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THE RESISTANCE OF SHIPS.

BY RICHARD LANO NEWMAN.

[*A paper read before the Section of Engineers and Naval Architects, January 24, 1894.*]

No branch of the theory of naval architecture has a richer literature than that which forms the subject of this paper. It would be a formidable task merely to enumerate the names of eminent mathematicians, and experimentalists who have endeavored to discover the laws of the resistance which water offers to the progress of ships, and still more formidable would be any attempt to describe the very various theories that have been devised. Again and again, has the discovery been announced of the "form of least resistance," but none of these have largely influenced the practical work of designing ships, nor can any be regarded as resting on a thoroughly scientific basis. In fact, at the present time it is generally accepted as a fact, that the problem is one that pure theory can never be expected to solve.

Before dealing with what is generally known as the modern theory (*i. e.*, the stream line theory, on which the most successful of our high-speed ships have been built), let us take a brief glance at what a few of the many workers in this field of science have contributed to the solution of the problem during the past 150 years.

Foremost among those who have investigated this difficult problem is Sir Isaac Newton, who, in the second book of his *Principia*, has demonstrated that the resistance opposed to bodies which move in a fluid varies as the square of the velocity of the body; but this has been proved to be applicable only to bodies having comparatively low velocities. It is evident, therefore, that a theory based on such conditions would not be applicable to naval architecture, one of the objects of which is to obtain high velocities.

Following Newton came Daniel Bernoulli. He considered that the resistance should be represented by two terms, one denoting the square of the velocity, the other being a constant; but this was opposed by D'Alembert, who carried on his enquiries in a different manner, and succeeded in representing the theory of fluids in a more general formula than had hitherto been done.

In attempting to apply a theory of resistance to naval architecture, most of the authors of the greatest eminence who wrote on this subject down to the time of the Abbé Bossut followed Newton in supposing the resistance to vary as the square of the velocity; for, up to this time, the theory that affirmed this to be correct had not been shown to be erroneous.

In the year 1775, a series of experiments was made at Paris, under the direction of the Comptroller-General of Finances, with the assistance of the Abbé Bossut, M. D'Alembert and the Marquis de Condorcet. The magnitude of these experiments exceeded anything that had hitherto been attempted in this direction. The experiments were first carried out with the object of testing the then existing theories, and if none of them could be verified, to procure data to serve as a basis for a new solution.

The Abbé Bossut remarked, in his report, that that advice

was the more conclusive, as M. D'Alembert had solved the question by a new and strictly analytical method, which would leave nothing to be wished for, could the equations which are deduced be integrated, either by converging series, or by any other method. But unfortunately this was the point on which they failed. The results of these experiments did not agree with any of the then known theories, as they all previously supposed the resistance to vary as the square of the velocity. Although an investigation of the tabulated results would prove very interesting, it must suffice for our purpose to give a brief summary of the report, as time will not permit a further investigation.

Summary of Report.—The resistances experienced by the same body, whatever may be its figure, moved with different velocities through a fluid infinite in extent, are very nearly in proportion to the squares of the velocities. It has been shown that the resistance varies in a rather greater ratio than that of the square. Experiment, therefore, agrees on this point very nearly with theory. (Here we must remember that the velocities at which the models were propelled were comparatively low, the highest being only 260 feet per minute.)

The resistance which arises from motion in oblique directions do not diminish, everything else remaining the same, in proportion to the square of the sines of the angles of incidence; therefore, on this head, the common theory of the resistance of fluid should be abandoned altogether, when the angles of incidence are small; as then the results deduced from it would be erroneous. It is evident, also, that it cannot be employed to find the solid of least resistance, nor generally to determine any curve, for in such problems the law of the curvature is an unknown element; but for curves in which the angles of incidence are large, as from 50° to 90° , we may make use of the theory; always remembering that the resistance which will result will be rather less than those given by experiment, and that the error will be greater in proportion as the angles of incidence are smaller.

It is also interesting to note that these same investi-

gators touched on the question of resistance as affected by the depth of water, and their experiments proved conclusively that this item was not to be neglected. Of the truth of this law, we have quite recently had an illustration viz: when the cruiser *New York* went on her official run.

The Chevalier du Buat deduced from his experiments a conclusion directly at variance with the common theory, and I only give it, that you may compare it with that now generally accepted. He gave the result of his experiments which present the following ratio: The pressure of a stream on the anterior surface of a stationary body being 1, that on a body moving through a still fluid is only 0.843. Whatever may have been the cause of the difference he observed, the result showed that the subject requires further investigation by practical means.

A paper on this subject, in the *Encyclopædia Britannica*, contains the suggestion of the existence of a quantity of stagnant fluid at the anterior and posterior parts of the body; but Du Buat arrived at the conclusion that the water at the head of a vessel is not perfectly stagnant; but that it recedes in filaments, from the axis, in curves which converge to the surface of the vessel, and ultimately escapes with an accelerated velocities round its sides.

The same author continues that if it were fully established that there is a quantity of water stagnant, or nearly stagnant, the next step to be considered would be that form of the extremities which would reduce this quantity of stagnant water to a minimum.

Now, at first sight this seems a peculiar theory, but, if carefully looked into, it will be found to compare favorably with our present views, especially in respect of the latter portion.

The same investigator also proved that by adding to a cubical body so as to make its length three times its breadth, its resistance was considerably reduced, showing, as you see, that in these early days it was recognized that the length of a ship was a factor to be considered in relation to the question of her speed.

Another worker in this field was Don George Juan, a

Spanish nobleman of high rank in the naval service of his country, and a member of most of the principle scientific bodies in Europe. To attempt an explanation of his theory would be rather beyond the scope of this paper, and would, I am afraid, prove of little service to us, as he bases his theory on the assumption that the resistance will vary as the hydrostatic head; but those who desire to examine his views will find them set forth in the first volume of Creuze's *Naval Architecture*.

Between the years 1796 and 1798, some very exhaustive experiments were made by the Society for the Improvement of Naval Architecture, at the Greenland Dock, London, England. They showed that the power of the velocity of the bodies used in the experiments of the year 1798, at two miles per hour, was, in general, a little above the square, but that the ratio gradually decreases as the velocity increases, and becomes a little less than the square at the velocity of eight miles per hour. And, with respect to the bodies used in the year 1796, it also appears that the power of the velocity, with the said bodies, is considerably less than that of the bodies used in 1798, and is always less than the square. This difference in the power of the velocity of 1798 and 1796, arises from the bodies used in 1796 having a much greater surface exposed to frictional resistance than the bodies used in 1798, and also because the said friction always increases in a much smaller ratio than the square. So that the friction of the bodies used in 1796 forms a greater proportional part of their total resistance than it does in the bodies used in 1798.

Colonel Beaufoy, who was engaged on the foregoing experiments, at a later date continued his investigations to test the correctness of the formulæ :

Oblique resistance = direct resistance \times $\sin^2\theta$, and he succeeded in proving the assumption to be incorrect, but we will revert to this subject later on.

In the year 1806, Admiral F. H. Chapman, of the Swedish Royal Navy (who had previously developed a theory of resistance which in itself is rather a curiosity), gave to the world the labors of the later years of his life, in which he

advocates the parabolic system of constructing ships. What he did was to base his reasonings on the results of ships which had been found to possess good qualities, and then subjecting the same to scientific investigation. He began by endeavoring to discover whether the reduction of the areas of the transverse sections in well-constructed ships followed any law. For this purpose he calculated the areas of the sections of several ships; and in order to make the numbers more convenient, he divided the areas by the breadth of the midship section; then setting off from the water-line, at the respective stations on the drawing, distances equal to the quotients, he traced a curve representing the areas, which he called a curve of sections. He then endeavored to find the equation to the curve, or rather, that of another curve which would coincide with this for the greatest length; he found that if the power and parameter of a parabola were so determined as to allow that curve to pass through three given points of the curve of sections, the two curves would nearly coincide. Chapman consequently concluded that if the areas of the several sections of a ship were made to follow the law of the abscissæ of a parabola, a vessel of good qualities might be formed. This, as you see, is opposed to the theory of M. Romme, who inferred, from his experiments, that it made no difference whether the water was divided by a curved surface or by a plane surface, being the chord of such curve.

Now, gentlemen, having taken a rough survey of what some of the most eminent workers in this field have done, we will come down to the early sixties, and see what progress had taken place up to that time.

In the year 1863, a naval architect, in advocating the probability of crossing the Atlantic in one-half the time then occupied, made the following remark, which in itself seems to me to be more or less of an apology for the rashness of his statement: "our present necessities demand a class of vessels that will reduce the voyage between Europe and America to an average of one-half the time, and at a cheaper rate. I have endeavored to indicate how, I think,

this may be accomplished, and trust that my ideas may be regarded by the enterprising merchants of this country, if not by the admiralty, as worthy of consideration. If the thousands of intellects at work on this problem did not believe that it was susceptible of a solution, it would indicate a species of wide-spread monomania. I simply believe that the prevailing sentiment and conviction foreshadows the event."

At the present time we know that the event is not only possible but an accomplished fact, and the several causes that have enabled us to accomplish it may be enumerated as follows:

- (1) Improved methods and materials used in construction.
- (2) Recent researches to establish the form of least resistance, turning principally on the modern theory of resistance.
- (3) Improvements in the machinery used for propulsion, etc.

In the year 1862, a number of experiments were made with H. B. M. SS. *Warrior* and *Black Prince*. As these ships were built from the same drawings, and the engines were built by the same firm from one set of patterns, it might reasonably have been supposed, under these circumstances, that the two ships would have been as nearly as possible equal in speed; but the results proved the *Black Prince* to be the slower boat by at least one knot. The reasons assigned to account for this at the time were many and unreliable. One expert stated the cause as follows: On trial the *Black Prince* drew eight and one-half inches more water than her sister ship, consequently her resistance would be greatly augmented. He says: "in the aggregate, I estimate the law of resistance to be according to arithmetical progression. That is, if the resistance to a solid body, moving at a given velocity, be represented by 1 at the first foot from the surface, it will be 2 at the second, 3 at the third, and so on." This is entirely opposed to our modern theory, and to which I particularly wish to draw your attention, as I have no doubt some of my hearers hold views on this subject similar to those which I at

one time did, and which upon investigation I found to be erroneous.

Mr. Scott Russell, who was a great authority on all subjects connected with ship-building, used to compute the probable resistance of a ship in the following manner. He had ascertained that at ten knots per hour, with a vessel of what he termed the proper form (?) of 1,500 tons burden, the head resistance could be reduced to fifty pounds per square foot. He had also ascertained how much a similar vessel could be propelled with, by engine power alone, including the loss due to the working of the engines, and he found that whilst the direct resistance to a ship going ten knots per hour was only fifty pounds per square foot of midship section, including all loss from communication by paddle wheels, air pumps and other sources, except the slip, this resistance was not more than sixty-five pounds per square foot of midship section. Thus he could calculate confidently to a quarter of a knot, as he had done for many years with his peculiar shape of ship, the amount of power necessary to propel a given ship at a given speed; for instance, where a speed of ten knots was desired he provided fifty pounds per square foot of midship section, for the resistance of that ship; and when he had to overcome the resistance of the machinery also, he made this up to sixty-five pounds per square foot.

This in all probability was a very good rough-and-ready rule for the then comparatively low speeds run, but, as you see, it only involves the midship section, and had he used this rule for higher velocities, he would have found that there were other conditions to be considered.

The Stream Line Theory.—Many eminent English mathematicians have been concerned in the introduction and development of this theory, but chief among them are the late Professor Rankine and the late Mr. W. Froude. The former practically applied the theory to calculations (see his treatise on *Ship-building, Theoretical and Practical*), and the latter for years conducted experiments for the British Admiralty, beyond all comparison in value with any that have gone before them. Since his death, his son has continued the

experiments on the lines laid down by the father, the results of which may be judged by the number of high-speed ships now traversing the ocean.

Water, as you know, is not a perfect fluid; that is to say, its particles do not move past one another with perfect freedom, but exercises a certain amount of rubbing or *friction* upon one another, and upon any body past which they move. Suppose a thin board with a plane surface to be moved through water. It will experience what is known as *frictional resistance*. The amount of this resistance will depend upon the area and the length of the plane, as well as its degree of roughness and the rate of its motion. If this same plane be moved in a direction at right angles to its surface, it experiences what is termed *direct* or *head* resist-

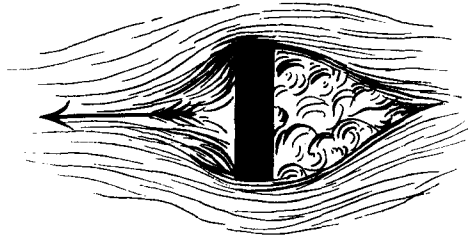


FIG. 1.

ance, the amount of which depends on the area of the plane and the rate of its motion. Should the plane be moved obliquely it experiences a resistance which may be regarded as a resultant of *frictional* and *direct* resistance.

Suppose either of those resistances to take place, the plane would leave an eddying *wake* behind it, as indicated by *Fig. 1*, and this disturbance among the particles of water is a very important element to the resistance of the body. If the plane is not wholly immersed, or its upper edge is near the surface, it will heap up water in the front as it advances, and create waves which will pass off into the surrounding water, to be succeeded by others. Such wave-making requires the expenditure of power, and constitutes a virtual increase in the resistance. If the plane were wholly immersed, it would create little or no surface disturbance,

and, consequently, the body would require less force to propel it at a given speed. If there were no surface disturbance, the resistance would remain constant, irrespective of the depth of immersion. This statement is directly opposed to the opinion, frequently entertained, which confuses the greater hydrostatical pressure on the plane, due to its deeper immersion, with the dynamical conditions incidental to motion. It may, therefore, be desirable to add a brief explanation.

Suppose a plane to be deeply immersed; it is evident that the forces on its back and front balance one another at any depth. Now suppose the plane to be in motion, at each instant it has to impart a certain amount of motion to the water disturbed by its passage, but the momentum thus produced is not influenced by the hydrostatic pressure on the plane corresponding to its immersion. Water being practically incompressible, the weight of water set in motion will be constant at any assigned speed, and consequently the resistance, neglecting of course any surface disturbance. For instance, Colonel Beaufoy proved by experiment that the resistance of a plane moving normally to itself, at depths of three, six and nine feet below the surface, were practically identical. The following rule was also established as the result of these experiments. The resistance per square foot of area, sustained by a wholly submerged plane moving normally to itself through sea-water at a uniform speed of ten feet per second (which is very near six knots per hour), is 112 pounds; and for other speeds, the resistances vary as the square of the speed.

As before stated, Colonel Beaufoy also showed that the oblique resistance was not equal to the direct resistance $\times \sin^2$ of the angle of incidence. Table II contains a summary of his results.

Angle of Plane with Line of Motion.	90°	80°	70°	60°	50°	40°	30°	20°	10°
Sines of angles, . .	1	'985	'940	'866	'766	'643	'5	'342	'174
(Sines) ² of angles, .	1	'97	'88	'75	'587	'413	'25	'177	'03
Resistances,	1'00	'915	'845	'828	'722	'579	—	'321	'272

From this table it appears that up to angles of 50° to 60° , the resistance varies with a fair approach to agreement, but for angles from 50° down there is a considerable difference.

The theoretically correct law has been determined by Lord Rayleigh, and is as follows :

Let P = the direct resistance, and P' the corresponding resistance due to the inclination of the surface.

Then

$$P' = \frac{2 \pi \sin a}{4 + \pi \sin a} \times P = \frac{\sin a}{.637 + .5 \sin a} \times P$$

In Table II the results of this formula is shown :

Angle of Plane with Line of Motion.	90°	80°	70°	60°	50°	40°	30°	20°	10°
Sines of angles, . .	1	.985	.940	.866	.766	.643	.5	.342	.174
P' ,	—	.872	.849	.809	.7509	.6708	.56	.423	.2403
Resistances,	1.00	.915	.845	.828	.722	.579	—	.321	.272

This formula takes no account of the negative pressure on the back surface of the plane.

M. Joëssel, of the French Navy, has conducted a series of valuable experiments on the same subject, and has deduced therefrom a formula similar in form but not identical with Lord Rayleigh's. It is as follows :

$$P' = \frac{\sin a}{.39 + .61 \sin a} \times P$$

In Table III the result of this formula is shown :

Angle of Plane with Line of Motion.	90°	80°	70°	60°	50°	40°	30°	20°	10°
Sines of angles, . .	1	.955	.940	.866	.766	.643	.5	.342	.174
P' ,	—	—	—	—	—	—	—	—	—
Resistances,	1	.915	.845	.828	.722	.579	—	.321	.272

Frictional resistance is measured by the momentum imparted to the water in a unit of time; this momentum being imparted, at each instance, to a current or *skin* of

water, which is adjacent to the surface. The extent to which the frictional resistance causes disturbance—that is to say, the “thickness of the skin”—varies with the velocity and other circumstances of the motion. From instant to instant the frictional current thus created is left behind in the form of a “frictional wake,” which follows the surface. The governing conditions of the frictional resistance are the area and length of the plane, its degree of roughness and the speed of advance.

The following are a few of the experiments of the late Mr. Froude, as summarized by himself.

NATURE OF SURFACE.	LENGTH OF SURFACE OR DISTANCES FROM CUT-WATER, IN FEET.											
	2 feet.			8 feet.			20 feet.			50 feet.		
	A	B	C	A	B	C	A	B	C	A	B	C
Varnish,	2'09	'41	'390	1'85	'325	'264	1'85	'278	'240	1'83	'250	'226
Paraffine,	1'95	'38	'370	1'94	'314	'260	1'93	'271	'237	—	—	—
Tinfoil,	2'16	'30	'295	1'99	'278	'263	1'90	'262	'244	1'83	'246	'232
Calico,	1'93	'87	'725	1'92	'626	'504	1'89	'531	'447	1'87	'474	'423
Fine sand,	2'00	'81	'690	2'00	'583	'450	2'00	'480	'384	2'06	'405	'337
Medium sand, . .	2'00	'90	'730	2'00	'625	'488	2'00	'534	'465	2'00	'488	'456
Coarse sand, . .	2'00	1'10	'880	2'00	'714	'520	2'00	'588	'490	—	—	—

He says: “This table represents the resistances per square foot due to various lengths of surface, of various qualities, when moving with a standard speed of 600 feet per minute, accompanied by figures denoting the power of the speed to which the resistances, if calculated for other speeds, must be taken as approximately proportional.

“Under the figure denoting the length of surface in each case are three columns, *A*, *B*, *C*, which are referenced as follows:

“*A*. Power of speed to which resistance is approximately proportional.

“*B*. Resistance in pounds per square foot of surface, the length of which is that specified in the heading, taken as the mean resistance for the whole lengths.

“C. Resistance per square foot on unit of surface, at the distance sternward from the cut-water specified in the heading.”

From these experiments the following deductions have been made :

(1) That the law formerly assumed to hold is very nearly conformed to, the frictional resistance varying approximately as the square of the velocity, when the area, length and condition of the surface remains unchanged.

(2) That the length of the surface sensibly affects the mean resistance per square foot of wetted surface; especially so when very short lengths are compared with planes of fifty feet and upward. For greater lengths than fifty feet it appears that the mean resistance per square foot of area remains nearly constant. Mr. Froude explains this important experimental fact as follows: The portion of surface that goes first in the line of motion, in experiencing resistance from the water, must in turn communicate motion to the water in the direction in which it is itself travelling; consequently, that portion of the surface which succeeds the first will be rubbing, not against stationary water, but against water partially moving in its own direction, and cannot, therefore, experience as much resistance from it.

A third important deduction is the great increase in frictional resistance due to a very slight difference in the apparent roughness of the surface. For instance, the frictional resistance of a surface of unbleached calico was shown to be about double that of a varnish surface, and a varnished surface gave results about equal to that of a surface coated with smooth paint, tallow, or composition such as is generally used on the bottoms of ships. The frictional resistance of such a surface, moving at a speed of 600 feet per minute, would be about one-fourth pound per square foot, which would give a frictional resistance of about one pound per square foot of immersed surface for the clean bottoms of iron ships when moving at a speed of about 12·8 knots. This unit is worth noting.

The foregoing will assist us in following the reasoning

of the more difficult problems connected with the resistance of ship-shaped solid bodies, as it is now generally acknowledged that satisfactory experiments on the resistance of ships can only be made with ship-shaped models of reasonable dimensions.

In the modern theory, the total resistance is considered to be made up of three principal parts:

(1) Frictional resistance due to the gliding of particles over the rough bottom of the ship.

(2) "Eddy-making" resistance at the stern.

(3) Surface disturbance, or wave-making resistance.

The second of these divisions only acquire importance in exceptional cases; it is known to be very small in well-formed ships. We will, therefore, bestow most attention upon frictional and wave-making resistance, examine the conditions governing each, and contrast their relative importance. In considering this subject we will assume the ship is either dragged or driven at a uniform speed by some external force which does not affect the flow of water relatively to her sides. The reason for this is to enable us to consider those resistances which are affected by the ship's form, the condition of her bottom, etc., whereas there are other conditions to be considered when treating of propulsion and which I hope to touch on before finishing this paper, as the compilation of these notes was first intended for my own information only, and to enable me, if possible, to obtain a clearer insight into those several elements that constitute the total resistance of a ship.

Suppose the ship to be moving ahead at a given velocity through an ocean unlimited in extent, and motionless relatively to the ship other than the disturbance caused by her passage. Now this would be equivalent, and the condition would remain unchanged if we assume the ship to remain stationary and the ocean to move past it in a direction opposite, and at a velocity equal, to that of the ship. This latter supposition enables us to trace more simply the character of the disturbance caused by the introduction of a hull of a ship at a certain speed into water that was previously undisturbed. Let us also assume the water to be

absolutely frictionless, and the bottom of the ship perfectly smooth. This is of course a hypothetical condition, and is only introduced to enable us at a later stage of the enquiry to arrive at what are the actual conditions.

In *Fig. 2*, let the black body in the centre represent the water-line plan of a ship, and the lines the paths traversed by the water in passing it. If we imagine for a moment the ship to be lifted out of the water, the path traversed by any set of particles would be represented by a straight line running parallel to the centre line of the ship. Now, if we immerse the ship, as indicated by *Fig. 2*, any set of particles in a given stream line will still continue to approach the ship in a direction parallel to her keel until such times as it reaches that sphere influenced by her presence, when their path will be diverted laterally, as indicated by the stream lines. How far in front of a ship her influence would be



FIG. 2.

felt would, I think, be difficult to conjecture; but there would no doubt be a limit, both in front and at her sides, at which points the water would still continue to move in its original direction. If the foregoing is correct, it follows that with this lateral diversion, and limit to the sphere of influence at the sides, the velocity of flow at the midship section must be accelerated. This acceleration should be gradual, but will depend on three causes :

- (1) The velocity of flow.
- (2) The bow of the ship.
- (3) The breadth of the ship, or the amount of this lateral deflection.

At the broadest part of the ship the velocity of the particles will be the greatest, owing to the fact of the stream line being at its narrowest, and the same quantity of water having to pass as at the foremost area. After the midship

section has been passed the particles should converge gradually toward the keel line, and their speed will again receive a check. Finally, after flowing past the ship, and attaining such a distance astern as to place them beyond the influence of the ship they again attain their original direction and flow, providing there is no surface disturbance. This last-named condition would only be possible in a ship wholly submerged at a great depth below the surface of an ocean limitless in extent. But in actual ships partly immersed, the retardation and acceleration referred to must cause the formation of a bow and stern wave.

[*To be concluded.*]

BOOKS RECEIVED.

[In sending books for notice in the *Journal*, publishers are requested, for the information of the reader, as well as for their own advantage, to give the price. This announcement by title will be followed, in most cases, by a review, which will appear at the earliest opportunity.]

Commonwealth of Pennsylvania. Report of Commission Appointed to Investigate the Waste of Coal Mining, with the View to the Utilizing of the Waste. Philadelphia: Allen, Lane & Scott. 1893. 8vo.

Knudsen, A. Triangular Surveys from Single Stations. San Francisco: Brunt & Co. 1893. 18mo.

Van Nostrand Science Series. No. 101. The Sextant and other Reflecting Mathematical Instruments. New York: D. Van Nostrand Company. 1891. 18mo. Price, 50 cents.

Do. No. 105. Determinants, an Introduction to the Study of, with Examples and Applications. New York: D. Van Nostrand Company. 1892. 18mo. Price, 50 cents.

Do. No. 109. The Measurement of Electric Currents. Electrical Measuring Instruments. Meters for Electrical Energy. New York: D. Van Nostrand Company. 1893. 18mo. Price, 50 cents.

Vick's Floral Guide for 1894. Rochester: James Vick's Sons. n. d. 8vo. pph. Price, 10 cents.

American Humane Education Society. Autobiographical Sketches and Personal Recollections of George T. Angell. Boston: Society. n. d. 8vo. pph. Price, 10 cents.

The Strike at Shane's. Gold Mine Series No. 2. Sequel to "Black Beauty." Boston: Society. n. d. 12mo. pph. Price, 10 cents.