Laser Doppler Measurement of Local Flow Field in Collapsible Tube during Self-Excited Oscillation*

Kenkichi OHBA**, Atsushi SAKURAI**
and Junji OKA***

The local velocity field in a self-excited oscillating flow through a collapsible tube has been precisely measured using a fiber optic laser Doppler velocimeter. Velocity distributions along the tube axis and across the tube cross section were measured. Time-varying flow rate at downstream end of the tube and pressure drop in the tube were also measured simultaneously. The following results were obtained: In the vicinity of the most strongly collapsed portion fluid is pushed to the downstream and upstream sides and then sucked back into the distending portion as the tube wall collapses and then recovers during the oscillation, and therefore superposition of this back-and-forth fluid motion to the gently varying flow gives rise to a sharp dent at the peak of the velocity waveform at upstream and a very sharp peak of the velocity waveform at downstream. Sufficiently far upstream from the collapsed portion, flow velocity is not influenced by the wall motion.

Key Words: Collapsible Tube, Self-Excited Oscillation, LDV Measurement, Bio-Fluid Mechanics

1. Introduction

A self-excited oscillation often takes place in a flow through a collapsible tube, i.e., a soft, elastic tube with a thin wall such as a venular vessel, a ureter, an airway of the lung, a rubber tube, etc., when the tube *in vitro* is perfused at constant external pressure. There is, however, no evidence that such an oscillation takes place *in vivo*. This phenomenon has been investigated for a long time as related to the so-called "vascular waterfall" phenomenon in the medical and physiological fields⁽¹⁾. However, the mechanism of oscillation has not yet been revealed⁽²⁾⁻⁽⁸⁾. The knowledge of the local flow field in the collapsible tube during oscillation is indispensable for an elucidation of the mechanism of the oscillation. It has not yet

been measured, however, due to the difficulty caused by a very large motion of the tube wall.

Therefore, we tried to make an LDV measurement of the local flow field in a collapsible tube *in vitro* during the self-excited oscillation using a fiber optic LDV system.

2. Apparatus and Procedure of Experiments

A schematic diagram of a flow system is shown in Fig. 1. For a collapsible tube we used a silicone rubber tube (Penrose tube) 6 mm in outer diameter, 0.15 mm in thickness and 160 mm in length. It was immersed in a liquid contained in a transparent airtight box. An air compressor was used for applying external pressure p_e on the tube. A sucrose solution of 61.5% was used both as a working fluid and a surrounding fluid of the tube in order to make the tube almost transparent for laser light in a fluid. The density and the kinematic viscosity of this fluid were 1230 kg/m³ and 12.9×10^{-6} m²/s at 20°C, respectively. The temperature of the working fluid was kept constant by cooling water. Fluid from Tank 1 was supplied to a flow system by a pump. After its flow rate was measured by a rotameter, it passed through a collapsible tube

* Received 14th July, 1997. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 63, No. 607, C (1997), p. 668-673 (Received 15th July, 1996)

** Faculty of Engineering and High-technology Research Center, Kansai University, 3-3-35 Yamatecho, Suita, Osaka 564, Japan

*** Sharp Corporation, 22-22 Nagaike-cho, Abeno-ku, Osaka 545, Japan

flowing out into the atmosphere, and returning back to Tank 1. The temporal values of pressure drop through the tube p_n were measured by a pressure transducer and the flow rate at the downstream end of the tube Q_2 by an electromagnetic flowmeter.

Fig. 1 Schematic diagram of the flow system

Fig. 2 Schematic diagram of the optical measurement system

Fig. 3 Sketch of the experimental apparatus for examinations of the effect of silicone rubber membrane on the transmission of laser light

Figure 2 shows a schematic of an optical measurement system. We used an optical fiber LDV capable of easy access of the flow system. A monochromatic light from a 5 mW He-Ne laser was divided into two beams using a beam splitter. Each beam passed through a beam compressor and was focused onto the entrance of a polarization preserving single mode fiber 4 μm in core diameter and 125 μm in cladding diameter, and to which each end a selffocusing micro-lens was attached. Two laser beams transmitted through the fibers were focused to intersect each other and form a measuring point in a collapsible tube through a lens mounted to a probe tip. The half angle of intersection was 4.89° in the air. A laser light was able to transmit through the tube because the tube is almost transparent in the sucrose solution. We used a white pigment as scattering particles. The forward scattered light was collected by a photomultiplier tube through a receiving lens system. The Doppler signal was processed by a spectrum analyzer and a frequency tracker. A local flow velocity signal u_{LDV} from the tracker as well as p_n and Q_2 were recorded by a fast pen recorder simultaneously.

3. Results and Discussions

3.1 Effect of tube wall on transmission of laser light

When the LDV is applied to flow measurement in a collapsible tube, a laser beam must intersect the wall of the collapsible tube in liquid. Sketches of two kinds of apparatus used for clarifying the effect of the surrounding fluids and the tube wall on the transmission of laser are shown in Fig. 3. The left illustration shows an apparatus for observing the effect of the spread of the laser beam after passing through the tube wall. The right illustration shows an apparatus for observing the effect of the tube walls on the formation of spatial fringe pattern produced by the intersection of two beams reflected by a steel sphere 2 mm in

Fig. 4 Photographs showing spread of laser beam after passing through silicone rubber membrane

Fig. 5 Effects of silicone rubber membrane and surrounding fluid on the formation of fringe pattern

diameter. A silicone rubber membrane was made by cutting and opening a collapsible tube. Water and sucrose solution of several different concentrations were tested as a surrounding fluid. Photographs of the spread of laser beam are shown in Fig. 4. In the case of water, laser beams spread widely, but in the case of sucrose solution, the spread of the beam decreases with an increase in the concentration of the solution; the smallest spread of beam was obtained with a solution of 61.5% concentration. The refractive index of the solution of 61.5% was 1.44. Figure 5 shows fringe patterns for several kinds of surrounding fluids. A very clear fringe pattern was produced in water without the membrane. Contrarily, in water with the membrane, the fringe pattern was distorted and its visibility became worse and non-uniform. In the case of a 61.5% sucrose solution, however, the effect of the rubber membrane decreased considerably and a uniform fringe pattern was produced. Therefore, these observations showed that LDV is applicable to local flow measurement in a collapsible tube.

3.2 Measurement of local flow velocity

Figure 6 shows a series of sketches representing typical tube behavior during oscillation, which were obtained by using a high speed video camera. The figure shown at the right-hand of each sketch represents the elapsed time. As seen in Fig. 6, the tube

Fig. 6 Sketch of typical tube behavior during oscillation

begins slowly collapsing at its downstream side and then the collapsed portion becomes localized within its downstream end. Next, the collapsed portion re-bounds and the tube becomes fully open again.

A co-ordinate system for the collapsible tube is shown in Fig. 7. The z -axis was taken in the main flow direction and the x -axis in the direction of the laser beam. The y -axis was taken in the direction

Fig. 7 Co-ordinate system for the collapsible tube

Fig. 8 Temporal variation of flow velocities u_{LDV} , pressure drop through the tube p_n and downstream flowrate of the collapsible tube Q_2 at the downstream side of the tube

perpendicular to the other two axes. The origin of the co-ordinate system was located at the center in the tube cross section. The quantity l represents the distance from the downstream end of the tube against the flow direction.

Figure 8 shows temporal variations of the flow velocities u_{LDV} at three different positions nearby the downstream end of the tube. The waveforms of the pressure drop through the tube p_n and the downstream flow rate Q_2 of the tube are also shown. The quantities Q_n and p_e show the time-averaged value of the flow rate and the external pressure, respectively. In this experimental condition the tube is not entirely collapsed as seen in Fig. 6, and flow is laminar ($Re \approx 300$). As seen in Fig. 8, a measurement position indicated by $l=1$ mm is located in the downstream side to the most strongly collapsed portion of the tube. On the other hand, a measurement position $l=6$ mm is located in the upstream side to the collapsed portion. The velocity waveform measured at $l=1$ mm has a very sharp peak in phase with the waveform of p_n . On the contrary, the velocity measured at $l=6$ mm has a sharp decrease at the phase of the peak in p_n waveform. On the other hand, the waveform of u_{LDV} at $l=11$

Fig. 9 A model of the motion of the tube wall and the flow velocity variation near the oscillating (collapsed) portion of the tube

mm is similar to that of Q_2 .

These remarkable differences in the velocity waveforms at different positions can be explained clearly by using a model of an interaction between a wall motion and an unsteady flow during the oscillation as shown in Fig. 9. In the present model, one period of the oscillation is divided into four stages. In the first stage, Q_2 gradually increases with the cross sectional area A of the tube kept almost constant, and therefore u also gradually increases. The increase in u causes gradual decrease in A because the internal pressure decreases due to the frictional pressure loss and a transmural pressure $p_{tr}(=p_i - p_e)$ decreases. In the second stage, the tube is rapidly collapsed and p_n rapidly increases. Then the fluid nearby the collapsed portion is pushed aside in both the upstream and downstream directions by the wall motion. Therefore, the flow velocity in the downstream side nearby the collapsed portion increases rapidly and that in the upstream side rapidly decreases. In the third stage, the tube wall bounces back and the tube rapidly opens, and so p_n rapidly decreases. The fluid is sucked back to the place it was. Therefore, the flow velocity of the downstream side near the collapsed portion decreases rapidly, and that of the upstream increases. In the fourth stage, the tube opens fully and p_n changes slightly, and so u decreases gradually. But, Q_2 increases due to the increases in a cross sectional area A of the tube.

Figure 10 shows temporal variation of u_{LDV} in the far upstream region. Velocity waveforms at $l=1$ and

Fig. 10 Temporal variation of u_{LDV} , p_n and Q_2 at the upstream side in the tube

Fig. 11 Temporal variation of u_{LDV} across the tube near by the downstream end and the far upstream of the tube

6 mm are shown for reference in this figure. In the far region, the tube cross section is kept almost constant because the wall oscillation is localized in the downstream side as seen in Fig. 6. Velocity waveforms are similar to each other without regard to the value of l , and the amplitude of the variation of u_{LDV} decrease with the increase in l . The velocity waveform at the nearest position to the upstream end of the tube is

Fig. 12 Velocity profiles at four different phases in a period of the oscillation

almost steady. Furthermore, these velocity waveforms are similar to that of downstream flow rate Q_2 . The flow velocity in this region is considered to be proportional to Q_2 because the cross sectional area of the tube is kept almost constant while the self-excited oscillation takes place. Figures 8 and 10 show that the wall motion due to self-excited oscillation of flow influences only the flow field in the vicinity of the collapsed portion.

Temporal variation of u_{LDV} at different positions across the tube is shown in Fig. 11. The top two figures of Fig. 11 show u in the vicinity of the downstream end of the tube. At $l=1$ mm, u_{LDV} has a high velocity only at the center of the tube, while the velocity near the wall shows only a small variation in comparison with that at the center. This indicates that downstream from the most strongly collapsed position a high speed jet-like flow exists in the center of the tube cross section and the fluid near the wall barely moves because of flow separation. However, at $l=5$ mm all the velocities across the duct vary remarkably, although their waveforms differ from each other. This indicates that the fluid is greatly intermixed across the tube upstream of the collapsed position due to the existence of the strong reverse flow (see the waveforms of u at $l=6$ mm in Figs. 8 and 9). The bottom two figures of Fig. 11 show the waveforms of u in the far upstream region. All the velocities across the duct change in phase.

Figure 12 shows velocity profiles at four different phases in a period of the oscillation shown in the top illustration of the figure. Lower graphs represent

Fig. 13 A model of flow velocity profiles across the duct through the tube for two different phases in a period of the oscillation

profiles of dimensionless velocities normalized by the velocity at the center. As seen from these figures, in the upstream side of the tube the velocity profile is kept parabolic during oscillation due to a laminar flow, although a small amplitude oscillatory motion is considered to be superimposed on it, especially in the region near the wall because of Womersley's parameter $\alpha (=R\sqrt{\omega/\nu}=2.5)$ slightly larger than unity.

Finally, on the basis of the above-mentioned measurements, we made a model of typical flow velocity profiles across the tube at the phase 1 and 3 of the oscillation. These profiles are shown in Fig. 13. At phase 1, the velocity profile at $l=1$ mm shows a high speed jet-like flow at the center of the tube and a flow separation is expected nearby the wall because the tube collapses at this phase and the downstream side of the tube forms a divergent tube. At $l=5$ mm, the velocity profile has approximately a saddle shape where the velocity at the center is decreased by the wall motion. In the far upstream side of the collapsed portion, the velocity profile is kept parabolic. In phase 3, velocity profiles are parabolic through the tube because the tube opens fully.

4. Conclusions

LDV measurements of local flow velocity in a collapsible tube during a self-excited oscillation were made. As a result, the following facts have been established.

1) A clear and uniform fringe pattern was produced by two laser beams after passing through the thin-walled silicone rubber tube by using a sucrose solution of high concentration as both a working fluid and a surrounding fluid of the tube. This indicates an applicability of the LDV to local flow measurements in collapsible tube.

2) Fluid is pushed aside and then pulled into both the upstream and the downstream sections of the collapsed portion of the tube by the wall motion due to a self-excited oscillation. At the far upstream side from the collapsed portion, fluid is not influenced by the wall motion and the velocity waveform is similar to that of flow rate.

3) At the far upstream region velocity profiles across the duct remain parabolic during the oscillation. On the other hand, downstream from the collapsed position velocity profiles show a high speed jet-like flow at the center of the tube cross section.

A part of this research was supported by the Grant-in-Aid for Scientific Research (B) (No. 08455096) from the Ministry of Education, Science, Sports and Culture.

References

- (1) Holt, J.P., American J. Physiol., Vol. 134 (1941), p. 292-299.
- (2) Conrad, W.A., IEEE Trans., Bio-Med. Eng., Vol. 16, No. 4 (1969), p. 284-295.
- (3) Kamm, R.D. and Shapiro, A.H., J. Fluid Mech., Vol. 95, Pt. 1 (1979), p. 1-78.
- (4) Pedley, T.J., The Fluid Mechanics of Large Blood Vessels, (1980), p. 301-368, Cambridge Univ. Press.
- (5) Ohba, K., Aono, M., Yoneyama, N. and Sakurai, A., Progress and New Directions of Biomechanics, (1989), p. 213-227, Mita Press.
- (6) Hayashi, S., Tanba, M. and Hayase T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 60, No. 579, B (1994), p. 3636-3641.
- (7) Matsuzaki, Y. and Ikeda, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 57, No. 534, B (1991), p. 468-493.
- (8) Sakurai, A., Ohba, K., Futagami, Y. and Tsujimoto, M., JSME Int. J., Ser. B, Vol. 39, No. 2 (1996), p. 361-367.