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SOIL / CUTTERHEAD INTERACTION UNDER WAVE CONDITIONS

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Summary

A computer programme of a simulation model of a cutter suction dredger, operating in offshore conditions, is a useful tool to establish the requirements for swell compensation of the ship under certain wave conditions. In order to set up the programme, in addition to other requirements, it is necessary to know the mathematical relationship of the interaction of the cutterhead and the soil. To this end a number of experiments were performed in the test-rig of the laboratory "The Technology of Soil Movement", of the Delft University of Technology. Wave height and frequency on model scale were simulated by submitting the cutterhead to a vertical oscillation, imposed by a hydraulic servo-activator controlled by a function generator. The experiments were conducted under water in compacted sand with a disc bottom cutterhead with additional cutting blades in the bottom plate. Experiments with a crown cutterhead are still in progress.

The processing of the information derived from the experiments, was done by filtering the signals which were recorded on an analogue recorder with a 20 Hz Butterworth "Low Pass" filter. The filtered signals were sampled at 50 Hz and a Fourier transformation was applied to the sampled values. The peak values of the soil reaction forces and of the cutter torque were derived from the Fourier transformation of the recorded signals of 32 experiments. A multiple power regression applied to these values led to a number of equations, which give an indication of the influence of the wave frequency and of the vertical cutter response amplitude on the interaction between the cutterhead and the soil.
These equations are being used in the joint research project of the "Delft Hydraulics Laboratory" and the Delft University of Technology, which is described in the paper "Calculation Method for the Behaviour of a Cutter Suction Dredger operating in irregular Waves", presented at this congress, and also for the design of swell compensators in the laboratory "The Technology of Soil Movement" of the Delft University of Technology.
From the equations mentioned it follows that the load on the cutterhead can be greatly reduced by the choice of low swing velocities and high cutter revolutions.

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NOMENCLATURE

D_c = diameter of the cutterhead (m)

F_i = force resulting from still water dredging (N)

$F_{max\ i}$ = peak force under wave conditions (N)

i = 1 - M_c/R_c

i = 2 - F_{surge}

i = 3 - F_{sway}

i = 4 - F_{heave}

Fr = Froude number

H_c = height of cutterhead (m)

H_s = significant wave height (m)

L = length (m)

L_v = vertical cutter response amplitude (m)

M_c = cutter torque (Nm)

R_c = radius of the cutterhead (m)

T = wave period (s)

V = velocity (ms^{-1})

V_s = swing velocity (ms^{-1})

S(t) = vertical displacement of the cutterhead (m)

V(t) = vertical velocity of the cutterhead (ms^{-1})

a_o = average in the Fourier series

$a_{1,2,..}$ = constant in the Fourier series

$b_{1,2,..}$ = " " " " "

$c_{o,1,2,..}$, $d_{1,2,..}$, $e_{1i,\ 2i,..}$ — constants

f = wave frequency (s^{-1})

f(t) = value of function at point of time t

g = gravitation constant (ms^{-2})

h = height of a cut (m)

i = index

k = subscript

n = number of revolutions (r.p.m.)

t = time

p_i, q_i, r_i, u_i, w_i, x_i, y_i, z_i = powers

1. INTRODUCTION

In recent years the construction of new harbours or the extension of existing ones has required the offshore dredging of harder soil or rock. Sometimes it is not possible to make use of trailing suction hopper dredgers. In such cases cutter suction dredgers might be used with success, providing the conditions are favourable with regard to waves and soil.
The construction of a cutter suction dredger which can work under unfavourable offshore conditions presents problems which can be solved by :

a) Applying a dredger which is not influenced by wave action, e.g. a lifting dredging platform.

b) Applying a dredger with a swell compensated ladder. Existing dredgers might well be modified by the addition of swell compensators to both ladder construction and positioning system.

The "Delft Hydraulics Laboratory (D.H.L.)" and the Delft University of Technology are coōperating in the "Workgroup Offshore Technology (W.O.T.)". Members of the staffs of the department "Maritime Structures" of "D.H.L." and the laboratories "The Technology of Soil Movement" and "Ships Hydromechanics" of the University are involved in the work of this group.
W.O.T. is designing a computer programme which will make possible the calculation of the responses of a cutter suction dredger to the waves, while cutting soil. This requires a mathematical model of the relationship between the motion of the cutterhead and its responding dynamic soil load.
Scale model experiments, using an experimental cutterhead in compacted sand, were performed in the laboratory "The Technology of Soil Movement". The cutter response was simulated by imposing a sinusoid motion on the cutterhead in a vertical direction.
In a future programme horizontal and combined motions will also be tested.
The methods used and the results obtained are discussed in the following paragraphs.

2. DESCRIPTION OF THE TEST RIG

The main part of the test rig is a reinforced concrete tank with the following inside dimensions : Length 30 m, width 2,5 m and height 1.35 m.
The tank is partly filled by sand with a mean grain size of 180 μm (Fig. 1).
The water level in the tank is approximately 0.6 m above the sand level.
A main carriage can be moved on rails along the full length of the tank, towed by two endless cables, which are connected to the drums of an electric-hydraulic winch of 35 kW. In both directions a velocity of 0.05 to 1.0 m/s is possible.
An auxiliary carriage, mounted in the main carriage, moves transversely to it.
A moveable frame containing the cutter installation is mounted in the auxiliary carriage and hydraulic cylinders are used to maintain the required vertical cutting depth and to maintain a given angle between the drive shaft of the cutterhead and the horizontal.
Two electronically controlled hydraulic servo-motors are used to impose a horizontal and/or a vertical oscillating motion on the cutterhead (wave response simulation) (Fig. 2)
The cutter shaft has a hydraulic drive of 20 kW.
The number of revolutions is variable between zero and 150 r.p.m.
A dredge pump is mounted on the main carriage.
A 15 kW variable electric drive allows a mean flow velocity of 1.5 to 4.0 m/s in the 100 mm diameter suction and pressure line.
The slurry produced is transported to a settling tank. The overflow of this tank is returned to the main tank. The sand remaining in the settling tank is weighed continuously. When a test is completed the sand in the settling tank is returned to the main tank,by means of a second slurry pump, to restore the original profile.
The sand is then levelled off and compacted by the use of two vibrators.
In order to ensure that the test conditions are as uniform as possible the sand bed preparation is always carried out in the same manner. A drainage system on the bottom of the main tank makes it possible to compact the sand to a higher degree.
This is achieved by pumping pore water through it which is then returned into the main tank. The average cone resistance of the sand in the top layer of 9 cm depth is ± 700 kPa.

3. EXPERIMENTS

3.1 Type of cutterhead used.

The experiments were carried out with a scale model disc-bottom cutterhead, diameter 475 mm, height 184 mm, with eight vertical cutting blades round the circumference and eight bottom blades (Fig. 3). This type of cutterhead was selected because of the geometric distinction between the horizontal and vertical cutting blades, which makes it possible to consider the influences of vertical and horizontal wave movements quite separately. It should be noted that as a first step only the vertical movement is used in the tests described in this paper.
The anticipated dimensions and parameters of the prototype cutterhead upon which the design of the scale model cutterhead was based, are as follows :

diameter D_c = 3000 mm scale factor $\lambda = \frac{D_{c_p}}{D_{c_m}} = \frac{3000}{475} = \sim 6.25$

height H_c = 1150 mm

revolutions n = 12 r.p.m.

swing velocity V_s = 15 - 30 cm/sec

wave period T = 5 - 10 sec (Ref. 2)

significant wave height H_s = 1.5 m

vertical cutter response amplitude L_v = 250 mm

The limitation placed on the vertical movement of the cutter was a maximum of 500 mm (amplitude = 250 mm). This limitation must be attained by the application of a swell compensating system.

3.2 Model rules.

The model rules were based on the Froude number (Ref. 1)

$$Fr = \frac{V^2}{g.L} .$$

With index p for the prototype and index m for the scale model :

$$\frac{V_p^2}{g_p L_p} = \frac{V_m^2}{g_m L_m} \qquad g_p = g_m \qquad \text{thus :}$$

$$\frac{V_p}{V_m} = \left(\frac{L_p}{L_m}\right)^{\frac{1}{2}} \qquad \frac{L_p}{L_m} = \lambda \text{ (scale factor)}$$

This means that for the scale model :

swing velocity $V_{s_m} = \frac{V_{s_p}}{\lambda^{\frac{1}{2}}}$

number of revolutions $n_m = \lambda^{\frac{1}{2}}.n_p$

wave period $T_m = \frac{T_p}{\lambda^{\frac{1}{2}}}$

wave frequency $f_m = \frac{1}{T_m}$

vertical cutter response amplitude $L_{v_m} = \frac{L_{v_p}}{\lambda}$

scale factor $\lambda = \frac{D_{c_p}}{D_{c_m}} = \frac{3000}{475} = \sim 6.25.$

3.3 The execution of the experiments.

The experiments were carried out according to the cutting pattern shown in Fig. 4.
The length of a cut is 10 m. The middle part of 4.5 m length is used as the actual measuring traject.
The first cut is the bank-opening cut, the second and third are the actual cuts during which measurements are taken. To ensure that the starting conditions for cuts 2 and 3 were reproducible, the first cut was always made with the same number of revolutions and swing velocity, without wave movements. For cuts 2 and 3 the following parameters were varied according to the model scale rules.

1. n : 20, 30 and 40 r.p.m.
2. V_s : 60, 90 and 120 mm/sec
3. $\left[\begin{array}{l} f \\ L_v \end{array}\right.$ 0.25, 0.3, 0.4 and 0.5 Hz; 20, 30 and 40 mm

In addition to the parameters mentioned above the following variables were also measured.

$\left.\begin{array}{l} F_x \\ M_x \end{array}\right]$ resulting in the force in the swing direction : F_{sway}

$\left.\begin{array}{l} F_y \\ M_y \end{array}\right]$ resulting in the force perpendicular to the swing direction : F_{surge}

F_z vertical force : F_{heave}

M_c cutter torque

The 9 signals mentioned were recorded on an analoge tape recorder. Further analysis was carried out by using two computer programmes for this purpose written.

4. THE PROCESSING OF THE RECORDED SIGNALS

Because high frequencies do not have any influence upon the movement of an anchored ship, the 9 signals recorded were filtered by a 12 dB "Low Pass" Butterworth filter with a cross-over frequency of 20 Hz.
Over the measuring traject the filtered signals were sampled during 20 seconds with a sampling frequency of 50 Hz, so that each signal was represented by 1001 values which were given with an interval of 1/50 of a second.
Because the wave motion was simulated by subjecting the cutterhead to a sinusoid motion, it could be expected that the signals measured would demonstrate a periodic character, with a period equal to that of this motion.
In order to obtain a good impression of the signals recorded during one period of the sinusoid motion to which the cutterhead was subjected, it was decided to analyse the signals by means of a numerical Fourier transformation. The result of this was a description of the periodic part of each signal by a Fourier series.
The general form for the description of a signal f(t) with a period T, by a Fourier series is :

$$f(t) = \sum_{k=1}^{\infty} \{a_k \, . \cos(k.2.\pi.t/T) + b_k \, . \sin(k.2.\pi.t/T)\} + a_o \qquad (1)$$

The constants a_o, a_k and b_k were determined by the Fourier transformation of the 1001 samples per signal by the use of a computer programme, so that the periodic part of each signal could be made deterministic and thus reconstructed.
From the processing of the measurements recorded during the course of 32 experiments, it appeared that only the first six terms of the Fourier series were relevant to the behaviour of the signals recorded, so that equation (1) was changed to :

$$f(t) = \sum_{k=1}^{6} \{a_k \cdot \cos(k.2.\pi.t/T) + b_k \cdot \sin(k.2.\pi.t/T)\} + a_o \tag{2}$$

Figures 5 and 6 give representative examples when equation (2) is applied.
The graphs show the progression of the cutter torque, the surge force, the sway force and the heave force as a function of the oscillation to which the cutterhead was subjected.
Figure 5 illustrates the overcut.
Figure 6 illustrates the undercut.
For the key of force directions, see figure 4.
The Fourier series as applied in equation (2) is in fact a description of the signals in the frequency domain. Whereas the main computer programme of the "W.O.T." group operates in the time domain, it is necessary to change the description of the forces and the cutter torque from the frequency domain to the time domain. This is achieved by making equation (2) equal to equation (3).

$$f(t) = \sum_{k=1}^{6} c_k \cdot \{L_v \cdot \sin(2.\pi.t/T) + d_k \cdot \frac{2.\pi}{T} \cdot L_v \cdot \cos(2.\pi.t/T)\}^k + c_o \tag{3}$$

With :

$$S(t) = L_v \cdot \sin(2.\pi.t/T) \text{ and } V(t) = \frac{2.\pi}{T} \cdot L_v \cdot \cos(2.\pi.t/T) \tag{4}$$

This gives :

$$f(t) = \sum_{k=1}^{6} c_k \cdot \{ S(t) + d_k \cdot V(t) \}^k + c_o \tag{5}$$

The computer programme mentioned earlier has also been used to calculate the values for c_o, c_k and d_k. For each experiment it is now possible to give the relations of the forces and the cutter torque as a function of the vertical displacement and the vertical velocity of the cutterhead in the time domain.
Because equation (5) is non-linear the superposition principle is not applicable. Therefore it was not possible to simply average the coefficients d_k for the range of performed experiments. Reliable results have been derived for the individual experiments however.
For this reason non-linear relations for the peak values of the cutter torque, the surge force and the heave force were deduced with the aid of multiple power regression based on the least squares method. These peak values may be responsible for the failure of teeth, cutterhead or ladder. The reason that the relationship has not been determined for the sway force is, that this force behaves in an irregular way. In all the experiments the sway force was a factor 4 to 10 smaller than the surge force.
It was assumed that the surge force, the heave force and the cutter torque are functions of the varying parameters V_s, n, f, L_v.
Primary these relationships were deduced from experiments during which the cutterhead was not subjected to vertical oscillations (still water dredging), thus

$$F_i = e_{1i}\left(\frac{V_s.60}{n.2\pi.R_c}\right)^{u_i} \tag{6}$$

The relations found are only valid in the area in which the parameters V_s, n, f, L_v are varied, according to paragraph 3.3. It was then assumed that the peak values of the surge force, the heave force and the cutter torque are respectively the sum of a force or torque caused by still water dredging according to equation (6) and a force or torque caused by the oscillation of the cutterhead. This produced the following equation :

$$F_{max\ i} = e_{1i} \cdot \left(\frac{V_s.60}{n.2.\pi.R_c}\right)^{u_i} \cdot \left[1 + e_{2i} \cdot V_s^{w_i} \cdot n^{x_i} \cdot f^{y_i} \cdot L_v^{z_i}\right] \tag{7}$$

From this it appeared that the correlation coefficients between the calculated peak forces according to equation (7) and the measured peak forces varied between 0.92 and

0.99, which can be considered high and thus indicate reliable relations. Equation (7) can also be approached by using dimensionless numbers instead of the varying parameters. The relation derived from this is shown in equation (8).

$$F_{max\,i} = e_{1i} \cdot \left(\frac{V_s.60}{n.2.\pi.R_c}\right)^{u_i} \cdot \left[1 + e_{3i} \cdot \left(\frac{V_s}{f.D_c}\right)^{p_i} \cdot \left(\frac{L_v}{h}\right)^{q_i} \cdot \left(\frac{f.L_v.60}{n.R_c}\right)^{r_i}\right] \qquad (8)$$

The dimensionless numbers used have the following physical significance :

$\left(\frac{V_s.60}{n.2.\pi.R_c}\right)$ gives an impression of the thickness of the slices and the free running angle of the blades on the circumference of the cutterhead, the slice being the layer of sand which is cut off by one blade.

$\left(\frac{V_s}{f.D_c}\right)$ gives the ratio between the wavelength of the movement to which the cutterhead was subjected and the diameter of the cutterhead.

$\left(\frac{L_v}{h}\right)$ gives the ratio beween the amplitude of the movement to which the cutterhead was subjected and the height of the cut, that is the depth of cut per swing.

$\left(\frac{f.L_v.60}{n.R_c}\right)$ gives an impression of the thickness of the slices and the free running angle of the bottom blades of the cutterhead.

It would appear that the peak forces measured could also be adequately described when dimensionless numbers are used. In this case correlation coefficients were found between 0.92 and 0.98, which again points to reliable relations.

The part after the plus sign in equations (7) and (8) can be seen as the relative increase of the loads on the cutterhead resulting from the motions to which the cutterhead was subjected. Thus this part gives the factor by which the loads are increased compared with the loads for still water dredging.

5. RESULTS OF THE RESEARCH

The progression of the forces and the cutter torque for each experiment was calculated with equations (2) and (5). The related computer programme was also used to make a plot, as illustrated in the figures 5 and 6 for each experiment.
The pattern of the forces and the cutter torque, as shown in these graphs, demonstrates peak values. When the cutterhead is pressed into the ground, these occur between the point where the vertical velocity of the cutterhead is at its maximum and the point where the vertical displacement and thus the depth of the cut is at its maximum.
The surge force and the cutter torque have the same pattern, with a maximum value which occurs between 1/16 T and 1/8 T after the maximum vertical velocity has been reached (after 1.0 sec in the figures 5 and 6 was passed).
The heave force reaches its maximum somewhat later, about 1/8 T after this point.
The sway force is irregular in character.
No clear relationship has been found between the moment at which the maximum values occur and the frequency and the amplitude of the oscillation.
In the figures 7, 8 and 9 the measured peak values of 32 overcutting experiments of the surge force, the heave force and the cutter torque are set out on the Y axis and the peak values calculated according to the calibration equations derived from equation (8) along the X axis.
The straight lines indicate the corresponding relationships, while the broken lines indicate a deviation of 25%.

In the figures 10, 11 and 12 the measured peak values of 32 undercutting experiments of the surge force, the heave force and the cutter torque are set out on the Y axis and the peak values calculated according to the calibration equations derived from equation (8) for undercutting experiments along the X axis.
Again the straight lines indicate the corresponding relationships and the broken lines a deviation of 25%.

The correlation coefficients found between the peak values measured and the peak values calculated for figures 7 to 12 fall between 0.950 and 0.978.

The relative increase of the cutter torque and the surge force, as a result of the movement to which the cutterhead was subjected, appears to be dominated by the amplitude and frequency of this movement. Both frequency and amplitude are represented approximately quadratically.
The swing velocity and the number of revolutions have only little influence on this increase. The relative increase of the heave force appears to be dominated by the amplitude, the number of revolutions and the swing velocity, which are represented respectively by the approximate powers 2, -2, 1.5, while the frequency is represented by the approximate power 1.0.

6. INTERPRETATION OF THE RESULTS

As the cutterhead moves out of the ground a relatively thin slice of sand is cut, so the cutting forces and the cutter torque are minimal. This situation is shown in figures 5 and 6, between 0 and 0.5 sec and between 1.5 and 2.0 sec, and presents no danger with regard to the failure of the mechanical construction.
Such danger does exist, however, if the cutterhead has a velocity which is directed towards the ground. This is shown in figures 5 and 6 in the area between 0.5 and 1.5 seconds.
The forces on the cutterhead increase strongly in this area as a result of :

- the small free running angle of the bottom blades, which can be reduced to 0° by the vertical velocity of the cutterhead ;
- the increase of the cutting depth of the blades round the circumference of the cutterhead ;
- the increase in the hardness of the ground at greater cutting depths ;
- the increase in the thickness of the slices which are cut by the bottom blades, in consequence of increasing vertical velocity of the cutterhead.

With a high amplitude value of the oscillation this increase can lead to the occurance of impacts which may result in damage to the mechanical construction.

The reason that the maximum in the heave force occurs somewhat later than the maximum of the surge force and the cutter torque is, that the heave force originates from the cutting forces on the bottom blades and is thus strongly dependent upon the hardness of the sand. This hardness increases with the cutting depth so the heave force shows a maximum which is closer to the maximum cutting depth.

The fact that the relative increase in the cutter torque and the surge force is dominated by the amplitude and the frequency of the movement to which the cutterhead was subjected, means that this increase is largely a result of the vertical velocity of the cutterhead.
The relative increase in the heave force was dominated by the amplitude, the number of revolutions and the swing velocity. This indicates that this increase is largely a result of the vertical displacement of the cutterhead, the thickness of the slices cut by the bottom blades and the ratio of the oscillation wave length and the cutter diameter.

7. CONCLUSIONS

The methods used for processing the observations of this research have proved satisfactory in providing both a qualitative and a quantitative impression of the dynamic behaviour of a cutterhead.
A qualitative impression was obtained by making graphs such as figures 5 and 6 for each experiment and a quantitative impression from the numerical values which were found for the calibration equations derived from equations (7) and (8).

Summarising it can be postulated that an oscillating movement of the cutterhead in the heave direction can lead to momentary increases in the surge force, the heave force and the cutter torque. Even with an amplitude of the oscillation of 20% of the height of the cut, the increases may be ten times the comparable loads measured during still water dredging.
An increase in the number of revolutions and a decrease in the swing velocity will lead to a marked decrease in the maximum values of the loads on the cutterhead.

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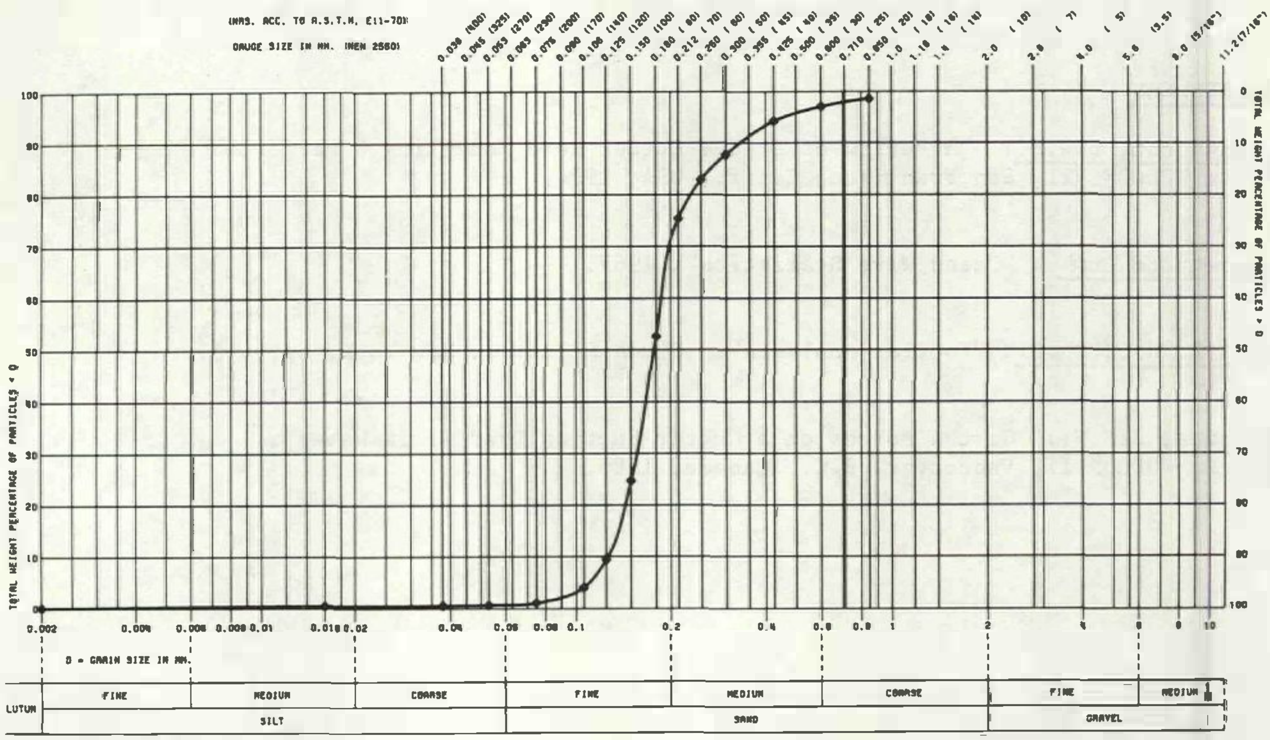

DATE: 22-09-1982
TIME: 10:35:00
INFO: SAMPLE OF BED IN TEST-RIG

FIG.1

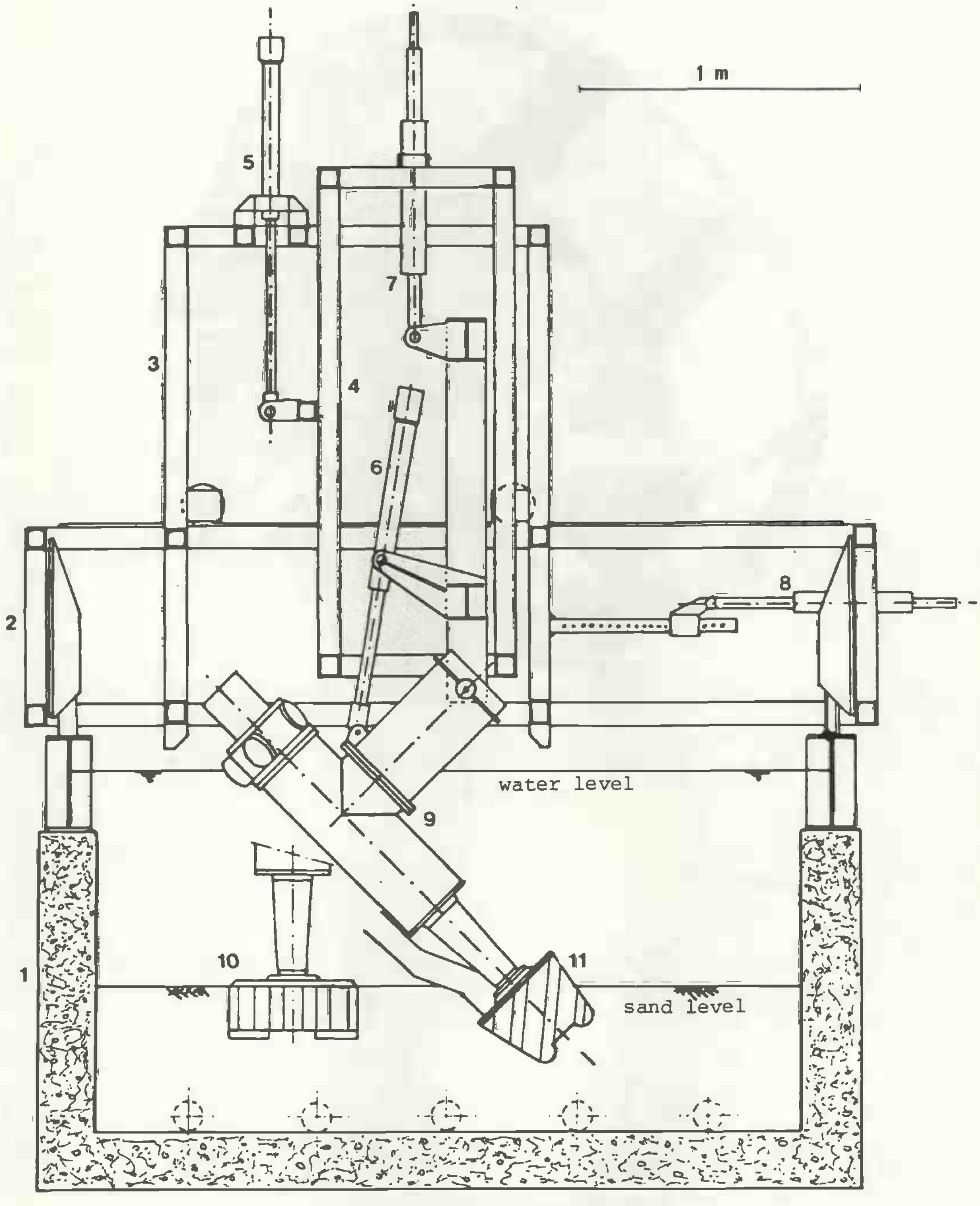

FIG.2: CROSS SECTION OF THE TEST RIG.

1. Reinforced concrete tank
2. Main carriage
3. Auxiliary carriage
4. Subframe
5. Hydraulic cylinder for vertical positioning of cutterhead
6. Hydraulic cylinder for positioning of ladder angle
7. Hydraulic servo-motor for vertical wave simulation
8. Hydraulic servo-motor for horizontal wave simulation
9. Ladder
10. Disc-bottom cutterhead
11. Crown cutterhead

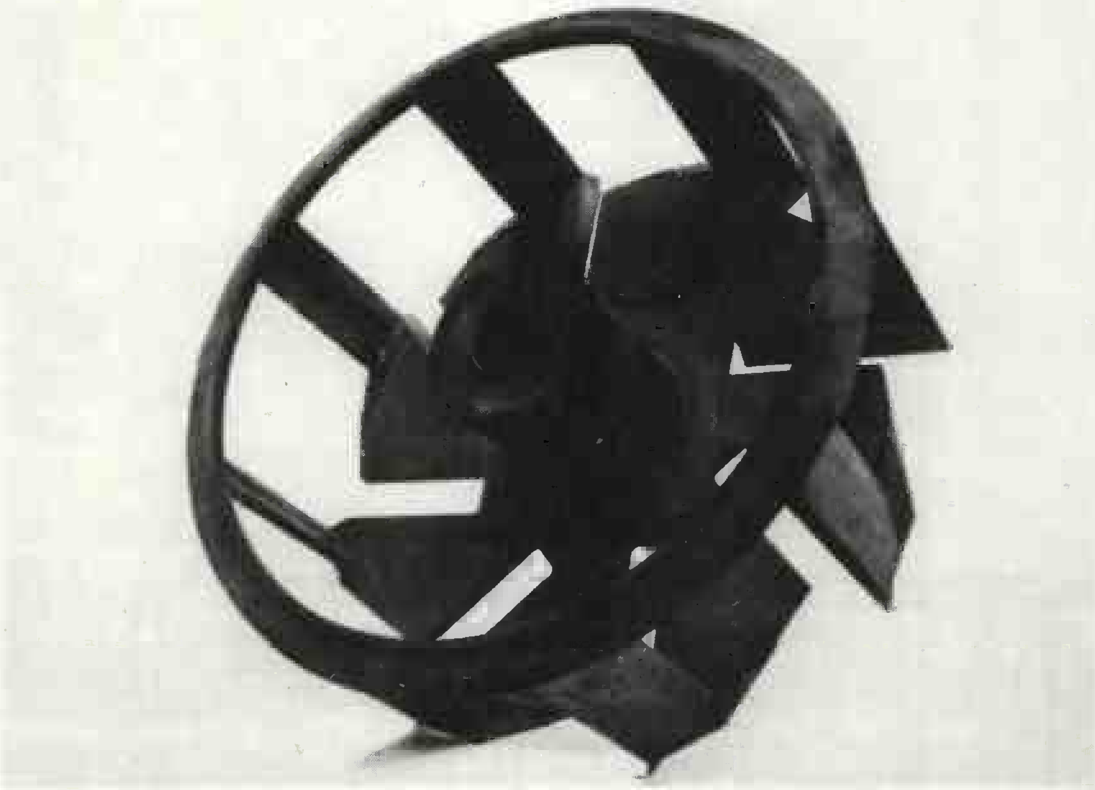

FIG. 3: DISC-BOTTOM CUTTERHEAD WITH BOTTOM BLADES

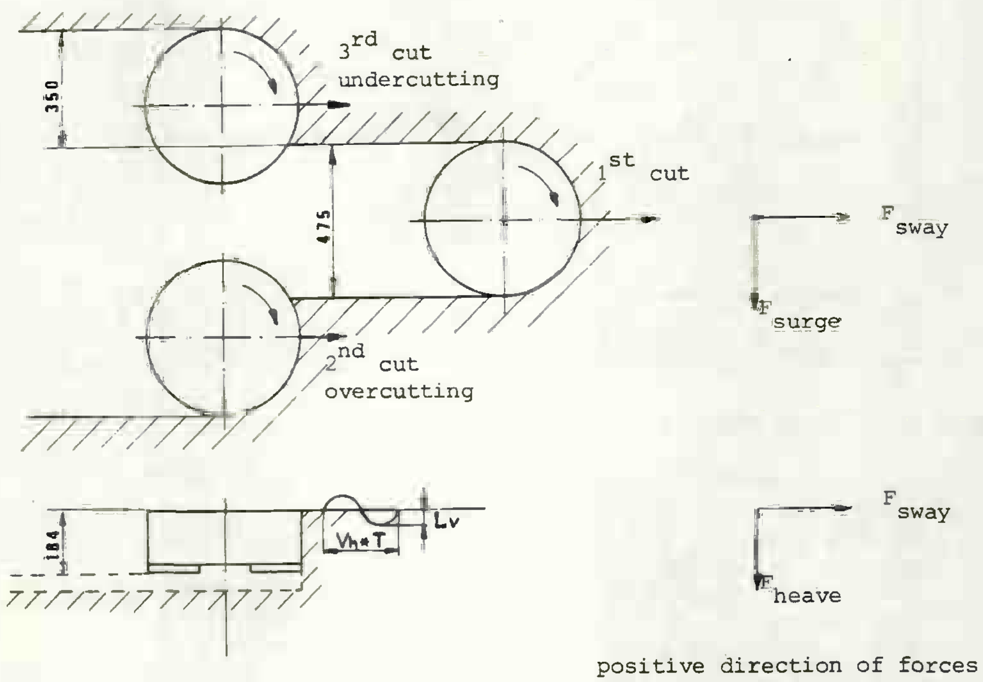

FIG. 4: CUTTING PATTERN

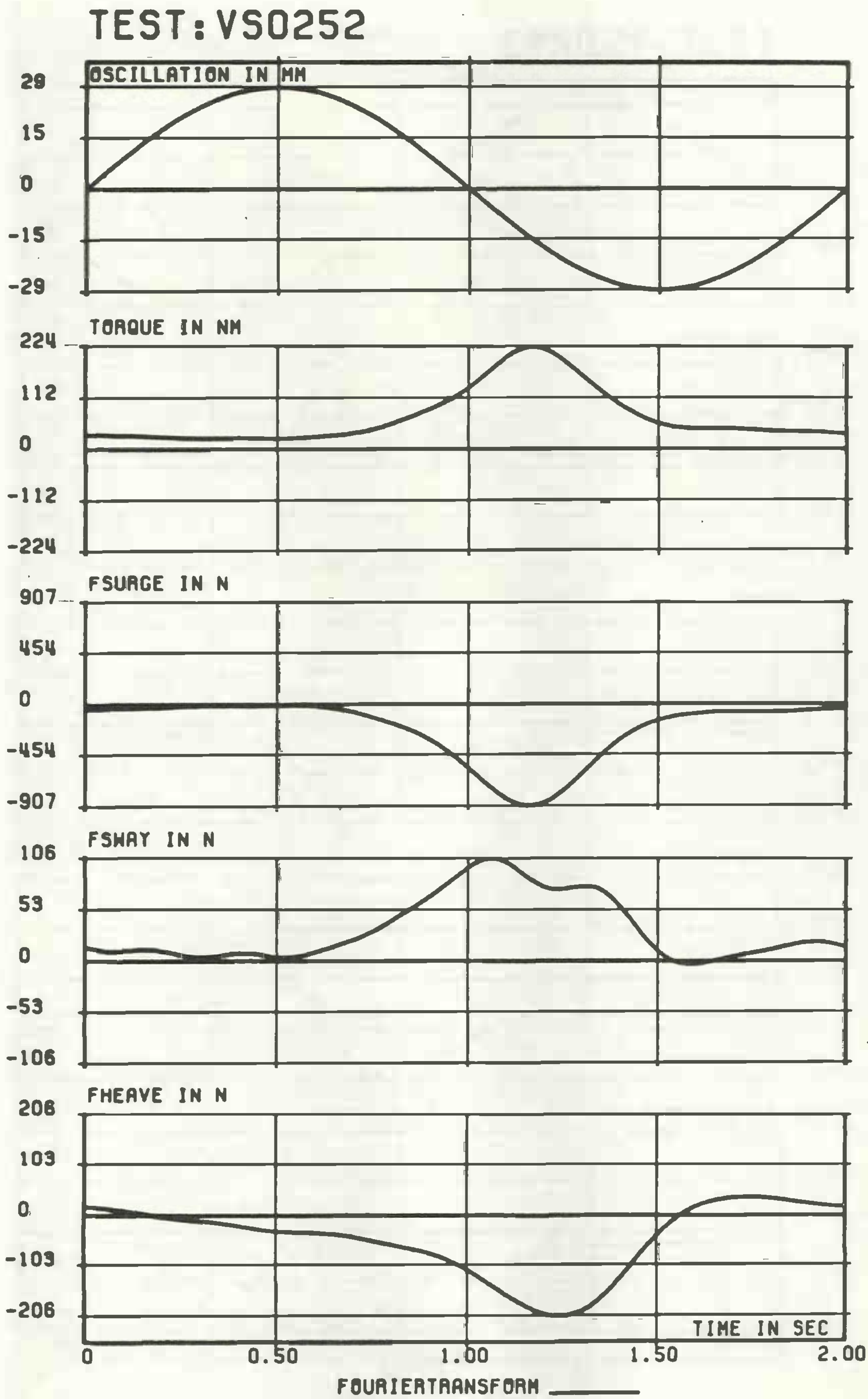

FIG.5: AN OVERCUTTING EXPERIMENT

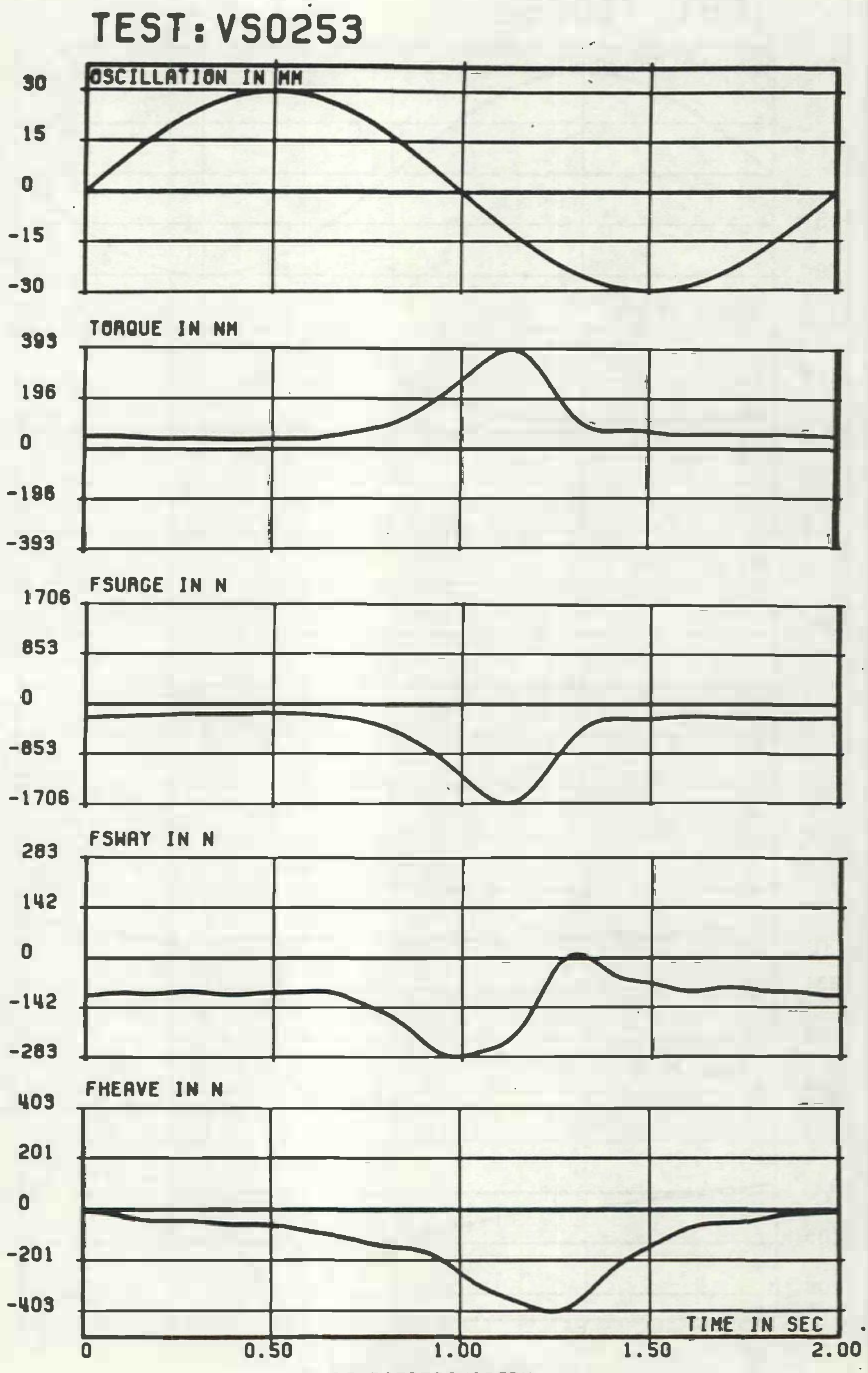

FIG. 6: AN UNDERCUTTING EXPERIMENT

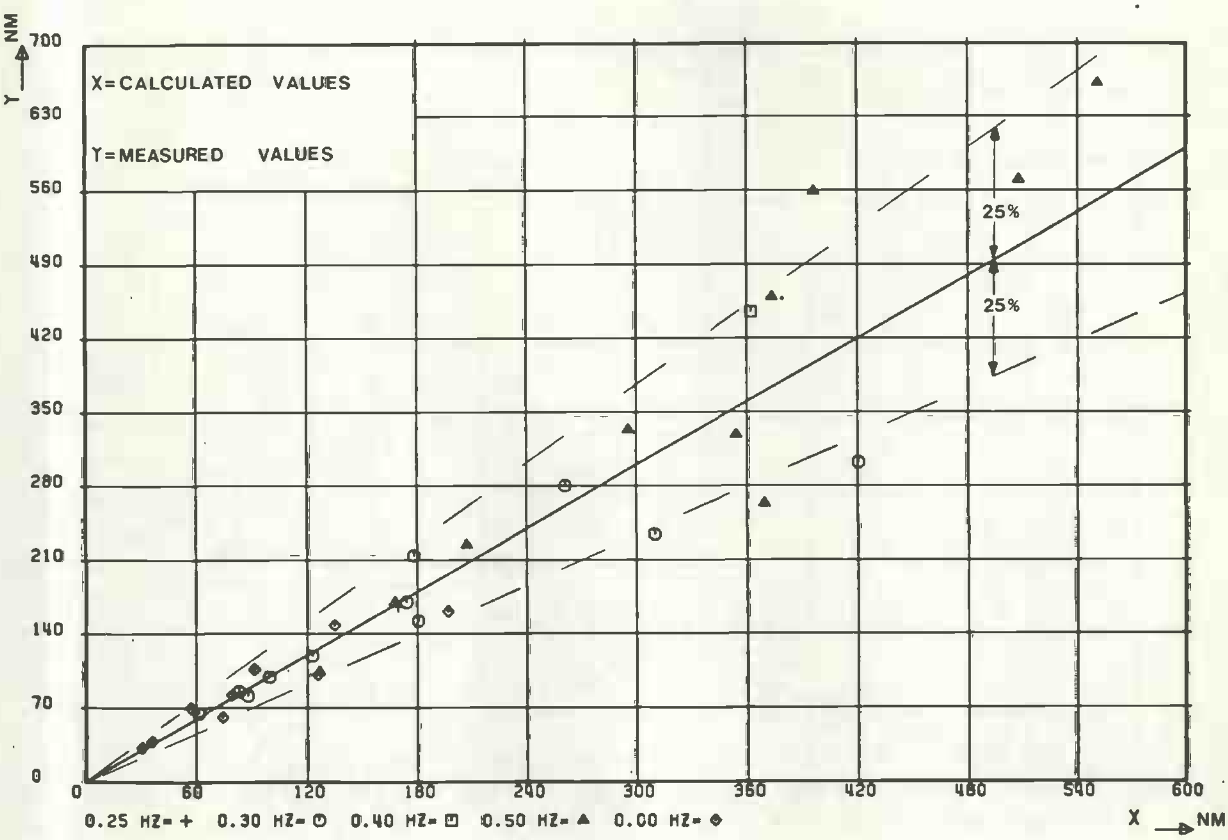

FIG.7:

The deviation of the measured values for the cutter torque from the calculated values (overcutting).

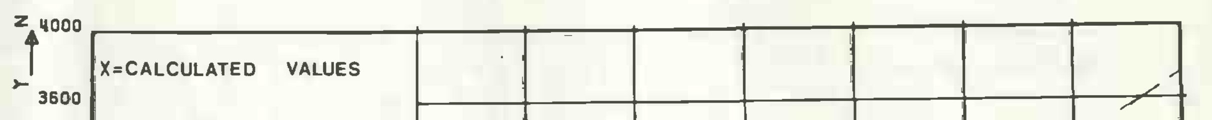

FIG.8:

The deviation of the measured values for the surge force from the calculated values (overcutting).

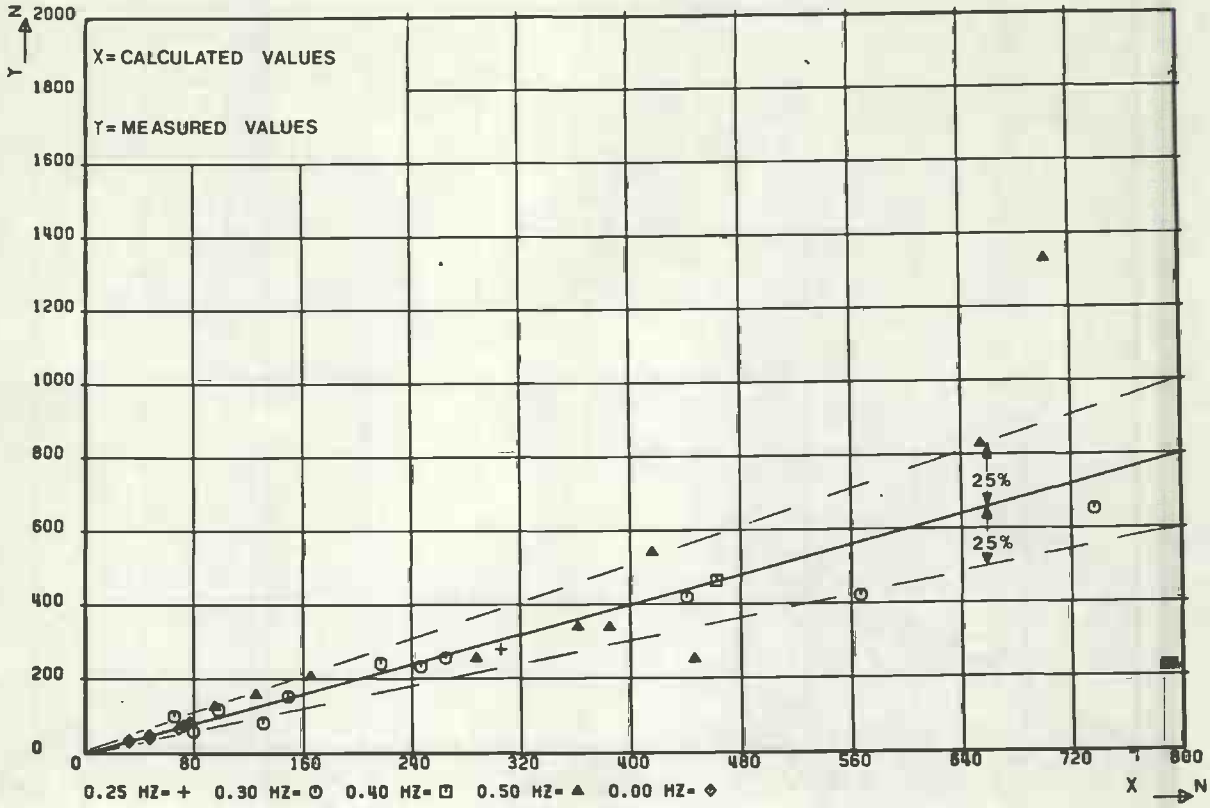

FIG. 9:

The deviation of the measured values for the heave force from the calculated values (overcutting).

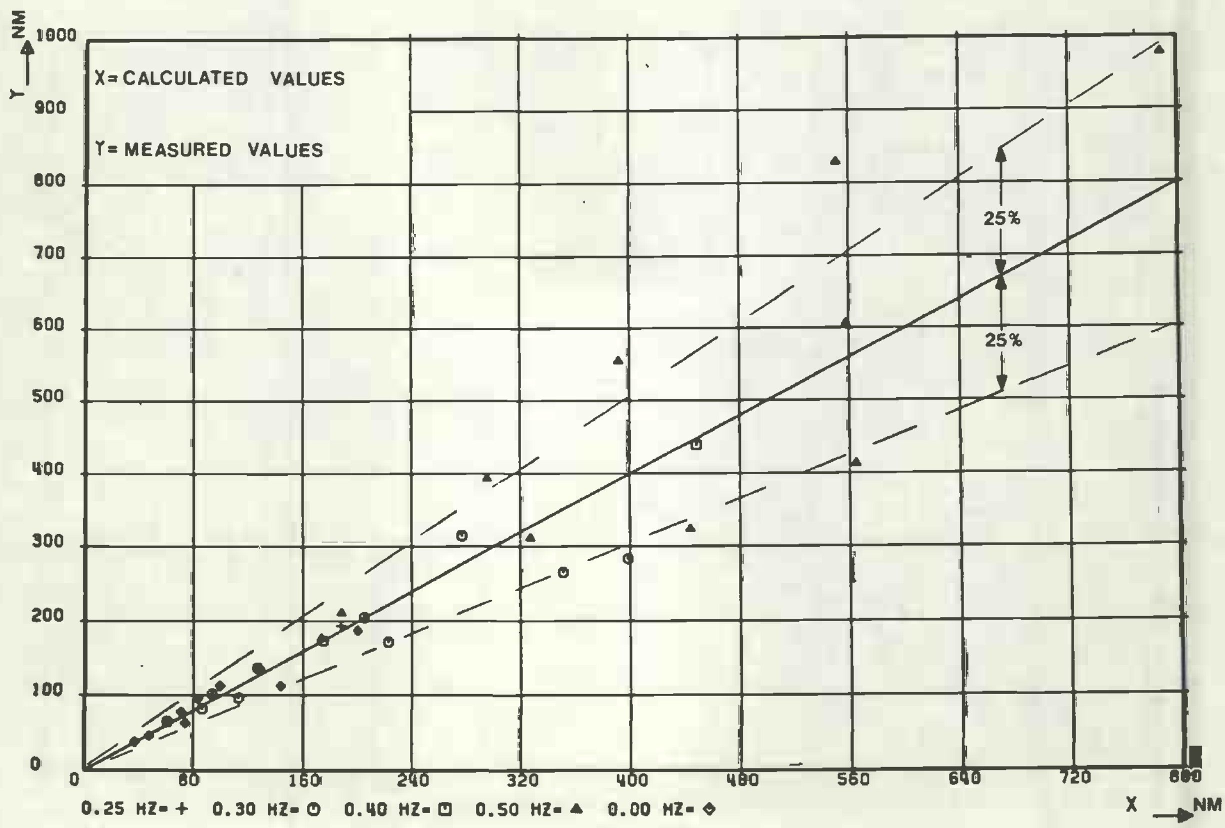

FIG. 10:

The deviation of the measured values from the calculated values for the cutter torque (undercutting).

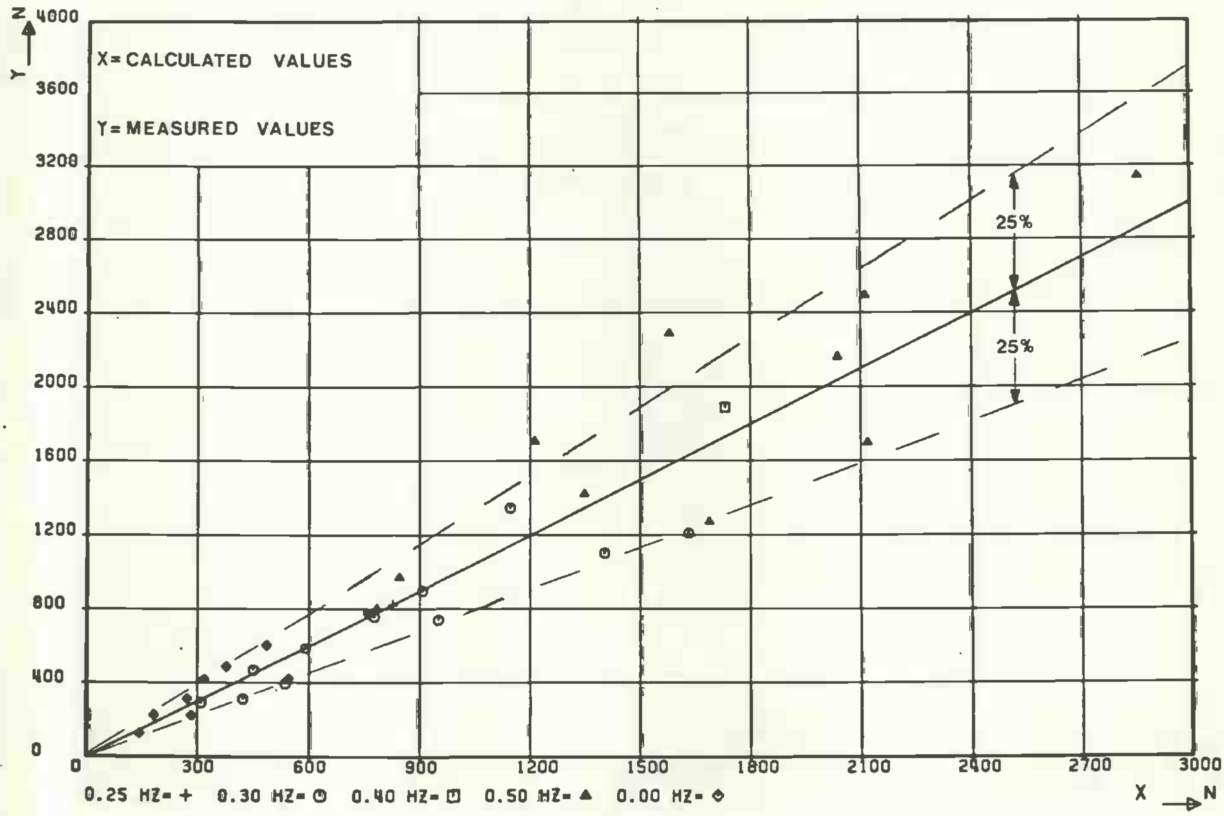

FIG.11:

The deviation of the measured values from the calculated values for the surge force (undercutting).

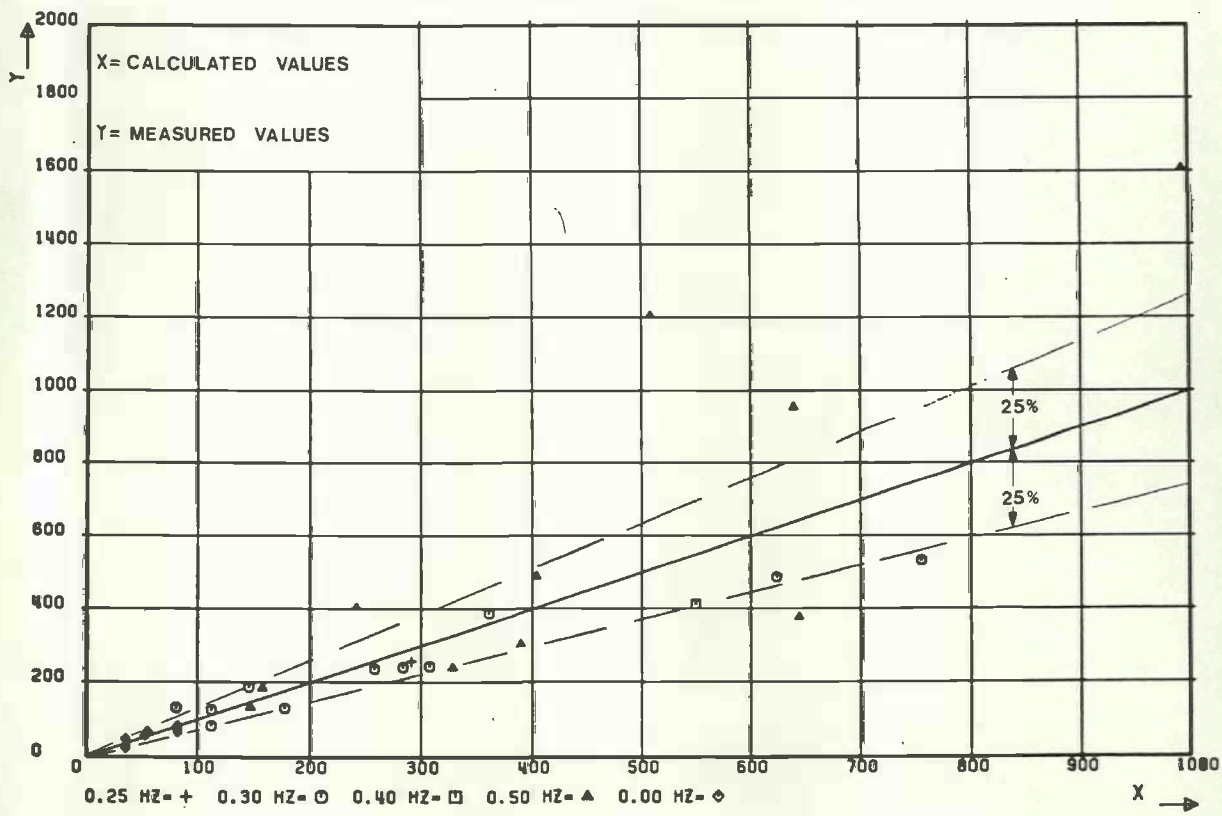

FIG.12:

The deviation of the measured values from the calculated values for the heave force (undercutting).