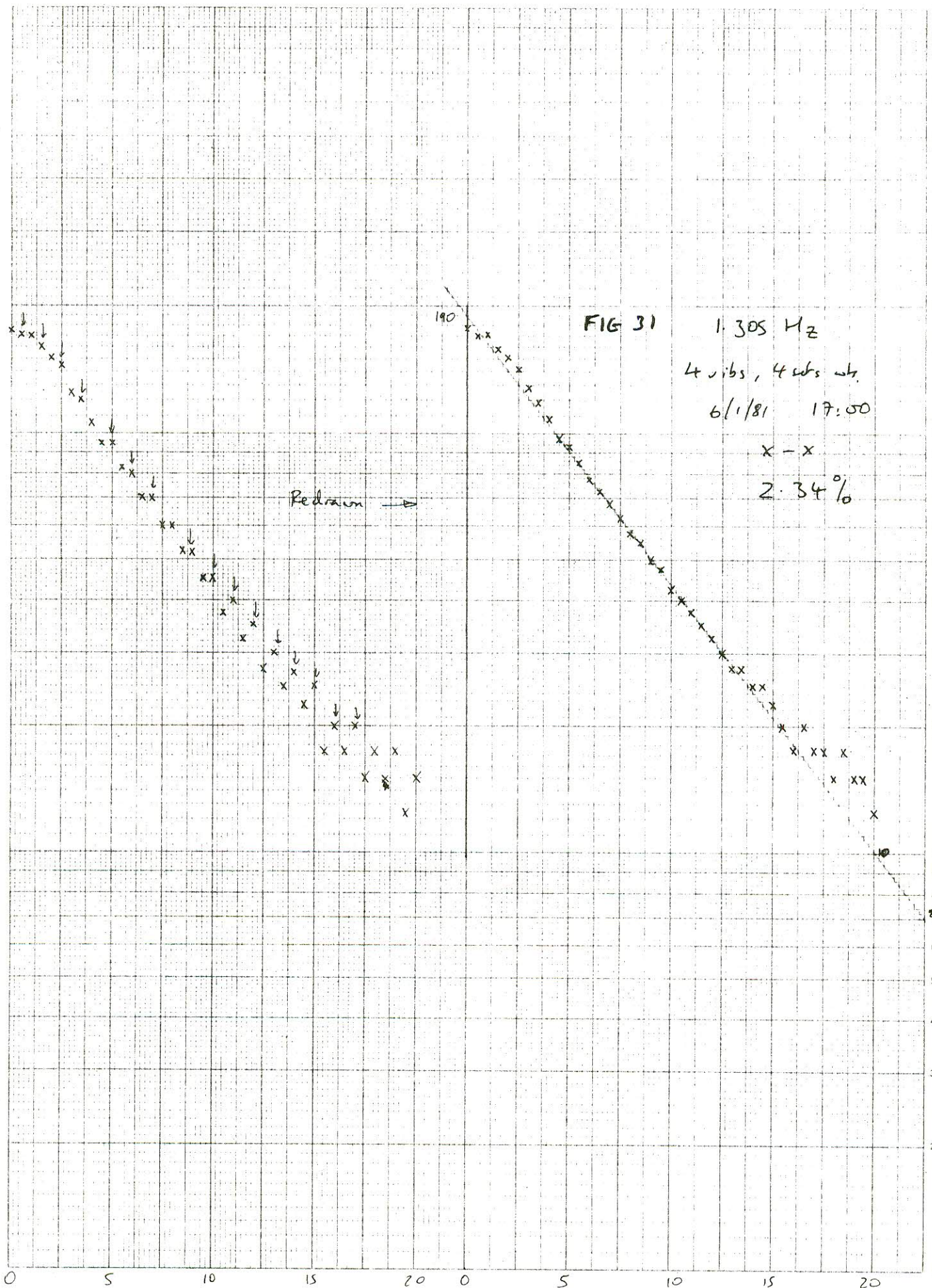
6/1/81 16:40

X-X.

2.40%

17B





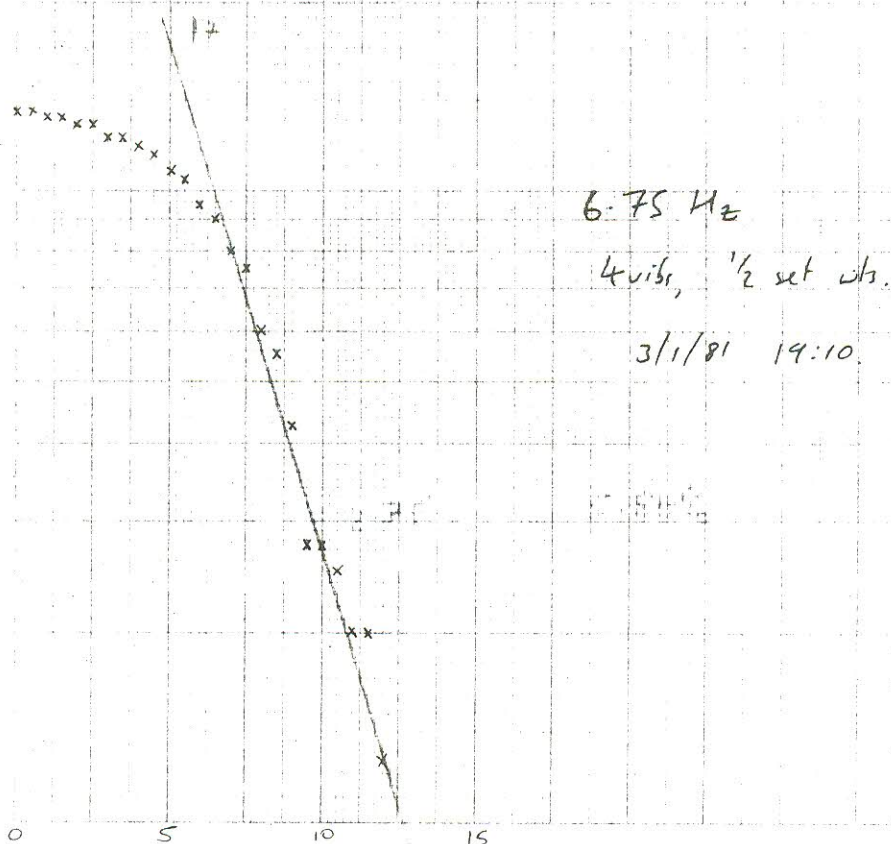
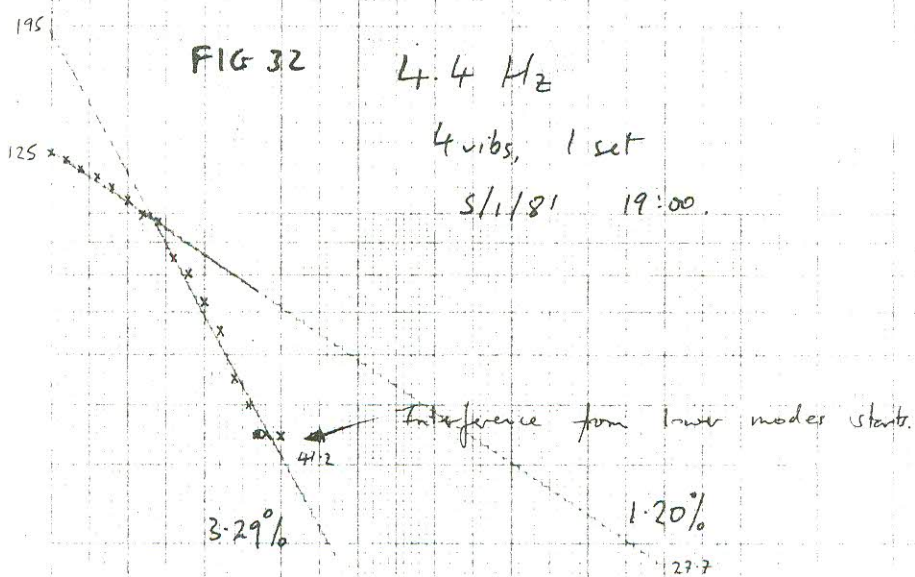


FIG 73

1.321 Hz

to vibs 1 set wts

6/1/81 17:40

X-X.

2.23%

13.2

$\frac{1}{2\pi n}$ R $\frac{4}{a}$

218

0 5 10 15 20

12-40

1-321 Wz.

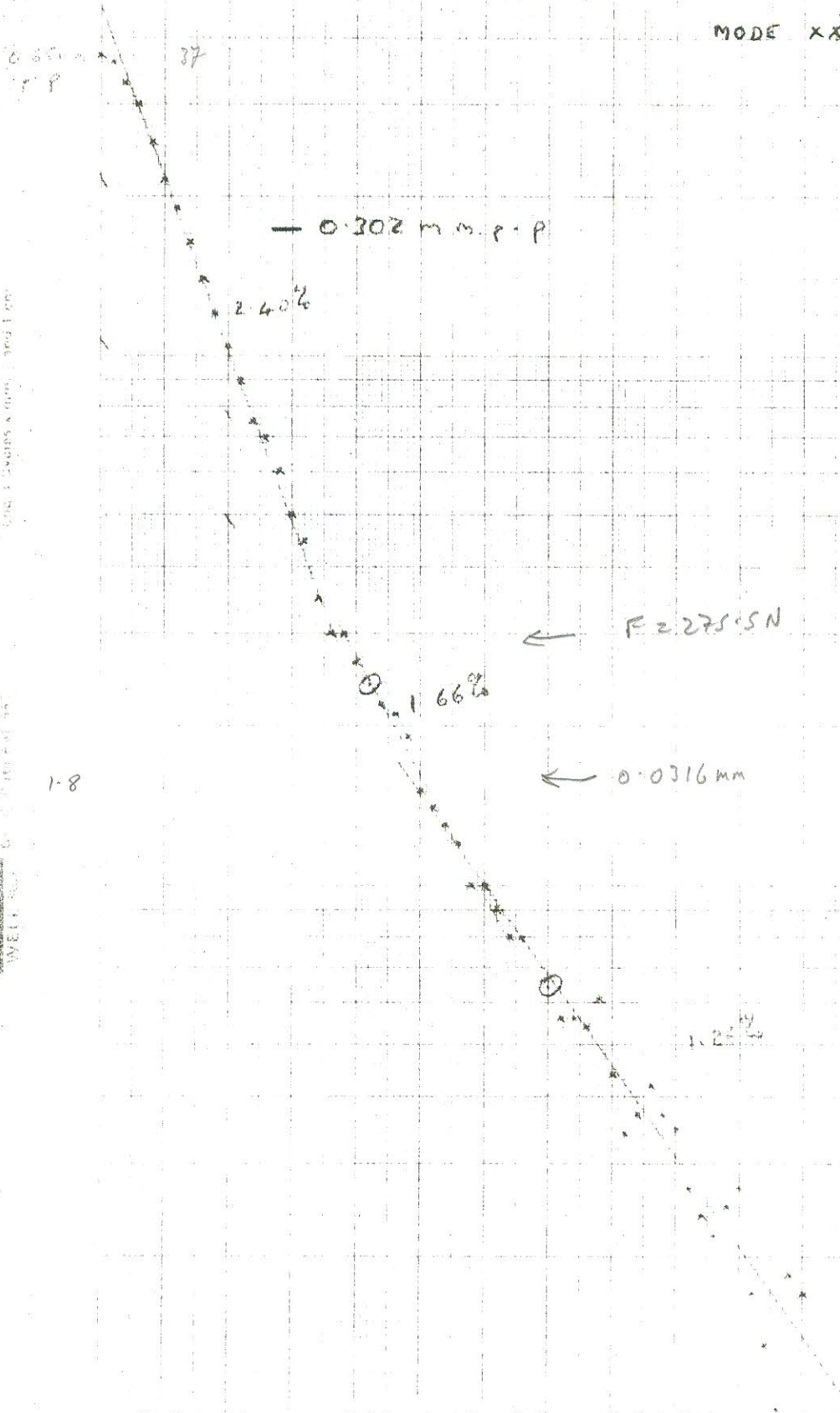


FIG 25 Decay from 4-2 6/1/81 17-17

1.17 mm
P-P

MODE xx4

2.50%

0.202 mm

2.16%

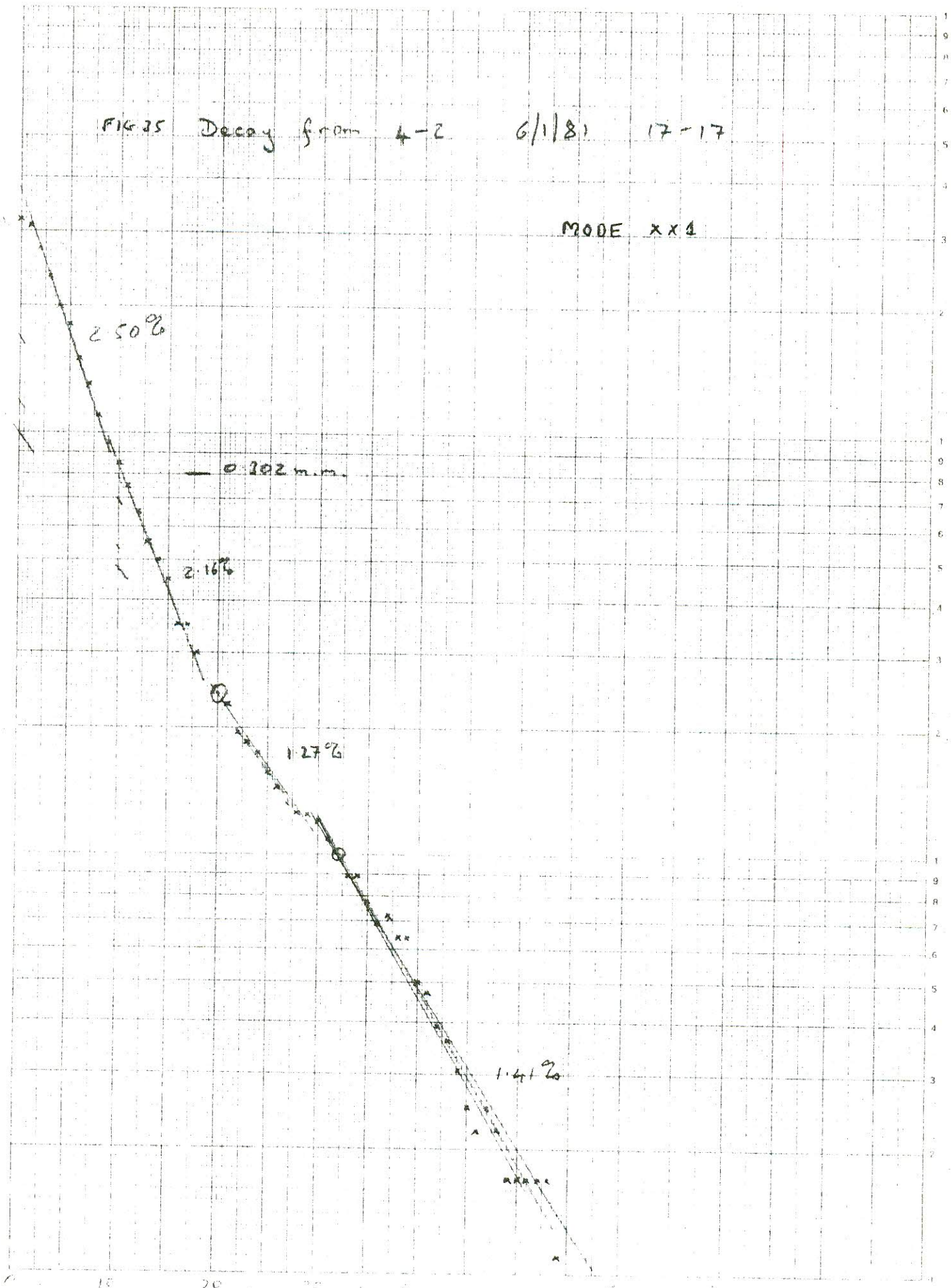
1.27%

1.41%

Log 2 Cycles x mm 3 0.01 mm

Graph Data Ref 5531

WELL



WATKINS' HANGS

147

151

1XX

171

174

173

171

171

172

171

170

171

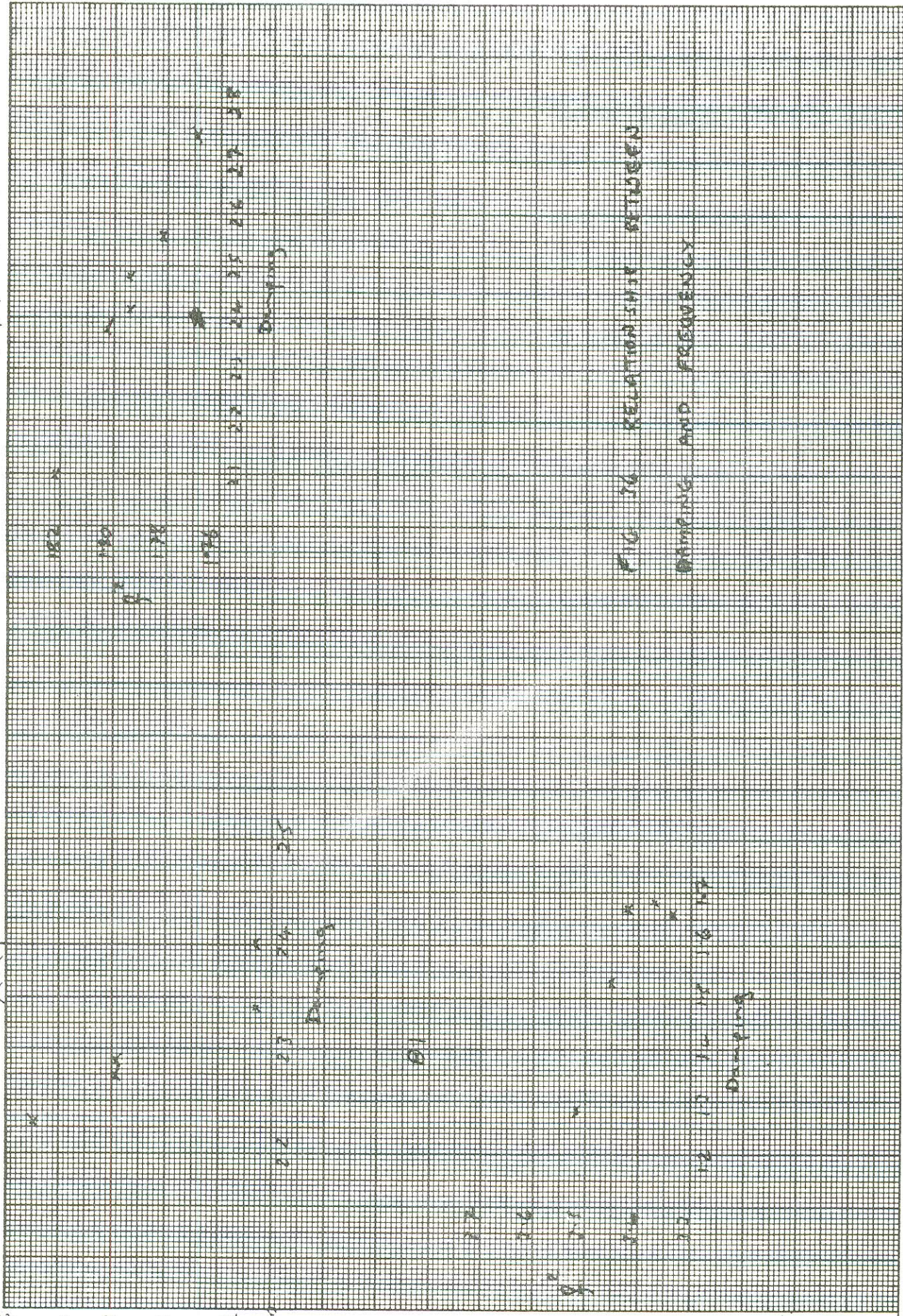
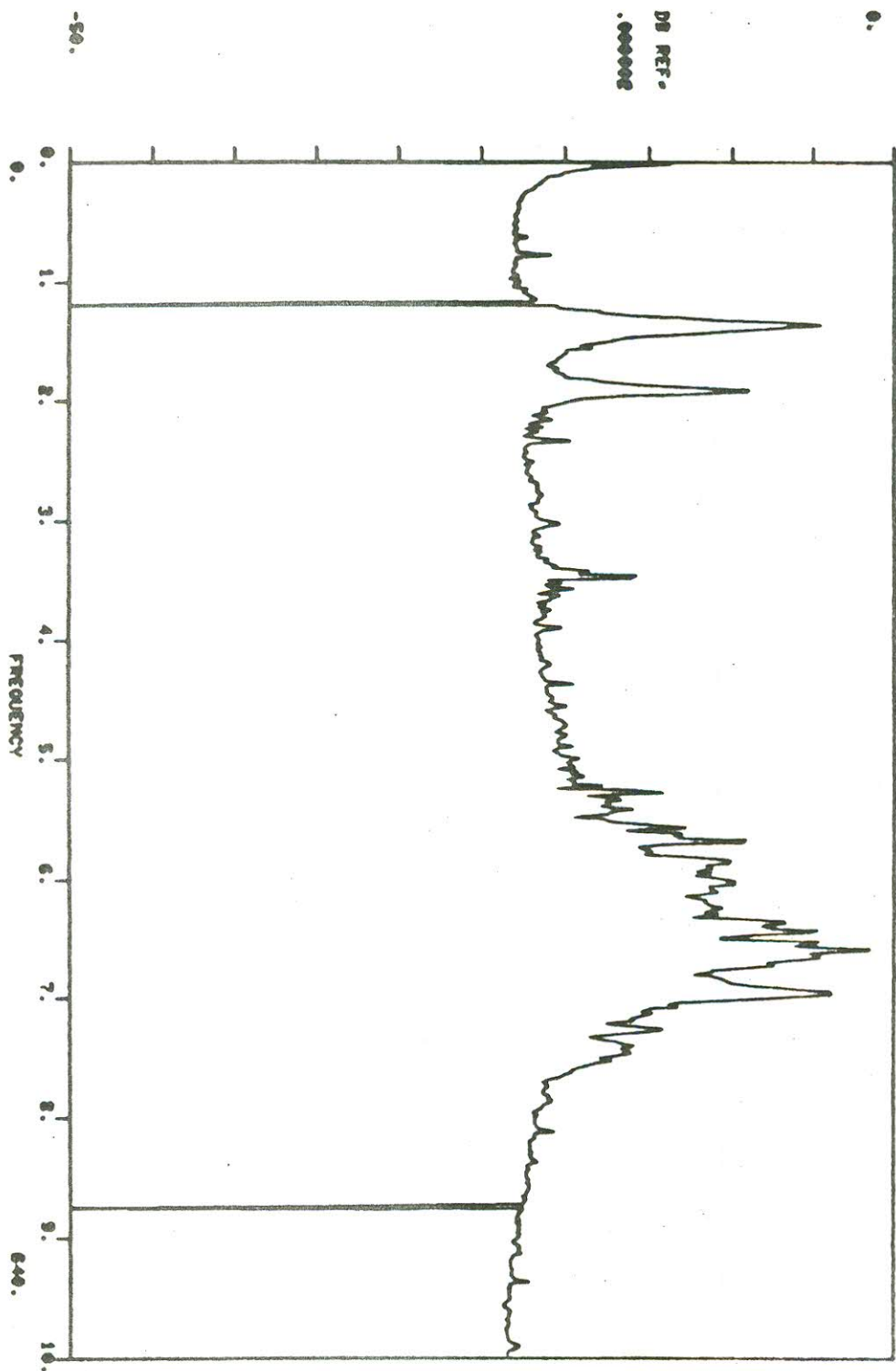


FIG 36 RELATIONSHIP BETWEEN DAMPING AND FREQUENCY

28
 FIG. 28
 ENHANCED UNCOMBENT OUTPUT SPECTRUM
 BT-500 ACCEPTANCE AT CONEENCE OF .2 & BELOW
 TRACK 9 SOUTH STONEHILL HOUSE
 X84 SPEED UP



DB REF.
.00004998

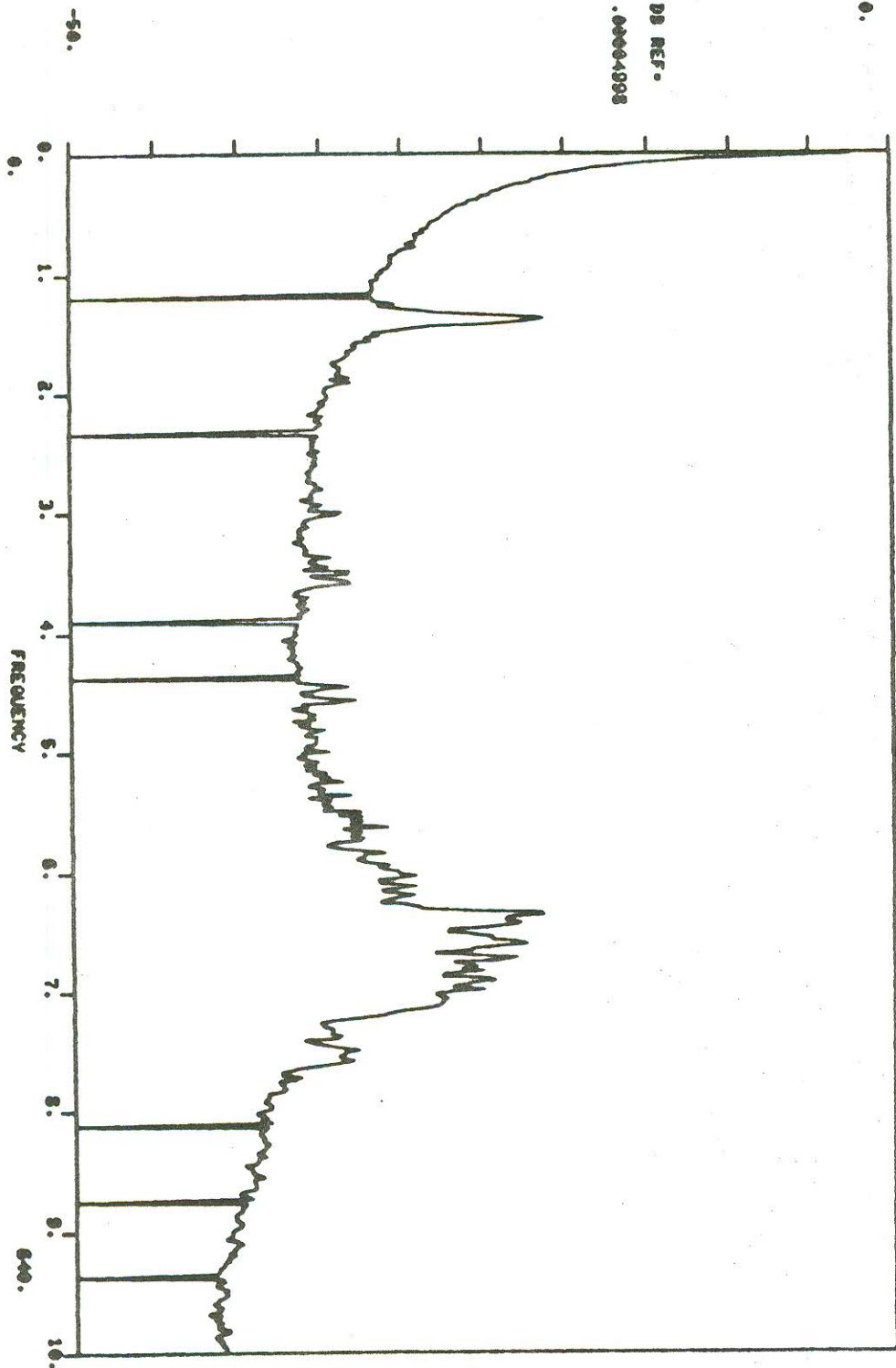


FIG 27
27

ENHANCED UNCOMBENT OUTPUT SPECTRUM
BT. 500 ACCEPTANCE AT COHERENCE OF .2 & BELOW
TRACK 7 SOUTH STONEHAM HOUSE
X64 SPEED UP

