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A CALCULATION TOOL FOR SCREW PROPELLERS PERFORMANCES IN NON-AXIAL FLOW

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ABSTRACT

At first the paper describes the experimental methodology utilized for the screw propellers tested in inclined flow at the Naval Engineering Department of the University "Federico II" of Naples.

Then the paper gives a mathematical model, obtained by means of the regression analysis on the experimental data, in order to evaluate the characteristic of a screw propeller acting in non-axial flow from that one, in axial flow.

At the end an experimental validation of the mathematical model has also been carried out by using a sample of screw propellers having different geometrical characteristics from those ones used for the model generation.

INTRODUCTION

A regression analysis has been carried out on the experimental results of a sample of screw propellers tested in non-axial flow.

At first the paper briefly describes the experimental methodology utilized for the screw propellers tested with the shaft inclination angle of 0°, 5°, 10°, 15°, 20°.

Then, by means of the regression analysis of the experimental data, the paper gives a mathematical model of the differences between the hydrodynamic performance coefficients relative to the non-axial flow and those ones relative to the axial flow.

These differences have been expressed as functions of the geometrical parameters, the cinematic parameters and the shaft inclination angle of the screw propeller.

An experimental validation of the mathematical model has been carried out by using a sample of screw propellers different from those ones used for the model generation.

The results so obtained are very reliable and therefore provides the naval designer with a very useful calculation tool for the choice of a screw propeller acting in non-axial flow, the open water characteristic of the screw propeller in axial flow being already given.

THE EXPERIMENTAL METHODOLOGY

A sistematic experimental study has been carried out at the towing tank of the Naval Engineering Department of the University "Federico II" of Naples, by testing 21 B-Wageningen screw propellers.

The relative experimental methodology has been based on the following principles:

- It is necessary to avoid all the phenomena depending on kinematic parameters, which are different from the advance coefficients. Therefore, the screw axis draught is experimentally arranged to avoid surface waves generation (indipendence from the Froud number) and the number of revolutions has been selected in order to assure both the absence of cavitation phenomena and the existence of a hydrodynamic turbolent flow (indipendence from the cavitation index and the Reynolds number).

- It is necessary to neglect all the forces acting on the boss, both the viscous drag forces (such as those generated in the shaft line bearings) and the gravitational forces (like weight and buoyancy, trasferable within a Froud type law of comparison) therefore we have been assumed the following expression for the hydrodynamic Σ_e action operating on the propeller blades [8]:

$$\Sigma_e = \Sigma_{tot} - \left[\Sigma_{tot}^{(m)} + \left(\Sigma_{st} + \Sigma_g \right) - \left(\Sigma_{st}^{(m)} + \Sigma_g^{(m)} \right) \right] \qquad (1)$$

being:

Σ_e = the hydrodynamic action due only to the propellers blades;

Σ_{tot}, $\Sigma_{tot}^{(m)}$ = total action on the propeller and the boss respectively;

Σ_{st}, $\Sigma_{st}^{(m)}$ = static action (corresponding to the rest level) on the propeller and the boss;

Σ_g, $\Sigma_g^{(m)}$ = gravitational forces acting on the propeller and the boss.

The law of similitude, therefore, can be expressed in the general form:

$$K = K\,(s, \gamma, J) \qquad (2)$$

where:

γ = shaft inclination angle;

s = appropriate set of geometrical shape parameters;

K = propeller coefficient;

J = advance coefficient.

The sistematic tests on the 21 B-Wageningen propellers have been carried out in axial and non-axial flow by adopting for each propeller five inclination angles in the vertical plane: 0°, 5°, 10°, 15°, 20°.

The adopted instrumentation mainly consists of a Kempf & Remmers H29 dynamometer, schematized in fig. 1, which allows to know the test values of the revolutions number n and of the following quantities:

T_γ = thrust;

Q_γ = torque;

Z_γ = vertical force;

$M_{z\gamma}$ = moment acting around z axis.

These forces and moments are sketched in fig. 2.

UTILIZATION OF THE EXPERIMENTAL RESULTS

The K(J) functions utilizable in the screw propeller's design are normally referred to the axial flow conditions, while the actual work conditions of a ship screw propeller are generally those ones of non-axial flow. Therefore it would be very useful for the marine designer to know the following functions:

$$\Delta K(s,\gamma,J) = K(s,\gamma,J) - K(s,0°,J) \qquad (3)$$

In this way it is possible to obtain for any screw propeller the K-functions relative to the real work conditions, summing up the ΔK functions to the experimental functions, obtained by open water tests in axial flow:

$$K(s,\gamma,J) = K(s,0°,J) + \Delta K(s,\gamma,J) \qquad (4)$$

In order to carry out the functions ΔK, being already available the experimental data relative to the B-Wageningen sample, have been assumed the following hypotheses:

- the s-set parameters coincides with the following one:

$$\{ P/D, A_e/A_o, Z \}$$

being:

P/D = pitch ratio;

A_e/A_o = blade area ratio;

Z = blades number.

- the ΔK functions are indipendent from the Z parameter. Therefore is valid the following functional representation:

$$\Delta K = \Delta K\,(P/D, A_e/A_o, \gamma, J). \qquad (5)$$

It follows from these hypotheses that a numerical representation of the ΔK functions can be obtained by a regression analysis, carried out on the experimental data, relative to a sample of B-Wageningen screw propellers.

REGRESSION ANALYSIS

The regression analysis has been carried out by using RLSEP routine of the STAT-LIBRARY of IMSL Libraries, implemented on a MicroVax II (Digital).

The following indipendent parameters have been assumed:

$$P/D,\ A_e/A_o,\ \gamma,\ J.$$

The dipendent parameters are the variations ΔK, previously defined, of the following coefficients:

$$K_{T_\gamma} = \frac{T_\gamma}{\rho n^2 D^4}$$ thrust coefficient;

$$K_{Q_\gamma} = \frac{Q_\gamma}{\rho n^2 D^5}$$ torque coefficient;

$$K_{Z_\gamma} = \frac{Z_\gamma}{\rho n^2 D^4}$$ vertical force coeffient.

being:

ρ = water density;

D = propeller diameter;

n = number of revolutions.

These coefficients could also be used in order to obtain the expression of the efficiency by the following relation:

$$\eta_{o_\gamma} = \frac{J}{2\pi}\frac{K_{T_\gamma}\cos\gamma - K_{Z_\gamma}\,sen\gamma}{K_{Q_\gamma}} \qquad (6)$$

As for the range of the used sample the following values have been considered (Table I):

- five values of P/D, spaced by .20 in [.6, 1.4];
- five values of A_e/A_o, spaced by .15 in [.35, .95];
- five values of γ, spaced by 5° in [0°,20°].

As for as J, $\Delta K_{T\gamma}$, $\Delta K_{Q\gamma}$ and $\Delta K_{Z\gamma} = K_{Z\gamma}$ are concerned the experimental values have been considered.

As for the regression equation we assumed a polynomial equation of degree m initially equal to 1 and then increasing until the steady conditions of the mean squares for the residual sources of variation are practically reached.

The values, so obtained, for m were equal to three in any case.

As, with four indipendent parameters, the number of the indipendent variables of the polynomial regression equation of the selected order m is given by:

$$\frac{(m+4)!}{4!\,m!} - 1$$

We have consequently the construction of an input data matrix of $\frac{(m+4)!}{4!\,m!}$ columns.

In the table II, are reported the regression coefficient parameters for the $\Delta K_{T\gamma}$, $\Delta K_{Q\gamma}$ and $\Delta K_{Z\gamma} = K_{Z\gamma}$ polynomials.

EXPERIMENTAL VALIDATION OF THE PROPOSED FORMULATIONS

In order to verify the practical applicability of the so obtained ΔK espressions, we have carried out tests, in axial and non-axial flow, on a sample of three stock screw propellers, whose principal geometrical parameters are reported in table III.

These propellers have been tested by the experimental methodology previously illustrated, and by adopting for each propeller three different inclination angles in the vertical plane: 0°, 10°, 20°.

For the three above-mentioned screw propeller we have reported in figures 3, 4 and 5 respectively the experimental results of $K_{T\gamma}$, $K_{Q\gamma}$ and $K_{Z\gamma}$, and the "theoretical" curves obtained by the relation (4), where the ΔK values are given by the regression polynomial expressions.

For these three propellers we have also reported in the table IV, V and VI the "theoretical" values and the experimental ones obtained by fairing the experimental results by a polinomyal expressions of fourth order.

CONCLUSION

From the figures 3, 4 and 5, and from the tables IV, V and VI, it follows that there is a good agreement between the theoretical and the experimental data. Neverthless, the size of the sample utilized for the validation is too small to draw definitive conclusions.

For this reason at the towing tank of the Naval Engineering Department of Naples it is being developed a large programme of experimental tests on screw propellers of different geometrical characteristics.

However at present the regression formulations can be already utilized for the prevision of the real performance of a ship screw propeller in a first stage of the propeller design.

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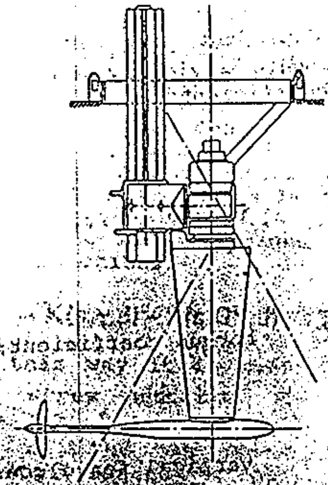


Fig.1

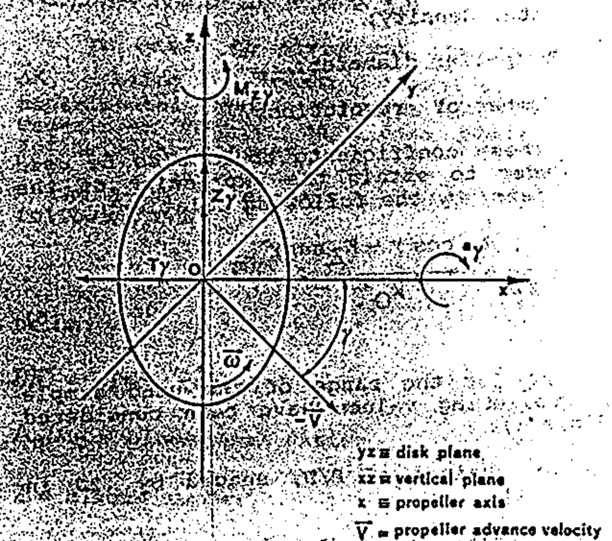


Fig. 2

TABLE I

code	n. ord.	P/D	A_e/A_o
E053	1	0.6	.35
E038	2	0.8	.35
E039	3	1.0	.35
E037	4	1.2	.35
E036	5	1.4	.35
E052	6	0.6	.50
E034	7	1.0	.50
E035	8	1.4	.50
E050	9	0.6	.65
E054	10	0.8	.65
E046	11	1.0	.65
E051	12	1.2	.65
E047	13	1.4	.65
E055	14	0.6	.80
E049	15	1.0	.80
E048	16	1.4	.80
E040	17	0.6	.95
E041	18	0.8	.95
E043	19	1.0	.95
E044	20	1.2	.95
E042	21	1.4	.95

TABLE II

Variables	ΔK_T	$10 * \Delta K_Q$	$10^3 * \Delta K_Z$
Intercept	-.019088	.074813	-39.925915
J	0	.099307	52.996948
γ	.001919	.002749	1.842678
P/D	-.072913	-.338959	39.830607
A_e/A_o	.226565	.051404	80.314227
J^2	.030606	.064790	-19.747195
γ^2	0	$3.201 \cdot 10^{-4}$	.106795
$(P/D)^2$	.102459	.412101	17.844274
$(A_e/A_o)^2$	-.436472	0	-87.431541
$J\ \gamma$	-.002242	-.009295	-1.537626
$J\ (P/D)$	-.020549	-.161855	-79.264991
$J\ (A_e/A_o)$	0	-.062675	6.559538
$\gamma\ (P/D)$	-.003733	-.002567	-5.813266
$\gamma\ (A_e/A_o)$	0	-.001867	-1.741612
$(P/D) \cdot (A_e/A_o)$	0	-.060883	-74.591691
J^3	-.009093	.017733	12.364963
γ^3	$-1\ 045 \cdot 10^{5}$	0	-.002395
$(P/D)^3$	-.032618	-.142903	-10.916820
$(A_e/A_o)^3$	.236806	0	63.589567
$J^2\ \gamma$	.000924	.001176	-.179783
$J^2\ (P/D)$	0	-.057882	12.430025
$J^2\ (A_e/A_o)$	-.030549	-.058727	-4.608635
$\gamma^2\ J$	.000139	.000209	-.084350
$\gamma^2\ (P/D)$	0	0	.040116
$\gamma^2\ (A_e/A_o)$	0	0	-.018027
$(P/D)^2\ J$	0	.060119	2.900021
$(P/D)^2\ \gamma$	.001333	0	1.106018
$(P/D)^2 \cdot (A_e/A_o)$	-.046309	0	15.726822
$(A_e/A_o)^2\ J$	0	0	-44.998483
$(A_e/A_o)^2\ \gamma$	-.001861	-.001373	-.0457029
$(A_e/A_o)^2 \cdot (P/D)$	.047063	0	6.454909
$J\ (P/D)\ \gamma$	0	.004223	5.673346
$J\ (P/D) \cdot (A_e/A_o)$	.036490	.103101	50.583517
$J\ \gamma \cdot (A_e/A_o)$	.000854	.003155	1.162117
$\gamma\ (P/D) \cdot (A_e/A_o)$	.002821	.003761	2.956918

TABLE III

code	P/D	A_e/A_o	Z
1472	0.884	0.486	4
464	1.216	0.450	4
847	1.0529	0.600	3

TABLE IV

PROPELLER n. 847

$Z = 3$ $A_e/A_o = .60$ $P/D = 1.053$

J	$K^*_{T0^\circ}$	$K^*_{T10^\circ}$	ΔK_{T10°	K_{T10°	$K^*_{T20^\circ}$	ΔK_{T20°	K_{T20°
0	.529	.530	0	.530	.531	0	.530
.1	.486	.488	.001	.487	.498	.002	.488
.2	.439	.443	.002	.441	.456	.006	.445
.3	.390	.395	.002	.392	.409	.009	.399
.4	.341	.346	.003	.344	.361	.013	.354
.5	.292	.299	.005	.297	.341	.018	.310
.6	.246	.252	.006	.252	.269	.022	.268
.7	.201	.207	.007	.208	.227	.028	.229
.8	.156	.164	.009	.165	.187	.033	.189
.9	.112	.119	.010	.122	.148	.038	.150
1.0	.065	.075	.012	.077	.108	.044	.109
1.1	.013	.026	.013	.026	.063	.050	.063

J	$10\ K^*_{Q0^\circ}$	$10\ K^*_{Q10^\circ}$	$10\ \Delta K_{Q10^\circ}$	$10\ K_{Q10^\circ}$	$10\ K^*_{Q20^\circ}$	$10\ \Delta K_{Q20^\circ}$	$10\ K_{Q20^\circ}$
0	.807	.807	0	.807	.807	0	.807
.1	.746	.748	.005	.751	.752	.008	.754
.2	.682	.682	.007	.689	.693	.013	.695
.3	.618	.618	.008	.626	.633	.018	.636
.4	.555	.556	.009	.564	.573	.023	.578
.5	.493	.494	.010	.503	.514	.028	.521
.6	.431	.432	.011	.442	.455	.033	.464
.7	.368	.369	.012	.380	.398	.039	.407
.8	.304	.306	.013	.317	.340	.046	.350
.9	.237	.241	.015	.252	.281	.053	.290
1.0	.166	.172	.018	.184	.219	.061	.227
1.1	.091	.099	.021	.112	.151	.070	.161

J	$10^3\ K^*_{Z10^\circ}$	$10^3\ K_{Z10^\circ}$	$10^3\ K^*_{Z20^\circ}$	$10^3\ K_{Z20^\circ}$
.2	-	-	4.503	5.393
.3	3.648	2.703	8.230	10.114
.4	5.519	5.909	13.913	14.797
.5	7.832	9.187	19.954	21.516
.6	10.846	12.612	25.283	26.346
.7	13.408	16.258	29.433	31.360
.8	16.557	20.198	32.547	35.634
.9	19.916	24.508	35.371	38.240
1.0	23.500	29.261	39.260	43.254
1.1	27.351	34.531	42.315	46.750

K^* = Experimental value

Δk = Regression value

$K = K^*_{o^\circ} + \Delta K$

TABLE V

PROPELLER n. 1472

$Z = 4$ $A_e/A_o = .486$ $P/D = .884$

J	$K^*_{T0^\circ}$	$K^*_{T10^\circ}$	ΔK_{T10°	K_{T10°	$K^*_{T20^\circ}$	ΔK_{T20°	K_{T20°
0	.3861	.3880	0	.3861	.3903	0	.3861
.1	.3504	.3530	.0003	.3507	.3560	.0027	.3531
.2	.3135	.3173	.0032	.3167	.3217	.0053	.3188
.3	.2760	.2810	.0037	.2797	.2875	.0085	.2845
.4	.2382	.2440	.0044	.2426	.2532	.0123	.2505
.5	.1994	.2058	.0054	.2048	.2183	.0164	.2152
.6	.1586	.1654	.0066	.1652	.1819	.0211	.1787
.7	.1141	.1219	.0080	.1224	.1429	.0260	.1401
.8	.0634	.0737	.0096	.0730	.0998	.0372	.0946
.9	.0037	.0191	.0112	.0145	.0508	.0368	.0405

J	10 $K^*_{Q0°}$	10 $K^*_{Q10°}$	10 $\Delta K_{Q10°}$	10 $K_{Q10°}$	10 $K^*_{Q20°}$	10 $\Delta K_{Q20°}$	10 $K_{Q20°}$
0	.4327	.4408	0	.4327	.4362	0	.4327
.1	.4038	.4075	.0025	.4063	.4065	.0039	.4077
.2	.3749	.3783	.0023	.3772	.3791	.0063	.3812
.3	.3454	.3502	.0022	.3476	.3525	.0091	.3545
.4	.3142	.3207	.0024	.3166	.3252	.0123	.3265
.5	.2798	.2877	.0030	.2828	.2956	.0162	.2960
.6	.2407	.2497	.0040	.2447	.2623	.0208	.2615
.7	.1950	.2053	.0056	.2006	.2238	.0261	.2211
.8	.1404	.1541	.0079	.1483	.1787	.0324	.1728
.9	.0745	.0956	.0110	.0855	.1256	.0398	.1143

J	10^3 $K^*_{Z10°}$	10^3 $K_{Z10°}$	10^3 $K^*_{Z20°}$	10^3 $K_{Z20°}$
.3	1.685	1.062	8.166	7.560
.4	4.061	3.771	12.009	11.655
.5	6.721	6.521	16.048	15.755
.6	9.492	9.386	20.368	19.935
.7	13.026	12.440	25.262	24.267
.8	16.470	15.758	30.967	28.827
.9	19.413	20.008	35.685	33.688

K^* = Experimental value

Δk = Regression value

$K = K^*_{o°} + \Delta K$

Fig. 3

PROPELLER SCREW 847 γ= 20°

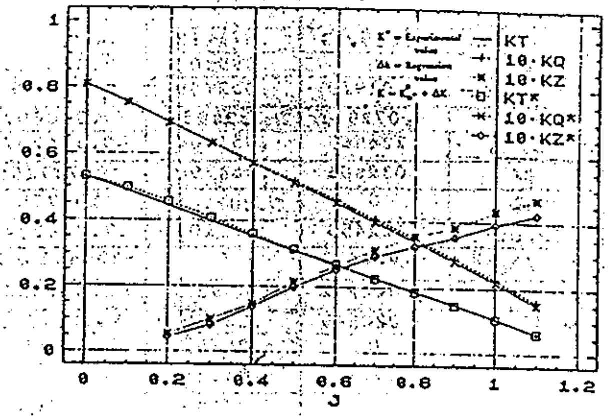


TABLE VI

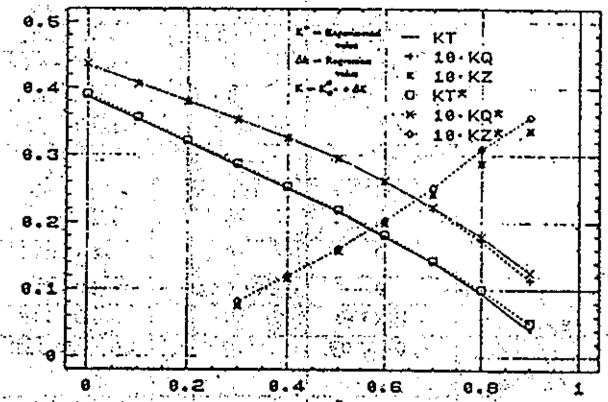
PROPELLER n. 464

Z = 4 Ae/Ao = .45 P/D = 1.216

J	$K^*_{T0°}$	$K^*_{T10°}$	$\Delta K_{T10°}$	$K_{T10°}$	$K^*_{T20°}$	$\Delta K_{T20°}$	$K_{T20°}$
0	.4942	.4946	0	.4942	.4932	0	.4942
.1	.4804	.4828	.0041	.4848	.4840	.0047	.4851
.2	.4561	.4608	.0042	.4603	.4617	.0070	.4631
.3	.4244	.4308	.0043	.4287	.4343	.0100	.4344
.4	.3881	.3957	.0048	.3929	.4034	.0134	.4015
.5	.3491	.3576	.0057	.3548	.3705	.0174	.3665
.6	.3089	.3181	.0068	.3157	.3364	.0218	.3307
.7	.2684	.2782	.0080	.2764	.3018	.0266	.2950
.8	.2278	.2383	.0094	.2372	.2668	.0317	.2595
.9	.1868	.1984	.0109	.1977	.2314	.0371	.2239
1.0	.1445	.1577	.0124	.1569	.1951	.0427	.1872
1.1	.0994	.1150	.0140	.1134	.1571	.0484	.1476
1.2	.0496	.0684	.0153	.0649	:1162	.0543	.1039

Fig. 4

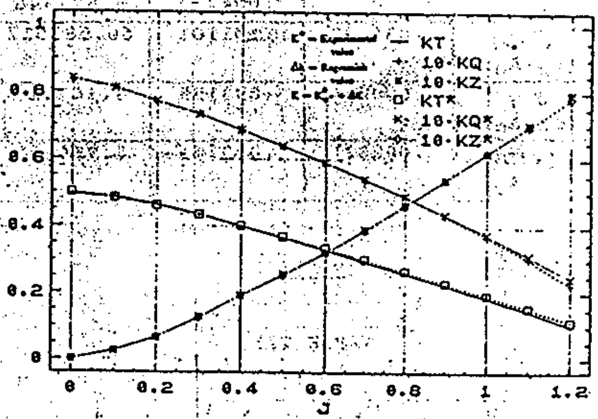
PROPELLER SCREW 1472 γ= 20°



J	10 $K^*_{Q0°}$	10 $K^*_{Q10°}$	10 $\Delta K_{Q10°}$	10 $K_{Q10°}$	10 $K^*_{Q20°}$	10 $\Delta K_{Q20°}$	10 $K_{Q20°}$
0	.8379	.8377	0	.8379	.8397	0	.8379
.1	.8059	.8078	.0085	.8144	.8098	.0082	.8141
.2	.7645	.7679	.0093	.7738	.7732	.0129	.7674
.3	.7168	.7214	.0099	.7267	.7319	.0176	.7344
.4	.6652	.6706	.0105	.6757	.6874	.0225	.6877
.5	.6114	.6176	.0110	.6224	.6405	.0277	.6391
.6	.5562	.5632	.0117	.5679	.5920	.0332	.5894
.7	.4997	.5077	.0127	.5124	.5420	.0392	.5389
.8	.4412	.4508	.0139	.4551	.4903	.0458	.4870
.9	.3793	.3911	.0156	.3949	.4363	.0530	.4323
1.0	.3118	.3268	.0172	.3297	.3788	.0640	.3728
1.1	.2357	.2551	.0208	.2565	.3163	.0699	.3056
1.2	.1474	.1726	.0245	.1719	.2470	.0799	.2273

Fig. 5

PROPELLER SCREW 464 γ= 20°



J	10^3 $K^*_{Z10°}$	10^3 $K_{Z10°}$	10^3 $K^*_{Z20°}$	10^3 $K_{Z20°}$
.2	-	-	6.700	6.536
.3	3.958	4.009	12.402	12.892
.4	6.883	7.154	19:348	19.264
.5	10.562	10.425	25.262	25.727
.6	13.602	13:897	32.293	32.355
.7	17.215	17.645	38.841	39.222
.8	21.388	21.741	46:017	46.403
.9	26.125	26.261	53.883	53.971
1.0	31.100	31.279	62.199	62.000
1.1	36.514	36.868	69.994	70.566
1.2	43.183	43.059	78.329	79.741

K^* = Experimental value

Δk = Regression value

$K = K^*_{o°} + \Delta K$