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VERTICAL MOTIONS OF SHIPS WITH BULBOUS BOWS

by

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"VERTICAL MOTIONS OF SHIPS WITH BULBOUS BOWS",

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Summary.

Ship motions and hydrodynamic coefficients were calculated for the models of ships with two values of block coefficient and different forms of bulbous bow.

The computed results of ship motions for two models were compared with the results of the experiment, which was made in the Delft Shipbuilding Laboratory.

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I. Introduction.

It was proved that for higher speeds, where the wave making resistance accounts for an important part of the total resistance experienced by a ship, a correctly constructed bulb can reduce the still water resistance considerably. Lindblad (1), Inui (2) and others (3), (4) showed that by adopting large bulb-areas great reduction can be obtained in the speed range Fn = 0.24 - 0.28.

In last years several publications appeared concerning the influence of the bulbous bows on the ship motions in waves. Dillon and Lewis (5) made an experiment with four models of passenger liners with bulb size 0%, 4.5%, 9.0% and 13.5% in smooth water and in waves. In their experiments they found that a wide variation in bulb size has a rather small effect on the ship motions and resistance in waves. They stated that a choice of a large bulb could be done on the basis of calm water resistance.

Doust (6) in his experiments with trawlers found that the speed loss in waves is less for the bulbous bow form for $Fn > 0.22$, below - the speed loss is larger than for the conventional form. Depending on the wave-ship length ratio and speed the motions of the trawler with bulbous bow in regular head waves are larger or less than for a ship without a bulb.

Takezawa (7) investigated the performance of the destroyer model without bulb and with 26% bulb. In his research he came to the conclusion that the large bulbous bow can decrease the ship motions, but it concerns only pitch amplitudes, because no data for heave are given in Takezawa's paper. The thrust increase in waves of the hull with large bulbous bow was slightly bigger than that of the ordinary hull due to the reduction of the propulsive efficiency in waves, which was caused by the decrease of the mean immersion of the propeller, and due to larger resistance increase in waves. The total EHP in irregular waves seemed to be less or nearly equal that of the conventional hull, except for the case of the very high seas.

Gerritsma and Beukelman (8) compared the performances, with regard to motions and propulsion in longitudinal irregular waves, of a $C_B = 0.65$ Series Sixty hull and its modification with 10% bulb and correspondingly modified forebody. It was shown that the bulbous bow has a smaller pitching motion but an increased heaving motion in comparison with the parent model. The difference appeared to be not large, and it was concluded that the ship motions in longitudinal waves were not much influenced by the bulbous bow.

The same was stated for the wetness characteristics, for there was no strong indication that the hull with bulbous bow had better qualities than the parent model. As to the propulsive performance in waves it was shown that the power increase was larger for the ship form with the bulbous bow; the same for the increase of torque and revolutions. Based on the average weather conditions the difference in propulsive performance between the two ship forms was estimated to be small. A conclusion was made that for that considered particular case the bulbous bow did not have superior qualities in a seaway.

Wahab (9) investigated the behaviour of a fast cargo liner ($C_B = 0.62$) with a conventional and with a bulbous bow (17.2%) in a seaway. He found that in regular waves the added resistance due to the waves was higher for the ship with a bulb than for the ship with a conventional bow, especially when the waves were longer than the ship's length. The pitching motion was slightly reduced by fitting a bulb, the heaving motion and the relative motion between the ship and the wave surface were both reduced in rather short waves and increased by the bulb in long waves.

Experiments in irregular seas showed that the speed increase due to the bulb with constant power was smaller in adverse weather than in smooth water. The advantage of the bulb was expected to vanish in bad weather. The probability of shipping green water and slamming was small for both bow configurations in sea states corresponding to wind forces under Beaufort 8. In extremely bad weather, Beaufort 8 and higher, the bulb caused an increased liability to slamming.

Van Lammeren and Pangalila (10) made experiments with models of a 24,000 DWT bulkcarrier ($C_B = 0.764$) with conventional and bulbous bow (9% in full load condition). They perceived that in loaded condition application of a bulb had hardly any effect on power both in still water and in waves. In ballast condition a gain in speed was obtained by bulb for speeds above 13 knots. Bending moments were not affected adversely by the bulbous bow. Relative motion of the bow was decreased noticeably by the bulb for the ship in full load condition; in ballast condition there was no difference. Pitching motions were practically the same for the models with and without bulbous bow.

Ochi (11) made model experiments to determine the effect of a bulbous bow on ship's slamming. The experiments were conducted on two models, the mariner with 4% bulb and modified mariner without bulb.

From the results of his experiments he made conclusions that the mariner had less resistance than the mariner without bulb, both in still water and in waves, bow acceleration for the mariner was less than that for the modified one, however, the pitching and heaving motions for the mariner were larger than those for the modified mariner. Slamming acceleration for the mariner was a little less at comparatively low speed but became larger than for the modified mariner at high speed.

Van Mater (12) made an experimental investigation of the behaviour in calm water and in waves of a model equipped with an extremely large bow and stern bulbs. It was found that such a ship had advantages related to the resistance in calm water and in waves in comparison with conventional ships. Pitching motions in head waves were substantially less for high speeds, heaving motions were larger, especially in long waves.

Smith (13) and Smith and Salvesen (14) made an investigation the main objective of which was to prove the validity of the Korvin-Kroukovsky strip theory for high speed destroyer hulls with large bulbs. It was stated (13) that for ships with bulbous forms the usual Lewis-form station representation, which was used in most strip theory ship motion computer programs could give results, which differed from those obtained from strip theories utilising a more accurate close-fit ship section representation, and for this reason a new close-fit method was developed and used in that work. The heave and pitch amplitudes and their phase angles were computed for two hull forms, the Davidson A destroyer and the Friesland class frigate. The "Davidson A" had larger heave amplitudes than the "Friesland" for the entire wave-length range; the pitch, on the other hand, was increased by the bulb in the long wave range and decreased in the short wave range, the heave and the pitch phases were reduced by the effect of the bulb by as much as about 70 degrees.

The computations show that the bulbs in general have the effect of increasing heave while decreasing pitch, but most experiments with destroyers with large sonar domes did not show this large difference as indicated by the strip theory. For this reason in (14) it was decided to test carefully the "Davidson A", by investigating different testing techniques and the effect of non-linearity and to compare experimental results with computations. During the experiment it was found that heave staff technique, which practically universally has been adopted for measuring pitch and heave in head waves, could seriously affect the measurements.

Hulls with large bulbs have considerably larger heave response than the regular forms. Finally free-running tests were performed in regular seas with the model self propelled and remotely steered. The investigation of non-linear effect showed a decrease in the non-dimensional heave amplitude with an increase of the wave height. The pitch responses were found to be affected similarly by the wave height, while the pitch and heave phases were not influenced by the change in wave height. The final experimental results were compared with computed results obtained from (13), where the program was written according to the Gerritsma-Beukelman version of the Korvin-Kroukovsky strip theory (15) and each ship section was represented accurately by the close-fit mapping procedure. The comparison showed good agreement between computed results and free-running experimental results.

Beukelman (16) experimentally determined the coefficients of equations of ship motions and wave forces and moments for the model of the Davidson A destroyer. The measured results were compared with the results of computations based on two modes of strip theory and on a "rational" strip theory for slender bodies. It was shown that in most cases experimentally determined coefficients better agreed with computed results according to (15). The calculated ship motions according to different versions were rather near, but it was pointed out, that in the limit case of infinite long waves the non-dimensional motion amplitudes z_a/ζ_a and $\theta_a/k\zeta_a$ should tend to the value 1 and the phase angles for heave and pitch should respectively tend to 0 and 90 degrees. But this tendency is only correct for the motion results according to version (15) and appears to grow more important for higher speeds.

In the present paper there are presented results of systematic calculations, which were carried out for models with two values of block coefficient with conventional and bulbous bows. It is shown that bulbous bows have more influence on the ship motions for models with small block coefficient than for models with higher values of block coefficient. The calculated values of the coefficients of equations of ship motions are presented. Finally the calculated results for two models are compared with experimental datas; the agreement appeared to be rather good.

II Models.

It is known, that in the present moment bulbous bows are used for different types of commercial ships, starting from high-speed cargo liner with rather small values of block coefficient ($C_B \approx 0.60$) to huge super tankers with high values of block coefficient ($C_B \approx 0.80$). In these investigations it was decided to determine the influence of bulbous bows on motions of ships with different values of block coefficient. For this reason two groups of models were considered - one on the basis of Sixty Series model with $C_B = 0.65$ (5 models), the other on the basis of Sixty Series model with $C_B = 0.75$ (3 models). In each group the comparison is made between the model with conventional bow and two modifications, each with an added cylindrical bulb of 10% and 20% of the middle cross section. Cylindrical bulbs are based on a sphere located in front of the ship, while the centre of the sphere is always in the longitudinal plane of symmetry of the ship on the F.P., and the lowest point of the sphere is on the base line.

Two modifications of Sixty Series with $C_B = 0.65$ have the afterbody of the original model and 10% and 20% bulbous bow with correspondingly changed forebody according to (1).

In table 1 the main particulars of the models are given, their body plans are given in figure 1.

III Calculations.

In the present moment several versions of the strip theory or of the slender body theory are used in different ship-motion computer programs. These are: Gerritsma — Beukelman version of the Korvin-Kroukovsky strip theory (15), versions of Vugts (17), Blagowetsjenskij (18) and Netsvetaev (19) and a "rational" strip theory for slender ships by Ogilvie and Tuck (20), the later is used in ~~the Frank close-fitship-motion computer program~~ (21). It was not the task of present work to investigate different versions of theory, so keeping in mind the results obtained in (14) and (16), it was decided to use for the present calculation the standard ship-motion computer program of the Delft Shipbuilding Laboratory (13), (15) and (16), according to the first mentioned version.

In this program the coefficients of the equations of motion are for

$$\left.\begin{aligned}&\text{heave } (a+\rho\nabla)\ddot{z} + b\dot{z} + cz - d\ddot{\theta} - e\dot{\theta} - g\theta = F\\&\text{pitch } (A + k_{yy}^2\rho\nabla)\ddot{\theta} + B\dot{\theta} + C\theta - D\ddot{z} - E\dot{z} - Gz = M\end{aligned}\right\}\quad\text{and}$$

having the following form

$$a = \int_L m'dx$$

$$b = \int_L N'dx - v\int_L \frac{dm'}{dx}dx$$

$$c = 2\rho g\int_L y_w dx$$

$$d = \int_L m'xdx + \frac{v}{\omega_e^2}\int_L N'dx - \frac{v^2}{\omega_e^2}\int_L \frac{dm'}{dx}dx$$

$$e = \int_L N'xdx - 2v\int_L m'dx - v\int_L \frac{dm'}{dx}xdx$$

$$g = 2\rho g\int_L y_w xdx$$

$$A = \int_L m'x^2dx + \frac{v}{\omega_e^2}\int_L N'xdx - \frac{v^2}{\omega_e^2}\int_L \frac{dm'}{dx}xdx$$

$$B = \int_L N'x^2dx - 2v\int_L m'xdx - v\int_L \frac{dm}{dx}x^2dx$$

$$C = 2\rho g\int_L y_w x^2dx$$

$$D = \int_L m'xdx$$

$$E = \int_L N'xdx - v\int_L \frac{dm}{dx}xdx$$

$$G = 2\rho g\int_L y_w xdx$$

the wave force

$$\frac{F_a}{\zeta_a}\begin{matrix}\cos\\ \sin\end{matrix}\,\varepsilon_{F\zeta} = 2\rho g\int_L y_w e^{-kT^*}\begin{matrix}\cos\\ \sin\end{matrix}(kx)dx \mp \omega\int_L \left(N' - v\frac{dm'}{dx}\right)e^{-kT^*}\begin{matrix}\sin\\ \cos\end{matrix}(kx)dx - \omega^2\int_L m'e^{-kT^*}\begin{matrix}\cos\\ \sin\end{matrix}(kx)dx$$

the wave moment

$$\frac{M_a}{\zeta_a} \begin{matrix}\cos\\ \sin\end{matrix} \varepsilon_{M\zeta} = -2\rho g \int_L y_w x e^{-kT^*} \begin{matrix}\cos\\ \sin\end{matrix} (kx)dx \pm \omega \int_L \left(N' - v \frac{dm'}{dx}\right) x e^{-kT^*}$$

$$\begin{matrix}\sin\\ \cos\end{matrix} (kx)dx + \omega^2 \int_L m' x e^{-kT^*} \begin{matrix}\cos\\ \sin\end{matrix} (kx)dx$$

where $T^* = -\frac{1}{k} \ln \left(1 - \frac{k}{y_w} \int_{-T}^{0} y e^{kz} dz\right)$

and T = sectional draught.

In (14) and (16) it was shown that for ships with a transom stern it is necessary to take into account the ending terms, this is the added mass and damping coefficient for the stern cross section. In the case of ships with a bulbous bow it is necessary to take into account the added mass and damping coefficients of the cross section on the forward perpendicular. So in our case the coefficients of the equations of motion are

$$a = \int_L m' dx$$

$$b = \int_L N' dx - v m_{20}$$

$$c = 2\rho g \int_L y_w dx$$

$$d = \int_L m' x dx + \frac{v}{\omega_e^2} \int_L N' dx - \frac{v^2}{\omega_e^2} m_{20}$$

$$e = \int_L N' x dx - v \int_L m' dx - v m_{20} x_{20}$$

$$g = 2\rho g \int_L y_w x dx$$

$$A = \int_L m' x^2 dx + \frac{v}{\omega_e^2} \int_L N' x dx + \frac{v^2}{\omega_e^2} \int_L m' dx - \frac{v^2}{\omega_e^2} m_{20} x_{20}$$

$$B = \int_L N' x^2 dx - v m_{20} x_{20}^2$$

$$C = 2\rho g \int_L y_w x^2 dx$$

$$D = \int_L m' x dx$$

$$E = \int_L N' x dx + v \int_L m' dx - v m_{20} x_{20}$$

$$G = 2\rho g \int_L y_w x dx$$

The two dimensional added mass and damping of the cross sections were received by using Ursell's (22) solution for a circular cylinder oscillating at the free surface. For this reason the conformal transformation of the cross section to the unit circle was used.

The methods using a three coefficient or Lewis-form transformation are usefull for cross sections of conventional ships (Tasai (23), Grim (24)) but fail for sections with extreme shapes. In this case it is necessary to extend the Lewis form transformation to a multi-coefficient transformation as given by Smith (13) or de Jong (25), or to use the close-fit method developed by Frank (21). In our case it was decided to use the transformational method which is given in (25). This method allows to receive up to 19 transformational coefficients depending on the form of the cross section and on the given accuracy.

Only in extreme cases (with 20% bulb) where the above mentioned method failed, the (13) method is used, which gives up to 61 transformational coefficients.

IV Analysis of the calculated results.

The calculated ship motion amplitudes, phase angles, wave forces and moments, the coefficients of the equations of motion for different models are given in a non-dimensional form as follows:

for heave	for pitch
z_a/ζ_a	$\theta_a/K\zeta_a$
$1+\frac{a}{\rho\nabla}$	$1+\frac{A}{\rho\nabla K_{yy}^2}$
$\frac{b\sqrt{gL}}{\rho g\nabla}$	$\frac{B}{\rho\nabla L\sqrt{gL}}$
$\frac{d}{\rho\nabla L}$	$\frac{D}{\rho\nabla L}$
$\frac{e}{\rho\nabla\sqrt{gL}}$	$\frac{E}{\rho\nabla\sqrt{gL}}$
$\frac{F_a}{\rho g\zeta_a A_w}$	$\frac{M_a}{\rho g I_L K\zeta_a}$

where $A_w = \int_L y_w dx$ and $I_L = \int_L y_w x^2 dx$.

The calculated ship motions and their phase angles for different models are given in figures 2 - 9, for Fn = .20 and Fn = .30. From these figures it is possible to see that the bulbous bow increases the heave amplitudes, practically in the whole range of waves. A greater bulb causes a stronger increase in heave amplitudes. For the models with a low block coefficient the increase of heave amplitudes for cylindrical bulbs is practically the same as in the case of changed form. For the models with a high block coefficient the tendency of the change of the heave amplitudes is the same, but the difference between models with conventional bow and with bulbous bow became less. At the same time it is interesting to note that the increase in heave amplitudes for all models is practically independent of the speed, so with the increase of model's speed the relative increase of heave amplitudes became less.

The pitch amplitudes of the models with bulbous bow are, generally, larger than of the models with conventional bows in long waves and less in short waves. The bigger bulb the greater difference in pitch amplitudes.

The wave length for which the models with bulbous bow became superior in pitch amplitudes depends on the model's speed; with the increase of speed the bulbous models became superior in pitch for longer waves. At the same time it is showed, that for the models with a low block coefficient the difference in pitch amplitudes is more significant, than for the models with a high block coefficient; this difference is very small in the whole range of waves.

The pitch and heave phase angles for all models are practically not influenced by the bulbous bows. For the models with a low block coefficient it is possible to notice, that the difference in phase angles between the models with conventional and bulbous bows, is greater for pitch phase angles and less for heave phase angles, while the models with a high block coefficient practically show no difference.

We may conclude that bulbous bows cause larger heave amplitudes, and increase in pitch amplitudes in long waves and decrease in short waves, the last depends on the ship's speed. The motions of the ship with a low block coefficient are more influenced by a bulbous bow than of the ship with a high block coefficient. The phase angles are not influenced by the form of the bow.

The calculated coefficients of the equations of motions are given in the figures 10 - 26 as well as the wave forces and moments.

Concerning the coefficients of the motion equations it is apparent that coefficients "a" and "A" are practically the same for the models with conventional and bulbous bows, their values are independent of the form of the bow; so, added mass and added moment of inertia of a ship are not influenced by the bulbous bow.

Coefficients "b" and "B" for models with bulbous bow are smaller than for the models with conventional bow, the difference is bigger at low frequencies and decreases with the increase of frequency. The difference in coefficient B is dependent on the speed and increases with the increase of speed. For the models with a high block coefficient the difference in the coefficients "b" and "B" is smaller than for the models with a low block coefficient.

As to the cross coupling coefficients "d", "D", "e" and "E" it is possible to say that the difference in the coefficients "d" and "D" for models with conventional and bulbous bows is very small, the coefficients "e" and "E" are more sensitive for the form of the bow, but at the same time the difference in these coefficients is practically independent of the speed.

The comparison of the calculated values of the wave exciting forces and moments shows that the bulbous bow practically don't influence them; a small difference could be found only in short waves for the models with a low block coefficient.

From the statements which were made above it is possible to conclude that the main difference in motions for ships with conventional and bulbous bows is caused by the difference in coefficients of the equations of motion "b", "B", "e" and "E". As it was shown by the preliminary calculations the magnitude of these coefficients (especially of the cross-coupling coefficients) to a high degree depends on the accuracy of determining the sectional added mass and damping of the end cross sections, so the bulb cross sections. And as this accuracy is mainly defined by the accuracy of the conformal transformation of these cross sections, this problem must be treated very carefully. From this point of view it is difficult to agree with the statement made by Beck in (26), that even the poor representation of bulb type sections by a Lewis form does not influence the resulted ship motions. Such a statement is possible only in the case that the ship motion equations are solved without taking into account the end terms.

It was shown by Ursell and Porter that semisubmerged circular, elliptic and Lewis form cylinders give rise to non-zero forces for heaving oscillation at finite frequencies in deep water. Motora and Koyama (27) had measured the heave exciting forces on circular and elliptic cylinders with vertical struts in regular waves. Their results indicated the excistense of almost vanishing minimum forces for some of their test models. They conjectured that corresponding to these minimum exciting forces on the tested bulbous forms, the damping coefficients for the respective wave number must be practically zero. Frank showed in (28) by direct computation that for different bulbous cylinders the damping vanish for some wave numbers; this wave number depends on the geometry of the bulbous cylinder. From the same calculations it could be seen that the added mass of such cylinders is also dependent on the geometrical form.

From this it might be possible to draw the conclusion that in special cases by a particularly constructed bulbous bow it is possible to receive a certain change in ship motions in some range of waves and speeds. But this question needs additional and thorough investigation.

In the present moment it is possible to say that for transport ships the bulbous bow leads to the increase of heave amplitudes, while pitch amplitudes in most cases are increased in long waves and decreased in short waves. But the last depends on the ship's block coefficient and with its increase the difference became less.

V. Experiment.

In order to check the possibility of the strip theory to predict the pitch and heave amplitudes and their phase angles for hulls with a bulbous bow, an experiment was made in the Delft Shipbuilding Laboratory, with the ship models ($C_B = 0.65$) with a conventional bow and with a 20% cylindrical bulb. The principal datas of these models are given in table 1. The models were tested in the small towing tank in regular waves $\lambda/L = 0.6 - 1.6$ with a constant wave height of $2\zeta_a = 1/50$ L and a speed range of $Fn = 0.20 - 0.30$.

The results of the experiment are shown in the figures 27 - 28.

The results of the experiment show that the model with a bulbous bow practically in all waves has smaller pitch amplitudes than the model with a conventional bow. The heave amplitudes are practically the same for both models in the range of waves which was investigated; only for long waves the model with bulbous bow shows the trend for higher heave amplitudes than the model with the conventional bow.

The heave and pitch phase angles are practically the same for both models.

During the experiments the added wave resistance for both models was measured; it appears, that the model with the bulbous bow has higher added wave resistance than the model with the conventional bow in the whole range of waves and speeds (figure 29).

The results of the experiment were compared with the calculated results. It was done for the model with $C_B = 0.65$ and 20% cylindrical bulb, which was tested during investigations, and for the model $C_B = 0.65$ with 10% bulb and changed forepart; in this case the experimental results were taken from (8). The results are shown in the figures 30 - 33.

From the comparison it is possible to see that experimental and calculated pitch amplitudes are in a rather good agreement; the same could be said about heave and pitch phase angles. For the heave amplitudes, it appears that the measured values are smaller than the calculated ones, especially in the resonance region. But as it was stated in (14) the experimental heave amplitudes are greatly influenced by the applied test technique. In our experiments the model was tested with a heave staff, which according to (14) can decrease the heave amplitudes, because they are very sensitive for all extra friction that could occur in the heave staff.

However recent tests in the Shipbuilding Laboratory in Delft, the results of which would be published later, shows that non-linearity may be the main reason of the derivation between calculated and measured heave motions.

It is possible to conclude, that strip theory can predict ship motions for hulls with bulbous bow with sufficient accuracy.

VI Conclusion.

From this investigation the following conclusions can be derived.

For a normal transport ship the bulbous bows cause an increase of heave amplitudes practically in the whole wave range. This increase can be very significant and depends on the bulb size - the bigger bulb the greater increase of heave. The pitch amplitudes in most cases are decreased in short waves and increased in long waves, but the difference in pitch amplitudes is not so significant. The pitch and heave phase angles practically are not influenced by the bulbous bows.

The influence of the bulbous bows on the ship motions is greater for ships with low values of the block coefficient and rather small for ships with a high block coefficient.

The comparison between the calculated and experimental results shows that the theory can quite accurately predict the pitch and heave amplitudes and their phase angles for hulls with different bulbs.

While using ship-motion computer programs it is necessary to pay much attention to correct close-fit representation of bulb sections, especially for those located near the fore perpendicular. The accurately calculated sectional added mass and damping for such cross sections will lead to more correct ship motions results.

At the same time bulbous bows can lead to the increase of added resistance in waves in comparison with conventional ships.

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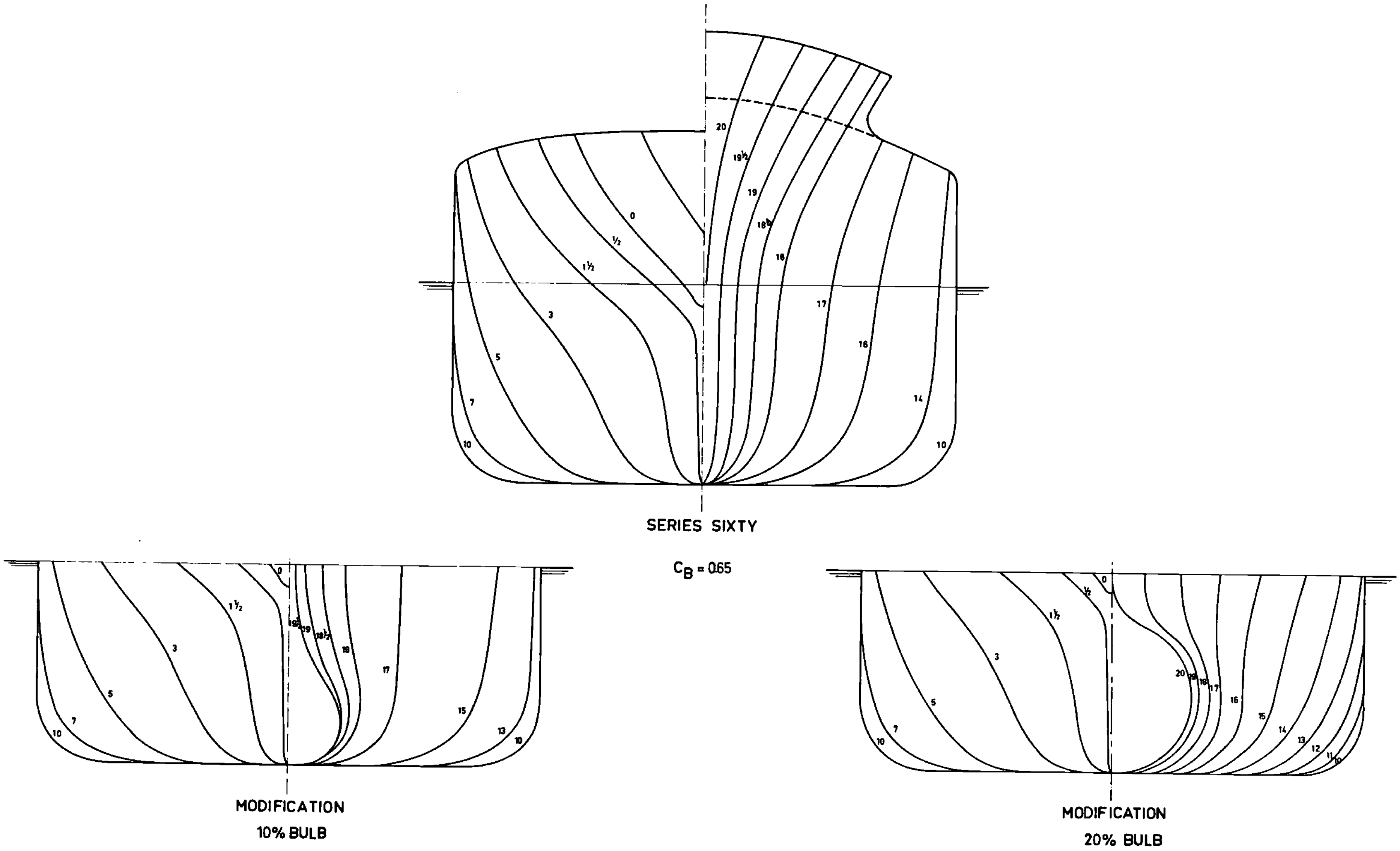
Nomenclature.

a b c d e g	coefficients of the equations of motion
A B C D E G	for heave and pitch
A_w	area of waterplane
C_B	block coefficient
F	wave force
Fa	wave force amplitude
Fn	Froude number
g	acceleration of gravity
I_L	longitudinal moment of inertia of waterplane area
$k = 2\pi/\lambda$	wave number
k_{yy}	longitudinal radius of inertia of the model
L	length between perpendiculars
M	wave moment
Ma	wave moment amplitude
m'	sectional added mass
m20'	sectional added mass at the bow
N'	sectional damping
T	draught of the model
v	forward speed of the model
y_w	half width of waterline
z	heave displacement
za	heave amplitude
ε	phase angle between motions
ζ	instantaneous wave elevation
ζ_a	wave amplitude
θ	pitch angle
θ_a	pitch amplitude
λ	wave length
ρ	density of water
∇	volume of displacement
ω	circular frequency
ω_e	circular frequency of encounter

Table 1.

MODEL DIMENSIONS AND PARTICULARS.

	Model designation and condition	Series 60	I modification	II modification	Series 60 plus cylindrical bulb	Series 60 plus cylindrical bulb	Series 60	Series 60 plus cylindrical bulb	Series 60 plus cylindrical bulb
1	Displacement	56.970	56.970	56.970	57.300	58.020	75.300	75.660	76.210
2	Length between perpendiculars	2.26	2.26	2.26	2.26	2.26	2.26	2.26	2.26
3	Breadth	0.311	0.311	0.311	0.311	0.311	0.335	0.335	0.335
4	Draught	0.125	0.125	0.125	0.125	0.125	0.134	0.134	0.134
5	Block coefficient	0.65	0.65	0.65			0.75		
6	Midship section coefficient	0.982	0.982	0.982	0.982	0.982	0.990	0.990	0.990
7	Prismatic coefficient	0.661	0.661	0.661	0.661	0.661	0.758	0.758	0.758
8	Waterplane coefficient	0.746	0.733	0.728	0.746	0.746	0.827	0.827	0.827
9	Half angle of entrance	9.1	7.8	7.0	9.1	9.1	22.5	22.5	22.5
10	Centre of effort of waterplane	-0.060	-0.076	-0.077	-0.060	-0.060	-0.016	-0.016	-0.016
11	Centre of buoyancy	-0.0113	-0.0099	-0.0026	-0.0048	0.0060	0.0299	0.0347	0.0419
12	Longitudinal radius of inertia	$0.25L_{BP}$	$0.25L_{BP}$	$0.25L_{BP}$	$0.25L_{BP}$	$0.25L_{BP}$	$0.25L_{BP}$	$0.25L_{BP}$	$0.25L_{BP}$
13	Bulb area in percent of midship area	0	10	20	10	20	0	10	20



SERIES SIXTY

$C_B = 0.65$

MODIFICATION
10% BULB

MODIFICATION
20% BULB

Fig.1: BODY PLANS

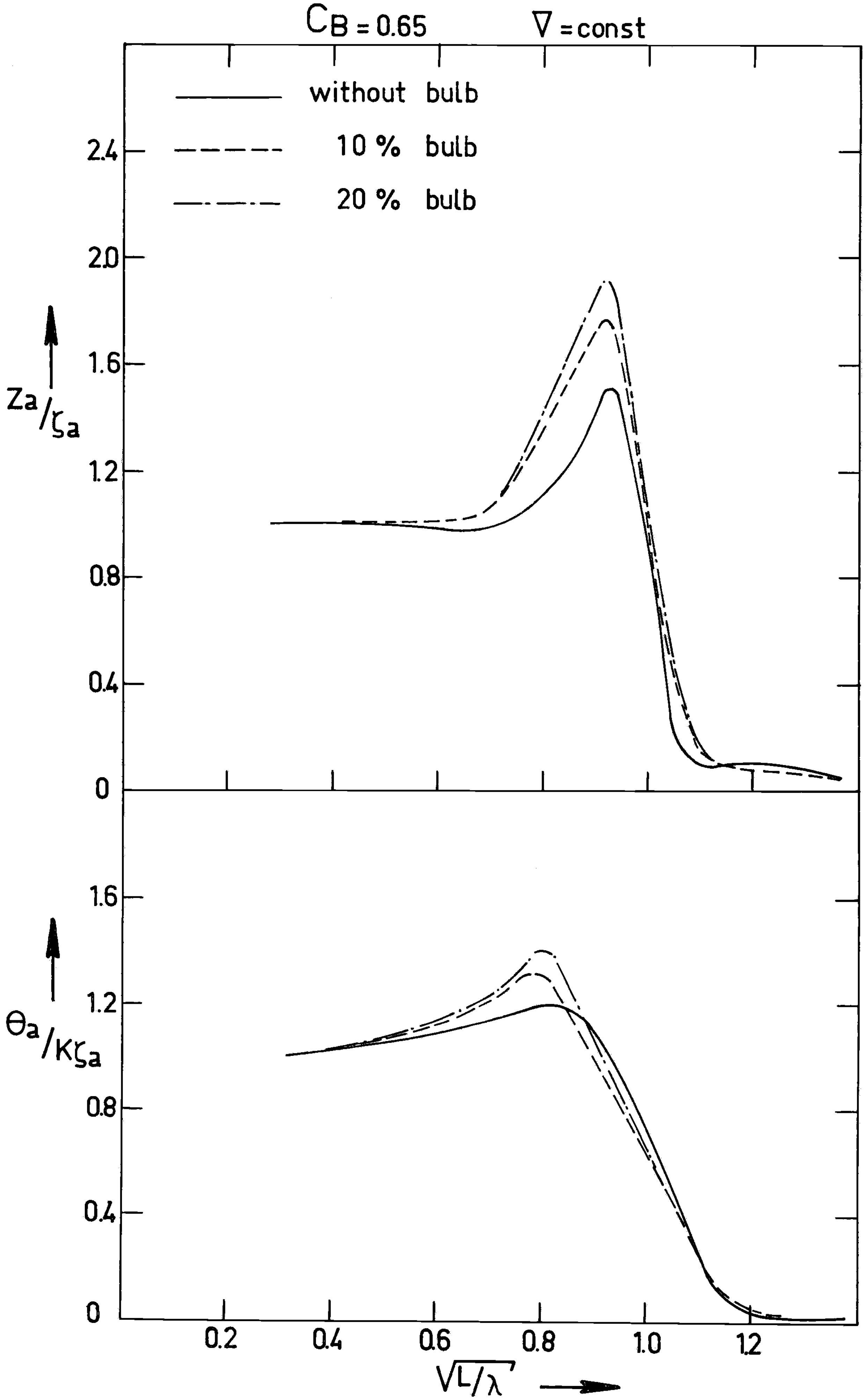


Fig 2 Heave and pitch amplitudes for Fn = 0.20.

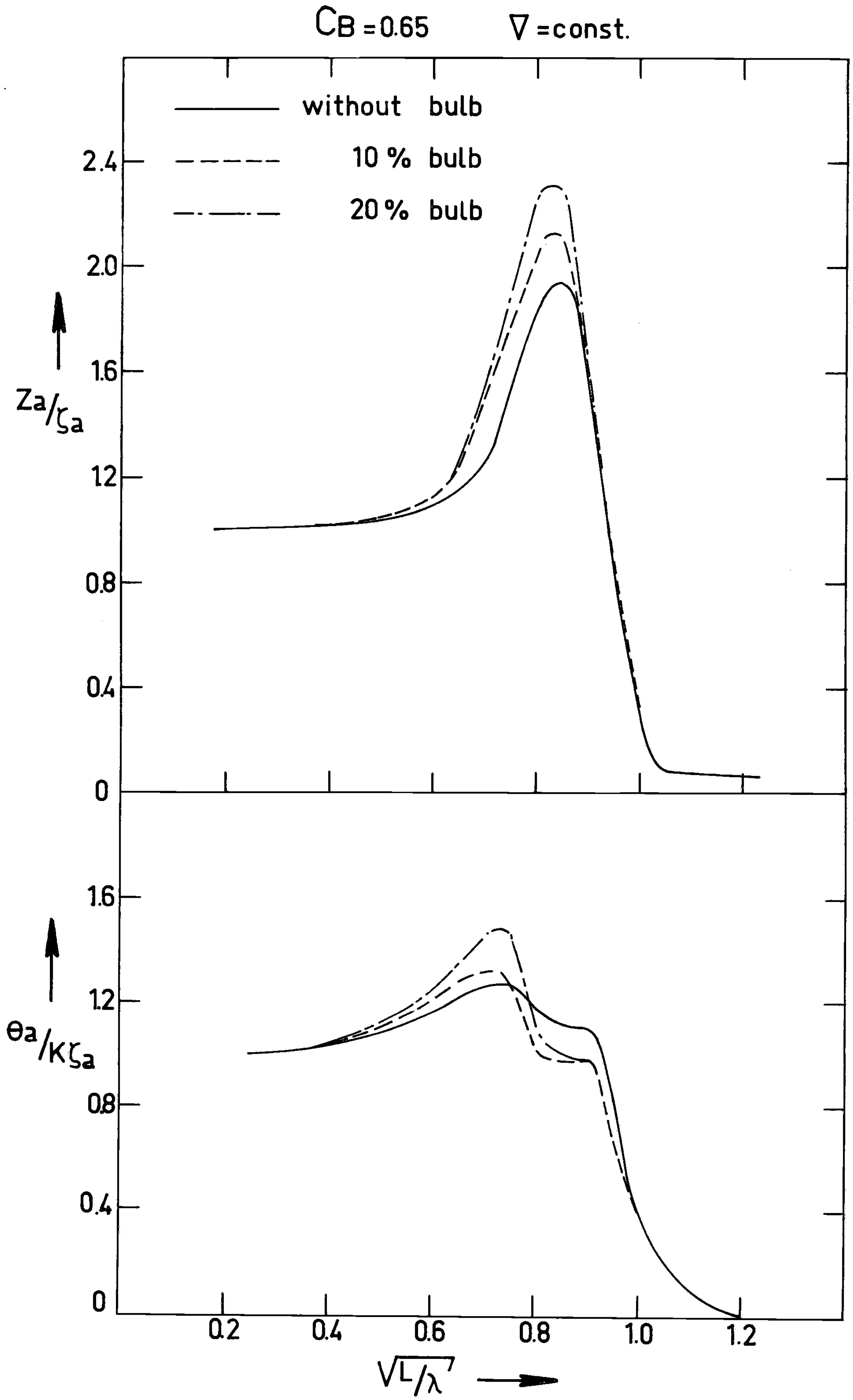


Fig 3 Heave and pitch amplitudes for Fn = 0.30.

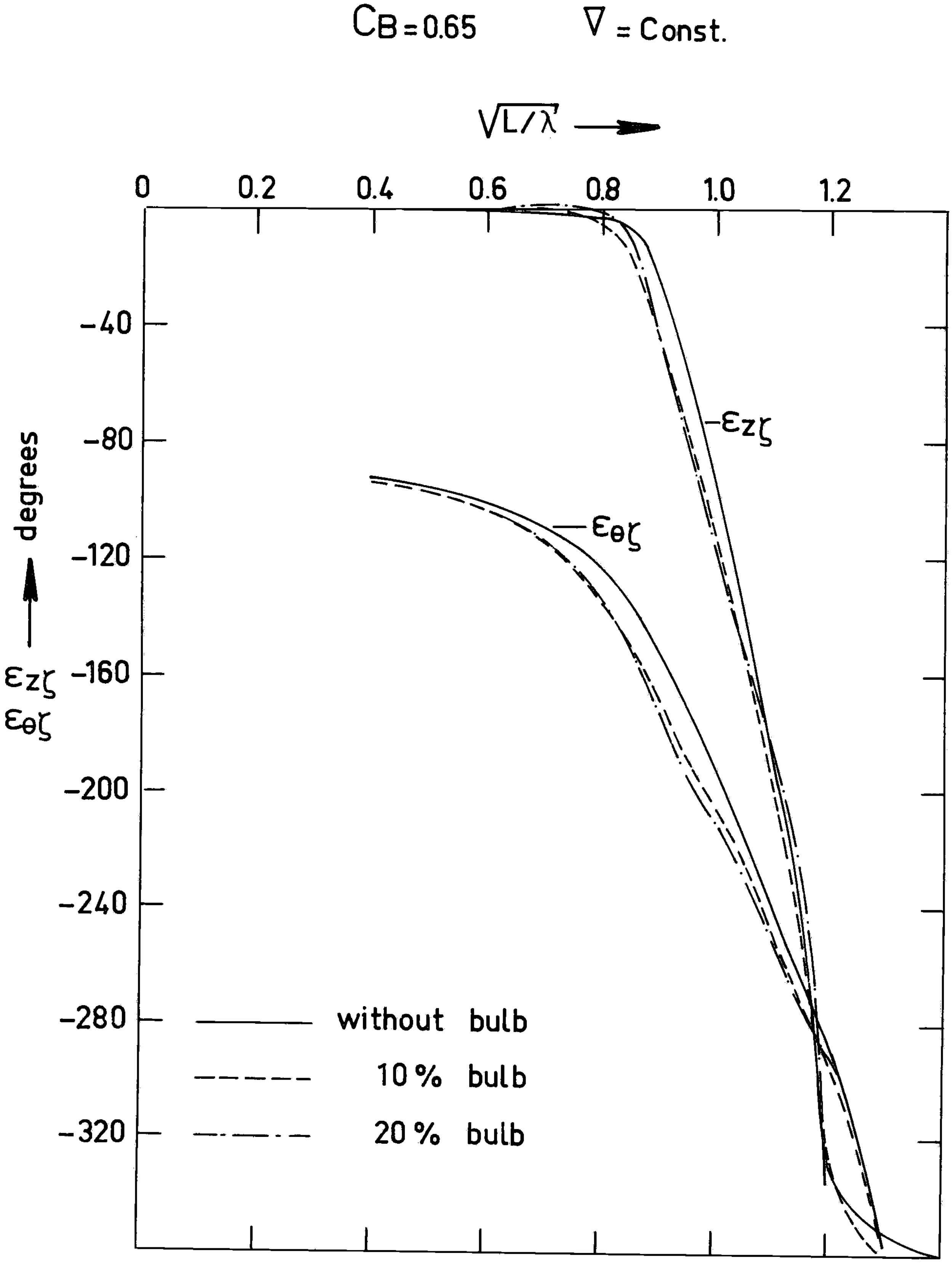


Fig 4 Heave and pitch phases for Fn = 0.20.

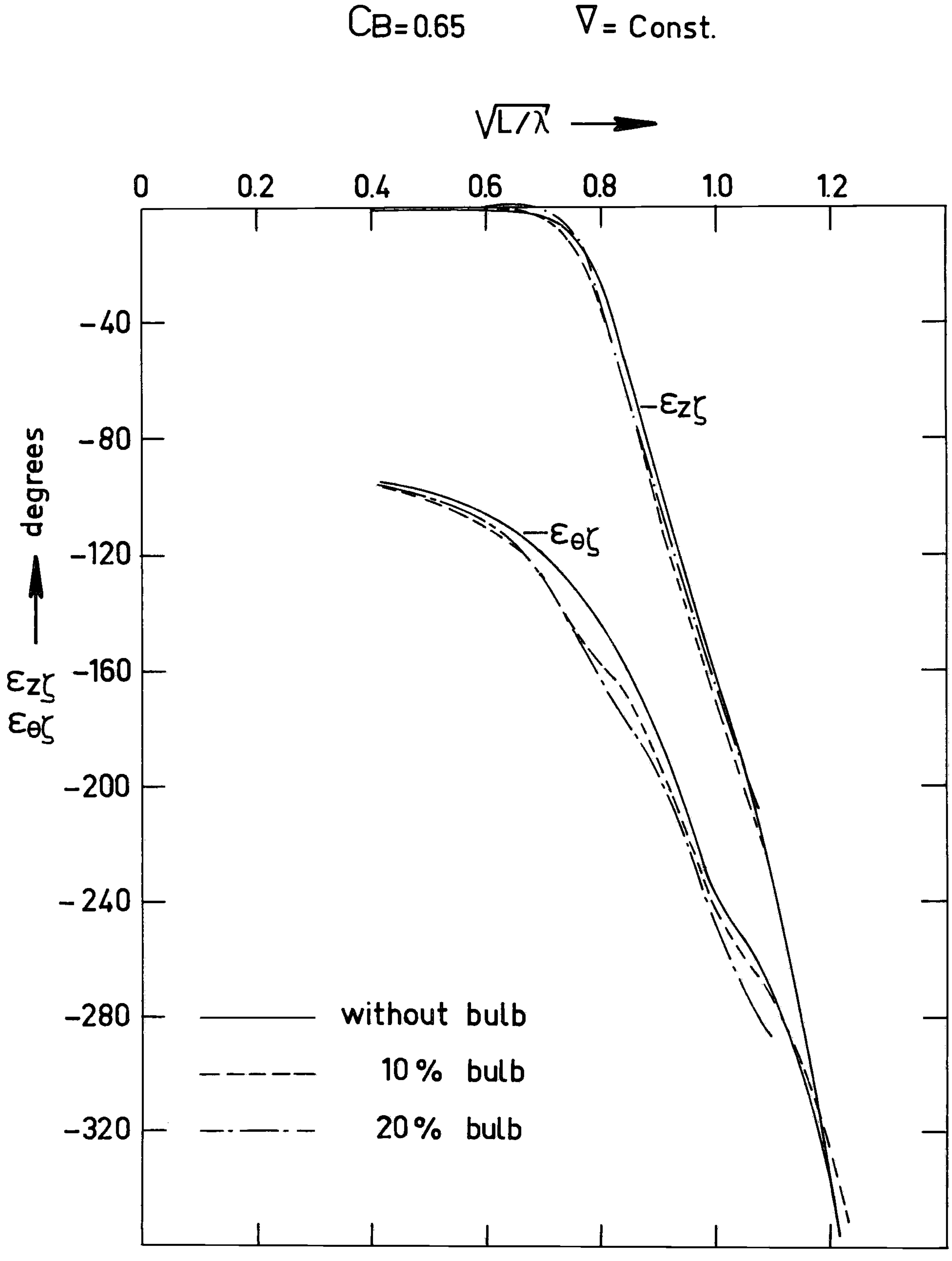


Fig 5 Heave and pitch phases for Fn = 0.30.

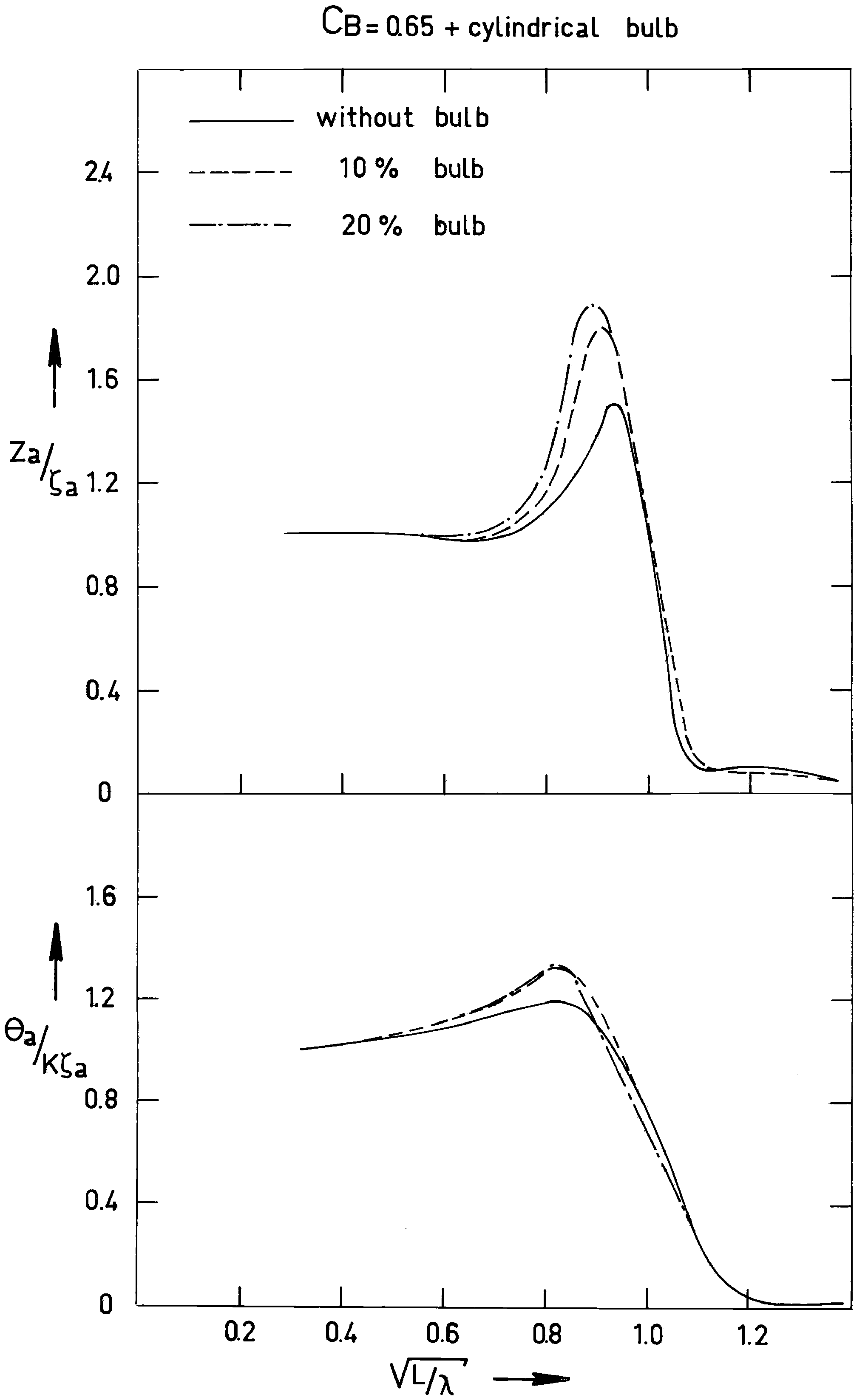


Fig 6 Heave and pitch amplitudes for $Fn = 0.20$.

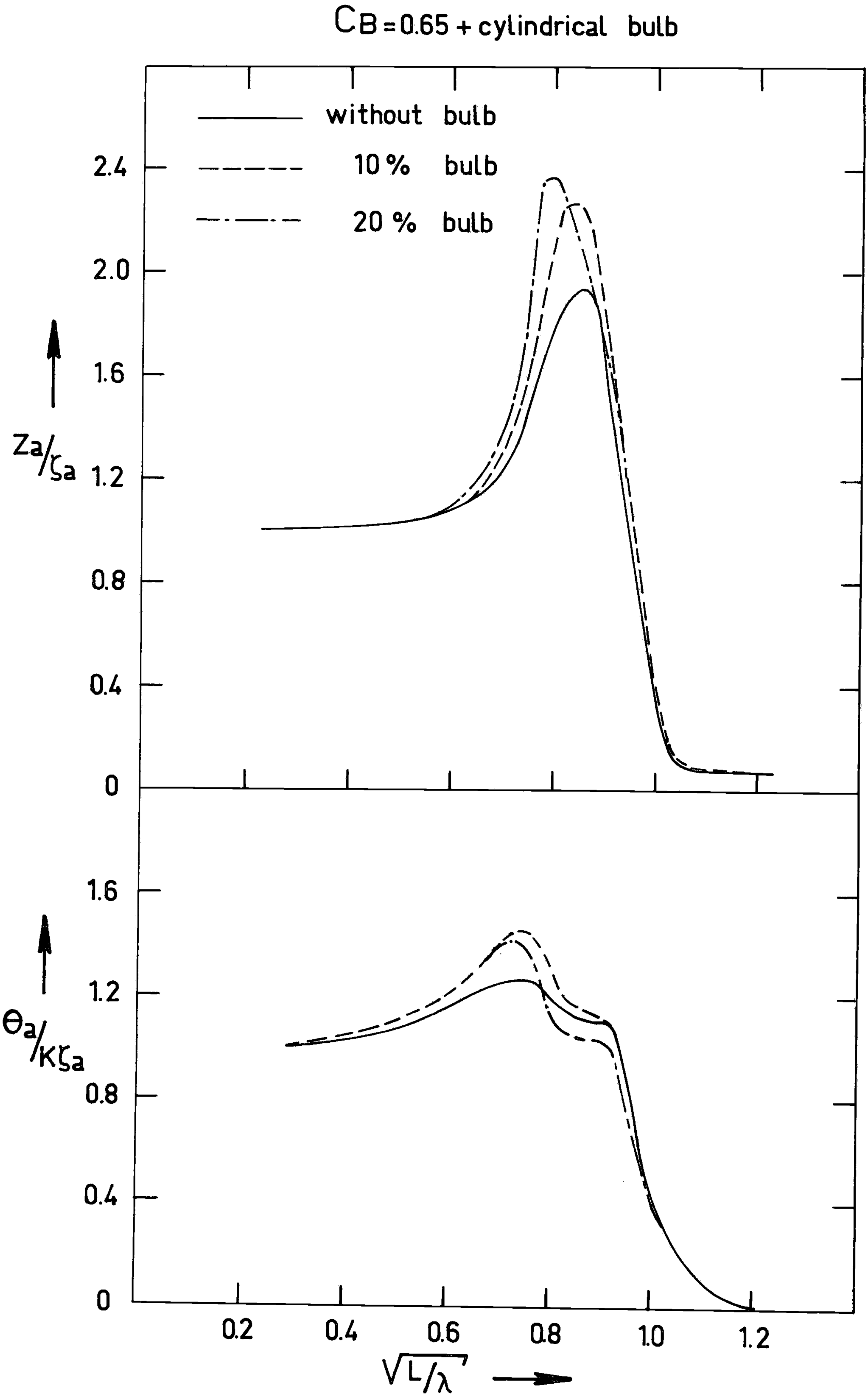


Fig 7 Heave and pitch amplitudes for Fn = 0.30.

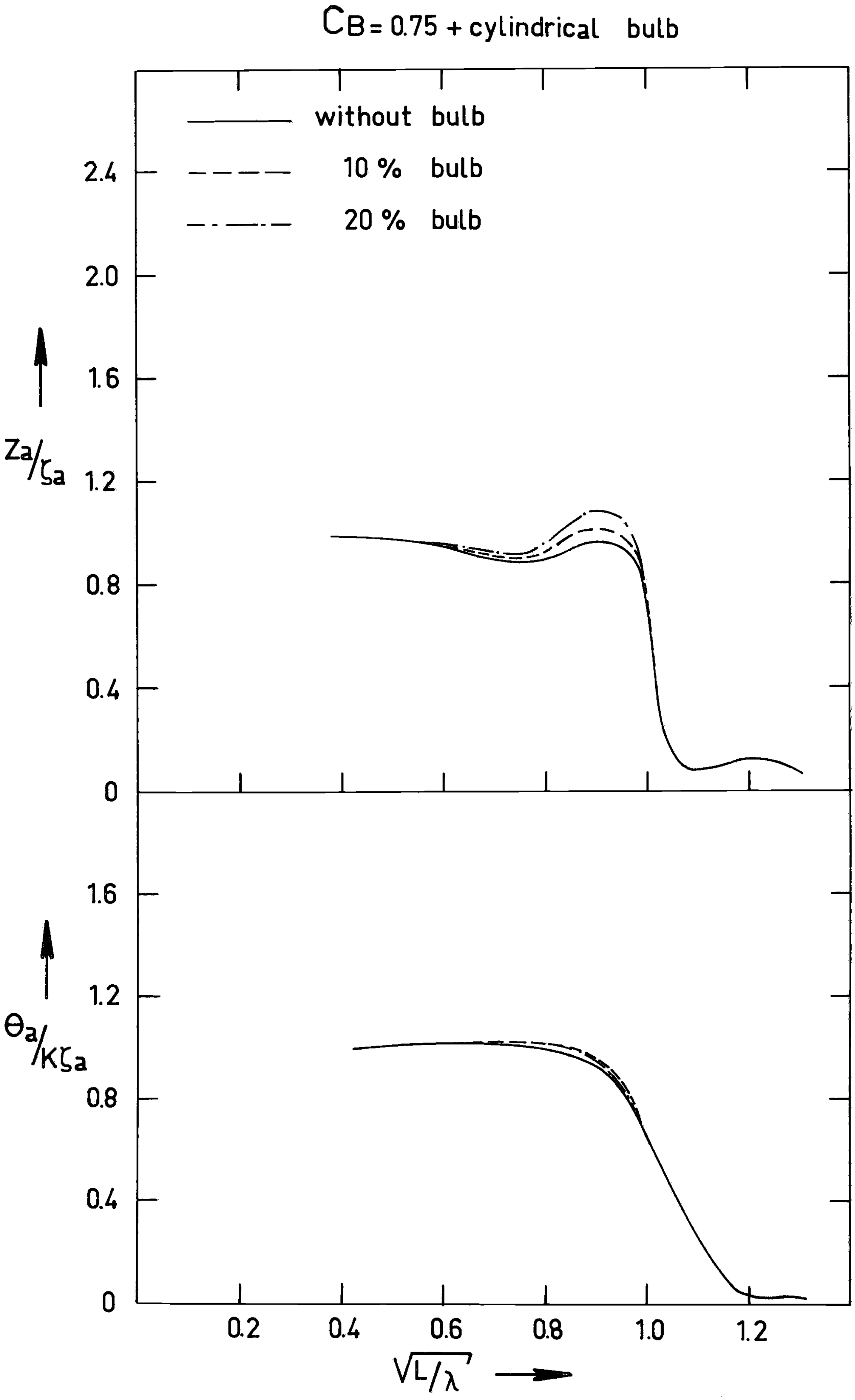


Fig 8 Heave and pitch amplitudes for Fn = 0.15.

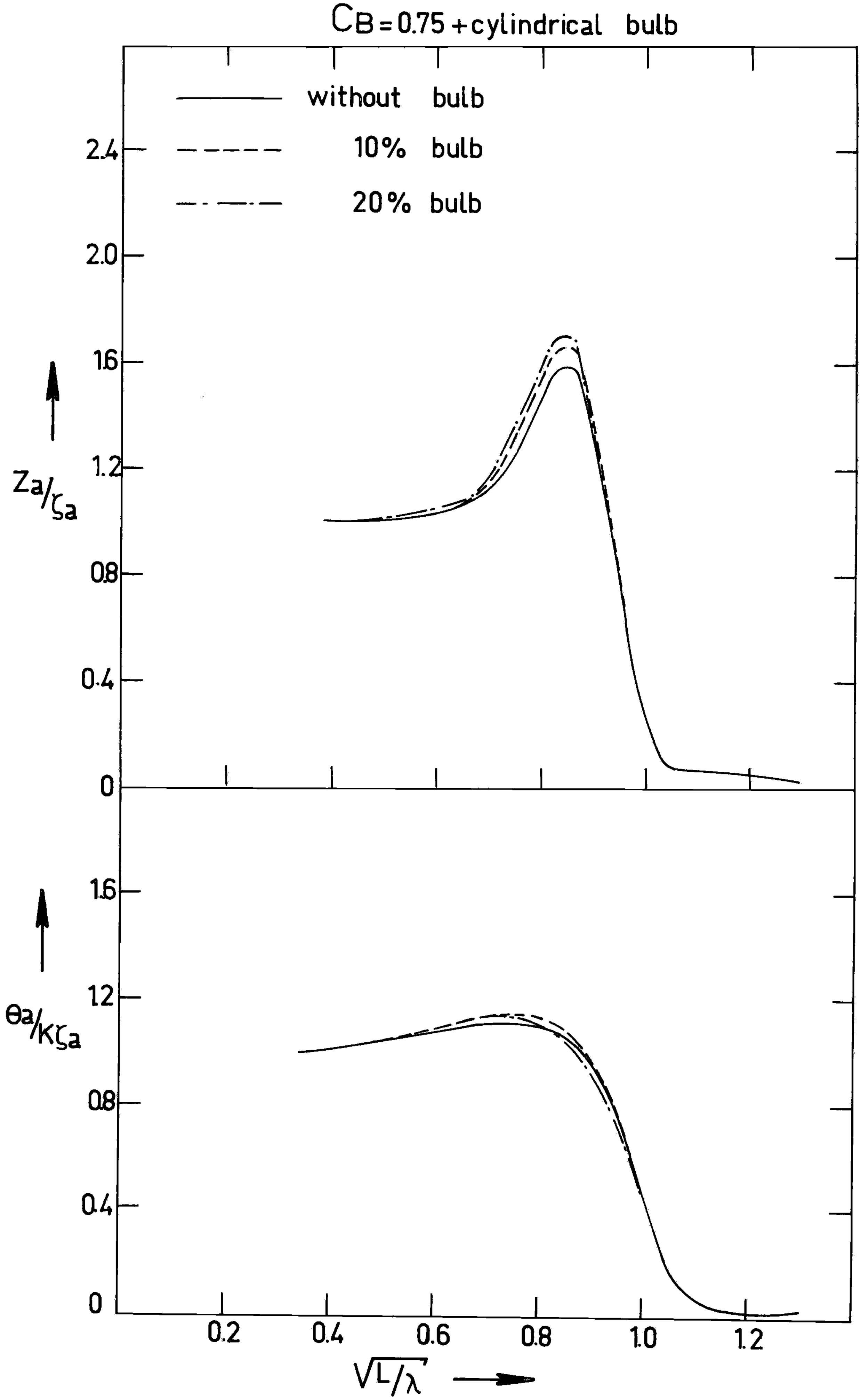


Fig 9 Heave and pitch amplitudes for Fn = 0.25.

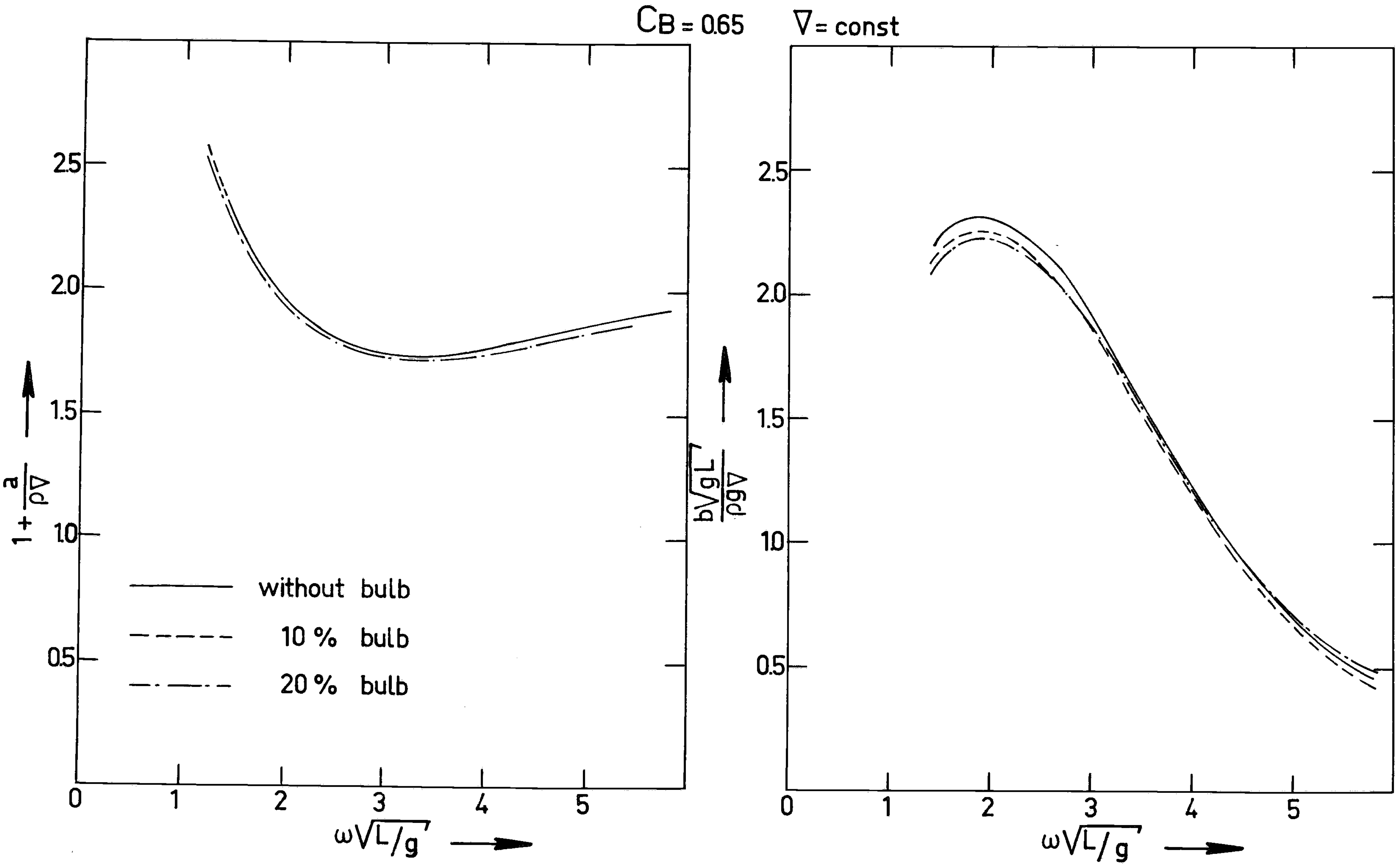


Fig 10 Coefficients of added mass "a" and damping "b" for Fn = 0.20.

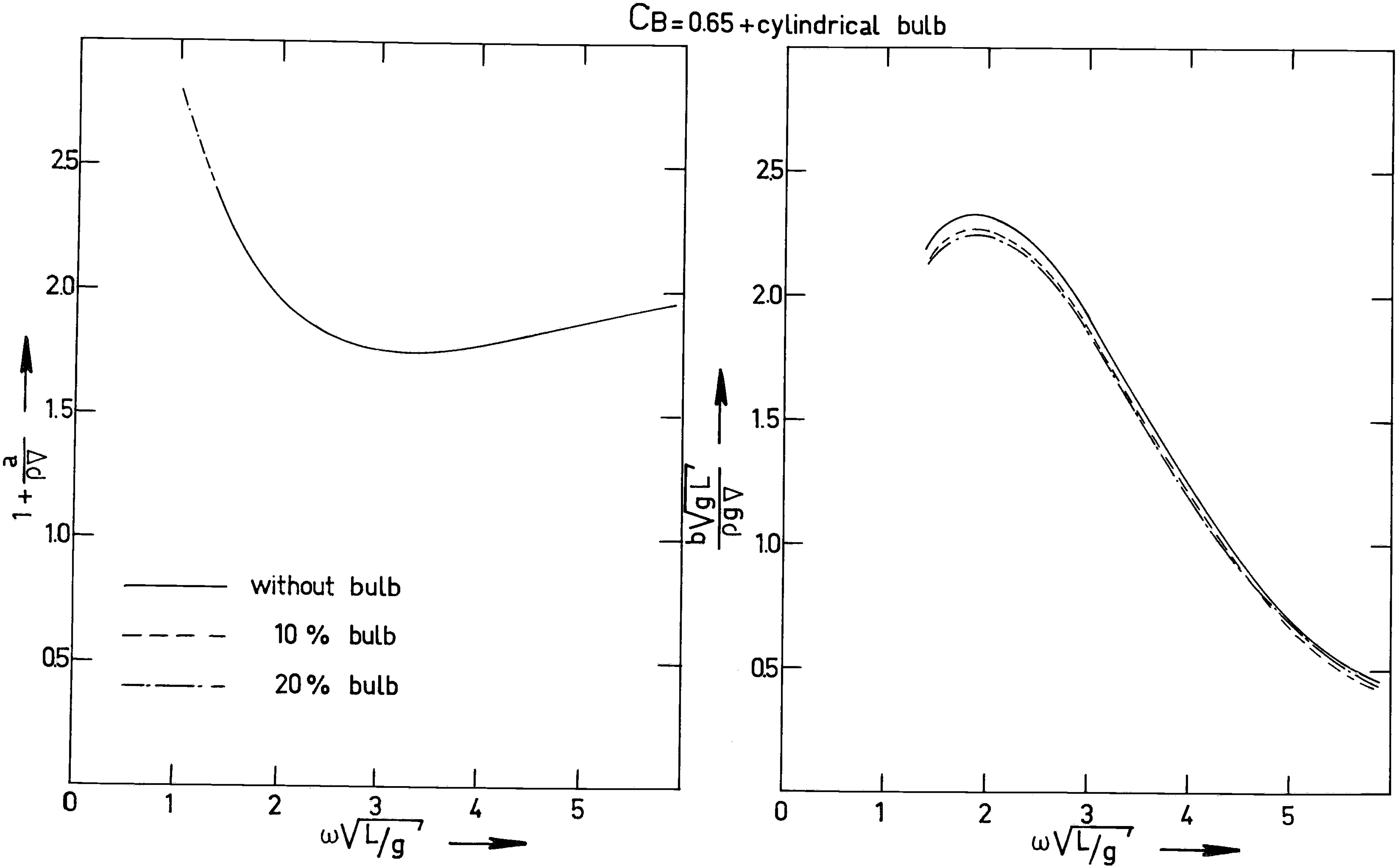


Fig 11 Coefficients of added mass "a" and damping "b" for Fn = 0.20.

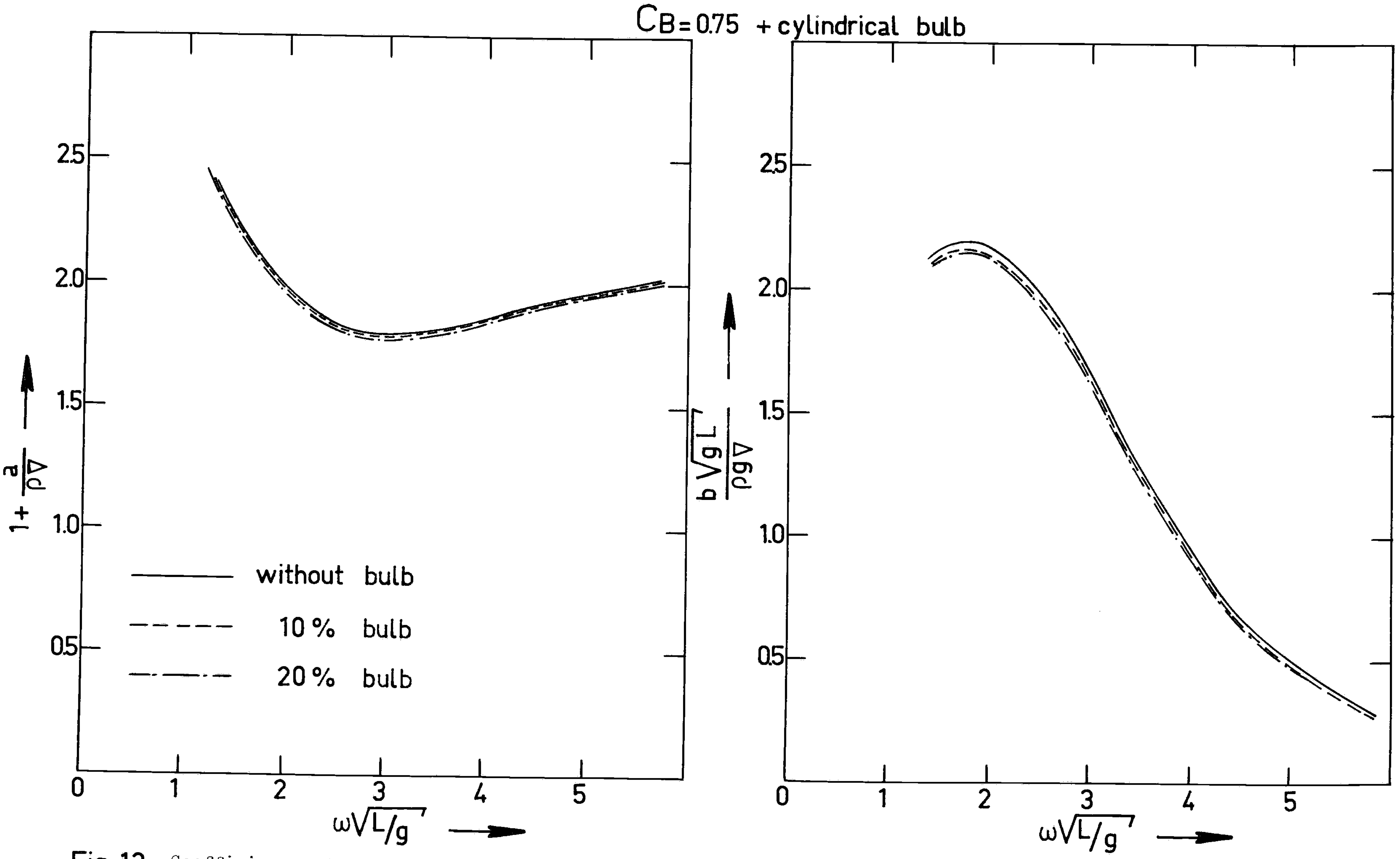


Fig 12 Coefficients of added mass "a" and damping "b" for Fn = 0.20.

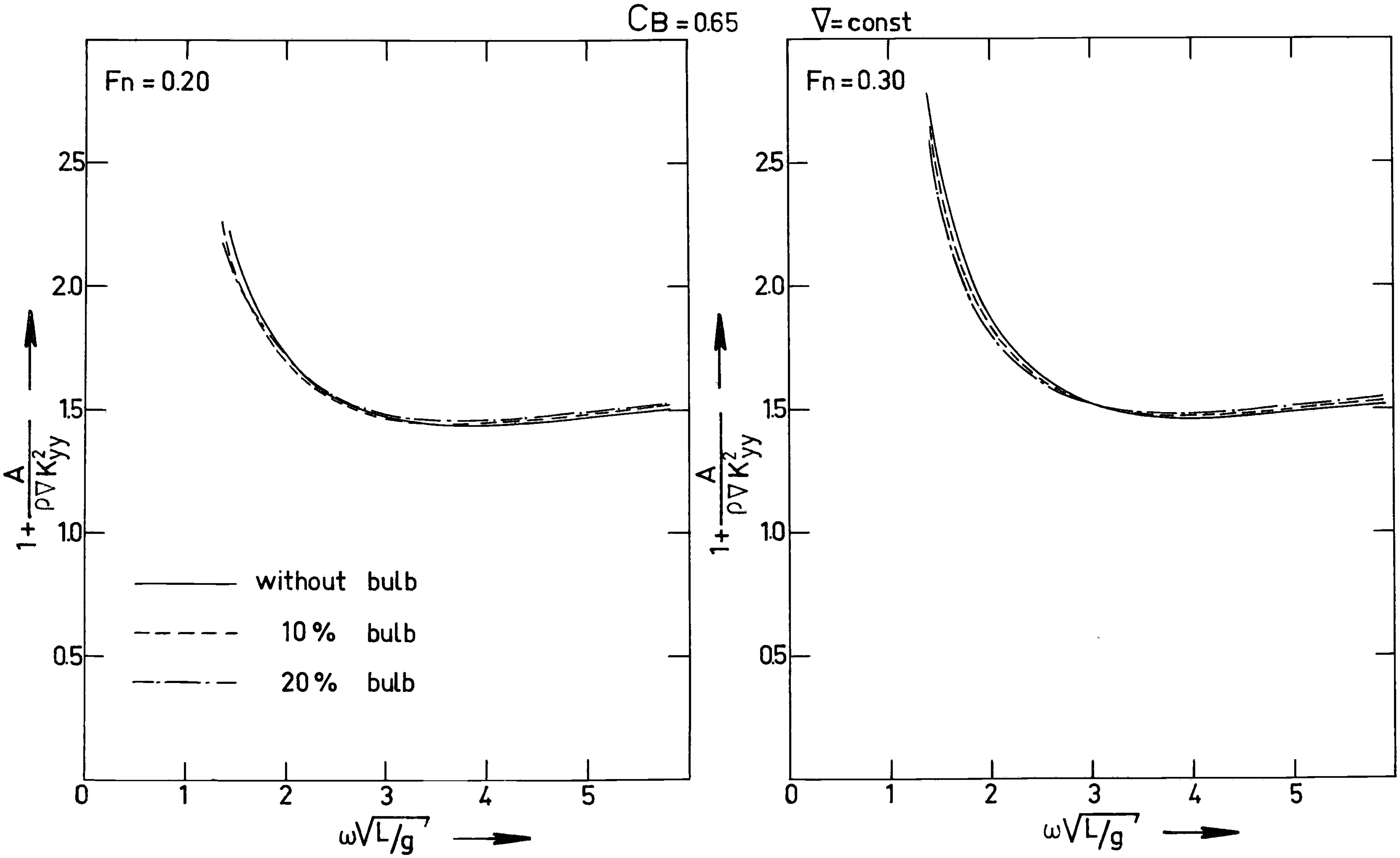


Fig 13 Coefficients of added mass moment of inertia "A".

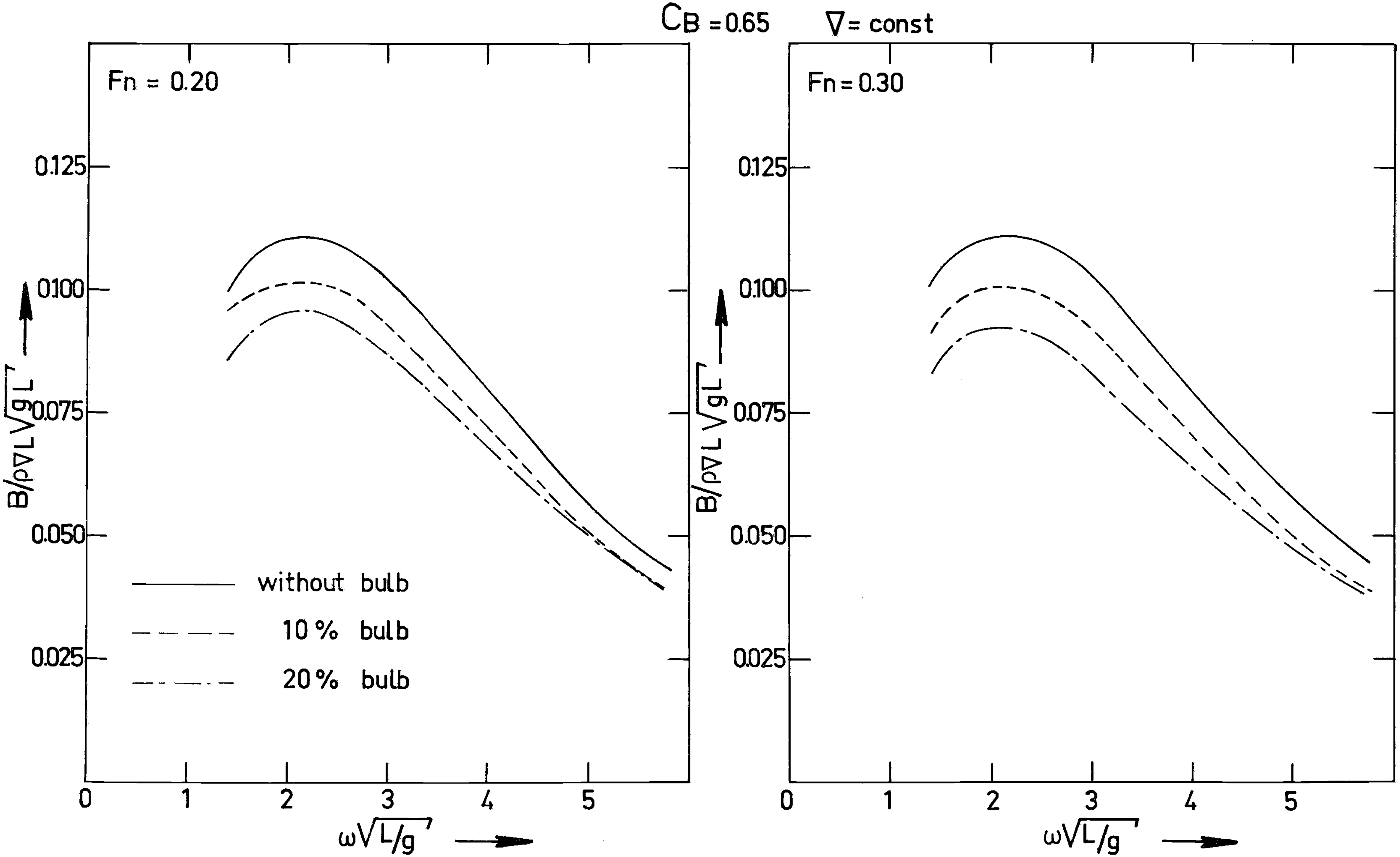


Fig 14 Damping moment coefficients "B".

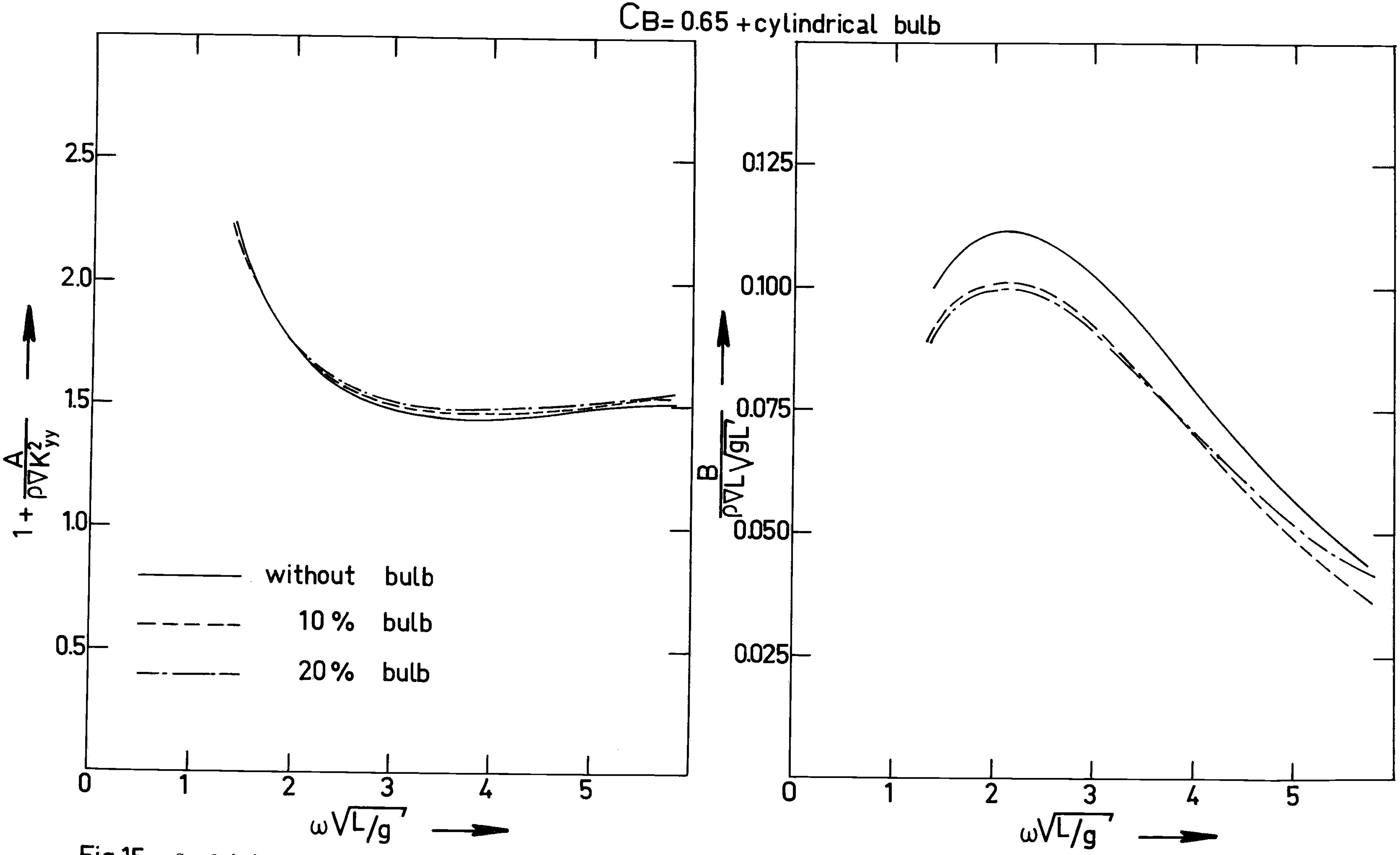


Fig 15 Coefficients of added mass moment of inertia "A" and damping moment "B" for Fn = 0.20.

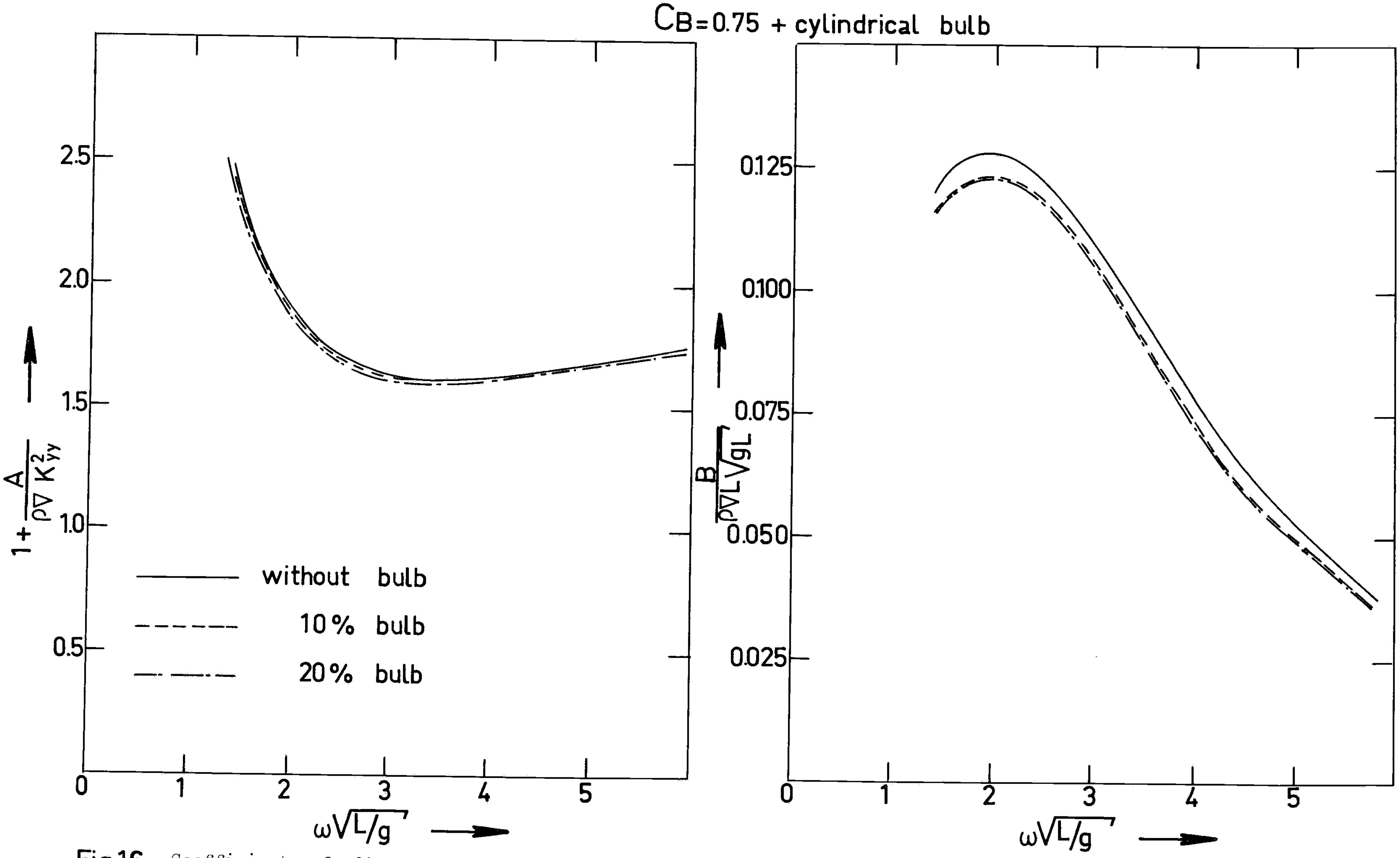


Fig 16 Coefficients of added mass moment of inertia "A" and damping moment "B" for Fn = 0.20.

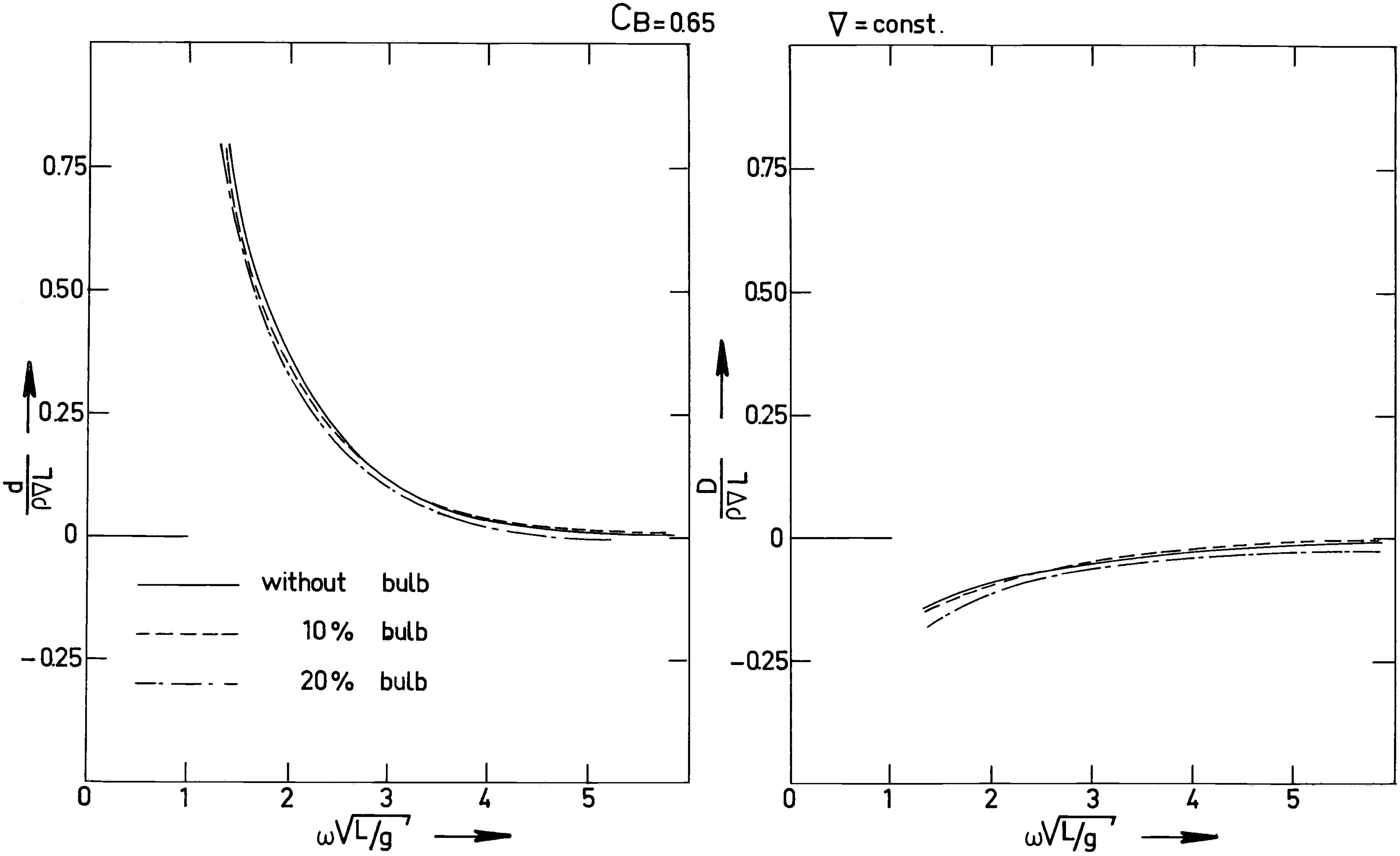


Fig 17 Mass coupling coefficients "d" and "D" for Fn = 0.20.

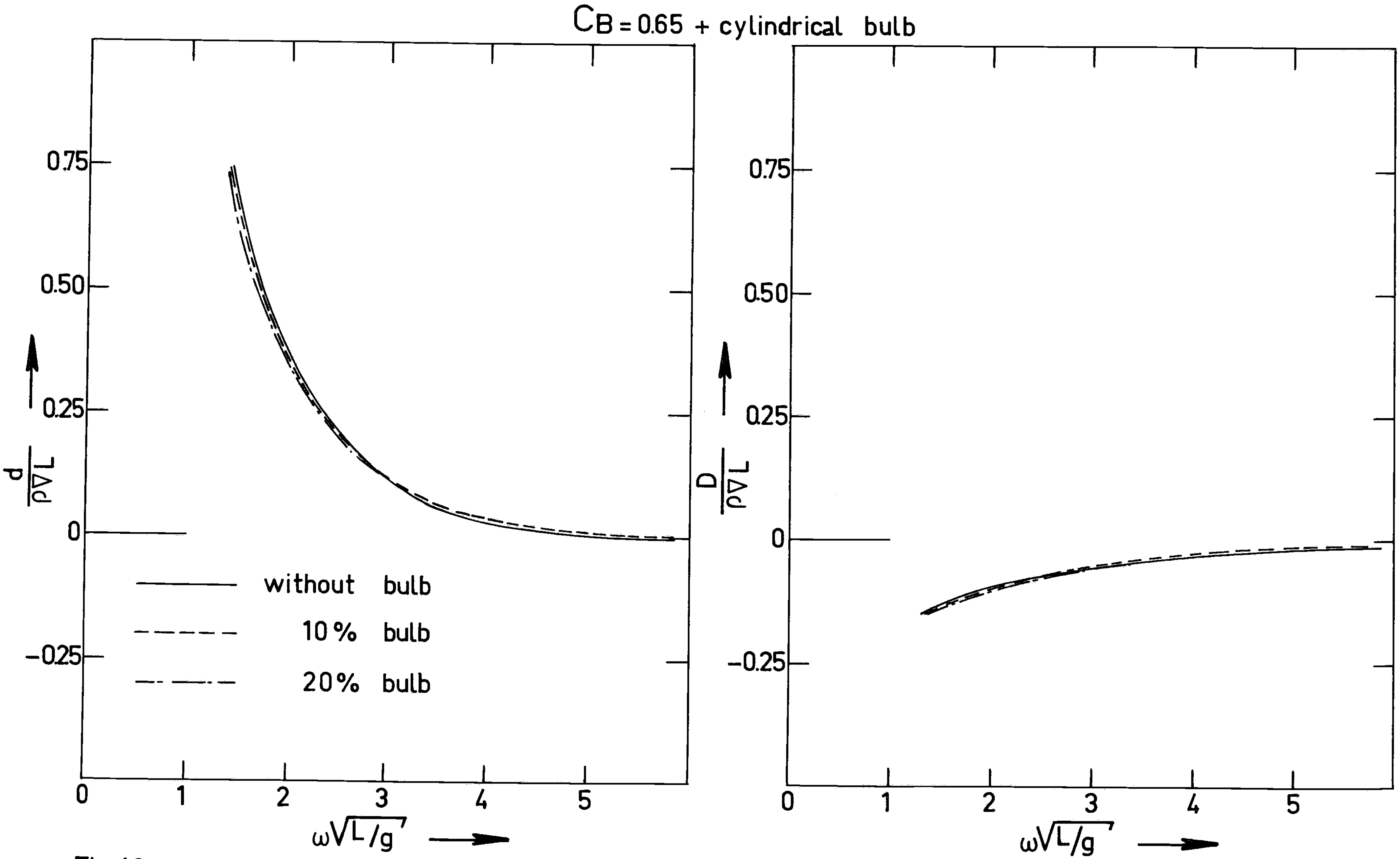


Fig 18 Mass coupling coefficients "d" and "D" for Fn = 0.20.

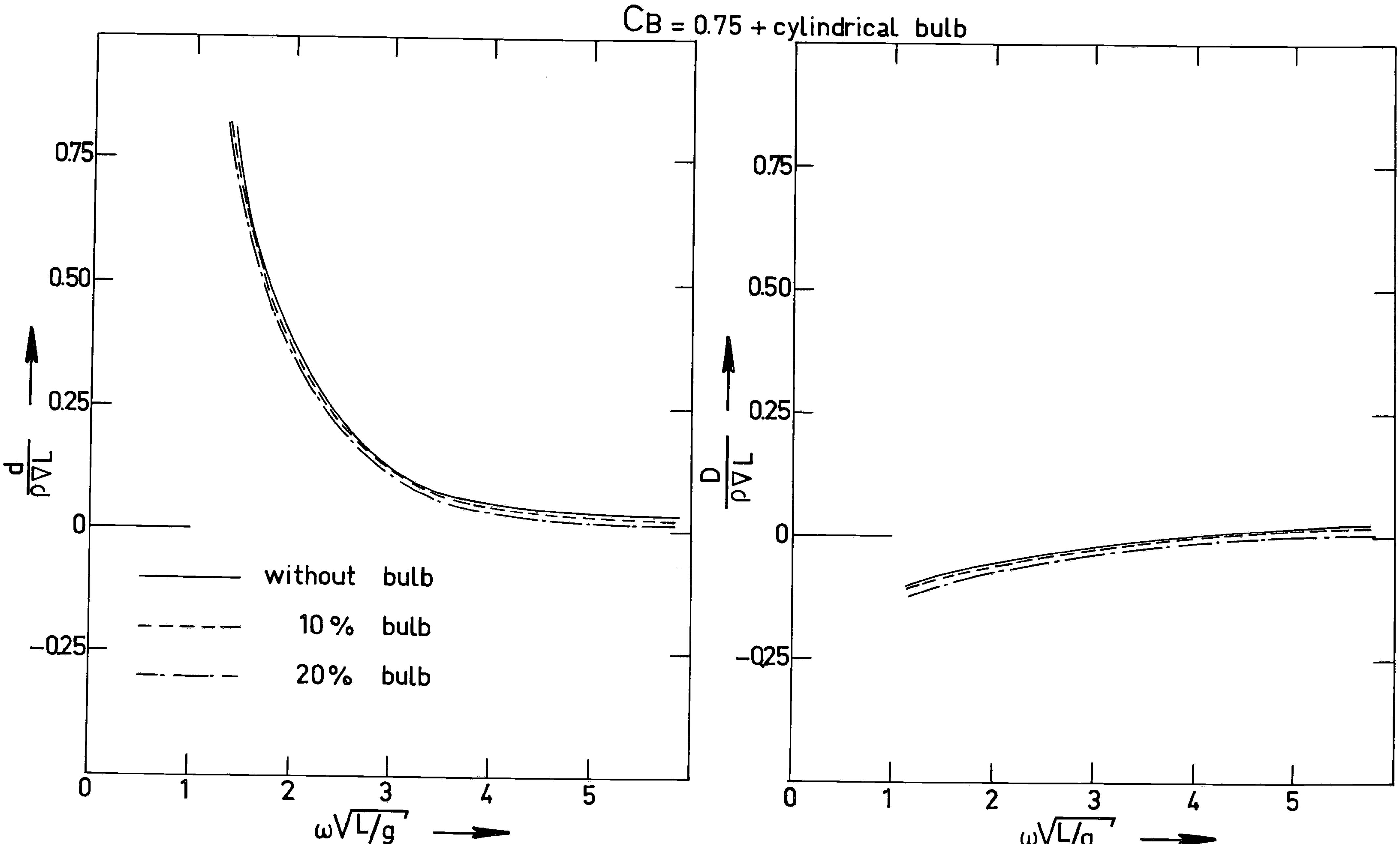


Fig 19 Mass coupling coefficients "d" and "D" for Fn = 0.20.

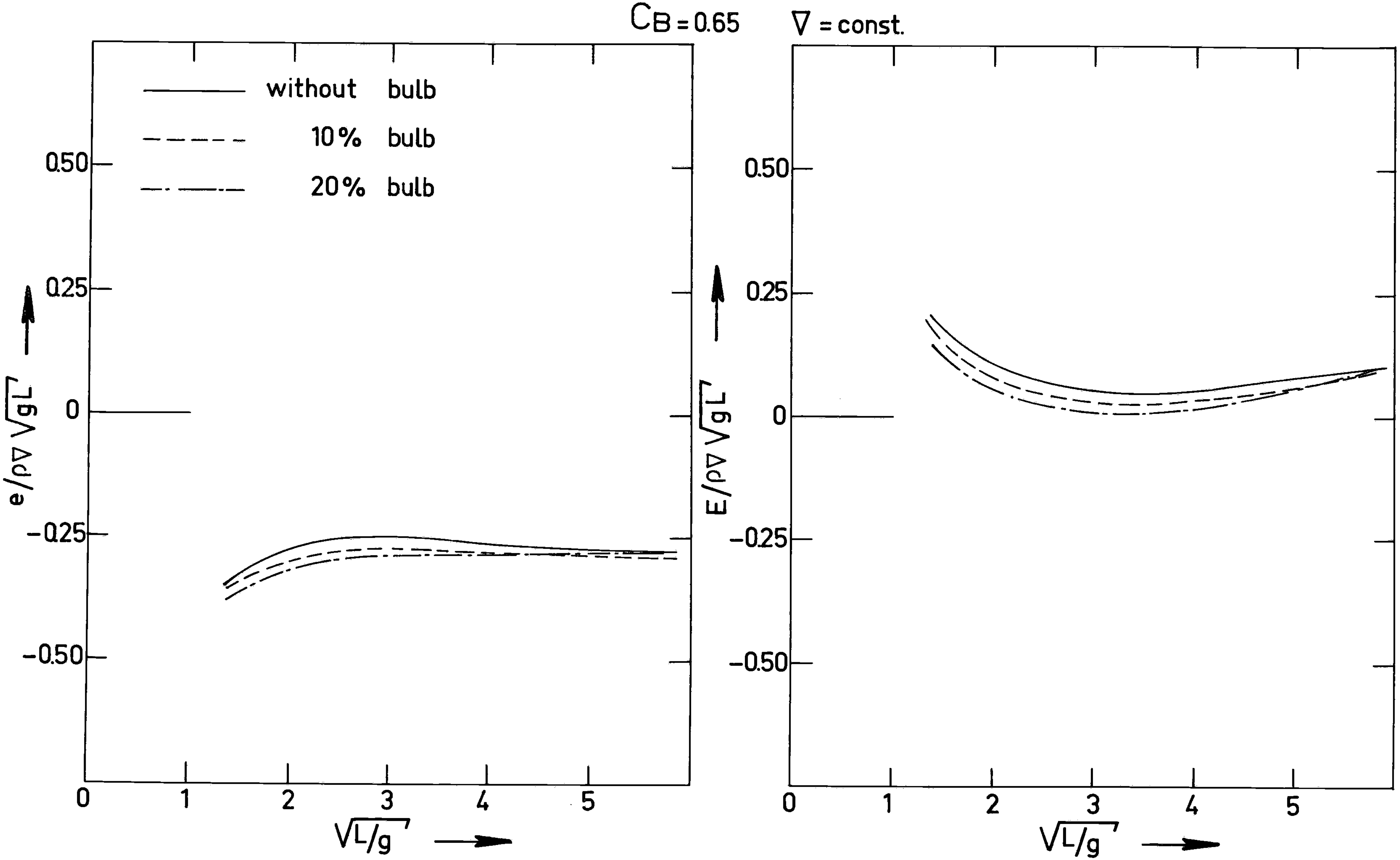


Fig 20 Coupling coefficients for damping "e" and "E" for Fn = 0.20.

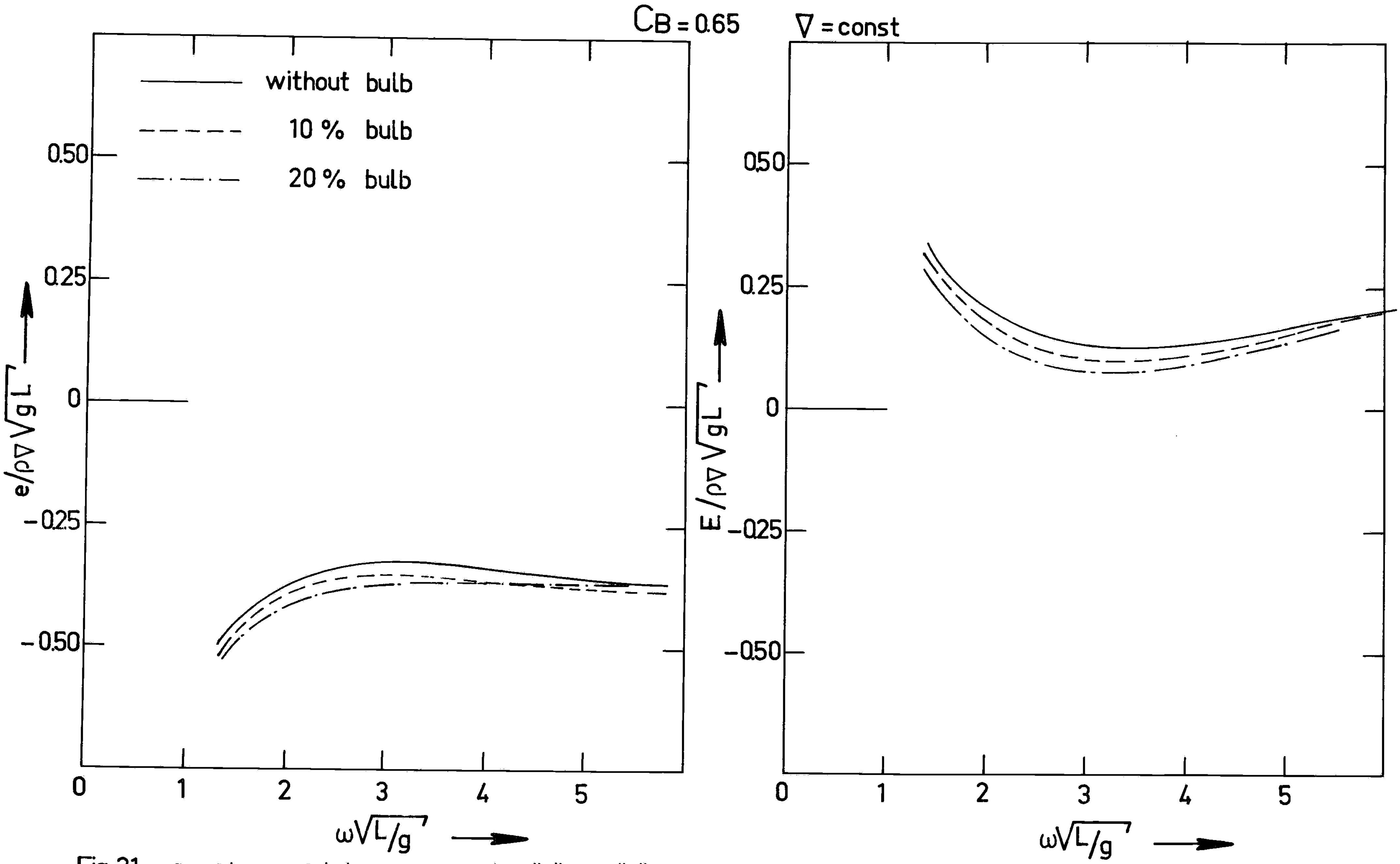


Fig 21 Coupling coefficients for damping "e" and "E" for Fn = 0.30.

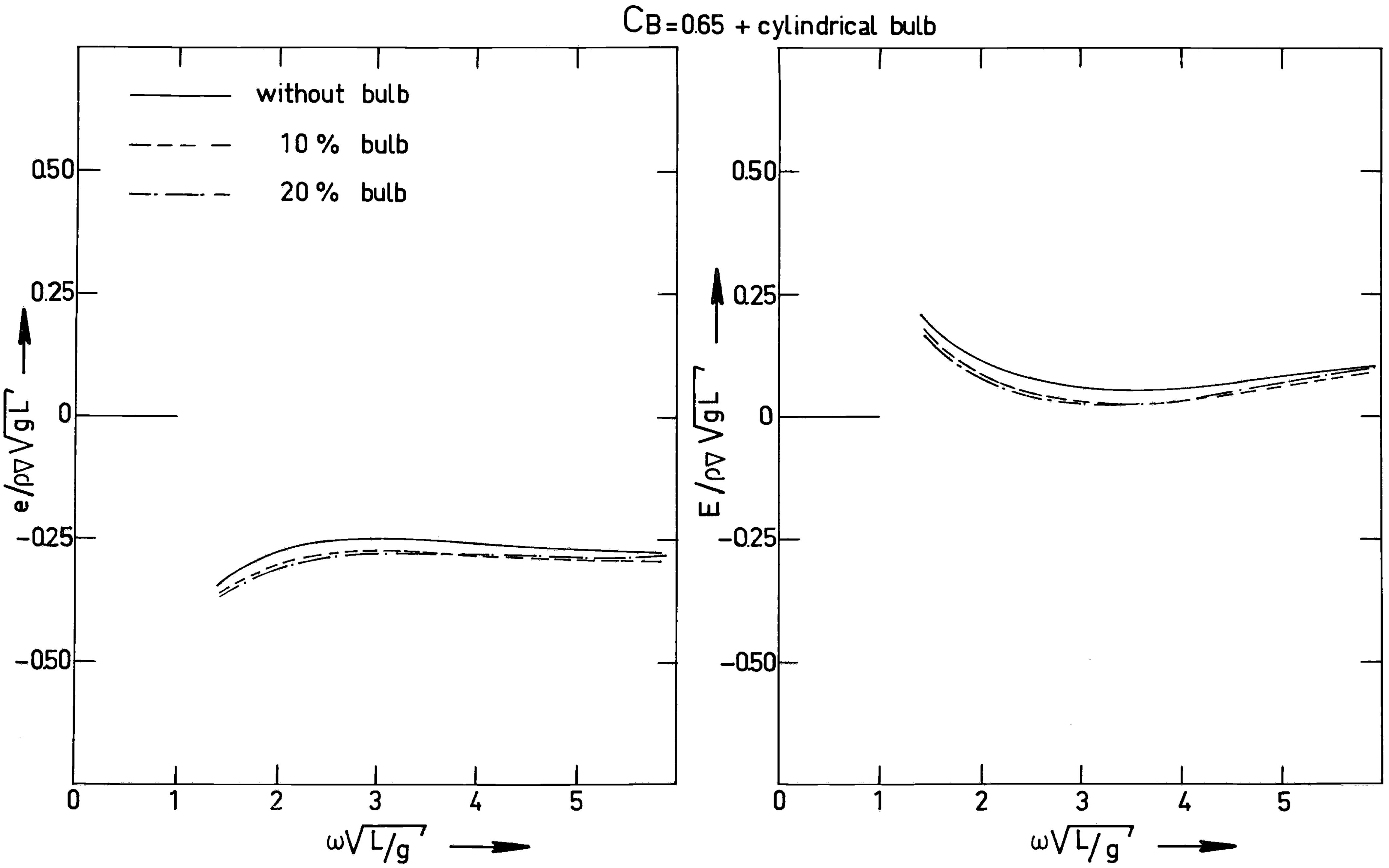


Fig 22 Coupling coefficients for damping "e" and "E" for Fn = 0.20.

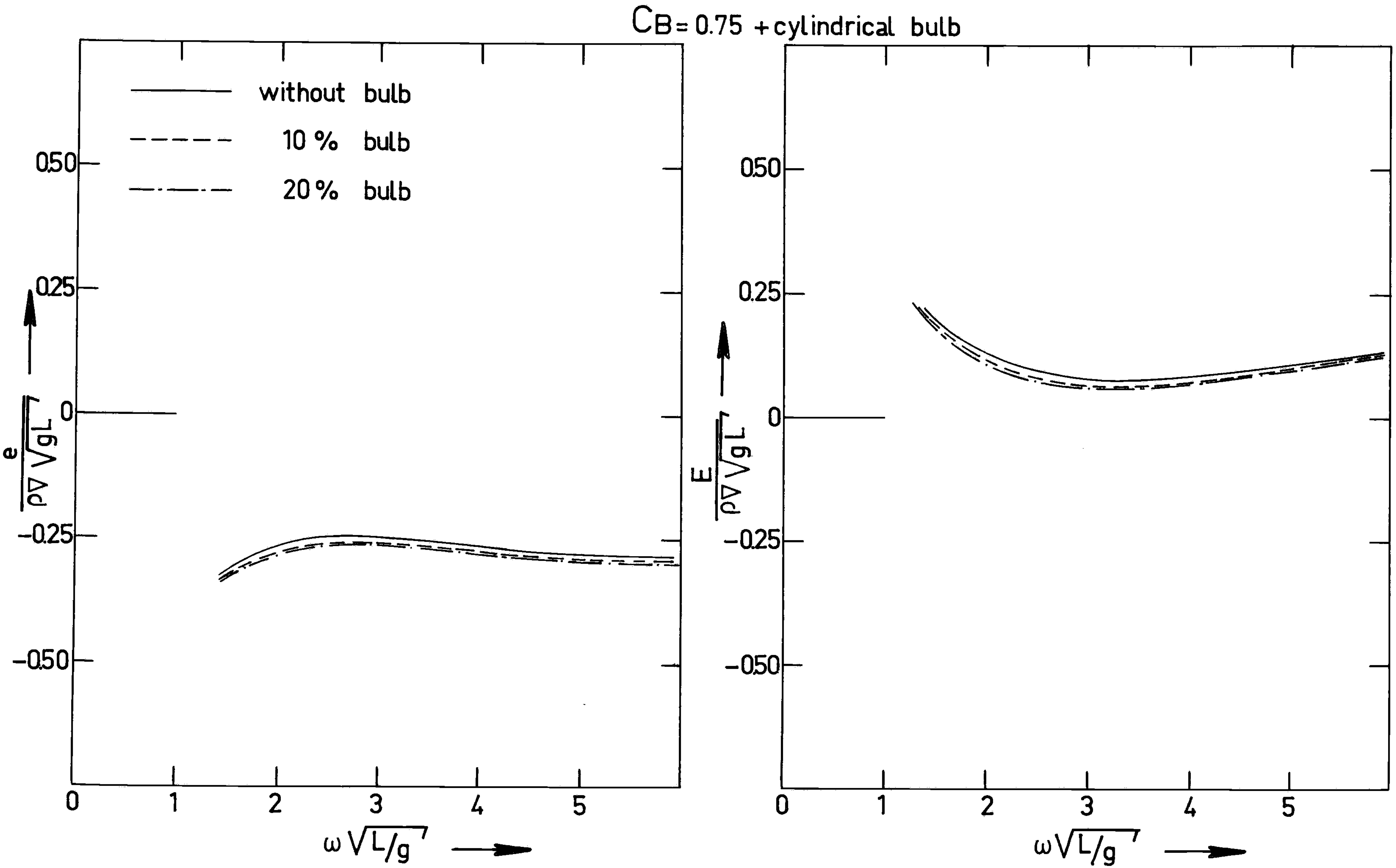


Fig 23 Coupling coefficients for damping "e" and "E" for Fn = 0.20.

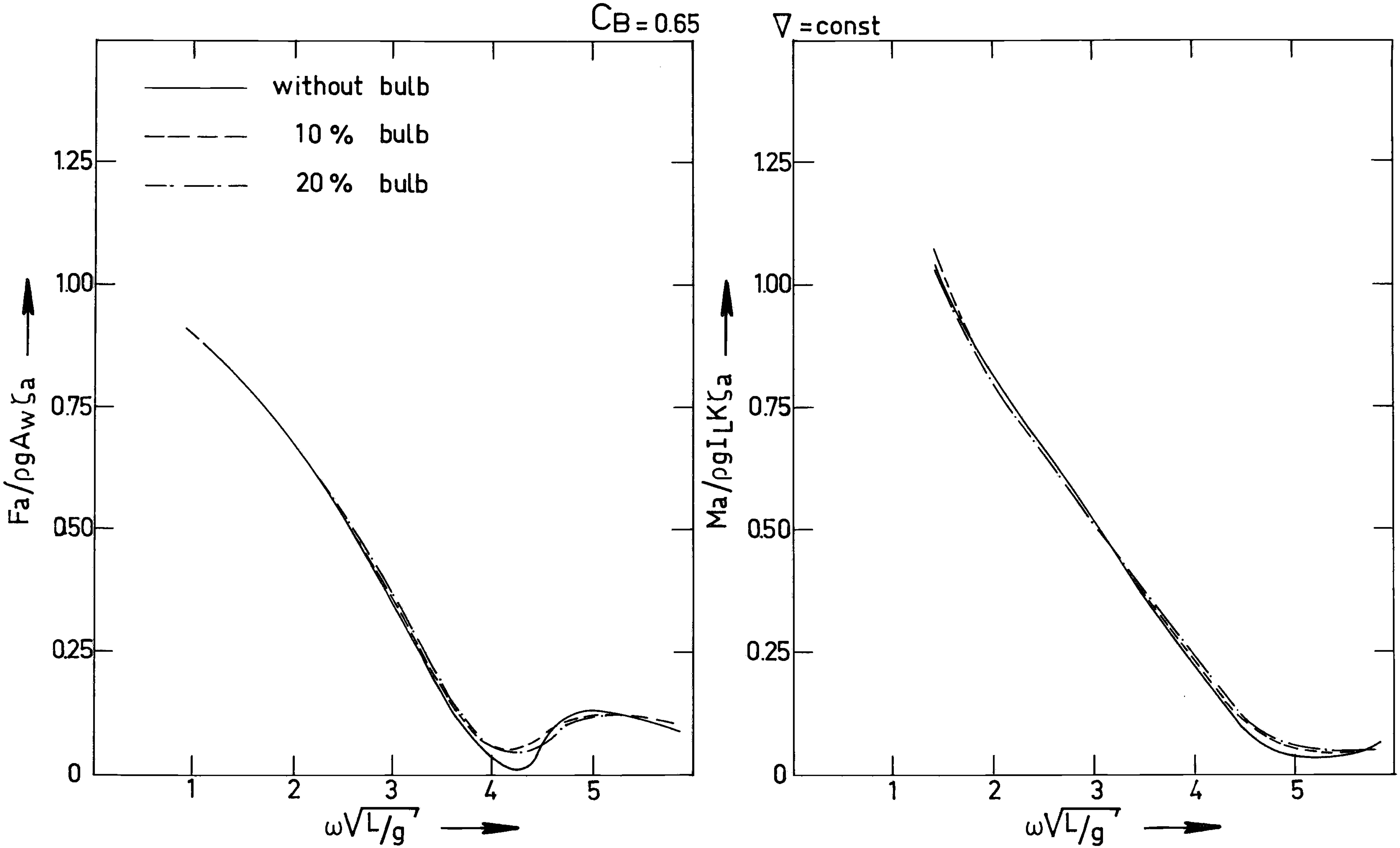


Fig 24 Wave exciting forces and moments for Fn = 0.20.

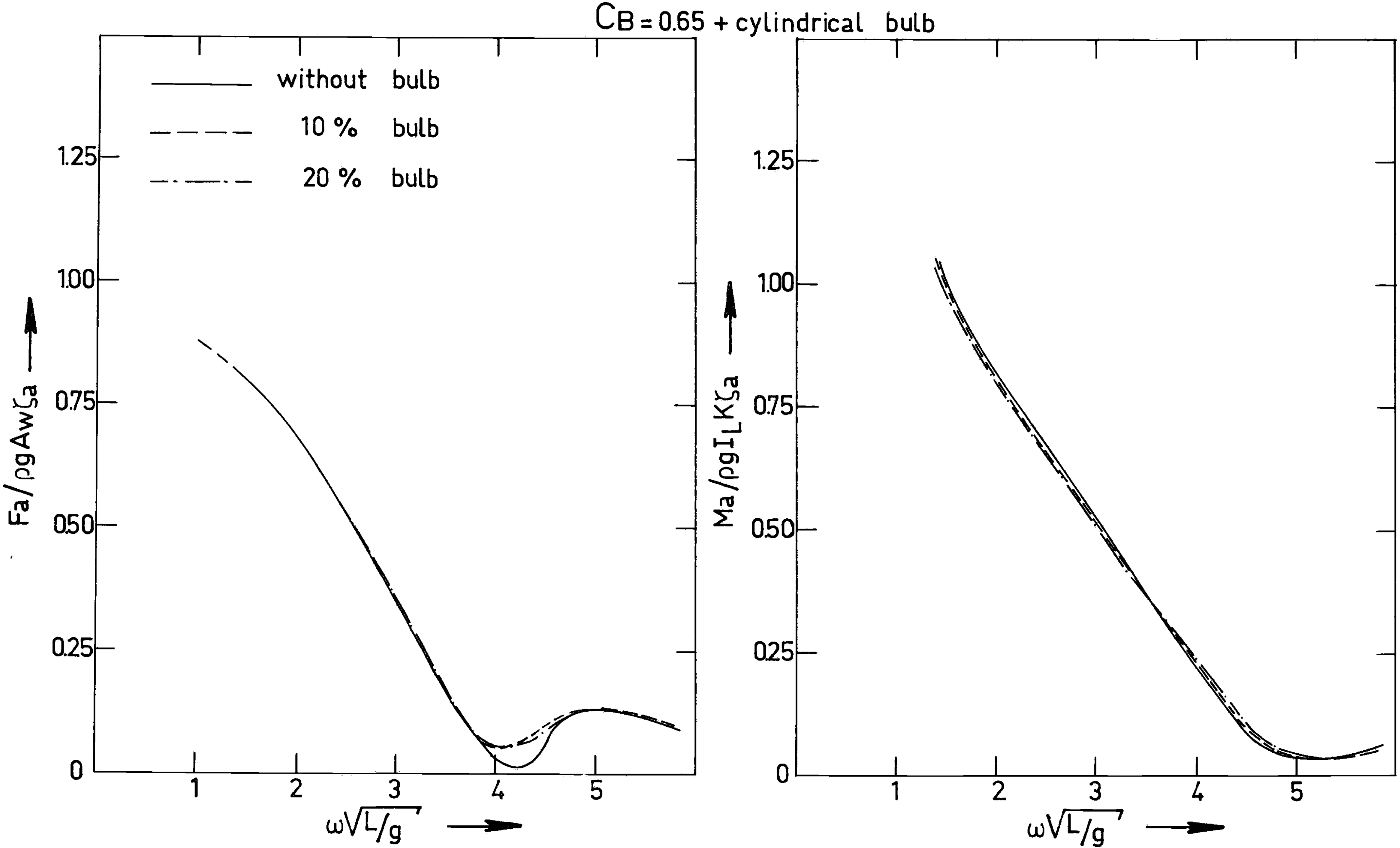


Fig 25 Wave exciting forces and moments for Fn = 0.20.

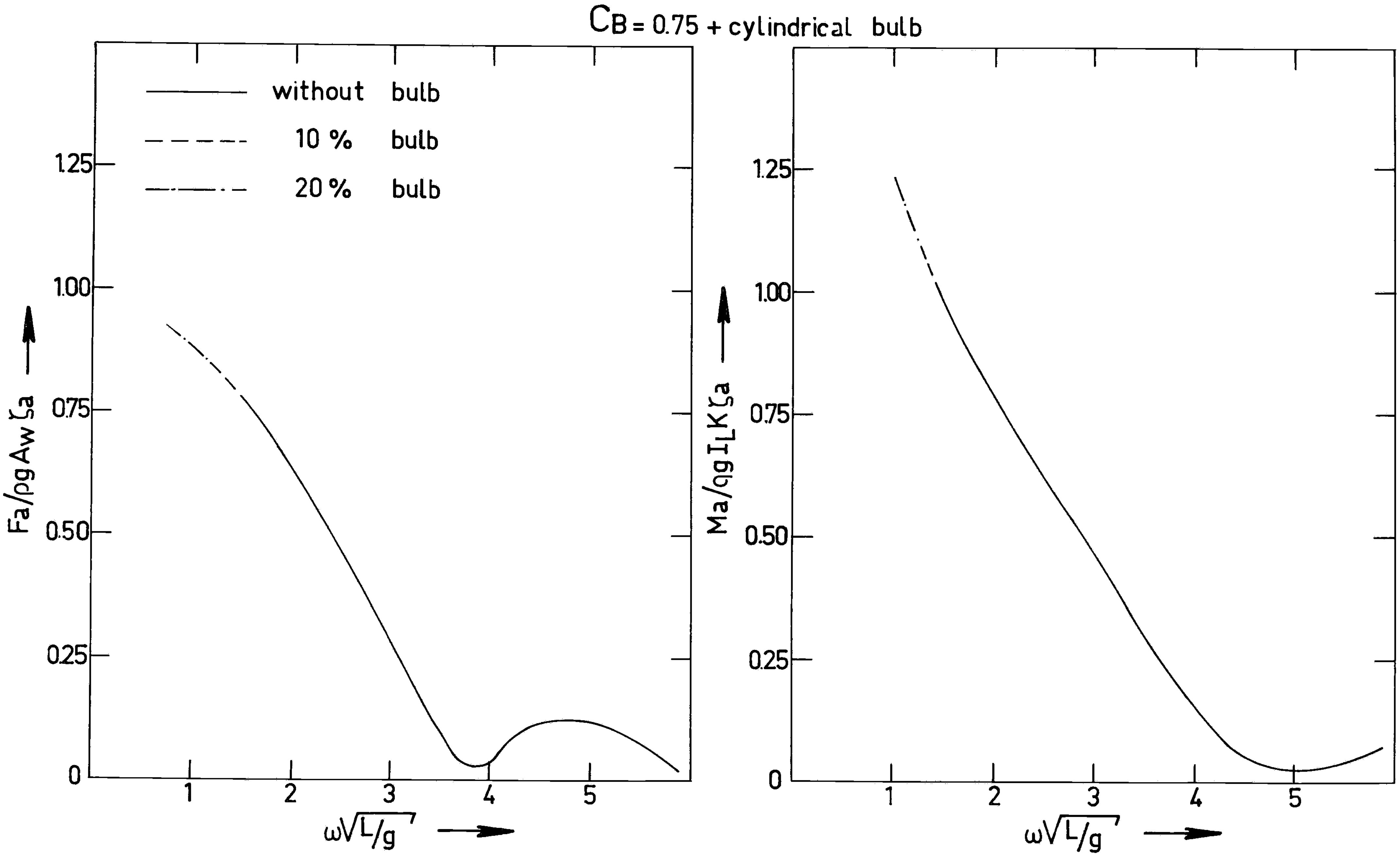


Fig 26 Wave exciting forces and moments for Fn = 0.20.

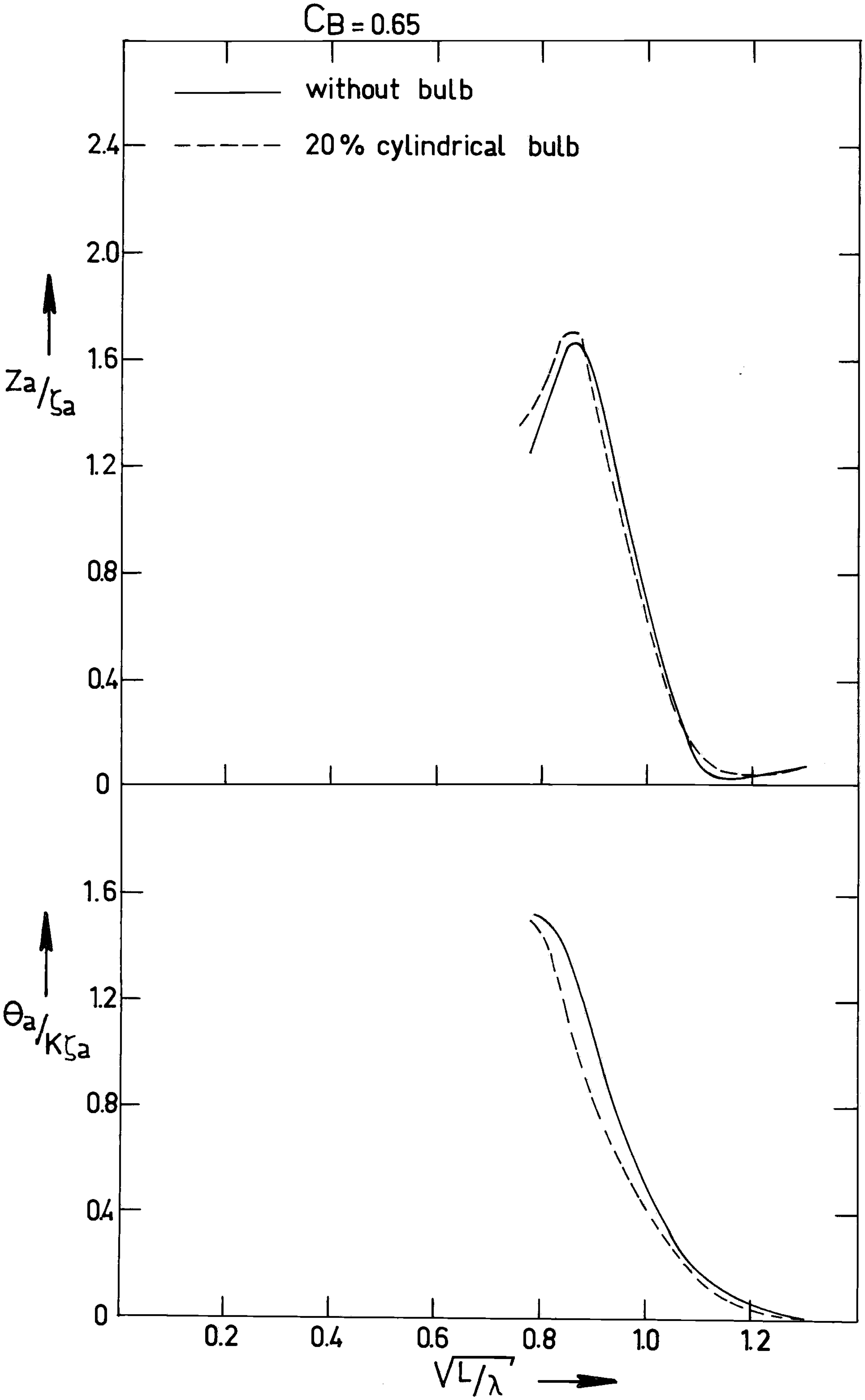


Fig 27 Experimental heave and pitch amplitudes for Fn = 0.25.

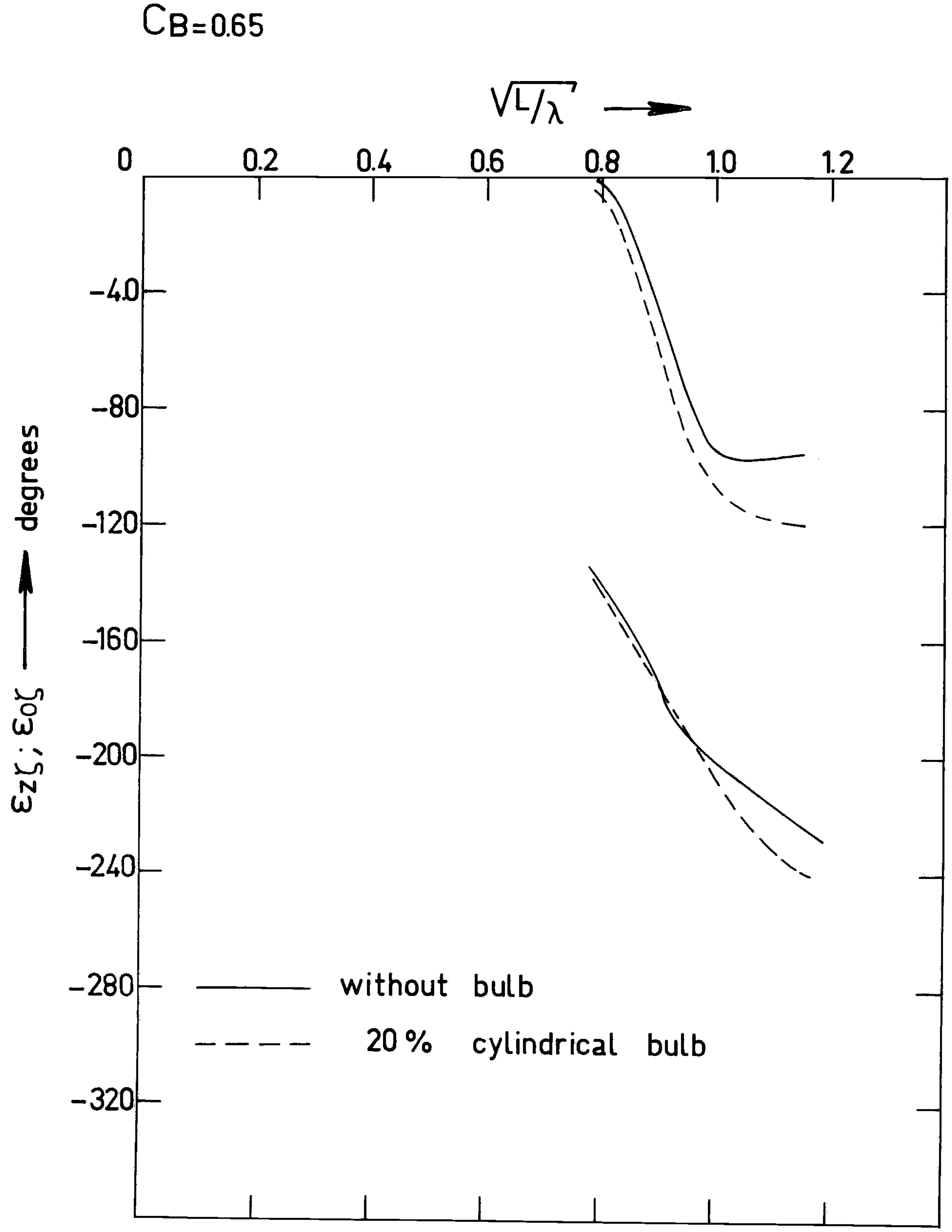


Fig 28 Experimental heave and pitch phases for Fn = 0.25.

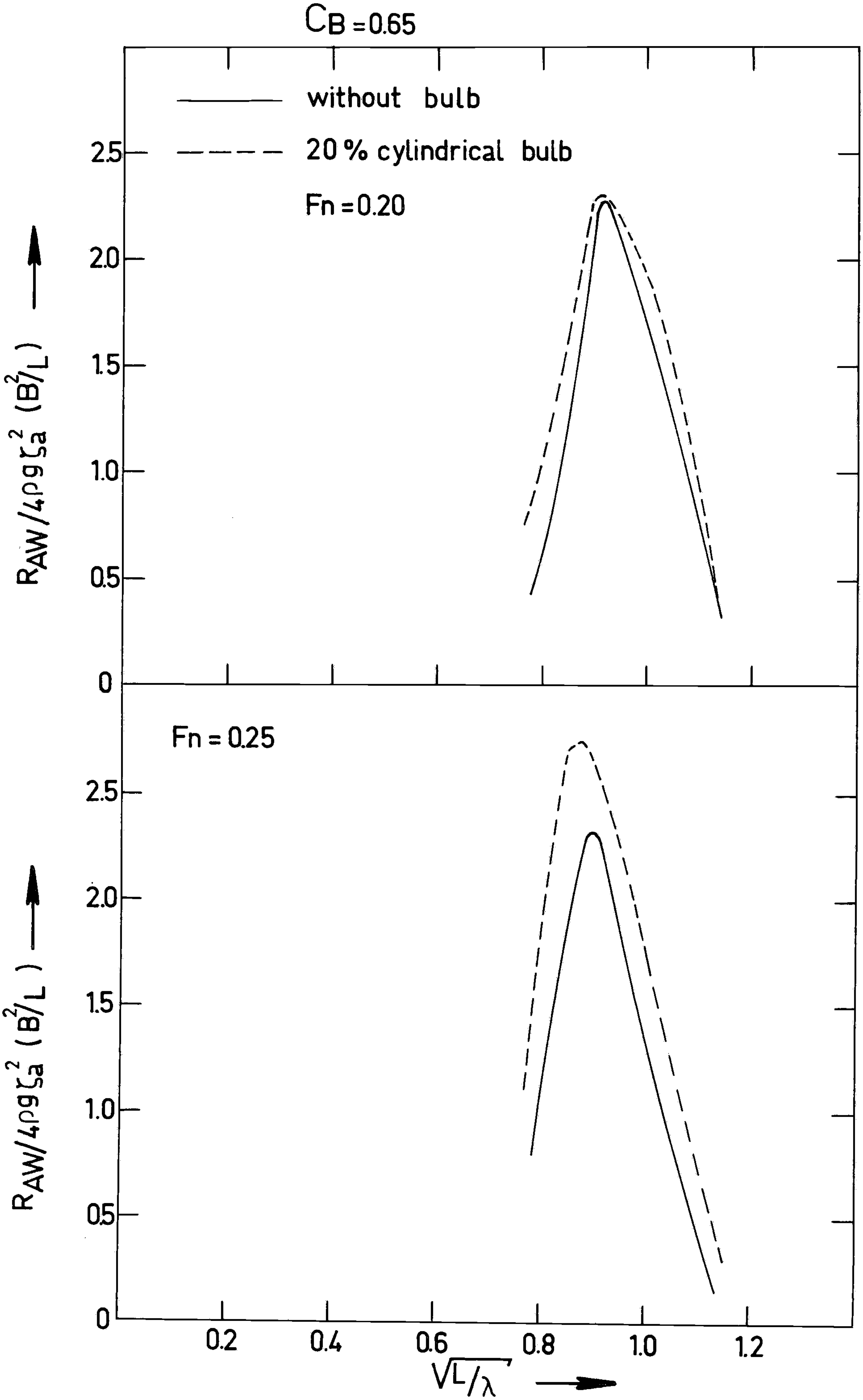


Fig 29 Added resistance in waves.

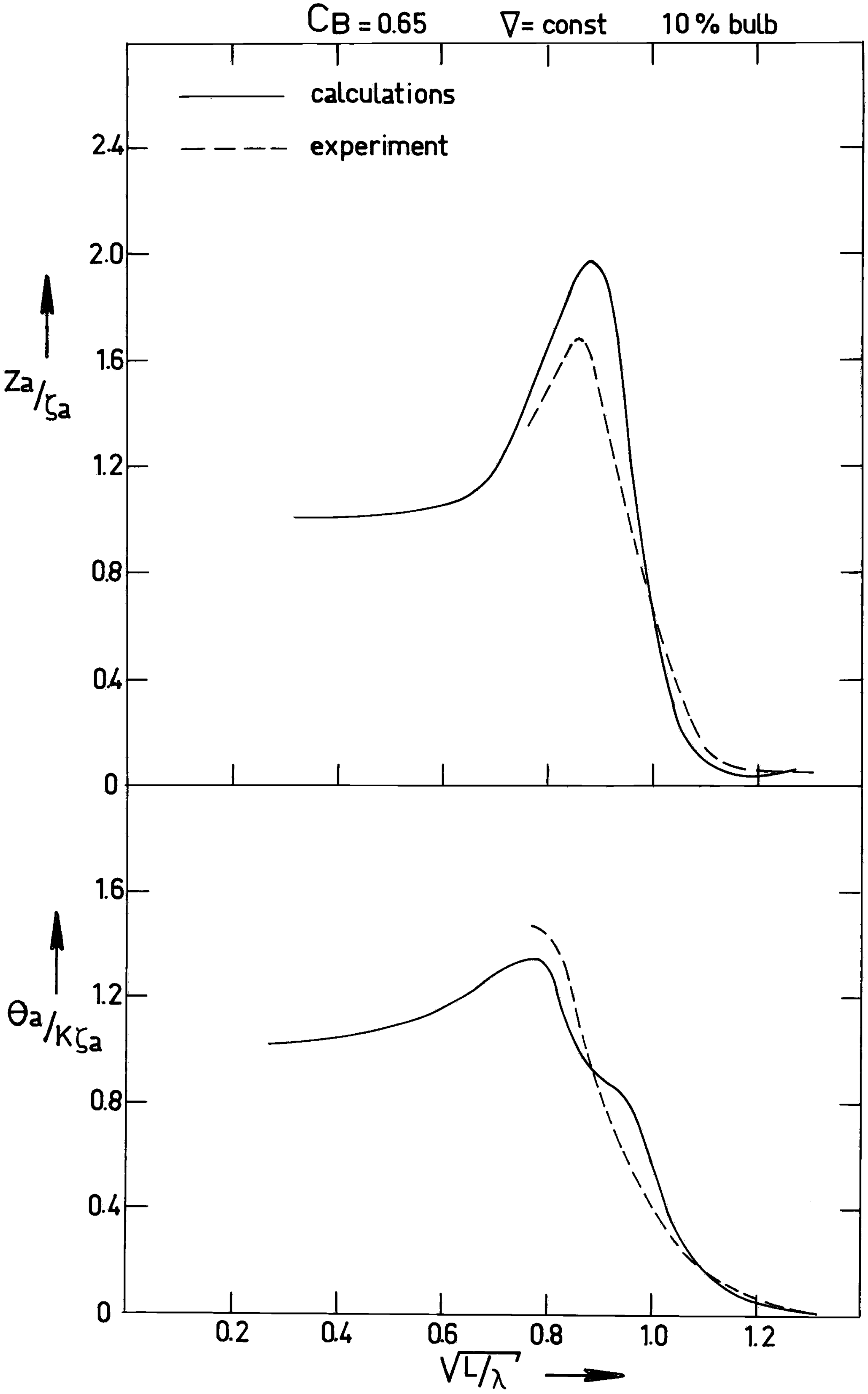


Fig 30 Heave and pitch amplitudes for Fn = 0.25.

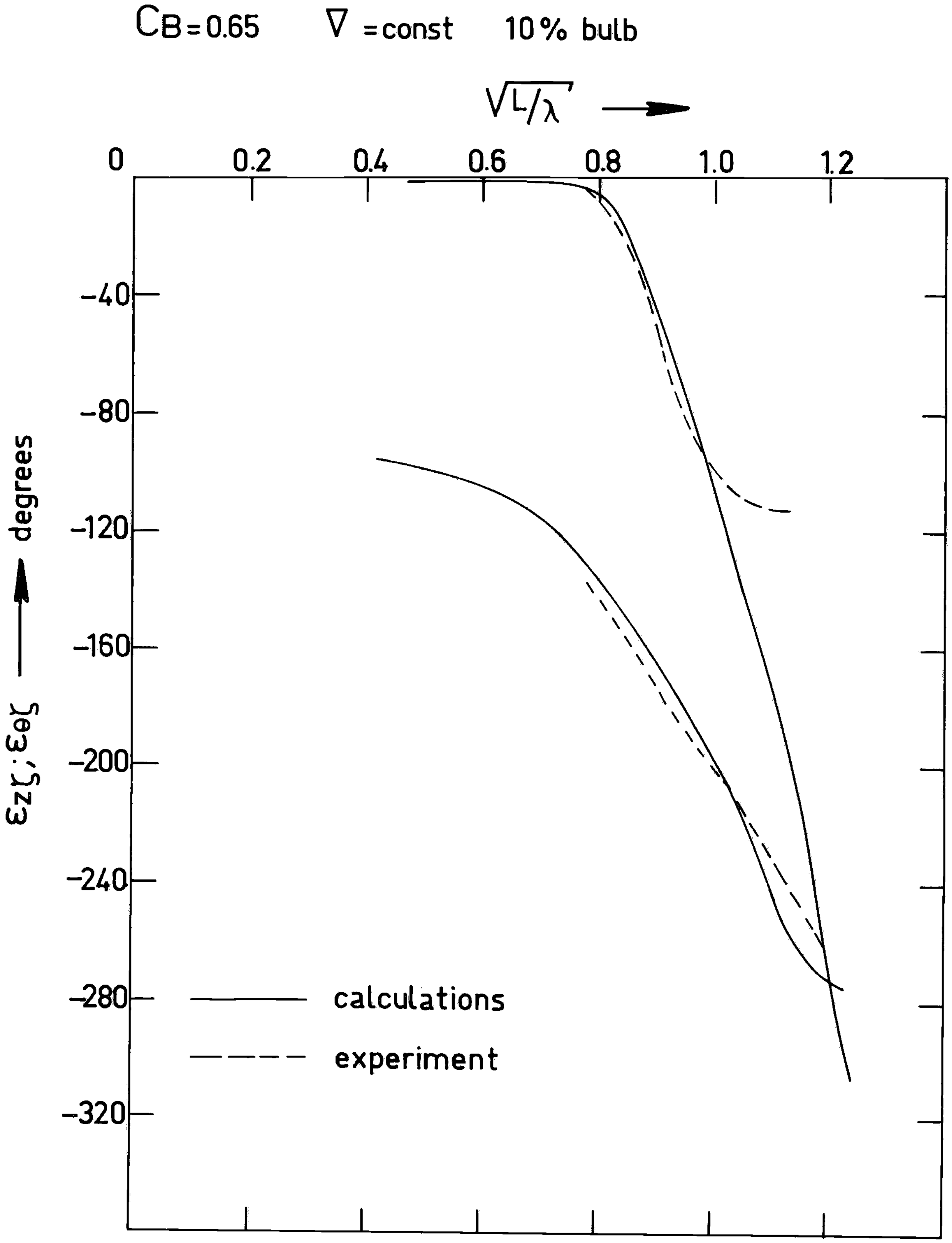


Fig 31 Heave and pitch phases for Fn = 0.25.

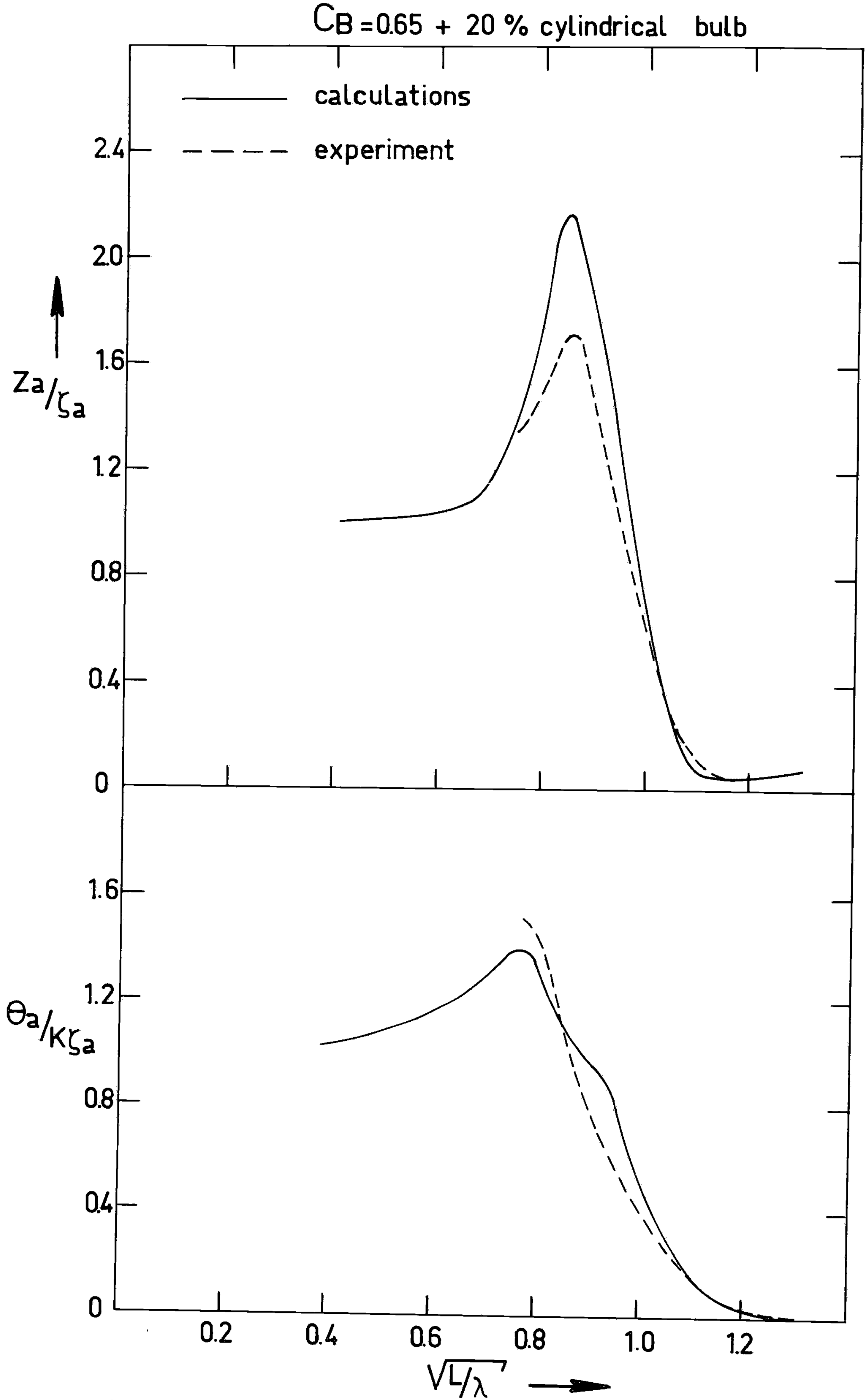


Fig 32 Heave and pitch amplitudes for Fn = 0.25.

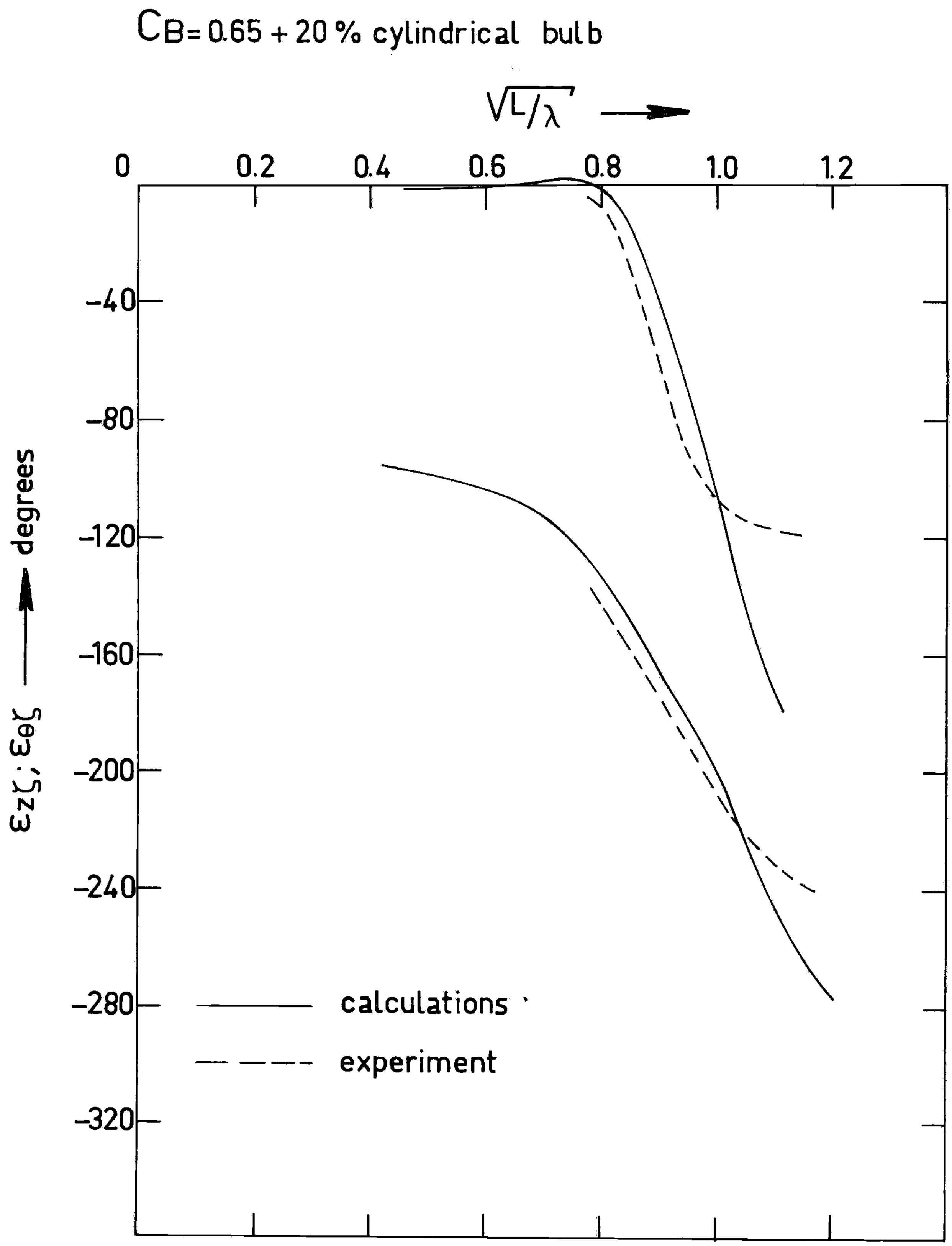


Fig 33 Heave and pitch phases for Fn = 0.25.

(W&S 8226)