THE GENERATION OF VORTEX RINGS

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THE GENERATION OF VORTEX RINGS

By Jun-ichi OKABE and Susumu INOUE

The formation of a vortex ring of colored liquid ejected vertically upwards from a mouthpiece into still water is photographed. Comparing a number of these photographs, an interpretation is given for the mechanism of the generation of a vortex ring, which may be summarized as follows:

1) The ejected liquid is first piled up over the mouthpiece, then immediately begins to curl axisymmetrically owing to the friction of the surrounding water.

2) The liquid column connecting the rotating liquid mass with the mouthpiece is stretched and finally broken as the mass goes up in the water.

3) The upper half of the broken column is hauled up gradually into the whirling liquid, and

4) In the end a vortex ring is completed when a hole is made at the center.

These processes are illustrated schematically by *a*, *b*, *c*, and *d* of Figure 3 in the text.

1. Introduction

It is well-known that vortex rings can be produced experimentally by, for example, filling a box with a flexible back wall and a circular hole in the front wall with smoke and striking the back wall,[1] or ejecting impulsively a small quantity of colored liquid upwards in water by making use of head difference,[2] or else with tobacco smoke and skillful lips.

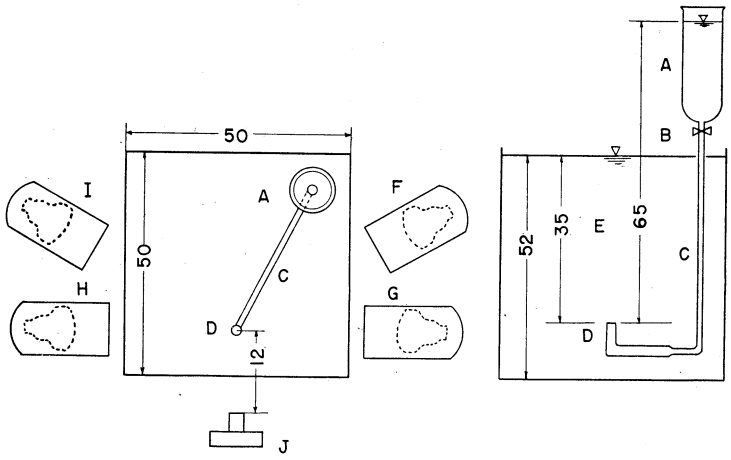
Employing the second method above-mentioned, the present writers took up the series of experiments to study in detail the generation, the development, and the behavior of vortex rings. The note which follows outlines the Part 1 of the experiments.

2. Experiment

With a view to analyzing the process by which vortex rings are generated, an equipment was constructed composed of a glass basin of cubic shape with the dimension of 50 cm × 50 cm × 50 cm and a glass pipe with both a reservoir serving

1) PRANDTL, L. *Führer durch die Strömungslehre* (Friedr. Vieweg und Sohn, Fünfte Auflage, 1957) S. 51; quoted from PRANDTL, L. *Essentials of Fluid Dynamics* (translation of the above-mentioned book by W. M. DEANS, Blackie and Son, 1953) p. 52.

2) TANI, I. *Nagare Gaku* (Fluid Dynamics) (Iwanami, revised edition, 1955), p. 71.



Plan Elevation

FIG. 1. General Arrangement (unit in cm).

A, reservoir (serving as the head)
B, cock
C, pipe
D, D', mouthpieces (interchangeable)
E, water
F, I, 100 watt mercury lamps
G, H, 700 watt mercury lamps
J, camera

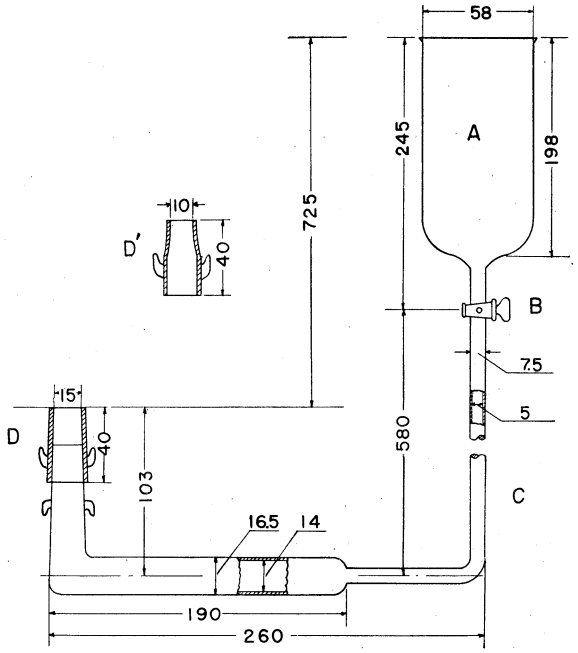


FIG. 2. Glassware (unit in mm).

as a head and interchangeable mouthpieces. The lower half of the glass pipe is immersed in the water filling the glass basin. The whole installation, the arrangement of which is shown in Figure 1, was so designed as to be convenient for taking photographs.

The glassware denoted by A, B, C, and D in Figure 1 and shown in detail in Figure 2 is full of water containing small quantities of fluorescein ($C_{20}H_{12}O_5$) and of sodium hydroxide (NaOH) and colored reddish green. As soon as the cock (B) is opened, the liquid within the pipe is pushed out through the mouthpiece (D) by the head (A). If the cock is next closed after a short time, the efflux is stopped immediately, and a small lump of colored fluid is emitted upwards and ascends curling in the surrounding water.[1)]

In order to photograph this phenomenon, the whole installation was brought in the dark room and the mouthpiece and its neighborhood were illuminated by four high tension fluorescent mercury lamps (two 700 watt lamps and two 100 watt lamps). Photographs were taken with a camera equipped with the extension tubes suited for close-up works (lens aperture F=4, shutter speed=1/125 sec).

3. Results

Numerous pictures were taken at random with almost uniform probability over the whole duration of the ascending motions of the small masses of colored fluid. Photographs nos. 1 to 10 were chosen out of them in such a manner that this series of pictures may represent, in one way or another, the various stages characterizing the generation and the development of vortex rings.[2)] It should be noted, therefore, that these pictures do not trace the successive transformations of a particular vortex, but correspond to miscellaneous moments in the course of the metamorphoses of different vortices. From these photographs, the process through which a vortex ring is formed may be summarized in what follows.

1) In the earliest stage of the development, the emitted liquid is increasingly piled up over the mouthpiece, taking the form of a segment of a sphere somewhat flattened. But in a second the liquid begins to curl axisymmetrically owing to the friction of the surrounding water (Photographs nos. 1, 2).

2) The higher the liquid mass grows up rolling in the water, the longer the column in the central part is stretched which connects the liquid mass with the

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1) The specific gravity of the colored liquid is a little greater than that of water. So the emitted liquid lump ascends a certain distance (determined by the head difference, the specific gravity of the liquid, and the manner of operating the cock) and then begins to descend slowly and finally collapses. But so far as our observations were concerned, the difference between the specific gravities of the liquid and the water had no remarkable effects upon the generation of vortices, because by using the liquid of diverse concentrations, within a small range, of course, of fluorescein and of sodium hydroxide, we could not notice any sensible variation in the character of the birth of vortices.

2) The vortex rings shown in these photographs were produced using the mouthpiece with the inner diameter of 15 mm. However, only Photograph no. 10 was chosen out of the series of the pictures (omitted here) of the vortices from the mouthpiece of 10 mm inner diameter. The essential features of the generation and of the development of the rings, except their dimensions, were not influenced by the variety of the mouthpieces.

mouthpiece (Photographs nos. 3, 4, 5, 6, 7).[1]

3) The elongated column (or, to be more graphic, the *stem*) is finally broken, and the upper half of it is hauled up step by step into the rotational motion of the liquid (Photographs nos. 8, 9).

4) After having hauled up all the stems, the vortex still sucks up water from its center. A vortex ring is thus completed, when liquid is replaced by water and a hole is made at the center (Photograph no. 10).

These processes are shown schematically in *a*, *b*, *c*, and *d* of Figure 3.

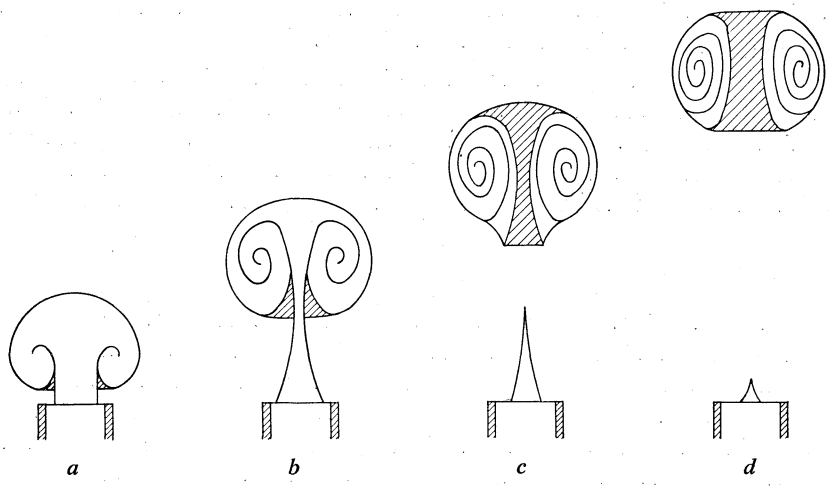

FIG. 3. Formation of a vortex ring.

Finally, Photographs nos. 11, 12, 13, and 14 show the various phases of the interpenetrating motion of a vortex into another one. These two rings were produced from the mouthpiece with inner diameter of 15 mm by repeating the open-and-close motion of the cock with a small interval of time. These pictures were taken at miscellaneous stages in different trials just as in the cases of Photographs nos. 1 to 10. At first the writers wanted to record the whole developments of the coupled motion of the lower vortex penetrating *through* the upper one. But on account of large Reynolds' numbers, these two rings became entangled and collapsed without exception at the moment when the former passed through the latter, and our first plan had to be carried forward to the future.

The writers are very grateful to Mr. Haruo Aoki for his assistance.

1) A small quantity of the surrounding water is dragged continuously into the whirling motion of the colored liquid, forms a thin layer of the surface of revolution, and by leaving the dark lines on the photographs makes the vortex motion visible.

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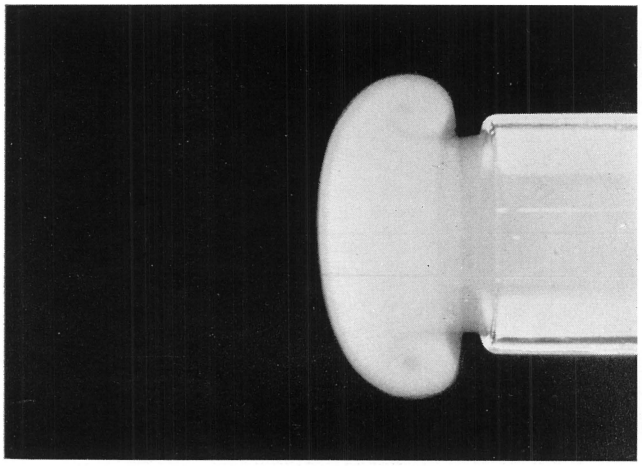

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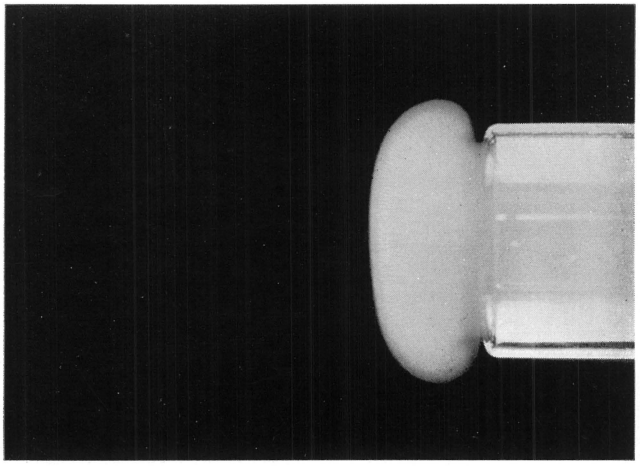

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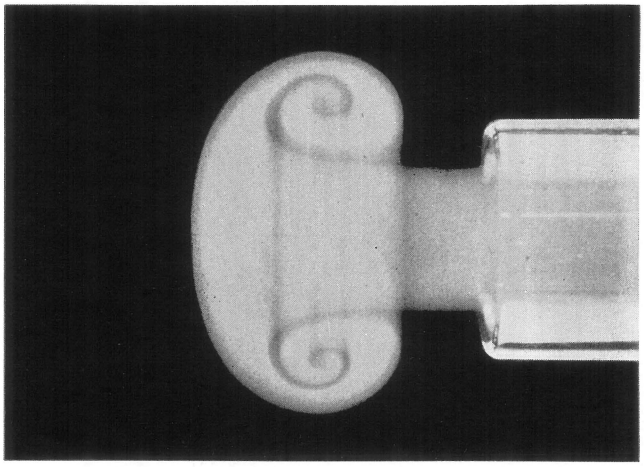

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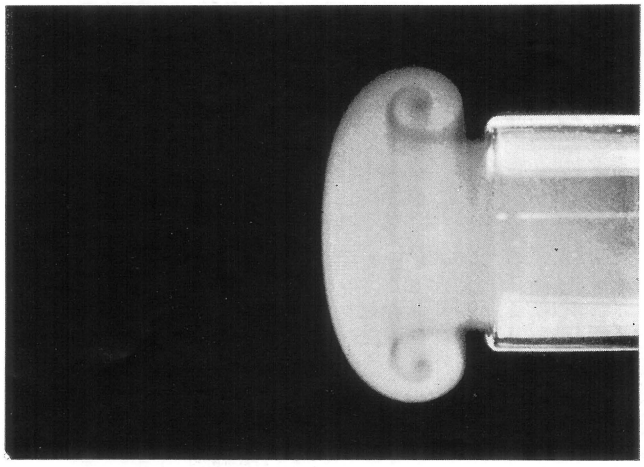

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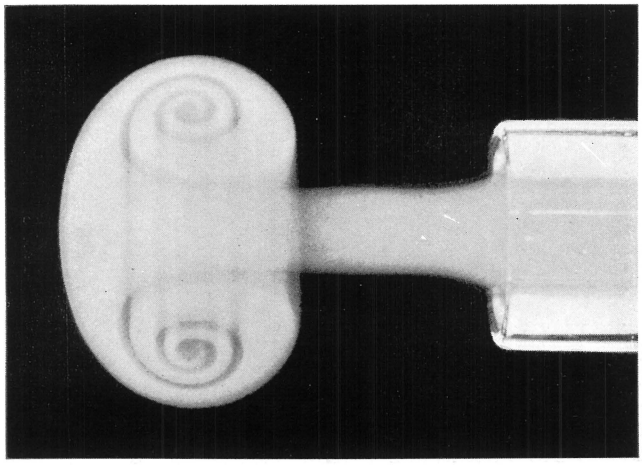

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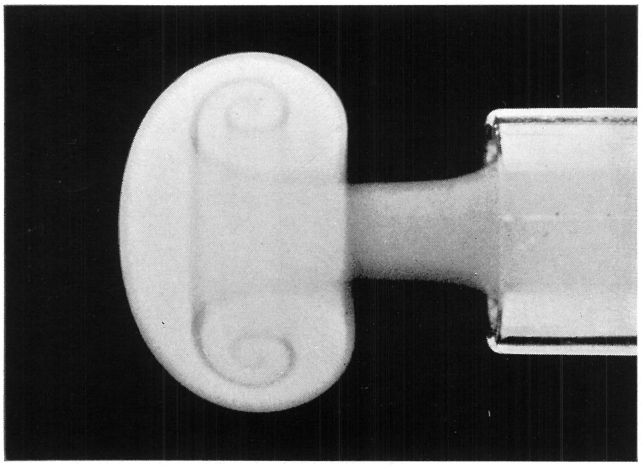

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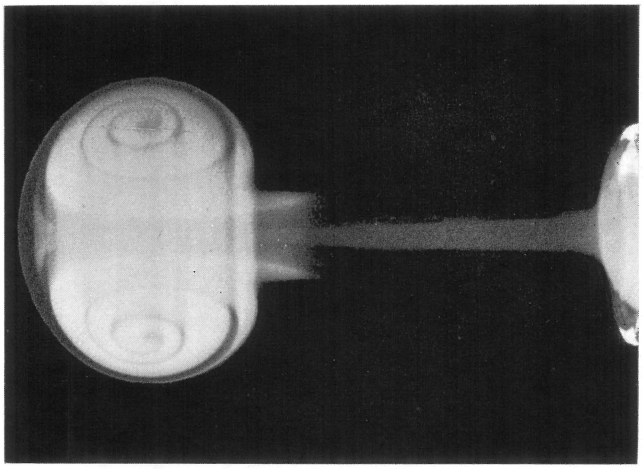

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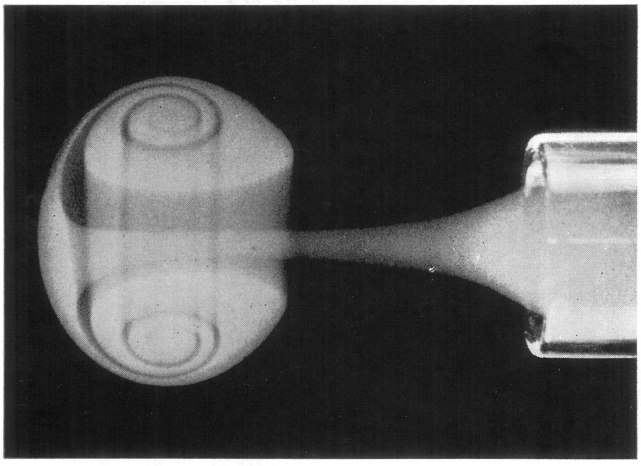

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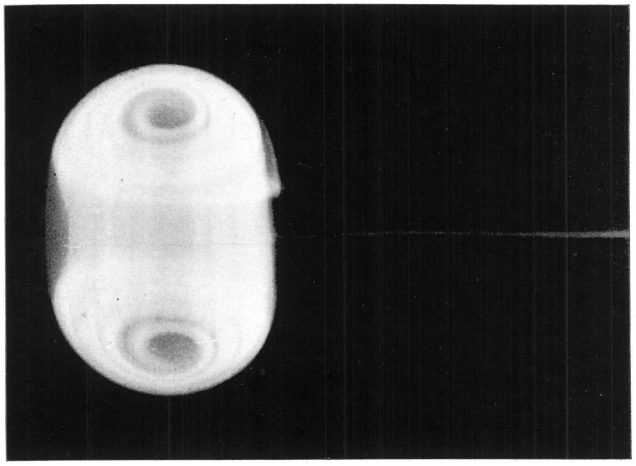

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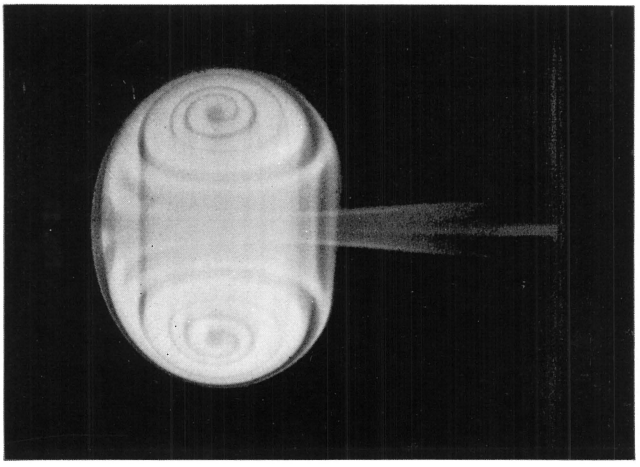

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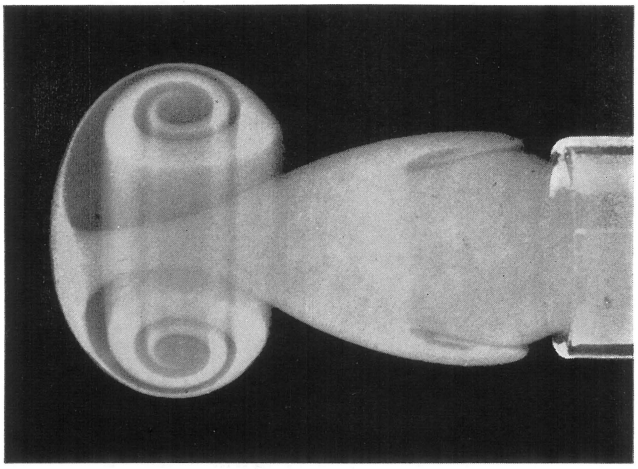

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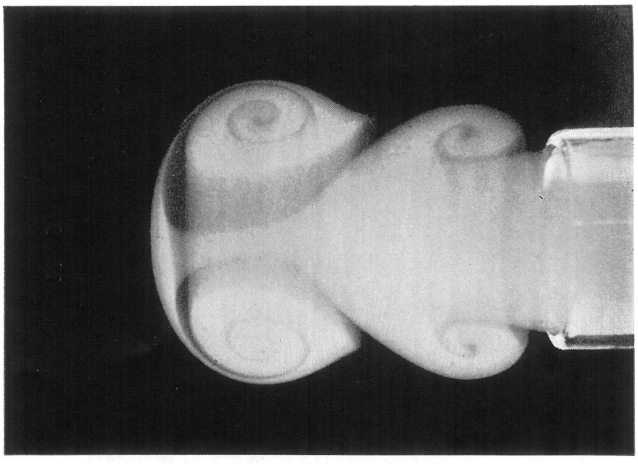

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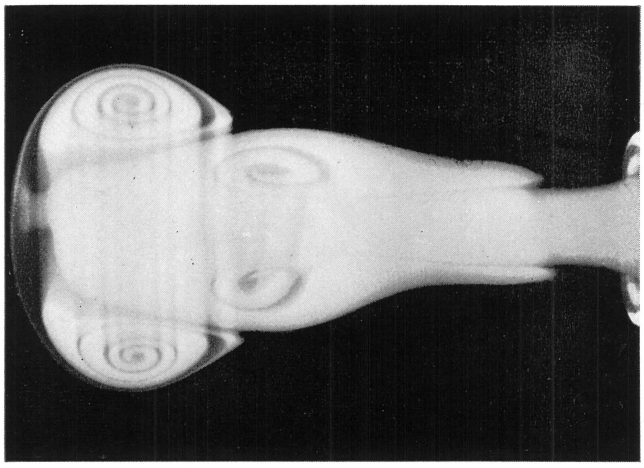

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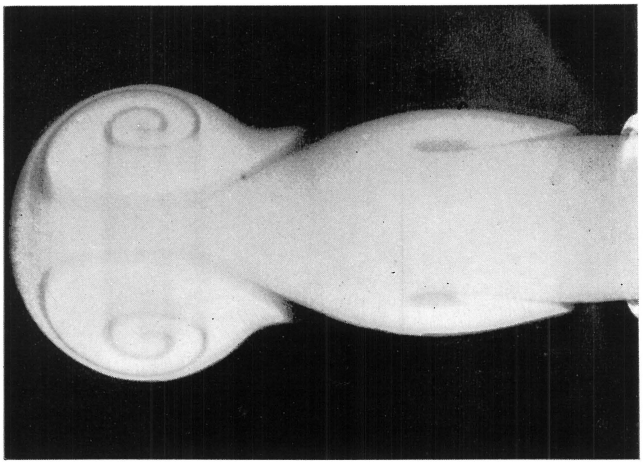

No. 13

ERRATA

Reports of Research Institute for Applied Mechanics
Vol. VII, No. 25, 1959.

Page 69, line 3, for "No. 25" read "No. 12."

Reports of Research Institute for Applied Mechanics
Vol. VIII, No. 29, 1960.

Page 322, line 3, for "No. 11, 1958" read "No. 14, 1960.