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VIBRATION CONTROL AND STRENGTHENING MEASURES IN AN OFFICE BUILDING

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ABSTRACT

Uncomfortable vibrations have been felt by the workers in a two storey office building of a sugar factory at times when one or more blades of its second stage cane cutter broke during its normal operation. The cane cutter is generally allowed to run with upto two or three broken blades to minimise production loss.

Various proposals to control the vibrations in the office building have been examined in the paper including possibility of reduction of vibrations at the source and stiffening of the building. However, keeping in view the nature of building and the vibrations, structural stiffening of the building was considered to be the most feasible solution. The same has been analysed in deail in the paper.

INTRODUCTION

A sugar factory has been provided with two cane cutters along the cane conveyor for chopping the cane into small pieces before it is fed into the crushers. The second stage cutter foundation is at a distance of about 70 m from the office building of the factory. This cane cutter is a source of vibrations which reach the maximum permissible limits when two blades of the cutter break simultaneously on the same side of the shaft. Disturbing vibrations are then felt at some locations on the first floor of the office building causing discomfort to the staff working in the office. The vibrations also resulted in falling of plaster from the roof of first floor at some places.

Measurements of vibration levels and discussions with staff revealed that though the vibrations of the foundation block were within permissible limits for the design forces of the foundation yet uncomfortable vibrations were felt in the office building at some locations.

Various proposals to control the vibrations, including stiffening or strengthening the building, were considered and discussed. However, in view of the nature of the building and level of vibrations, the control of local vibrations in the office building through suitable structural measures was considered to be the most appropriate measure.

The paper briefly describes the various alternatives for controlling the vibrations in the building. The proposal for strengthening the building by providing additional stiffeners has been described in detail.

DESCRIPTION OF OFFICE BUILDING

Plan of the office building is shown in Fig. 1. The building has a steel frame structure with brick masonry walls and brick arch roofs. Spacing of the 300x140 I-section columns is 12 ft. (3.6 m) in one direction and 20 ft. (6.0 m) in the other direction, while the roof arches span 5 ft. (1.5 m) and 15 ft. (4.5 m) respectively in the two directions. The beams are also 300x140 I-sections. Each floor height is 15 ft. (4.5 m) and outer wall thickness is 1.5 ft. (0.45 m).

VIBRATION MEASUREMENT

Vibrations were measured on the floor of the building at seven points as shown in Table 1 and marked in Fig. 1.. The vibrations were recorded in the vertical direction as the maximum horizontal vibration amplitude was less than 1 micron. From Table 1 it may be noted that the maximum amplitude of vibration is 3.7 microns at location 8 near the middle of the main hall. The next point of highest vibration is also in the main hall at location 4 where the amplitude is 3.1 microns. At other points the amplitude of vibrations varied from 1.3 to 2.7 microns. However, peak acceleration values at locations 4 and 8 are 0.015 and 0.017 times the acceleration due to gravity.

TABLE 1 - Vertical Vibrations on the First Floor of the Office Building

S.No.	Location	Displacement p-p μ m	Velocity pk mm/s	Acceleration ÷ g pk
1.	1	2.5	1.0	0.007
2.	2	4.0	1.7	0.010
3.	3	5.3	2.1	0.013
4.	4	6.2	2.5	0.015
5.	6	3.3	1.2	0.009
6.	8	7.3	3.0	0.017
7.	14	2.5	1.0	0.006

Vibrations at the remaining ten locations marked in Fig. 1 were not measured as the perception of vibrations were extremely small at these locations.

As per IS:2974-Part I (1982) the vibrations at points 3,4 and 8 are in the disturbing range while the vibrations at the remaining four points, though not disturbing, can be felt by the persons.

CHECKING VIBRATIONS AT SOURCE

It was considered desirable to check if the foundation of cane cutter no. 2 was creating excessive vibrations and also to check the adequacy of design of this foundation with respect to the resonant condition.

Accordingly, vibrations were measured, without cane load, on one of the pedestals at all its four corners both at the base level (0.4 m) and at the top level (3.4 m above GL) in the horizontal (H) as well as the vertical (V) directions after removing two blades of the cutter and are reported in Table 2.

TABLE 2 - Vibrations of the Foundation Block of Cane-Cutter No. 2

	1		2		3		4	
Direction	V	H	V	H	V	H	V	H
Base of pedestal (0.4 m height from GL)								
Displ. (µm p-p)	24	14	24	12	19	15	17	12
Vel. (mm/s pk)	9	5.5	9.3	5.2	7.2	5.7	6.5	4.8
Accl. ÷ g (pk)	0.08	0.08	0.07	0.12	0.14	0.14	0.06	0.06
Top of block (3.4 m height above GL)								
Displ. (µm p-p)	25	37	26	26	20	41	17	38
Vel. (mm/s pk)	10	15	10	10	8	15	6.4	15
Accl. -g (pk)	0.30	0.50	0.40	0.22	0.50	0.26	0.30	0.35

The response of the block is seen to increase from base towards the top. The displacements at the base level are higher in the vertical direction than in the horizontal direction while the trend changes at the top of the block. However, the responses are within the permissible range for the 600 rpm operating speed of the machine (IS:2974 - Part I-1982).

Further, to check the natural frequency of vibration of the foundation, a sweep-through test was conducted by switching off the machine and recording the velocity response at the top of the block in the horizontal direction, thus constructing the resonance curve (Fig. 2). The test was repeated. The observations were taken down to a speed of about 350 rpm. The observed vibration amplitudes were increased by multiplying them by the square of the ratio of the operating to the recorded speed of the machine in order to obtain the response for a constant dynamic force exerted at the full speed of the machine. The recorded and modified responses are presented in Table 3. Also the curve, when extended to the left till zero speed is reached yields a 'static amplitude' of 80 µm. This extrapolated static amplitude value has been used for the computations of the resonant frequency.

Figure 2 reveals that the resonance peak is not obtained upto the operating speed of 600 rpm. However, the resonant frequency is required for computation of response and checking the design values assumed for the elastic coefficients (dynamic modulii) of the subgrade.

The mathematical equation of the curve of Fig. 2, with the ordinates non-dimensionalised with respect to the initial value of 80 µm to obtain the dynamic amplification factor μ, is given by the expression :

$$\mu = [(1 - \eta^2)^2 + (2\eta \zeta)^2]^{-0.5} \tag{1}$$

where η is the ratio of machine speed, to the resonant frequency f (the natural frequency of vibration of the foundation) and ζ is the fraction of critical viscous damping taken as 6.4% (log decrement, $\Delta = 0.4$) in the design (Major, 1980).

Substituting the value of μ, obtained from any point of the resonance curve (Fig. 2), and the corresponding machine speed ω, the natural frequency of vibration of the foundation f is obtained.

TABLE 3 - Vibration Response from "Sweep through Tests"

Sl.No.	Ist Test				2nd Test			
	Speed, ω (rpm)	V (mm/s)	V^*_m (mm/s)	X_m (µm)	Speed, ω (rpm)	V (mm/s)	V^*_m (mm/s)	X_m (µm)
1.	600	13.7	13.7	218	600	12.5	12.5	199
2.	584	10.5	11.1	182	576	10.5	11.4	189
3.	551	8.0	9.5	165	560	8.5	9.8	167
4.	519	6.4	8.6	158	544	7.0	8.5	149
5.	503	5.2	7.4	140	528	6.2	8.0	145
6.	487	4.6	7.0	137	512	5.4	7.4	138
7.	470	3.9	6.4	130	496	4.7	6.9	133
8.	454	3.5	6.1	128	480	4.1	6.4	127
9.	438	2.9	5.45	119	464	3.7	6.2	127
10.	422	2.4	4.9	111	448	3.5	6.3	134
11.	405	2.1	4.6	108	432	3.0	5.8	128
12.	389	1.8	4.4	108	416	2.5	5.2	119
13.	373	1.7	4.3	110	400	2.2	5.0	119
14.	357	1.5	4.2	112	384	1.8	4.4	109
15.	-	-	-		468	1.5	4.0	104
16.	-	-	-		352	1.2	3.5	95

$^*V_m$ = response modified for constant dynamic force; $X_m = 60\ V_m\ (2\pi\omega)$

Three points on the curve of Fig. 2 have been selected to obtain f as follows :

i) x_m = 118 µm, μ = 1.475, = 440 rpm

ii) x_m = 140 µm, μ = 1.750, = 506 rpm

iii) x_m = 200 µm, μ = 2.500, = 589 rpm

Substituting $\xi = 0.064$, $\mu = 1.475$ and $\eta = 440/f$ in Eq. (1) for the first point the natural frequencies of vibration f_1 and f_2 of the foundation block are obtained as

$$f_1 = 342 \text{ cpm}, \qquad f_2 = 770 \text{ cpm}$$

Similarly the second and third points yield values of the higher natural frequency f_2 as 767 cpm and 752 cpm respectively.

The average value of the foundation's upper natural frequency is therefore,

$$f_2 = (770 + 767 + 752) / 3 = 763 \text{ cpm}$$

The first natural frequency, f_1 is too low compared to the machine operating speed of 570 rpm, and is inconsequential in the design of the foundation.

At the cane-cutter's operating speed of 570 rpm, with fraction of critical damping as 6.4%, the dynamic amplification factor μ as obtained from Eq. 1 is 2.212. This yield the amplitude of vibration of the foundation as 0.26 mm under two broken blade condition, while a value of 0.02 mm is obtained under the normal running condition (Kumar and Ranjan, 1990). The maximum permissible amplitude is 0.6 mm (IS 2974-Pt I).

Based on the "actual" natural frequency of the foundation obtained from the above extrapolation technique applied to the partial resonance curve constructed from the sweep-through test, any remedial measures at the source seemed more logical to be applied, provided these are found to be feasible. Since the vibration level at source can be reduced by increasing the natural frequency of the foundation, it would be essential to use some kind of stiffening technique, like increasing the base width of the foundation, providing a skirting of piles, stabilising the soil under the foundation, etc. However, the stiffening of the foundation and/or subgrade was not feasible on account of the following considerations :

(a) The foundation block is old, massive and requires heavy stiffening measures.

(b) Adequate space is not available all around the foundation block for cutting and placing equipment, etc., required to carry out the stiffening measures.

(c) Even if the stiffness of the foundation could be increased, it would perhaps not be practicable to sufficiently bring down the vibration levels.

MEASURES FOR CONTROLLING VIBRATIONS

Following schemes were considered for controlling vibrations in the office building :

(a) Making a narrow trench about 10 m deep between the source and the building.

(b) Using undamped vibration absorbers.

(c) Isolating the vibrations by providing spring mountings on the tables and chairs at locations of excessive vibrations.

(d) Stiffening the floors of the building.

Trench for Arresting Vibrations

The trench should be deep to effectively cut off the vibrations. However, narrow trench cutting machines may not be available. Even if such a machine is available in the country, its mobilisation cost is likely to be relatively prohibitive in view of the small magnitude of the job. Besides, the maintenance of the trench, usually filled with sawdust, may be difficult. Inview of this the construction of trench was not considered as an effective measure.

Vibration Absorbers

Undamped vibration absorbers could possibly be used by clamping them to the I-beams from below the floors, that is, from the roof of ground floor. Several such absorbers would however be needed due to localised action of the absorber as well as limitation on its size.

Since the vibration absorber is primarily meant for transferring the force directly applied to the main mass, its effectiveness in the present problem would be partial. Hence the provision of vibration absorbers was not considered as an attractive solution.

Vibration Isolation

Encased springs permitting only vertical deflections can be attached to the legs of chairs and tables to effectively isolate the vibrations of the floor. About 50 mm high springs with stiffness of 15 kg/cm, one under each leg of the chair and table would reduce the vibrations to one-third. The springs might, however, initially cause some inconvenience due to 'softness' induced in the furniture but are likely to be a welcome change to the users.

Structural Measures

Since the vibrations in the building are mainly in the vertical direction (the horizontal vibrations on floor being insignificant), they can best be controlled by stiffening the floors vertically. The jack arches of 5 ft (1.5 m) span are in themselves quite stiff, so that only the stiffening of the I-beams supporting them is required.

For an average thickness of the jack arch floor as 25 cm and a live load of 200 kg/m^2, the total floor load is obtained as 700 kg/m^2. The natural frequency of the system of I-beams spanning in the two directions and forming a grid can be worked out and the effect of stiffening them on the vibration response can then be computed (Appendix-A).

The natural frequency of the floor system f_1 (Appendix-A) is about half of the machine operating speed, at which a sub-hormonic of the exciting force is possible, leading to build-up of vibration amplitudes due to near resonant condition.

Also, the second natural frequency of the floor system, f_2 is about four times of f_1, that is 1100 cpm, which is again close to twice the machine operating speed of 570 rpm, at which the first super-harmonic can cause excessive vibrations due to resonance.

To avert resonance and bring down the vibration levels of the floor within acceptable limits, the natural frequency of vibration of the floor system may be increased by stiffening the floor beams. This can be conveniently achieved by attaching firmly another I-Section ISMB 200 @ 25.4 kg/m below the 20 ft (6.0 m) long floor beam which increases the moment of inertia of X-Section of floor beam to 23,671 cm^4. The revised natural frequency of the floor system is computed in Appendix-B.

The first natural frequency of vibration of the floor system after stiffening (Appendix-B) increased from 274 to 357 cpm and the second mode frequency from 1100 to 1430 cpm (= 4 f_1). Consequently, these natural frequencies of floor system will lie far away from the resonant frequencies of half and double the machine *speed, that is 285 and 1140 cpm.*

Frequency ratio η = 1140/1430 = 0.80

Dynamic amplification μ = $[(1-0.8^2)^2 + (2 \times 0.8 \times 0.064)^2]^{-0.5}$

= 2.67

At present, with f_2 = 1100 cpm and the first super-harmonic as 1140 cpm;

Frequency ratio η = 1140/1100 = 1.0 approx.

Dynamic amplification μ = $1/(2 \times 0.064)$ = 8.0 approx.

Hence reduction in the amplitudes of vibration will be given by the multiplication factor $\mu = (2.67/8.0) \times (0.8184/1.474) = 0.20$ approx.

If can thus be concluded that the vibration levels will reduce to about one-fifth by adding ISMB 200 sections below the 6.0 m long beams supporting the 1.5 m wide jack arches.

CONNECTION OF ISMB 200 STEEL SECTIONS

The existing 6 m long beams need be cleaned of all paint, rust, dirt, etc to a minimum width of 25 mm on either edges of the lower flange to connect the ISMB 200 steel sections at their bottom by means of welding.

Intermittent 4 mm size fillet weld over 33% length in staggard configuration will be sufficient. The welded stretch may be kept 7.5 cm long and the unwelded stretch 15 cm long.

The added I-Sections be extended, as nearly as possible, upto the end of the beams to which they are attached, but need not be supported at the ends as they are meant for stiffening the existing beams and not for carrying any vertical loads on the floor.

CONCLUSIONS

Structural stiffening in the building is apparently the most viable measure for controlling the vibrations transmitted to it from the cane-cutter foundation. Stiffening by welding ISMB 200 steel sections below the 6.0m long I-beams of the first floor of the building at the locations of disturbing vibrations has reduced the vibration levels to about one-fifth.

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APPENDIX - A

NATURAL FREQUENCY OF THE SYSTEM OF I-BEAMS

The grid work, loading and equivalent dynamic system is shown in Fig. 3.

Spacing of 6.0 m long ISMB 300 beams supporting the jack arches = 1.5 m

Span of main ISMB beams supporting the 6.0 m long beams = 3.6 m

Load per meter on 6.0 m long beams = 700 x 1.5
= 1,050 kg/m

Conc. load every 1.5 m on main beams, W = 1050 x 6.0
= 6,300 kg

Distance of conc. load from support of main beam for symmetrical loading, a = 0.5 (3.6-1.5)
= 1.05 m

Moment of inertia of X-section of beams, I = 8,600 cm^4

Deflection under the conc. load, Δ_s,

= deflection at support of 6m long beam

$$= W a^2 (3L - 4a) / 6 \; EI$$

$$= \frac{6300 \times (105)^2 \; (3 \times 360 - 4 \times 105)}{6 \times 2 \times 10^6 \times 8600} = 0.4442 \text{ cm}$$

Central deflection of the 6.0m beam with respect to its support, Δ_c

$$= 5 \, WL^3 / 384 \; EI$$

$$= \frac{5 \times 6300 \times (600)^3}{384 \times 2 \times 10^6 \times 8600} = 1.0302 \text{ cm}$$

Total deflection with origin at the left support,

$$y = 0.444 + 1.030 \sin \pi \, x/6$$

$$\Delta = y_{max} = 0.444 + 1.030 = 1.474 \text{ cm}$$

Deflected shape, ϕ = y/y_{max} [= 1.0 at mid-span]

$$= 0.301 + 0.699 \sin \pi \, x/6$$

$$\text{Load factor } K_L = (1/L) \int \phi \, dx = (1/6) \int_0^6 (0.301 + 0.699 \sin \pi x/6) \, dx = 0.7460$$

$$\text{Mass factor } K_M = (1/L) \int \phi^2 \cdot dx = (1/6) \int_0^6 (0.0906 + 0.4886 \sin^2 \pi x/6 + 0.4208 \sin \pi x/6) dx = 0.6028$$

The natural frequency of vibration of the first mode, f_1 is then given by (Biggs, 1964).

$$f_1^2 = \frac{K_L g}{K_m \Delta} \; ; \qquad g = \text{acceleration due to gravity}$$

$$= \frac{0.7460 \times 980}{0.6028 \times 1.474} = 823$$

$$f_1 = 28.69 \text{ rad/s} = 4.565 \text{ cps} = 274 \text{ cpm}$$

APPENDIX - B
REVISED NATURAL FREQUENCY OF THE FLOOR SYSTEM

Cross-sectional area of ISMB 200 = 32.33 cm^2

Moment of inertia of X-Section = $2,235 \text{ cm}^4$

Distance of C.G. of combined section from top

$$= \frac{56.26 \times 15 + 32.33 \times 40}{56.26 + 32.33} = 24.12 \text{ cm}$$

Moment of inertia of combined section, I

$$= 8604 + 56.26 (24.12 - 15)^2 + 2235 + 32.33 (40 - 24.12)^2 = 23,671 \text{ cm}^4$$

Central deflection of 6.0m long beam w.r.t. its supports Δ_C

$$= 5 WL^3/384 EI = 1.0302 \times 8600/2371 = 0.3742 \text{ cm}$$

Total deflection, $y = 0.4442 + 0.3742 \sin \pi x/6$

$$\Delta = y_{max} = 0.4442 + 0.3742 = 0.8184 \text{ cm}$$

Deflected shape, ϕ	=	y/y_{max} [illegible] at mid-span		
	=	$0.5428 + 0.4572 \sin \pi x/6$		
Load factor K_L	=	$0.5428 + 0.4572 \times 2/\pi$	=	0.8339
Mass factor K_M	=	$(0.5428)^2 + 0.5(0.4572)^2 + 2 \times 0.5428 \times 0.4572 \times 2/\pi$	=	0.7151
First mode freq. f_1^2	=	$K_L \, g/K_M \Delta$		
	=	$0.8339 \times 980/0.7151 \times 0.8184$		
	=	1396		
f_1	=	37.37 rad/s	=	[illegible] 357 cpm

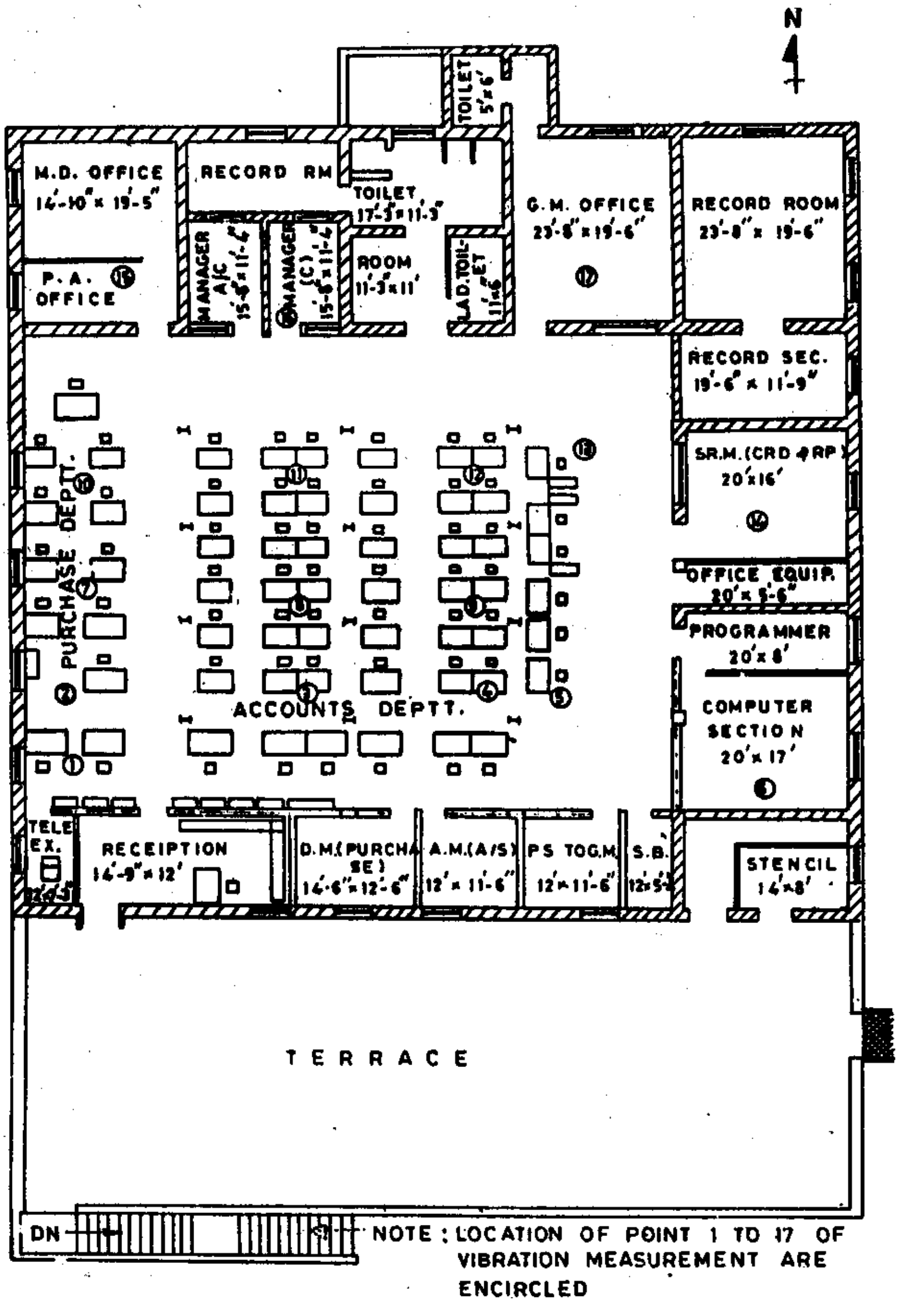

FIG. 1– PLAN OF THE CENTRAL OFFICE BUILDING

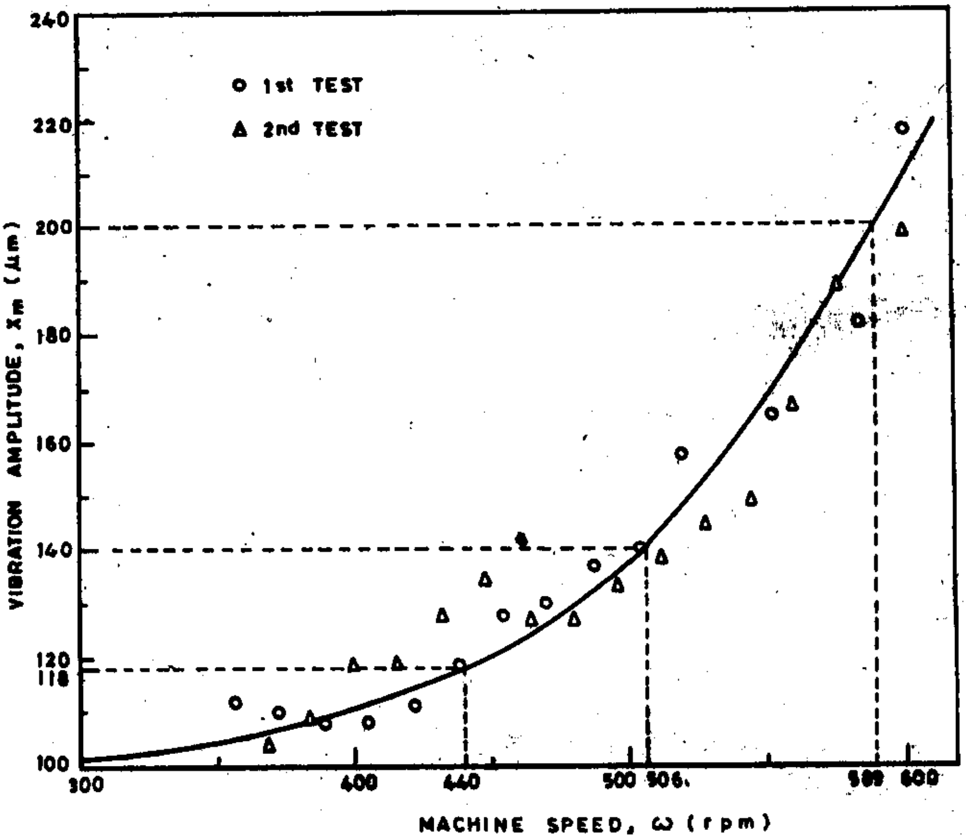

FIG.2 — RESONANCE CURVE OF THE CANE CUTTER FOUNDATION FROM SWEEP-THROUGH TESTS

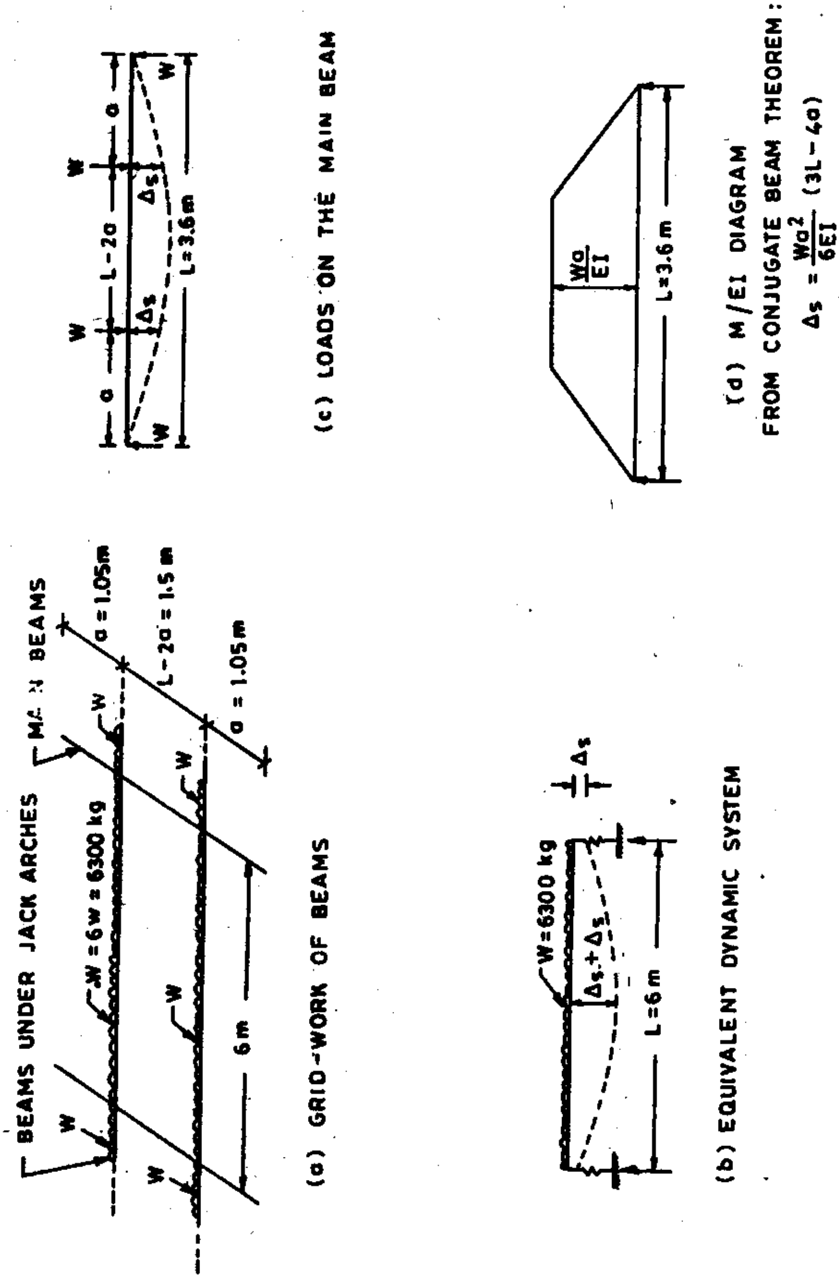

FIG.3- GRID-WORK OF BEAMS WITH LOADING AND THE EQUIVALENT DYNAMIC SYSTEM