A PARAMETRIC STUDY OF A SYNTHETIC JET IN A CROSS FLOW

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Abstract

Preliminary research using synthetic jets to control the separation line of a turbulent boundary layer on a circular cylinder, has revealed that periodic ejection and suction through an orifice leads to a time averaged jet structure, and a time averaged delay of the separation line. To answer the question of how a periodic ejection and suction can produce this effect, research has been undertaken to study the behavior of the vortex rings in quiescent, cross flow and shear flow condition. Finally, a hypothesis is presented to link these preliminary findings to the structures seen on the cylinder.

1 Introduction

The efficient and practical control of separating flows is still a goal that the research community strives toward nearly a century after Prandtl's pioneering work. Hitherto, many methods such as constant blowing or suction, vibrating flaps and vortex generators, have been either inefficient and/or impractical. A possible solution to these problems is the use of synthetic jets, also known as massless jets.

The term 'synthetic' arises from the synthesising of a jet from a train of vortex rings which are ejected periodically from an orifice, caused by the oscillation of a surface inside the cavity as shown in Figure 1. The opposite occurs during the suction cycle and therefore the jet is formed with zero-net mass addition (hence the term massless jet). The oscillating surface is often a mechanical piston, loudspeaker or as in the present work, a permanent magnet shaker.

The authors have previously reported [1] on the development of small synthetic jets that have been used for flow control research on a circular cylinder. These devices use piezoceramic unimorphs for the oscillating surface, which are 25mm in diameter and driven at their resonant frequency. The piezoceramic acts similar to a capacitor, and when driven at resonance, requires very low power. A further reduction in the power requirement can be made possible by using self-exciting unimorphs, which require only a 9V battery for operation.

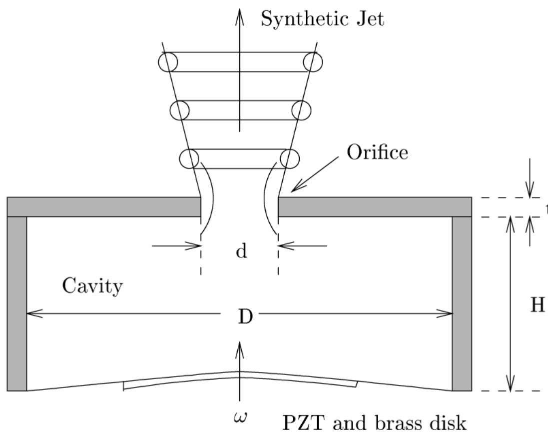

Figure 1: Schematic diagram of a synthetic jet formed using an oscillating diaphragm clamped in a cavity

In the practical sense, synthetic jets require no external air supply and they can be microfabricated [2], meaning that they will have minimum impact on the structure of the aircraft. A possible disadvantage of the synthetic jet is that dirt may become lodged in the jet orifice during the suction cycle.

Preliminary results using synthetic jets to delay the turbulent separating boundary layer on a circular cylinder, have been reported by Crook *et al.* [3]. The cylinder currently has eleven synthetic jets spaced 10mm apart, and allows jet spacing and the azimuthal position of the orifices to be varied. The cylinder is placed in the Avro 9′x7′ low speed wind tunnel at The Goldstein Research Laboratory, with the results shown below at a Reynolds number of 550x10^3. Figure 2 shows a near-surface view of the cylinder centreline with the orifices placed at 80 degrees (measured from the front stagnation line). The surface flow visualisation (a mixture of UV fluorescent powder and kerosene) shows that a few orifice diameters downstream of the jet orifice two streamwise structures develop which feed into the time-averaged separation line, causing a local delay. The picture with the orifices placed at 90 degrees in Figure 3, also shows more clearly how the structures from one synthetic jet interact with the cross flow at the separation line and also the structures from other jets.

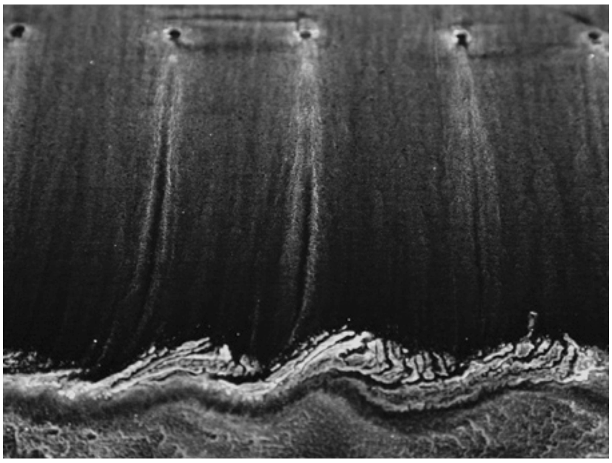

Figure 2: Close up view of left of cylinder centreline for 80 degree position

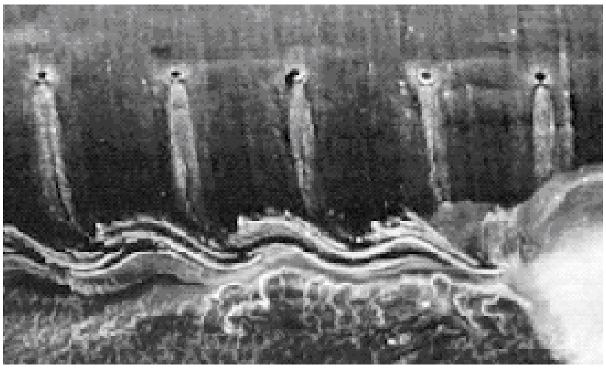

Figure 3: Close up view of right of cylinder centreline for 90 degree position

These results have left an unanswered question: How does a periodic ejection and suction through an orifice develop into what appears to be quasi-steady structures, which in turn cause a delay in the *time-averaged* separation line? The purpose of the research presented in this paper is to try and answer this fundamental question.

2 Experimental apparatus and method

To study the effect of a cross flow on a synthetic jet, a closed return water tunnel at The Goldstein Research Laboratory shown in Figure 4 was used. To measure the speed of the water in the working section a Novar Streamflo 403 vane anemometer was used.

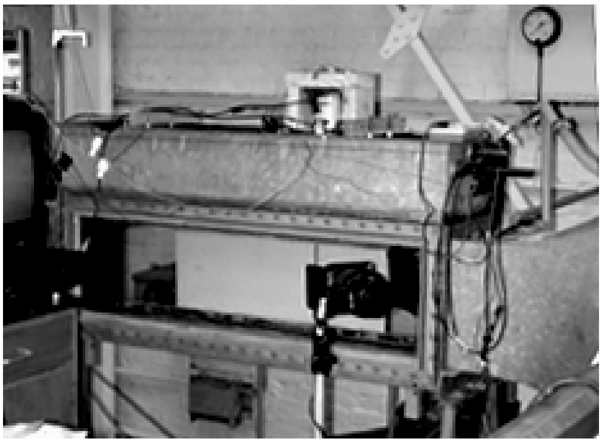

Figure 4: Closed-return water tunnel

The experimental setup is similar to that used for the flow visualisation in quiescent conditions, with a permanent magnet shaker driving a stainless steel diaphragm, and a micrometer head used to measure the amplitude of the diaphragm. Food colouring replaces the smoke, and to date a laser sheet has not been used. The results are recorded using a video camera and VCR. Injection of dye from ports around the orifice is possible as shown in Figure 5, although this feature has not yet been used. The geometry of the synthetic jet is given in Table 1.

Parameter	*Value(mm)*
Orifice depth	8
Orifice diameter	5
Cavity height	20

Table 1: Geometric parameters

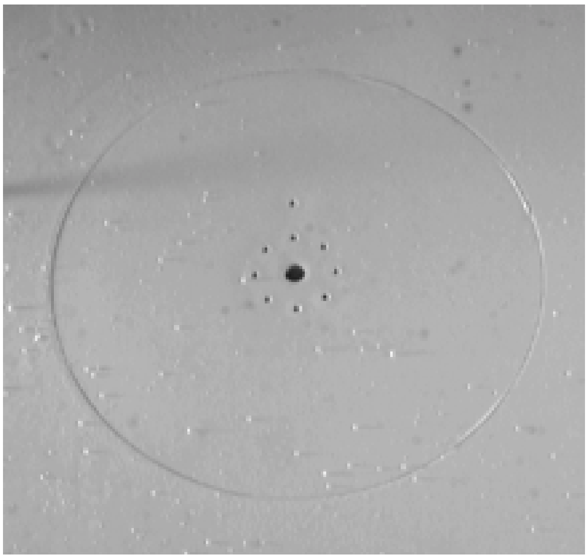

Figure 5: Details of orifice and additional dye ports

3 Results

The purpose of the preliminary results presented in this paper is to give an insight into the possible fluid dynamic interactions occurring between the thin shear layer and the synthetic jets on the cylinder. Considering the difference in the scale of the synthetic jets on the cylinder and that in the water tunnel, the following non-dimensional parameters are potentially important in describing the behaviour of a synthetic jet in a cross flow:

$$f\left(\frac{Uj}{Us}, \frac{fD}{Us}, \frac{fD}{Uj}, \frac{UjD}{\nu}, \frac{X}{D}, \frac{Y}{D}\right)$$

To date however, the data collected has been classified in terms of the diaphragm peak-to-peak displacement. The displacement is both a function of the driving frequency, *f*, and the peak value of velocity at the synthetic jet orifice, *Uj*. The approximate non-dimensional parameters for the cylinder and present water tunnel experiments are given in Table 2. Three driving frequencies of 2, 5 and 10Hz each at three different cross flow speeds of 4, 6 and 8cm/s, have been studied. When comparing the non-dimensional Strouhal number and jet velocity ratio for the cylinder and water tunnel experiments, one must remember that the synthetic jet on the cylinder is in a shear layer and therefore the local boundary layer thickness will be an additional variable.

Parameter	***Cylinder***	***Water tunnel***
fD/Us	0.3	1.25 - 12.5

Table 2: Non-dimensional Strouhal number

The cylinder results are at the low end of the Strouhal number range of our current investigation, which means that the separation distance between the vortex rings is likely to be important. To gauge the effect of a given parameter upon the behavior of the synthetic jet, the results have been presented with one parameter held fixed in each case.

With the speed held constant, the diaphragm displacement was varied at two driving frequencies. Figure 6 shows the case when the upstream speed is held constant at 4 cm/s, and the driving frequency is set to 5 and 10 Hz. It is clear to see that at 5Hz, the jet velocity is lower than for the 10Hz case with equal diaphragm amplitudes. The lower jet velocity allows the ring to roll-up in a more regular fashion, and that the ring becomes turbulent at a lower amplitude when the actuator is driven at 10Hz.

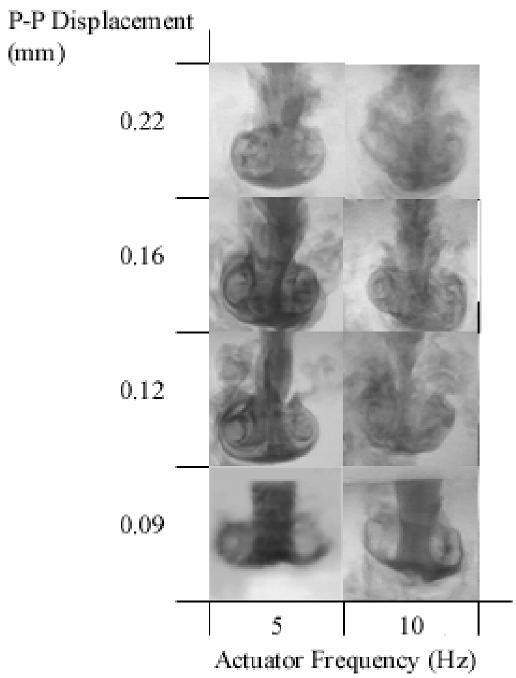

Figure 6: Effect of frequency and amplitude for a speed of 4 cm/s

In Figure 7, the speed is held constant at 6 cm/s, with again the structure of the higher frequency ring (in this case 5Hz) becoming more irregular and turbulent at a lower amplitude. At low jet velocities, the vortex ring is unable to roll-up, with the structure either ingested back into the orifice during the suction cycle, or being convected downstream. It is interesting to note that in the 2Hz case at higher amplitudes, the ring undergoes a significant amount of tilt. This may be due to the upstream side of the ring being forced towards the vortex sheet of the ring, and the ensuing interaction with the wall, but it is also due to the suction cycle of the synthetic jet, which draws the fluid towards the orifice.

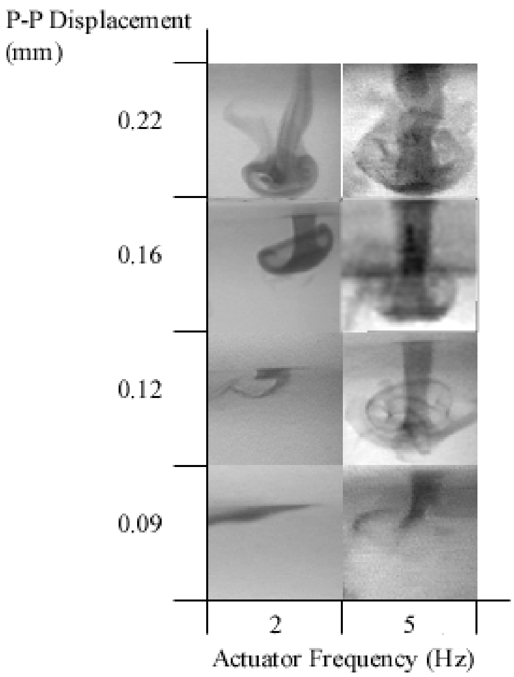

Figure 7: Effect of frequency and amplitude for a speed of 6 cm/s

With the frequency held constant at 2Hz, and the freestream speed and diaphragm deflection varied (Figure 8), the ring formation is suppressed at all but the lowest speeds and high diaphragm deflections. At higher displacements the ring is seen tilt with increasing freestream speed. Increasing the cross flow speed while maintaining a peak-to-peak diaphragm deflection of 0.16mm, appears to keep the ring in a coherent form, compared with the lower 4 cm/s flow speed at the same frequency. At this condition the vortex ring no longer rolls-up smoothly, and appears to have become turbulent.

Focussing on the far-field pictures in Figures 9 – 11, which are for the same conditions as the near-field shots above, the lack of coherence, and the level of turbulence is clear to see at the 10Hz frequency. The trajectory of the synthetic jets for the 10Hz case in Figure 9, is also fairly similar as the

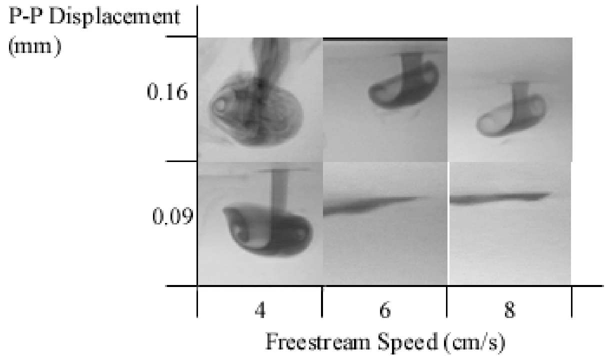

Figure 8: Effect of flow speed and amplitude for a frequency of 2Hz

amplitude is increased. This may be due to the large amount of interaction, which occurs when the separation distance between neighbouring rings is small. At a peak-to-peak displacement of 0.22mm, the 5Hz jet also appears to have an initial jet trajectory similar to the picture of the 10Hz jet to the right. At lower amplitudes and frequencies, larger ring spacing lead to less interaction between the vortex rings, and they therefore retain their coherence for a longer distance. The trajectory of the vortex rings remains however, similar to that of the higher diaphragm deflection and frequency synthetic jets. At the higher freestream speed of 6 cm/s, and lower driving frequencies, the amplitude of the diaphragm greater affects the trajectory of the vortex rings as is shown in Figure 10.

In Figure 11, the trend towards a more developed ring is clear to see as the flow speed is reduced for the two diaphragm displacements shown. However at the lowest speed of 4 cm/s and the highest amplitude, the vortex rings are turbulent further downstream and rapidly lose their coherence. Once again the tilting of the rings is clear to see at the higher velocities.

The tilting mechanism of the vortex rings is of extreme importance because in a shear layer, and with the rings spaced further apart, as is the case on the cylinder, the rings would

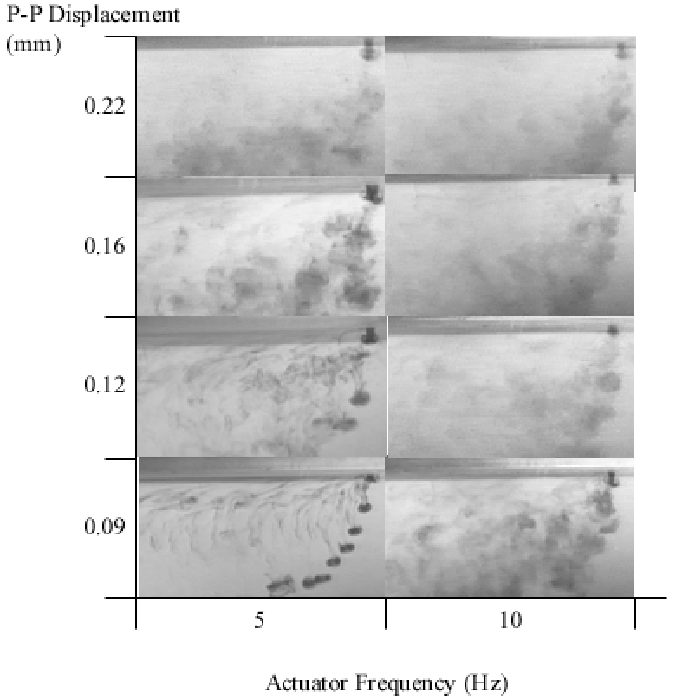

Figure 9: Effect of frequency and amplitude on far-field for a speed of 4 cm/s

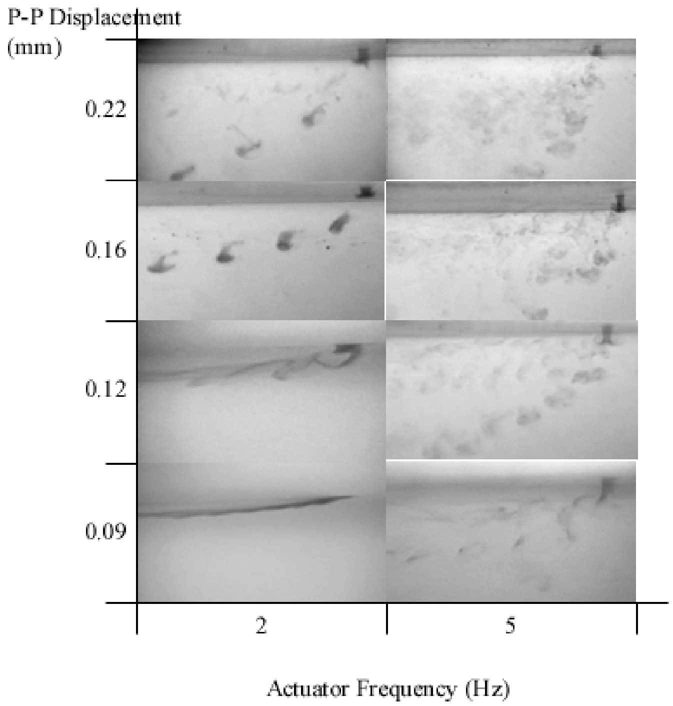

Figure 10: Effect of frequency and amplitude on farfield for a speed of 6 cm/s

stretch to form the longitudinal vortices that have been seen using the surface flow visualisation. Without the tilting of the vortex ring, the shear layer would merely convect the ring downstream without being deformed or interacting with neighbouring vortex rings. With a tilt, the ring is stretched by the shear layer, and through some form of induced velocity interaction, the rings act to stretch each other until the vorticity contained within the ring is aligned mainly in the streamwise direction. An example of two rings interacting downstream after tilting during their initial development is shown in Figure 12. Figure 13 shows the tilting mechanism for a driving frequency of 2Hz. Around the sixth frame, the suction cycle begins and the ring can be clearly seen be drawn back into the orifice.

4 Conclusions

A preliminary study has been carried out to assess the behavior of vortex rings at different diaphragm displacements, freestream speeds and driving frequencies. The key factor in the behavior of the jet appears to be the ratio of the jet velocity to the cross flow speed and also the separation distance between the vortex rings. A hypothesis has been presented based upon these preliminary results as to how the longitudinal vortex structures that appear in the surface flow visualisation on the circular cylinder, can be produced by a time periodic injection of fluid into the boundary layer. Further work is underway to investigate the non-dimensional parameters mentioned in the introduction of the paper

Acknowledgements

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References

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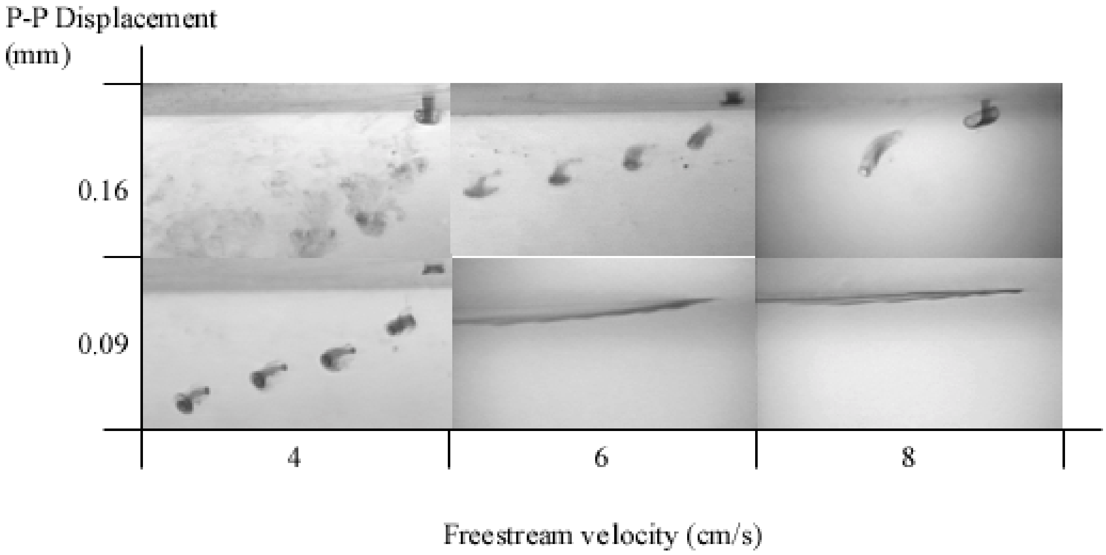

Figure 11: Effect of cross flow velocity and amplitude for a frequency of 2Hz

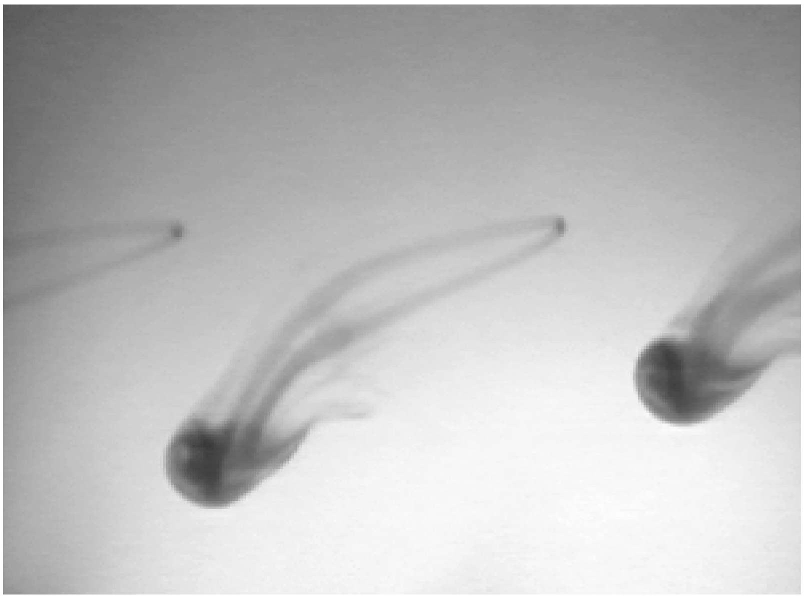

Figure 12: Two vortex rings being mutually stretched

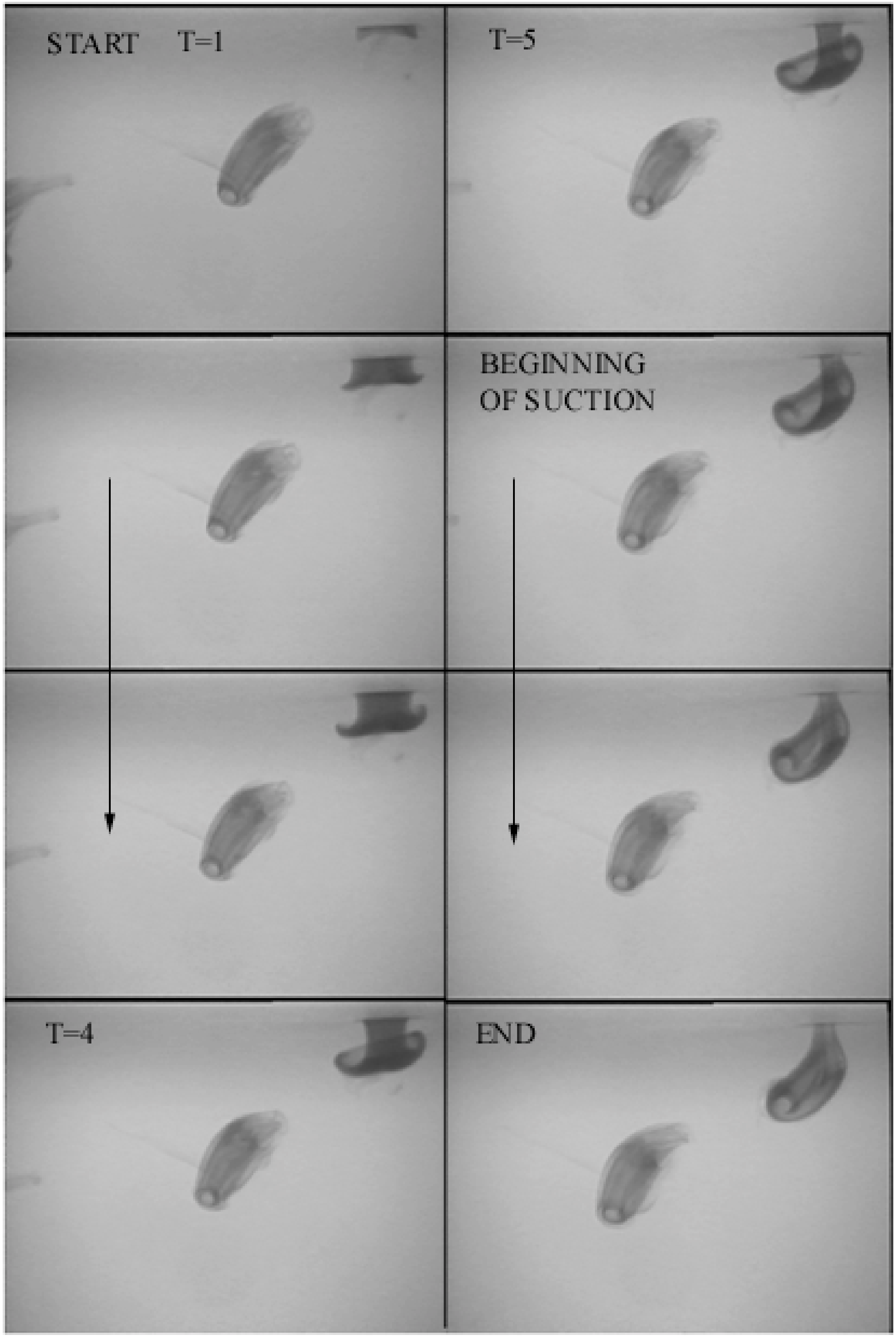

Figure 13: Time sequence showing a vortex ring tilting mechanism