11. Natural Vibration of Jack-Up Oil Rig

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Summary

It is important to investigate the characteristics of the vibration of jack-up oil rigs in order to ensure their successful design. FEM is available for the accurate calculation of natural frequencies, but there are a few unknown quantities to be studied such as the virtual mass of a leg vibrating in water, and the supporting condition of the sea bed, among others.

This paper, first of all, deals with the calculation of natural frequencies and mode shapes, using an idealized model, composed of beam elements and plate elements, and vibration tests of an actual jack-up oil rig which has been constructed during the past two years. In these tests, four oil rigs were excited by the wire cutting method to obtain the lower natural frequency and logarithmic decrement. At the same time, the vibration of the leg due to wind was also measured in order to obtain its natural frequency.

The main conclusions are as follows.

(1) It may be accepted that the virtual mass coefficient of a leg composed of circular cylinders, C_v, equals 1.0.
(2) In calculating the natural frequency of the oil rig in a jacked-up condition, the spring effect should be taken into account.
(3) In estimating the dynamic response of the oil rig, the lowest three natural frequencies govern the dynamic response, due to wave force.
(4) The wire cutting method is very useful for measuring the natural frequency and logarithmic decrement of the oil rig.
(5) The measured lower natural frequencies are approximately proportional to $h^{-3/2}$ (h: platform height) and $W^{-1/2}$ (W: platform weight)
(6) The logarithmic decrement indicated is from 0.2 to 0.3, which is larger than that for ship's.
(7) The first and second modes of the legs are governed by their bending and torsional deformation, respectively. Their natural frequencies are approximately proportional to l^{-2} (l: leg length) and l^{-1}, respectively.

1. Introduction

Recently many jack-up oil rigs have been constructed by shipbuilders at home and abroad, while engineers and researchers have been studying the engineering and technical problems connected with oil rigs especially concerning dynamic response due to wave force. To solve these problems, it is important to gain a knowledge of the characteristics of the vibrational behavior of the oil rig as a structure. However there are a few unknown quantities which must be investigated, such as the virtual mass of legs vibrating in water, and the supporting conditions of the sea bed.

In this paper the authors obtained the vir-

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tual mass experimentally, using leg models, because it is very difficult to calculate theoretically the virtual mass of legs composed of circular cylinders. In addition they studied the effect of the sea bed on the natural frequency of an oil rig.

It is necessary and important to carry out vibration tests on an oil rig in actual operating conditions, for checking against the theoretical natural frequency and also for obtaining the logarithmic decrement, which is unable to be estimated theoretically. However we could find few technical papers about the experiments of units in actual operating conditions.

Here, the authors have tried to gather useful data concerning natural frequencies and logarithmic decrements, in the vibration tests of four units. In these tests, the oil rigs were excited by the wire cutting method, which is usually used for land structures. This is perhaps the first time that this method has been used on offshore structures.

2. Theoretical analysis of the natural vibration of oil rigs

2.1 Added virtual mass of legs

It is usual to take the dead weight of the legs as the added virtual mass of the legs vibrating in water. The authors carried out their experiments on the legs' vibration in water using the scale model of leg, according to the following procedure.

(1) Models used and experimental procedure

The authors used the circular cylinder steel model and the 1/20 scale model of a leg, (Fig. 1). The former model was used for checking the accuracy of the experimental method, because the theoretical added mass of a circular cylinder is able to be calculated easily. As shown in Fig. 1, the latter model is a two-dimensional model with an edge plate (850 mmϕ, t=6 mm) at each end, as shown in Fig. 1. The leg model is composed of stainless steel pipes, a sal-vinyl plastic edge plate and

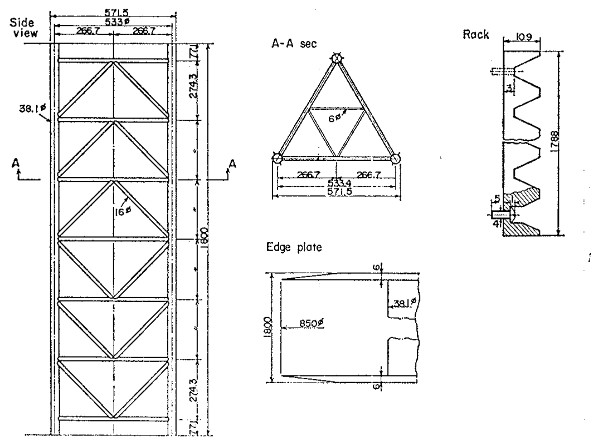


Fig. 1 Leg scale model (scale: 1/20)

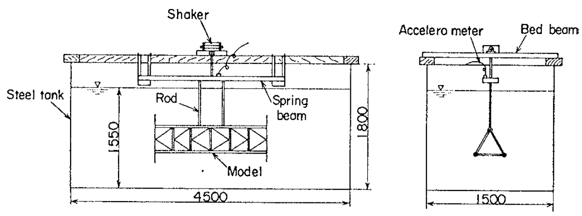


Fig. 2 Experimental apparatus

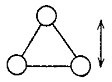
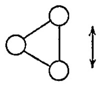
an acrylic rack.

The experiments were carried out in a steel tank ($L \times B \times D = 4.5$ m $\times$ 1.5 m $\times$ 0.8 m) as shown in Fig. 2. The models were suspended by two rods at midspan of a spring beam. The fundamental natural frequencies of the spring beam were measured with the model in water and in air. Table 1 shows details of the experiment.

(2) Results

Table 2 shows the natural frequencies measured. Fig. 3 and Fig. 4 show examples of measured mode shapes. These figures led to conclusion that the model vibrated only in the vertical direction, and that the difference between the natural frequencies in air and water was only due to the increase of weight at the midspan of the spring beam, which means added mass. The following equation is derived from the relation between the natural frequency in air and that in water, including the added mass.

Table 1 Details of experiment

Model	Span of spring beam (mm)	Weight (kgf) {N}	Direction of motion
Circular cylinder model (P)	2200	12.1 {118.7}	
Leg scale model : Vertical vib. (PA)	2200 (PA-I)	31.1 {305.0}	
	1600 (PA-II)		
Leg scale model : Horizontal vib. (PB)	2200 (PB-I)	37.7 {369.7}	
	1600 (PB-II)		
	580 (PB-III)		

* Weight of spring beam is 37.1 kgf {363.8 N}

Table 2 Experimental natural frequencies

unit : Hz

Model \ Span		l = 2200 mm (I)	l = 1600 mm (II)	l = 580 mm (III)
P	air	23.8		
	water	21.5		
PA	air	18.6	24.4	
	water	16.8	21.5	
PB	air	16.7	24.3	31.1
	water	14.9	22.4	28.6

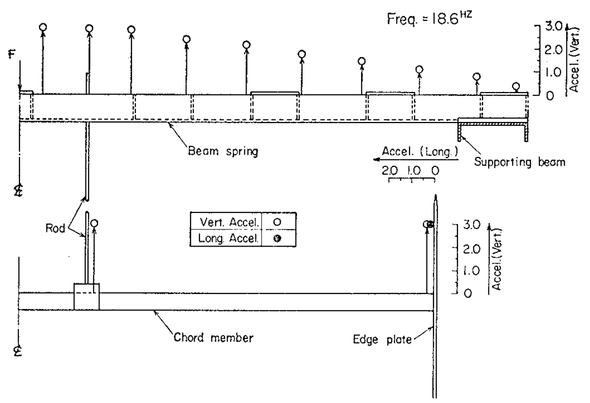


Fig. 3 Mode shape of spring beam with the leg scale model

$$\left(\frac{f_a}{f_w}\right)^2-1=\frac{M_F}{M_M+M_B} \quad (1)$$

where

f_a : Natural frequency in air

f_w : Natural frequency in water

M_F : Added mass

M_M : Total weight of model and attachments

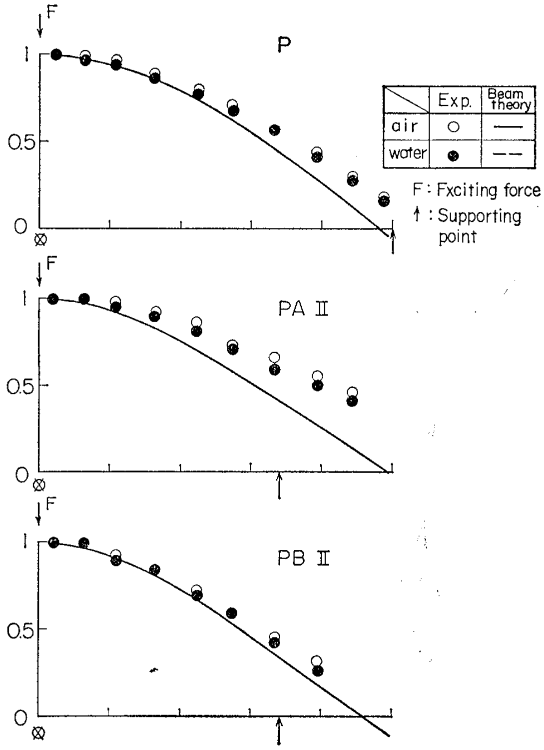


Fig. 4 Experimental mode shape of spring beam in air and water

M_B : Available weight of spring beam vibrating

The two-dimensional added mass of a body with a circular cross-section is equal to the dead weight ($=\rho gV$). So the added virtual mass coefficient C_v is defined as the ratio of the body of undefined cross-section to one with a circular cross-section expressed as the equation:

$$C_v=M_F/\rho V \quad (2)$$

Table 3 shows the experimental added virtual mass coefficient C_v calculated from the measured natural frequencies in Table 2 using Eq. (1) and Eq. (2). The experimental C_v of the circular cylinder model is 0.99, which agrees well with the theoretical value 1.0. Therefore the accuracy of the authors' experiment was verified. In Table 3 it is apparent that variations in the spring beam's span cause diversification of the experimental C_v of the leg model and also that the value of C_v varies

Table 3 Experimental added virtual mass coefficient C_v

Experiment name	ε^*		W (kgf){N}	W_F (kgf){N}	C_v
P	0.225		30.3 {297.1}	6.83 {67.0}	0.99
PA - I	0.226	0.257	49.3 {483.5}	12.66 {124.2}	1.15
PA - II	0.288				
PB - I	0.256	0.205	56.2 {551.1}	11.53 {113.1}	1.05
PB - II	0.177				
PB - III	0.183				

$^* \varepsilon = (f_a/f_w)^2 - 1$

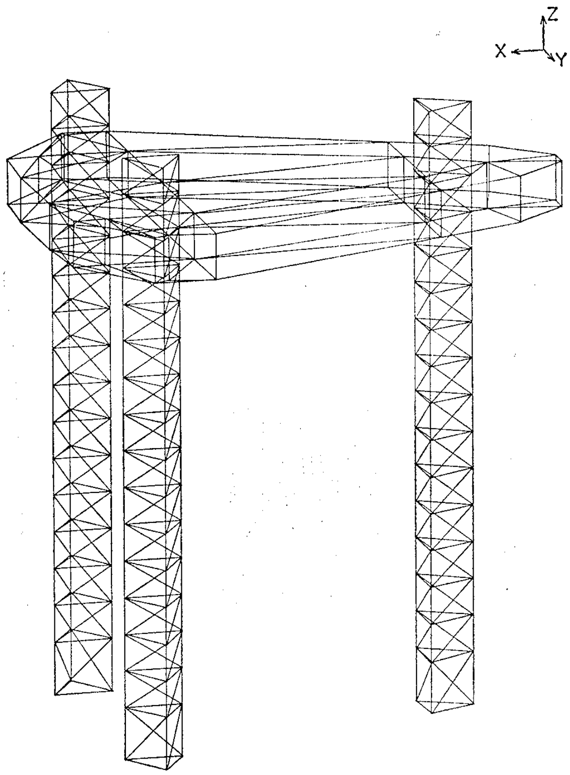
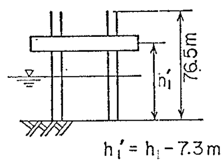


Fig. 5 Idealized model of oil rig for FEM

Table 4 Effect of spud tank upon natural frequency

order \ cond	with spud tank	without spud tank
1	0.4289 Hz	0.3919 Hz
2	0.4319	0.4278



a little in accordance with the direction of model's motion. However C_v can be given an approximate value of 1.0 for the purpose of analysis of vibration.

2.2 Calculation method

An idealized oil rig structure is used for analyzing the natural vibration with FEM, in the following manner.

The three-dimensional idealized model of the oil rig is composed of beams and rigid plates. The former form the lattice structure of the legs and the latter form the box structure of the platform. Fig. 5 shows an example of a three-dimensional model of an oil rig. This model contains 209 nodes, 450 beams and 76 plates. The authors assumed that a weightless rigid bar would connect the legs and platform, because this connection is tightened by inserting a wedge into the gap between the leg and the leg guide.

The usual oil rig is equipped with a spud tank which is highly rigid at the bottom end of each leg. This spud tank is supposed to be the most rigid part of the leg. It is obvious from the calculation results shown in Table 4 that the spud tank causes the natural frequency to be slightly higher, due to the constrained rotation of the leg end at the sea floor. Subsequently the authors analyzed the natural vibration of the oil rig model with a spud tank.

The natural frequency of an oil rig can be expected to be considerably affected by the constraint at the sea floor. In order to investigate this effect, two conditions involving support are taken into consideration. One is simple support, the other is elastic support. From the calculated natural frequency given in Table 5, the condition of elastic support (LK) gives a frequency which is 8～15% lower than the simple support condition (LS). Accordingly, the effective spring constant of the sea floor is a very important factor, and it must be taken into account in calculating the natural frequency of an oil rig.

Table 5 Natural frequencies

unit : Hz

Cond.	N2			N5		
	LS	LK		LS	LK	
Order	f_t		f_e	f_t		f_e
1	0.3684	0.3157		0.2624	0.2273	
2	0.3713	0.3191	0.313	0.2657	0.2307	0.238
3	0.3917	0.3390		0.2838	0.2488	
4	2.606	2.411	2.488	2.380	2.211	
5	2.694	2.473	2.575	2.439	2.261	
6	2.737	2.619	2.750	2.544	2.448	
7	2.772	2.737	2.825	2.545	2.538	
8	2.777	2.771		2.570	2.560	
9	2.789	2.774		2.664	2.562	
10	2.864	2.855		2.805	2.612	
11	2.975			2.824		
12	3.093			2.832		
13	3.335			2.858		
14	3.334			2.902		
15	3.345			2.970		

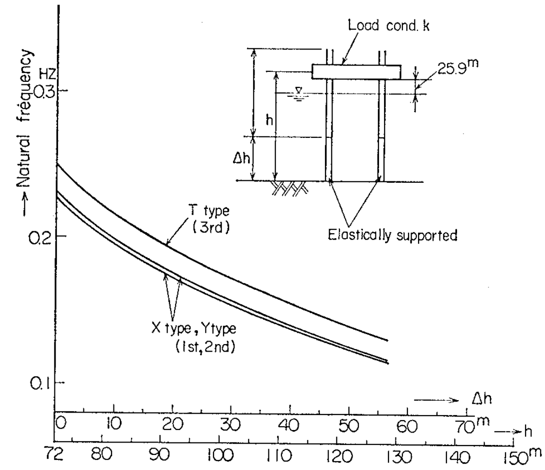


Fig. 7 Relation between platform height (water depth) and natural frequency

2.3 Calculation results

(1) Natural frequency

The authors analyzed three platform heights, 51.7 m, 62.7 m and 72.1 m respectively, for investigating the effect of platform height in water of constant depth. The results of these calculations are given in Fig. 6. As shown in Fig. 6, the first three natural frequencies vary inversely with platform height. Fig. 7 shows the relation between platform height (including water depth) and natural frequency of an oil rig of which the legs are enlogated in proportion to the increase of water depth. It is easy to estimate the natural frequency of an oil rig in the same scale as shown in Fig. 7.

(2) Mode shape of oil rig

Figs. 8 (a)～(f) shows the mode shape of an oil rig operating in deep water (Leg length 150 m and platform height 108 m). The mode shape of an oil rig can be generally classified into two types of vibration, namely global vibration and local vibration. In the former, motion of platform predominates and the mode shape is determined by the combined motion of three legs. In this case the platform and legs are

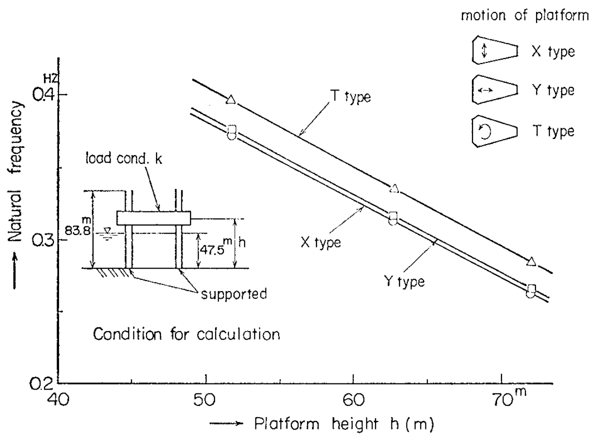


Fig. 6 Relation between platform height and natural frequency

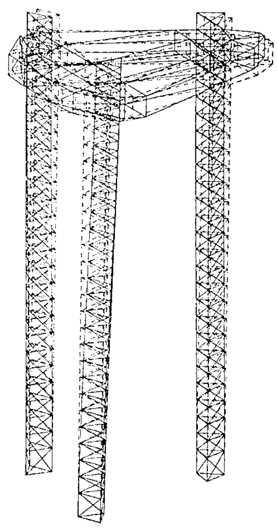


Fig. 8 (a) Mode 1. Frequency 0.12 Hz

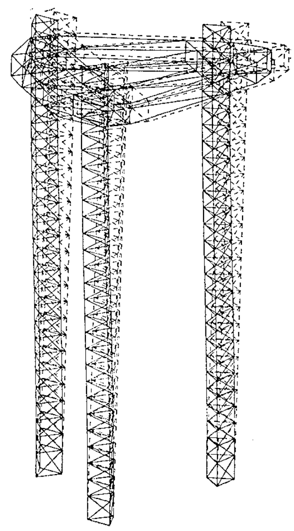


Fig. 8 (b) Mode 2. Frequency 0.12 Hz

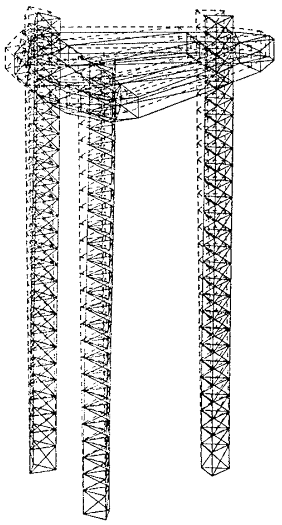


Fig. 8 (c) Mode 3.
Frequency 0.13 Hz

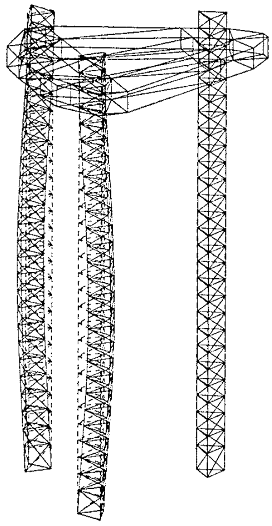


Fig. 8 (d) Mode 4.
Frequency 1.07 Hz

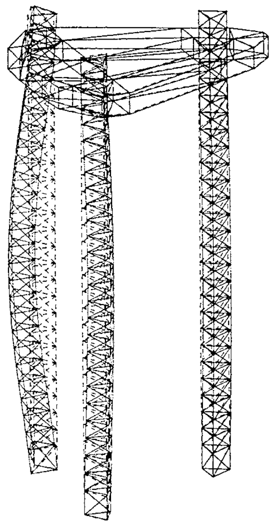


Fig. 8 (e) Mode 5.
Frequency 1.08 Hz

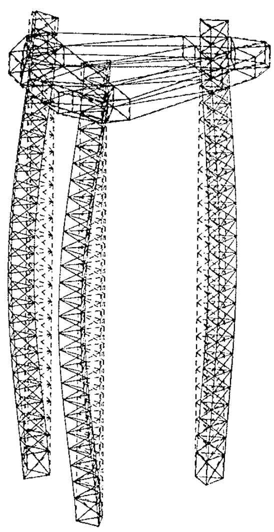


Fig. 8 (f) Mode 6.
Frequency 1.09 Hz

Fig. 8 Theoretical mode shape of an oil rig operating in deep water

supposed to act as mass and spring, respectively. In local vibration the amplitude of platform is relatively small compared with that of the legs. When the legs protrude above the platform in shallow water operation, local vibration is frequently observed.

Fig. 9 summarizes the order of natural frequency and mode shape. The lowest three natural frequencies, namely, two sway modes

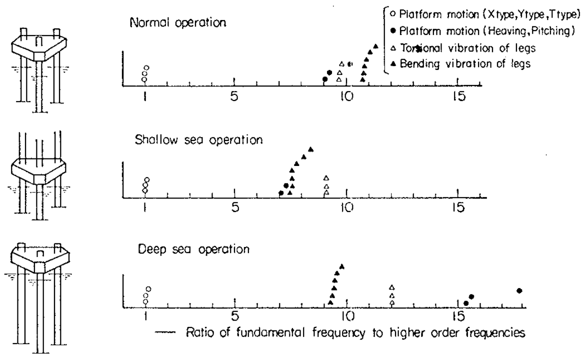


Fig. 9 Order of natural frequencies of oil rig

and a torsional mode, are very close to one another in every operating condition. As natural frequencies beyond the fourth order mode are 10∼7 times as high as the first, frequencies higher than third order can be disregarded in calculating dynamic response in connection with wave action.

3. Vibration tests in actual oil rigs

3.1 Method of vibration tests

(1) Test conditions

The authors induced vibration in four actual oil rigs selected from among the many constructed by their company between 1977 and 1980. Test conditions are shown in Table 6. Fig. 10 shows the profile of a jack-up oil rig,

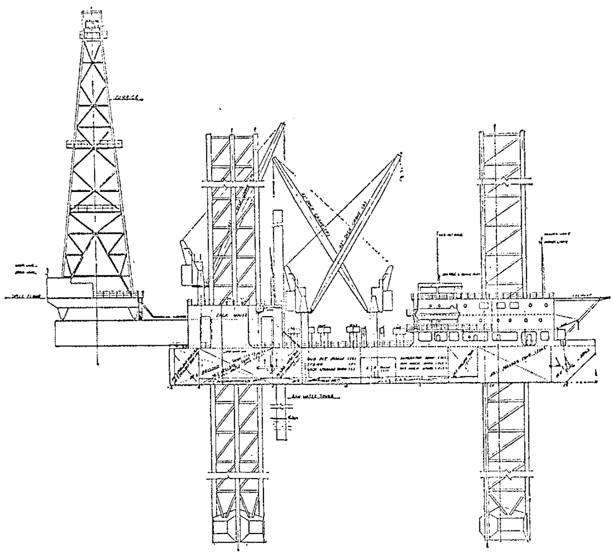
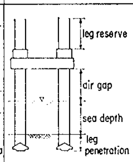


Fig. 10 Profile of a jack-up oil rig

Table 6 Test condition

Item \ Rig	N					F	O	L	Remark
Test name	N1	N2	N3	N4	N5	F1	O1	L1	
Load (tf)	543	519	5600	916	560	360	984	802	
Air gap (m)	9.6	5.7	5.7	25.4	21.4	5.5	15.0	16.0	
Leg reserve (m)	44.0	22.3	22.3	2.3	5.3	17.6	76.9	30.8	
Sea depth (m)	13.8	42.8	42.8	45.2	47.5	40.0	15.0	40.0	
Leg penetration (m)	6.7	1.3	1.3	1.3	1.3	1.0	5.5	1.5	
Test place	A work	Off Shimabara					O work	Off Shimabara	
Exciting way	Wind	Exciter	Exciter	Exciter	Wire	Wire	Wire	Wire	
Date	S.54. 8.26.	S.54. 8.29.	S.54. 8.31.	S.54. 9.1.	S.54. 9.1.	S.55. 3.25.	S.55. 9.26.	S.56. 6.11.	

as an example of an oil rig.

In Table 6, tests N2～N5, F1 and L1 were all conducted at the same location off Shimabara, where the sea bed is relatively hard, and leg penetration was very small, ranging from 1 m to 1.5 m. On the other hand, tests N1 and Q1 were carried out in the sea off the factory piers, where the soft sea floor resulted in deep leg penetration.

Loading in each test was constant, at about 10% of platform weight, except for that of test N3, for which loading was about 5000 tf. However, platform heights varied from 30 m to 71 m. Tests N4 and N5 were considered to be tests of deep sea operation conditions, while tests N1 and O1 were for testing shallow water operation conditions. Other tests were regarded as being in normal operation conditions.

(2) Methods of inducing vibration

i) Wind

A long reserved leg is constantly excited by normal wind because its structure is flexible. We can obtain the natural frequency of a leg by spectrum analysis of data measured during a few minutes. In the case of F and L oil rigs, leg vibration due to wind was measured during the towing period. In the case of N leg, vibration caused by a typhoon was also measured. From this data, natural frequency and logarithmic decrement could be obtained by spectrum analysis and the half-powerband width method respectively.

ii) Exciter

The authors tried to excite the oil rig N using a weight unbalance type exciter with a maximum output of 5 tf, following the same method as for a ship hull vibration test. In this experiment, an exiter installed at the approximate center of gravity of the platform excited the oil rig horizontally. However the authors failed to obtain a resonance curve for the oil rig because of the insufficiency of the exciting force.

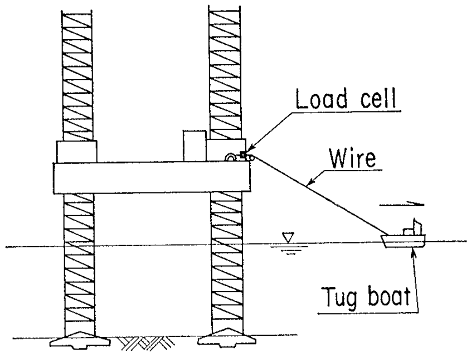


Fig. 11 Cutting wire method

iii) Wire cutting method

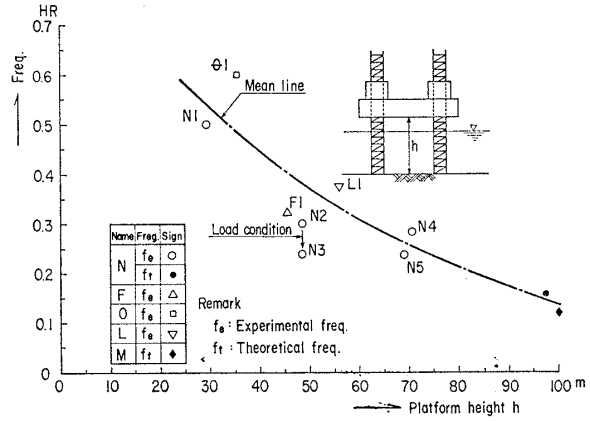
The wire cutting method is sometimes applied to large structures on land because of being able to obtain their natural frequency and logarithmic decrement. This is a simple method applying tension to structures by means of wire, and releasing them suddenly to induce free vibration.

The authors applied this method to an offshore structure for the first time. As shown in Fig. 11, a tug boat was employed to pull an oil rig in along its length, by means of a wire. The wire was cut after the tensile force in the wire reached beyond 60 tf. This method enabled simple and short-term measurement of the natural frequency and logarithmic decrement for global vibration of the oil rig.

3.2 Results of vibration tests

(1) Measured natural frequencies

The natural frequency depends on many parameters, including platform height, platform weight, water depth, leg rigidity, leg weight, and support conditions at the sea floor. The



Name	Freq.	Sign
N	f_e	○
	f_t	●
F	f_e	△
O	f_e	□
L	f_e	▽
M	f_t	◆

Fig. 12 Relation between natural frequency and platform height

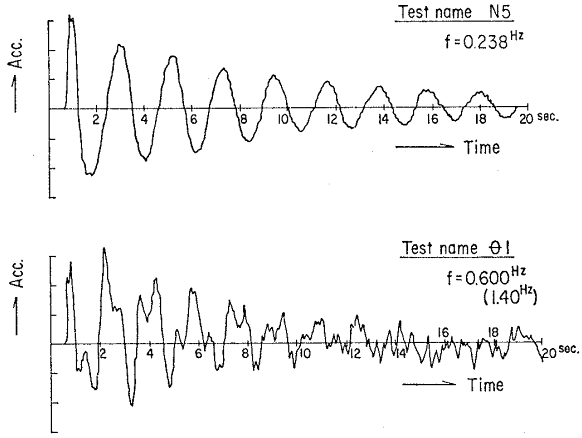


Fig. 13 Time history of measured acceleration at the center of gravity in platform

sizes of the four actual units shown in Table 6 are almost same and so platform height is regarded as the most predominant parameter here.

Fig. 12 shows the relation between platform height h (=airgap+sea depth+leg penetration) and the measured natural frequencies in all tests in Table 6. This figure indicates that regardless of differences in rig structure and loading, measured natural frequencies have a tendency to decrease gradually as platform height increases, while the broken line in this figure shows the mean line which is approximately in proportion to $h^{-3/2}$. As shown in Fig. 12, the theoretical natural frequencies, with symbols ● and ◆, of oil rigs operating in deep water, approach 0.1 Hz. So, we must give attention to the natural frequencies rigs, with regard to the predominant wave periods of the seas in which they operate.

Generally speaking, the natural frequency of an oil rig is inversely proportional to $W^{1/2}$ (W: total weight of oil rig). Here, in order to verify this point, we will take the cases of tests N2 and N3, of which the test conditions were identical except with respect to loading, as shown in Table 6. The natural frequency of test N3, as calculated from the measured frequency of test N2, 0.313 Hz, was 0.230 Hz and this value is close to the measured natural frequency, 0.238 Hz, of test N3.

(2) Measured logarithmic decrement

Before calculating the wave-caused dynamic response of an oil rig, the logarithmic decrement must first be known. However, little data on logarithmic decrements has been obtained from the experiments of actual oil rigs. Therefore, the authors performed systematic experiments to find a simple way to measure logarithmic decrement using the cutting wire method.

Time history examples of measured acceleration induced in the platform just after wire cutting are shown in Fig. 13. Acceleration in test N5 shows typical damped free vibration, but acceleration in test O1 shows disorder of the wave combined with two waves having different periods, 1.7 s and 0.7 s, respectively. This is not only because leg penetration is increased by the soft sea bed, but also because the pulling direction of the tug did not equal the oil rig's principal axis. The authors concluded that attention must be paid to the pulling direction in order to obtain acceptable data.

Table 7 summarizes the measured logarithmic decrements obtained from the acceleration wave. These values are between 0.2 and 0.3, which are 5～10 times greater than the

Table 7 Measured logarithmic decrement of actual oil rig

Item \ Rig name	N	F	O	L
Test Name	N5	F1	O1	L1
Logarithmic decre.	0.214	0.333	0.242	0.288
Natural frequency	0.238	0.325	0.600	0.375

logarithmic decrement for ship hull vibration. The authors surmised that the reason might be due to dissipation of large vibration energy from the leg into the soil of the sea bed. According to the Det Norske Veritas rule, logarithmic decrement δ of an offshore structure is given as 0.031 in air and 0.126 in water. In comparison with these values, the author's logarithmic decrement seems to be slightly larger, but they are assumed to be reasonable taking into account of the scattering of the measurement.

(3) Comparison of measured and calculated natural frequencies

Table 8 shows a comparison of measured natural frequencies and frequencies calculated by the analysis mentioned in Section 2. As shown in Table 8, fairly good agreement is observed between the measured and calculated natural frequencies.

In the case of test F1, the measured natural frequency is between those calculated for oil rigs with simple support and elastic support. Fig. 14 shows the calculated mode shape of the three lower vibrations of test F1, in which

Table 8 Results of natural vibration analysis with FEM

Item / Test name	Calculated natural freq. 1st	2nd	3rd	Calculation model: Supporting cond	Platform	Mode shape	Measured natural freq.
N2	0.316	0.319	0.339	Elastically supported	Plate element (Rigid)	Fig.8 in ref(1)	0.313
N5	0.227	0.231	0.249				0.238
F1	0.249	0.262	0.315	Simply supported	Beam element (Equivalent rigidity)	Fig.7	0.325
	0.434	0.474	0.530	Elastically supported			
O1	0.545	0.864	0.909	Simply supported		Fig.8	0.600 (1.400)
L1							0.375

Unit Hz

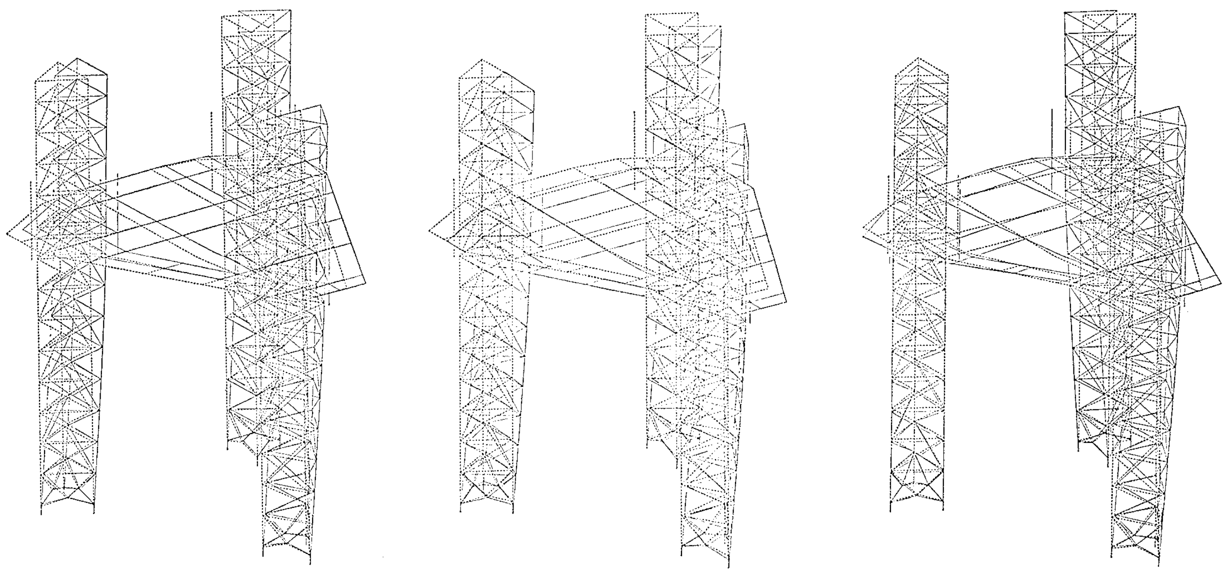


Fig. 14 Mode shape of oil rig (test F1)

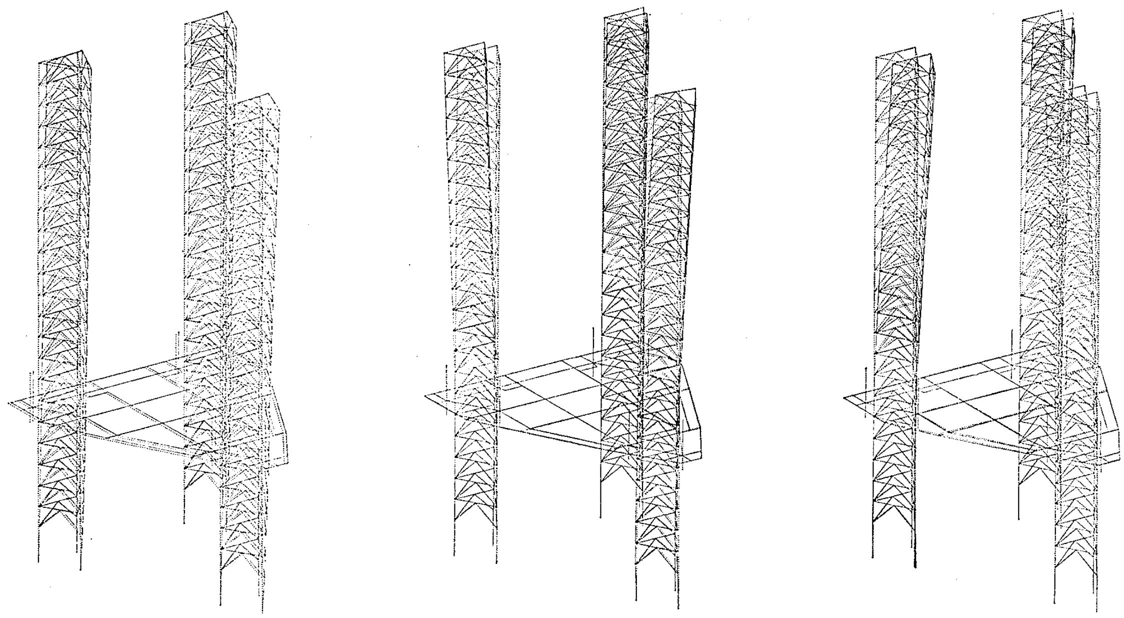


Fig. 15 Mode shape of oil rig (test O1)

horizontal vibration, fore-aft vibration and torsional vibration of the platform occur sequentially.

In the calculation of natural vibration for O1, the bottom ends of legs were assumed to have simple support. Fig. 15 shows the theoretical mode shape. Leg reserve was so long that the amplitute of the leg was much larger than the platform's. The calculation result shows that the order of natural frequencies is different from natural frequencies in other cases. Here, the sway mode has the lowest natural frequency and the local vibration of the leg reserve has the higher two natural frequencies. Therefore, the measured natural frequency, 0.60 Hz might be the natural frequency of the sway mode.

4. Natural vibration of legs

Service engineers frequently have the opportunity to observe leg vibration due to wind when towing oil rigs to sea or during shallow water operation. Since this phenomenon may be torsional vibration induced by a Karman vortex occuring in the rack of the leg, the anothers performed a study on leg vibration characteristics.

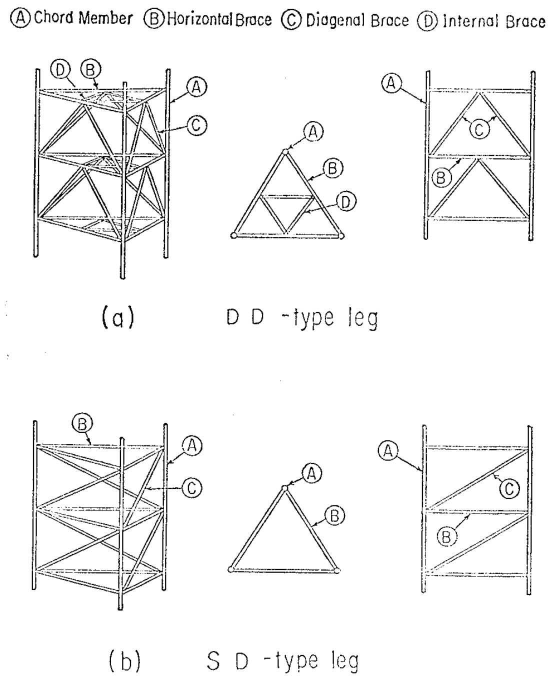


Fig. 16 Leg construction of rig

4.1 Measured natural frequencies

There are two types of leg constructions, the double-diagonal type (DD type) and single-diagonal type (SD type), as shown in Fig. 16.

Natural frequencies of the leg measured by the authors are given in Table 9. The authors obtained the two lower natural frequencies of two different lengths of leg reserves. Bending vibration produced the lower natural frequency, and torsional vibration produced the higher one. These are marked by B and T respectively in Table 9. Torsional vibration with the higher frequency occurs more often than bending vibration is relation to the exciting force of Karman vortex at the edges of the three code member.

4.2 Calculated natural frequencies

The authors analyzed the natural vibration of a leg using FEM. In this analysis, the boundary condition at the bottom end of the leg was assumed to have simple support.

Calculated natural frequencies and mode shapes of the leg are shown in Table 9, Fig. 17 and Fig. 18 respectively. Table 9 shows good agreement between calculated and measured natural frequencies. By the theoretical mode shape in Fig. 17 and Fig. 18, the first and second natural vibrations are determined to be bending and torsional vibrations, respectively.

The reason why there are two mode shapes for bending vibration at the same frequency is that one section of the leg has six principal axes from an equilateral triangular. Each equivalent moment of inertia surrounding these axes equals each other.

Fig. 19 shows the relation between the theoretical natural frequencies and leg length l. The first and second natural frequencies are proportional to l^{-2} and l^{-1} respectively.

Table 9 Natural frequency of a leg

Rig name	Leg type	Exciting way	Condition	Natural frequency (Hz) Experimental	Natural frequency (Hz) Theoretical
R		Wind	70.5 m	1.1 (B) 2.2 (T)	1.15 2.10
N		Wind (Typhoon)	44.0 m	1.94(B) 2.61(T)	2.14 2.40
		Exciter (5^{tf})	72.1 m	1.16(B) 1.51(T)	1.00 1.50
L		Wind (Towing)	48.0 m	1.35(B) 1.98(T)	
		Wind (Towing)	88.3 m	0.37(B) 0.55(T)	

Remark (B) : 1st Mode (bending deflection)
(T) : 2nd Mode (Twisting deflection)

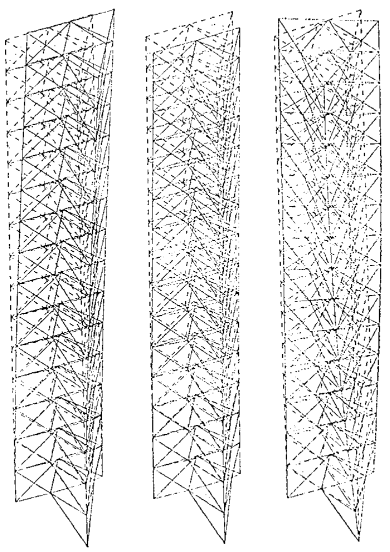


Fig. 17 Mode shape of D-D type leg

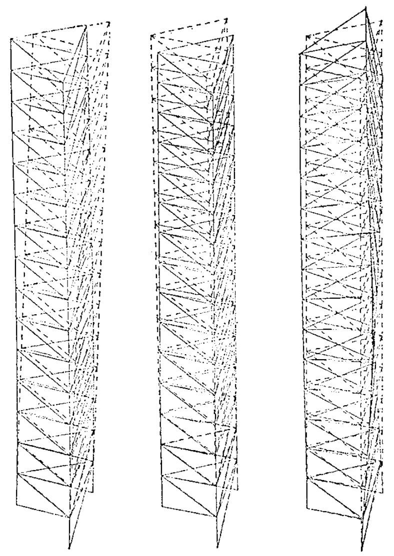


Fig. 18 Mode shape of S-D type leg

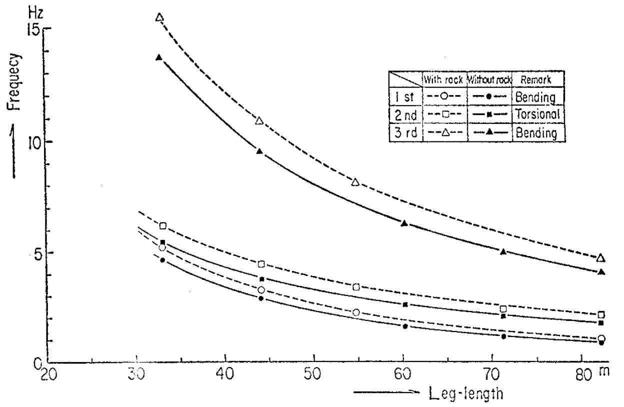


Fig. 19(a) Theoretical natural frequency of D-D type leg

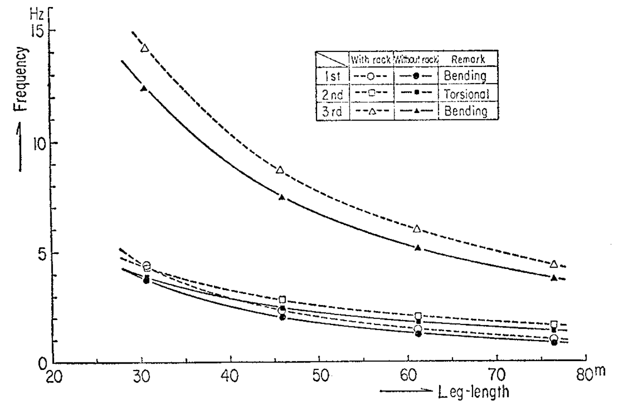


Fig. 19(b) Theoretical natural frequency of S-D type leg

5. Conclusion

The authors studied a few uncertainties such as the virtual mass of the leg, the effective spring constant for the sea floor, etc. to calculate the natural frequency of a jack-up oil rig and carried out vibration tests of actual units. From discussion the authors derived conclusions as follows.

(1) It may be accepted that the virtual mass coefficient of a leg composed of circular cylinders, C_v, equals 1.0.

(2) In calculating the natural frequency of the oil rig in a jacked-up condition, the spring effect should be taken into account.

(3) In estimating the dynamic response of the oil rig, the lowest three natural frequiencies govern the dynamic response, due to wave force.

(4) The wire cutting method is very useful for measuring the natural frequency and logarithmic decrement of the oil rig.

(5) The measured lower natural frequencies are approximately proportional to $h^{-3/2}$ (h: platform height) and $W^{-1/2}$ (W: platform weight)

(6) The logarithmic decrement indicated is from 0.2 to 0.3, which is larger than that for ship's.

(7) The first and second modes of the legs are governed by their bending and torsional deformation, respectively. Their natural frequences are approximately proportional to l^{-2} (l: leg length) and l^{-1}, respectively.

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