MOTIONS OF JACKUP DRILL RIGS IN HEAD SEAS

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by

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ABSTRACT

Previous predictions of barge motions in head seas are extended to include forces and moments on cylindrical legs in order to analyze wave-induced motions of jackup drill rigs in the transition phase while the legs are being lowered. Predicted motions for a typical jackup drill rig in head seas with legs up, half down and full down (but not touching the ocean bottom) are shown to be in good agreement with corresponding scale model test results. It was found that the major effect of the legs is to modify the inertia of the vehicle while the damping effect of the legs is small and for practical purposes can be represented by the theoretical motion-induced damping force and moment.

KEYWORDS

Hydrodynamic Forces

Wave-Exciting Forces

Motions of Jackup Drill Rig

Jackup Drill Rig With Legs Down

TABLE OF CONTENTS

LIST OF FIGURES

Figure

NOMENCLATURE

A_w	waterplane area
a	wave amplitude
B	beam of the hull or restoring coefficient
d	diameter of the leg
F	force or moment
G	center of gravity
g	gravitational constant
h	wave elevation
I	moment of inertia of the hull about an axis through the center of gravity
L	length of hull
ℓ	hydrodynamic moment arm or length of the leg
M	moment or inertial coefficient
M''	three-dimensional added mass
m	sectional mass
m''	two-dimensional added mass
N	two-dimensional or three-dimensional damping coefficient
O	origin of the coordinate system
T	draft or period
t	time
W	weight
w	weight per foot of the leg
x,y,z	coordinate system fixed at the origin O

x',y'	coordinate system fixed at the origin O_1

Subscripts

H	indicates heave in two-dimensional hydrodynamics
h	suffix designating wave
i	$\sqrt{-1}$, or suffix indicating the imaginary part or damping part
R	suffix indicating pitch in two-dimensional hydrodynamics
r	suffix indicating the real part or inertial part
S	suffix indicating surging motion in two-dimensional hydrodynamics

Superscripts

H	suffix indicating hull
L	suffix indicating leg

Greek Letters

ψ	pitch, or suffix designating pitching motion or pitch-exciting moment
Δ	displacement
δ	damping coefficient or displacement of leg per foot
ϵ	phase difference
ξ	surge, or suffix designating suring motion or surging-exciting force
$\varkappa$	radius of gyration
λ	wave length
μ	wave incidence
ν	wave number
ζ	heave, or suffix designating heaving motion or heave-exciting force
ω	circular frequency
ρ	water density

INTRODUCTION

A reliable method for predicting wave-induced motions for jackup drill rigs is required so that structural damage and operational delays due to wave conditions can be minimized by means of analytical studies in the design stage. To meet this need of the ocean platform industry, predictive techniques have been developed over the past two years particularly suited for the shallow-draft barge-type hull which is typical of jackup drill rigs.

In previous reports, Kim[1] has derived and illustrated a two-dimensional strip theory for predicting the wave-exciting forces and moments on a barge-type hull at zero forward speed. These results were combined with a similar approach for calculating the forces and moments due to the motion of the hull.[2] Combining these force and moment representations, the motions of barge-type hulls were predicted for the case of oblique long-crested waves.[2] Predicted motions were found to be in good agreement with corresponding scale model test results.[2] In order to bring this approach to a form which can be easily used by ocean platform designers, the wave-induced forces and moments and the motion-induced forces and moments were calculated for a family of prismatic barges and the procedure for predicting motions was illustrated in detail.[3]

These previously reported results were for bare hulls with no appendages in the water. In this report, the motions prediction technique is extended to include the hydrodynamic and inertial effects of slender cylindrical legs at various depths of submergences. It is assumed that the hydrodynamic forces on the legs and hull can be calculated separately and the previous representation of the hull has been incorporated here without change. The hydrodynamic characteristics of the hull are

[1] Superior numbers in text matter refer to similarly numbered references listed at the end of this report.

described in Appendix A. The legs are assumed to be slender circular cylindrical columns with specified inertial properties. No other appendages were included, such as footings or damping plates. At all times the legs are assumed not to be in contact with the ocean bottom. Due to the slenderness of typical platform legs, the vertical hydrodynamic forces are assumed negligible. The hydrodynamic representation of the legs follows the procedures described by MacCamy and Fuchs,[4] Newman,[5] and Hooft,[6] and the analysis is presented in Appendix B.

A series of numerical calculations were carried out in order to illustrate the contribution to the hydrodynamic forces and moments due to the legs. Motions predictions were also carried out for a typical jackup drill rig configuration with legs up, half down and full down. The predicted results are found to be in acceptable agreement with corresponding scale model tests. We are therefore encouraged to expect practically reliable predictions of wave-induced motions for jackup drill rigs with other hull configurations such as triangular, pentagonal, hexagonal barges or barges with stern wells.

MODEL DESCRIPTION

The particular jackup drill rig configuration chosen to illustrate the analytical procedure developed in this study is a rectangular hull with proportions obtained as an average of models recently tested at the Davidson Laboratory, for commercial clients. The model consists of a shallow-draft doubly-symmetric rectangular barge with four uniform cylindrical legs mounted at the four corners as shown in Figure 1. In typical cases, footings or damping plates are added to the lower end of the legs; however, to simplify the theoretical analysis in this initial effort, such appendages were not included. For the same reason, a rectangular shaped barge has been selected. The geometric, hydrostatic and inertial characteristics of the hull and legs are summarized in Tables 1, 2 and 3 as well as the properties of the hull-legs combinations. Scale model tests were carried out at the Davidson Laboratory in which measurements were made of the heaving and pitching motions with legs up, half down and full down. These tests were carried out in regular head seas over a range of wave length. The various symbols used in Tables 1, 2 and 3 are defined in Figure 1.

DISCUSSION OF RESULTS

Wave-induced motions of a jackup drill rig in regular head seas, with cylindrical legs at various depths of submergence, were analyzed by theoretical means and by scale model experiments. The measured and derived results are illustrated in Figures 2 through 10.

The pitching motion of this configuration is one of the more significant ones and the contribution of the pitching inertial, damping and wave exciting moments on the legs is shown in Figures 2, 3 and 4 over a range of wave-ship length ratios. With legs half down, the virtual pitching inertia of the legs varies between 25- and 40-percent of that for the hull while with legs full down, the legs contribution is between 70- and 100-percent of that for the hull. These trends are to be expected for the proportions of the vehicle described in Tables 1, 2 and 3.

The motion-induced pitch damping moments are also shown in Figures 2 and 3 for the legs and hull separately over a range of wave-ship length ratios. It is seen that the calculated leg damping moments are negligible in comparison with the calculated hull damping moments for both leg positions. Also shown in Figures 2 and 3 are the empirical pitch damping moments as estimated from free pitch response tests by the technique described by Kim.[2] This procedure, which includes non-linear viscous damping effects not included in the theory, is also described here in Appendix A. With either leg position, the comparison between the empirical pitch damping moment and the theoretical one is not very good. However, since the measured and predicted motions are in satisfactory agreement, it is concluded that the discrepancy in pitch damping moment is not significant for motions analysis. Since the discrepancy between empirical and predicted damping moments diminishes in the range of wave-ship length ratio near the natural frequencies, satisfactory motion predictions are obtained even near synchronism between wave frequency and natural frequency where motions amplitudes are usually largest.

The wave-exciting moment in pitch which acts on the legs is shown in Figure 4 together with that for the hull. It is seen that the moment due to the legs in the full-down condition is about 3- to 16-percent of that due to the hull, while for the half-down condition the leg exciting moment is from 3- to 8-percent of that on the hull.

Having discussed the relative importance of the hydrodynamic forces on the legs, we now consider the measured and predicted pitching motion in head seas for the three-leg positions as shown in Figures 5, 6 and 7. It is interesting to see that the pitching motions are smallest for the half-down condition. It does not allow us intuitively to judge the reason why the small pitch is obtained for the half-down condition since the motion is governed by many different moments such as restoring, damping, inertial, coupled damping, coupled inertial moments, etc. Comparing Figures 5 and 7, it is seen that the pitch motion with legs full down is greater than those with legs up at wave-ship length ratios greater than 3 and is less for smaller values. In general, the agreement between measured pitching motions and those predicted by the theoretical technique is practically acceptable. Also shown in these figures is the predicted pitch motion using the empirical pitch damping force. The discrepancy between the two predicted motions is not large for the cases with legs full down and half down. However, the legs-up pitch motion is somewhat more reliably predicted using the empirical pitch damping moment, particularly near the peak pitch response. The phase of the pitch response is seen to be predicted reliably in all cases using the theoretical technique.

The surge response of the jackup drill rig in head seas is shown in Figure 8 for both amplitude and phase difference. When the legs are submerged, the predicted surge amplitude is decreased generally from that with the legs up. The sudden drop of amplitude with increasing wave length is found to coincide with the pitch natural frequency of each leg configuration. These hollows are thus a result of pitch-surge coupling effects in the equations of motion. These coupling forces are both inertial and hydrodynamic. It is also interesting to note that the maximum surge amplitude of the jackup drill rig with the legs full down in this case did not occur at long wave lengths but rather at the medium wave length range. This is contrary to the surge response amplitude variation with wave length at the other leg positions shown. The results presented in Figure 8 suggest that the variation of motion response amplitudes with leg position is a complicated phenomenon which cannot be left to intuitive judgment during the jackup operation but must be carefully analyzed to find allowable wave conditions for this critical operation.

Finally, we add a note on the heaving motions. Heaving is an uncoupled motion in this study. Since the vertical hydrodynamic forces on the legs are negligibly small, the hydrodynamic heave added mass and damping coefficients as well as the heave-exciting forces are only due to the hull which may have three different drafts according to the leg positions such as legs up, half down and full down. The inertial mass of the drill rig and the restoring force coefficient are the same for all the three cases of leg configurations. Thus it is anticipated that the differences of heaving motions due to the different submergence of legs are very small. Figures 9 and 10 illustrate that the predictions are in good agreement with the experimental values and prove, in addition, that the above reasoning is appropriate.

CONCLUSIONS

The theoretical method for predicting wave-induced motions of ocean platforms previously developed by Kim[1,2,3] is extended to include the hydrodynamic and inertial effects of slender cylindrical legs. Predicted motions of a typical jackup drill rig with legs up, half down and full down in regular head seas are compared with corresponding measurements from scale model tests. Based on this combined theoretical and experimental analysis, the following conclusions are stated:

1) The contribution of the legs of the jackup drill rig to the inertia in pitch is substantial while the contribution to the wave-exciting moment is small. The contribution of the legs to the motion-induced pitch damping moment is negligible.

2) Although the empirical damping moment is somewhat more reliable, the theoretical damping moment yields motion predictions which are acceptable for practical purposes.

3) The predicted pitch and heave motions are in acceptable agreement for the rectangular hull with four legs tested. It is thus anticipated that the theoretical procedure will be found reliable for a large variety of hull configurations.

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TABLE 1

HULL PARTICULARS

Length, L, ft	2.558
Beam, B, ft	1.704
Depth, D, ft	0.248
Draft, T_o^H, ft	0.126
Weight, W_o^H, lb	34.4
VCG, $\overline{KG}_o^H$, ft	0.27
VCB, $\overline{KB}_o^H$, ft	0.063
Pitch Gyradius, $\kappa_{o\psi}$, ft	0.73
section form	uniform rectangular cross sections

TABLE 2

LEG PARTICULARS

Length, ℓ_o, ft	3.65
Diameter, d, ft	0.1458
Weight per foot, w, lb/ft	0.6247
Displ per ft, δ, lb/ft	1.04176
Total Weight, W^L, lb	9.12

TABLE 3

HYDROSTATICAL AND INERTAIL PARTICULARS
OF HULL-LEG COMBINATION

		Legs Up	Half Down	Full Down
Wetted Leg Draft	T^L-T^H	0.0	1.6083	3.2166
Leg Displacement	Δ^L	0.0	6.7020	13.404
Weight of Hull-Leg Comb.	W	43.52	43.52	43.52
Adjusted Hull Draft	T^H	0.16	0.1353	0.1107
Leg Draft	T^L	0.16	1.7436	3.3273
VCB of Leg	* $\overline{O_1B}^L$	0.0	-0.9394	-1.719
VCG of Leg	* $\overline{O_1G}^L$	1.665	0.0814	-1.5023
VCG of Hull + Leg Comb.	* $\overline{OG}$	0.4359	0.1235	-0.1889
Metacentric Height	$\overline{GM}_\psi$	2.8933	3.0838	3.0529
Pitch Gyrad. of Hull	κ_ψ^H	0.7994	0.7300	0.8088
Pitch Gyrad. of Hull+Leg Comb.	κ_ψ	1.1297	0.936	1.154

*minus signs designate that B^L, G^L and G are below the waterline.

TABLE 4

NATURAL FREQUENCY AND DAMPING OF THE MODEL

	Legs Up	Half Down	Full Down
ω_ψ, (rad/sec)	5.7909	6.1964	4.7313
T_ψ, (sec)	1.085	1.014	1.328
δ_1	0.565	0.592	0.1712
δ_2, (1/deg)	0.0	0.0	0.6437

When the damping is nonlinear ($\delta_2 \neq 0$), the wave slope was taken as $\frac{\pi}{52.5}$ in the iteration procedure to solve the non-linear equation (see Eq. A-1).

λ	6.0274	5.26436	9.02955
λ/L	2.356	2.058	3.53

APPENDIX A

THE HULL FORCES

In this study, we have considered the motions of a jackup drill rig with legs up, half down and full down, in head seas. The model is assumed symmetric about the longitudinal and transverse axes through the center of gravity. In head seas then the equations of motion consist of the uncoupled heave equation and the coupled pitch and surge equations of motion which Kim[2,3] has derived in the form

$$
\begin{aligned}
(-\omega^2 M_{\zeta\zeta} + i\omega N_{\zeta\zeta} + B_{\zeta\zeta})\bar{\zeta} &= \bar{F}_\zeta \\
(-\omega^2 M_{\xi\xi} + i\omega N_{\xi\xi})\bar{\xi} + (-\omega^2 M_{\psi\xi} + i\omega N_{\psi\xi})\bar{\psi} &= \bar{F}_\xi \\
(-\omega^2 M_{\xi\psi} + i\omega N_{\xi\psi})\bar{\xi} + (-\omega^2 M_{\psi\psi} + i\omega N_{\psi\psi} + B_{\psi\psi})\bar{\psi} &= \bar{F}_\psi
\end{aligned}
\qquad \text{(A-1)}
$$

where M = virtual inertial force or moment per unit acceleration
N = damping force or moment per unit velocity
B = restoring force or moment per unit displacement
$\bar{F}$ = wave exciting force or moment

and where the first subscript on M, N or B designates the motion inducing component and the second designates the force or moment component. For example $(\cdot)_{\xi\psi}$ denotes the surge-induced pitch moment. The bars denote complex amplitudes of the various quantities in order to represent phase lags with respect to a crest at the center of gravity. The virtual inertial force or moment per unit acceleration M consists of dynamic and hydrodynamic parts, which are represented in terms of the inertial mass or mass moment of inertia of the body M_o and the added mass or added mass moment of inertia M'', respectively. The term M_o and the restoring force coefficient B are readily determined for the model by making use of Tables 1, 2 and 3.

In determining the coefficients M'' and N and the wave force $\bar{F}$, we assume that each hydrodynamic force component for the model is represented as the sum of the component forces due to the hull and leg motions, respectively. By this assumption, we neglect the interaction effect between the motions of the hull and legs. The coefficients are then formally written in the form

$$M = M^H + M^L \quad , \quad N = N^H + N^L \quad , \quad \bar{\bar{F}} = \bar{\bar{F}}^H + \bar{\bar{F}}^L \qquad \text{(A-2)}$$

where the superscripts H and L designate the terms due to the hull and legs, respectively. The theoretical procedure to determine the hydrodynamic forces and moments exerted on the hull oscillating in a given incident wave are presented in References 1, 2, and 3.

In determining the hydrodynamic forces on the legs, we confine ourselves to the calculation of the lateral forces, since the vertical forces on the long-slender columns are assumed to be negligibly small. A brief description of the calculation of the lateral forces on the legs, such as M^L, N^L and $\bar{\bar{F}}^L$, is given in Appendix B. The hull force coefficients are defined in the following table in terms of sectional forces and moments calculated according to the close-fit method of Kim.[1,2,3]

HULL FORCE COEFFICIENTS

$$M^H_{\xi\xi} = \int_B m''_S \cdot dy + \frac{W^H_o}{g}$$

$$M^H_{\zeta\zeta} = \int_B m''_H \cdot dy + \frac{W^H_o}{g}$$

$$M^H_{\psi\psi} = \int_B m''_R \cdot dy + \frac{W^H_o}{g} \cdot \varkappa^{H^2}_{\psi}$$

$$M^H_{\psi\xi} = \int_B m''_R / \ell_{Rr} dy$$

$$M^H_{\xi\psi} = \int_B m''_S (\ell_{Sr} + \overline{OG}) dy$$

$$N^H_{\xi\xi} = \int_B N_S \cdot dy$$

[Cont'd]

$$N^H_{\zeta\zeta} = \int_B N_H \cdot dy$$

$$N^H_{\psi\psi} = \int_B N_R \cdot dy$$

$$N^H_{\psi\xi} = \int_B N_R/\ell_{Ri}\, dy$$

$$N^H_{\xi\psi} = \int_B N_S\, (\ell_{Si} + \overline{OG})\, dy$$

$$B_{\zeta\zeta} = \rho g A_W$$

$$B_{\psi\psi} = W\, \overline{GM}_\psi$$

$$\bar{F}^H_\zeta = \int_B \bar{F}_H\, dy$$

$$\bar{F}^H_\xi = \int_B \bar{F}_S\, dy$$

$$\bar{F}^H_\psi = \int_B \bar{F}_R\, dy$$

$$M^H_{\psi\xi} = M^H_{\xi\psi}$$

$$N^H_{\psi\xi} = N^H_{\xi\psi}$$

$\int_B$ = designates the integral over the beam of the barge

A_W = waterplane area

ρ = water density

W^H_o = weight of the hull

W = weight of hull+legs combination

κ^H_ψ = pitch gyradius of hull about the axis through CG of hull+legs combination

$\overline{OG}$ = vertical CG from the waterline (positive when G is above O)

$\overline{GM}_\psi$ = pitch metacentric height (see Tables 1,2,3)

m''_S = surge added mass per unit length of a longitudinal cross section

m''_H = heave added mass per unit length of a longitudinal cross section

m''_R = pitch added mass moment of inertia per unit length of a longitudinal cross section about the transverse axis through the center of gravity G of the hull-legs combination

N_S = surge damping force coefficient per unit length of a longitudinal cross section

N_H = heave damping force coefficient per unit length of a longitudinal cross section

N_R = pitch damping moment per unit length of a longitudinal cross section about the transverse axis through the center of gravity G of the hull-legs combination

$\bar{F}_S$ = surge-exciting force per unit length of a longitudinal cross section in head seas

$\bar{F}_H$ = heave-exciting force per unit length of a longitudinal cross section in head seas

$\bar{F}_R$ = pitch-exciting moment per unit length of a longitudinal cross section about the transverse axis through the center of gravity G of the hull-legs combination in head seas

ℓ_{Sr} = surge-induced inertial moment arm of a longitudinal cross section about the origin 0

ℓ_{Si} = surge-induced damping moment arm of a longitudinal cross section about the origin 0

ℓ_{Rr} = pitch-induced inertial moment arm of a longitudinal cross section about the center of gravity G of the hull-legs combination

ℓ_{Ri} = pitch-induced damping moment arm of a longitudinal cross section about the center of gravity G of the hull-legs combination

To investigate the importance of non-linear damping moments in pitching motion of a jackup drill rig with legs up, half down and full down, the free pitch oscillation of the model in calm water was recorded. The empirical pitch damping moment was obtained from these extinction curves in the form[2]

$$N_{\psi\psi} = \frac{M_{\psi\psi}}{\pi} \omega_\psi \left(\delta_1 + \delta_2 \frac{\omega}{\omega_\psi} |\bar{\psi}|\right) \tag{A-3}$$

where δ_1, δ_2 = coefficients obtained from pitch extinction curve

ω_ψ = natural pitching frequency

ω = wave frequency

$M_{\psi\psi}$ = pitch virtual moment of inertia

The empirical factors ω_ψ, δ_1 and δ_2 are summarized in Table 4, for the three leg positions and model described in Tables 1,2 and 3.

APPENDIX B

LEG FORCE COEFFICIENTS

We consider one of the legs as a uniform circular section of diameter d centered at $0_j(x_{oj},y_{oj})$ in the given incident wave (see Fig. 1) with wave elevation given by

$$h = a\cos(\nu x\cos\mu + \nu y\sin\mu - \omega t)$$
$$= a\cos(\nu x' + \epsilon_j - \omega t) \qquad \text{(B-1)}$$

with

$$\epsilon_j = \nu(x_{oj}\cos\mu + y_{oj}\sin\mu) \qquad \text{(B-2)}$$

where

a = wave amplitude

ν = wave number

ω = wave frequency

j = designates the j^{th} leg

We assume that the leg stands alone in the wave and the water flow is not influenced by neighboring structures such as the hull and the other legs. The lateral wave-exciting force on the j^{th} column in the x'-direction per unit length of the leg at the depth z is given by MacCamy[4]

$$\frac{dF_j^L}{dz} = \frac{4\rho g a}{\nu}\, e^{\nu z}\; A\left(\nu\frac{d}{2}\right)\cos\left(\omega t - \alpha - \epsilon_j + \frac{\pi}{2}\right) \qquad \text{(B-3)}$$

where

$$\left.\begin{aligned} \alpha &= \tan^{-1}\left(\frac{J_1'(\nu\frac{d}{2})}{Y_1'(\nu\frac{d}{2})}\right) \\ A\left(\nu\frac{d}{2}\right) &= \frac{1}{\sqrt{J_1'^2(\nu\frac{d}{2}) + Y_1'^2(\nu\frac{d}{2})}} \end{aligned}\right\} \qquad \text{(B-4)}$$

J_1', Y_1' = derivatives of the Bessel Functions J_1, Y_1 with respect to $(\nu \frac{d}{2})$

Now the force per unit length [Eq. (B-3)] is readily integrated over the wetted length of the leg (see Fig. 1) so as to obtain the resultant lateral force as well as the resultant moment about the origin 0 (or 0_j). But since the legs are not extended to the bottom of the water, as assumed in the derivation of Eq. (B-3), the integration is valid under the assumption that the end effects of the legs are negligible. The force and the moment per unit amplitude of the incident wave as well as the force center on the j^{th} leg are specifically represented in the form

$$\frac{F_j^L}{a} = \frac{4\rho g}{\nu^2}\left(e^{-\nu T^H} - e^{-\nu T^L}\right) A\left(\nu \frac{d}{2}\right) \cos\left(\omega t - \alpha - \epsilon_j + \frac{\pi}{2}\right) \tag{B-5}$$

$$\frac{M_j^L}{a} = \frac{4\rho g}{\nu^2}\left[\left(-T^H e^{-\nu T^H} + T^L e^{-\nu T^L}\right) - \frac{1}{\nu}\left(e^{-\nu T^H} - e^{-\nu T^L}\right)\right] A\left(\nu \frac{d}{2}\right) \cdot \cos\left(\omega t - \alpha - \epsilon_j + \frac{\pi}{2}\right) \tag{B-6}$$

where

T^H = hull draft

T^L = leg draft

j = designates the j^{th} leg (See Fig. 1)

with moment arm ℓ_W given by

$$\ell_W = -\frac{T^L e^{-\nu T^L} - T^H e^{-\nu T^H}}{e^{-\nu T^H} - e^{-\nu T^L}} + \frac{1}{\nu} \tag{B-7}$$

The lateral damping coefficient of a leg induced by the lateral oscillation is generally small in the low frequency parameter range but it is exactly determined by Haskind-Newman method[5] in terms of the wave-exciting force. Hooft[6] calculated the coefficient, which is represented in non-dimensional form

$$\frac{N_j^L}{\rho\left(\frac{d}{2}\right)^2\sqrt{\frac{d}{2}g}} = \left[\frac{F_j^L}{\rho g a\left(\frac{d}{2}\right)^2}\right]^2 \frac{\left(\nu\frac{d}{2}\right)^{3/2}}{4} \quad \text{(B-8)}$$

and the center of the damping force N_j^L is given by ℓ_W (Eq. B-7). The damping force determined in the above Eq. (B-8) is a purely wave-making damping force. The viscous damping force which is proportional to the square of the oscillatory velocity of the leg $\dot{\xi}$ should be added to the above wave damping force. The coefficient $(N^L)_{vis}$ of the viscous damping force

$$(N_j^L)_{vis} \cdot |\dot{\xi}|\dot{\xi} \quad \text{(B-9)}$$

is approximately estimated by the formula[7]

$$(N_j^L)_{vis} = C_D \tfrac{1}{2}\rho\, S_j \quad \text{(B-10)}$$

with $C_D \approx 1.0$, $S_j = d\cdot(T^L - T^H)$; and ρ = water density.

However, since the leg damping has been found small, the motions are adequately predicted using just the theoretical damping.

The added mass generated by the lateral motion of the leg amounts approximately to the displaced volume of the leg when the frequency $(\nu\frac{d}{2})$ is small.[6] Thus the added mass on a leg is

$$M_j''^L = \rho\left(\frac{\pi d^2}{4}\right)(T^L - T^H) \quad \text{(B-11)}$$

and the center of the mass is at $\frac{T^L + T^H}{2}$ from the waterline.

By summing up these coefficients for the four legs with respect to the center of gravity of the jackup model, we determine the resultant leg force coefficients M^L, N^L, $\bar{\bar{F}}^L$ in the forms

$$M^L_{\xi\xi} = \sum_{j=1}^{4} \frac{W^L_j}{g} + \sum_{j=1}^{4} M''^L_j$$

$$N^L_{\xi\xi} = \sum_{j=1}^{4} [N^L_j + (N^L_j)_{vis}]$$

$$M^L_{\xi\psi} = \sum_{j=1}^{4} M''^L_j \left(\frac{T^H + T^L}{2} + \overline{OG}\right) - \sum_{j=1}^{4} \frac{W^L_j}{g} \cdot \left[\frac{\ell_o}{2} - (T^L + \overline{OG})\right]$$

$$N^L_{\xi\psi} = \sum_{j=1}^{4} N^L_j \ (\ell_W + \overline{OG})$$

$$M^L_{\psi\xi} = M^L_{\xi\psi}$$

$$N^L_{\psi\xi} = N^L_{\xi\psi}$$

$$M^L_{\psi\psi} = \sum_{j=1}^{4} M''^L_j \left[\left(\frac{T^H + T^L}{2} + \overline{OG}\right)^2 + \frac{1}{12}(T^L - T^H)^2\right] + \sum_{j=1}^{4} \frac{W^L_j}{g} \left[\left(T^L + \overline{OG} - \frac{\ell_o}{2}\right)^2 + \frac{\ell_o^2}{12} + x^2_{oj} + \frac{1}{4}\left(\frac{d}{2}\right)^2\right]$$

$$N^L_{\psi\psi} = \sum_{j=1}^{4} N^L_j \ (\ell_W + \overline{OG})^2$$

$$M^L_{\zeta\zeta} = \sum_{j=1}^{4} \frac{W^L_j}{g}$$

$$N^L_{\zeta\zeta} = 0$$

$$\mathrm{Re}\left[\frac{\bar{\bar{F}}^L_\xi}{a} \ e^{i\omega t}\right] = \sum_{j=1}^{4} - \frac{F^L_j}{a} \cos\mu$$

$$\mathrm{Re}\left[\frac{\bar{\bar{F}}^L_\psi}{a} \ e_i^{i\omega t}\right] = \sum_{j=1}^{4} - \frac{F^L_j}{a} \cos\mu \ [\overline{OG} + \ell_W]$$

[Cont'd]

(μ = 180° indicates the head seas)

$\bar{F}_{\zeta} \approx 0$

$\frac{W_j}{g}$ = mass of the jth leg

It is to be noted that the positive directions of the motions $\bar{\zeta}$, $\bar{\xi}$, and $\bar{\psi}$ are as shown in Figure 1 and that the positive signs of the hull and leg force coefficients as well as the wave-exciting forces on both the hull and legs are determined according to that sign convention.

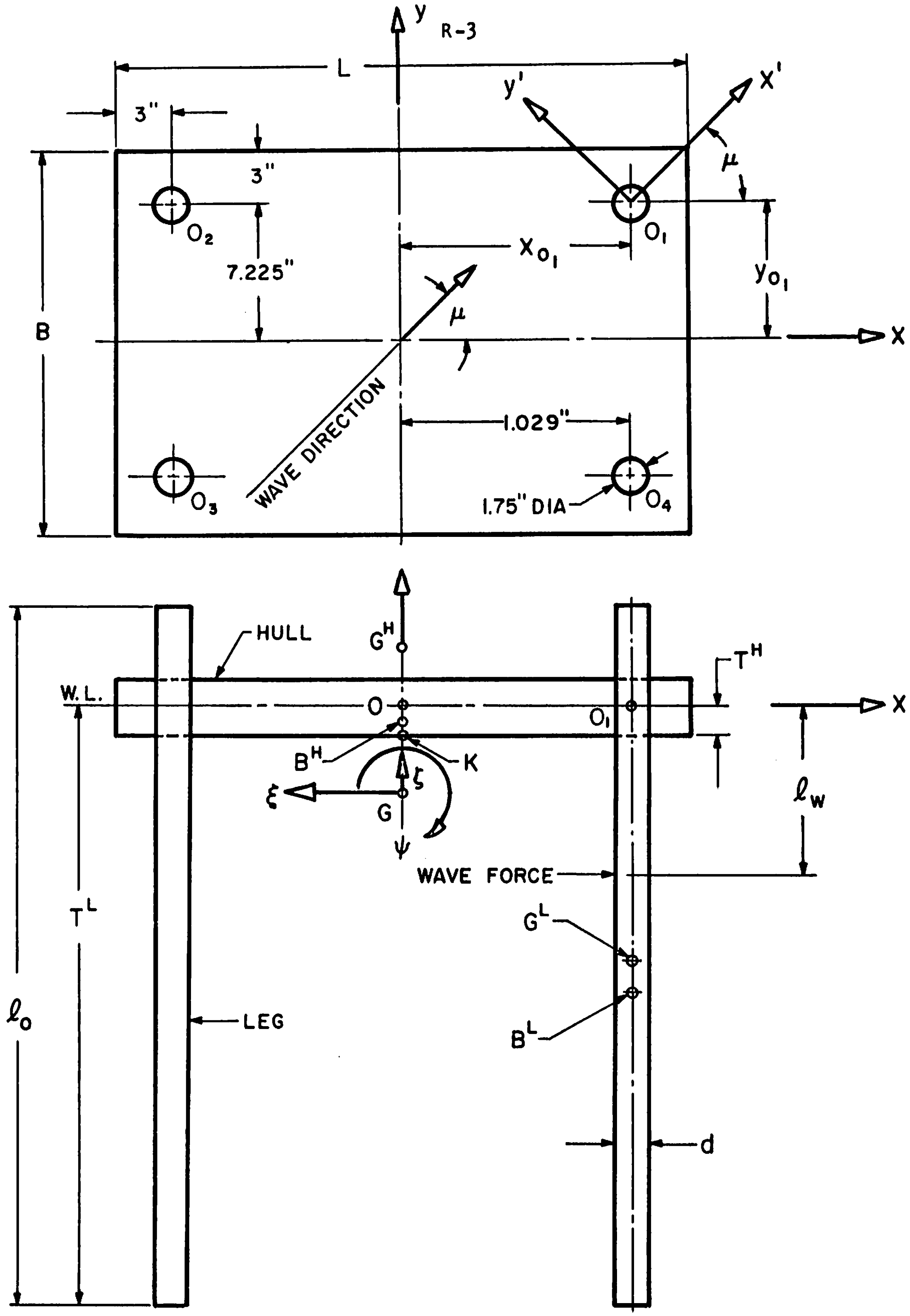

FIG. I. SKETCH OF THE JACK-UP RIG MODEL WITH LEGS DOWN

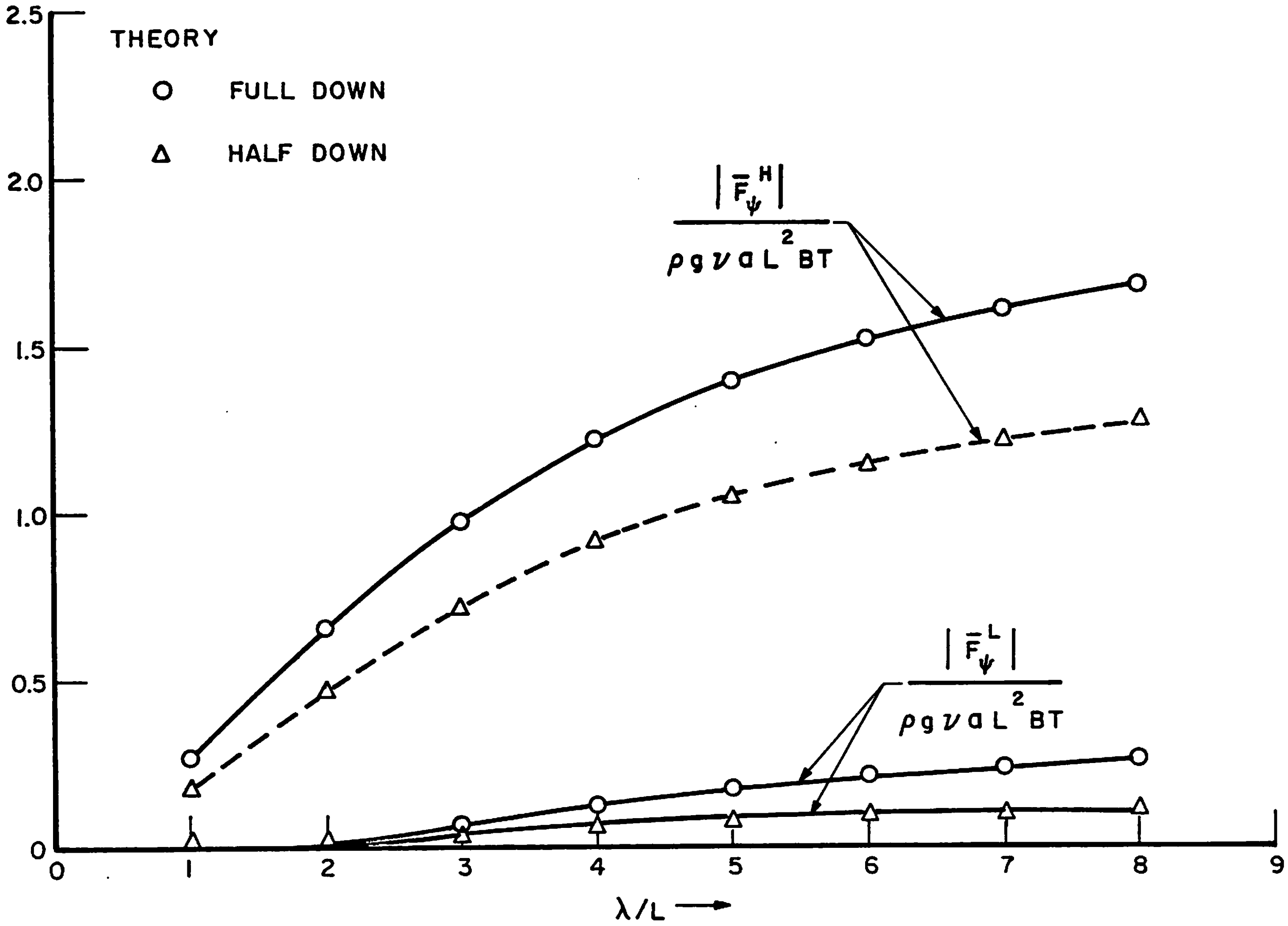

FIG. 4. PITCH-EXCITING MOMENTS OF HULL AND LEGS

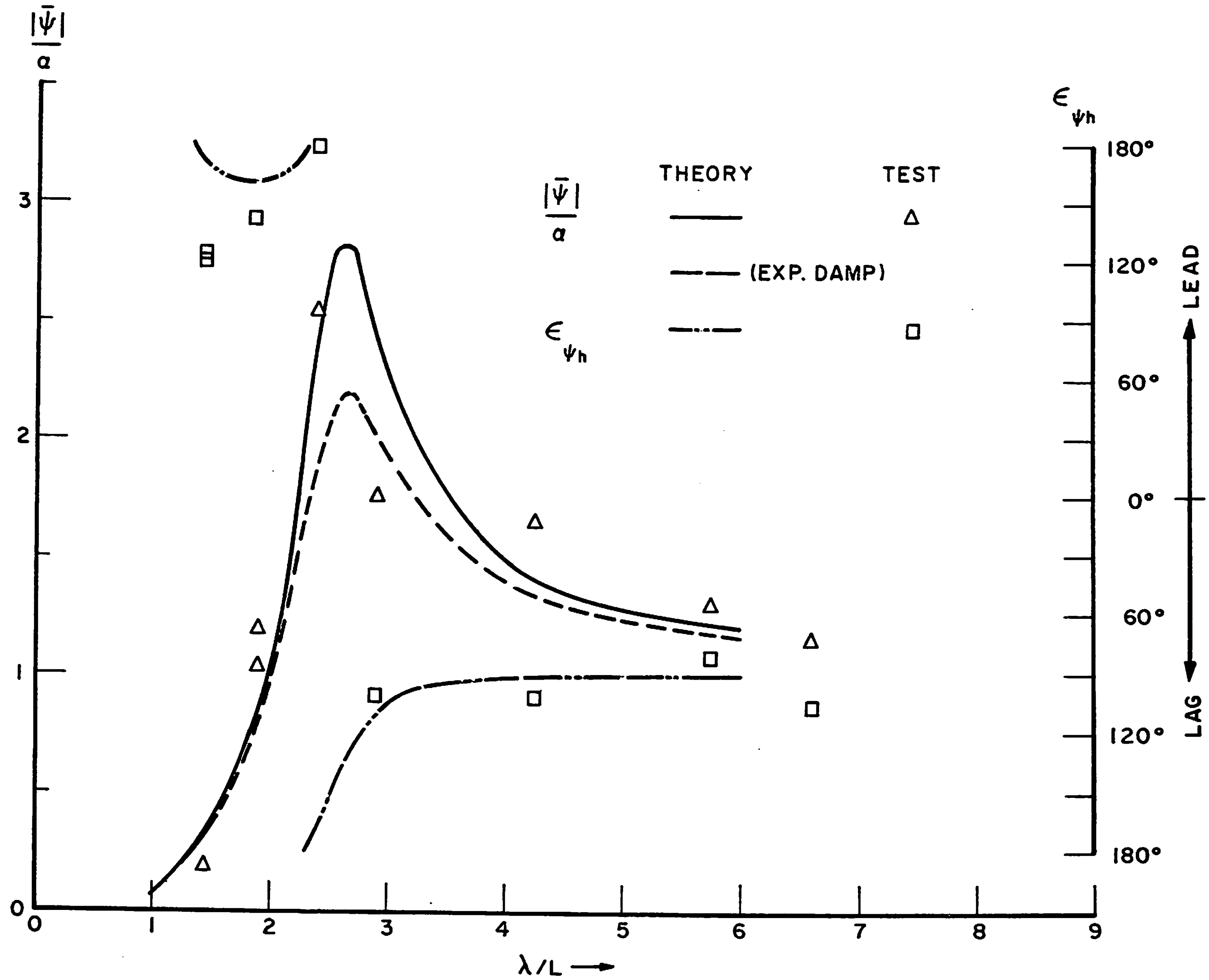

FIG. 5. PITCHING MOTION OF THE RIG MODEL WITH LEGS UP IN HEAD SEAS

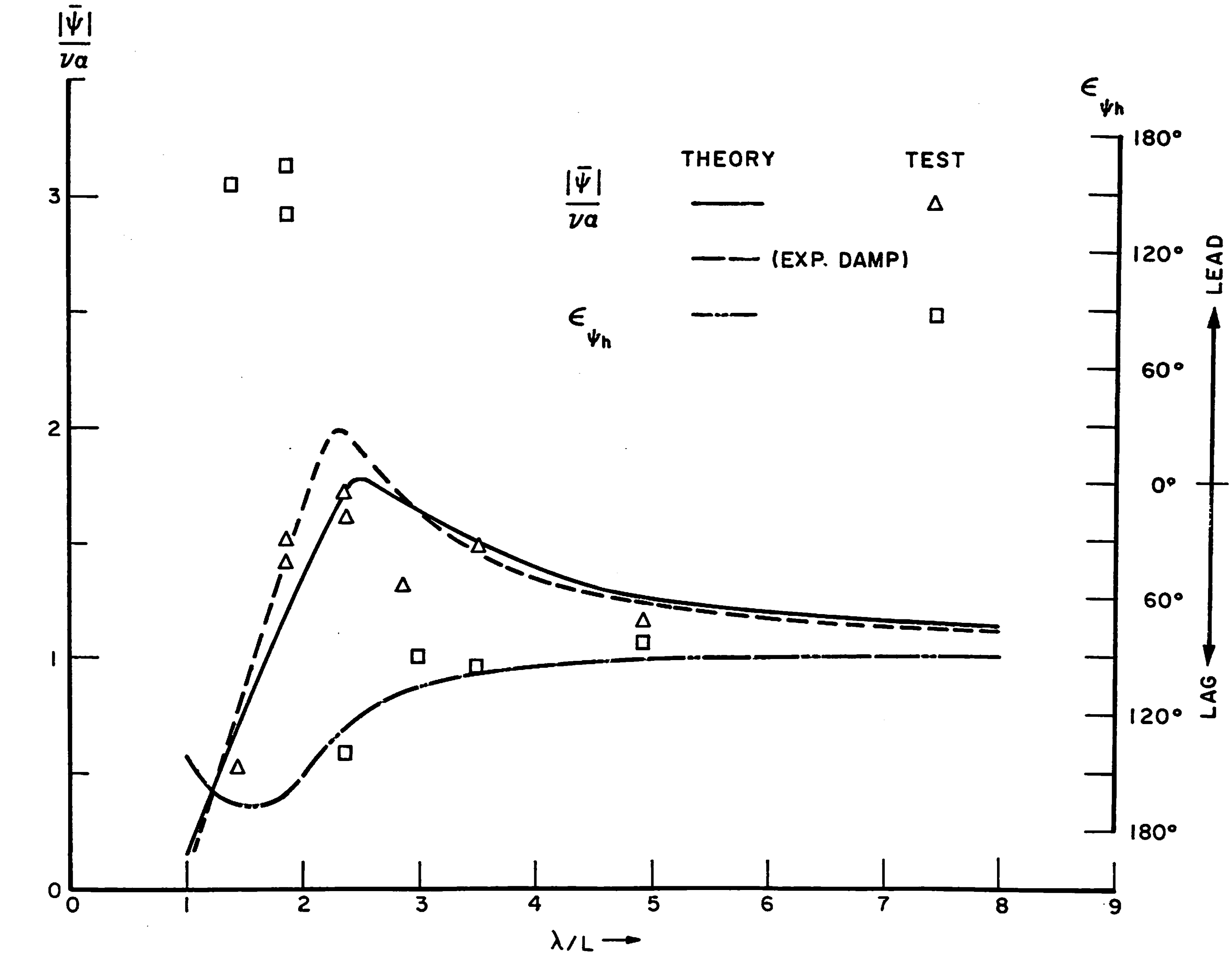

FIG. 6. PITCHING MOTION OF THE RIG MODEL WITH LEGS HALF DOWN IN HEAD SEAS

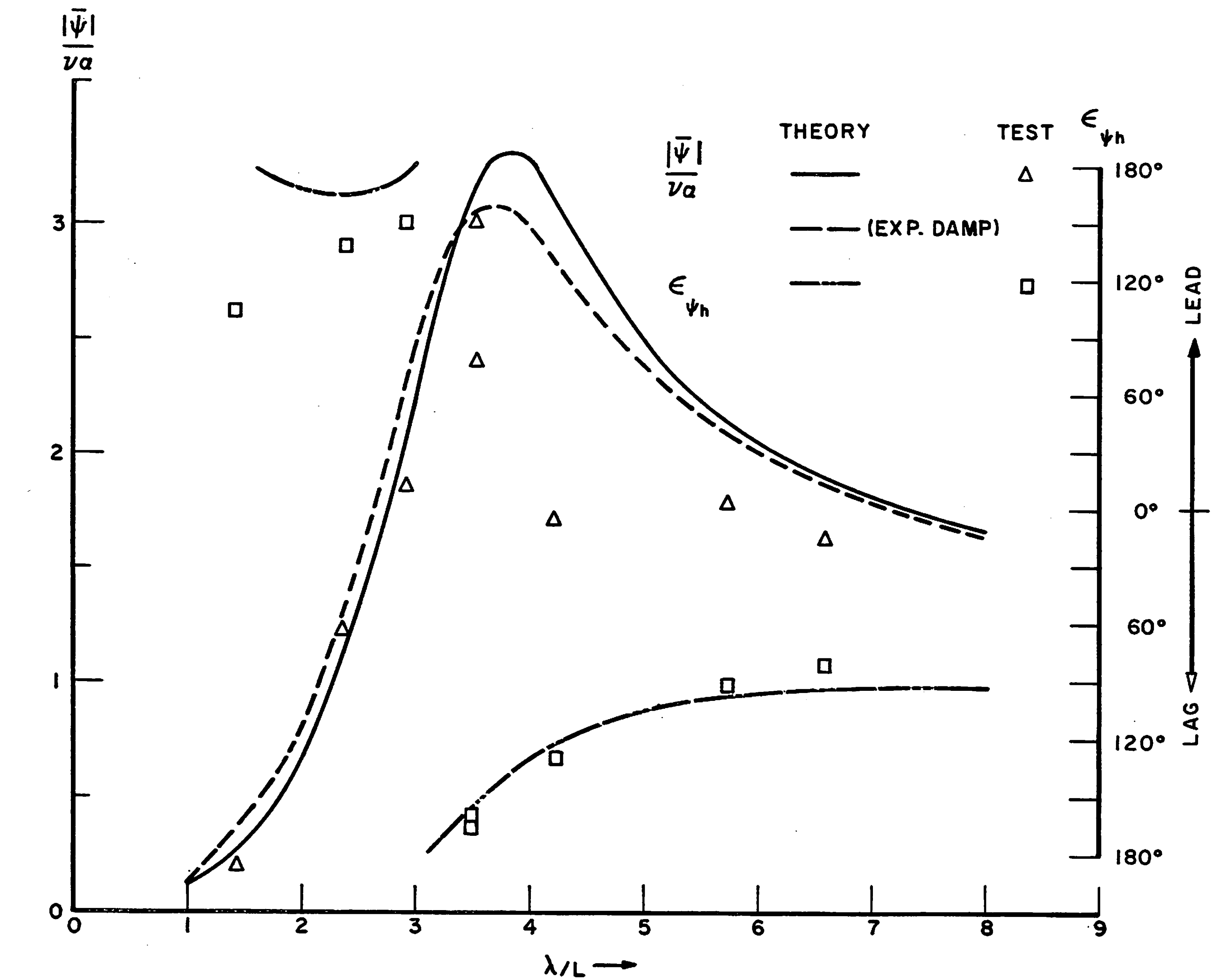

FIG. 7. PITCHING MOTION OF THE RIG MODEL WITH LEGS FULL DOWN IN HEAD SEAS

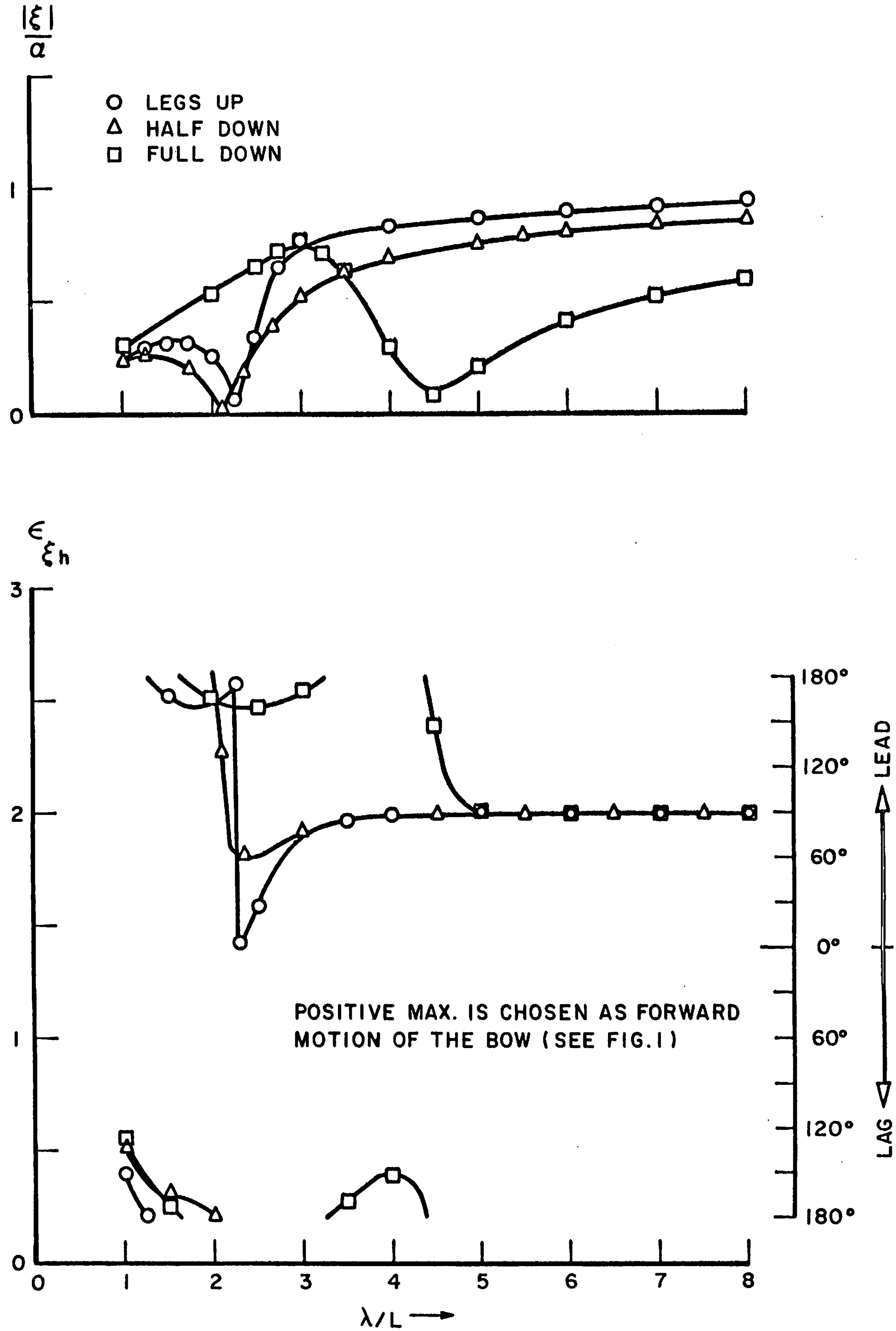

FIG. 8. SURGING MOTION OF THE RIG MODEL IN HEAD SEAS

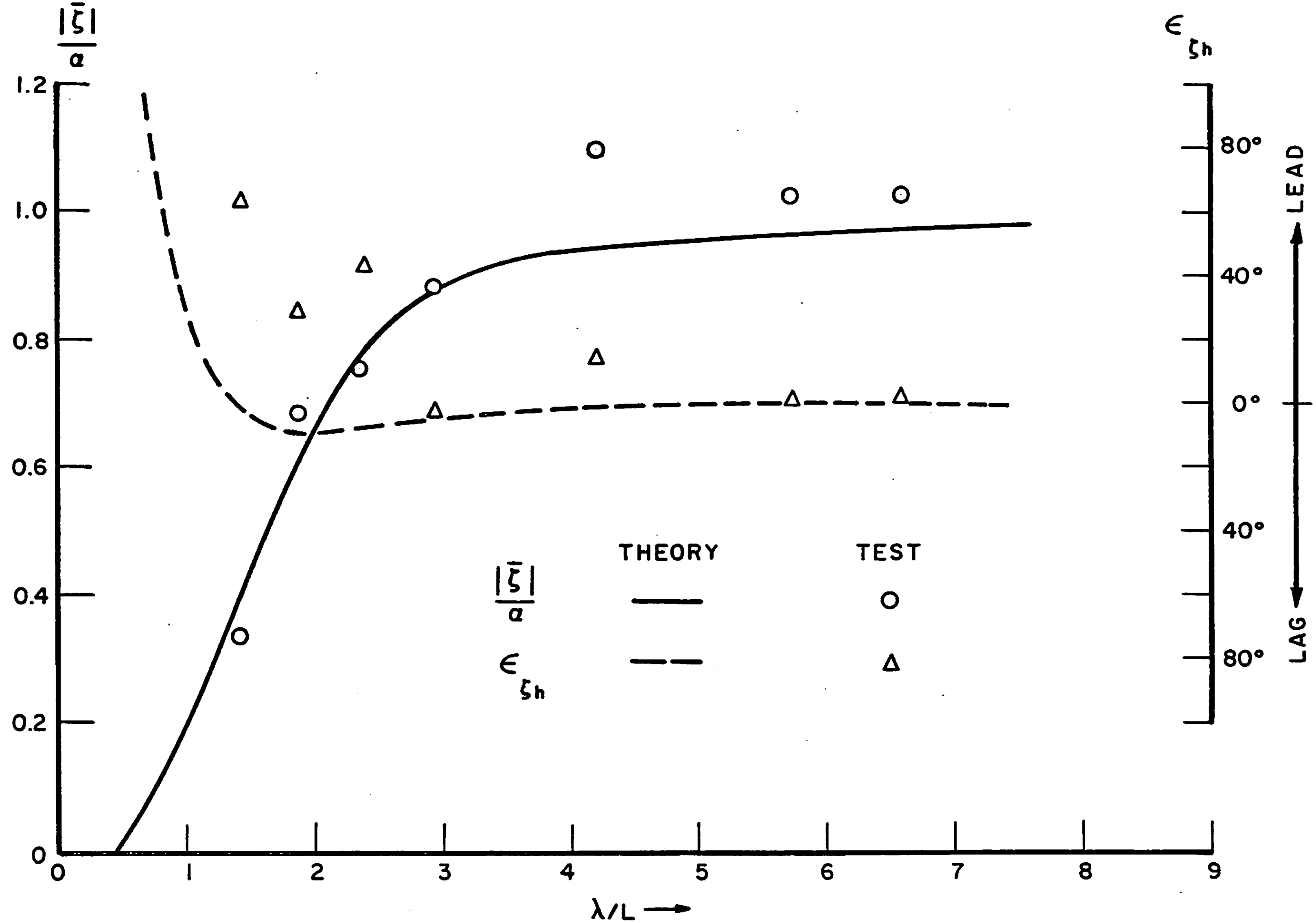

FIG. 9. HEAVING MOTION OF JACK-UP RIG MODEL WITH LEGS UP IN HEAD SEAS

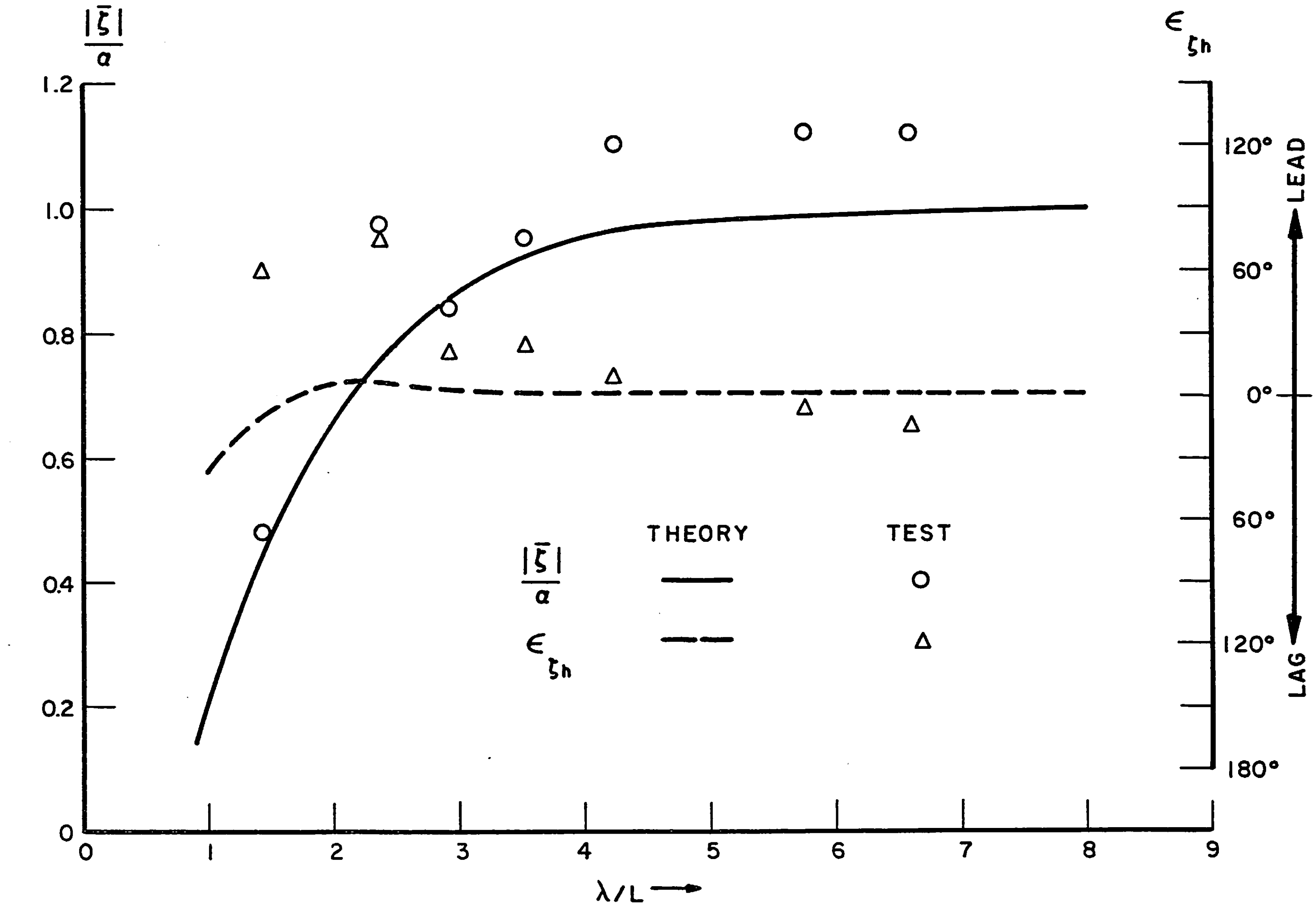

FIG. 10. HEAVING MOTION OF JACK-UP RIG MODEL WITH LEGS FULL DOWN IN HEAD SEAS

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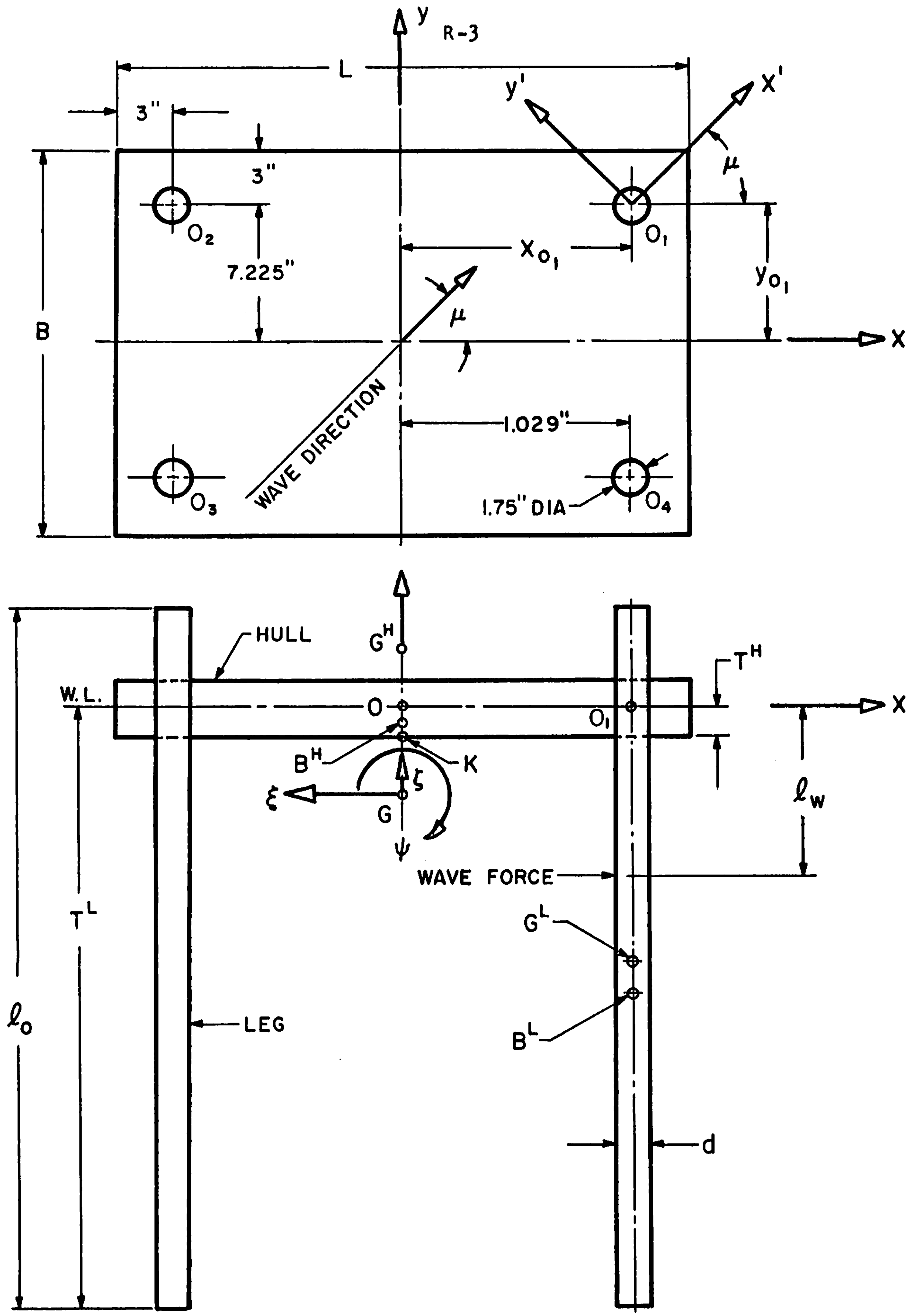

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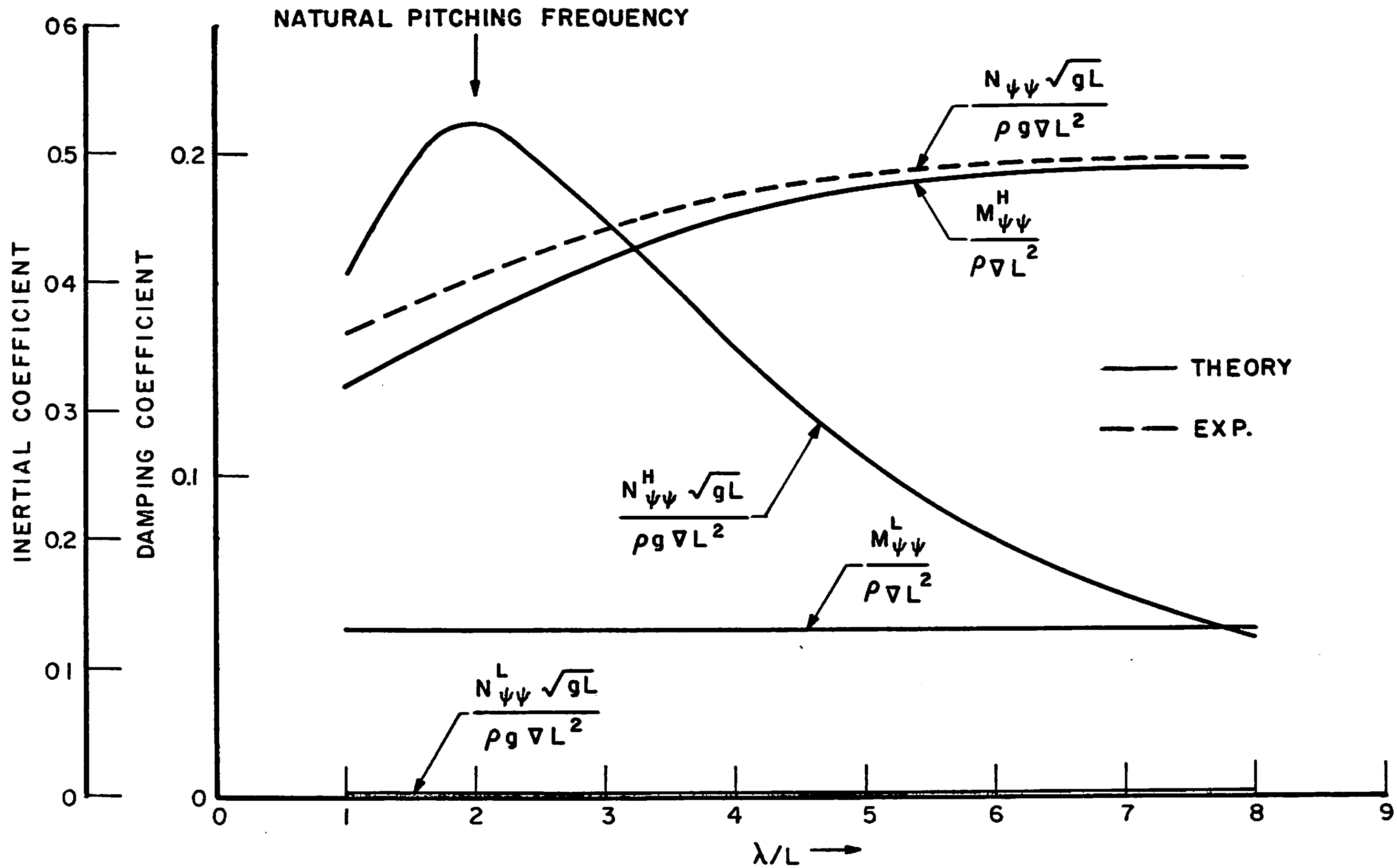

FIG. 2. PITCHING INERTIAL AND DAMPING COEFFICIENTS OF THE RIG MODEL WITH LEGS HALF DOWN

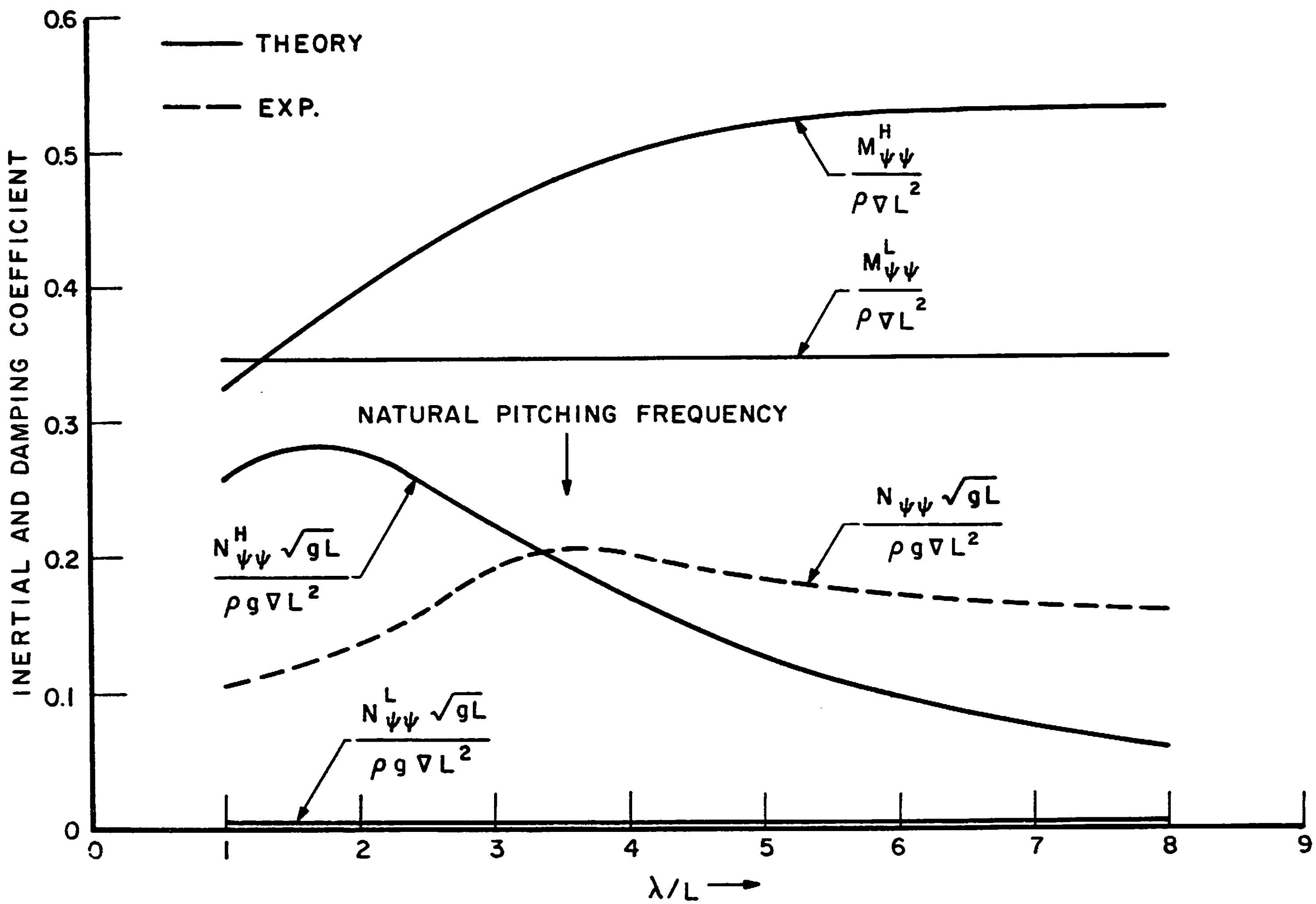

FIG. 3. PITCHING INERTIAL AND DAMPING COEFFICIENTS OF THE RIG MODEL WITH LEGS FULL DOWN

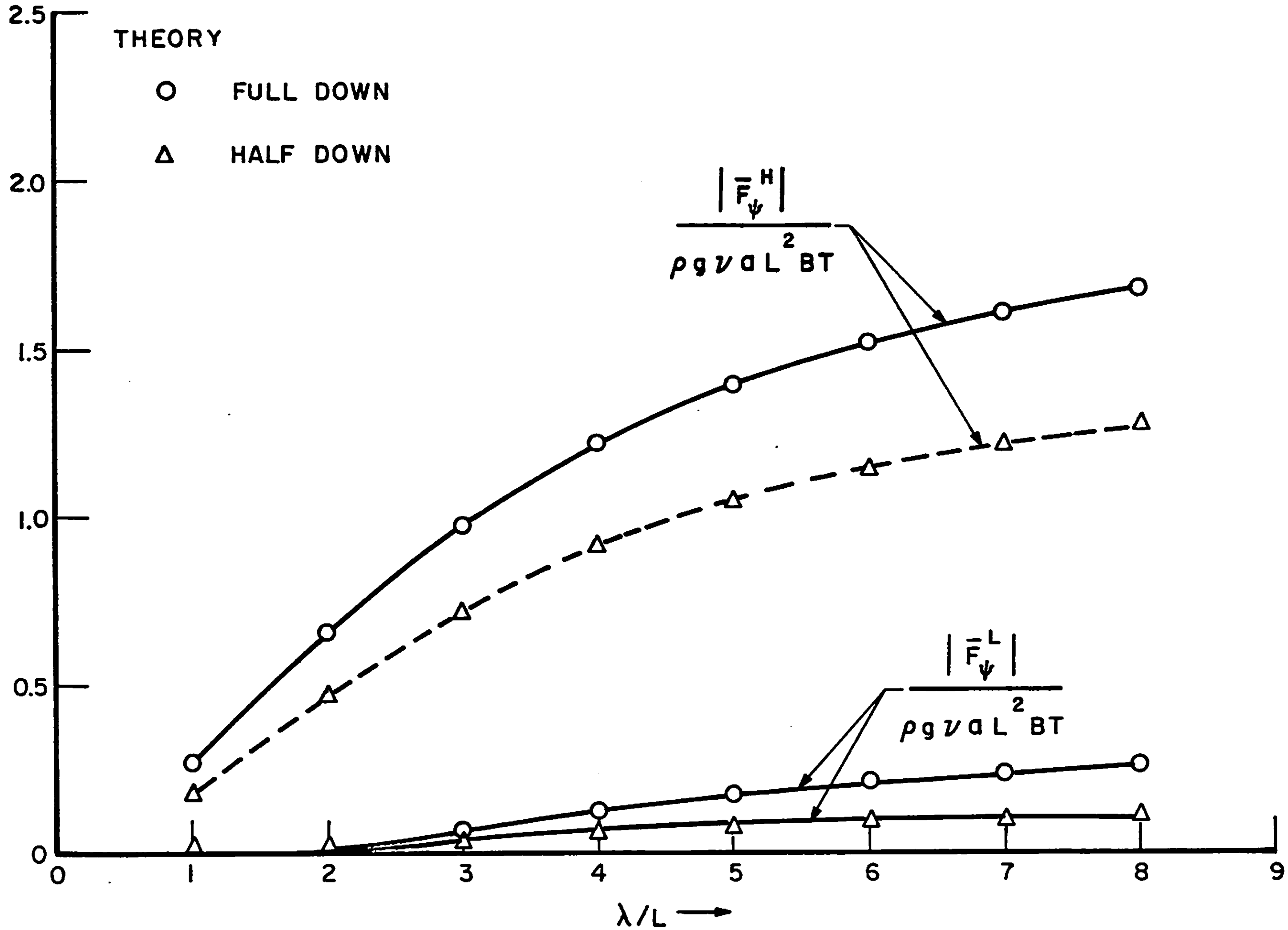

FIG. 4. PITCH-EXCITING MOMENTS OF HULL AND LEGS

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MOTIONS OF JACKUP DRILL RIGS IN HEAD SEAS

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x + 31 pp., 2 appendices, 10 figures.

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