

# Small Waterplane Area Ship Models: Re-Analysis of Test Results Based on Scale Effect and Form Drag

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## **Abstract**

The first systematic model series of hulls with small waterplane area (both single hulls and twin-hulls) was designed and tested in Krylov Shipbuilding Research Institute in the middle of the 1980's. The series was intended to cover a broad range of Froude numbers, hull aspect ratios, design drafts, and spacing between hulls. In the present paper, these test results are re-analyzed by accounting for the scale effect in the form drag, obtained from the comparison with test data of larger out-of-series models. Illustrative results are also given for the influence of the cross-section hull shape, strut configuration, and shifted hulls on the residual resistance and for dynamic trim and draft. Some data are compared with those of the later series tests of twin-hull models with small waterplane area carried out in HSVA, Germany. Factors influencing the residual resistance of ships of this type are discussed.

*Keywords:* Small waterplane area ships; Systematic series; Residual resistance; Form drag; Scale effect

## **1. Introduction**

A lack of built prototypes of small waterplane area (SWA) ships makes difficult to efficiently design new ships of this type. A deficit of experimental data for SWA ship towing resistance and uncertainty in errors of calculated resistance demonstrate a need for systematic SWA model series.

The first systematic series of SWA hulls was designed and tested in Krylov Shipbuilding Research Institute, Russia, in the middle of the 1980's. Main results on towing resistance were reported in the book by Dubrovsky (2001). Later, a series of SWA twin-hull models was studied in HSV A (Schenzie, 1995) that included self-propelled tests.

Most SWA models of the first series had rather small dimensions, so the viscosity scale effect in the model residual resistance could be significant. In order to make these data more useful for practical design of SWA ships, a modification for minimizing the scale effect in that series is proposed in this paper by comparing test data with those of larger models. The result is the corrected residual resistance coefficients that can be used for more accurate predicting of the resistance of full-scale SWA ships.

Description of the series design is given in Section 2. The correction procedure is outlined in Section 3. Corrected results for residual resistance coefficients are presented in Section 4 for variable Froude number, hull aspect ratio, draft, and spacing between hulls. In Section 5, the dependence of the residual resistance coefficients on other parameters (non-circular gondola shape, strut configuration, and shifted hulls), as well as typical variations of draft and trim of SWA ships with Froude number, is selectively shown for illustration purposes. A comparison of this series results with data of HSV A series and an out-of-series model test is given in Section 6.

## **2. Series design description**

The model series is designed to cover a broad range of dimension correlations of SWA ships. An important goal is to include the minimum and maximum values of possible relative length of full-scale SWA hulls. This means that a step in the model elongation must be large enough to keep reasonable the total number of tests. Each SWA hull contains an underwater gondola with a long strut. When applied together, two such SWA hulls form a duplex-type SWATH. Models of this series have gondolas with circular cross sections. The design draft is 1.5-2.0 times the gondola diameter. Draft is the main restrictive dimension of an SWA ship. Only sufficient hull lengthening can ensure the required displacement of a twin-hull SWA ship with circular gondolas.

The beam of blocks that form model gondolas is equal to 0.2 m and the block length is 0.6 m (Fig. 1). This means that the minimum aspect ratio of a hull is equal to 6, when the bow and stern blocks are connected together. The highest aspect ratio of a hull is chosen to be 24 (eight blocks). The models that were tested in a full parametric range had the hull aspect ratios equal to 9, 15, and 24, and the systematic results are presented in this paper for these hulls only. The waterplane strut beam  $B_S$  is 0.1 m (half the gondola beam). The spacing of twin-hulls (distance between hull centerlines) varies from 0.25 to 0.60 of the hull length. The end blocks are made of foam with a light-alloy frame and the cylindrical blocks are made of tubes and plates. The block surface is covered by a paraffin wax.

The displacement and wetted area of models are shown in Fig. 2 versus the hull lengthening  $L/D$ , where  $L$  is the gondola length and  $D$  is the gondola diameter. The models with  $L/D = 9, 15, 24$  have the lengths 1.8, 3.0, 4.8 m and the waterplane areas 0.12, 0.24, 0.42 m<sup>2</sup>.

For design purposes, two relative presentations of the model geometry can be convenient. Figure 3 shows the relative hull length  $L/V^{1/3}$  ( $V$  is the hull displacement) and the relative wetted area  $\omega_I = \Omega/V^{2/3}$  ( $\Omega$  is the wetted surface area) versus the hull lengthening  $L/D$ . The relative wetted area of a  $N$ -hull ship with identical hulls can be defined as  $\omega_N = N^{1/3} \omega_I$ .

### 3. Test conditions and scale-effect correction

The models were tested with fixed draft and fixed zero trim. As was found by Dubrovsky (2001), the residual resistance of fixed models is approximately the same as that of free-towed models with an additional stabilizing stern foil having area of about 5% of the hull waterplane area. This fact will be used below in accounting for a scale effect.

The total resistance coefficient is defined as follows

$$C_T = 2R / (\rho U^2 S), \quad (1)$$

where  $R$  is the measured towing resistance,  $\rho$  is the water density,  $U$  is the model speed, and  $S$  is the wetted surface area. Referring to the original Froude method of towing resistance re-scaling, the total resistance consists of frictional and residual components. Residual resistance contains wave resistance and form (viscous) drag. The residual resistance coefficient can be approximately presented (Kostyukov, 1966) as

$$C_R = C_T - C_F = C_T - 0.455 / (\lg Re)^{2.58}, \quad (2)$$

where  $Re$  is the Reynolds number based on the model length and  $C_F$  is the Prandtl-Schlichting skin-friction resistance coefficient of a flat plate in turbulent flow (trip wires were applied to stimulate turbulence).

The length of SWA ship models used in this series, especially with low aspect ratios, is smaller than currently recommended for reliably determining the residual coefficient applied for full-scale resistance prediction (Bertram, 2000). If Reynolds number is too low, the viscous scale effect appears in the form drag. Possible local separation of flow at the gondola and strut sterns at low Reynolds numbers is one of the reasons for the needed correction of test data.

The basis for correcting residual resistance is the comparison between single-hull series models and larger 5m-long out-of-series free-towed SWATH models with stabilizing small stern foils. (Viscous interaction between hulls of large SWATH models was negligibly small.) The residual resistance coefficients for both model types at Froude number 0.2 are shown in Fig. 4. At this value of Froude number, the wave resistance is small, and the difference between residual resistance coefficients of the series models and out-of-series models is conditioned mainly by the form-drag viscous scale effect that appears on the series models. The proposed correction for the series models is the difference between lines 1 and 3 in Fig. 4. It is assumed that this correction depends only on the relative length of an SWA hull. The out-of-series models had slightly different shapes and were tested in a free-towing regime; therefore, this correction is rather approximate. However, this shift is certainly in a right direction and it improves practical value of data available from the series tests.

#### **4. Corrected data for residual resistance coefficients**

##### *4.1. Single-hulls*

The viscous scale-effect correction has been applied to the series data in order to obtain more practical residual resistance coefficients of single-hull models, which are shown in Figs. 5-7 for three hull aspect ratios, three drafts, and Froude number ranging from 0.2 to 1.0-1.2.

Resistance of hulls with an intermediate aspect ratio can be estimated by interpolation, keeping the same a correlation between the design draft and the gondola diameter. For non-circular gondola cross-sections, resistance can be estimated in the first-order approximation by using the effective diameter  $(B*H)^{1/2}$ , where  $B$  is the gondola beam and  $H$  is its height.

#### 4.2. Interaction coefficients of twin-hull models

The same hulls were tested in pairs forming a standard SWATH configuration. The distance between the hulls,  $2b$ , was a variable parameter, while the draft was the same, 0.3 m, for all twin-hull models. The interaction coefficient is defined as follows

$$I(L/D, Fn, 2b) = C_{R2}(L/D, Fn, 2b) / C_R(L/D, Fn) , \quad (3)$$

where  $C_{R2}$  and  $C_R$  are the residual resistance coefficients of the twin-hull and single-hull SWA arrangements, respectively. The viscous scale-effect correction, discussed in Section 3, has been applied to raw data as a function of the relative single-hull length. The interaction coefficients of various hulls are shown in Figs. 8-10. For design purposes, the interaction coefficients for intermediate values of parameters  $L/D$  and  $2b$  can be found by interpolation.

### 5. Illustrations of other effects

This section provides examples of the influence of variations in some parameters of SWA hulls on the residual resistance. A typical dependence of the trim and draft of a free-towed SWA model on Froude number is also shown. These examples illustrate main effects, but without a detailed parametric description. Most results of this section were obtained using out-of-series models and the scale-effect correction was not applied to residual resistance coefficients, so the only goal here is to demonstrate a qualitative influence of some hull parameters.

#### 5.1. Influence of oval-shaped gondola

A circular cross section of an SWA gondola ensures minimal relative wetted hull area. But this shape is not the best from the seaworthiness standpoint. An estimation of the resistance penalty associated with a non-circular form should be helpful for a naval architect. Figure 11 shows an illustrative comparison of products of the relative wetted area and the residual resistance coefficients for two twin-hull models with the same length, overall beam, and draft, but with different displacements (heavier models had oval-shaped gondolas with the beam-to-height ratio of two). For the circular-gondola model, the hull aspect ratio was 19.5 and relative spacing 0.32. As one can see in Fig. 11, the model with a circular shape is practically always better than that with an oval shape from the residual resistance standpoint.

### 5.2. Strut effects

For investigating the influence of struts on residual resistance, an additional series of single gondolas (without struts) was tested. The series included three underwater gondolas with  $L/D = 12, 16,$  and  $20$  and a hull diameter  $0.35$  m. An example of results of these tests is shown in Fig. 12. A small aspect ratio gondola ( $L/D = 12$ ) is characterized by only one maximum in the residual resistance coefficient at  $Fn \sim 0.45$ ; larger aspect ratio gondolas have two maximums in  $Fn$  intervals  $0.25-0.3$  and  $0.45-0.5$ .

One long or two short struts attached to the gondola generally increase the residual resistance coefficient. An example of the increments in the value proportional to the residual resistance is shown in Fig. 13, when one and two struts (with the same beam) were added to a gondola. The length of one long strut was equal to the gondola length, and the length of each of two short struts was 40% of the gondola length. One long strut is certainly better for low values of relative speeds from the residual resistance standpoint. In principle, two struts can be more effective in high-speed regimes, if each strut is thin enough and has a small own wave resistance. Two short struts can also have smaller wetted area and frictional resistance in comparison with one long strut. Besides, from a seakeeping point of view, a two-strut option is practically always better.

Some out-of-series tests demonstrate that a strut shifted to the stern strongly affects the residual resistance coefficient, especially for moderate values of the relative speeds. Figure 14 presents an example of the influence on the residual resistance coefficient by a strut shift on the one-strut model with the strut length equal to the hull length. The reason for a radical drop in residual resistance around  $Fn = 0.35$  is the compensation between wave systems generated by a gondola and by a strut.

### 5.3. Shifted hulls

A possibility of using wave system interactions was also examined by towing tests of twin-hull models with a longitudinal shift of hulls. An example of such test results is shown in Fig. 15 for the model with hulls having  $L/D = 6$ . A hull-shifted configuration can be quite effective. However, this variant has very unusual characteristics of hydrostatics and controllability, and it is unlikely to find many practical applications.

### 5.4. Dynamic trim and draft

Dynamic trim and draft of SWA ships depend strongly on a speed, because of essentially lower longitudinal stability and smaller waterplane area in comparison with conventional ships. In the high-speed regime, variations in trim and draft of SWA ships are quite significant. Figure 16 shows examples of the dynamic trim and draft versus Froude number.

The dependence of trim on Froude number has three distinct phases: positive trim at very low  $Fn$ , negative trim in the intermediate speed regime, and again positive trim at high  $Fn$ . Usually, a negative trim is compensated by a modified shape of the gondola or by adding fins. The large positive trim must be compensated too, because it can result in a surface-piercing bow of the gondola, which is accompanied by flow separation and the growth in resistance, as well as in the increased longitudinal bending moment.

Figure 16 shows mainly a negative dynamic draft of a twin-hull model for a broad range of Froude numbers. This means that a high-speed SWATH can be designed with a relatively small static draft, which will increase at the design speed. Besides common hull forms, some unusual SWA shapes characterized by different behavior of dynamic draft and trim have also been studied (Dubrovsky and Matveev, 2005).

## 6. Comparison with the other SWA series tests

The other series of SWATH models was tested later in HSVA, Germany. The results were presented in main by Schenzie (1995). That series contained models with  $L/D = 10, 12.5, 16.7, \text{ and } 20$ . The following elements of the model geometry were similar (at least in some tests) to those of the series described in this paper:

- gondola cross sections had circular shapes
- strut length was the same as the gondola length
- strut beam was a half of the gondola diameter  $D$
- draft was equal to  $1.5D$ .

The essentially different characteristics of the second series models were:

- strut was shifted aft by 6% of its length with respect to the gondola (this shift is certainly better for practical purposes)
- only twin-hulls were tested
- models were free to sink but restricted in trim.

Due to these and other hull form discrepancies, the exact correspondence between two series is not possible. Only a demonstration of approximate correlation can be shown.

An example of the series comparison will be given for the parameters corresponding to a large (5-m long) out-of-series twin-hull model tested experimentally. The strut on the model was displaced aft by 10% of the length from the hull bow. Main parameter correlations of this model, experimental results, and approximate predictions obtained from the series databases are shown in Fig. 17. The calculation by the series presented in this paper accounted for the strut shift influence (Fig. 14). The series predictions and test results demonstrate a qualitative agreement over a broad range of Froude number. However, the series data tend to overpredict the residual resistance coefficient, which may be due to inexact correspondence between series and out-of-series model hull forms and approximations made in deriving the scale-factor correction.

The database of the series presented in this paper can be used for a conservative estimation of the resistance in early stages of designing SWA ships. The requirements for propulsive power may be reduced later when model tests are carried out.

## **7. Conclusions**

The examined model series comprised simple SWA models with one long strut on each gondola. Although an application of this shape for modern ship designs is unlikely, these data can be used for demonstrating the effects of the SWA hull dimensions and spacing between hulls on the ship residual resistance, at least in the first approximation. For more accurate correspondence to other hull geometries, some correction coefficients are needed. The reported series data can be used for conservative and approximate resistance predictions of full-scale SWA ships.

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## Figure captions

- Fig. 1. Schematics of the series models: (a) smallest model (side view), (b) horizontal cuts of end blocks of gondola and strut, (c) mid-plane cut, (d) largest model (side view).
- Fig. 2. Displacement and wetted area of single hulls;  $d$  is the draft
- Fig. 3. Relative length and relative wetted area of single hulls.
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- Fig. 6. Corrected series data of residual resistance coefficients,  $L/D = 15$ .
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- Fig. 14. Influence coefficient of the strut shifted aft by 10% of hull length for out-of-series models with  $L/D = 16$ .
- Fig. 15. An example of the hull shift influence.
- Fig. 16. Examples of SWATH dynamic trim and draft.
- Fig. 17. An example of the residual resistance coefficient comparison.

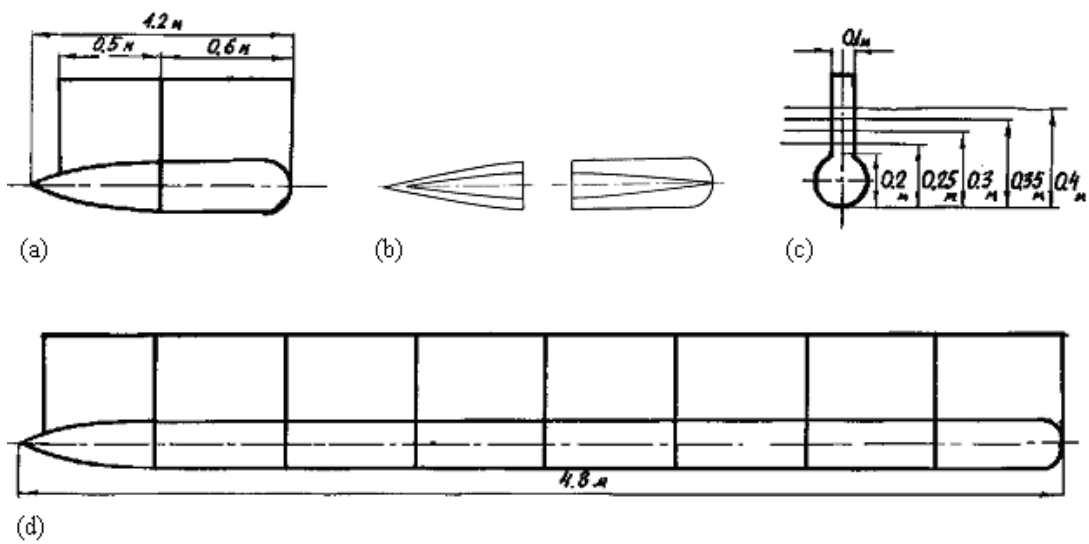


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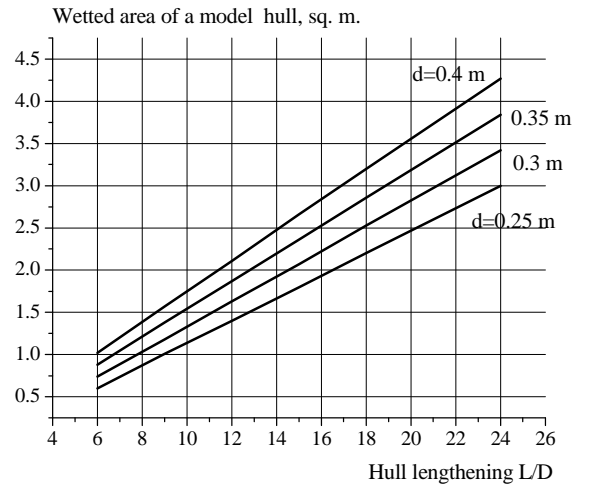
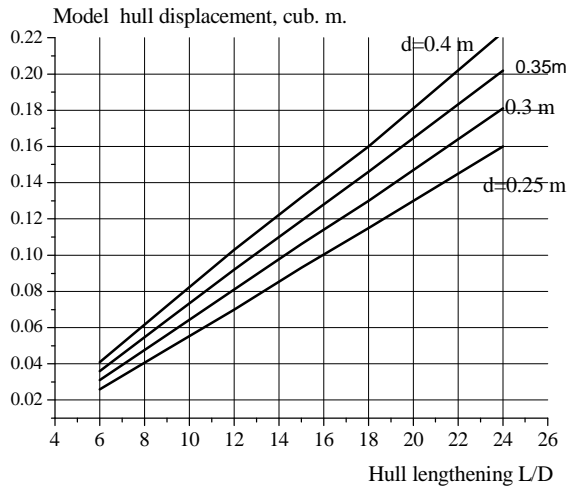


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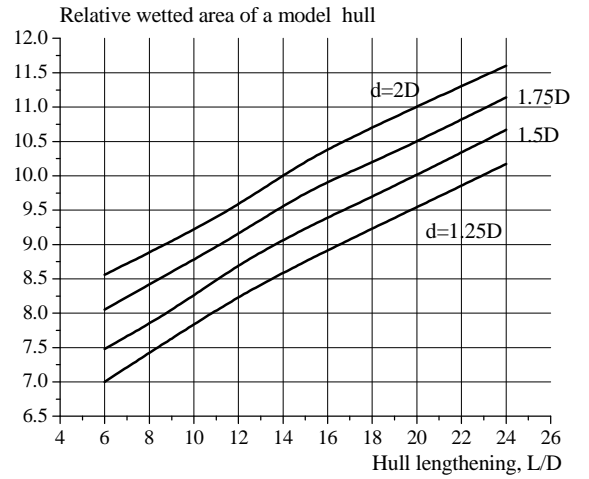
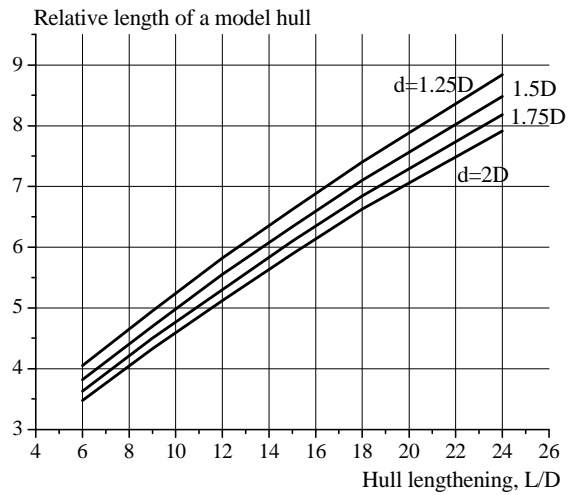


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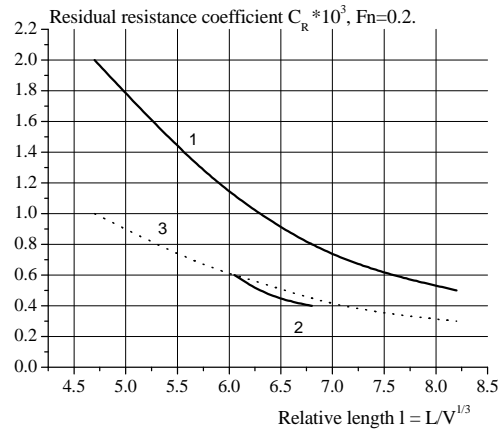


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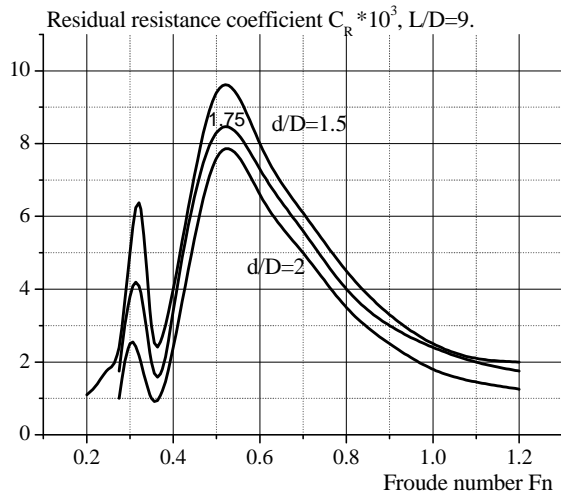


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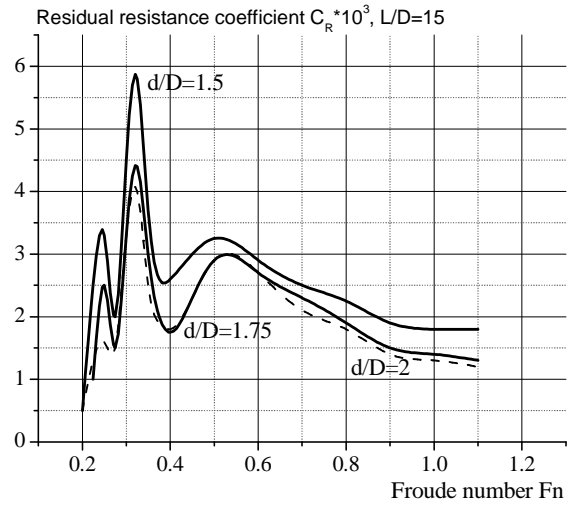


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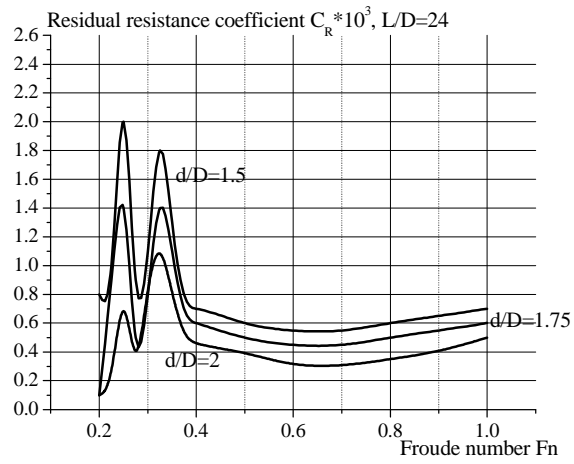


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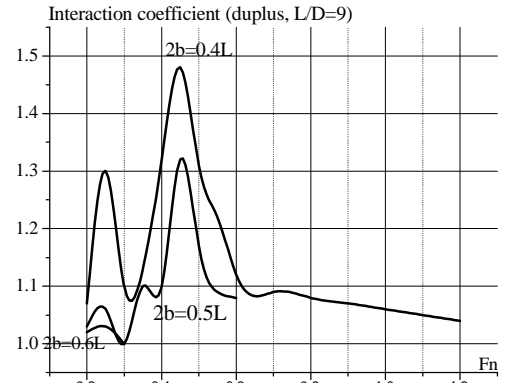
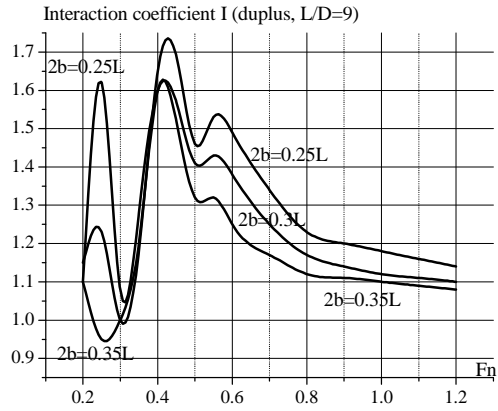


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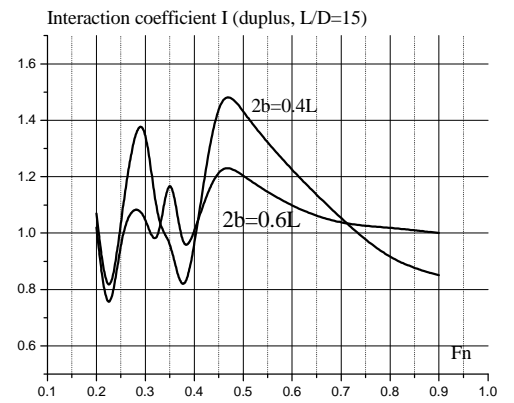
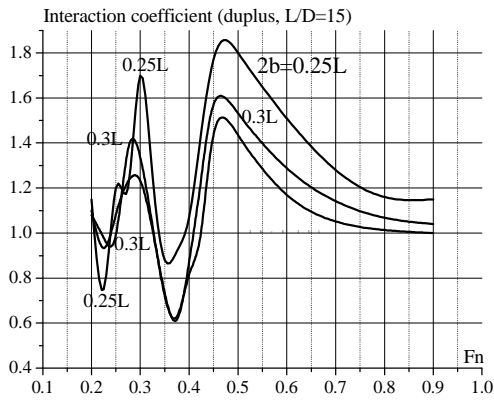


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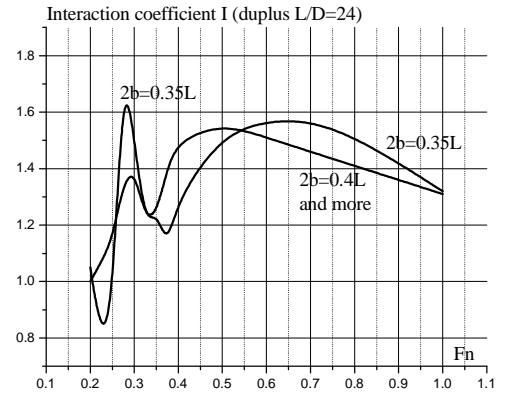
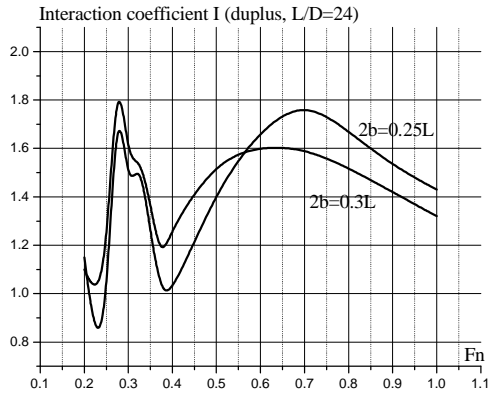


Figure 10.

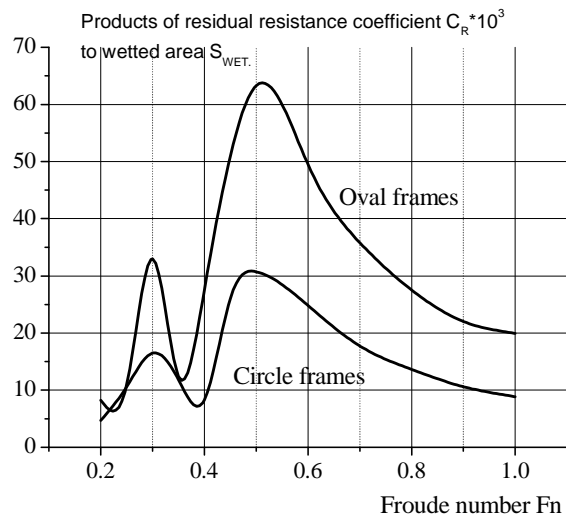


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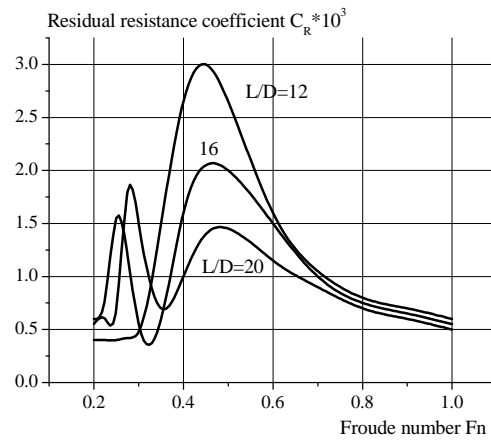


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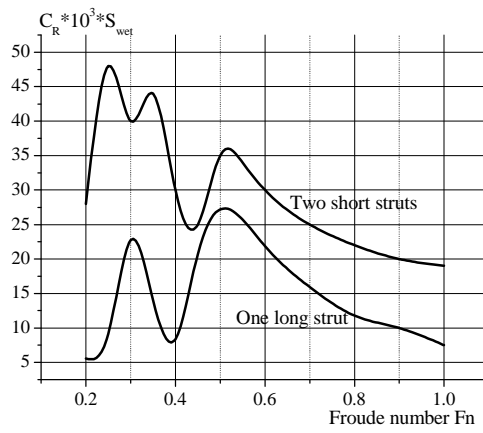


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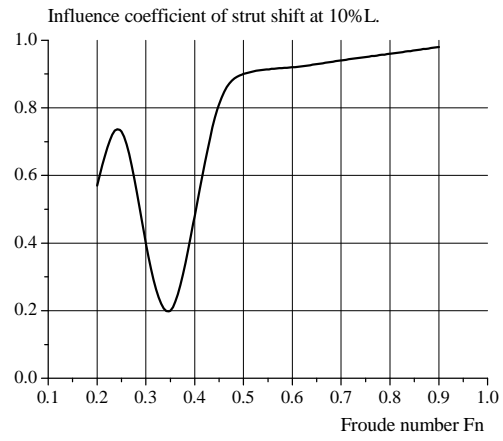


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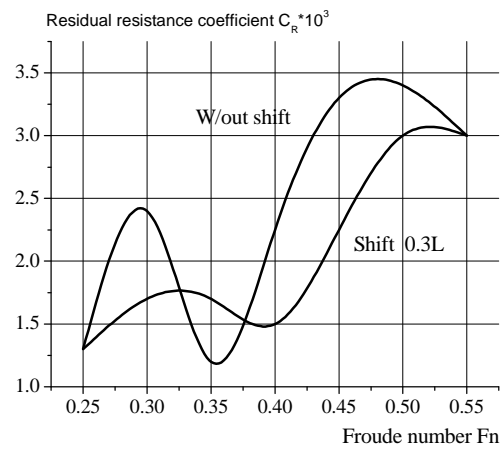


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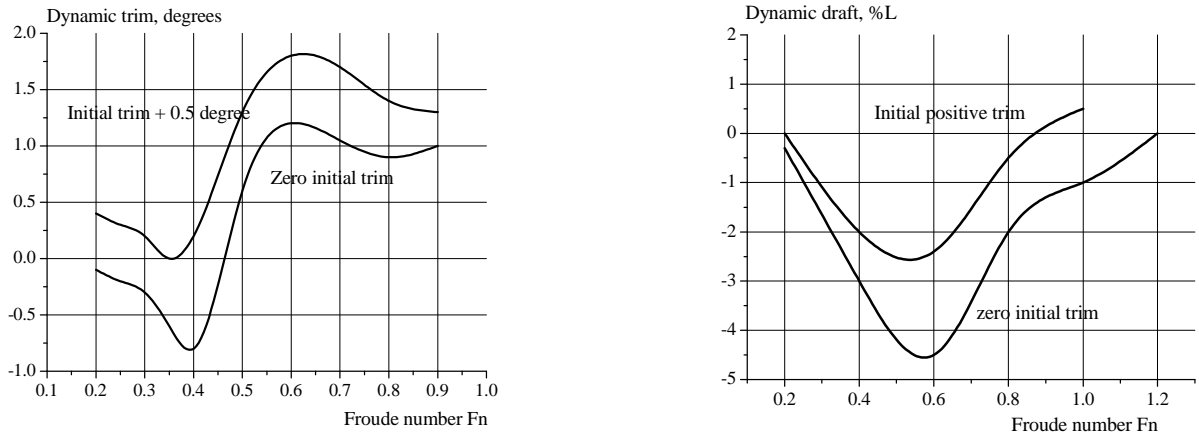


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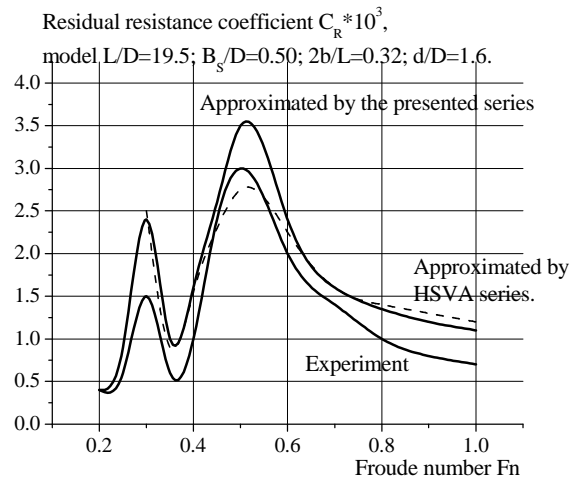


Figure 17.