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by

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ABSTRACT

Oblique towing tests were conducted with a Series 60 Model (L/B=7.5, B/T=2.5, C_B=.60) to study some general features of the wavemaking of a ship moving along at an angle of drift. Longitudinal force, lateral force and yawing moment were measured directly at six speeds ($gL/2V^2$=8,7,6,5,4 and 3) and three drift angles (β=0,±5 and ±10°). Wave-pattern resistance and cross force were derived from a Fourier transform analysis of "longitudinal" wave cuts recorded (parallel to the direction of motion) at four speeds ($gL/2V^2$=6,5,4 and 3) and three drift angles as above. Although the wave pattern at nonzero drift angles was highly asymmetric the effect on wave-pattern resistance was surprisingly small (<10%) and the wave-pattern cross force accounted for only about 15% of the total measured cross force even at the highest speed tested ($gL/2V^2$=3 or F_n=.41).

NOMENCLATURE

B	Beam
C	Cross force (see Fig. 1)
C_B	Block coefficient of hull form
$C_C=2C/\rho V^2 LT$	Coefficient of cross force C
$C_D=2D/\rho V^2 LT$	Coefficient of drag D
$C_N=2N/\rho V^2 L^2 T$	Coefficient of yawing moment N
$C_{RWP}=R_{WP}L/2\gamma_0^2 T$	Coefficient of wave-pattern resistance R_{WP}
$C_{TWP}=T_{WP}L/2\gamma_0^2 T$	Coefficient of wave-pattern cross force T_{WP}
$C^*(w,y)$	Modified Fourier cosine transform of wave cut
D	Drag (see Fig. 1)
$E(u)$	Nondimensional free-wave spectrum (amplitude)
$F(u),G(u)$	Nondimensional sine and cosine free-wave spectrum
$F_n=V/\sqrt{gL}$	Froude number
g	Acceleration due to gravity
$k_0=g/V^2$	Fundamental wave number
L	Length between perpendiculars
N	Yawing moment (see Fig. 1)
$Oxyz$	Coordinate system moving with the ship (see Fig. 1)
P	Index used to denote port side
R_{WP}	Nondimensional wave-pattern resistance (see Fig. 1)
S	Index used to denote starboard side
$S^*(w,y)$	Modified Fourier sine transform of wave cut y=const
T	Draft
T_{WP}	Nondimensional wave-pattern cross force (see Fig. 1)
u	Nondimensional transverse wave number
V	Ship speed
w	Nondimensional "longitudinal" wave number
X	Longitudinal force (see Fig. 1)
x	Nondimensional coordinate in direction of V (see Fig. 1)
Y	Lateral force (see Fig. 1)
y	Nondimensional coordinate normal to V (see Fig. 1)
z	Nondimensional vertical coordinate positive upward
β	Driftangle (see Fig. 1)
$\gamma_0=gL/2V^2$	Nondimensional speed parameter
$\zeta(x,y)$	Nondimensional free-surface elevation at point (x,y)
ρ	Density of water

[1]The experiments reported in this paper were done in 1971 when both authors were working for the *Sonderforschungsbereich 98* at Hamburg.

INTRODUCTION

This paper is probably an exception at this International Seminar on Wave Resistance in so far as it deals with the *cross force* associated with the wave pattern of a ship whereas almost all other papers focus properly on *resistance*. Although a method for calculating the cross force from measured wave cuts has been known in principle at least since 1964 (see Ref. 1), yet to the authors' knowledge this is the first time the method has been actually applied in tankery. The motivation for this work came from a broader project aimed at improving our capability to determine ship trajectories for arbitrary ship maneuvers, in particular those relevant for collision avoidance. It was expected that wave-pattern analysis would be a neat way of isolating free-surface effects also in maneuvering hydrodynamics. Oblique towing tests with force and wave measurements were conducted on a Series 60 model as a pilot study in 1971. For various reasons publication was deferred until the ISWR offered this ideal opportunity of presenting an out-of-the-rut application of wave-pattern analysis.

MODEL

The experiments were performed with a 15 foot model of parent form 4210 W of the well known Series 60 (L = 4.572 m, L/B = 7.50, B/T = 2.50, C_B = .600) which happened to be readily available at the Hamburg Ship Model Basin (HSVA Model No. 1512). It is a typical cargo-liner hull-form and has been the subject of numerous comparative studies among which Ref. 2 should be of particular interest in the present context.

TEST CONDITIONS

All tests were conducted in November 1971 in the large towing tank of the HSVA (280×18×6 m³) with the model constrained in all six degrees of freedom during the run. The rudder was fixed in its mean position and the propeller replaced by a fairwater. The tank water temperature was uniformly 15.8°C. A sand strip was used at L/20 aft of FP to stimulate turbulence. Measurements were taken at different constant speeds corresponding to round values of the parameter γ_0 and at three different drift angles including zero. It is not claimed that the test condition corresponds exactly to any particular condition encountered during an actual maneuver, which generally involves simultaneous motion in several degrees of freedom and nonzero rudder angle. However, it is believed to be a useful idealization for studying the general effect of drift angle on the wavemaking of a ship.

DIRECT FORCE MEASUREMENTS

As a first step horizontal forces X, Y and yawing moment N about a reference point O amidships (see Fig. 1) were measured at the following six speeds:

γ_0 =	8.00	7.00	6.00	5.00	4.00	3.00
F_n	.250	.267	.289	.316	.354	.408

with the drift angles of the towing device[1] set at β = 0, -5, -10, 5 and 10°. Cross force and drag were calculated by the simple transformation

$$C = Y\cos\beta + X\sin\beta \qquad (1)$$

$$D = Y\sin\beta - X\cos\beta \qquad (2)$$

The complete set of nondimensional coefficients C_D, C_C and C_N (see Nomenclature) is reproduced in Table 1. The scatter of the measured points was smoothed out in a least squares sense by fitting even quadratic polynomials in β to C_D and odd cubic polynomials in β to C_C and C_N. Cross curves of smoothed C_D, C_C and C_N for β = 0, 5 and 10° are plotted in Fig. 2 as functions of γ_0 to show the variation of horizontal forces with speed. The curve of C_D for β=0 shows, of course, the humps and hollows typical of wave resistance. But also the curves of C_C and C_N show a slight waviness. If we denote by ΔC_D the *additional* drag at nonzero drift angle then the variation of the three coefficients over the speed range tested can be expressed by the following ratios of standard deviations to mean values:

For	ΔC_D	C_C	C_N
β = 5°	.12	.08	.06
β =10°	.13	.06	.03

These show the degree of accuracy of the common assumption that drift induced forces are proprtional to speed squared.

WAVE PATTERN ANALYSIS

Foreword: As usual in wave-pattern analysis (see Ref. 3), in the following all quantities are understood to be *nondimensionalized* by multiplication with appropriate powers of the basic units g, V and ρ. For instance, coordinate $x = \underline{x}g/V^2$ and wave pattern resistance $R_{WP} = \underline{R}_{WP}g^2/\rho V^6$ where the dimensional physical quantities are here underlined for the sake of explanation. Such nondimensionalization simplifies the formulas and averages out the general effect of speed on various quantities thus facilitating comparison of diverse results.

[1] At the end of the first day of testing it was discovered that there was an alignment error of .5° between the towing device (carrying the force gauges) and the model so that the actual model drift angles were .5° higher. This was properly accounted for in the analysis of the horizontal forces and corrected before the wave cuts were taken on the next day, see Tables 1 and 2.

Longitudinal wave cuts y=const through the free surface $z = \zeta(x,y)$ advancing with the model were recorded at each of four speeds (γ_0= 6, 5, 4 and 3) and five drift angles (β= 0, ±5 and ±10°) using a stationary wave probe mounted at a transverse distance of 2.000 m on the port side of the track of the model center point O. Computer plots of the digitized wave cuts (40 points per second in real time) are reproduced in the top halves of Figs. 3 to 6, with the vertical scale exaggerated 333 1/3 times for the sake of clarity. There is a striking asymmetry in the wave pattern of the drifting model with the bow waves being much higher on the streamward side ($\beta > 0$), even though the bow passes closer to the probe on the other side ($\beta < 0$). For large negative x the wave cuts on either side approach the same asymptotic form (ignoring the extraneous effects of tank wall reflection).

The resistance R_{WP} and cross force T_{WP} associated with the measured wave pattern were calculated as follows. Define modified Fourier transforms of the wave cuts

$$C^*(w,y)+iS^*(w,y)= \int_{-\infty}^{\infty}\sqrt{w^2-1}\ \zeta(x,y)e^{iwx}dx \qquad (3)$$

where it is understood that the measured wave cut is to be truncated well ahead of the tank sidewall reflection and continued analytically to $x \to -\infty$ as explained in Ref. 3. Contributions of the wave pattern from either side are then given by

$$R_{WP}^{P,S}= \frac{1}{2\pi}\int_1^{\infty}\{(C^{*P,S})^2+(S^{*P,S})^2\}\frac{dw}{w^2\sqrt{w^2-1}} \qquad (4)$$

$$T_{WP}^{P,S}= \frac{1}{2\pi}\int_1^{\infty}\{(C^{*P,S})^2+(S^{*P,S})^2\}\frac{dw}{w^2} \qquad (5)$$

where the superscripts P,S denote port and starboard side respectively. For an asymmetric wave pattern the total forces become

$$R_{WP} = R_{WP}^P + R_{WP}^S \qquad (6)$$

$$T_{WP} = T_{WP}^P - T_{WP}^S \qquad (7)$$

For practical reasons the contributions of the starboatd side were obtained from wave cuts on the portside but with β reversed.

The wave induced drag and cross force were converted to coefficient form (see Nomenclature) and compared with the total measured drag and cross force (see Table 2). It is surprising that while the wave pattern accounts for up to 51% of the total drag at zero drift angle (Case γ_0=3), it accounts for practically none of the *additional* drag due to drift angle. What happens is that although the contributions to the wave drag from the two sides are very different their mean value is almost exactly the same as at zero drift angle! However, the wave pattern does account for up to 15% of the total cross force (Case γ_0=3, β=5°).

A closer scrutiny of the wave pattern is made possible by comparing the free-wave spectra which can be obtained as functions of the transverse wave number $u = w\sqrt{w^2-1}$ using the relations (see Ref. 4):

$$G(u)+iF(u) = \frac{4e^{iuy}}{2w^2-1}\{C^*(w,y)+iS^*(w,y)\} \qquad (8)$$

$$E(u) = \{G^2(u)+F^2(u)\}^{1/2} \qquad (9)$$

These are plotted in the lower halves of Figs. 3 to 6. Again, the asymmetry is evident. Theoretically the value at u=0 should be the same for positive or negative β and this is indeed observed remarkably in some cases, but unfortunately not in all.

CONCLUSIONS

Analysis of directly measured horizontal forces on an obliquely towed model verified the common assumption that these vary nearly with speed squared over the range of moderate Froude numbers. Analysis of measured wave cuts revealed that while the wave pattern can account for upto 15% of total cross force it does not seem to contribute at all to the extra drag at nonzero drift angles. The explanation is probably provided by a visual observation of the wave pattern (see Figs. 7 to 10). One is struck not only by the asymmetry of the wave pattern but even more so by the pronounced breaking of bow waves on the streamward side especially at high speeds and large drift angles. It follows that the wave pattern tells only part of the story. Further tests such as wake surveys behind surface models and force measurements on deeply submerged double models may be necessary to fully isolate free-surface effects from circulatory effects on a drifting ship.

ACKNOWLEDGEMENT

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Table 1 Measured force coefficients

No.	β/°	γ_0	$10^4 C_D$	$10^4 C_C$	$10^4 C_N$
1	.5	8.000	126	0	8
2	.5	3.017	308	- 6	13
3	.5	6.997	137	0	8
4	.5	4.001	181	8	9
5	.5	6.018	160	12	9
6	.5	4.993	162	10	9
7	- 4.5	7.990	152	- 207	- 84
8	- 4.5	3.008	332	- 238	- 95
9	- 4.5	6.973	156	- 206	- 86
10	- 4.5	3.978	202	- 241	- 81
11	- 4.5	5.994	177	- 197	- 88
12	- 4.5	4.988	186	- 210	- 88
13	- 9.5	7.990	219	- 519	- 185
14	- 9.5	3.008	402	- 613	- 201
15	- 9.5	6.950	211	- 531	- 186
16	- 9.5	3.984	269	- 580	- 194
17	- 9.5	6.012	234	- 510	- 198
18	- 9.5	4.988	248	- 533	- 203
19	5.5	7.981	153	223	109
20	5.5	3.008	353	242	132
21	5.5	6.958	170	218	112
22	5.5	3.981	215	264	118
23	5.5	6.006	185	221	117
24	5.5	4.988	197	229	114
25	10.5	8.000	238	580	226
26	10.5	3.006	448	635	247
27	10.5	6.997	236	586	228
28	10.5	4.005	310	624	236
29	10.5	5.994	255	565	234
30	10.5	4.993	273	589	239

Table 2 Summary of wave-cut analysis

		$10^5\times$	$10^5\times$	$10^4\times$	$10^4\times$	$10^4\times$	$10^4\times$
γ_0	β/°	$2R^P_{WP}$	$2T^P_{WP}$	C_{RWP}	C_{TWP}	C_D	C_C
6	0	1439	813	37	—	159	0
6	- 5	1076	432	38	12	181	211
6	+ 5	1859	1384				
6	-10	825	381	35	15	244	533
6	+10	1891	1537				
5	0	1100	983	41	—	165	0
5	- 5	761	543	43	19	189	222
5	+ 5	1523	1568				
5	-10	535	367	42	29	262	557
5	+10	1727	1917				
4	0	942	832	55	—	180	0
4	- 5	692	466	58	25	207	256
4	+ 5	1284	1304				
4	-10	551	305	60	42	290	597
4	+10	1485	1723				
3	0	1506	947	157	—	308	0
3	- 5	1205	565	160	38	339	246
3	+ 5	1858	1285				
3	-10	973	371	156	61	427	616
3	+10	2030	1536				

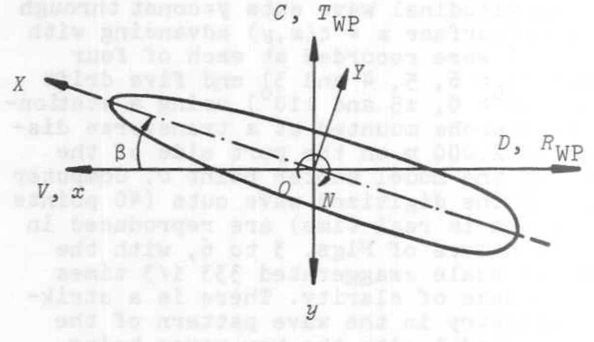

Fig. 1 Coordinate system and sign convention with all vectors shown positive

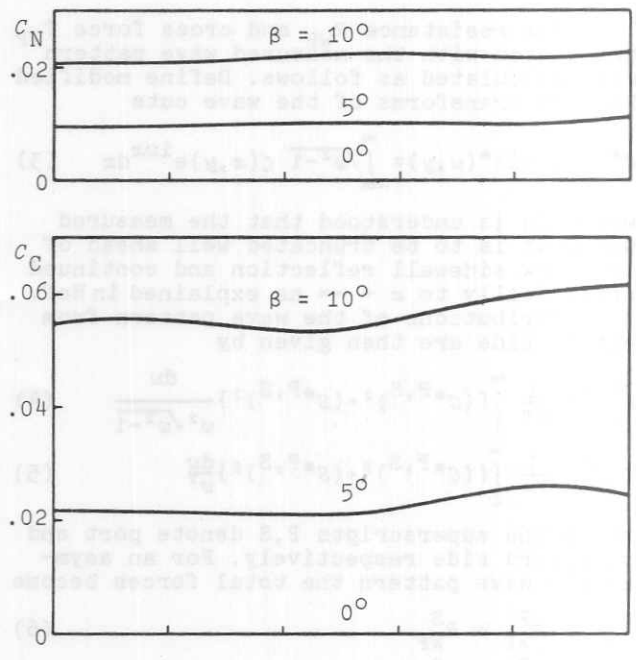

Fig. 2 Variation of horizontal force and moment coefficients with speed

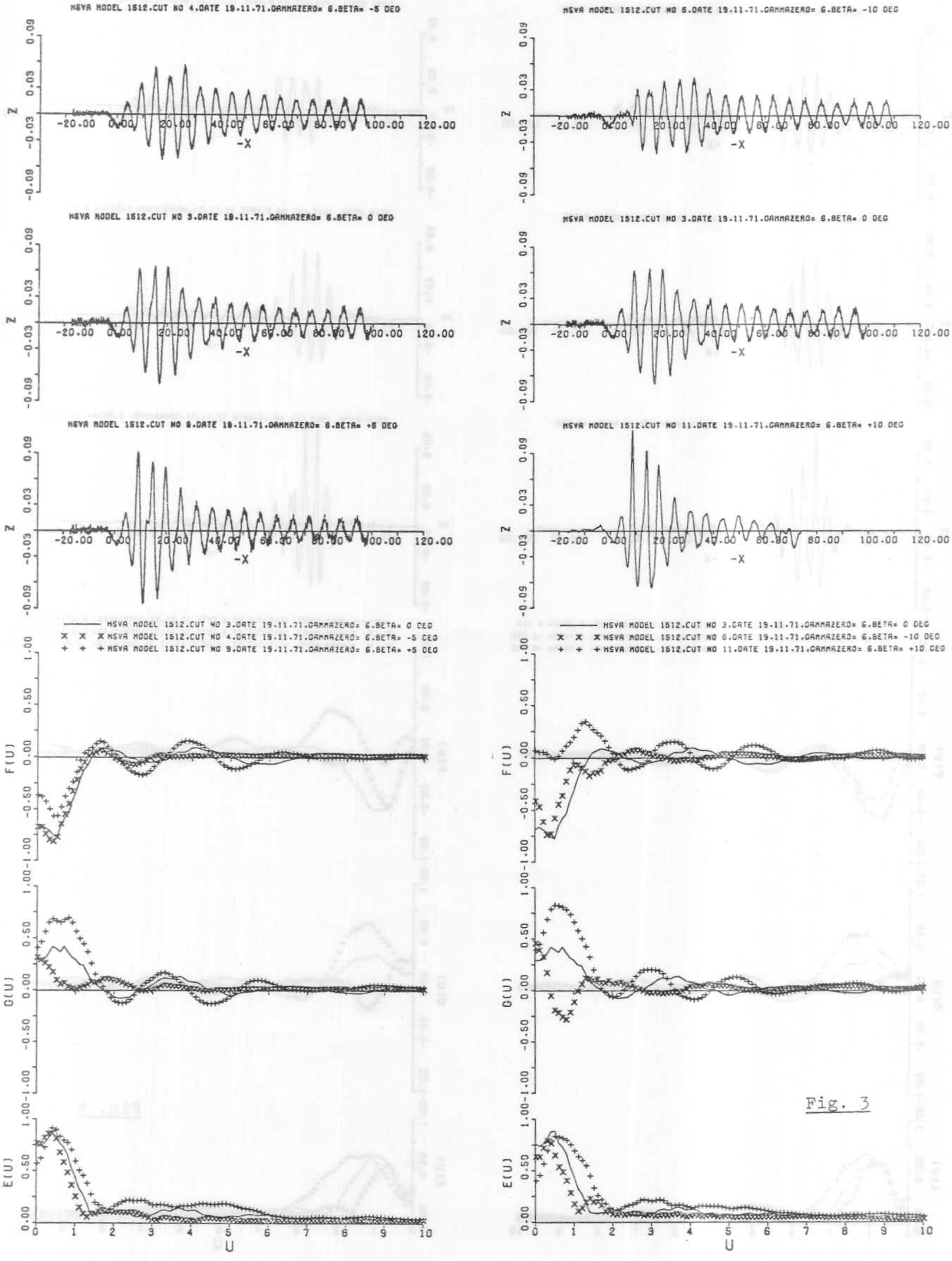

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Fig. 3

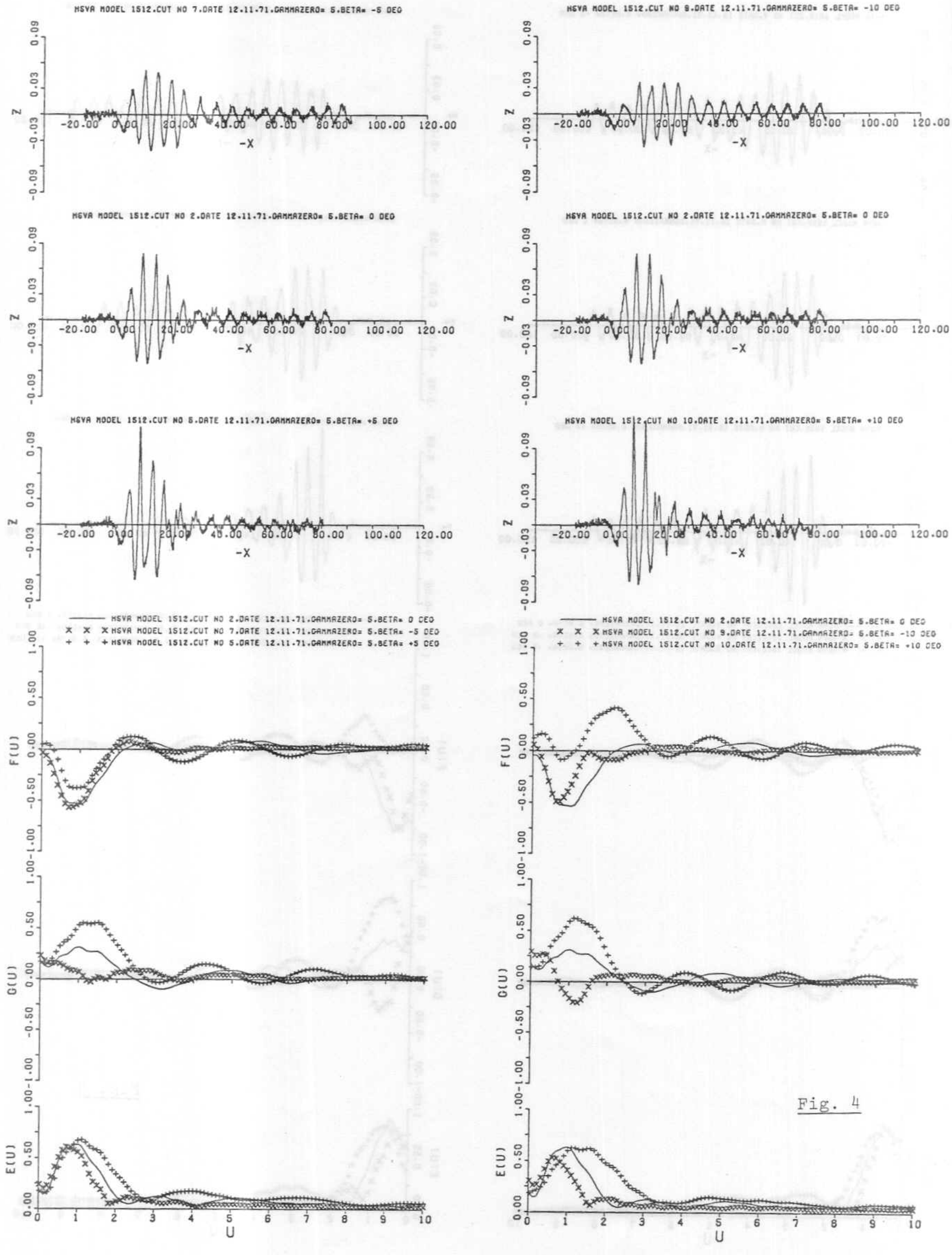
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Fig. 4

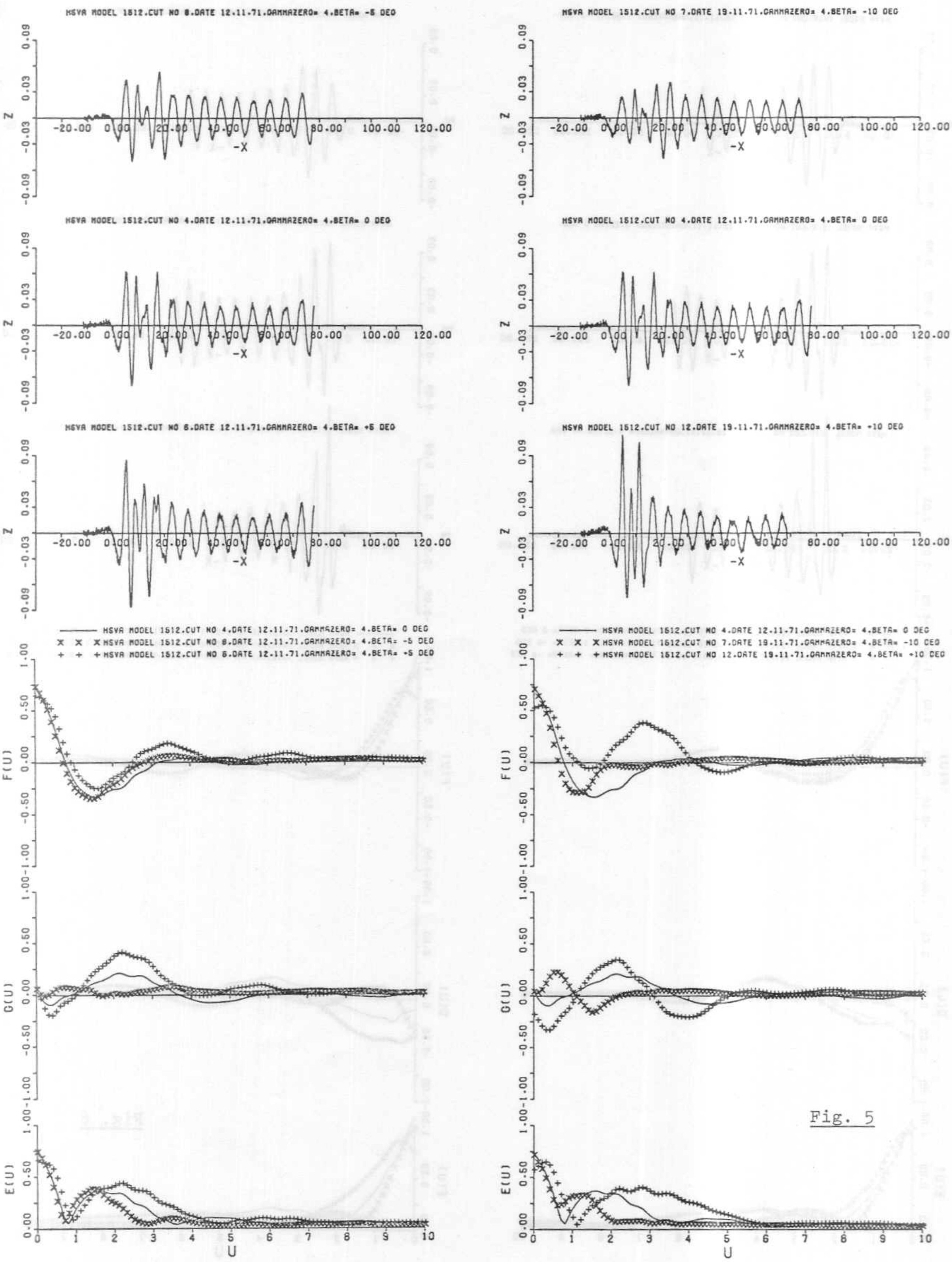

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Fig. 5

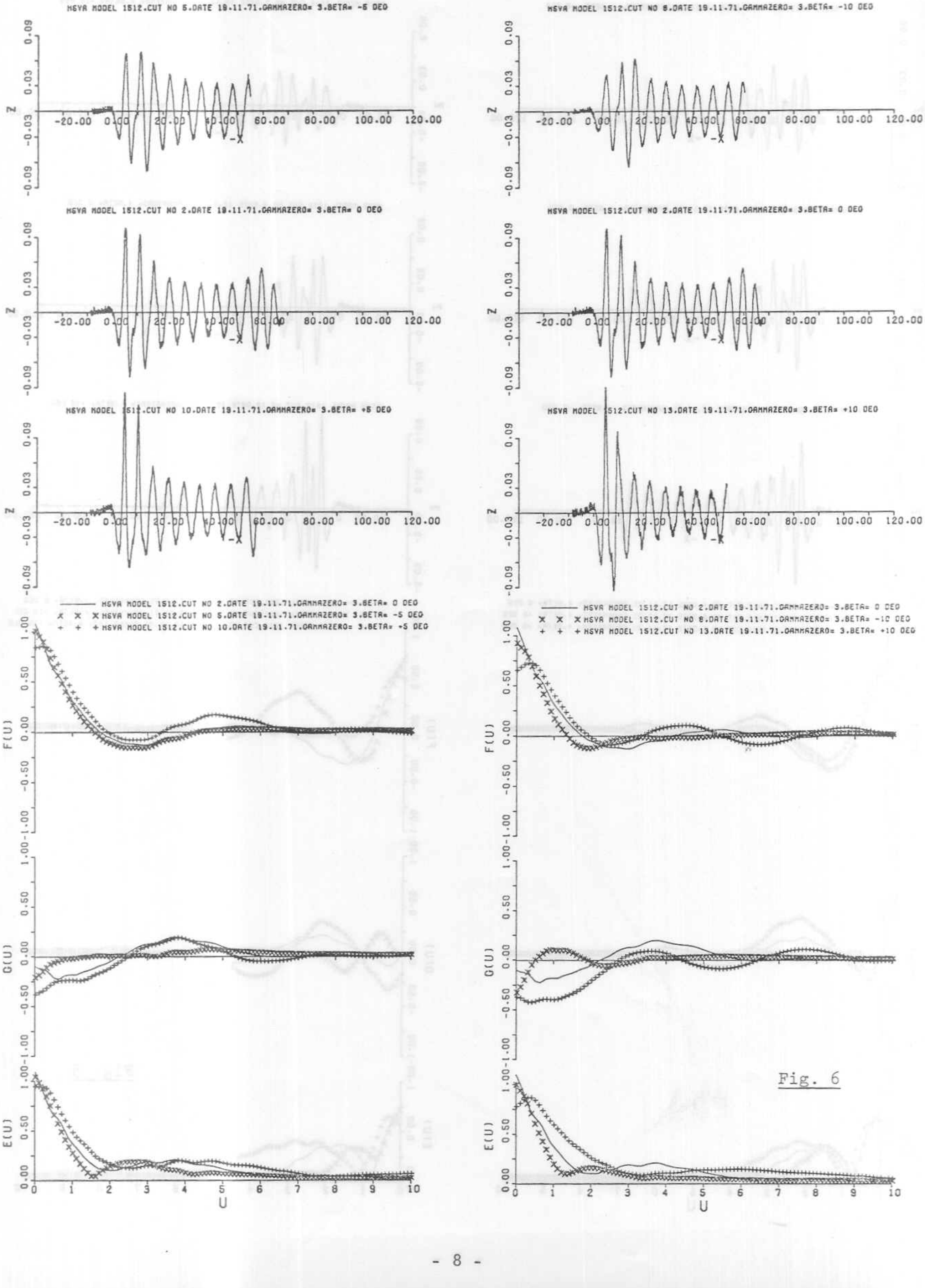

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Fig. 6

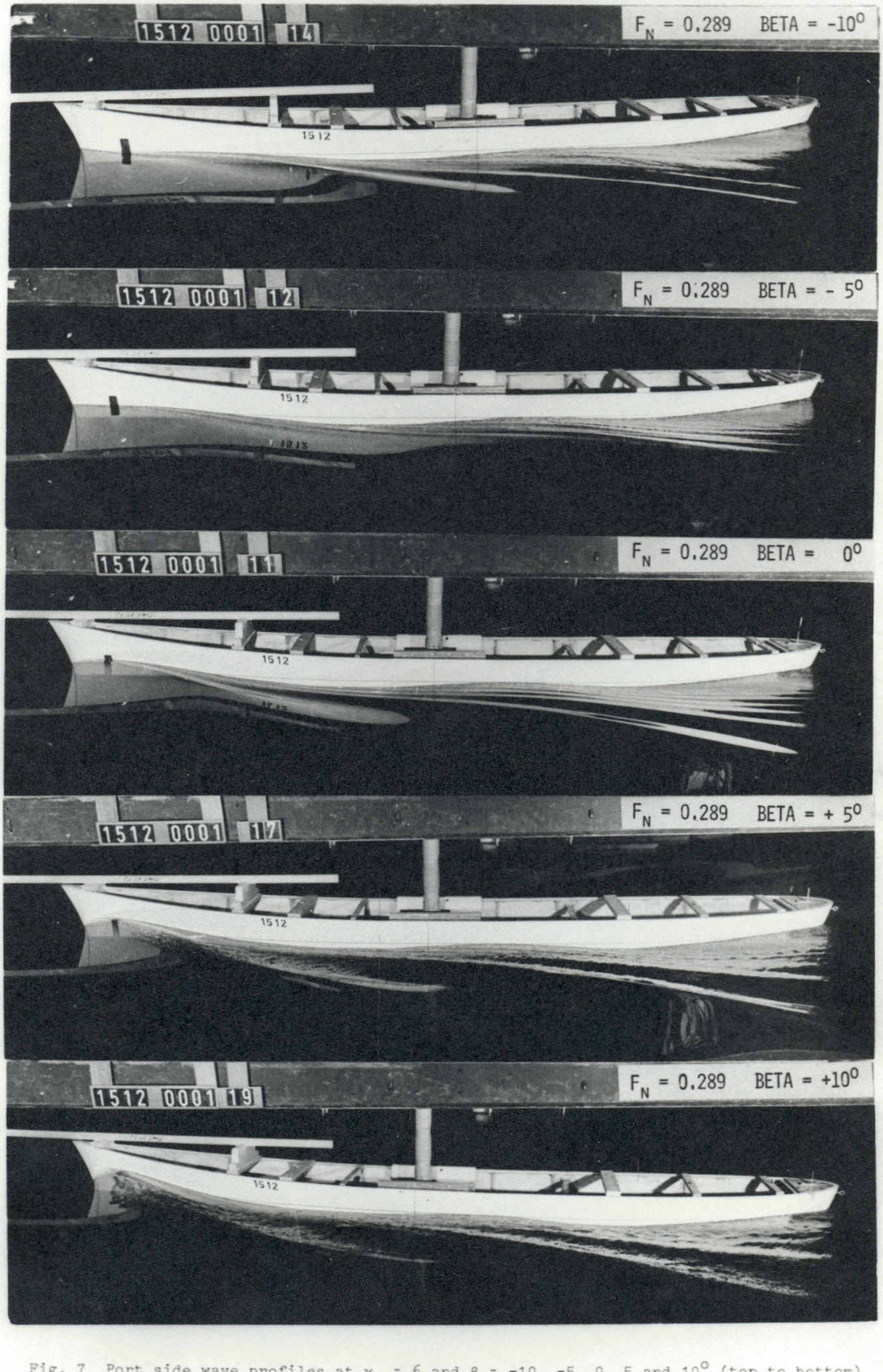

Fig. 7 Port side wave profiles at $\gamma_o = 6$ and $\beta = -10, -5, 0, 5$ and 10° (top to bottom)

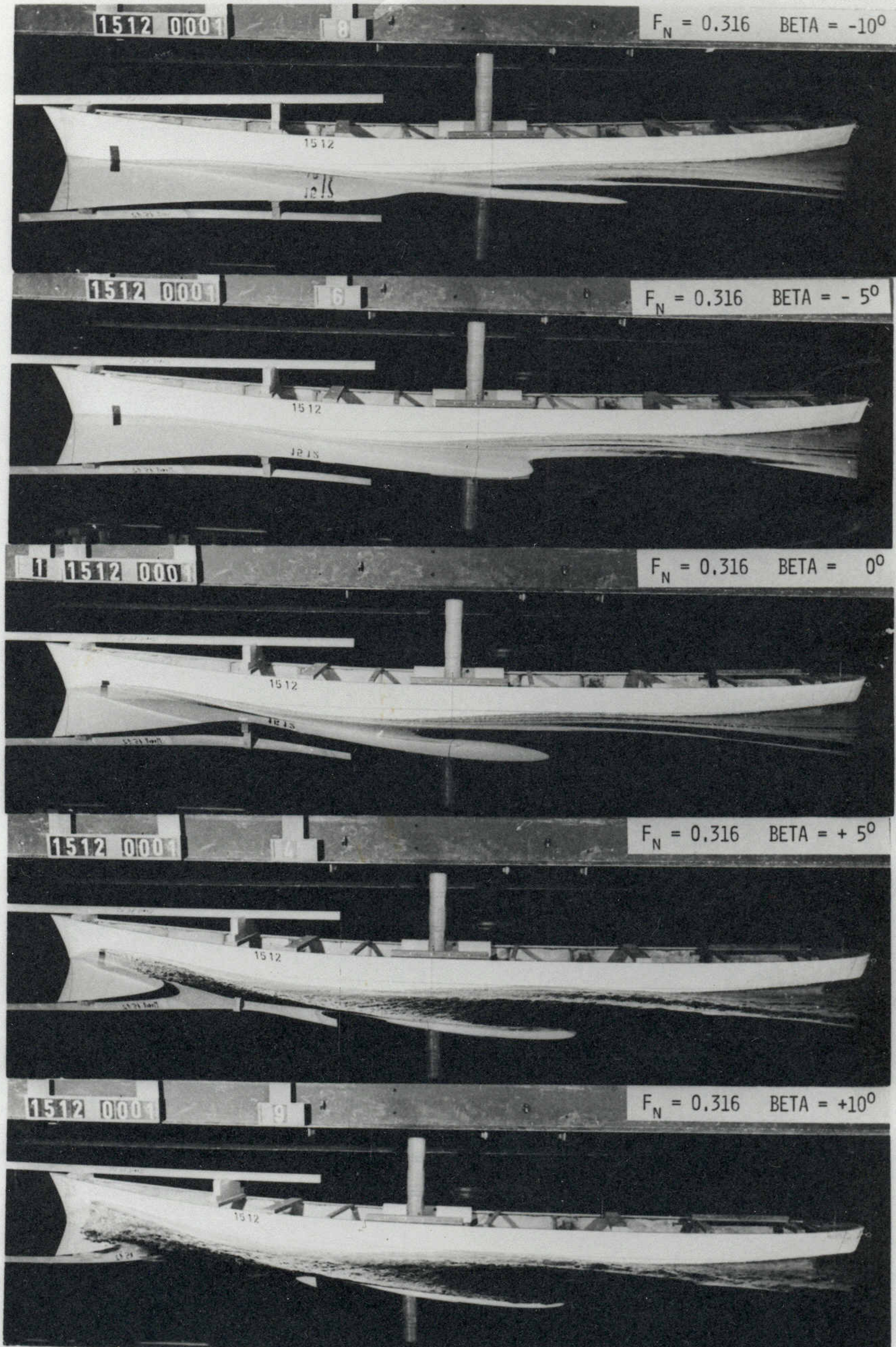

Fig. 8 Port side wave profiles at γ_o = 5 and β = -10, -5, 0, 5 and 10° (top to bottom)

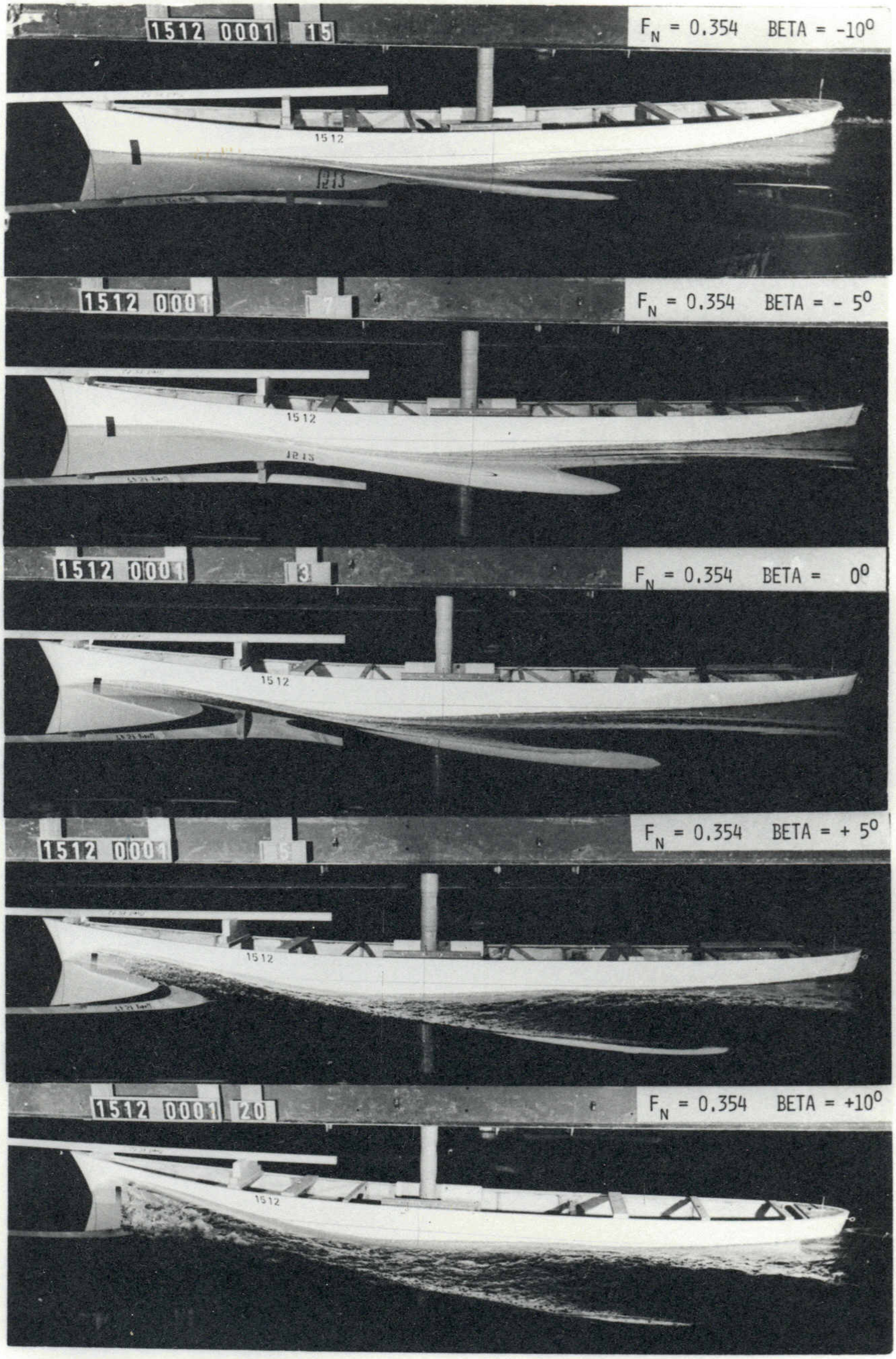

Fig. 9 Port side wave profiles at γ_o = 4 and β = -10, -5, 0, 5 and 10^o (top to bottom)

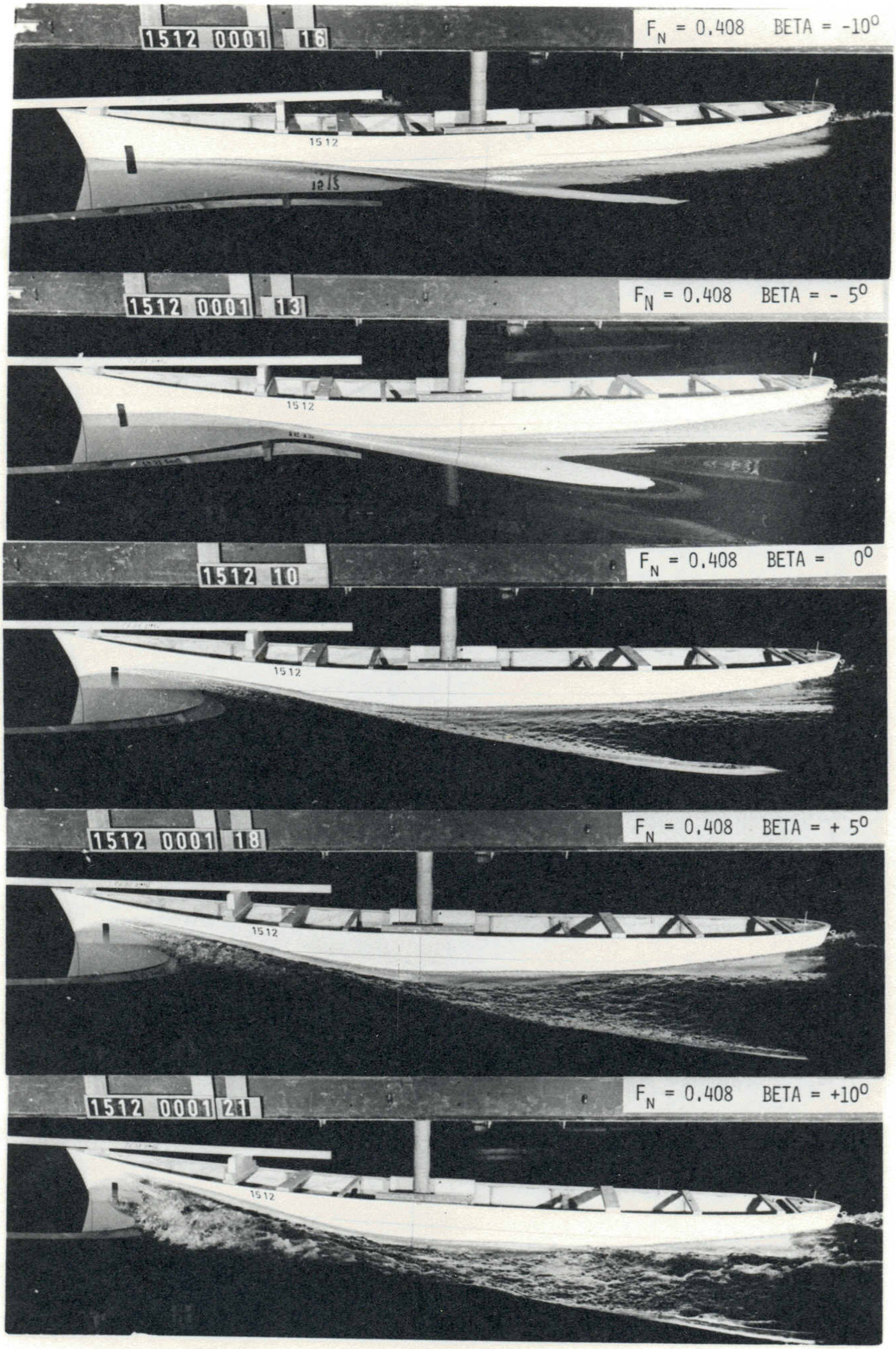

Fig. 10 Port side wave profiles at γ_o = 3 and β = -10, -5, 0, 5 and 10° (top to bottom)