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**David W. Taylor Naval Ship Research and Development Center**

Bethesda, MD 20084-5000



DTNSRDC/SPD-1225-01 June 1987

Ship Performance Department

Research and Development



# SURFACE WAVES GENERATED BY SUBMERGED BODIES (U)

by

Dane M. Hendrix

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DTNSRDC/SPD-1225-01 SURFACE WAVES GENERATED BY SUBMERGED BODIES (U)

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| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c. ADDRESS (City, State, and ZIP Code) | 10. SOURCE OF FUNDING NUMBERS |

| PROGRAM ELEMENT NO. | PROJECT NO | TASK NO. | WORK UNIT ACCESSION NO |
|---|---|---|---|
| 61152N | | ZR0230101 | 1542-145 |

11. TITLE (Include Security Classification)

SURFACE WAVES GENERATED BY SUBMERGED BODIES (U)

12. PERSONAL AUTHOR(S) Dane M. Hendrix

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| final | FROM ____ TO ____ | 1987 June | 31 |

16. SUPPLEMENTARY NOTATION

| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Slender Body; Potential Flow; Submarines; Surface Waves; Submerged Body |

19. ABSTRACT (Continue on reverse if necessary and identify by block number)


A computer code to compute surface waves generated by submarines is described. The code, based on slender body theory, treats an axisymmetric submersible as a distribution of constant density source segments along its centerline. The waves generated by a sail can be approximated in a similar manner using the thin ship approximation by positioning several source lines vertically one above the other.

This code was used to compute the height of waves generated by five bare hulls. In addition, the contribution of a typical sail to surface waves was calculated.

Some general observations on the character of submarine-generated waves are made. Wave height, when non-dimensionalized in terms of maximum hull radius, is dependent primarily upon Froude number and depth of submergence. Hull shape affects wave height to a lesser extent in two ways. One effect is local, changing the height of the waves directly over the submarine. The other is to change the height of the regular trailing waves by changing the effective wave-making length. The effect of the sail is found to be small at a large distance; however, there is a noticeable local effect.


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FIGURES

## NOTATION

| | |
|---|---|
| A | Cross sectional area of slender body |
| a,b,c | Constants as defined in text |
| d | Distance from some point to a field point |
| Fn | Froude number, $Uo/\sqrt{gL}$ |
| g | Acceleration due to gravity |
| L | Length of submarine hull |
| M | Source strength |
| r | Maximum radius of submarine hull |
| Uo | Speed of advance |
| x | Longitudinal coordinate |
| $\eta$ | Wave height |
| $\pi$ | Ratio of circumference to diameter |
| $\phi$ | Velocity potential |

## ABSTRACT

A computer code to compute surface waves generated by submarines is described. The code, based on slender body theory, treats an axisymmetric submersible as a distribution of constant density source segments along its centerline. The waves generated by a sail can be approximated in a similar manner using the thin ship approximation by positioning several source lines vertically one above the other.

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## ADMINISTRATIVE INFORMATION

The work described in this report was funded under the Independent Research program, Program Element 61152N, Task Area ZR0230101, and Work Unit 1542-145, at the David W Taylor Naval Ship Research and Development Center.

## ACKNOWLEDGMENTS

The investigation carried out in this program was possible only under the guidance of Dr. Ming Chang. I thank her for her contribution.

# INTRODUCTION

This report describes an efficient method for calculating the waves generated by submerged bodies. The Navy is particularly interested in the prediction of submarine-generated surface wave characteristics (such as wave length and wave height as shown in Figure 1) that pertain to detection by modern sensors. The effects of several factors on wave making were investigated using the prediction method developed to determine which are most important in limiting surface wave size.

# APPROACH

The wave pattern generated by a submarine was investigated analytically by Yim [1]. The waves produced by a submerged body can be readily represented by a summation of the waves generated by a distribution of sources. Slender body theory is used to approximate a bare hull by a distribution of constant strength source segments along the centerline. The waves generated by the source segments are calculated and then summed to give the waves generated by the body.

## SLENDER BODY THEORY

The source strength required by slender body theory is determined by the rate of change of the cross-sectional area with respect to longitudinal distance. That is, the source strength per unit length is

$$M = \frac{1}{4\pi}\frac{dA}{dx} = \frac{r}{2}\frac{dr}{dx} \qquad (1)$$

where A is the cross-sectional area,

x is the longitudinal distance,

and $r$ is the radius of a circular section with area A.

With source strength determined in this manner, a conic bow (one where $r = cx$, c being some constant), would be represented by $M = \frac{1}{2}cx$. In the same way an elliptic bow would yield $M = a\,(b-x)/b$ where, a is the maximum radius and b is the length from the bow to the point of maximum radius, a parabolic bow would result from a constant source strength.

For the sail, source strength per unit profile area, Ms is

$$Ms = \frac{1}{2\pi} \frac{df(x,z)}{dx} \tag{2}$$

where $f(x,z)$ is the offset of the sail surface at point $(x,z)$.

## WAVES GENERATED BY A SOURCE

The linearized wave height on the free-surface due to a constant strength source segment of length 2l centered at (Xo,0,-h) is

$$\eta(x,y) = Uo/g[\phi(x-Xo-l,y,0) - \phi(x-Xo+l,y,0)] \tag{3}$$

where Uo is the speed of advance,

l is the half-length of the source segment,

Xo is the longitudinal location of the segment's center,

h is the depth of submergence,

$f = g/Uo^2$,

and $\phi$ is the potential given by

$$\phi(x,y,0) = \frac{4f}{\pi}\int_0^{\pi/2}\int_0^{\infty} \frac{e^{(\xi h)} \cos(\xi x\cos\theta)\cos(\xi y\sin\theta)}{\xi\cos\theta\cos\theta - f}\, d\xi d\theta$$

$$- 4f\int_0^{\pi/2} e^{(fh\sec\theta\sec\theta)} \sin(fx\sec\theta)\cos(fy\sin\theta\sec^2\theta)\sec^2\theta\, d\theta \tag{4}$$

This formulation can be found in many sources (Wehausen and Laitone[2] for example).

## COMPUTATIONS

A total of five hull forms were investigated at various depths and speeds. Three bow forms shared a conventional axisymmetric afterbody: one a conventional submarine bow form, one an inflected bow and the third a spherical bow. The fourth hull form consisted of the spherical bow and a full stern. The final hull form represented the form a submarine tanker might take. Overall dimensions for this hull were approximated from data presented by Liang [3]. The sail for which calculations were made is 0.40 diameters high and extending from 0.20 L to 0.29 L. Figure 2 shows the profiles of the forms calculated.

## RESULTS

All wave heights and submergences are non-dimensionalized by maximum hull radius, and all wave lengths by hull length. Submergence is measured from the mean free surface to the hull centerline. Speeds are given in terms of Froude number ($Fn = Uo/\sqrt{gL}$) based on hull length.

Figure 3 shows the waves generated along its path of travel by the conventional bowform submerged 2.0 radii (2.0 r) moving at Fn = 0.46. Bow and stern of the submarine are marked by the vertical lines at x = 0.0 and x = 1.0. Figures 1 and 4 are respectively a perspective view and a contour plot for the same case as Figure 3.

Data are shown for the three bow forms with the same afterbody reduced to dimensionless form for comparison. In each of the following figures one parameter is varied independently of the others to show the effect of that parameter on wave characteristics.

Figures 5 through 7 show waves generated by the three bows at three speeds and 3.0 r submergence. Figure 5 shows waves generated by the three bows at Fn = 0.46. This figure shows little difference between the waves generated by the conventional bow and the spherical bow and waves about 5% higher for the inflected bow. Figure 6 shows the same condition except at Fn = 0.31. Here the conventional and inflected bows produce nearly the same waves while the spherical bow yields an increase in wave height of about 32%. Figure 7 shows the same three bows at Fn = 0.22. At this speed, again the conventional and inflected bows produce little difference while the spherical bow's waves are approximately 15% higher than either of the other two.

Figures 8 through 10 show the effect of varying submergence from 1.5 r to 3.0 r on the waves generated by the submarine with the conventional bow at three Froude numbers. At Fn = 0.46 (Figure 8), the maximum wave height was about 0.54 r with the submarine submerged 1.5 r and about 0.32 r when submerged 3.0 r. At Fn = 0.31 (Figure 9), the maximum wave height was about 0.30 r at 1.5 r and about 0.12 r at 3.0 r submergence. At Fn = 0.22 (Figure 10), the maximum waves were about 0.08 and 0.04 r at 1.5 and 3.0 r submergence. Maximum wave height is approximately an exponential function of submergence,

$$\eta = ae^{-(bc)} \tag{5}$$

where $\eta$ is wave height,

c is depth of submergence,

and a and b are positive factors dependent on the Froude number and hull geometry.

Figures 11, 12, and 13 show the effect of varying speed from Fn = 0.46 to 0.22 for submergences of 1.5, 2.0, and 3.0 r. These plots show wave height to be approximately proportional to speed squared, that is:

$$\eta = a\,Fn^{2} \tag{6}$$

where a is dependent on submergence and geometry. This approximation ignores the effects of constructive and destructive interference between the bow and stern waves. These effects are small for bodies with a fine entrance and run, a condition satisfied by most submarine hull forms.

Figures 14, 15, and 16 compare the submarine with a sail to the bare hull at three speeds for 2.0 r submergence. At Fn = 0.46 (Figure 14), the difference due to the sail is negligible. At Fn = 0.31 (Figure 15), the effect of the sail is seen only in the waves directly over the submarine. At Fn = 0.22 (Figure 16), there is a strong effect in the region directly over the submarine; however, this effect is exhibited as only a slight phase shift in the far field with little change in amplitude.

Less extensive calculations were made for the remaining hull forms. These calculations supported the results presented when non-dimensionalized in the same manner.

## CONCLUSIONS

The waves generated by a submerged body can be thought of as consisting of a local part which dies out not far from the body generating it, and a trailing far field effect which is proportional to $1/\sqrt{d}$, where d is the distance from the source generating the waves to the waves themselves. Wave height, when expressed in terms of hull diameter, is found to be dependent primarily upon Froude number and depth of submergence.

Bow shape has a local effect on wave height; however, the fullness of both the bow and the stern also affect the effective wave making length. By affecting the wave making length, bow and stern shape change the amplitude of the trailing regular waves. A less full bow or stern are less sensitive to speed changes and so produce smaller waves under most conditions than a fuller body of the maximum cross-section. Another way of thinking of this is that change in cross-sectional area causes waves. If the wave source is distributed, there will be more small waves combining rather than a few large waves which are less likely to cancel each other. The total displacement affects the waves formed only indirectly through the maximum cross-section of the hull and the length between wave-making centers.

The far field effect of the sail is found to be small, but there is a noticeable local effect due partly to the sail being closer to the surface than the rest of the submarine.

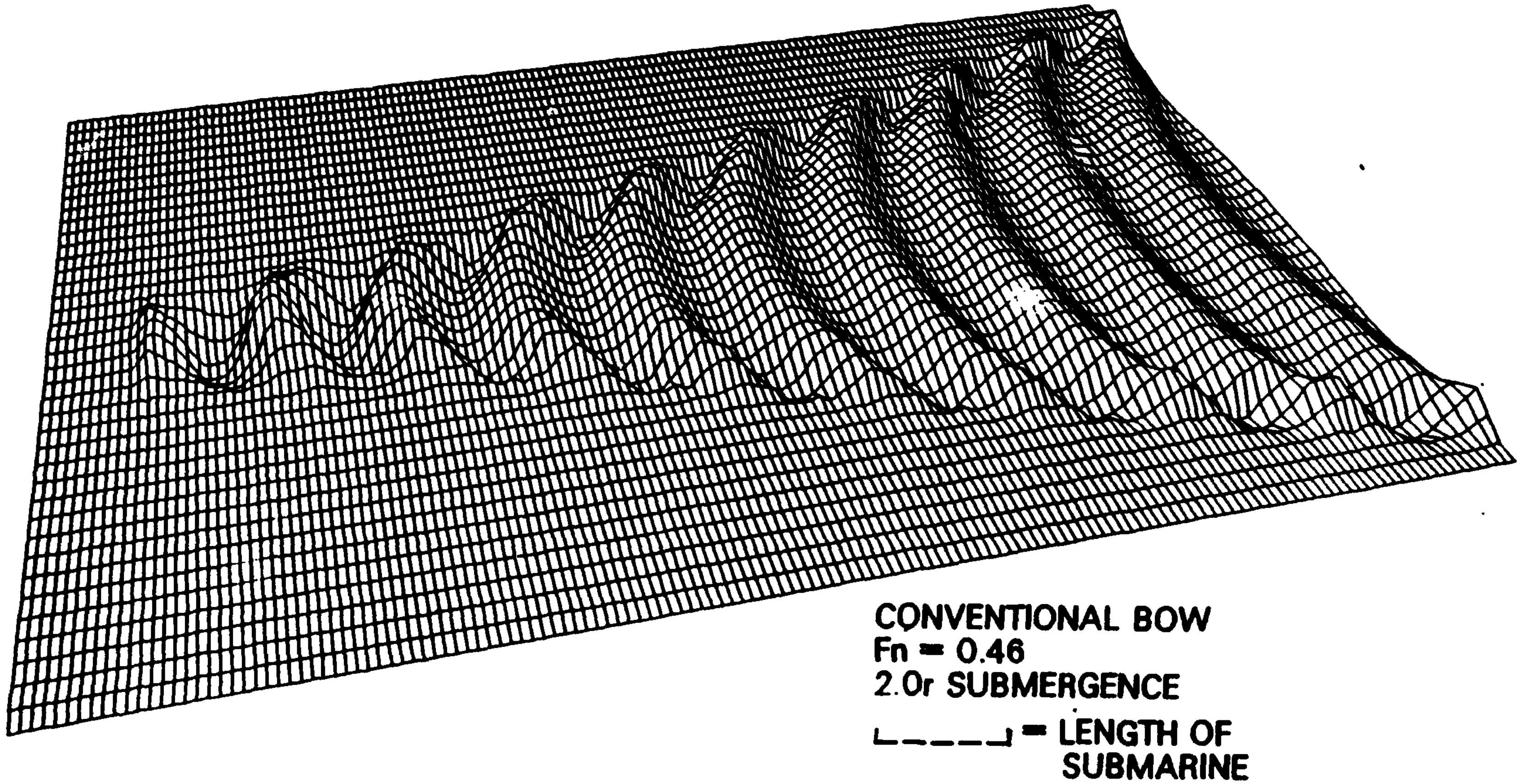


Fig. 1. Wave field generated by a submerged body.

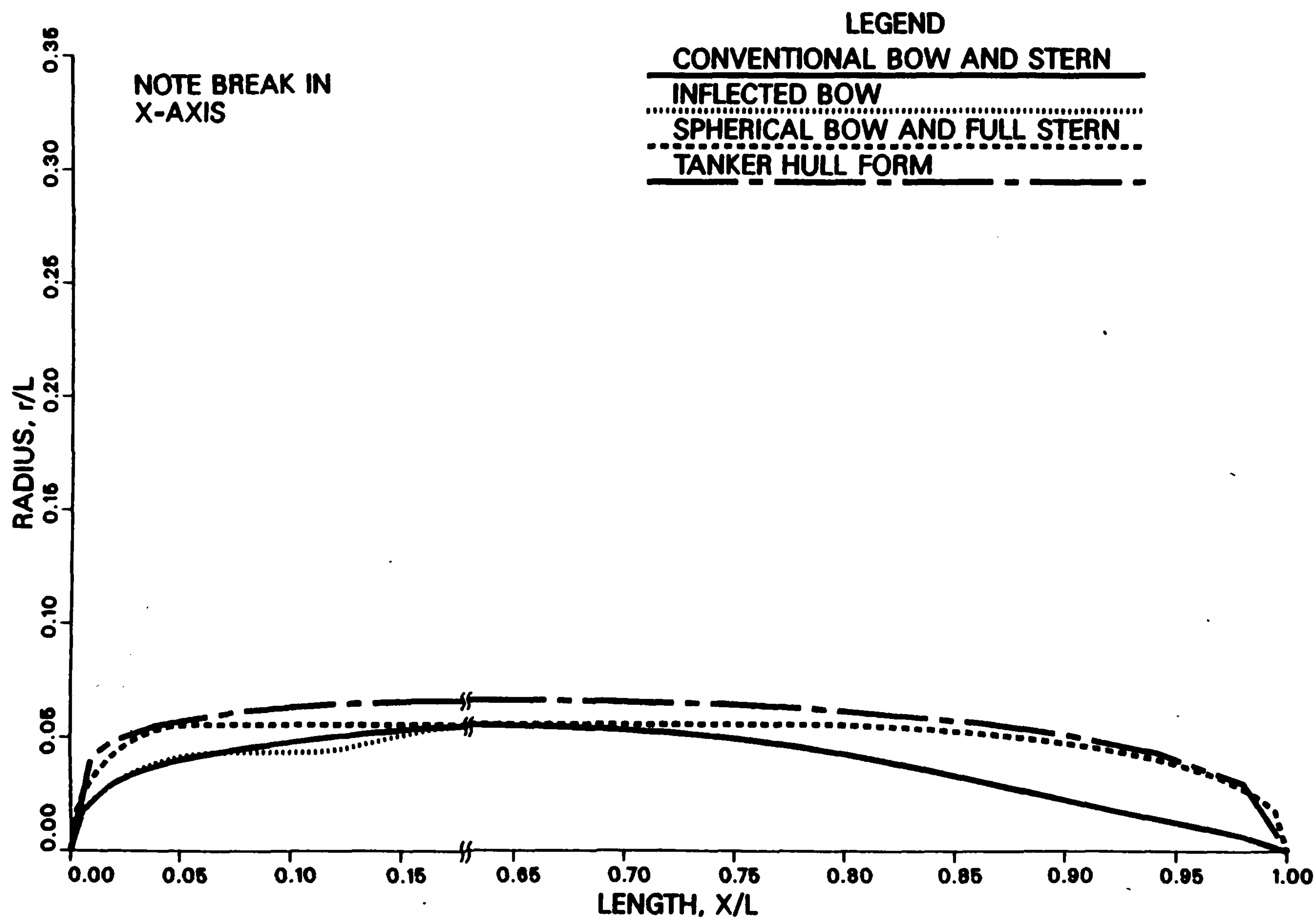


Fig. 2. Hull forms investigated.

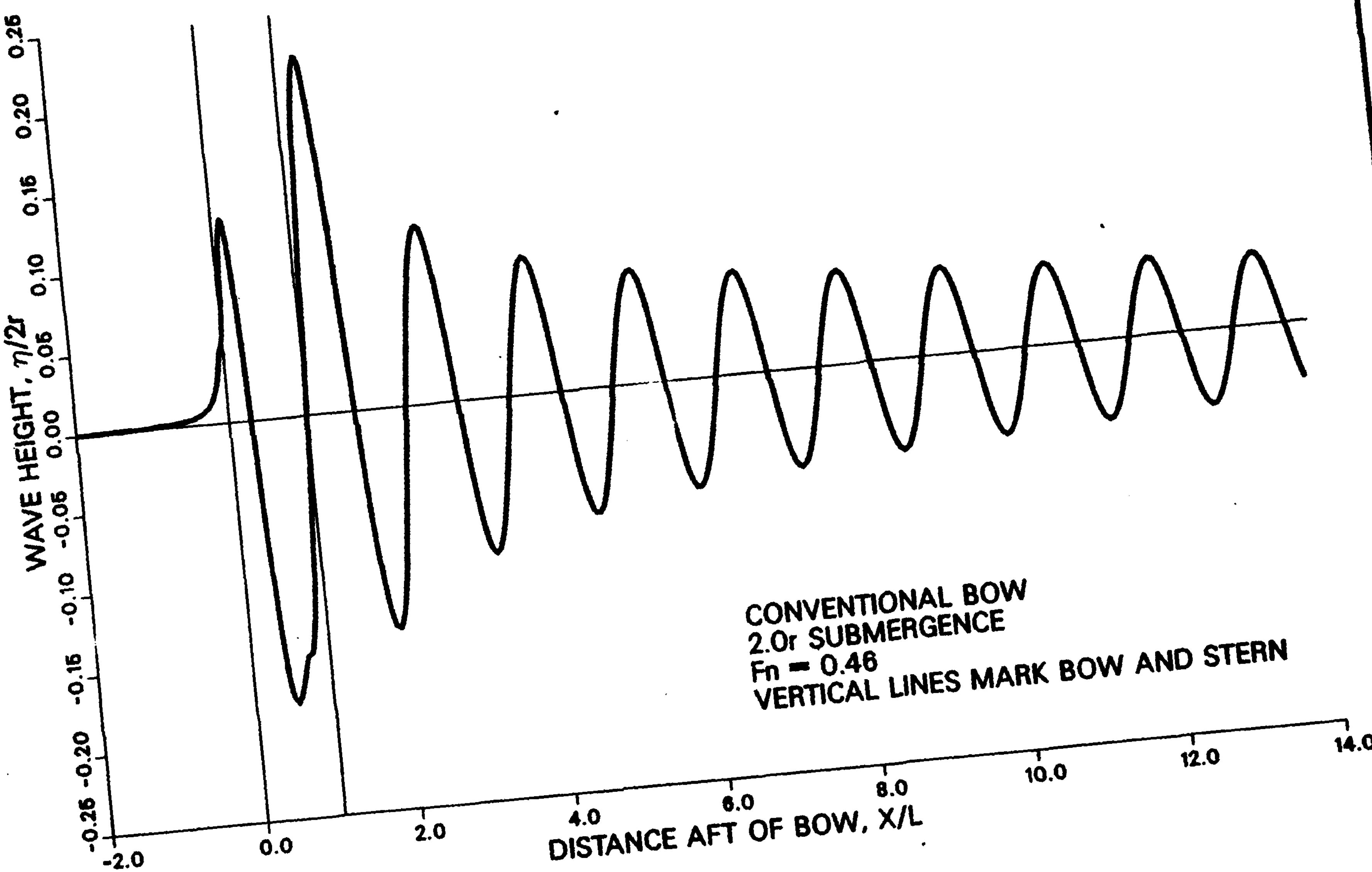


Fig. 3. Wave height along centerline.

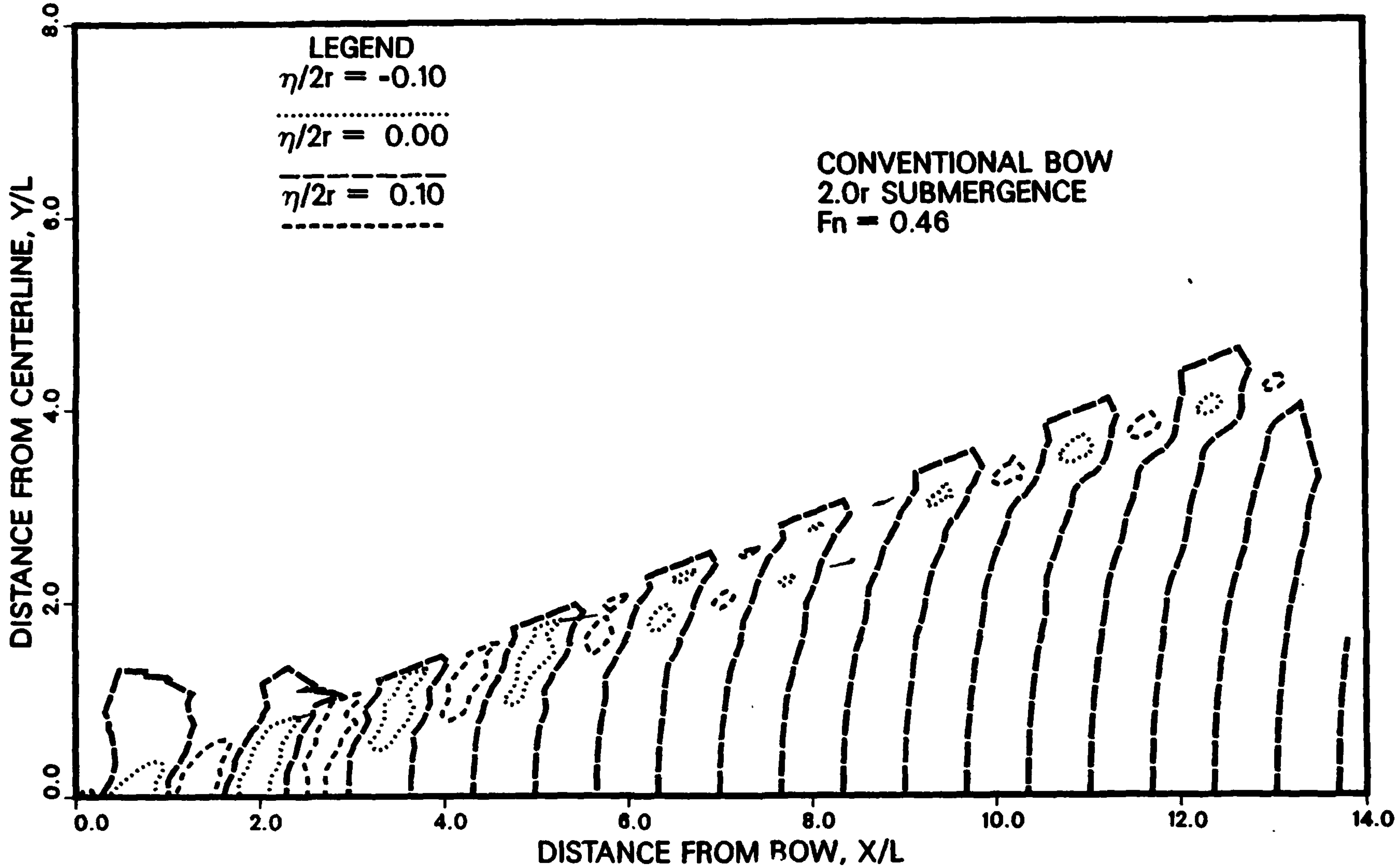


Fig. 4. Contour plot of wave field.

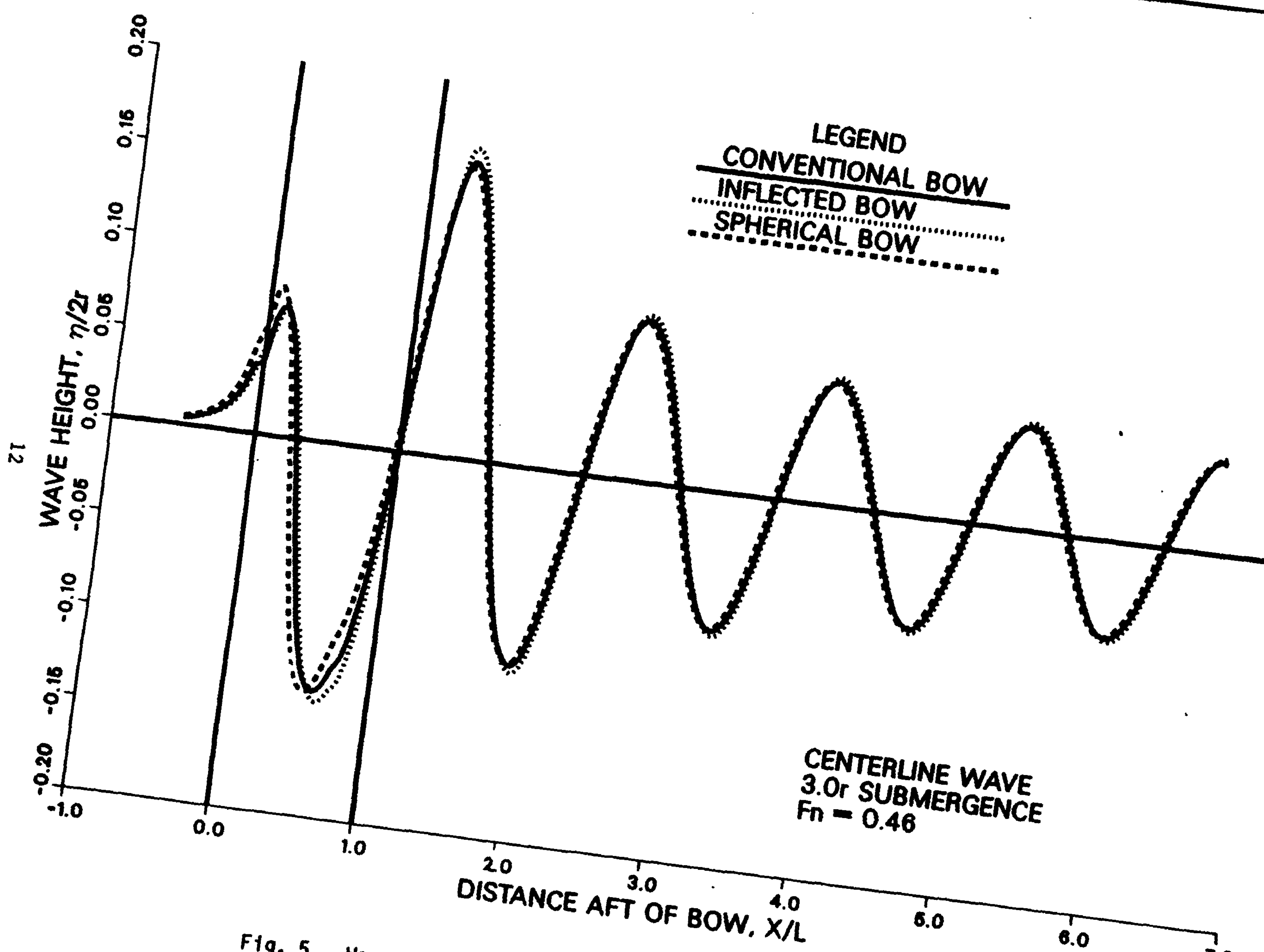


Fig. 5. Wave generated by different bows at Fn = 0.46.

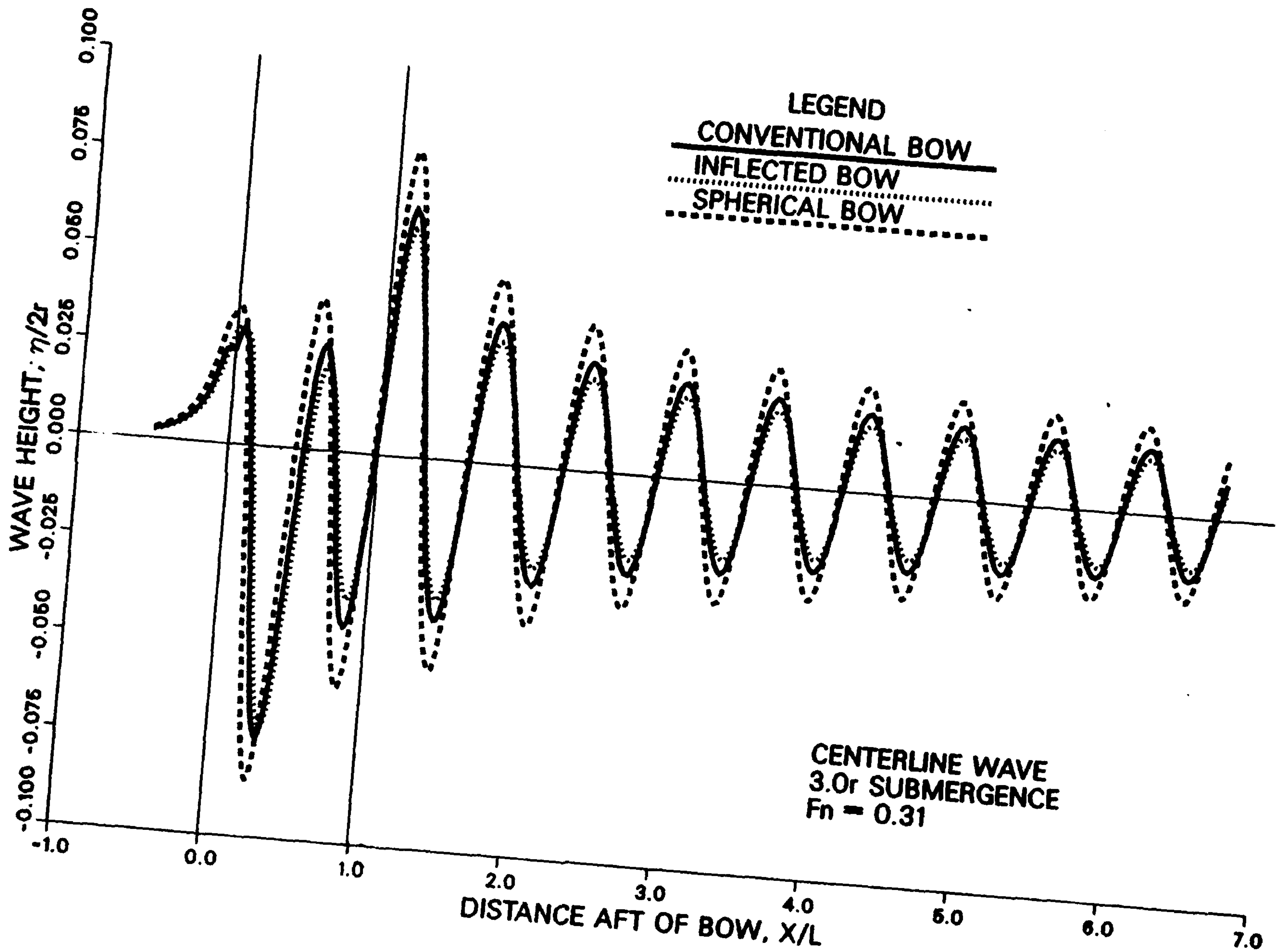


Fig. 6. Wave generated by different bows at Fn = 0.31.

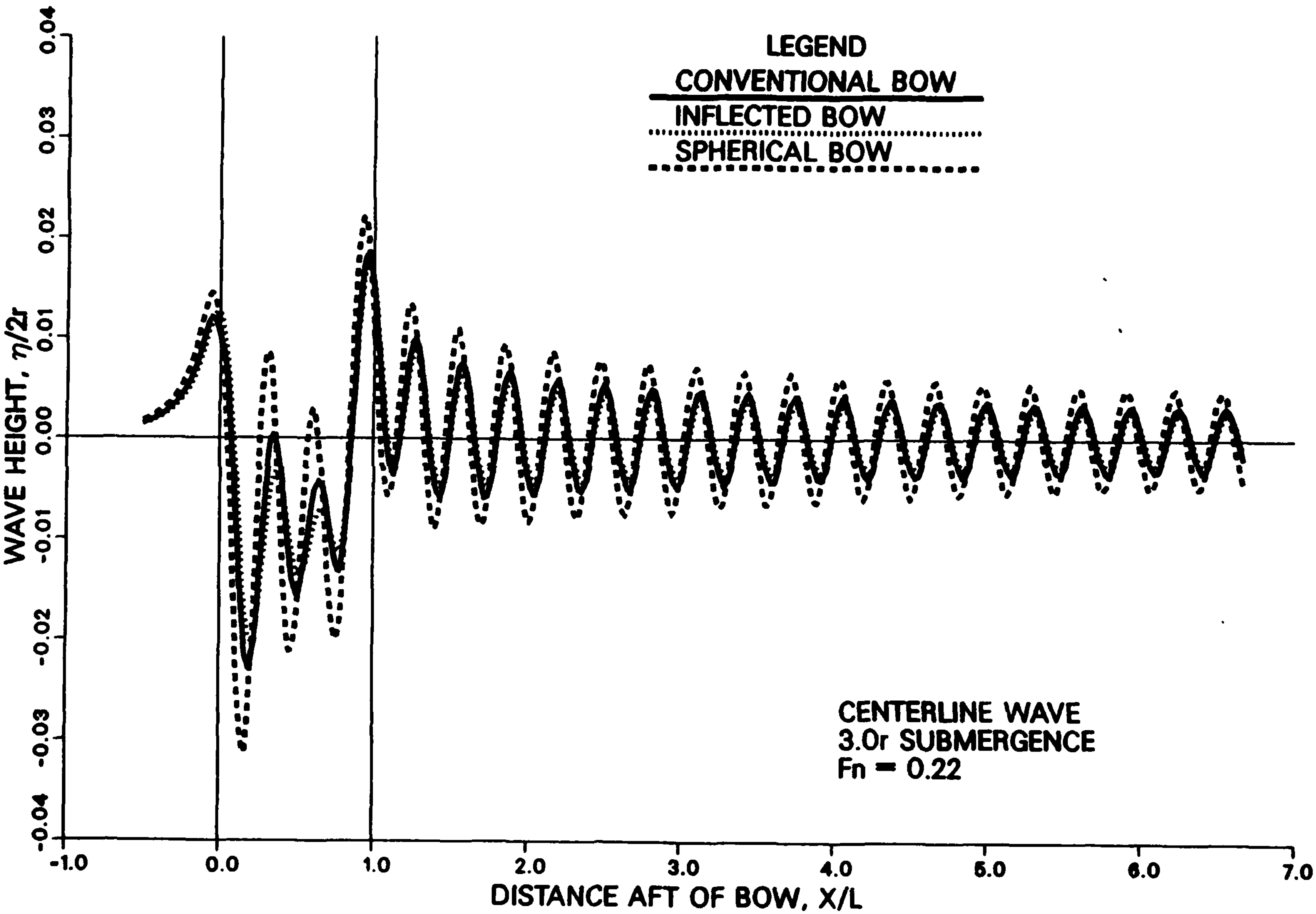


Fig. 7. Wave generated by different bows at Fn = 0.22.

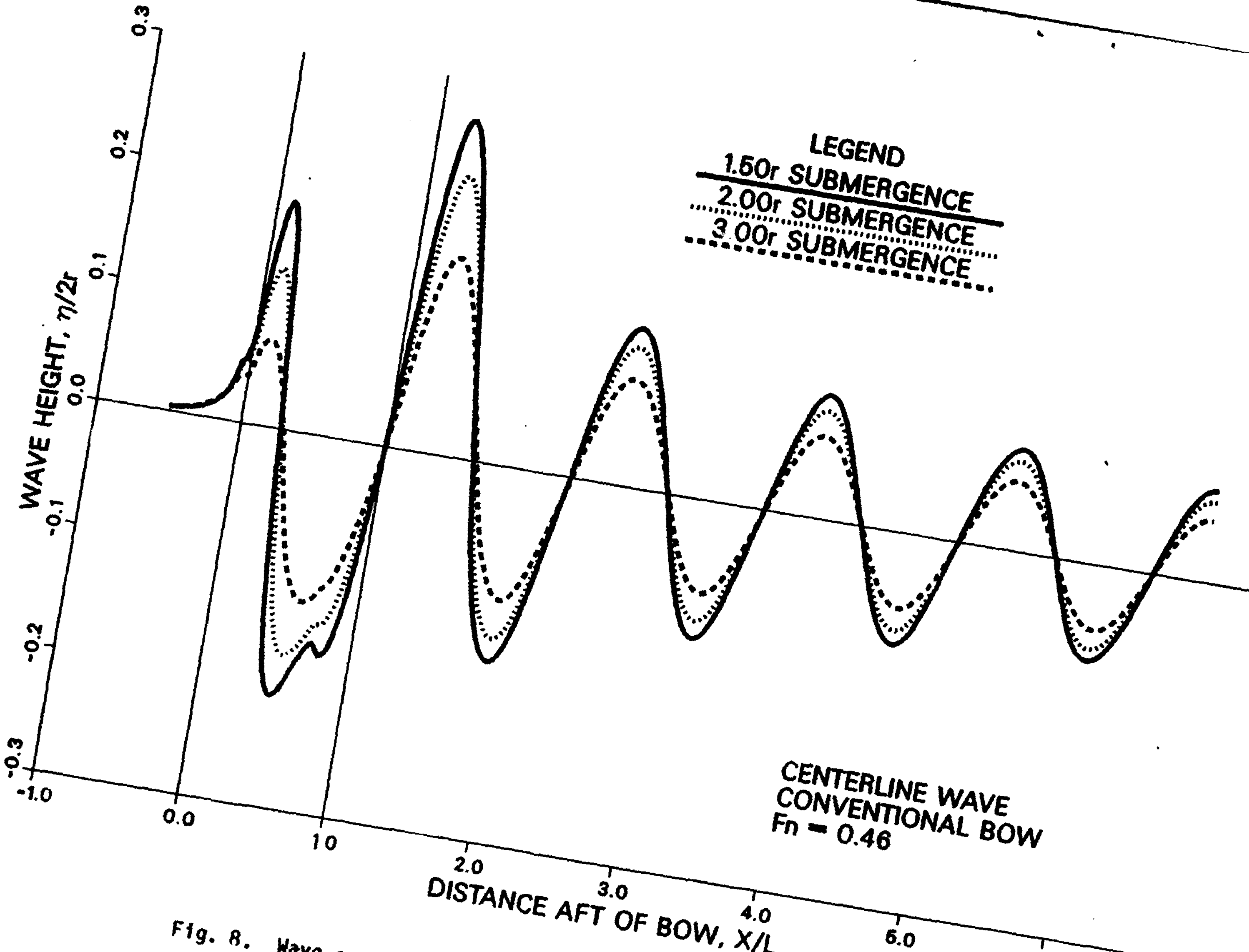


Fig. 8. Wave generated at different depths with Fn = 0.46.

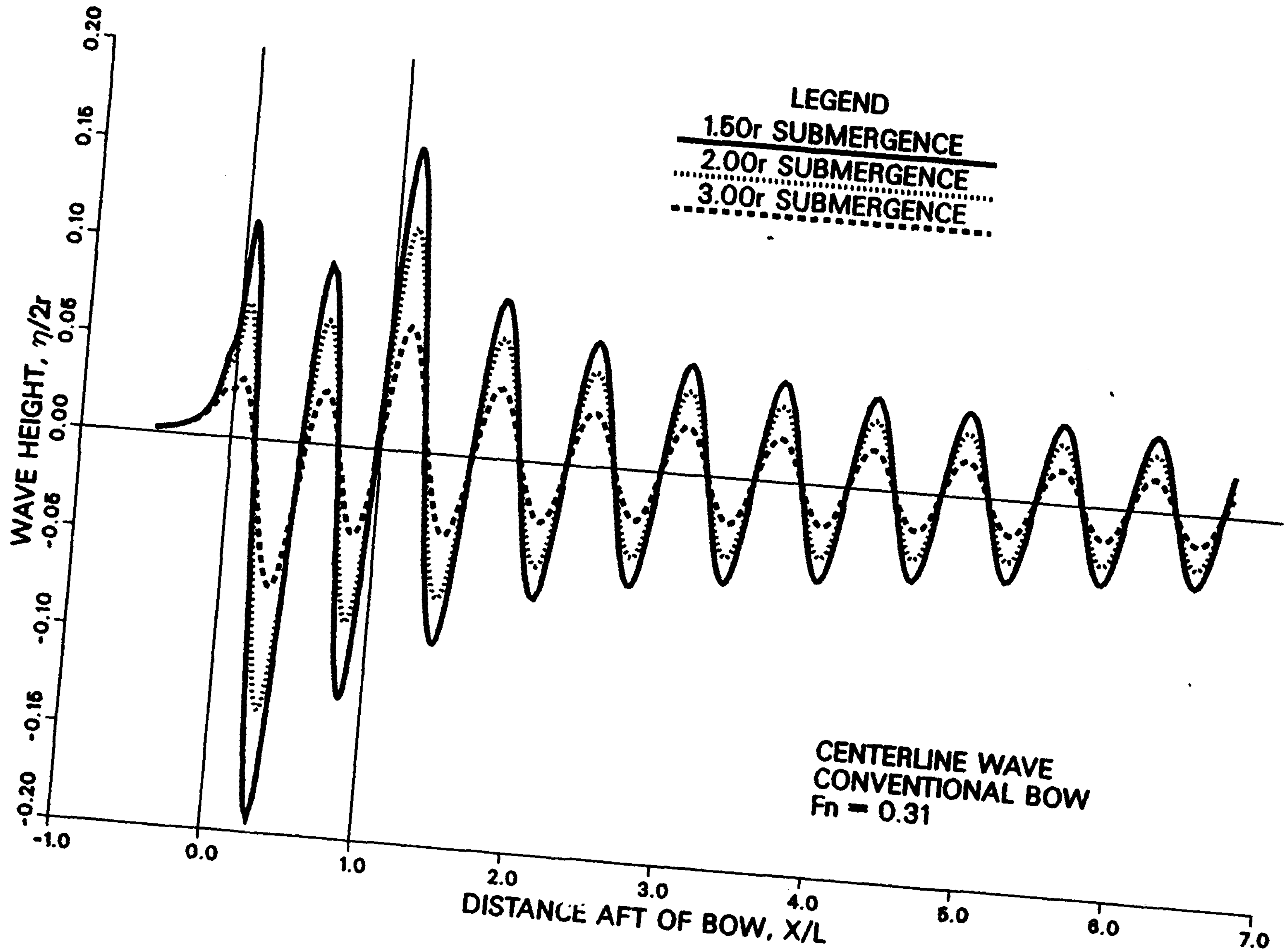


Fig. 9. Wave generated at different depths with Fn = 0.31.

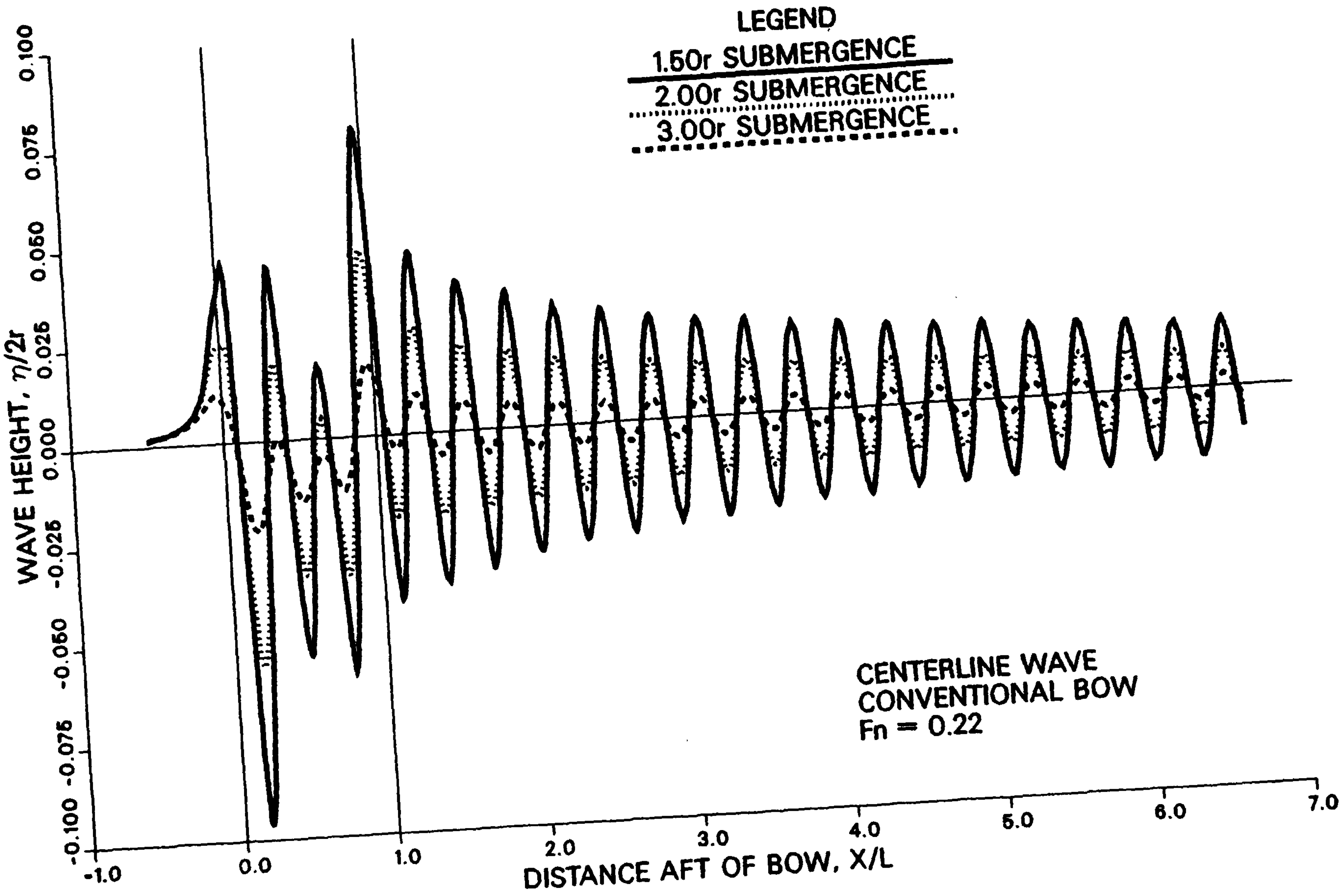


Fig. 10. Wave generated at different depths with Fn = 0.22.

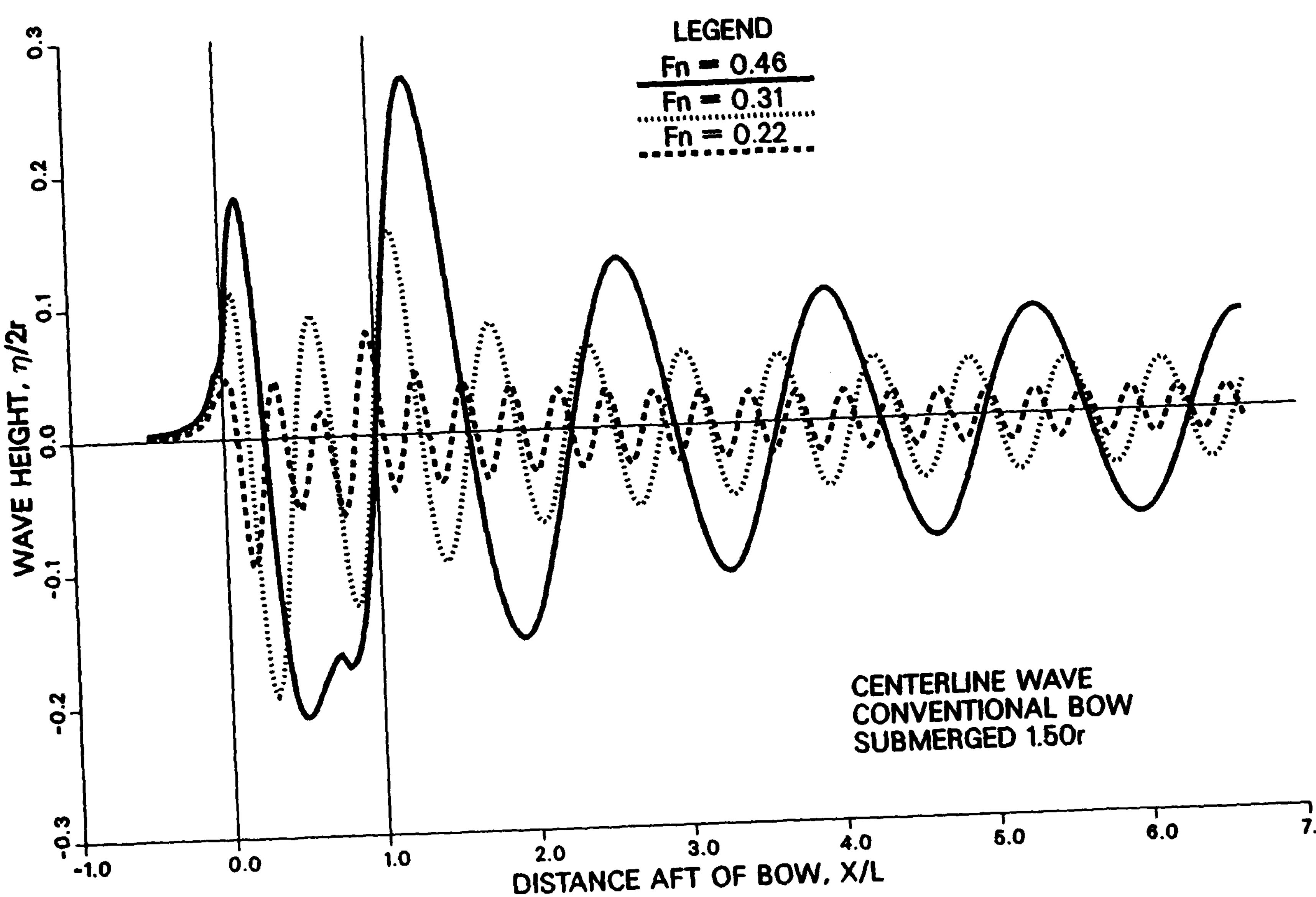


Fig. 11. Wave generated at three speeds and 1.5 radius submergence.

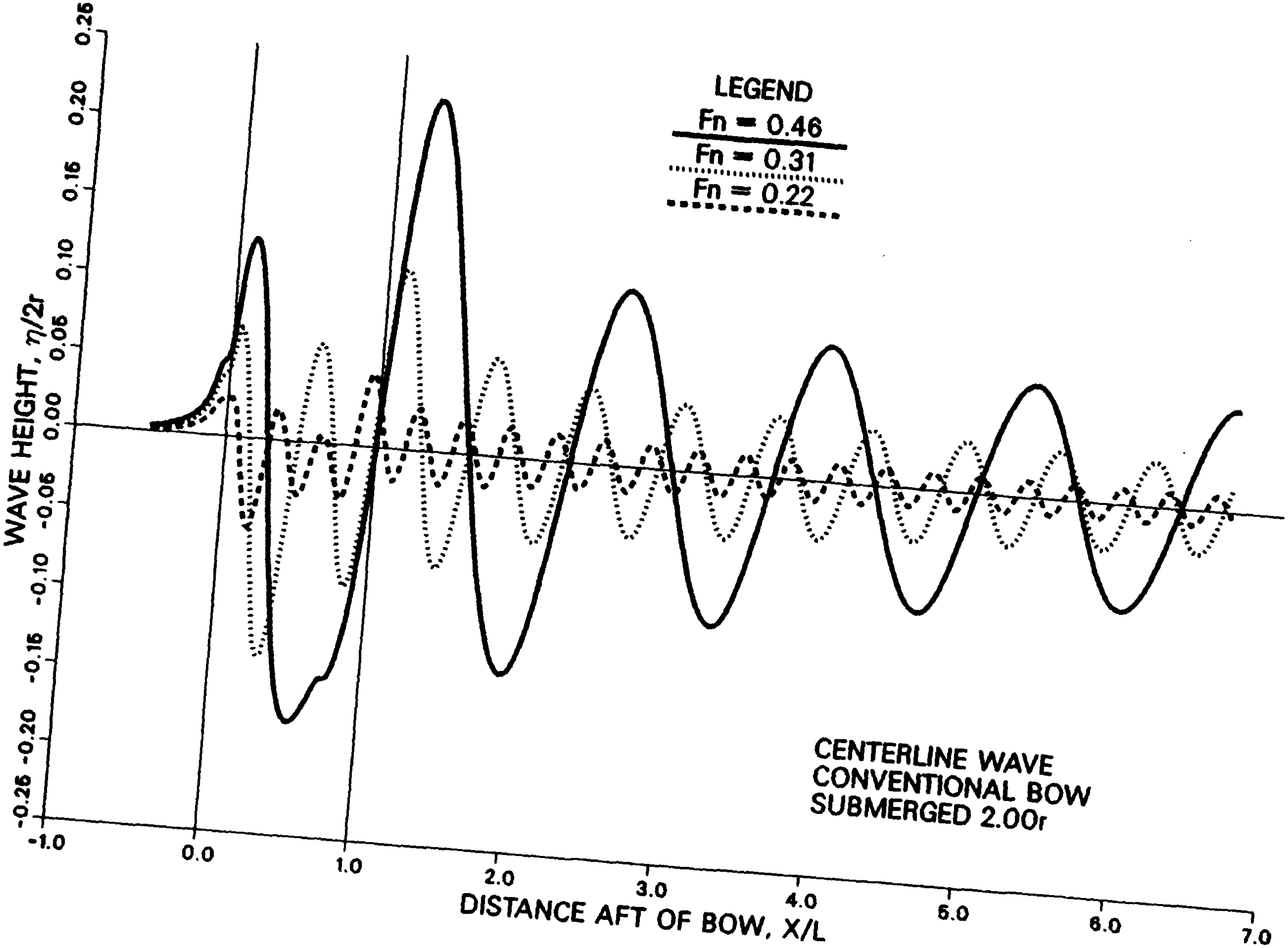


Fig. 12. Wave generated at three speeds and 2.0 radius submergence.

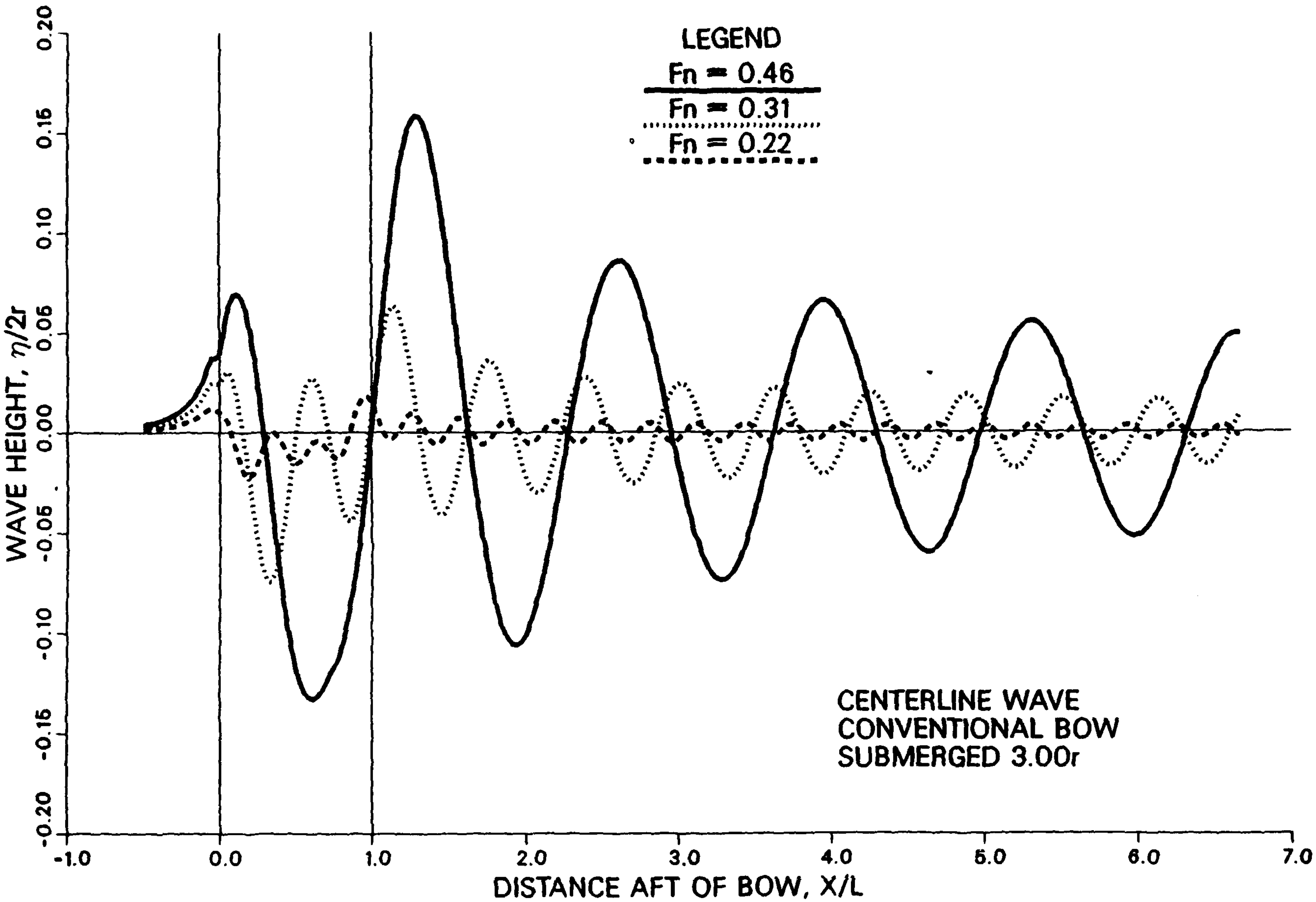


Fig. 13. Wave generated at three speeds and 3.0 radius submergence.

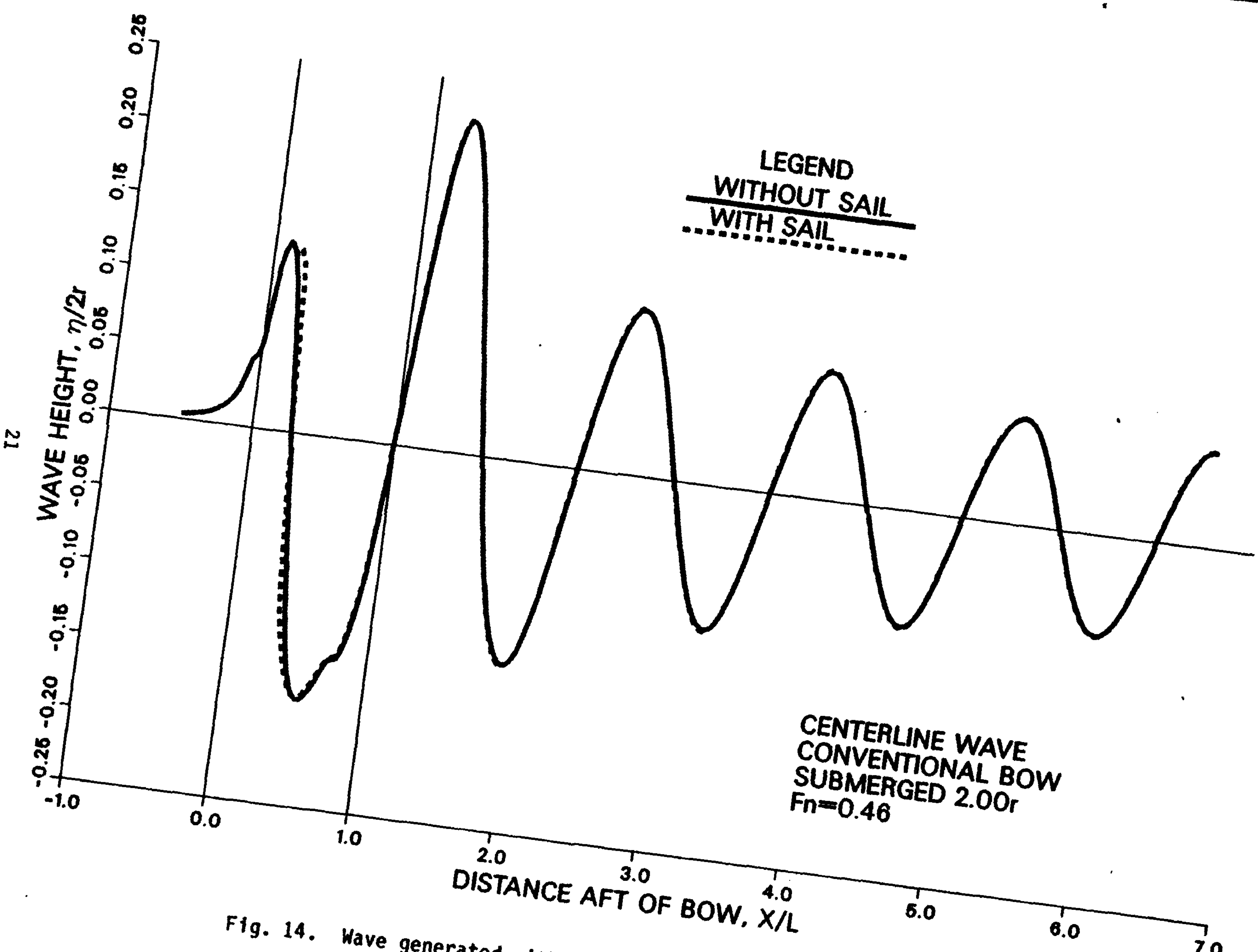


Fig. 14. Wave generated with and without sail at Fn = 0.46.

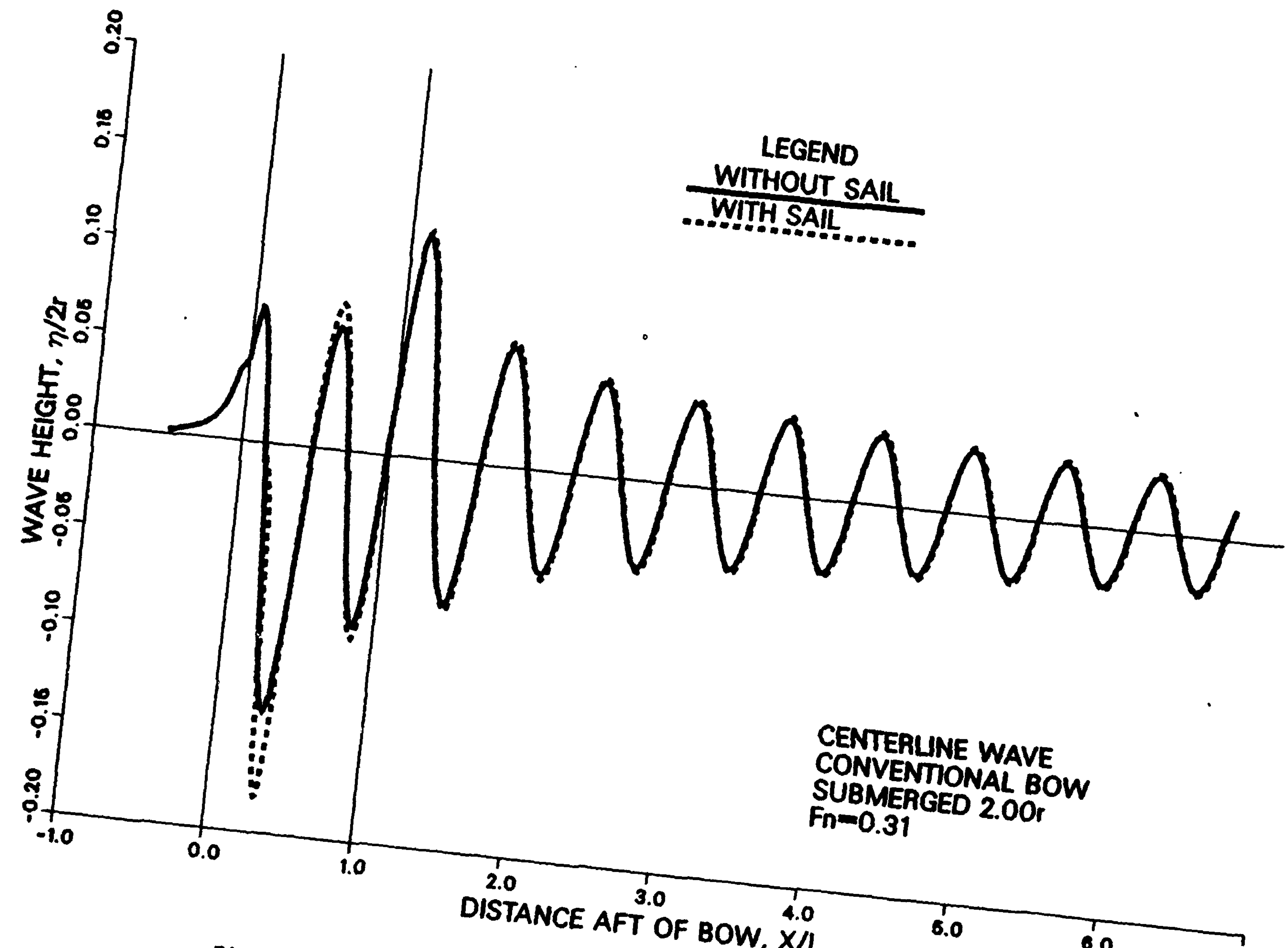


Fig. 15. Wave generated with and without sail at Fn = 0.31.

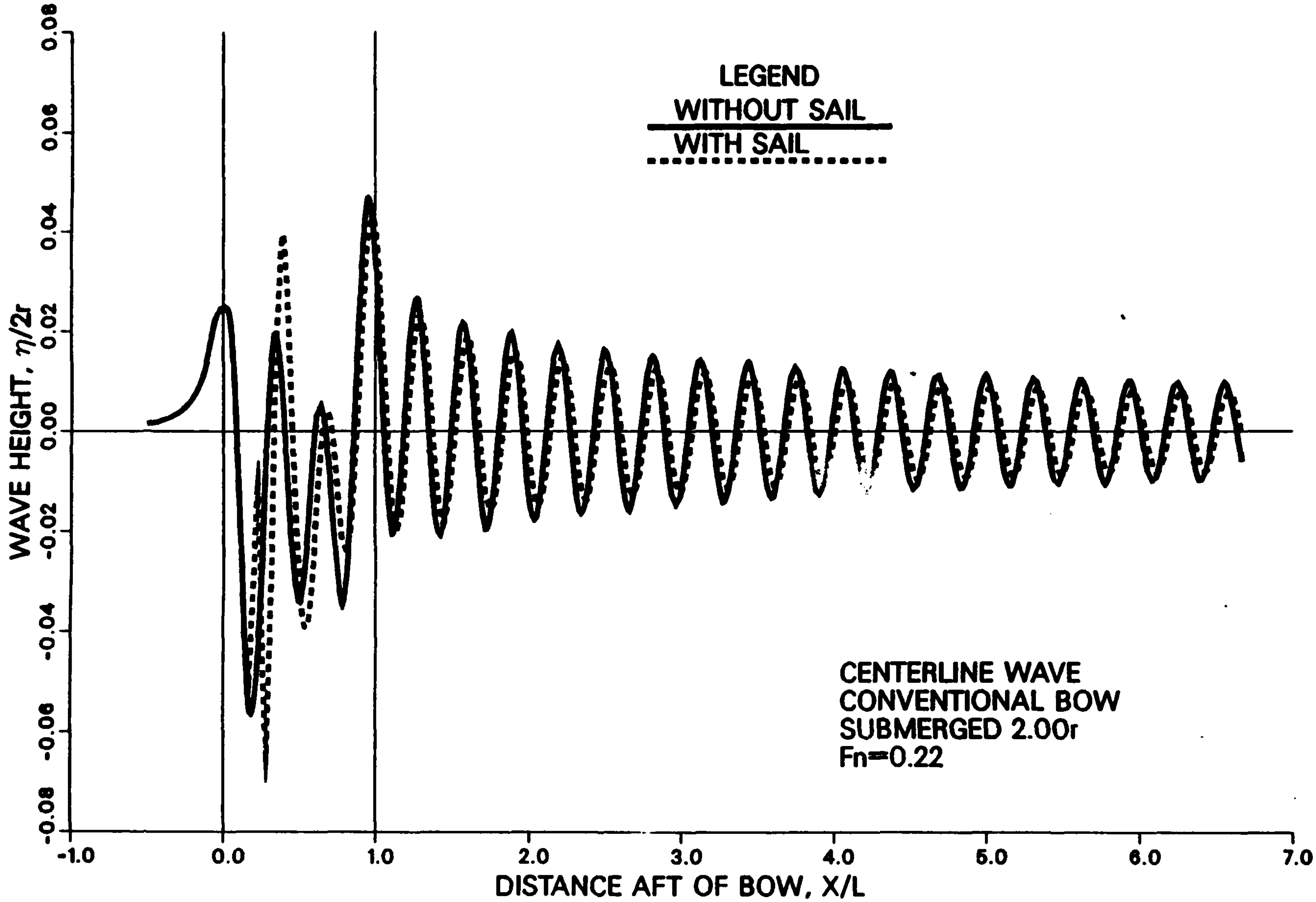


Fig. 16. Wave generated with and without sail at Fn = 0.22.

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