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THE HYDRODYNAMIC ROLE OF FISH SQUAMOSAL INTEGUMENT AS AN ANALOG OF SURFACES DIRECTLY FORMED BY TURBULENT FLOW

A. F. Kudryashov, V. V. Barsukov

Translation of " O Gidrodinamicheskoy roli cheshuynogo pokrova ryb kak analoga poverkhnostey, neposredstvenno sformirovannykh vikhreveym potokom" Zoologicheskiy zhurnal Vol. 46, No. 3, 1967, pp. 393-403

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16. Abstract

The distribution of squamae on the fish body and that of deposits in the bed of the river can be described by the same equation. The curves reflecting the relative elongation and stability of the body shape of the fish continue the curves showing the elongation of bank spit and stability of the bed of the river.

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THE HYDRODYNAMIC ROLE OF FISH SQUAMOSAL INTEGUMENT AS AN ANALOG OF SURFACES DIRECTLY FORMED BY TURBULENT FLOW

REPORT I. SIMILARITY BETWEEN IRREGULARITIES IN SQUAMOSAL INTEGUMENT AND THOSE ON SURFACES FORMED BY FLOW IN RIVER BEDS

O Gidrodinamicheskoy roli cheshuynogo pokrova ryb kak analoga poverkhnostey,neposredstvenno sformirovannykh vikhreveym potokom
Soobshcheniye I. Skhodstvo nerovnostey cheshuynogo pokrova s nerovnostyami na poverkhnostyakh,sformirovannykh potokom v ruslakh rek

A..F. Kudryashov and V. V. Barsukov

Zoologicheskiy zhurnal, Vol. 46, No. 3, 1967, pp. 393-403

The generally accepted view of the fish squama only as a means of protection from mechanical damages and parasites is poorly supported by specific observations and experiments. It is not sufficient since one can hardly doubt the great importance for the fish of the hydrodynamic qualities of its integuments. Works covering the hydrodynamic role of the squama began to appear only recently (Walters, 1962; Aleyev, 1963; G. Wahlert and H. Wahlert, 1964). In this article yet another attempt has been made to mark the way for future research in this area. This is an attempt to draw an analogy between the fish squamosal integument and the surfaces directly formed by the turbulent flow. Such surfaces that have been formed by water and air streams are widespread in nonliving nature (Kudryashov, 1959, 1960, 1965). */393

The surface formed by a turbulent flow changes simultaneously and in accordance with the turbulent perturbances of the viscous medium flowing around it. These are the surfaces of bank spits[1] and ridges in river beds, sand dunes, and snow drifts on the ground, waves on the water, clouds in the sky,etc. The water or air stream by means of turbulent mixing tears off particles from any of these surfaces and moves them along the boundary between two media (for example, solid and liquid). The transfer of this suspension to a certain measure suppresses the intensity of the turbulent impulses. This is confirmed, in particular, by the experiments with a water stream (Vanoni, 1953; Yufin, 1959). The suspension is settled in places with smaller impulses. It is elevated once more or shifted in places with greater impulses, reducing the latter. The formation of crests and valleys must act analogously on the surfaces of wind-driven waves. In the final analysis, the surfaces acquire a shape that guarantees the least hydro- or aerodynamic resistance with the given velocity and viscosity of the flow, with the given size and specific weight of the particles. The smaller the cohesive force between the particles, the larger the surface that is defined as directly formed by the water stream. The characteristics of the mobile irregularities on such a surface are constant while the listed conditions remain unchanged. The resistance to the flow is lower, the lower the velocity and viscosity of the flow, and

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[1] Pobochni--large accumulations of detritus that adjoin the shores of rivers, usually in a staggered order.

*Numbers in the margins indicate pagination in the foreign text the better the size and specific weight of the particles satisfy the force of their shifting or suspension.

The surfaces that we are discussing are called surfaces formed by a flow only for convenience. Actually the surface and the flow form each other. /394

Fish (and birds) move under conditions of a turbulent flow (Shuleykin, 1953; Rosen, 1961; Chestnoy, 1961; Lavrent'yev, M. A. and Lavrent'yev M. M., 1962; Aleyev, 1963; Patrashev, 1964). The requirement for the least resistance and the least energy outlays for movement is paramount for them. One can therefore expect some analogy between their integuments and the surfaces formed by turbulent flows in nonliving nature. However, a reduction in the energy outlays for production of particles that are moved by the flow is no less important for the organism. It needs to be explained how far the analogy of integuments goes. This refers in particular to fish and the analogy with the surfaces directly formed by the turbulent flow, and by what means can the loss of the aforementioned particles be prevented or reduced. Our article is the first step in this direction.[2]

Material and Technique

In order to clarify the question presented above, we should first of all know the motion velocity of fish and obtain data that characterize its body shape, the arrangement, and dimensions of the irregularities on its surface that are comparable to the analogous data for the aforementioned bodies of nonliving nature, primarily pobochni and ridges in river beds with low turbidity.

Well-recorded specimens of fish were selected from the collections of the Zoological Institute of the USSR Academy of Sciences. These were specimens of fish of those species and dimensions whose greatest motion velocity (V_{max}) has been measured by instrument (Ohlmer and Schwartzkopf, 1959; Blaxter and Dickson, 1959; Ohlmer, 1964; Radakov and Protasov, 1964). These specimens provided a fairly broad range of velocities. Fish were not included that had an unusually large content

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[2] The author is very grateful for critical examination to A. N. Svetovidov, G. U. Lindberg, A. P. Andriyashev, A. A. Strelkov, F. B. Mukhomediarov, G. Kh. Shaposhnikova, V. A. Klyukanov, A. V. Neyelov, Ye. A. Dorofeyeva and Z. V. Krasyukova.

water in the tissues and in whom one could expect excessive changes in body shape when kept in preserving fluids (Barsukov and Svetovidov, 1966).

In addition, museum specimens were used of tuna and swordfish, whose skin was set on a frame with preservation of the original body shape, since no folds or stretches are noticeable on it.

A Black Sea salmon caught in the Mzymta River in June 1959 was studied in fresh form. Its maximum velocity V_{max} was accepted as equal to that of the Atlantic salmon of similar dimensions.

For the purposes indicated above, a slide gage was used to measure the length of the fish (L) from a point on the jaw that projects forward the most, to the end of the vertebral column, as well as the greatest height (2 B) and width (2 θ) of the body. A flexible measuring tape was used to measure the perimeter of the greatest fish cross section (χ) without consideration for the fin sections. A protractor measured the angle of incline of the slanting rows of squamae to a perpendicular lowered on the tangent to the lateral line in the area of the greatest cross section (β), and in the middle of the distance between the greatest cross section and the end of the vertebral column (β_1). The radius of the circumference whose points coincide the best with the lateral surface of one of the symmetrical sides of the body ($R_{1.s}$) was measured in the greatest body cross section. The area of the latter (ω) was computed on millimeter paper.

The greatest length of the open section of squama (l_r), its width (b_r), as well as the distance between the two neighboring sclerites on the edge of the open section of squama (d_b--average of 10 measurements, from the edge of the squama to the center) were measured under a MBS-1 binoculars and MIS-11 microscope, MIR-1m and AM-9-2 micrometers. The squamae were taken at half of the body height at its greatest cross section. In the pike perch, fish with ctenoid squamae, the same 10 distances were measured between the sclerites that were arranged nearby with rows of spinules, while in the salmon and herring whose cycloid squama in the rear zone of the open section is devoid of sclerites, measurements were made nearby this zone.

The measurement results are given in tables 1 and 2. The increase in the ordinal number corresponds to the decrease in the values of

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Table 1. Body Dimensions and Motion Velocities

No. in order*	Names of fish	L^{**}	B	θ	V_{max}	$R_{l.s}$	ω	χ
1a	Swordfish (Xiphias gladius) with sword	149,0	9,85	9,85	3000	9,8	304,5	61,9
1b	The same without sword	104,0	9,85	9,85	3000	9,8	304,5	61,9
2	Tuna (Thunnus thynnus)	192,0	23,9	21,6	2000	24,0	1624,0	143,0
3	Red fish (Oncorhynchus nerka)	48,0	6,7	2,7	500	9,6	42,4	30,9
4a	Salmon, Black Sea (Salmo trutta labrax)	96,5	16,0	8,0	842	25,0	402,0	77,5
4b	Atlantic salmon (S. salar)	45,5	5,55	1,7	320	9,9	22,6	24,3
5	Sea-trout (S. trutta)	38,0	5,3	1,65	300	9,4	20,4	23,4
6	Crucian carp (Carassius auratus)	13,0	2,65	1,3	169	3,3	8,6	12,7
7	Baltic sprat (Sprattus sprattus balticus)	8,5	1,1	0,45	75	1,6	1,2	5,1
8	Pike perch (Lucioperca lucioperca)	37,5	4,29	2,2	180	5,3	23,4	20,9
9	Haddock (Melanogrammus aeglefinus)	25,0	2,75	1,45	140	3,3	9,9	13,5
10	Herring, Atlantic (Clupea harengus harengus)	30,0	3,5	1,9	200	4,2	16,5	17,2
11	Rainbow trout (Salmo irideus)	12,0	1,75	0,9	70	2,1	3,8	8,6
12	Bream (Abramis brama)	23,5	5,0	1,5	96	9,0	16,6	22,0
13	Crucian carp (Carassius auratus)	7,8	1,75	0,75	70	2,4	3,1	8,2

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*The studied fish are given by these same numbers in the figures and in tables 2,3,4,5.

**L--length of fish body to end of vertebral column, cm; B--half of the greatest fish body height, cm; θ--half of the greatest fish body width, cm; V_{max}--greatest motion velocity of fish, cm/s; $R_{l.s}$--greatest radius of circumference on lateral surface on fish body cross section, cm; ω--greatest area of fish body cross section, cm^2; χ--greatest wetted perimeter in fish body cross section, cm; only half of the height B and half of the greatest body width θ are taken for convenience to compare the fish with formations formed by the turbulent flow in river beds; the possibility is not excluded that the given motion velocity is not actually the maximum in all fish, and this of course, makes our conclusions only approximate.

the dynamic and kinematic characteristics of the fish. /396

Similarity between Irregularities of Squamosal Integument and Irregularities on Surfaces Formed by Flow in River Beds

The squama is arranged on the fish body in an order that is close to a staggered pattern. It forms transverse, longitudinal and oblique rows. The regularity of these rows is often disrupted and the oblique rows are preserved the best. Rows of irregularities (chains of ridges) in river beds, naturally are less regular, but there is a similar law in action here.

The arrangement of squamae on the fish body (fig. 1) is described fairly accurately by the equation of cycloid evolute:

Table 2. Angles of Incline of Oblique Rows of Squamae, Dimensions of Open Section of Squamulae and Distances between Sclerites

number in order*	β**	β_1	l_r	b_r	d_b
1a	--	—	no. squamae		
1 b	--	—	» »		
2	22	25	0,380	0,660	0,0024
3	30	25	0,319	0,406	0,0040
4a	25	26	0,420	0,868	0,0038
4 b	26	20	0,340	0,480	0,0030
5	32	30	0,240	0,290	0,0036
6	21	25	0,440	0,800	0,00342
7	24,5	30	0,160	0,280	0,00305
8	23	23,5	0,220	0,520	0,0036
9	30	41	0,150	0,150	0,00267
10	27,5	30	0,320	0,500	0,00232
11	25	26	0,070	0,080	0,00257
12	27	30	0,400	0,750	0,00421
13	21	25	0,200	0,400	0,00655

*For the names of fish see these numbers in table 1.

**β, β_1--angles of incline of oblique rows of squamae to perpendicular of tangential lateral line, in degrees (β--in the arrangement of the greatest cross section; β_1--in middle of distance between greatest cross section and end of vertebral column); l_r--length of open section of squamulae on half of body height in greatest cross section of fish, cm; d_b--distance between sclerites on end of open section of squamulae in greatest cross section of fish on half of body height, cm.

$$X_1 = a(t + \sin t)$$
$$Y_1 = -a(1 - \cos t). \qquad (1)$$

where Y_1--ordinate that coincides with direction of fish lateral line, t--angle of rotation of circumference. With the least approximation, this equation also describes the irregularities that are directly formed in the river beds by the turbulent flow. In this case the Y_1 ordinate coincides with the direction of the stream of greatest velocity.

The hypothesis that follows from here on finding the lateral line on the torso and tail usually at the sites of the greatest velocity of the stream flowing around the fish is supported by the following consideration. As is known, the external perturbances (including those acting on the lateral line of the fish) generate or intensify the /397 eddies in the boundary layer to a greater extent, the higher the velocity of the stream flowing around the body (Shlikhting, 1962). Consequently, these eddies must increase the sensitivity of the lateral line to oscillations and currents in water that are coming from the outside to

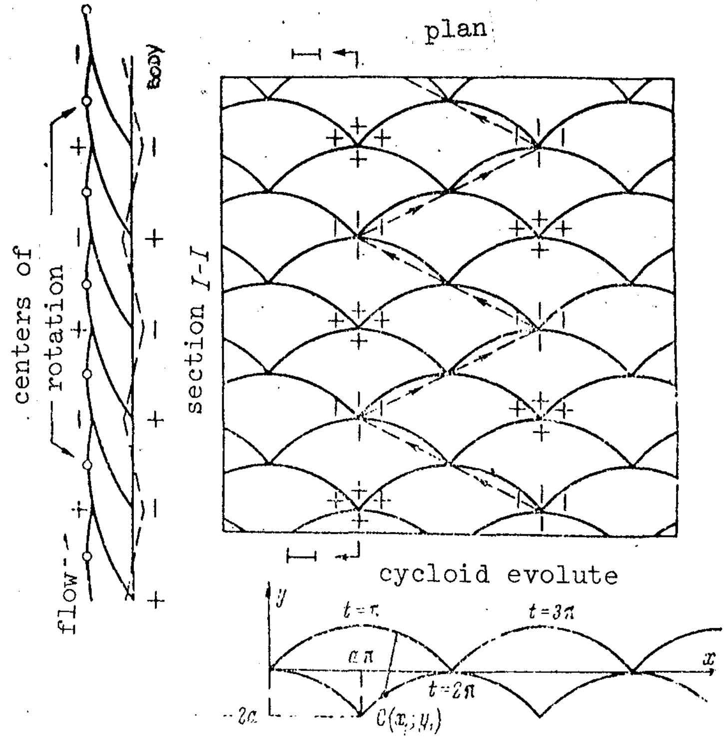

Figure 1. Plan of Integument Made of Squamae Lying on Each Other
The plus sign designates possible sites of elevation of the squama; the minus sign designates the sites of lowering. The arrows indicate a shift in the turbulent zone from the valley of one wave to the valley of another.

a stronger degree the closer it is located to the sites where the flow velocity is the greatest.

The angle of incline of the oblique rows of squama to the perpendicular of the lateral line in the studied fish in the region of their greatest cross section equals 21-31, and averages 25°. In the middle between this section and the end of the vertebral column it equals 20-41 and averages 26.5° (table 2). The chains of ridges on bank spits formed by the turbulent flow, form an angle to the perpendicular of the direction of the greatest velocity stream. This angle is close in value. In the ridge this angle is also usually somewhat smaller in the greatest section of the bank spits than in the middle between them and the end of the bank spits (Kudryashov, 1959).

The squamae carry concentric elevations, sclerites. The distance between them on the open section of the squama, judging from everything, characterizes the diameter of the turbulent formations in the boundary layer, like the irregularities on the surface of the ridges in river beds. It should be assumed that the elastic epithelium is deflected under the influence of turbulent formations, thus forming valleys between the sclerites. In such a case, the value d_b (table 2) determines the measure of irregularity, i.e., the energy of the turbulent formations, while the ratios

$$2l_r/d_b \text{ and } 2b_r/d_b$$

are the ratios of energy for the structural formations in the boundary layer. These ratios are associated with the dynamic and kinematic characteristics of fish, in particular, the Froude and Reynolds numbers.

One can adopt as the specific kinetic energy of fish the ratio of the square of the greatest velocity to the doubled acceleration of the gravity force $V^2_{max}/2q$ expressed in centimeters of water column. This is in accordance with other phenomena in hydrodynamics (Patrashev,1953).

For simplification of the problem, we will consider that the fish move at the same depth which is sufficient for wave resistance to be missing, but which is not far from the water surface. By analogy with other phenomena in hydrodynamics and hydraulics, in particular, the movement of a stream in an open alluvial bed directly formed by the turbulent flow, we can adopt as the potential energy the product of the specific weight of water γ times half of the thickness of the zone of displacement of the liquid by the fish body, i.e., $\gamma \cdot \theta$.

The sum of kinetic and potential energy, the so-called complete specific energy, is also expressed in centimeters of water column.

The ratio of specific kinetic energy to the specific potential in hydraulics of open beds is called the Bussinesk number, while their doubled ratio is called Froude's number (Makkaveyev and Konovalov, 1939). Froude's number expresses well the essence of the phenomenon only in calm pattern conditions, when it is less than or equal to 1, i.e., on the condition that the kinetic energy as compared to the potential is small. In our case where Froude's number is greater than 1, one should look at the ratio of specific kinetic energy to the complete kinetic energy e. Here $\tau \sim \mu \cdot (dV/de)$ is the tangential stress between the stream layers.

If one examines the product of the specific weight of water times

Table 3. Relative Dimensions of Body, Squama and Index of Maneuverability

№* in order	relative elongation of body				hydralic radius	index of maneuverability		
	$\frac{L}{B}$	$\frac{L}{\theta}$	$\frac{L}{R_{f.s.}}$	$\frac{B}{\theta}$	$\frac{\omega}{\chi}=R$, см	$\frac{L}{R}$	$\frac{2 \cdot l_r}{d_b}$	$\frac{2 \cdot b_r}{d_b}$
1a	15,13	15,13	15,13	1,00	4,92	30,3	—	—
1 b	10,56	10,56	10,56	1,00	4,92	21,2	—	—
2	8,04	8,88	8,00	1,10	11,35	16,9	317,0	550,0
3	7,16	17,76	4,98	2,48	1,37	35,0	159,6	202,6
4a	6,02	12,05	3,86	2,00	5,18	18,6	221,0	457,5
4 b	8,20	26,74	4,58	3,26	0,93	49,1	226,6	320,0
5	7,36	23,00	4,04	3,21	0,87	43,6	133,4	161,0
6	4,90	10,00	3,89	2,04	0,68	19,1	257,2	468,0
7	7,72	18,88	5,42	2,44	0,24	35,4	104,6	183,4
8	9,62	17,04	7,08	1,95	1,12	33,5	122,2	289,0
9	9,10	17,24	7,46	1,90	0,73	34,1	112,4	112,4
10	8,56	15,80	7,20	1,84	0,96	31,3	276,0	431,0
11	6,86	13,34	5,59	1,94	0,44	27,3	54,4	62,3
12	4,70	15,65	2,60	3,33	0,75	31,3	190,2	356,0
13	4,46	10,40	3,26	2,33	0,38	20,5	61,0	122,2

*For the names of the fish see these numbers in table 1.

the complete specific energy as the complete hydrodynamic pressure, then the ratio of kinetic energy to the complete hydrodynamic pressure will be the specific dynamic characteristic that is inverse to Euler's number. This characteristic changes from the values close to zero for open bed processes to those that approach 1 for fish.

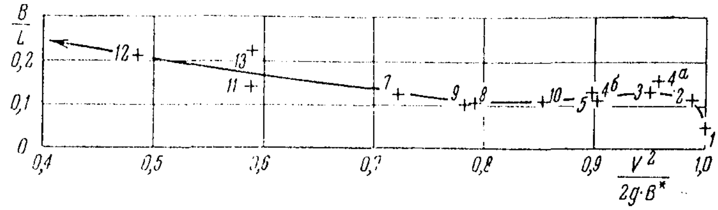

Figure 2. Dependence of Relative Elongation of Body from One of the Dynamic Characteristics of Fish

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Froude's number that was computed for the studied fish in the form $V^2_{max}/g\theta$, shows that they all move under conditions of a turbulent eddy flow, i.e., $V^2_{max}/g\theta>1$. Froude's number V^2_{max}/gL is also the dynamic characteristic for fish movement since L and θ are in definite ratios (tables 3,4 and 5). The dependence of relative elongation of the studied fish B/L on the dynamic characteristic of their movement $V^2/2gB^*$ [where $B^*=(V^2_{max}/2g)+B$] is expressed in the form of a curve (figure 2). Its continuation reflects an analogous relationship in the spontaneous formations in the bed processes. It follows from here that the dynamic characteristic for fish movement is the ratio of the inertia forces to the gravity forces. This determines the dynamics for the turbulent stream flowing around the fish.

The ratio of the product of the greatest fish movement velocity times its complete specific energy to the kinematic coefficient of water viscosity v is taken as the kinematic characteristic of fish movement, for example, $V_{max}\theta^*/v$ [where $\theta^*=(V^2_{max}/2g)+\theta$].

The ratio of the product of the greatest velocity V_{max} times the transverse θ or longitudinal L body dimension to the kinematic coefficient of water viscosity v in hydromechanics is called the Reynolds number (Karman, 1936), which is also the kinematic characteristic of fish movement.

The graphic dependence of the ratios $2l_r/d_b$ and $2b_r/d_b$ on one of the dynamic characteristics of the studied fish ($V^2_{max}/2g\theta^*$) is presented in figure 3. The obtained curves again represent a continuation of the analogous curves for ridges in river beds that are directly formed by the turbulent flow (Kudryashov, 1959).

The interrelationship of the distance between the sclerites, the length of the open section of the squama, the thickness of the fish body and the maximum velocity of their movement is also characterized by the relationship /399

$$2l_r/d_b=f(V_{max}\theta).$$

With a kinematic coefficient of water viscosity θ, computed at 15°, this relationship is analogous for the majority of studied fish (fig. 4) to the similar relationship for ridges in river beds (Kudryashov, 1959). With the same water temperature, the ratio of the doubled length of the open section of the squama to the distance between the sclerites increases as the fish velocity rises, despite the increase in the thickness of their body. The greater the distance between the sclerites, the more strongly this increase is pronounced.

It is apparent from here that with similar fish dimensions, similar distance between the sclerites, and close temperatures, with a drop in the fish movement velocity, the dimensions of the open section of the squama should diminish. The tench can serve as an example

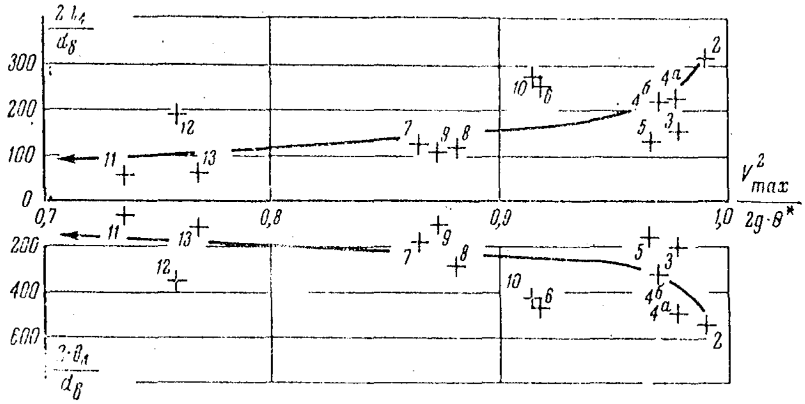

Figure 3. Dependence of Ratio of Structural Formation Dimensions in Boundary Layer on One of the Dynamic Characteristics of Fish

Table 4. Dynamic Characteristics

№ in order	specific energy of fish, cm water column					dynamic characteristics of fish				Froude's number
	kinetic energy	complete energy								
	$\frac{V_{max}}{2g}$	$\frac{V^2_{max}}{2g}+B=B^*$	$\frac{V^2_{max}}{2g}+\theta=\theta^*$	$\frac{V^2_{max}}{2g}+R=R^*$	$\frac{V^2_{max}}{2g}+R_{l.s.}=R_{l.s.}^*$	$\frac{V^2_{max}}{2g\cdot B^*}$	$\frac{V^2_{max}}{2g\cdot\theta^*}$	$\frac{V^2_{max}}{2g\cdot R_{l.s}^*}$	$\frac{V^2_{max}}{2g\cdot R^*}$	$\frac{V^2_{max}}{g\cdot L}=Fr$
1a	4590	4599,85	4599,85	4600	4594,92	0,999	0,999	0,999	0,999	61,70
1b	4590	4599,85	4599,85	4600	4594,92	0,999	0,000	0,999	0,999	88,50
2	2040	2063,90	2061,60	2064	2051,35	0,986	0,990	0,989	0,995	21,24
3	127,5	134,20	130,20	137,13	128,87	0,949	0,978	0,930	0,988	5,31
4a	361,0	377,00	369,00	364,86	366,18	0,957	0,978	0,988	0,985	7,48
4b	52,2	57,75	53,90	62,12	53,13	0,902	0,970	0,840	0,982	2,29
5	45,85	51,15	47,50	55,25	46,72	0,898	0,966	0,832	0,982	2,41
6	14,58	17,23	15,88	17,92	15,26	0,846	0,918	0,815	0,956	2,24
7	2,86	3,96	3,32	4,44	3,10	0,722	0,865	0,646	0,922	0,67
8	16,52	20,81	18,72	21,82	17,64	0,792	0,882	0,757	0,937	0,88
9	10,00	12,75	11,44	13,35	10,73	0,783	0,873	0,749	0,930	0,80
10	20,40	23,90	22,30	24,57	21,36	0,853	0,915	0,834	0,957	1,36
11	2,50	4,25	3,40	4,64	2,94	0,588	0,735	0,538	0,851	0,42
12	4,70	9,70	6,20	13,74	5,45	0,485	0,758	0,342	0,862	0,40
13	2,50	4,25	3,25	4,89	2,88	0,588	0,768	0,511	0,868	0,64

*For the names of the fish see these numbers in table 1.

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from the fish that we did not study. It differs little in body shape, distance between the sclerites (Galkin, 1958) and temperature pattern from many other carp. The not very mobile tench has very small squamae.

With a rise in water temperature, the coefficient ϑ diminishes. With the same body dimensions and movement velocities either the size of the open section of the squama must increase, or the distance between the sclerites must decrease. The increase in the length and width of the open section of the squama in fish of similar dimensions that

Table 5. Kinematic Characteristics

№ in order*	kinematic characteristics of fish with water temperature 15° + ϑ = 0,01141 cm^2/S				Reynolds number with water temperature 15° and ϑ = 0,01141 cm^2/S	
	$\frac{V_{max} \cdot B^*}{\vartheta}$	$\frac{V_{max} \cdot \theta^*}{\vartheta}$	$\frac{V_{max} \cdot R^*_{l.s.}}{\vartheta}$	$\frac{V_{max} \cdot R^*}{\vartheta}$	$\frac{V_{max} \cdot L}{\vartheta} = Re$	$\frac{V_{max} \cdot \theta}{\vartheta} = Re$
1a	$1,21 \cdot 10^9$	$1,21 \cdot 10^9$	$1,21 \cdot 10^9$	$1,21 \cdot 10^9$	$3,92 \cdot 10^7$	$2,59 \cdot 10^6$
1 b	$1,21 \cdot 10^9$	$1,21 \cdot 10^9$	$1,21 \cdot 10^9$	$1,21 \cdot 10^9$	$2,74 \cdot 10^7$	$2,59 \cdot 10^6$
2	$3,62 \cdot 10^8$	$3,64 \cdot 10^8$	$3,62 \cdot 10^8$	$3,61 \cdot 10^8$	$3,37 \cdot 10^7$	$3,79 \cdot 10^6$
3	$5,88 \cdot 10^6$	$5,72 \cdot 10^6$	$6,02 \cdot 10^6$	$5,65 \cdot 10^6$	$2,10 \cdot 10^6$	$1,183 \cdot 10^5$
4a	$2,78 \cdot 10^7$	$2,72 \cdot 10^7$	$2,69 \cdot 10^7$	$2,70 \cdot 10^7$	$7,12 \cdot 10^6$	$5,91 \cdot 10^5$
4 b	$1,62 \cdot 10^6$	$1,52 \cdot 10^6$	$1,75 \cdot 10^6$	$1,50 \cdot 10^6$	$1,28 \cdot 10^6$	$4,76 \cdot 10^4$
5	$1,35 \cdot 10^6$	$1,25 \cdot 10^6$	$1,46 \cdot 10^6$	$1,23 \cdot 10^6$	$1,00 \cdot 10^6$	$4,33 \cdot 10^4$
6	$2,54 \cdot 10^5$	$2,36 \cdot 10^5$	$2,66 \cdot 10^5$	$2,27 \cdot 10^5$	$1,93 \cdot 10^5$	$1,925 \cdot 10^4$
7	$2,61 \cdot 10^4$	$2,17 \cdot 10^4$	$2,92 \cdot 10^4$	$2,06 \cdot 10^4$	$5,60 \cdot 10^4$	$2,96 \cdot 10^3$
8	$3,29 \cdot 10^5$	$2,96 \cdot 10^5$	$3,45 \cdot 10^5$	$2,78 \cdot 10^5$	$5,92 \cdot 10^5$	$3,47 \cdot 10^4$
9	$1,56 \cdot 10^5$	$1,40 \cdot 10^5$	$1,64 \cdot 10^5$	$1,32 \cdot 10^5$	$3,08 \cdot 10^5$	$1,78 \cdot 10^4$
10	$4,20 \cdot 10^5$	$3,91 \cdot 10^5$	$4,32 \cdot 10^5$	$3,75 \cdot 10^5$	$5,27 \cdot 10^5$	$3,33 \cdot 10^4$
11	$2,61 \cdot 10^4$	$2,09 \cdot 10^4$	$2,85 \cdot 10^4$	$1,80 \cdot 10^4$	$7,37 \cdot 10^4$	$5,52 \cdot 10^3$
12	$8,20 \cdot 10^4$	$5,23 \cdot 10^4$	$1,16 \cdot 10^5$	$4,60 \cdot 10^4$	$1,98 \cdot 10^5$	$1,262 \cdot 10^4$
13	$2,61 \cdot 10^4$	$2,00 \cdot 10^4$	$3,02 \cdot 10^4$	$1,77 \cdot 10^4$	$4,80 \cdot 10^4$	$4,6 \cdot 10^3$

*For the names of the fish see these numbers in table 1.

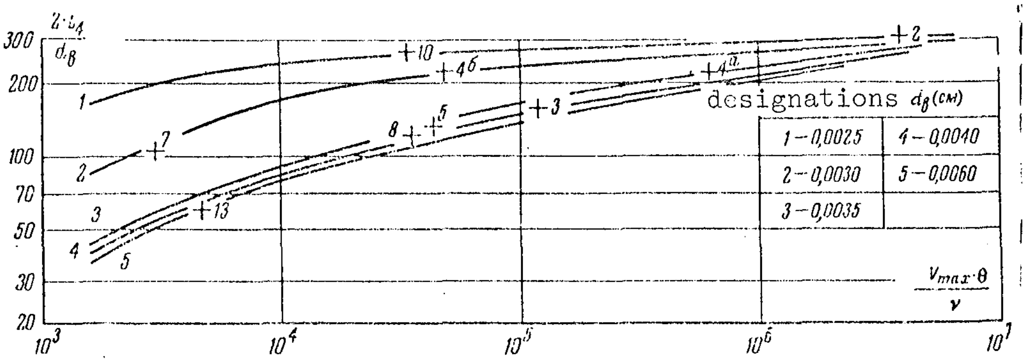

Figure 4. Dependence of Ratio of Structural Formation Dimensions in the Boundary Layer on Reynolds Number

belong to the same genus that is expressed in the reduced number of squamae in a direction for the northern parts of the area to the southern is a very widespread phenomenon in fish and is widely known.

The ratio of energy of the turbulent formations in the boundary layer that is characterized by the distance between sclerites (d_b) to the complete specific energy of fish B^*, θ^*, $R^*_{1.s}$ ($R_{1.s} = V^2_{max}/2g + R_{1.s}$) and R^* ($R^* = V^2_{max}/2g + R$; the hydraulic radius $R = \omega/\chi$) that is lost /401 over the length of the fish L, is adopted as the indicator for stability of the body shape:

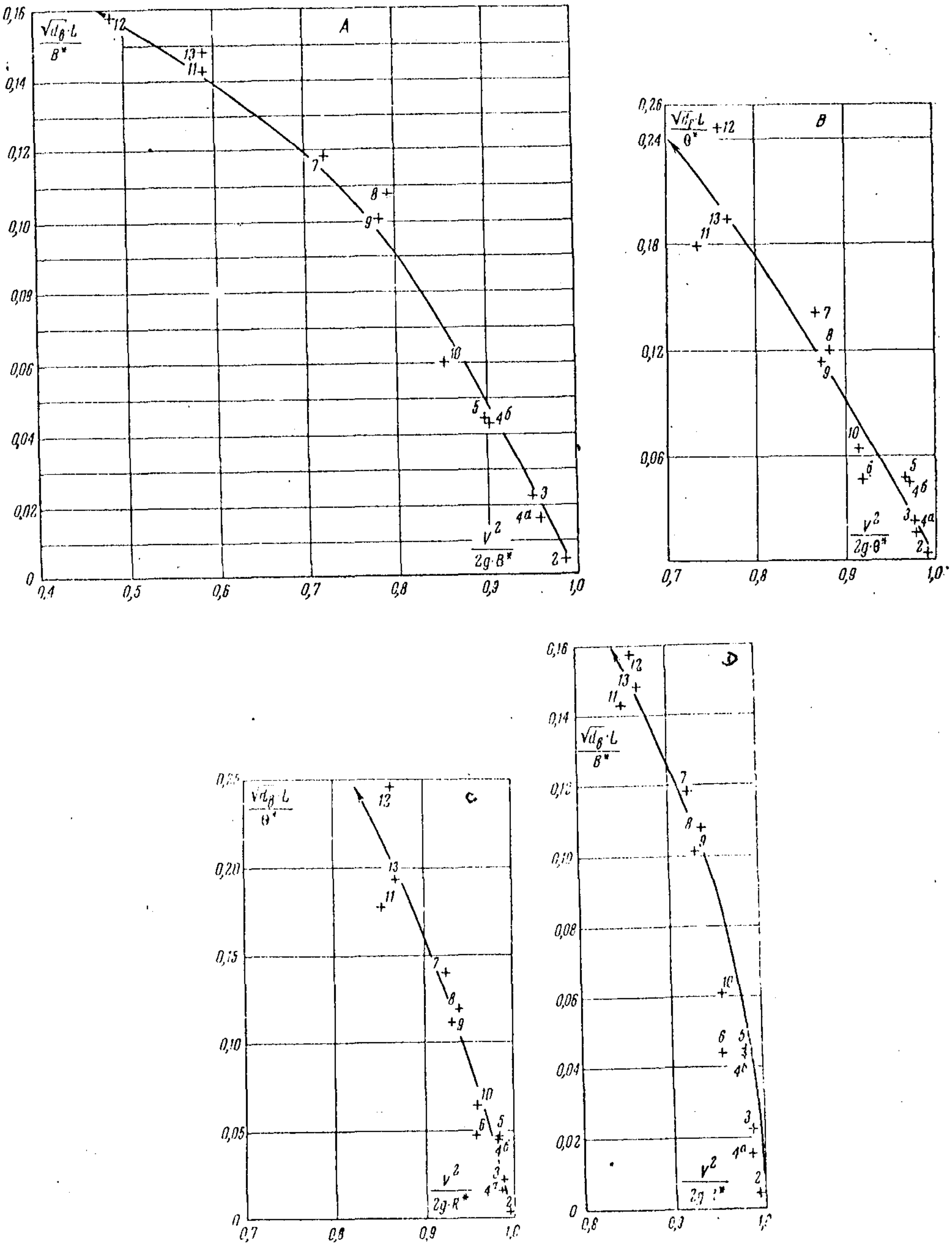

Figure 5. Dependence of Index of Stability of Body Shape on Dynamic Characteristics of Fish
a, d--according to body height; b,c--according to body thickness

$$\frac{\sqrt{d_b}\cdot L}{B^*},\qquad \frac{\sqrt{d_b}\cdot L}{\theta^*},\qquad \frac{\sqrt{d_b}\cdot L}{R^*_{1,5}},\qquad \frac{\sqrt{d_b}\cdot L}{R^*}$$

(the coefficient $a = A\cdot\frac{\nu^{2/3}}{g^{1/3}}$, characterizing the hydromechanical conditions in the boundary layer is accepted as equal to 1 cm of water

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column, and therefore is not introduced into the formula) (Kudryashov, 1965).

The indicators for stability of the the body shape diminish with an increase in the dynamic fish characteristics, i.e.,

$$\frac{V^2_{max}}{2gB^*} = 1 - \frac{\sqrt{d_b}\cdot L}{B^*} + \frac{d_b\cdot L^2}{3B^{*2}} - \frac{d_b\cdot L^4}{0{,}003\cdot B^{*4}}, \quad (2)$$

$$\frac{V^2_{max}}{2g\theta^*} = 1 - \frac{\sqrt{d_b}\cdot L}{\theta^*} - \frac{d_b L^2}{\theta^{*2}}, \quad (3)$$

$$\frac{V^2_{max}}{2gR^*} = 1 - 0{,}47\,\frac{\sqrt{d_b}\cdot L}{\theta^*} - \frac{d_b\cdot L^2}{\theta^{*2}}, \quad (4)$$

Here

$$\frac{L}{B^*} = \frac{83{,}7}{\sqrt{\frac{V^2_{max}}{2g\cdot d_b}}} \quad (5)$$

$$\frac{V^2_{max}}{2g} = \frac{0{,}068\cdot B^{*2}}{d_b\cdot L^2}. \quad (6)$$

The fastest moving fish possess the least variable body shape, while the slowest moving fish have the most variable body shape (fig. 5).[3] The presented curves are a continuation of the curves obtained by analogous computations for formations in river beds that are directly formed by a turbulent flow, and their models (Kudryashov, 1960, 1965).

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[3] The nature of fatty deposits in fish should therefore depend on their dynamic characteristics. Generally, the body shape of fish, as is apparent from equations (2)-(4) and fig. 5a,b, changes more easily in height than in width. This circumstance is reflected excellently in the very mobile attachment of the basalia of the dorsal and anal fins with spinal and hemal processes.

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