Effects from Supercritical Ship Operation on Inland Canals

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Abstract: Speed of commercial displacer vessels on inland waterways is a major disadvantage in comparison to truck and railway. A solution to shift cargo from congested roads and railways to inland waterways may be with high speed vessels as those issued in coastal waters. Inland waterways are restricted in depth and often in width, which leads to hydraulic impact on bottom and banks. Screening of existing high speed ship concepts in unrestricted waters showed twin hulls (catamarans) with and without air-cushion and monohulls as technically feasible on inland waterways. Three types of high speed ships were modeled and tested in a restricted laboratory canal regarding hydraulic impacts from generation of waves, water-level variations, and flow velocities. Ship interaction with existing structures and interference with other ships, as well as channel bed and banks, were also modeled and tested. For the air-cushioned twin hull (SES-Catamaran), high speed model tests showed that water-level variation and flow velocities increased by a factor of about 3 compared to low speeds. For displacement types of twin hulls (catamarans) and monohulls, increased speeds seem to have some potential, but further and systematic research on limitations is required.

SUBCRITICAL AND SUPERCRITICAL SPEEDS IN RESTRICTED WATERS

Navigational speeds on depth-restricted waters are distinguished according to the depth-related Froude number (Grollius et al. 1995)

$$\mathsf{F}_d = \frac{v_{\text{ship}}}{\sqrt{gH}} \tag{1}$$

F_d gives the relation between the ship's speed v_{ship} and the velocity c of a progressive wave in shallow waters

$$c = \sqrt{gH} \tag{2}$$

where g = acceleration of gravity; and H = water depth. Operating at speeds resulting in $\mathsf{F}_d < 1$ is defined as subcritical and $\mathsf{F}_d > 1$ as supercritical. However, due to wave reflections and dynamic ship trims there is a range $0.84 < \mathsf{F}_d < 1.15$, where no clear distinction between subcritical and supercritical is possible and which is defined as transcritical range (Fig. 1).

To overcome the transcritical range requires extra energy inputs due to wave resistance, apart from problems with the ship's stability and trim. Gliding of the ship in the supercritical mode is less energy consuming (Schneekluth 1988) although still in the exponential range compared to subcritical operations (Fig. 2).

Operations of larger ships (e.g., navy ships, ferries, and small boats) in the supercritical mode is a common feature in unrestricted waters. Limitations are more or less by energy requirements. However, waves as generated by ships in restricted waters and increased local velocities are considered to be a further limitation to ship operations at high or even transcritical speeds. Hydrodynamic, aerostatic, and aerodynamic lift concepts have been successfully applied for passenger high speed transport (e.g., with hydrofoils, surface effect ships, hovercrafts, etc.) even on inland waters. Supercritical displacers thus far are limited to service boats and pleasure crafts and are today generally not allowed to operate on restricted inland waters such as rivers and canals.

However, speeds of a commercial displacer vessel carrying hundreds of tons of cargo above the present 10–12 km/h on rivers and canals, as allowed in European waterways, would be of great interest to logistic chains. They would attract considerable freight traffic from congested roads and railways to waterways. No boundary conditions and limits for feasible types of ships and their possible load capacities and navigational behavior to be operated on existing waterways, together with conventional shipping, are known. Therefore, a research program has been set up, starting with the most critical part of the German waterway system, the artificial canals.

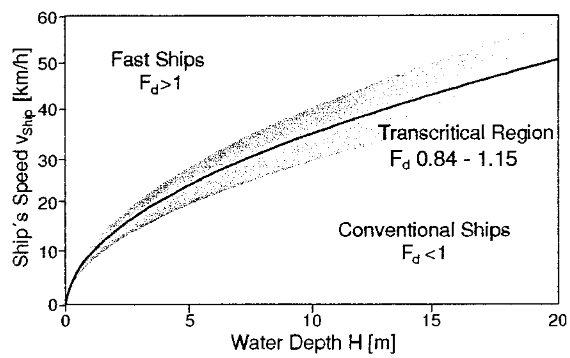

FIG. 1. Critical Speed in Depth Restricted Waters

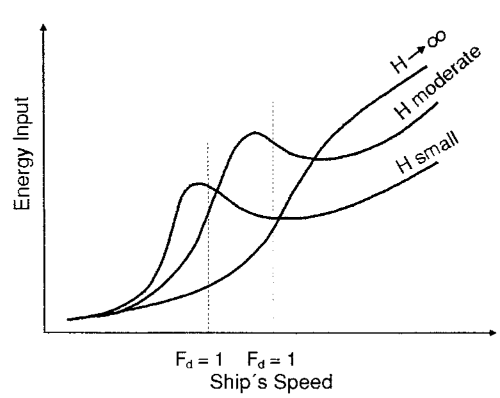

FIG. 2. Basic Relations between Ship Speed, Wave Resistance, and Energy Input (Schneekluth 1988)

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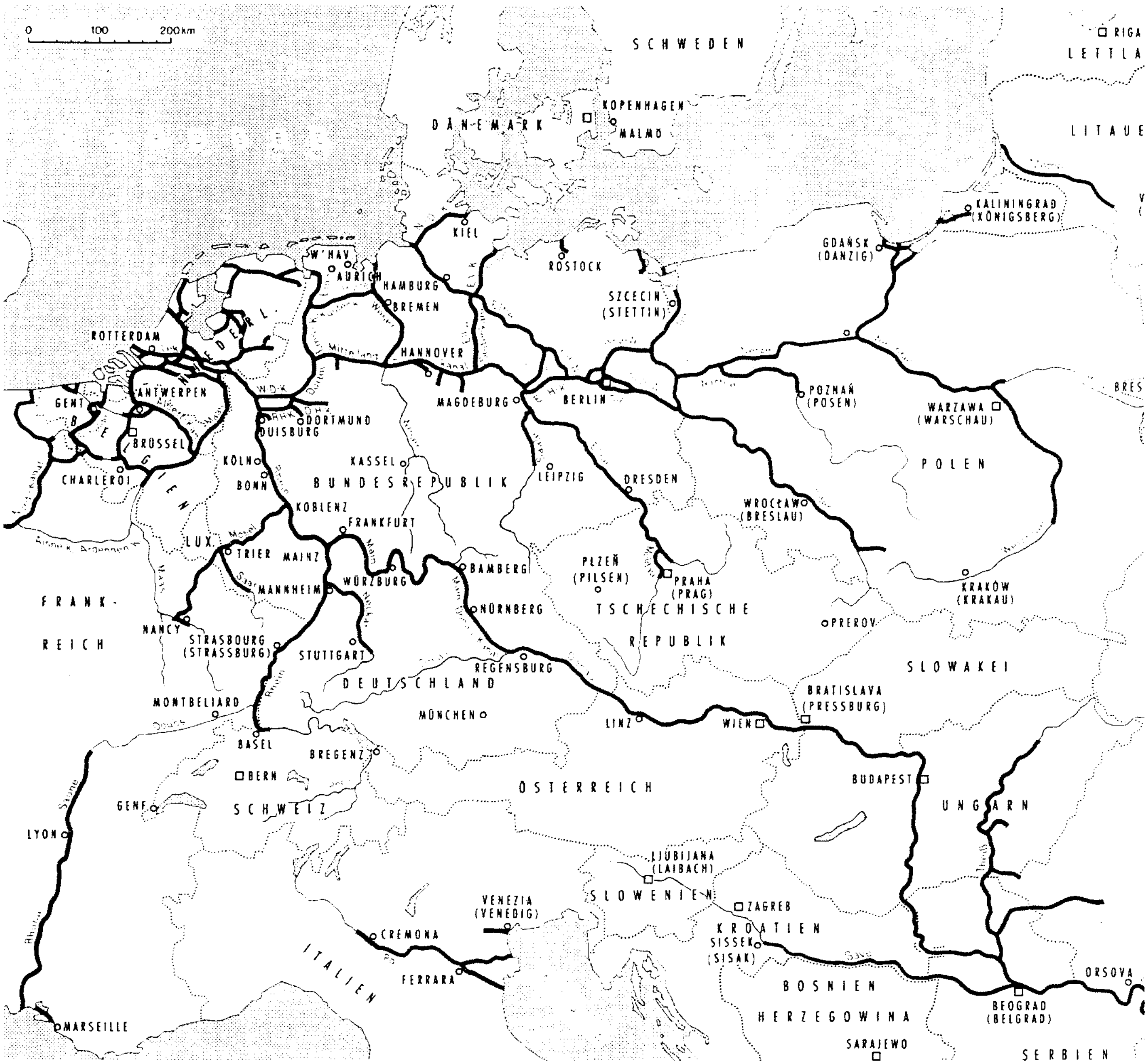


FIG. 3. Water Systems in Central Europe [BMVBW (EW 24) 1993]

CANALS: BOUNDARY CONDITIONS FOR HIGH SPEED NAVIGATION

Artificial canals are an integral part of the Central European Waterway System. They connect all major rivers and thus link the seaports with nearly all inland industrial centers (Fig. 3).

About 22% of cargo is transported on waterways in central Europe with a concentration on some major areas such as the Rhine. There is a long history of development in cross sections, which is closely related to sizes, draughts, and propulsions of ships. Four cross-sectional types of canals can be found in Germany, with a minimum depth of 4.0 m and a width of 42–55 m, allowing two-lane traffic (Fig. 4).

Dynamic canal water-level variations due to changing water supplies, lock operations, local storm water discharges, and undirectional wind shears may reach up to 0.5 m. Minimum clearance under bridges over canals are 5.25 m above maximum dynamic water levels. This limits ship superstructures and cargo heights depending on the ships' draught. The standard vessel has a length of 110–185 m, beam width of 11.4 m (lock width of 12.0–12.4 m), and draught of 2.8 m; thus the ratio between wetted canal cross section A_c and fully loaded ship cross section A_s is

$$n = \frac{A_c}{A_s} \geq (5.5) \tag{3}$$

Ship speeds are allowed up to 10 km/h for full draught and 12 km/h for unloaded vessels. The range in the depth-related Froude number is

$$0.44 < \mathsf{F}_d < 0.53 \tag{4}$$

depending on ship's draughts and velocities, which is well below supercritical mode.

Dynamic water-level sinkage (squat) alongside full draught ships at maximum speeds has been measured with 0.3 m < ΔH < 0.5 m resulting in an average squat up to 0.4 m, depending on trim and shape of the ship's hull (Felkel and Steinweller 1973).

Fixing the boundaries of the canal is done with steel sheet piling for rectangular sections and riprap for trapezoidal sections. Canal beds may be stabilized with riprap in dam sections with clay sealings to prevent leakage.

HIGH SPEED CARGO SHIPS FOR INLAND NAVIGATION

Doubling or even tripling speeds of cargo transport on inland waterways would improve competition to road and rail considerably for high valued and time sensible goods (e.g., containers or vehicles). For the depth-restricted canals this would result in velocities above 25–30 km/h, which is in the supercritical range $F_d > 1.1$. Various types of high speed ships have been developed basically for unrestricted, mostly coastal waters, carrying passengers and limited amounts of cargo and vehicles (Müller-Graf 1991). Examples are high speed ferries all over the world (Fig. 5).

To carry significant quantities of cargo excludes all types of ships with limited displacement. For canals, restrictions are for ship types with major uplifts to reduce resistance (hydrofoils) or which gain uplift with submerged buoyancy devices (SWATH). This leaves two ship types, twin hulls (catamarans) with or without additional air-cushioning and high speed adapted monohulls. Both are already applied in sea transport.

Two ship types have been investigated for feasibility of high speeds on inland waterways and modeled by the Versuchsanstalt für Binnenschiffbau, Duisburg, Germany. Dimensions have been selected to carry at least one layer of standard containers, twenty-foot equivalent unit (TEU), in three to four rows. This results in a capacity up to 32 TEU, depending on the average weight for each TEU (maximum total weight per TEU is 24 tons) and ship length.

Cost estimates and comparisons had shown that this might be a feasible load size to introduce waterways container transport between major container seaports and the hinterland. En-

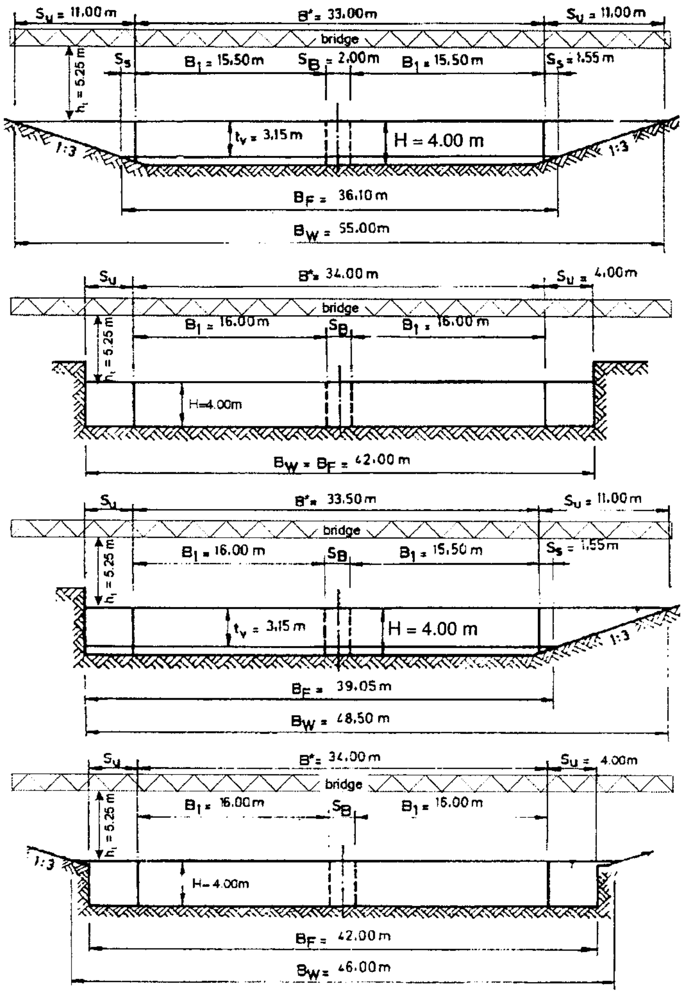


FIG. 4. Cross Sections of Canals in Germany

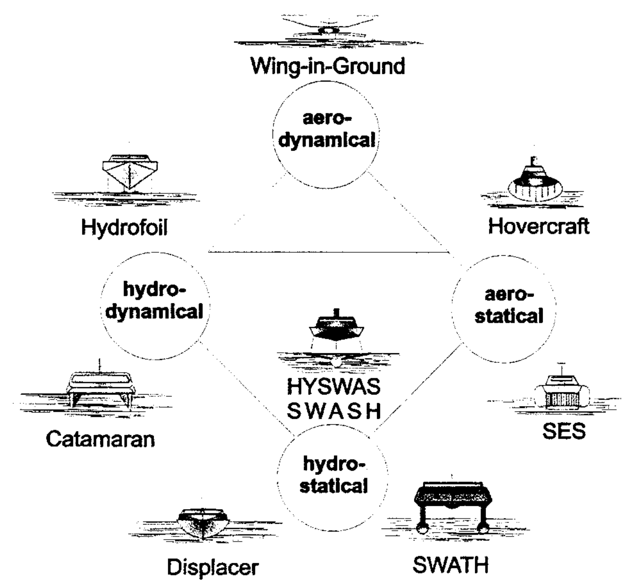
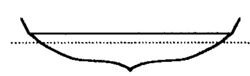
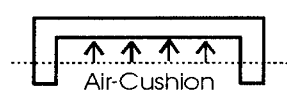
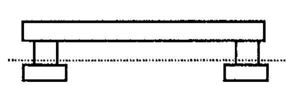


FIG. 5. Basic Types of High Speed Ships (Nitz and Muxfeld 1993)

TABLE 1. Ships Tested in Towing Tank

Ship Type (1)	(2)	B x L x T_a [m] (3)	Sections (4)	Model-propulsion (5)	Blockage [A_C/A_S] R (6)	T (7)	RT (8)
Monohull (pre-installed trim)	Prototype	9.91 x 79.80 x 1.00		tow	17	21	19
	Model [scale 1:14]	0.708 x 5.700 x 0.071					
SES-Catamaran (pre-installed trim)	Prototype	11.45 x 85.00 x 2.30		jet + tow	6	8	7
	Model [scale 1:14]	0.818 x 6.071 x 0.164					
Catamaran (free trim)	Prototype	11.40 x 96.00 x 2.50		tow	6	7	7
	Model [scale 1:16]	0.713 x 6.000 x 0.156					

ergy inputs are to be increased by a factor of at least 4, compared to conventional low speed shipping (Bross 1995).

Problems to be solved for hydrodynamic ship stability, maneuverability, and propulsions have been tackled by the Versuchsanstalt für Binnenschiffbau. But the main problem of operating high speed ships on canals is the generation of waves, water-level variations, and flow velocities. Compared to conventional shipping, interactions with existing structures, interference with other ships, maintenance, and, most importantly, the safety of mixed low and high speed traffic were also of major interest. To help solve these problems, laboratory tests have been carried out with scaled model ships.

LABORATORY TESTS

Three types of ship were tested with a scale of 1:14 or 1:16, applying Froude's laws in a still water towing tank, simulating restricted waterway conditions according to Fig. 4 and Table 1.

Ships were fixed to the towing vehicle with trim data (draught and longitudinal trim angle) obtained in preliminary trim and propulsion tests. Effects from jet propulsion, which is considered to be the mode to be applied with high speed ships, were tested with the air-cushioned twin hull (SES-Catamaran).

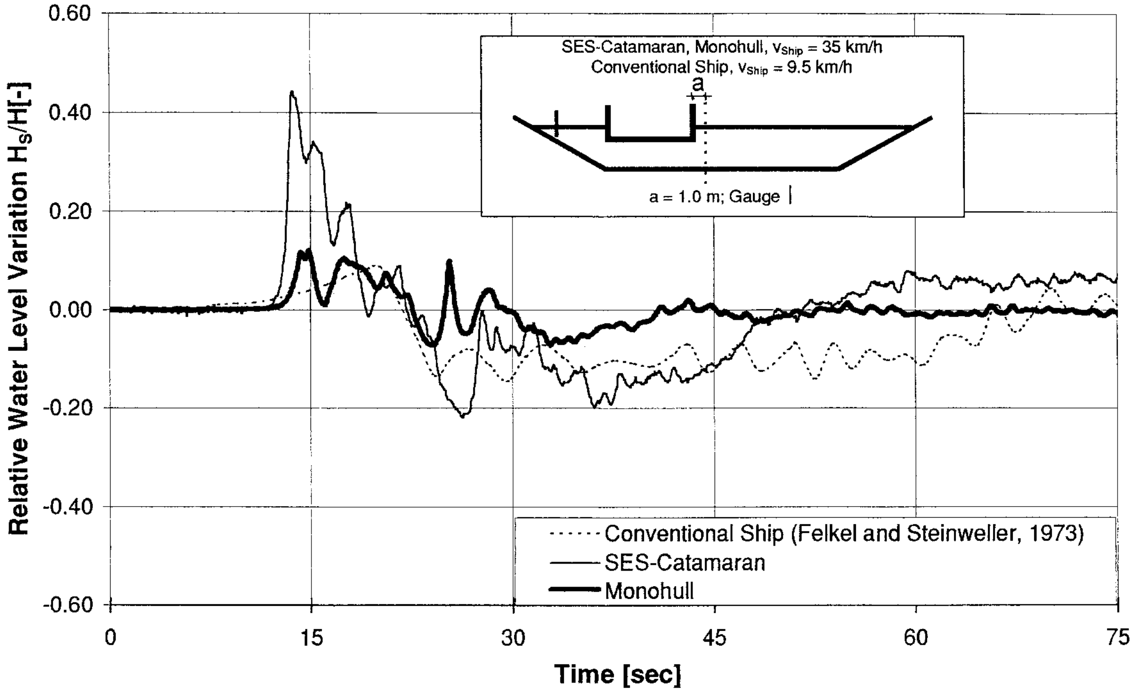


FIG. 6. Water-Level Variations for Different Ship Types and Ship Speed

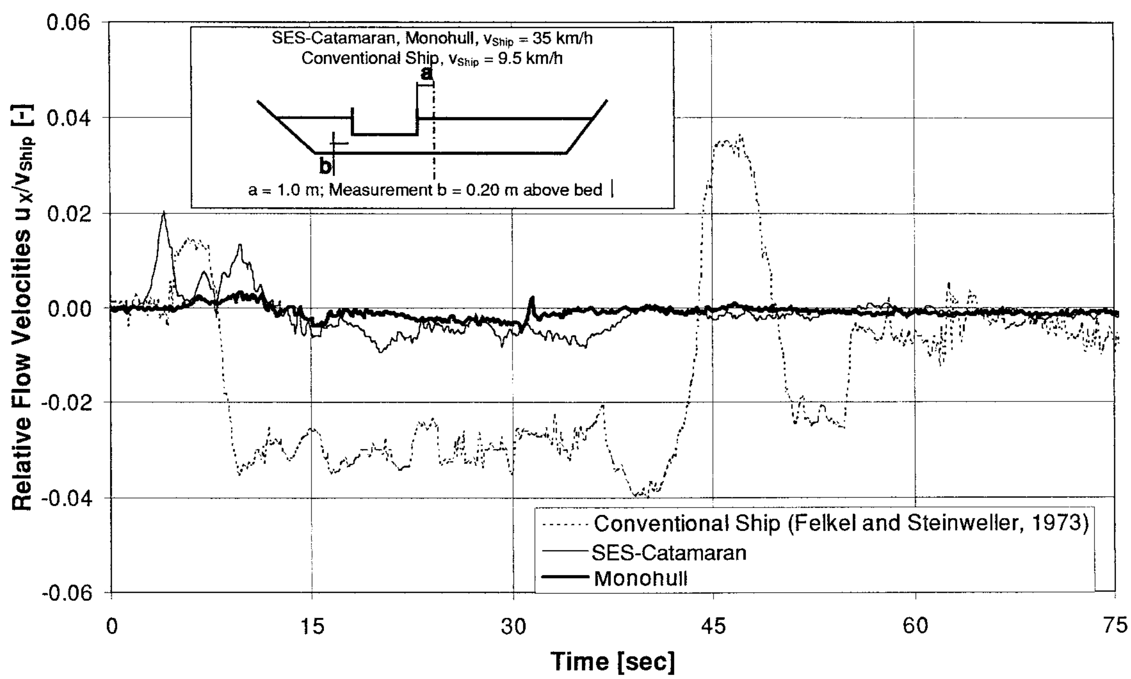


FIG. 7. Flow Velocities under Passing Ships at Fixed Location

TABLE 2. Water-Level Variation (Water Depth H = 4.00 m, Eccentric)

ECCENTRIC					R		RT		T	
Type of ship	Ship's Speed v_{Ship}		F_d	F_l	Water Level Deflection		Water Level Deflection		Water Level Deflection	
	[km/h]	[m/s]			max rise	max sink	max rise	max sink	max rise	max sink
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
SES-Catamaran	20.00	5.55	0.89	0.19	0.30	0.33	0.30	0.23	0.28	0.23
	25.00	6.94	1.11	0.24	0.65	0.38	0.44	0.25	0.48	0.19
	35.00	9.72	1.55	0.34	0.63	0.31	0.45	0.30	0.44	0.19
Monohull	20.00	5.55	0.89	0.19	0.20	0.31	0.20	0.26	0.15	0.20
	25.00	6.94	1.11	0.25	0.35	0.25	0.25	0.20	0.20	0.15
	35.00	9.72	1.55	0.35	0.30	0.15	0.13	0.10	0.13	0.10
Catamaran	20.00	5.55	0.89	0.18	0.37	0.38	0.27	0.26	0.23	0.18
	25.00	6.94	1.11	0.25	0.56	0.33	0.43	0.18	0.43	0.16
	35.00	9.72	1.55	0.35	0.53	0.20	0.31	0.12	0.33	0.16

TABLE 3. Water-Level Variation (Water Depth H = 4.00 m, Passage of Berthing Ship)

PASSAGE OF BERTHING SHIP					R	
Type of Ship	Ship's Speed v_{Ship}		F_d	F_l	Water Level Deflection	
	[km/h]	[m/s]			max rise	max sink
(1)	(2)	(3)	(4)	(5)	(6)	(7)
SES-Catamaran	20.00	5.55	0.89	0.19	0.30 (0.25)	0.25 (0.30)
	25.00	6.94	1.11	0.24	0.63 (0.58)	0.38 (0.34)
	35.00	9.72	1.55	0.34	0.75 (0.63)	0.25 (0.33)
Monohull	20.00	5.55	0.89	0.19	0.20 (0.23)	0.37 (0.38)
	25.00	6.94	1.11	0.25	0.35 (0.38)	0.30 (0.28)
	35.00	9.72	1.55	0.35	0.13 (0.20)	0.15 (0.19)
Catamaran	20.00	5.55	0.89	0.18	0.28 (0.25)	0.44 (0.38)
	25.00	6.94	1.11	0.25	0.70 (0.53)	0.44 (0.43)
	35.00	9.72	1.55	0.35	0.53 (0.50)	0.25 (0.24)

The program was carried out with three different ship speeds, one in the transcritical range and two tests series in the supercritical range. Recorded parameters during passage of the ship were water-level variations and flow velocities at fixed locations near the bank and above the bed. Water-level variations were taken with wave gauges. Three-directional flow velocities were recorded with acoustic Doppler velocity meters.

RESULTS

Some of the results on water-level variations from high speed ships in a trapezoidal canal are shown in Fig. 6. Maximum rise of water level (i.e., the bow wave) is with the SES-Catamaran, which reaches nearly half the canal water depth, whereas the monohull remains at H_s/H = 0.3. This is above acceptable levels, compared with conventional ships (Fig. 6).

Water-level depressions alongside the ships may reach about 0.15H, resulting in a corresponding squat of the ship. Stern waves reach about 0.1H. Flow velocities near the channel bed change their directions and may reach one-third of the ship's speed (Fig. 7).

A summary of the results on water-level fluctuations for the various canal shapes, ship types, and velocities is given in Tables 2 and 3. For the monohull and the catamaran the flow velocities are lower than with the SES-Catamaran, although still higher than with conventional ships (Tables 4 and 5).

CONCLUSIONS

Demand for high speed cargo transport on inland waterways raised the question as to which vessel type, already in operation in unrestricted open seas, might operate under the conditions of restricted waters, particularly depth- and width-restricted artificial canals.

Screening of existing high speed ship concepts showed only catamarans with and without air-cushioning and the monohull as technically feasible on inland canals. The towing tank tests with both types of ships in canal cross section exclude the air-cushioned SES-Catamaran from application. The apron for maintaining the air-cushion leads to a blockage generating extraordinary water-level increases and decreases. Also, local

TABLE 4. Velocity Variations near Canal Bed (Eccentric)

ECCENTRIC					R			RT			T		
Type of Ship	Ship's Speed v_{Ship}		F_d	F_l	Near Bed Velocities			Near Bed Velocities			Near Bed Velocities		
	[km/h]	[m/s]			u_x/v_{Ship}	u_y/v_{Ship}	u_z/v_{Ship}	u_x/v_{Ship}	u_y/v_{Ship}	u_z/v_{Ship}	u_x/v_{Ship}	u_y/v_{Ship}	u_z/v_{Ship}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
SES-Catamaran	20.00	5.56	0.89	0.19	-0.35	0.17	-0.10	-0.32	-0.19	-0.08	-0.40	-0.14	-0.09
	25.00	6.94	1.11	0.24	0.40	-0.22	-0.05	0.37	0.18	0.06	0.37	-0.13	0.07
	35.00	9.72	1.55	0.34	0.30	0.10	0.05	0.22	0.15	-0.04	0.27	0.09	0.05
Monohull	20.00	5.56	0.89	0.19	-0.31	0.09	0.09	-0.31	0.16	-0.05	0.27	0.09	0.06
	25.00	6.94	1.11	0.25	0.28	0.07	0.05	-0.17	-0.09	0.05	0.16	0.06	0.04
	35.00	9.72	1.55	0.35	0.17	0.04	0.03	-0.06	0.04	0.07	0.06	0.03	0.03
Catamaran	20.00	5.56	0.89	0.18	1.12	0.58	-0.18	-0.40	0.25	-0.18	0.32	-0.23	-0.12
	25.00	6.94	1.11	0.25	0.41	0.20	-0.17	0.38	-0.21	-0.16	0.37	0.12	-0.10
	35.00	9.72	1.55	0.35	-0.66	-0.24	-0.10	0.13	0.10	-0.11	0.14	0.09	-0.10

TABLE 5. Velocity Variations near Canal Bed (Passage of Berthing Ship)

PASSAGE OF BERTHING SHIP							
Type of Ship	Ship's Speed v_{Ship} [km/h]	[m/s]	F_d	F_l	Near Bed Velocities u_x/v_{Ship}	u_y/v_{Ship}	u_z/v_{Ship}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SES-Catamaran	20.00	5.56	0.89	0.19	0.33	-	0.11
	25.00	6.94	1.11	0.24	0.46	-	-0.15
	35.00	9.72	1.55	0.34	0.36	0.02	-0.06
Monohull	20.00	5.56	0.89	0.19	0.41	-0.12	0.05
	25.00	6.94	1.11	0.25	0.23	-0.08	-0.05
	35.00	9.72	1.55	0.35	-0.08	-0.05	-0.03
Catamaran	20.00	5.56	0.89	0.18	0.95	0.81	0.09
	25.00	6.94	1.11	0.25	-0.84	0.29	0.14
	35.00	9.72	1.55	0.35	0.31	0.19	-0.11

flow velocities are not acceptable, for traffic operations and stabilities and for maintenance of beds and banks.

Developments and optimizations appear possible and feasible only with displacement types of catamarans and monohulls. Limitations arise from draught/depth relations and beam/channel width, taking structural stability and safety criterion into consideration. This requires further and systematic research and testing. Particular considerations are to be given to interactions with other ships and necessary clearances between the ship and structures, including canal banks. Safe and easy operation, including mixed-traffic with conventional ships and small crafts, also requires extensive testing.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_c = wetted canal cross section;
A_s = fully loaded ship cross section;
a = eccentricity of ship;
B = ship’s width (beam);
B^* = necessary distance for passage;
B_F = width of fairway;
B_w = width of water level;
B_1 = width of traffic lane;
b = distance to measurement point;
c = velocity of a progressive wave in shallow water;
F_d = depth-related Froude number;
F_l = length-related Froude number;
g = acceleration of gravity;
H = water depth;
H_s = water-level variation;
h_t = passage height;
L = ship’s length;
n = aspect ratio;
R = rectangular profile;
RT = rectangular-trapezoidal profile;
S_B = safety distance between lanes;
S_s = safety distance to bank in depth t_v;
S_u = safety distance to bank;
T = trapezoidal profile;
T_a = ship’s draught;
t_v = standard draught;
u_x = velocity component in x- (longitudinal-) direction;
u_y = velocity component in y- (cross-) direction;
u_z = velocity component in z- (vertical-) direction;
v_{ship} = ship’s speed; and
ΔH = dynamic water-level sinkage (squat).