The Wave Drag of Hovercraft

HDL/63/127

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Summary

Data is presented for the estimation of hovercraft wave drag, in deep or shallow water. Theoretical and experimental results are compared as far as possible. Finally general conclusions are drawn regarding the factors which affect wave drag.

List of symbols

b	cushion breadth
h	water depth
l	craft length (actually the length of the cushion?)
p_c	cushion pressure
F	Froude number $V/(gl)^{0.5}$
R	wave resistance
S	cushion area
V	craft velocity
w	craft weight
ρ	water density

Introduction

A hovercraft travelling over water sets up a train of induced waves moving at the speed of the craft. Energy is supplied to these waves by the pressure of the cushion on the surface, the horizontal component of the reaction appearing as 'wave drag' on the craft.

The wave drag on a craft of a given size, shape, and weight is a function of the Froude number F and the water depth. Since wave drag is difficult to measure, theoretical results are normally used in hovercraft drag estimates.

The theoretical results suffer from the limitation that they assume small surface disturbances, and are liable to error at low Froude numbers and water depths. To check on these regions, a wave drag limitation based on the maximum wave steepness is described. Experimental results are compared with the theoretical results, and their limitations discussed.

THEORY

(1) Wave Drag

The bulk of theoretical estimates of wave drag are based upon a series of papers by Havelock, particularly ref 1. Expressions have been given for the wave resistance of a pressure distribution passing over the surface of water. These expressions have been applied and extended in refs 2 to 6.

Figures 1 to 11 show the theoretical non-dimensional wave drag coefficient plotted against Froude number F, for a variety of craft configurations, in deep and shallow water. The following general features can be seen.

1. The drag coefficient rises to a maximum at 'hump speed', corresponding to a Froude number between 0.5 and 1.0 in deep water. Other peaks, sometimes of greater height occur at lower speeds.
2. In shallow water the hump speed moves to lower Froude numbers, given approximately by $(h/l)^{0.5}$. The peak value of the drag rises indefinitely as the depth decreases.

Figures 1 to 6 give the wave drag in deep and shallow water for rectangular craft, (ref 2 and 4) while figures 7 and 8 give similar information for an elliptical craft (ref 3). Comparing the deep water results it can be seen that for a given value of beam/length ratio the elliptical craft has higher values of hump drag, but the rectangular craft has higher values at the lower speed peaks. The curves have not been plotted for lower Froude Numbers, because of the large number of points needed to define them, and the doubtful validity of the theory in these regions.

In shallow water the rectangular planform craft shows greater fluctuations in wave drag than does the elliptical craft (figs 3 and 8).

Figure 9 is taken from ref 5 and shows the theoretical wave drag for a rectangular pressure distribution travelling over a rectangular section canal. As the width of the canal is large compared with the model length, the results approach those for shallow water (fig 3). The most noticeable difference is the presence of discontinuities in the wave drag for the canal case. It can be seen that these discontinuities approach zero as the canal width approaches infinity.

Fig 10 shows the results of an attempt to estimate the drag of a hovercraft with double curtains for and aft, by using a step pressure distribution. In spite of the large number of points calculated, no double peaks or other unusual points are visible. The result is in fact closely similar to that for a rectangular craft with uniform pressure distribution.

In fig 11, the drag is shown of a rectangular craft with elliptical pressure distribution in the fore and aft direction. Comparing this with fig 4 the elliptical pressure distribution causes greater drag for most depths and Froude numbers, with the possible exception of the peak drag in very shallow water. This qualification is in some doubt however, due to the possibly inadequate number of points calculated.

Figure 12 gives the drag due toan ellipsoid pressure distribution on an elliptical planform (ref 6). The comparable values in fig 7 for a uniform distribution are appreciably lower particularly at the hump.

(2) Wave Steepness Limitations

The theoretical work so far described has the limitation that it assumes the surface disturbance to be small. This may account for the unrealistically high drag peaks predicted at small water depths and low Froude numbers. By considering the maximum steepness attained by waves before breaking, Hogben (ref 7) has deduced limiting values for wave drag, examples of which are shown in fig 13.

By plotting the wave drag limit against Froude number for various values of $\rho g(S)^{0.5}/p_c$, it is seen that the wave steepness limitation is most severe for small craft with high cushion pressure and low cushion area. Although the limiting value is not strictly valid for shallow water waves, and is a rough approximation in any case, it gives a useful indication of the maximum values of waves drag that may be experienced.

An example of the use of this limit in conjunction with the theoretical curves Is given in fig 14. Two limiting curves have been superimposed on fig 3. They correspond to craft with cushion pressures of 60 lb/ft^2, and cushion areas of 5000 and 1250 ft^2. For the smaller craft the maximum wave drag is predicted to occur at a Froude number of 0.43 and a depth/length ratio of 0.19, when it has twice the deep-water hump value. The secondary deep-water peak is partly cut off by the steepness limit. For the larger craft, the maximum wave drag coefficient is 3x the deep-water hump drag, occurring at a Froude number of 0.34 and a depth to length ratio of 0.12. In this case the secondary deep-water peak is not cut off and is greater than the hump drag.

From this example, it can be seen that th wave steepness limitation modifies the shape of the wave drag curves considerably for a small craft with high pc, but comparatively little for a large low-pressure craft. In any case an upper limit is set on wave drag, although its validity is questionable for shallow water.

(3) Experimental Results

1. Sidewall Craft

   Figure 15 shows an attempt to measure wave drag experimentally and correlate it with theory. A sidewall model was used with the main body of the craft isolated from the sidewalls, so that the drag measured did not include the sidewall drag. Air was supplied from the towing carriage in such a way as to eliminate momentum drag, and aerodynamic drag was measured separately. The experimental points have been plotted together with the theoretical curves for craft of beam/length ratios 0.267 and infinity (2D theory). Although the model had the former beam/length ratio the points fall mid-way between the curves, possible due to the effect of the sidewalls. These were unusually deep, with an immersion depth of 10% of cushion length, and an overall length of 110% of cushion length.

   They may therefore have modified the flow to approach the 2D case for the cushion.

2. Peripheral Craft

   In figures 16 to 19 experimental results are shown for a peripheral jet model of approximately elliptical planform over shallow water (refs 8 and 9). Comparing these with the theoretical curves, modified by the deep water wave steepness limitation, some agreement can be seen although this is not close, particularly for the smaller depths. Since water was in contact with the craft at certain speeds however, the amount of correlation is encouraging.

Conclusions

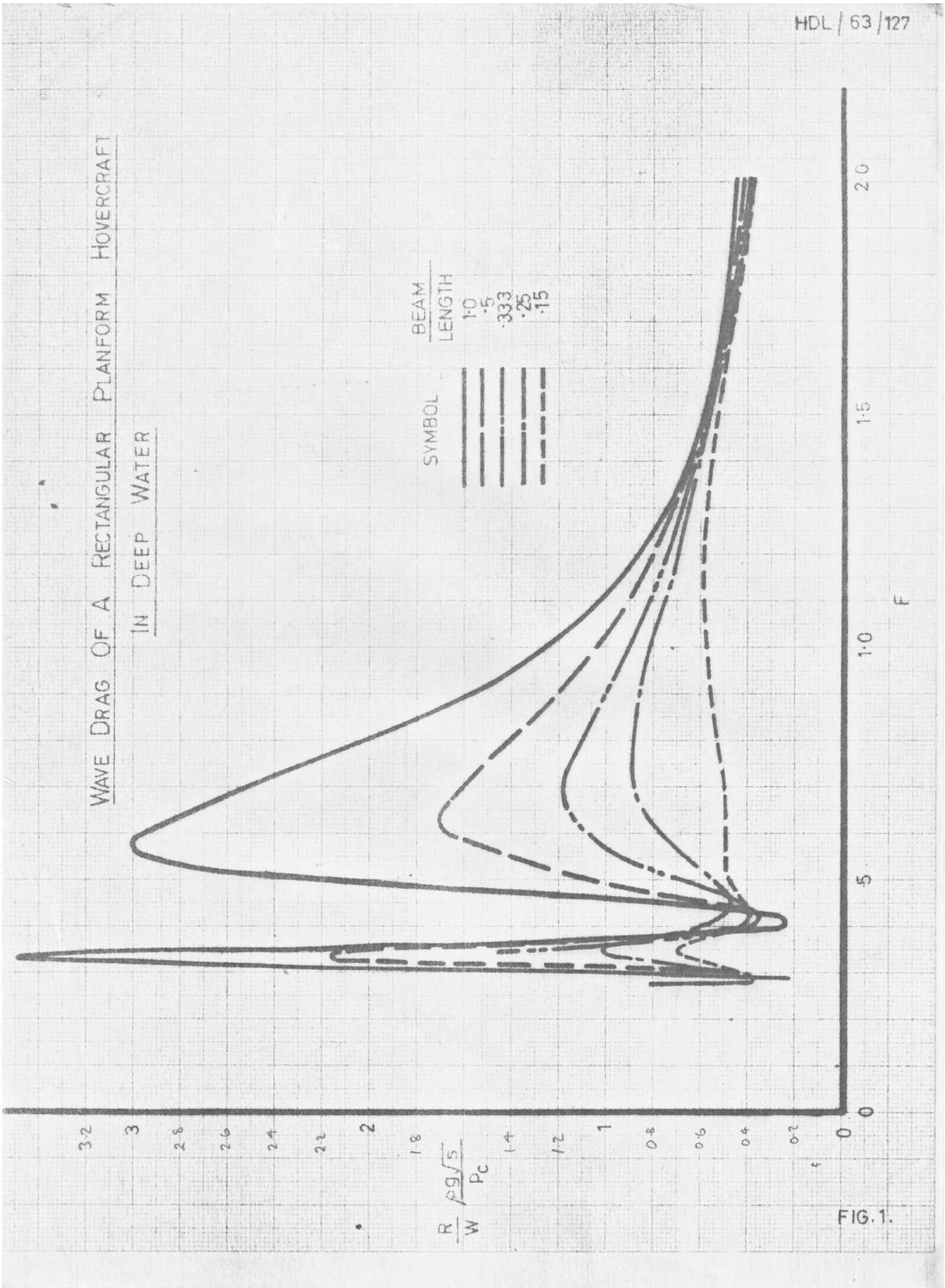
From the previous section it appears that neither theory nor experiment is yet completely reliable. However when the wave steepness limitations are superimposed on the theoretical results is generally fair agreement with experiment.

While caution is needed in using any specific result, some general conclusions may be drawn.

1. Elliptical planform hovercraft have greater hump drag than rectangular form hovercraft, but smaller low speed peaks, and smaller fluctuations in the wave drag curve.
2. From the pressure distributions examined, a uniform distribution gives the least wave drag. Small steps in the distribution corresponding to double jets have a negligible effect.
3. If a hovercraft has deep sidewalls, these alter the wave drag causing and increase in effective beam/length ratio.
4. For correct modelling of wave drag $p_c/(S)^{0.5}$ should be the same for model and full scale craft. Increasing this parameter tends to cut off the low-speed peaks in drag.
5. Applying the wave steepness limitation to shallow water drag and where there is high $p_c/(S)^{0.5}$ appears to reduce the peak wave drag coefficient

References

1. Havelock T H, 'The theory of wave resistance', Proceedings of the Royal Society, A138
2. Barratt M J, 'The wave drag of rectangular hovercraft', HDL Technical Memo HDL/62/113
3. Barratt M J, 'The wave drag of elliptical planform hovercraft', HDL Technical Memo HDL/62/119
4. Barratt M J, 'The wave drag of hovercraft in shallow water', HDL Technical Memo HDL/62/132
5. Newman J N, Poole F A P, 'The wave resistance of a moving pressure distribution in a canal', Schiffsteknikk 9, No 45
6. Squire H B, 'The wave resistance of hovercraft moving over deep water', Imperial College, Aeronautical Department, Technical Note 19A
7. Hogben N, 'Wave steepness limitations on hovercraft wave resistance', To be published
8. Crago W A, 'Shallow water tests on hovercraft model 51' Westland Aircraft Ltd, Saunders Roe division, Technical Note 9983
9. Cox R J, 'The wave drag of a hovercraft in shallow water – Analysis of experimental data', HDL Technical Memo HDL/63/128


HDL / 63 / 127
WAVE DRAG OF A RECTANGULAR PLANFORM HOVERCRAFT
IN DEEP WATER
SYMBOL
BEAM / LENGTH
1·0
·5
·333
·25
·15
$\frac{R}{W}\frac{\rho g \sqrt{S}}{P_c}$
F
0
·5
1·0
1·5
2·0
0·2
0·4
0·6
0·8
1
1·2
1·4
1·8
2
2·2
2·4
2·6
2·8
3
3·2
FIG. 1.

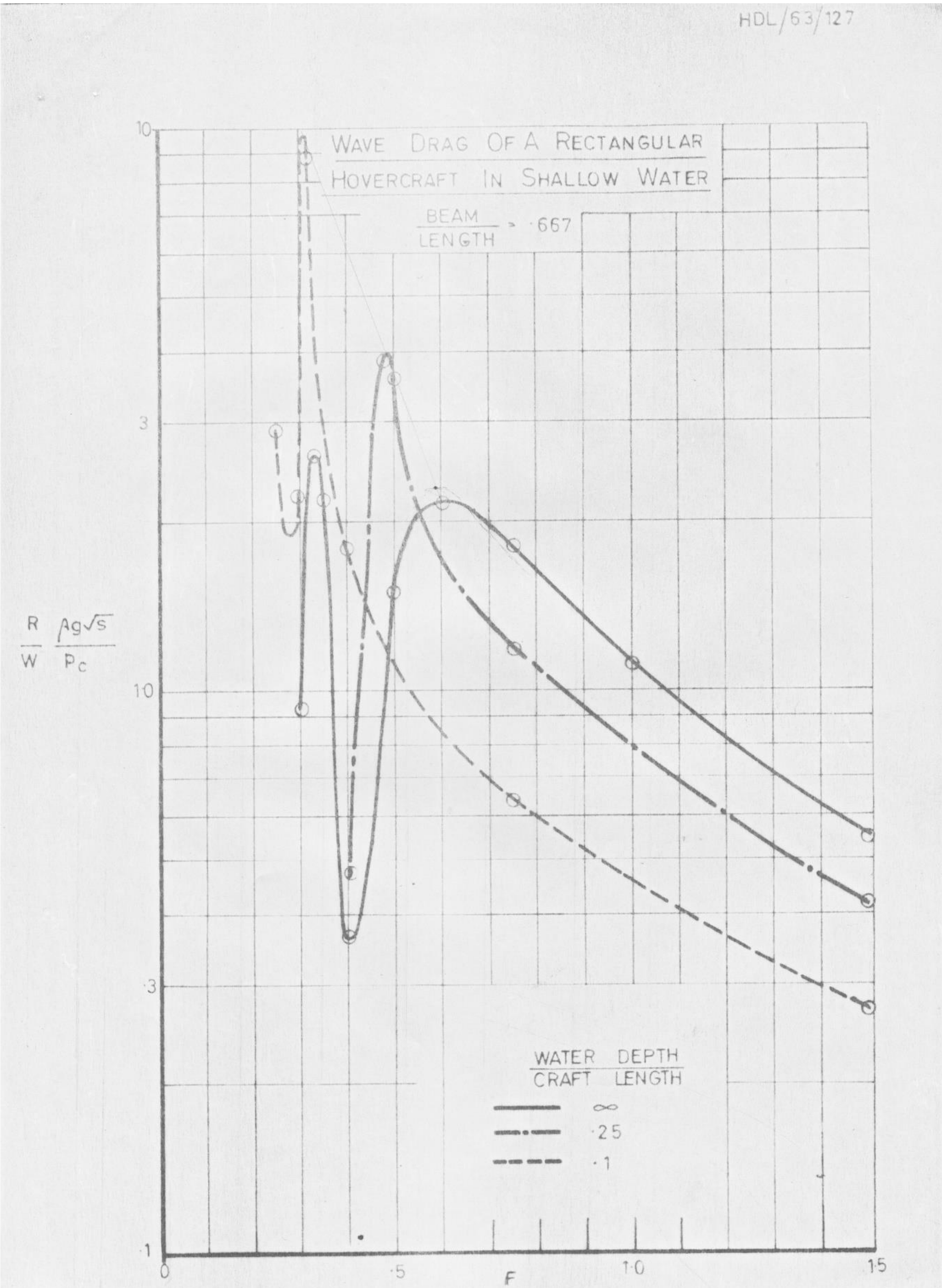
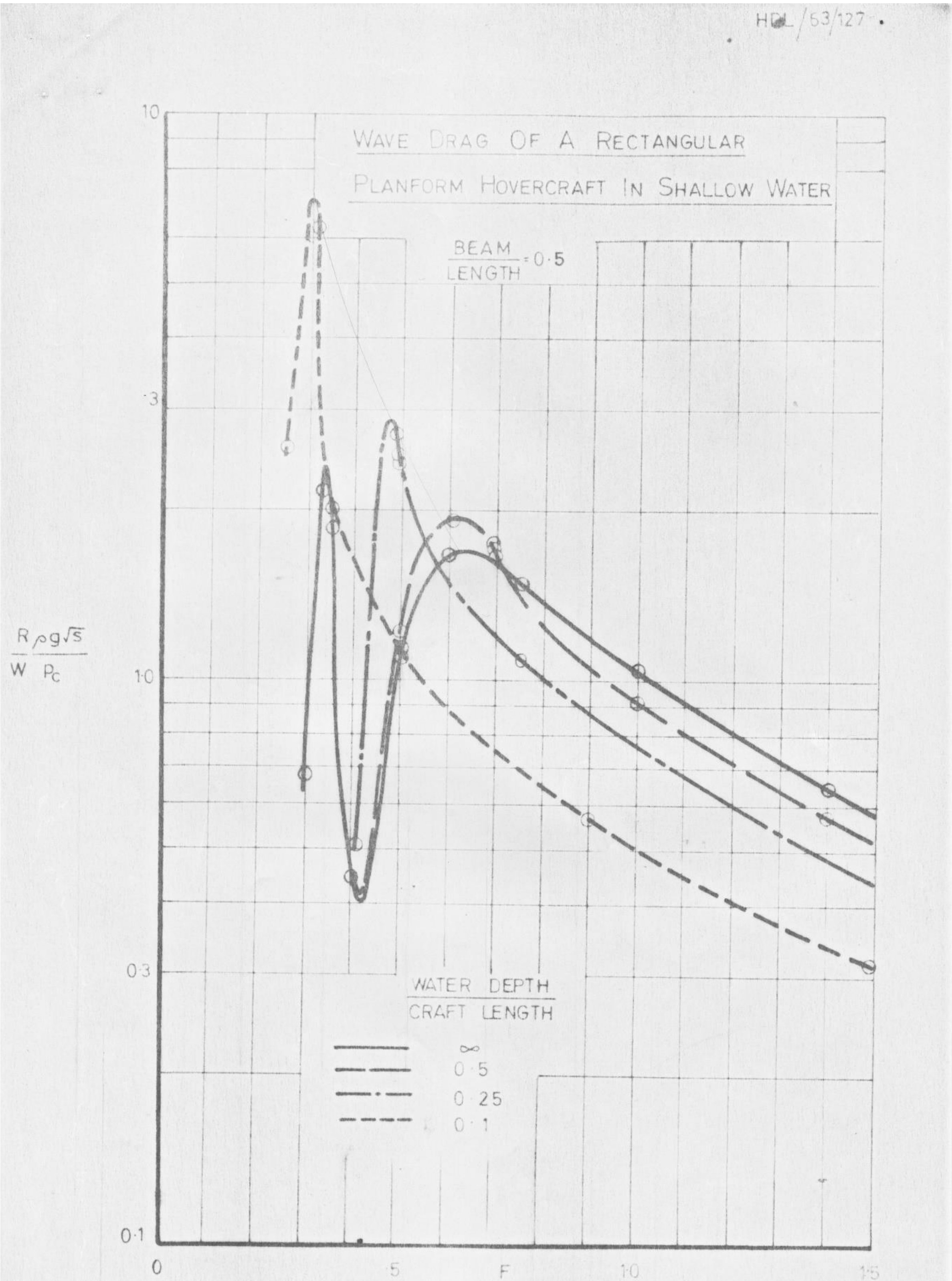

HDL/63/127
WAVE DRAG OF A RECTANGULAR HOVERCRAFT IN SHALLOW WATER
BEAM / LENGTH = ·667
R/W ρg√S/Pc
10
3
1·0
·3
·1
0
·5
F
1·0
1·5
WATER DEPTH / CRAFT LENGTH
∞
·25
·1

FIG. 2.


HDL/63/127
WAVE DRAG OF A RECTANGULAR
PLANFORM HOVERCRAFT IN SHALLOW WATER
BEAM / LENGTH = 0·5
R/W ρg√S/Pc
10
·3
1·0
0·3
0·1
0
·5
F
1·0
1·5
WATER DEPTH / CRAFT LENGTH
∞
0·5
0·25
0·1
FIG. 3

HDL / 63 / 127

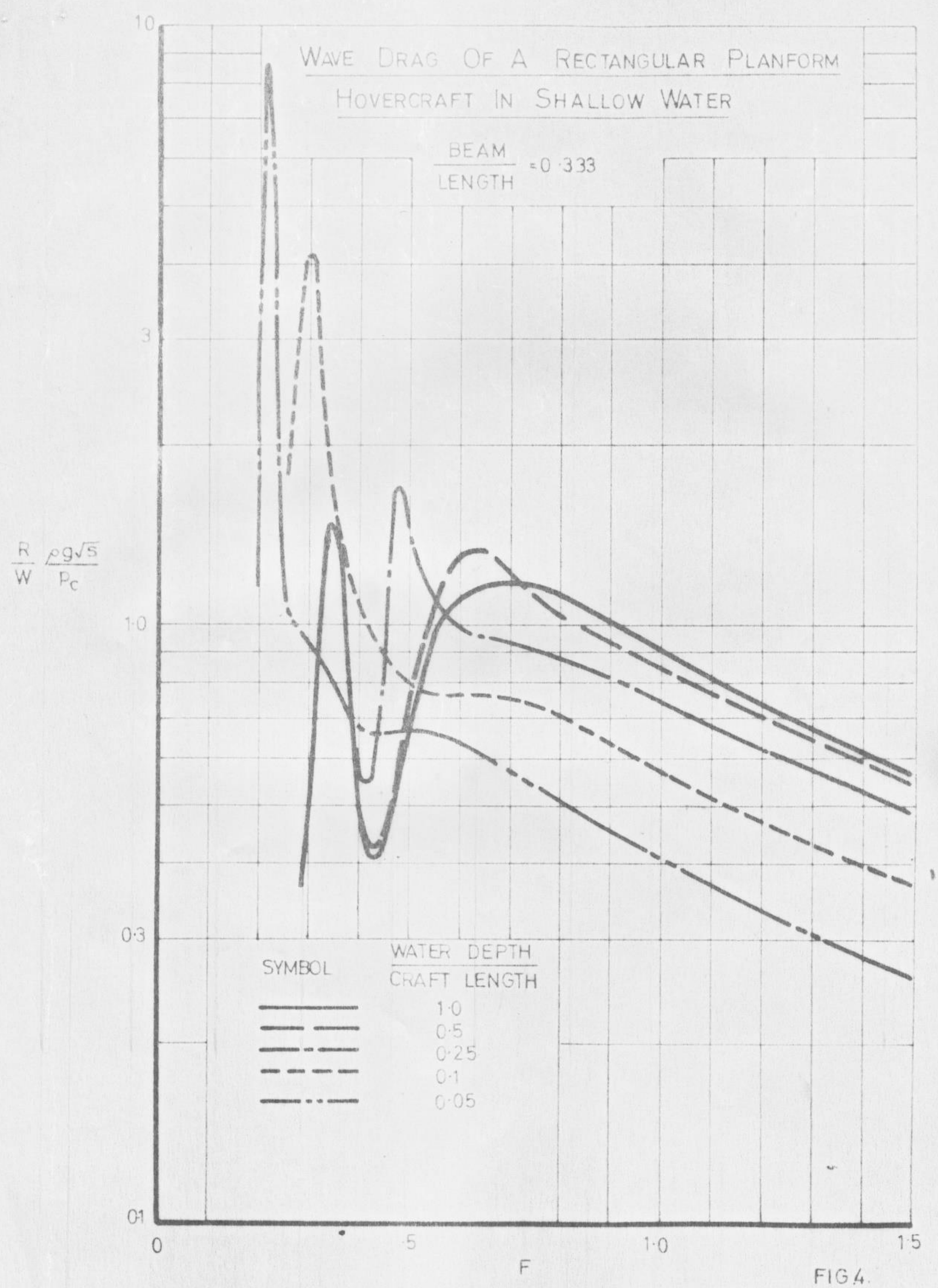


FIG 4.

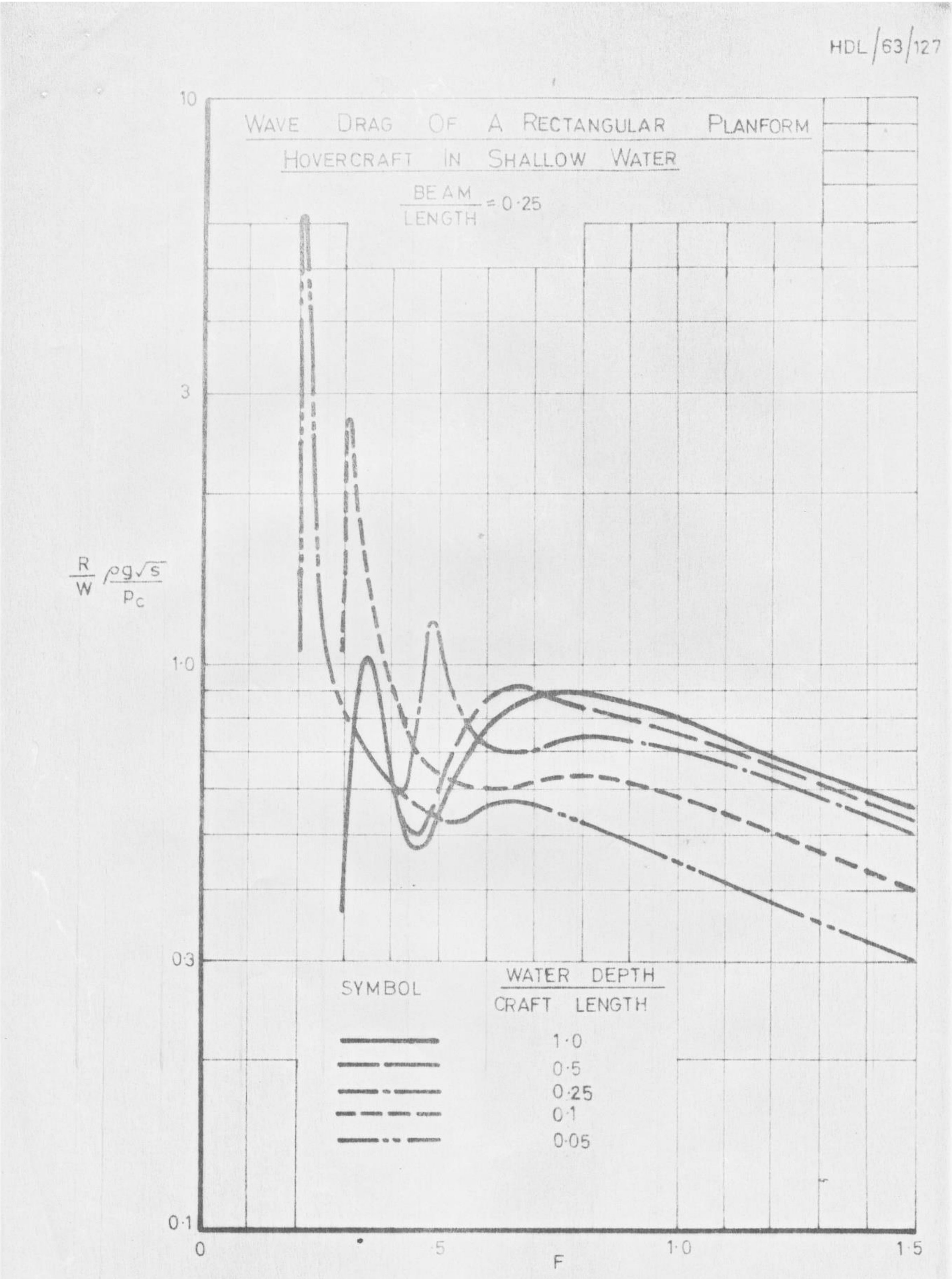

HDL/63/127
WAVE DRAG OF A RECTANGULAR PLANFORM
HOVERCRAFT IN SHALLOW WATER
BEAM/LENGTH = 0·25
10
3
1·0
0·3
0·1
R/W ρg√s/Pc
0
·5
1·0
1·5
F
SYMBOL
WATER DEPTH/CRAFT LENGTH
1·0
0·5
0·25
0·1
0·05

FIG.5.

HDL/63/127

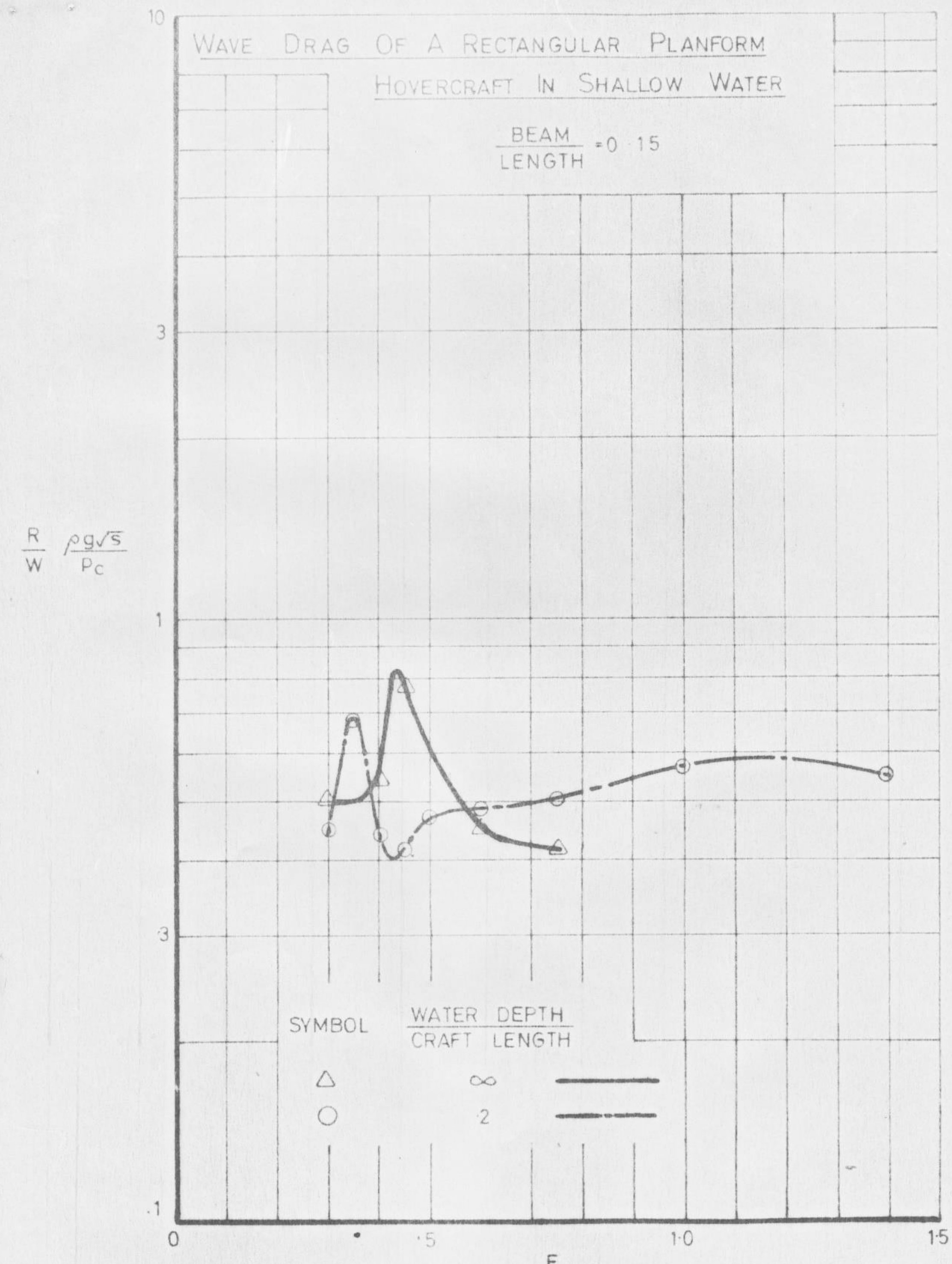


FIG. 6.

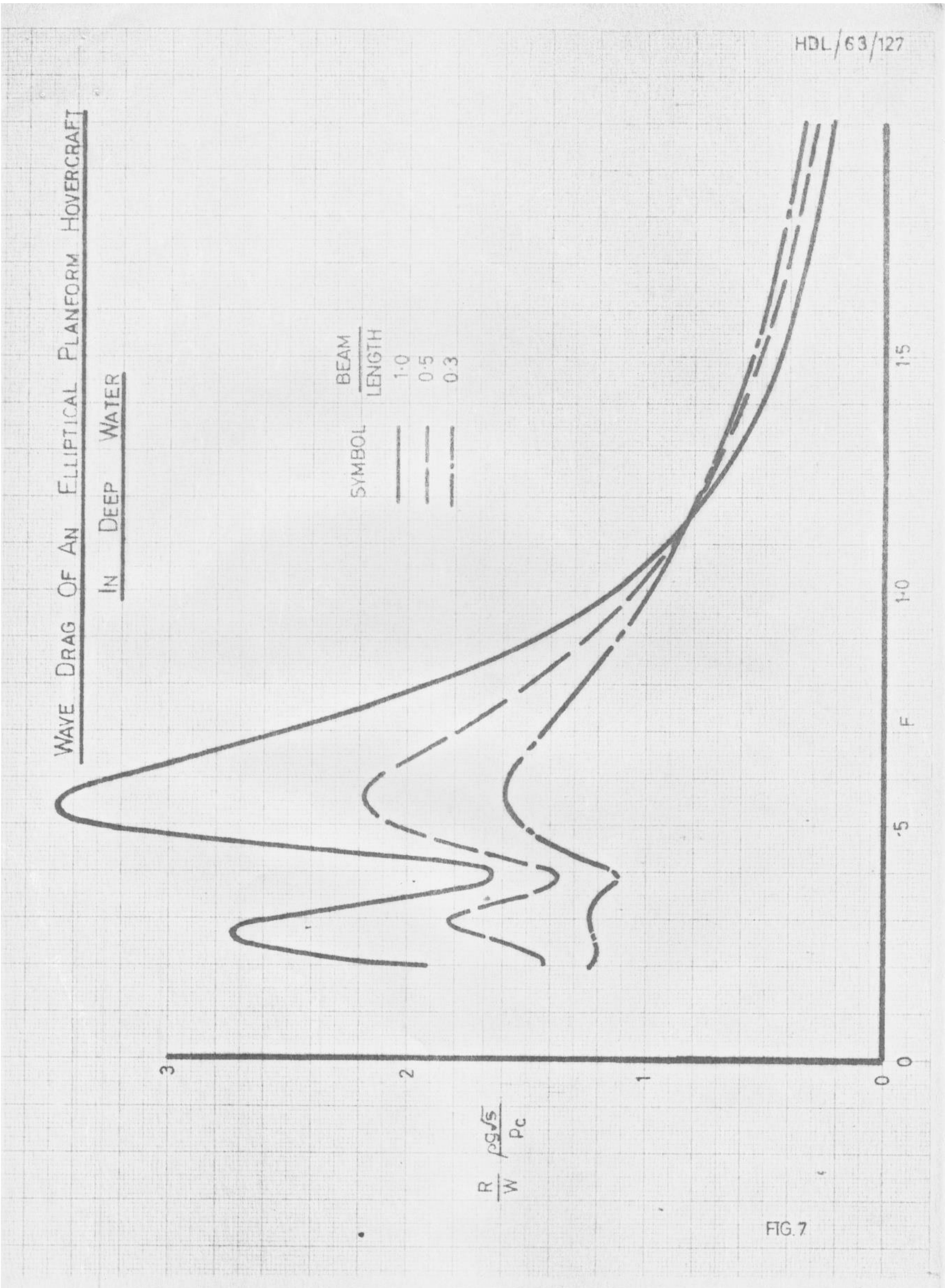

HDL/63/127
WAVE DRAG OF AN ELLIPTICAL PLANFORM HOVERCRAFT
IN DEEP WATER
SYMBOL
BEAM / LENGTH
1·0
0·5
0·3
$\frac{R}{W} \frac{\rho g \sqrt{S}}{P_c}$
3
2
1
0
0
·5
F
1·0
1·5

FIG. 7

HDL/63/129

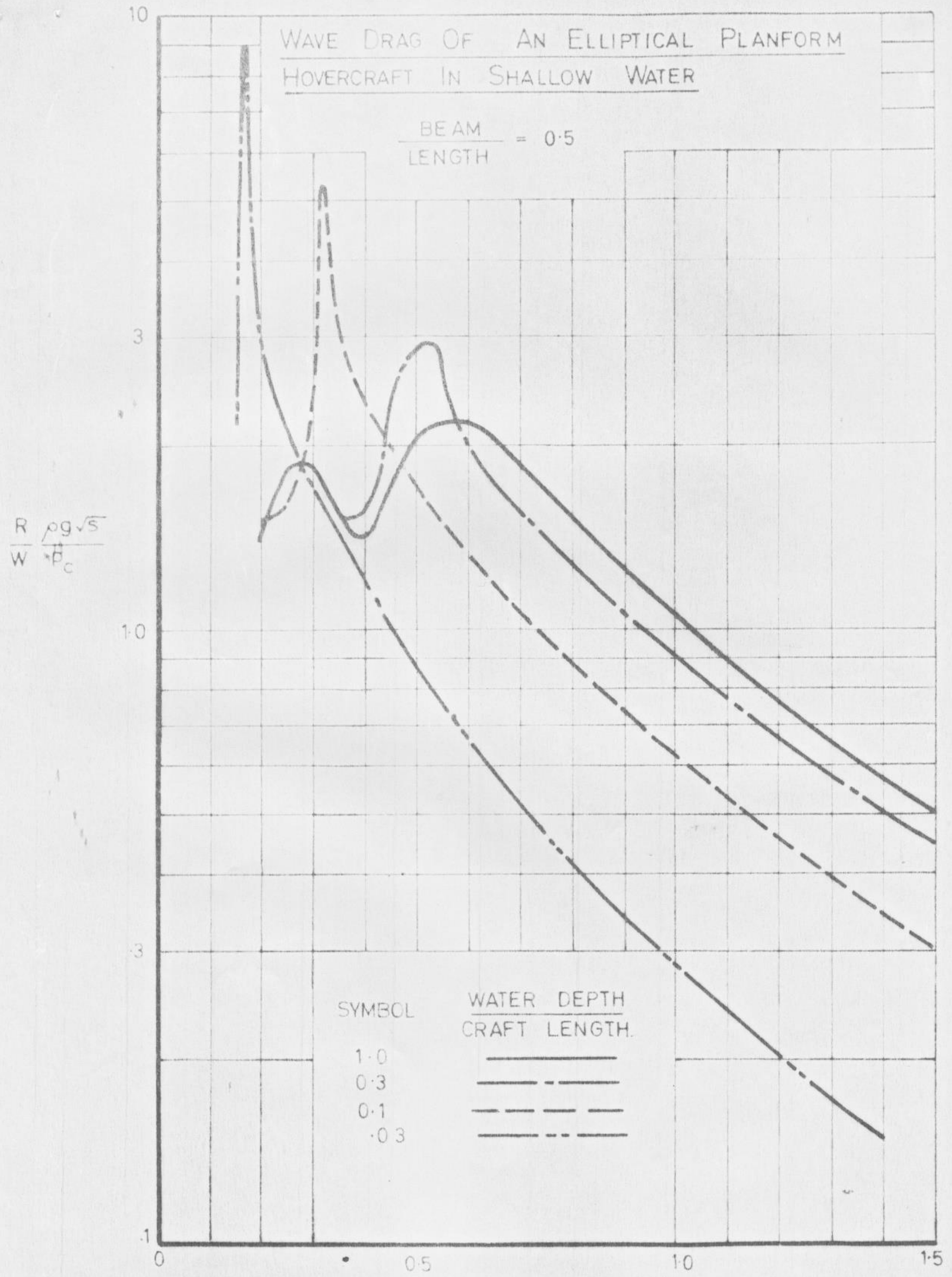


FIG. 8.

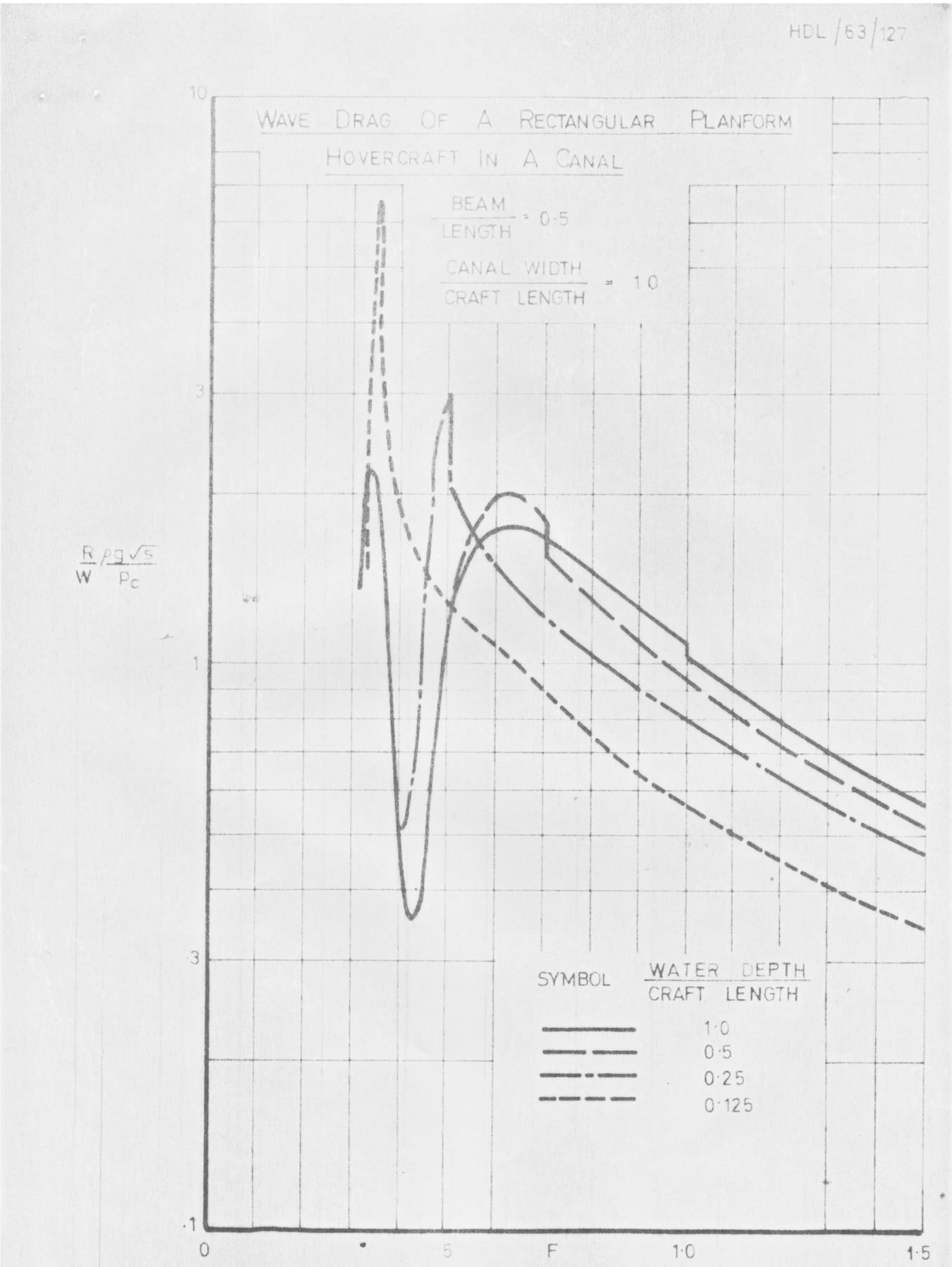

HDL/63/127
WAVE DRAG OF A RECTANGULAR PLANFORM
HOVERCRAFT IN A CANAL
BEAM / LENGTH = 0·5
CANAL WIDTH / CRAFT LENGTH = 1·0
R/W ρg√S/Pc
10
3
1
·3
·1
0
·5
F
1·0
1·5
SYMBOL
WATER DEPTH / CRAFT LENGTH
1·0
0·5
0·25
0·125

FIG 9

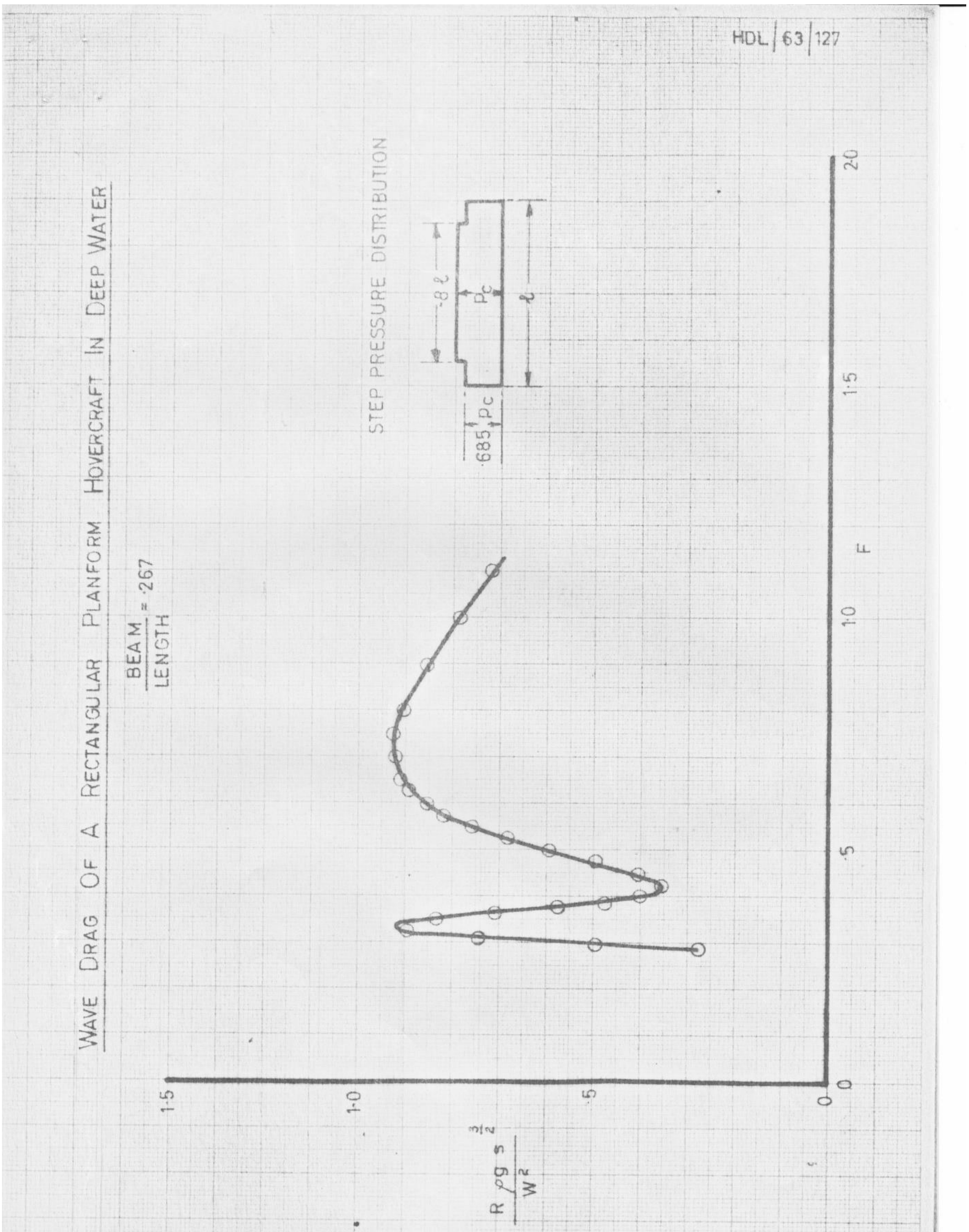

HDL/63/127
WAVE DRAG OF A RECTANGULAR PLANFORM HOVERCRAFT IN DEEP WATER
BEAM/LENGTH = ·267
STEP PRESSURE DISTRIBUTION
·8 ℓ
Pc
ℓ
·685 Pc
R ρg s^(3/2) / W²
F
0
·5
1·0
1·5
2·0

FIG. 10.

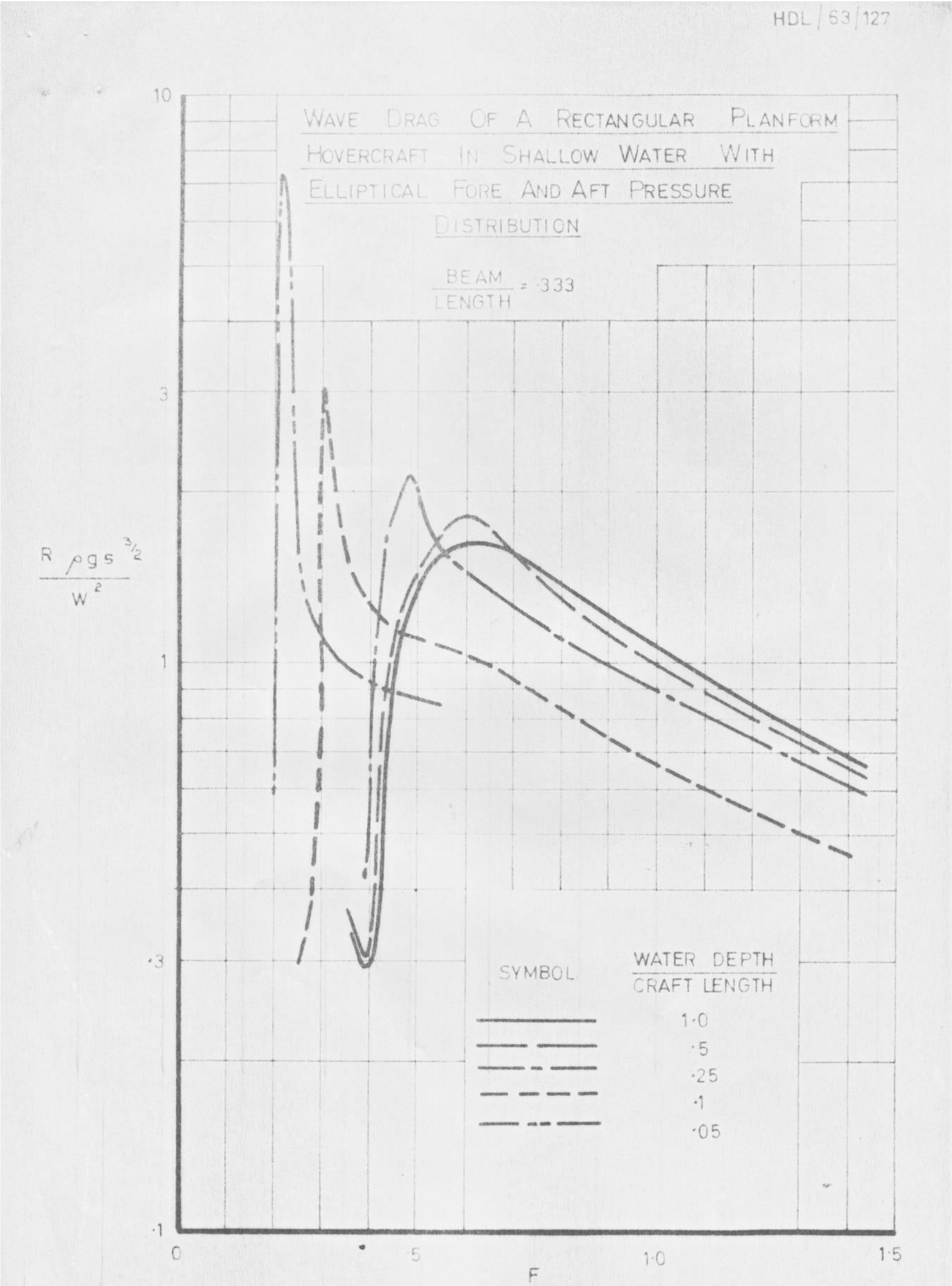

HDL / 63 / 127
WAVE DRAG OF A RECTANGULAR PLANFORM HOVERCRAFT IN SHALLOW WATER WITH ELLIPTICAL FORE AND AFT PRESSURE DISTRIBUTION
BEAM / LENGTH = ·333
10
3
1
·3
·1
R ρgs 3/2 / W 2
0
·5
1·0
1·5
F
SYMBOL
WATER DEPTH / CRAFT LENGTH
1·0
·5
·25
·1
·05

FIG. 11.

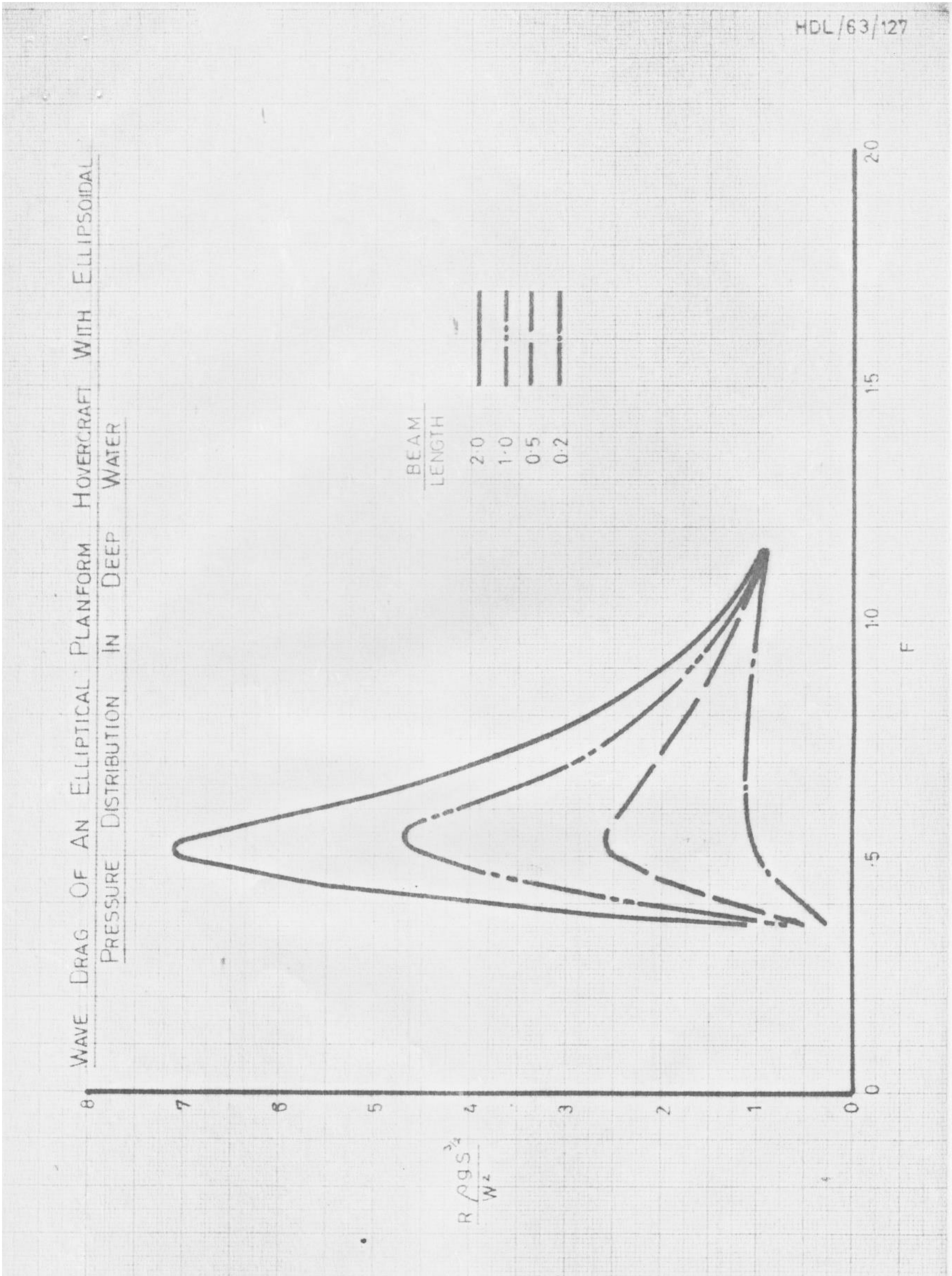

HDL/63/127
WAVE DRAG OF AN ELLIPTICAL PLANFORM HOVERCRAFT WITH ELLIPSOIDAL PRESSURE DISTRIBUTION IN DEEP WATER
BEAM/LENGTH
2·0
1·0
0·5
0·2
R ρgS^3/2 / W^2
F
0
·5
1·0
1·5
2·0
0
1
2
3
4
5
6
7
8

FIG. 12.

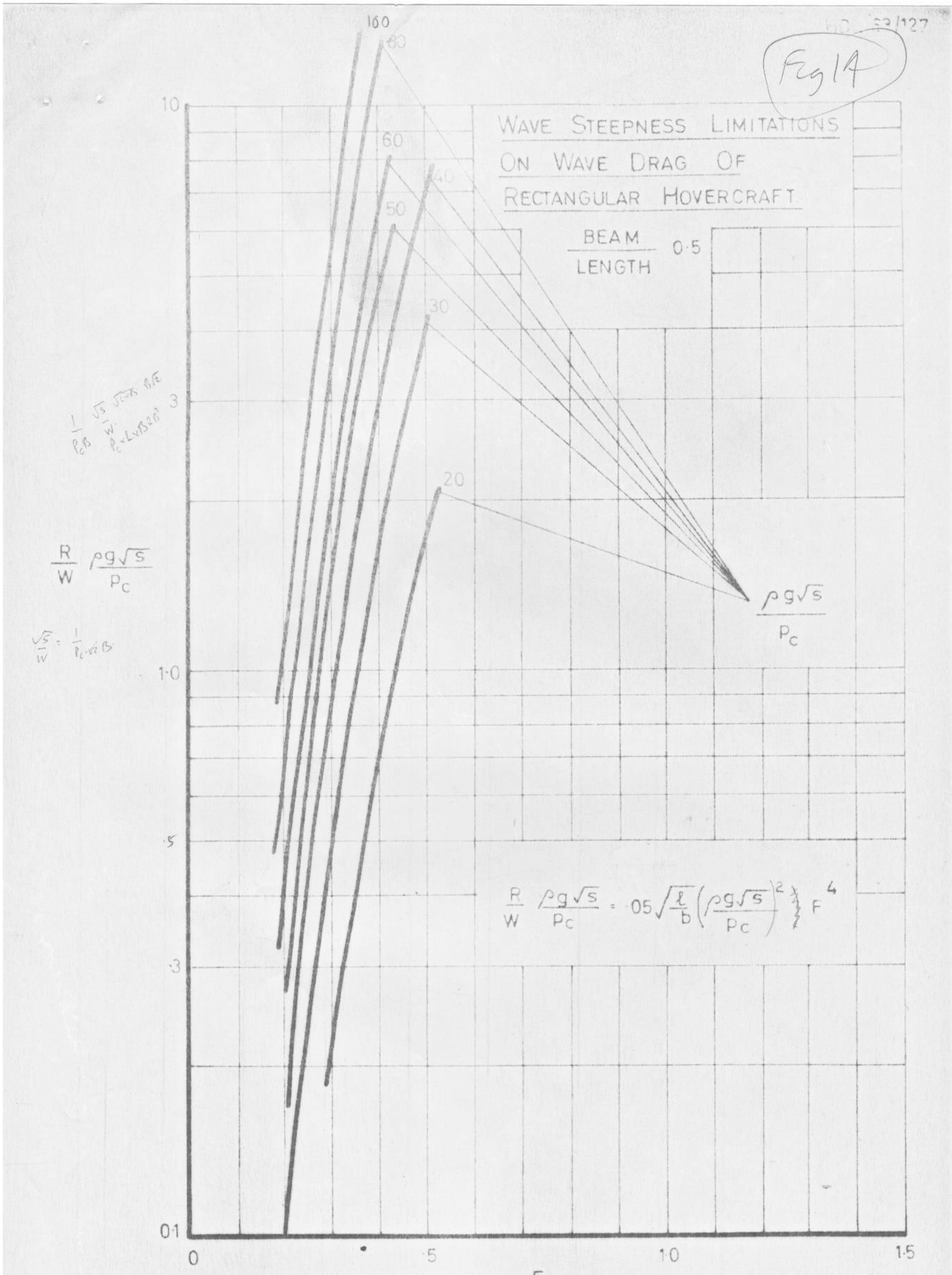


Fig 1A
WAVE STEEPNESS LIMITATIONS ON WAVE DRAG OF RECTANGULAR HOVERCRAFT
BEAM / LENGTH 0·5
160
80
60
50
40
30
20
10
3
1·0
·5
·3
·1
0
·5
1·0
1·5
F
R/W ρg√S/Pc
ρg√S/Pc
R/W ρg√S/Pc = ·05 √(l/b) (ρg√S/Pc)² F⁴

FIG. 13.

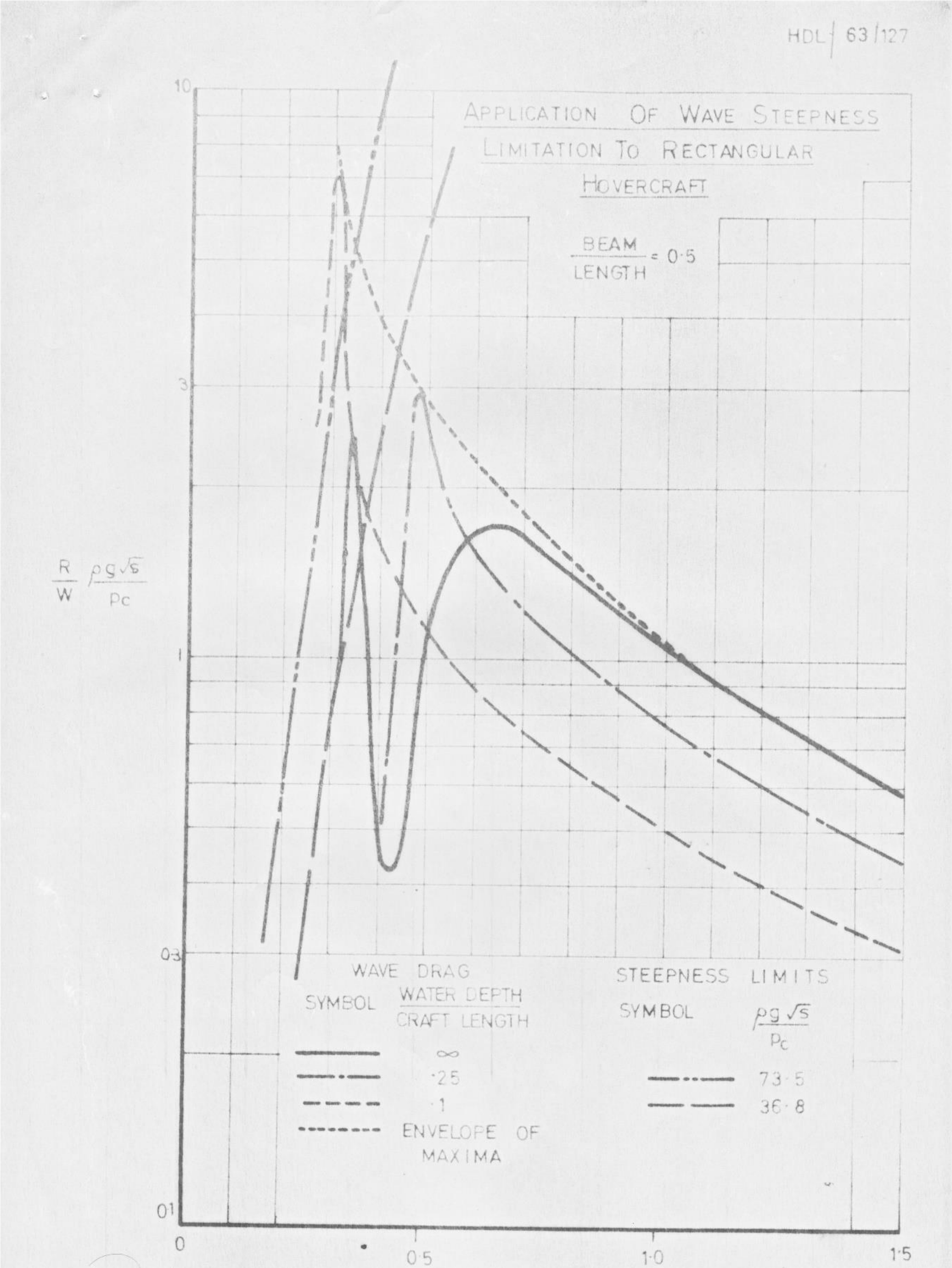

HDL 63/127
APPLICATION OF WAVE STEEPNESS LIMITATION TO RECTANGULAR HOVERCRAFT
BEAM / LENGTH = 0·5
R/W ρg√s/Pc
10
3
1
0·3
01
0
0·5
1·0
1·5
WAVE DRAG
SYMBOL
WATER DEPTH / CRAFT LENGTH
∞
·25
·1
ENVELOPE OF MAXIMA
STEEPNESS LIMITS
SYMBOL
ρg√s / Pc
73·5
36·8

FIG. 14.

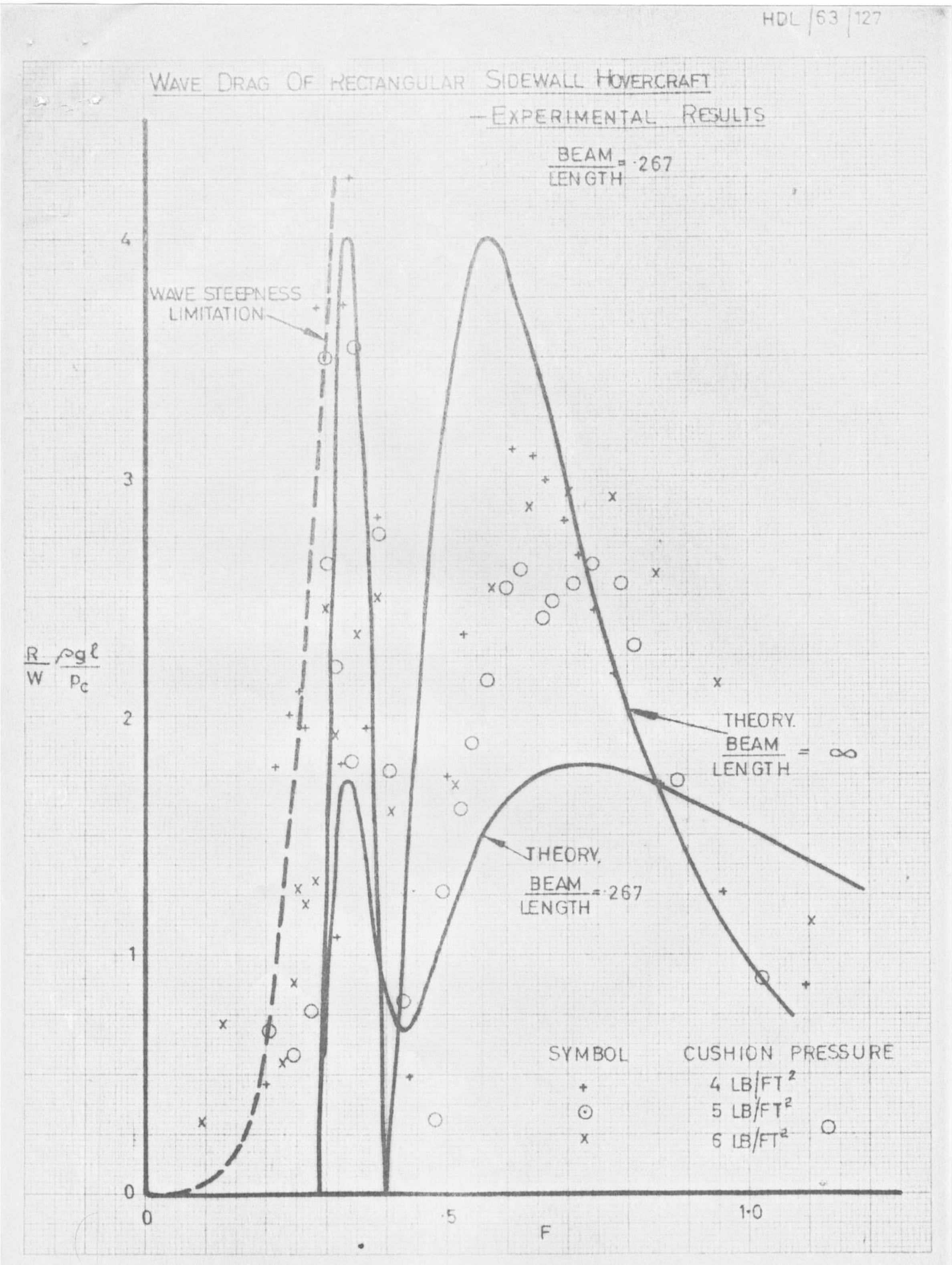

HDL/63/127
WAVE DRAG OF RECTANGULAR SIDEWALL HOVERCRAFT
— EXPERIMENTAL RESULTS
BEAM/LENGTH = ·267
WAVE STEEPNESS LIMITATION
R/W ρgℓ/pc
THEORY. BEAM/LENGTH = ∞
THEORY. BEAM/LENGTH = ·267
SYMBOL
CUSHION PRESSURE
4 LB/FT²
5 LB/FT²
6 LB/FT²
0
1
2
3
4
·5
1·0
F

FIG.15.

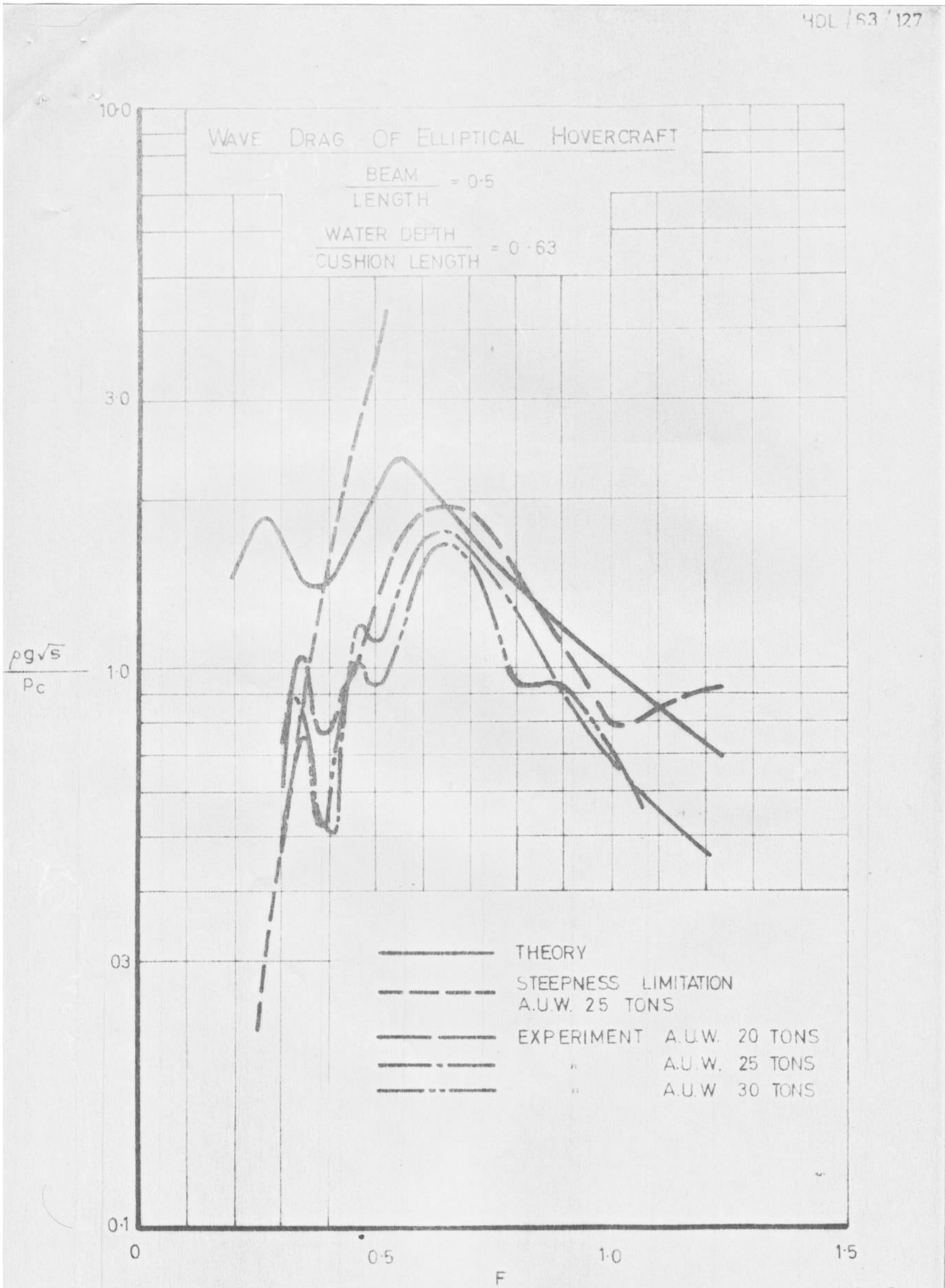

HDL / 63 / 127
WAVE DRAG OF ELLIPTICAL HOVERCRAFT
BEAM / LENGTH = 0·5
WATER DEPTH / CUSHION LENGTH = 0·63
10·0
3·0
1·0
03
0·1
ρg√s / Pc
0
0·5
1·0
1·5
F
THEORY
STEEPNESS LIMITATION A.U.W. 25 TONS
EXPERIMENT A.U.W. 20 TONS
" A.U.W. 25 TONS
" A.U.W 30 TONS

FIG.16.

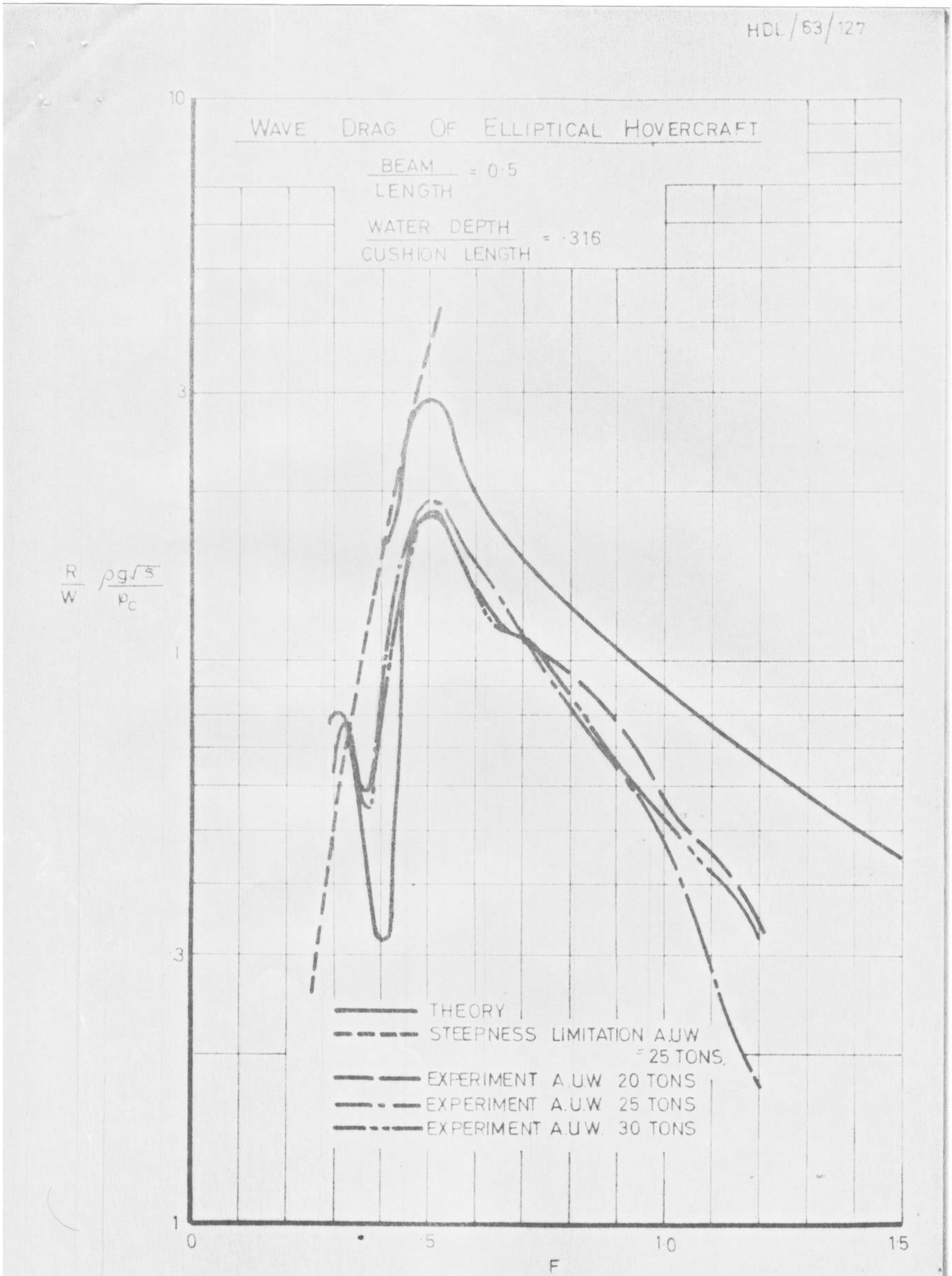

HDL/63/127
WAVE DRAG OF ELLIPTICAL HOVERCRAFT
BEAM / LENGTH = 0·5
WATER DEPTH / CUSHION LENGTH = ·316
R/W / ρg√S/p_c
10
3
1
·3
1
0
·5
1·0
1·5
F
THEORY
STEEPNESS LIMITATION A.U.W = 25 TONS.
EXPERIMENT A.U.W 20 TONS
EXPERIMENT A.U.W 25 TONS
EXPERIMENT A.U.W 30 TONS

FIG. 17

HDL/63/127

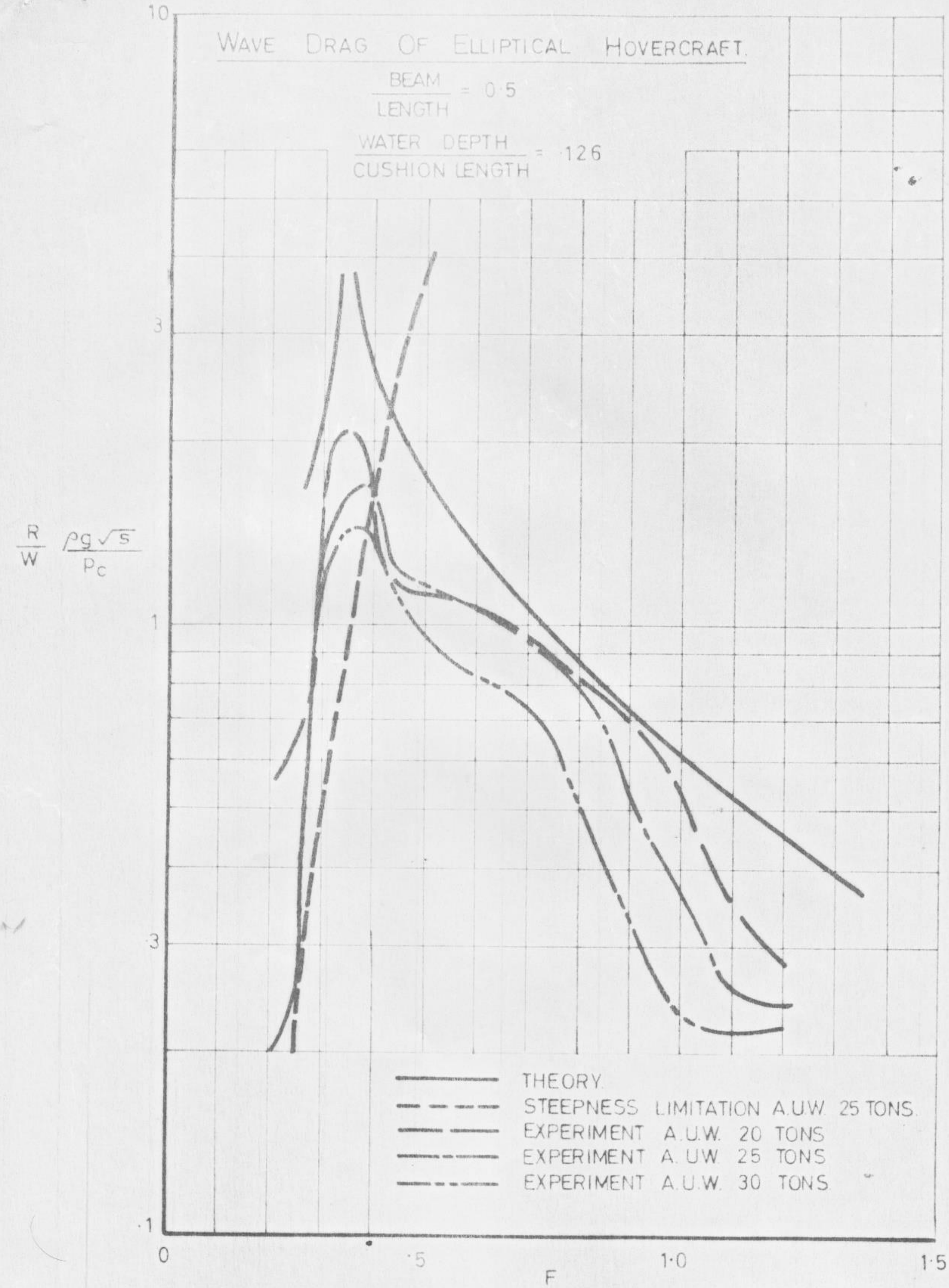
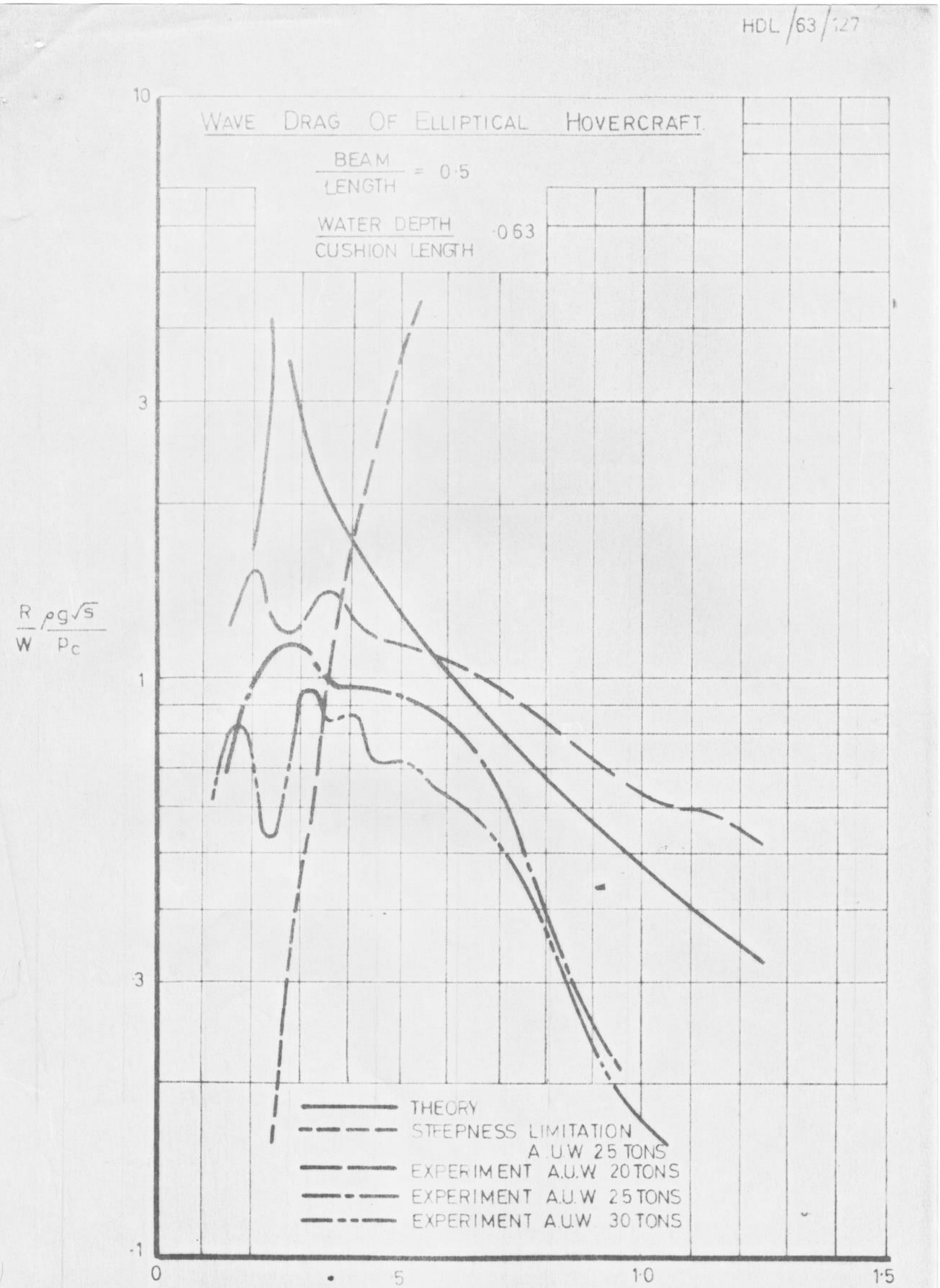


FIG. 18.


HDL /63 /127
WAVE DRAG OF ELLIPTICAL HOVERCRAFT
BEAM / LENGTH = 0·5
WATER DEPTH / CUSHION LENGTH ·063
R/W ρg√S/Pc
10
3
1
·3
·1
0
·5
1·0
1·5
F
THEORY
STEEPNESS LIMITATION A.U.W 25 TONS
EXPERIMENT A.U.W 20 TONS
EXPERIMENT A.U.W 25 TONS
EXPERIMENT A.U.W 30 TONS
FIG. 19.