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A Study on the Resistance and Wake Characteristics of a Full Ship Series

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Abstract

A series of towing tank tests were carried out for 18 full ship models of high block coefficients. The resistance coefficients and wake distribution at the propeller plane were measured and carefully examined. Regression analysis was employed to find out the relationships with the hull form parameters. Equations for wave resistance coefficient, form factor, and nominal wake are given. A harmonic analysis of measured wake was performed to look into the influence of the local stern shape on the magnitude of fluctuating wake components at three different radii. The amplitude of wake harmonics was also expressed by regression quations. It was found that the regression formulas were very useful in estimating resistance and circumferential wake characteristics of full ship models. It was also considered that the formulas presented in this paper could be utilized in the hull form improvement in a preliminary design.

1. Introduction

The towing tank tests have been the most effective way of hull form improvements for the last hundred years. However, in the preliminary stage of hull form determination, it is desirable to forecast the resistance and propulsive performance of a ship from the basic hull form parameters, ahead of the towing tank test. The statistical methods have been employed to elucidate the relationship of hull form and ship performance. In case of the full ship such as a bulk carrier and a tanker, however, only a few of series tests have been reported[1,2].The form resistance is usually a larger component than the wave-making resistance for the full ship. The shape of stern is more important than bow in determining the form resistance. On the other hand, the propulsive efficiency is also strongly influenced by the stern shape, but correlations are not clearly explored by the theoretical means. In the present study, 18 full ship models with the block coefficient of around 0.8 were chosen and resistance tests were performed for the range of Froude number between 0.11 and 0.19 (hereafter called as The SNUTT Series). The wake distribution in the propeller plane at the radii of 0.4R, 0.7R, 0.95R was measured for a design Froude number of 0.167 at Seoul National University Towing Tank. The experimental data obtained from the towing tank tests were statistically analyzed to produce reliable regression equations with hull form parameters, which can be used to estimate the resistance and the wake of full ships.A three-dimensional extrapolation method was utilized to identify the resistance components and results are statistically treated to produce regression formulas for wave-resistance coefficients and form factor for the design Froude number of 0.167. The nominal wake at the propeller plane was also analyzed and the regression equation is provided. A harmonic analysis of measured wake was performed to look into the influence of the local stern shape on the magnitude of fluctuating wake components at three different radii. The amplitude of wake harmonics was also expressed by regression equations. An efficient procedure, which provides reliable regression equations for ship performance based on a limited number of model tests, is proposed in the following. It is expected that this scheme can be used to estimate the resistance and propulsive performance of a full ship in the preliminary design of a hull form.

2. Selection of Model Ships

For a full ship, Todd's Series 60 of $C_b = 0.8$ with $LBP/B = 5.5$, 6.5, and 7.5 has been taken as standard hull forms[1]. In the present study three Todd's parent models were systematically combined to provide eighteen different hull form variations. The parent models were divided into three subdivisions; bow, parallel middle body, and stern parts with the length of 0.3L, 0.25L, and 0.45L, respectively. The resulting combination would give 27 different hull forms, However, the parallel middle body of $LBP/B = 5.5$ was excluded. Thus, a series of 18 hull forms were obtained to look into the effects of the variations in bow shapes, parallel-middle-body lengths and stern profiles with C_b between 0.793 and 0.816, and LBP/B of 5.75 ~7.5. Each model was named as three digit numbers, where the first digit represents LBP/B of bow part and so forth, for example, the model 567 was composed of the bow, middle body, and stern of $LBP/B = 5.5$, 6.5, and 7.5, respectively. The length of model ships ranged from 2.6m to 3.5m. The details of basic hull form parameters of 18 selected models are given in Table 2. The SNUTT Series can be considered as an extension of the Series 60 of $C_b = 0.8$ and a supplement to the MARAD Series[1,2,3]. The comprehensive study on propulsive efficiency using experimental and numerical methods was presented for eight model ships of this Series in a previous study, presented at PRADS'92[4]. The present study can be considered as a succession of the previous work of authors.

3. Experimental Results

3.1 Resistance and Wake Test

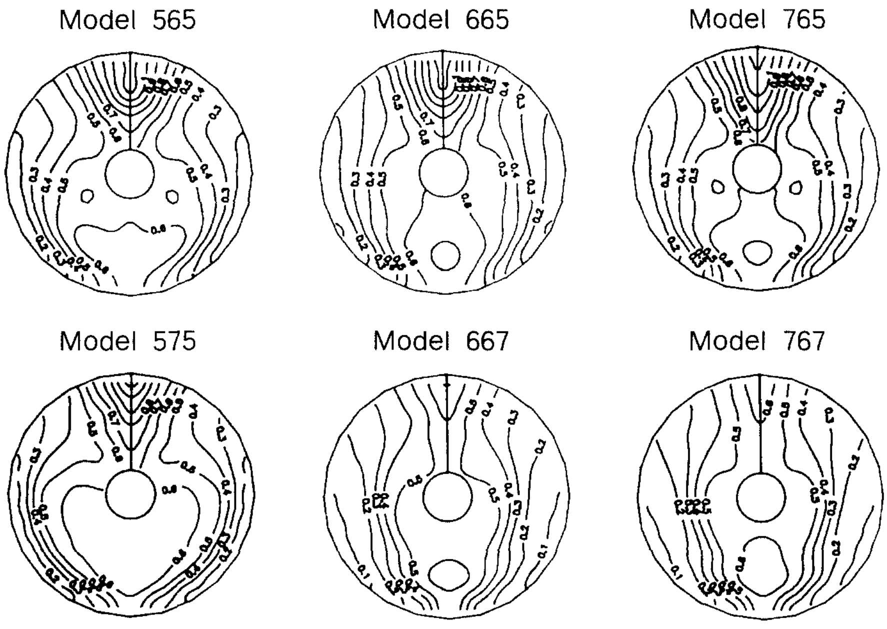
A three-dimensional extrapolation method was used to identify various resistance components from the towing tank tests. The form factor was obtained using a Prohaska's method with an exponent of four. The towing tank test results for 18 model ships are given in Table 1. The results obtained from the resistance tests will be discussed in the next chapter in conjunction with hull form parameters. The form factor and wave-making resistance coefficient are denoted as k and C_w, respectively, while W_n represents nominal wake fraction.

3.2 Wake Distribution

A wake rake with three Pitot tubes located at 0.4R, 0.7R, and 0.95R was used to document axial wake distributions at the propeller plane, where R represents the propeller radius of Todd[3]. Figure 1 shows the selected wake contours of six typical model ships. It was found that the wake distribution was more uniform when the stern and bow shape became fuller and the parallel middle body was shorter. The characteristics of circumferential wake distribution at the propeller plane are somewhat important because large variation of axial velocity in the circumferential direction can induce the fluctuation of pressure around a propeller and ship hull, causing a con-

Table 1. Towing tank test results of the SNUTT series

Model Ship	Experimental Result		
	K	W_n	W_n
565	0.3467	0.2869	0.5174
566	0.2544	0.3001	0.4719
567	0.1905	0.4986	0.3980
575	0.3592	0.2782	0.5300
576	0.2644	0.2404	0.4176
577	0.2080	0.3919	0.4079
665	0.3184	0.3048	0.4877
666	0.2048	0.2590	0.4281
667	0.1293	0.4341	0.3776
675	0.3452	0.2297	0.4969
676	0.2147	0.2797	0.4310
677	0.1459	0.3462	0.4079
765	0.2612	0.3689	0.5165
766	0.1576	0.3433	0.4162
767	0.1294	0.3549	0.3889
775	0.2856	0.3115	0.5410
776	0.2084	0.2243	0.4358
777	0.1262	0.3598	0.3955



Model 565 Model 665 Model 765

Model 575 Model 667 Model 767

Figure 1. Wake contours at the propeller plane of six typical model ships

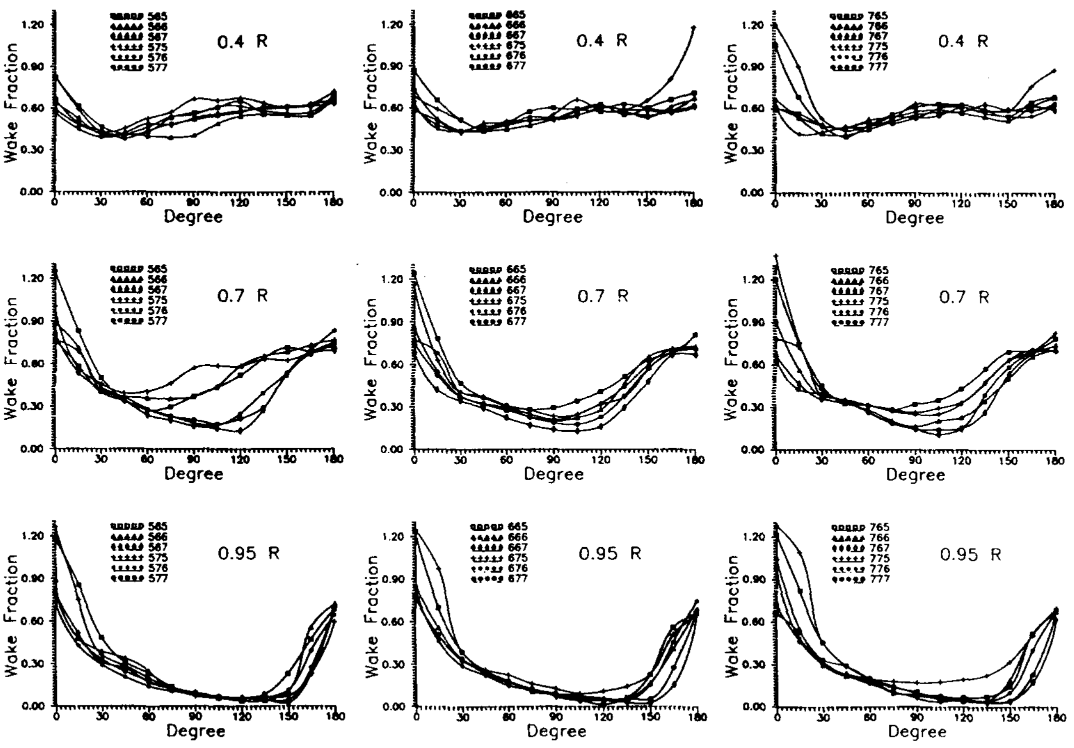


Figure 2. Circumferential wake distribution

siderable limitation in propulsive efficiency. The distributions of wake are shown in Figure 2. It was observed that the model ships with blunt bow have greater wake deviation at 0.7R due to the change of stern profiles. It is believed that if a ship has a blunt bow, the wake contours are more sensitive to the stern shape. It was also found that slight variation on the length of parallel middle body can cause a great deal of changes in wake distribution.

4. Statistical Analysis

4.1 Procedure for the Regression Analysis

Based on towing tank test results, the regression analysis was performed to find out the connectivity of the basic hull form parameters to resistance coefficients and nominal wake. Much efforts were directed to reducing independent regression variables keeping the high reliability. Process of regression analysis is described below.

A. Procedure:

1. Selecting the dominant hull form parameters
2. Examining relationships between hull form parameters
3. Investigating the dependency of resistance and wake upon hull form
4. Analyzing the results obtained from the previous three steps
5. Selecting regression variables and form of regression equations
   - linear, logarithmic, and 2nd order polynomial relations

Table 2. Hull form parameters of the SNUTT series

Ship	L_f / LBP	L_m / LBP	L_a / LBP	Cbf	Cba	L_cb / B	Ent.
565	0.2773	0.3304	0.3921	0.8600	0.7558	0.1390	0.2570
566	0.2572	0.3129	0.4298	0.8696	0.7330	0.1944	0.2463
567	0.2398	0.2977	0.4624	0.8780	0.7132	0.2494	0.2355
575	0.2658	0.3583	0.3758	0.8655	0.7657	0.1396	0.2511
576	0.2472	0.3395	0.4131	0.8744	0.7431	0.1953	0.2403
577	0.2311	0.3231	0.4456	0.8822	0.7234	0.2506	0.2296
665	0.3115	0.3157	0.3727	0.8437	0.7703	0.1025	0.2499
666	0.2900	0.3000	0.4100	0.8540	0.7450	0.1636	0.2391
667	0.2712	0.2863	0.4424	0.8630	0.7253	0.2187	0.2284
675	0.2992	0.3428	0.3579	0.8496	0.7765	0.1085	0.2439
676	0.2792	0.3259	0.3948	0.8592	0.7542	0.1643	0.2331
677	0.2618	0.3111	0.4270	0.8675	0.7346	0.2197	0.2224
765	0.3425	0.3023	0.3551	0.8289	0.7811	0.0714	0.2427
766	0.3198	0.2882	0.3919	0.8398	0.7559	0.1330	0.2319
767	0.3000	0.2758	0.4241	0.8493	0.7364	0.1882	0.2212
775	0.3295	0.3287	0.3416	0.8351	0.7863	0.0777	0.2367
776	0.3085	0.3134	0.3780	0.8452	0.7643	0.1335	0.2260
777	0.2900	0.3000	0.4100	0.8541	0.7450	0.1889	0.2152

Ship	*LBP/B*	Cwf	*Cwa*	Cvpf	Cvpa	Displ.	W.S.A
565	5.7500	0.8914	0.8697	0.9647	0.8690	0.0097	0.2601
566	6.2000	0.8993	0.8571	0.9670	0.8551	0.0083	0.2397
567	6.6500	0.9061	0.8463	0.9690	0.8427	0.0072	0.2226
575	6.0000	0.8959	0.8757	0.9660	0.8749	0.0090	0.2503
576	6.4500	0.9032	0.8627	0.9681	0.8613	0.0077	0.2316
577	6.9000	0.9095	0.8519	0.9699	0.8491	0.0067	0.2157
665	6.0500	0.8780	0.8765	0.9609	0.8789	0.0088	0.2481
666	6.5000	0.8866	0.8637	0.9634	0.8625	0.0075	0.2280
667	6.9500	0.8938	0.8530	0.9655	0.8503	0.0065	0.2126
675	6.3000	0.8829	0.8810	0.9623	0.8813	0.0081	0.2375
676	6.7500	0.8907	0.8688	0.9646	0.8680	0.0070	0.2209
677	7.2000	0.8975	0.8581	0.9666	0.8561	0.0061	0.2064
765	6.3500	0.8659	0.8824	0.9572	0.8852	0.0079	0.2359
766	6.8000	0.8748	0.8698	0.9599	0.8691	0.0069	0.2175
767	7.2500	0.8825	0.8590	0.9623	0.8572	0.0060	0.2033
775	6.6000	0.8710	0.8865	0.9588	0.8870	0.0074	0.2262
776	7.0500	0.8792	0.8744	0.9613	0.8741	0.0064	0.2110
777	7.5000	0.8865	0.8638	0.9634	0.8624	0.0056	0.1976

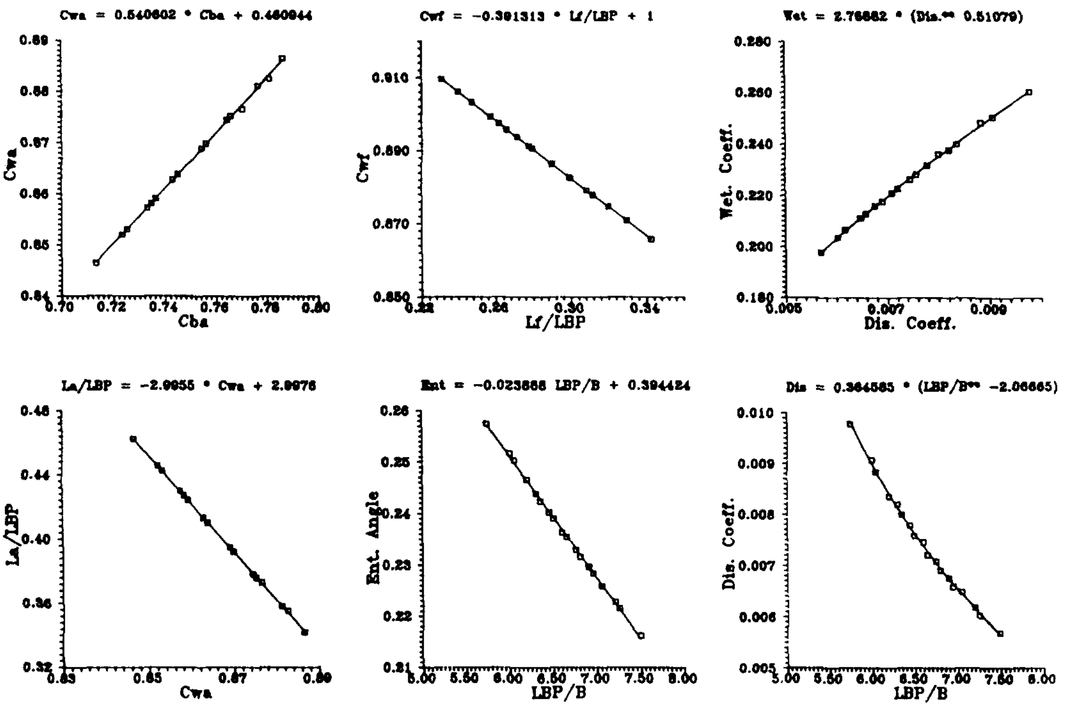


Figure 3. Correlation between Hull Form Parameters

6. Deriving the regression equations

B. Iteration: A.1 through A.6 steps until desired accuracy is obtained.

C. Final selection: regression relation of 2nd order polynomials with 3 independent variables

4.2 Correlations of Hull Form Parameters of SNUTT Series

To present the characteristics of hull form effectively, 14 different hull form parameters were chosen from the characteristics of bow, middle body, and stern. Correlations between hull form parameters were investigated to get most efficient sets of parameters. As shown in Figure 3, the set of L_f/LBP-Cbf-Cwf-Cvpf and the set of L_a/LBP-Cba-Cwa-Cvpa have linear relationships respectively, while the set of ∇/LBP^3-$W.S.A./LBP^2$-LBP/B has an exponential relationship. Hull form parameters defined in the present paper are given as follows.

L_f, L_a : length of bow, stern
Cbf, Cba : block coefficient of forebody, afterbody
Cwf, Cwa : water-plane area coefficient of forebody, afterbody and other
: nomenclatures follow conventional rules.

4.3 Statistical Analysis of the Resistance and Axial Wake

The influence of hull form parameters on the form factor was investigated to find a regression equation. Based on correlation coefficients and scattering diagrams, it was found that form factor decreases, if Cba, Cwa, displacement coefficient (∇/LBP^3), and entrance angle become smaller, or L_a and length-beam ratio(LBP/B) becomes larger. It was also observed that form factor is

Table 3 . The regression coefficients of C_w, k, W_n

No.	$C_w \times 1000$		k		W_n	
	Indep. Variables	Coeff.	Indep. Variables	Coeff.	Indep. Variables	Coeff.
1	$\log_{10}(L_f / LBP)$	+229.4	Cbf	+193.6	Cba	+42.96
2	$\log((Lcb / B)\times 10)$	+3.409	LBP / B	+50.25	LBP / B	+32.14
3	$\log_{10}$Cwf	+19870	$(\nabla / LBP^3)\times 10$	+2063	$(\nabla / LBP^3)\times 10$	+14260
4	$(L_f / LBP)^2$	+1234	Cbf	+13.58	Cba^2	+46.33
5	$((Lcb / B)\times 10)^2$	+0.7456	$(LBP / B)^2$	-1.584	$(LBP / B)^2$	-1.207
6	Cwf	-8512	$((\nabla / LBP^3)\times 10)^2$	-2718	$((\nabla / LBP^3)\times 10)^2$	-2188
7	$(L_f / LBP)\times (Lcb / B)\times 10$	+6.771	Cbf $\times (LBP / B)$	-22.21	Cba $\times (LBP / B)$	-109428
8	Cwf $\times (L_f / LBP)$	-4097	Cbf $\times 10 \times (\nabla / LBP^3)$	-946.4	Cbf $\times 10 \times (\nabla / LBP^3)$	-540.9
9	Cwf $\times (Lcb / B)\times 10$	-5.743	$(\nabla / LBP^3)\times (LBP / B)\times 10$	-117.1	$(\nabla / LBP^3)\times (LBP / B)\times 10$	-102.1
10	Const.	+8805	Const.	-333.2	Const.	-177.7

closely related to the block coefficient of afterbody(Cba), water-plane area coefficient of afterbody(Cwa), and the length of stern (L_a) . The relationships between hull form parameters and wave resistance were carefully studied, and it was found that the center of buoyancy(Lcb), and length of bow (L_f) , water-plane area coefficient of forebody(Cwf) have a strong influence on wave resistance. It was also found that nominal wake measured at the propeller plane was strongly connected to L_a/LBP, Cba, entrance angle, Cwa, ∇/LBP^3 and Lcb/B. Combination of hull form parameters which affect the form factor, wave resistance, and nominal wake were found. After a systematic process described in the previous section, wave resistance coefficient (C_w) , form factor(k), and nominal wake (W_n) are presented as regression equations. The final equations are given in Table 3. The regression equations given in Table 3 reproduced the experiments fairly well, as shown in the Table 4. In Table 4 the estimated values of C_w, k, and W_n using the newly obtained regression equations with multiple correlation and standard deviation error of estimate are compared with the experimental data to confirm the reliability of the present selection of independent variables in the regression equations. It is, of course, natural that the regression equation should be able to simulate the experimental data from which the regression coefficients are born. However, the agreement shown in Table 4 proves that the selection of combination of hull form parameters was performed successfully, considering that only three independent variables were used. In the preliminary stage of hull form design it will be handy to use fewer variables.

4.4 Statistical Analysis of Circumferential Wake Distribution

4.4.1 Harmonic analysis

Characteristics of the periodic fluctuation of wake in the circumferential direction are examined using a harmonic analysis. The harmonics of wake at $0.7R$ given in Table 5. It is likely that the

Table 4. Comparison of the estimated value of C_n, k, W_n with the experiments

Model Ship	$C_w \times 1000$		k		W_n	
	Exp.	Reg.	Exp.	Reg.	Exp.	Reg.
565	0.2869	0.2904	0.3467	0.3453	0.5174	0.5247
566	0.3001	0.3128	02544	0.2539	0.4719	0.4611
567	0.4986	0.4926	0.1905	0.1876	0.3980	0.4016
575	0.2782	0.2806	0.3592	0.3598	0.5300	0.5054
576	0.2404	0.2267	0.2644	0.2765	0.4176	0.4415
577	0.3919	0.3979	0.2080	0.1992	0.4079	0.4081
665	0.3048	0.3081	0.3184	0.3130	0.4877	0.5025
666	0.2590	0.2680	0.2048	0.1977	0.4281	0.4149
667	0.4341	0.4349	0.1293	0.1375	0.3776	0.3799
675	0.2297	0.2194	0.3452	0.3210	0.4969	0.5051
676	0.2797	0.2792	0.2147	0.2263	0.4310	0.4274
677	0.3462	0.3510	0.1459	0.1475	0.4079	0.4011
765	0.3689	0.3733	0.2612	0.2635	0.5165	0.5158
766	0.3433	0.3243	0.1576	0.1585	0.4162	0.4155
767	0.3549	0.3811	0.1294	0.1195	0.3889	0.3871
775	0.3115	0.3073	0.2856	0.2852	0.5410	0.5343
776	0.2243	0.2458	0.2084	0.2128	0.4358	0.4429
777	0.3958	0.3574	0.1262	0.1278	0.3955	0.3971
Multiple Correlation		0.9788		0.9935		0.9796
std.error of estimate		0.0221		0.0130		0.0158

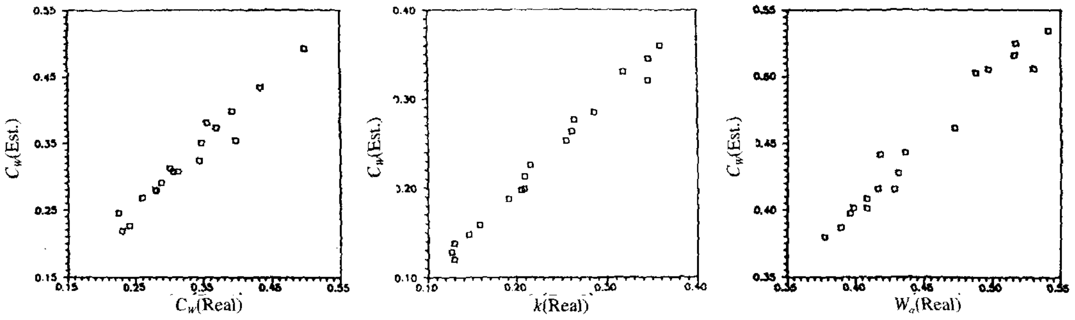


Figure 4. Comparisons of circumferential wakes obtained by the experiment and regression analysis

Table 5. Amplitude of harmonics in circumferential wakes(0.7*R*)

Period of Harmonics	Maximum Value	Minimum Value	Average Value	Standard Deviation
0π	0.57090	0.33240	0.44114	0.07380
1π	0.00917	-0.08890	-0.03517	0.02870
2π	0.29980	0.08740	0.24477	0.04579
3π	0.15030	-0.06900	0.02099	0.06217
4π	0.11760	0.01560	0.06554	0.02475
5π	0.08970	0.02250	0.04755	0.02029

Table 6. Regression equations of circumferential wake amplitudes in the propeller plane at the radius of 0.4R

No.	Indendent Variables	Dependent Variable					
		Wc4(0)	Wc4(1)	Wc4(2)	Wc4(3)	Wc4(4)	Wc4(5)
		Coefficients					
1	Cba	+1.980604	+3.418905	+9.999913	+4.466344	+6.630771	+5.646484
2	*LBP/B*	+0.189839	+0.160652	+0.001877	+0.172157	-0.006971	+0.116020
3	∇ / LBP^3	+82.08682	+63.54253	+10.03267	+81.68934	+7.188829	+47.44604
4	Y18-7R	+53.67699	+1084.389	-22.79915	+656.1880	+197.0671	+386.9516
5	Y18+7R	+2032.062	-4414.542	+5595.740	-3970.352	+2598.368	-3474.659
6	A18	-1938.071	+4657.400	-5560.148	+3999.499	-2521.860	+3484.340
7	Y18-7R	-1372.771	+730.1165	-3435.585	+941.0318	-2579.167	+1349.455
8	Y18+7R	+332.3114	-337.1115	+732.9762	-409.6971	+445.5115	-385.6383
9	A19	+563.9478	-2005.807	+1930.294	-1287.232	+1144.663	-1208.667
10	Const.	-272.06	+309.36	-633.58	+356.67	-361.31	+334.04

Table 7. Regression equations of circumferential wake amplitudes in the propeller plane at the radius of 0.7R

No.	Indendent Variables	Dependent Variables					
		Wc7(0)	Wc7(1)	Wc7(2)	Wc7(3)	Wc7(4)	Wc7(5)
		Coefficients					
1	Cba	+1.798177	+5.066609	+27.31792	-5.678527	-3.002774	+0.668116
2	LBP/B	+0.143894	-0.014175	-0.04348	+0.085141	-0.010097	+0.006665
3	∇ / LBP^3	+115.5414	-5.919971	-28.75966	+74.53117	+4.182621	+5.840218
4	Y18-7R	-429.5970	+61.162	+502.6192	+490.6561	+132.6162	+286.0343
5	Y18+7R	-6379.341	+2890.97	+5105.603	-6274.578	+281.8460	-872.657
6	A18	+5920.226	-2811.598	-5005.263	+6294.547	-188.1412	+928.4081
7	Y18-7R	+5026.515	-2944.453	-6221.483	+3750.098	-286.7631	-43.61143
8	Y18+7R	+1129.990	+519.0512	+933.3104	-816.1238	+96.33566	-53.82674
9	A19	-1622.382	+1501.006	+2881.089	-2720.891	-142.4817	-376.3397
10	Const.	+909.71	-405.91	+747.52	+681.127	-71.525	+51.435

Table 8. Regression equations of circumferential wake amplitudes in the propeller plane at the radius of 0.95*R*

No.	Indendent Variables	Dependent Variables					
		Wc95(0)	Wc95(1)	Wc95(2)	Wc95(3)	Wc95(4)	Wc95(5)
		Coefficients					
1	Cba	-5.016169	-17.58297	-3.700818	-18.13826	-2.088829	-10.71571
2	*LBP/B*	+0.067880	+0.378075	-0.086778	+0.152607	-0.077085	-0.016402
3	∇ / LBP^3	+48.43357	+161.9769	-16.75502	+64.10416	-29.30357	-4.148642
4	Y18-7R	+404.3599	+465.8383	-551.6277	+377.9095	+123.3242	+236.4655
5	Y18+7R	+1554.798	-1026.741	-327.9079	+264.0860	-232.9742	+1057.167
6	A18	-1411.446	+1432.748	+589.9656	+6.187631	+322.0921	-823.6114
7	Y18-7R	-1651.879	+1614.029	-514.3626	-236.7379	-83.34611	-730.6941
8	Y18+7R	+295.2957	+1.394588	+124.7072	+163.8569	+36.58154	+252.4764
9	A19	+272.8377	-2165.202	-756.8506	-739.7703	-239.7204	-242.7272
10	Const.	-244.49	+6.9705	-85.250	-120.17	-17.065	-195.72

amplitude of harmonics of circumferential wake at 0.7*R* decreases as a amplitude increases. The amplitude at two other radii will not be shown here since the similar tendency was found.

4.4.2 Regression Analysis

Selection of the hull form parameters

Variation of wake in the circumferential direction was related to the regression variables of *LBP/B*, ∇/LBP^3 and Cba. Besides, additional six parameters representing the stern shape are utilized for representation of the amplitude of harmonics of wake distribution in the circumferential direction, which are given below.

Y18-7R : breadth at the position of 0.7*R* vertically downward from the center
: the center of propeller at station 18, divided by maximum breadth
Y18+7R : breadth at the position of 0.7*R* vertically upward from the center
: of propeller at station 18, divided by maximum breadth
A18 : sectional area at station 18, divided by sectional area at midship
Y19-7R : breadth at the position of 0.7*R* vertically downward from the center
: of propeller at station 19, divided by maximum breadth
Y19+7R : breadth at the position of 0.7*R* vertically upward from the center
: of propeller at station 19, divided by maximum breadth
A19 : sectional area at station 19, divided by sectional area at midship

4.4.3 Regression equations

Using the hull form parameters chosen above, the regression analysis was performed to find out the relationship of harmonic amplitude with variables of *LBP/B*, ∇/LBP^3, Cba, and six parameters representing stern shape. The regressionequations with linear form are set out as given in Table 6, 7, and 8 for the radii of 0.4*R*, 0.7*R*, and 0.95*R*, respectively, where Wc(o) is a circumferentially averaged wake fraction and Wc(n) denotes to the amplitude of harmonics of n period of n=1,2,3,4,5. The estimated amplitude of harmonics of wake in circumferential direction was obtained from the regression equations given in Table 6, 7, and 8 and Fourier inverse transformation was carried out to yield the circumferential wake distribution for the model ships 665, 666, and 667, as shown in Figure 4. It is shown that the agreement between regression results and the experimental data is fairly good. It should be mentioned that utilizing this regression equations, a better propulsive efficiency can be achieved by reducing the fluctuation of wake Wc(n), n=1-5.

Summary

The measurements of resistance coefficients and wake distribution at the propeller plane were carried out for 18 full ship models. The independent regression variables were carefully selected after investigating correlation between hull form parameters and resistance and wake distribution. Regression equations for the form factor, wave resistance coefficient, and nominal wake were sought using only three sets of hull-form parameter combination. The circumferential distribution of wake in the propeller plane was examined using a harmonic analysis and equation for the amplitude of harmonics was given after regression.The newly obtained equations can be applied to improve the resistance performance of a full ship. Regression equations to estimate the distributions of circumferential wake can be also applied for the improvement of hull forms having highly uniform wake distribution at the propeller plane. It is recommended that more efforts should be concerted to obtain wider range of experimental data for the practical application to hull form development.

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