PERISTALTIC PUMP USING SOLENOID TYPE ACTUATOR

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Abstract. *The roller pump is a positive displacement pump that has the advantage of the simplicity and the inexistence of contact within pumped fluid and the rotor or other parts of a pump excepting the tube itself. Due to this characteristic, roller pump is widely applied in pharmaceutical industry, chemistry industry and food industry, i.e. applications where it is imperative minimizing the risk of contamination. For the same reason, roller pump is used as the first generation of artificial hearts. However, in this pump, the roller occludes completely the tube and there is no control about the force exerted on the tube. Therefore, when used as artificial heart, pumping blood, the roller pump causes severe injuries to the blood components. So as to investigate ways of minimizing this problem, this work proposes a new positive displacement pump that operates in a similar way of a roller pump. But, instead rollers, this pump uses three solenoid type electromagnetic actuators that presses a flexible tube sequentially, making the fluid inside de tube, be pumped in one direction. Since it mimetizes the motion observed in the intestine of humans and other mammals, this pump is called, Peristaltic Pump. The use of electromagnetic actuators opens possibilities for controlling: the pressing timing and sequence of the flexible tube as well as, the pressing force exerted on the tube. Moreover, the pumping speed can be easily controlled due to the fast response of electromagnetic actuators. This work presents the principle of the Solenoid Driven Peristaltic Pump and results obtained in the prototype.*

Keywords*: volumetric pump, peristaltic pump, electromagnetic actuator, mechatronics*

1. INTRODUCTION

In the decade of 1930, Michael DeBakey created a manually driven roller pump to be used in blood transfusion (Schmidt,2007, Fig.1). It consists of a flexible tube, arranged along a circular wall and a rotating arm with two rollers in each extremity. By rotating the arm, the rollers compress the tube progressively, pushing the blood in the direction of the roller motion. This pump was used in the first successful open-heart surgery in 1953. It is not clear who developed the first roller pump, however the DeBakey pump is one of important applications of the roller pump to be highlighted in the history. The DeBakey roller pump is still used today in surgeries however other pumps, based in different pumping principles, were developed for blood circulation since the roller pump causes important amount of hemolysis, i.e., damages to the blood components (Bennett *et al*.,2004). However, nowadays, the roller pump is used in a variety of applications, for example, chemical industry, pharmaceutical industry, food industry and so on (DirectIndustry,2009). Since this kind of pumps mimetize the contraction process observed for example in the intestine of mammals, roller pump is also called as peristaltic pump. Actually, peristaltic action can be mimetized not only by rollers as in roller pumps, but also by another mechanisms. Roller pump is one class of peristaltic pumps.

Not only roller pumps but also peristaltic pumps in general presents the followings as advantage over other type of pumps like centrifugal, axial or mixed flow type pumps:

- In the peristaltic pump, the pumped fluid is isolated completely from the external ambient, minimizing the risk of contamination. Moreover, since only the internal surface of the flexible tube is in contact with the fluid, it is easy to sterilize and clean the inside surface of the pump making peristaltic pump suitable for medical applications, pharmaceutical industry, chemical industry etc.
- Check valves are essential in volumetric pumps and bearings, in centrifugal pumps. None of these moving elements is present in a peristaltic pump. These elements are rapidly damaged on handling highly abrasive or corrosive materials.
- Because of the peculiar pumping principle, the peristaltic pump is more suitable for handling fluids with high viscosity or density. Such fluids are not efficiently pumped, for example, by a centrifugal pump in which, the pumping effect is due to the rotor rotating at a considerable high speed.
- Peristaltic pumps also minimize shear forces experienced by the fluid, which may help to keep colloids and slurry fluids from separating.
- Since there are no moving parts in contact with the fluid, peristaltic pumps are inexpensive to manufacture. Their lack of valves, seals and glands makes them comparatively inexpensive to maintain, and the use of a hose or tube makes for a relatively low-cost maintenance item compared to other pump types.
- The reduced number of constitutive elements in comparison to other type of pumps, gives to the peristaltic pump possibilities of obtaining pumps with higher efficiency and low risk of fail.

Considering the advange of peristaltic pumps, particullary, roller pumps, this work presents an alternative way for achieving a roller pump pump, by means of solenoid type actuators, i.e., a Solenoid Driven Peristaltic Pump

(SDPP). The use of solenoid type actuators, i.e., electromagnetic actuators instead rollers offers a series of advantages as mentioned later.

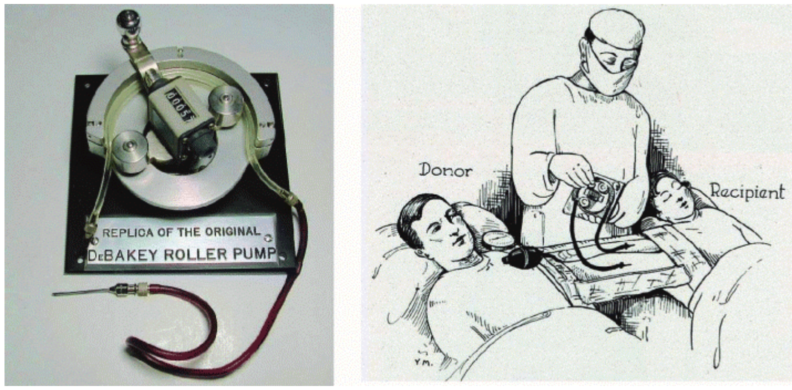


Figure 1. The DeBakey roller pump and its use in blood transfusion (Schmidt, 2007)

2. PRINCIPLE OF THE SDPP

The basic idea of the SDPP consists of locating actuators along a flexible tube and activating them so as to pressure the tube sequentially as shown in Fig.2. Each time the tube is compressed, the amount of liquid contained in the volume in front of the actuator is eliminated. The actuators are turned on or off in a way to create a flux in a desired direction.

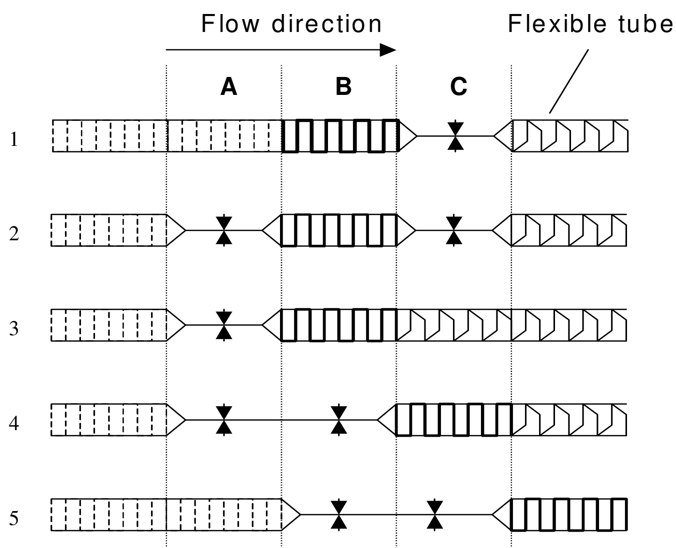


Figure 2 The principle of the SDPP

Figure 2 depicts part of a flexible tube in five different situations. Consider 3 portions of this tube (A, B and C). In front of each portion, an actuator (actuator A, B and C) is located. In the figure, arrows indicate the actuators. When each actuator is turned on (ON), the portion of the tube immediately in front of the actuator is compressed and the tube occludes. When the actuator is turned off (OFF), the tube expands and restores its original geometry. The actuators are turned ON and OFF according to the following sequence.

- Actuator C ON: the flux is interrupted in this portion.
- Actuator A ON: a portion of fluid is confined in the portion B.
- Actuator C OFF: a passage is open for the fluid contained in the portion B.
- Actuator B ON: the fluid contained in the portion B is pressed out toward the portion C.
- Actuator C ON: the fluid is pressed out from the portion C and, at the same time, the actuator A is turned OFF so as to enable the entrance of a new portion of fluid.

This pumping sequence is proposed assuming a static analysis of the fluid, i.e., considering very low flow rate in the tube. However, for higher values of flow rates, there is no necessity of occluding the tube completely. For example, if the tube occludes partially at the left side and the flow resistance to this side is higher than that to the right side, the flow will occur to the right side. In the experiments, the partial occlusion is also tested. This pumping principle is applied on micro-pumps. Matsumoto *et al*,1999, for example, presents a pump in which, instead of using mechanical check valves, the flow direction is determined by the difference between the flow resistances at both sides in a narrow channel.

A solenoid type electromagnetic is elected as actuator because it allies fast response with a considerable force, when compared with rollers or other type of actuators. Besides the simplicity on turning the solenoid ON and OFF, the solenoid offers possibility for controlling the force. The solenoid also offers possibilities for obtaining small size actuators resulting in small sized pumps. The use of solenoids is preferable than electric motors since solenoids generate directly a linear motion. In the case of electric motors, a sort of mechanisms must be used so as to convert rotary motion in linear one, increasing the part numbers, the complexity of the entire pump and in most of the cases, this increases the risk of fails. There are reports concerning pumps based on solenoids. In Guo *et al*, 2007, for example, a pump using solenoid is presented. The authors present arguments similar to those mentioned above to show the advantage of the use of solenoid actuator in comparison with other modality of actuators. However in this, a diaphragm compresses the fluid and the flow direction determined by check valves. The pump presented here does not use diaphragm or check valves. This can be an interesting feature if considering eventual application of this pump on pumping blood. There is high risk of blood coagulation on check valves. There is a report about peristaltic pump using solenoids. Carlson *et al*, 1980 reported a micro peristaltic pump based on the use of solenoids however, these solenoids are used to generate rotary motion. Also, Marchall, 2000 proposed and patented an electromagnetically driven peristaltic pump. In this, a chamber is set closer to the fluid passage. This chamber is filled with electrically conductive fluid. Submitting the conductive fluid to a magnetic field and applying an electrical voltage in some places of the fluid, the fluid is moved and this motion transmitted to the pumped fluid. Besides the fact that this pump is based in a complex mechanism, no information could be obtained about the pumping characteristics of this device.

3. THE DEVELOPMENT OF THE PROTOTYPE

Based on the principle described in the previous chapter, a prototype is developed. Fig.3 shows the flexible tube and the three solenoids. A silicon rubber tube of 20mm diameter and 0.5mm wall thickness is used. This tube is arranged between a solid wall and three solenoids. Each solenoid with 570turns has 8mm of internal diameter, about 25mm of external diameter and 20mm in length. Inside the solenoid, a rare earth magnet (6mm diameter by 6mm height) is positioned. Although in the previous chapter, it is mentioned that the solenoids work in two modes, ON and OFF, in order to obtain larger amplitude motions, the current in the solenoid are inverted. This does not affect the principle explained above. Depending on the direction of the current in the solenoid, the magnet is pulled or pushed. The magnet is attached to a rectangular shoe that presses the flexible tube, as shown in the figure. So as to obtain a large amplitude oscillation of the shoe, the magnet and the shoe are attached to a mass spring oscillatory system depicted in Fig.4. The solenoid is driven at the natural resonance frequency of the mass-spring oscillatory system, of approximately 20Hz. Fig.5 shows CAD drawing of the assembled pump. The solenoids are driven by a full bridge power IC (LM298, ST Microelectronics) commanded by a PC computer through serial interface. A PC type computer is used due to facility on testing a sort of synchronisms on driving the solenoids. Once the synchronism is optimized, this PC can be replaced by a small micro-controller.

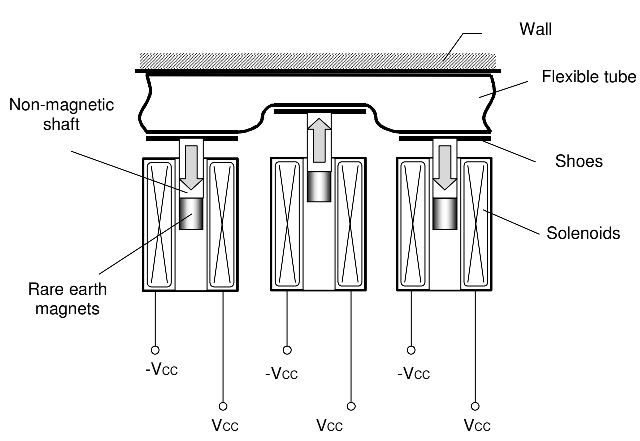


Figure 3 Solenoids

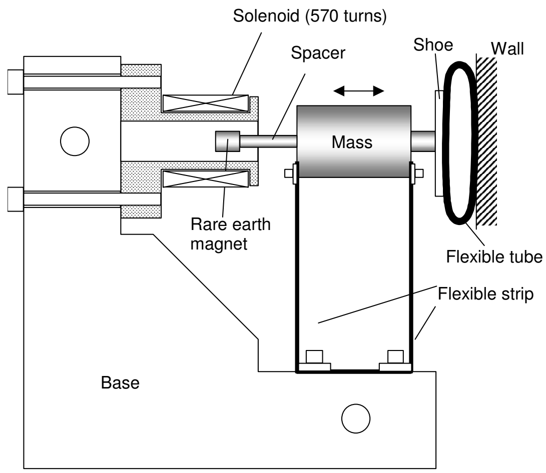


Figure 4 Oscillatory system

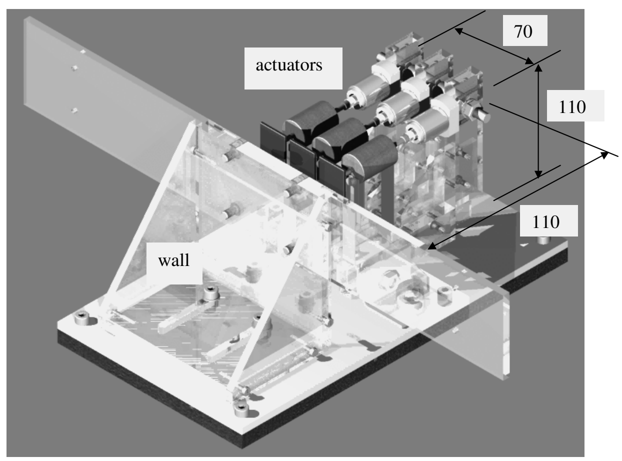


Figure 5 CAD drawing of the prototype

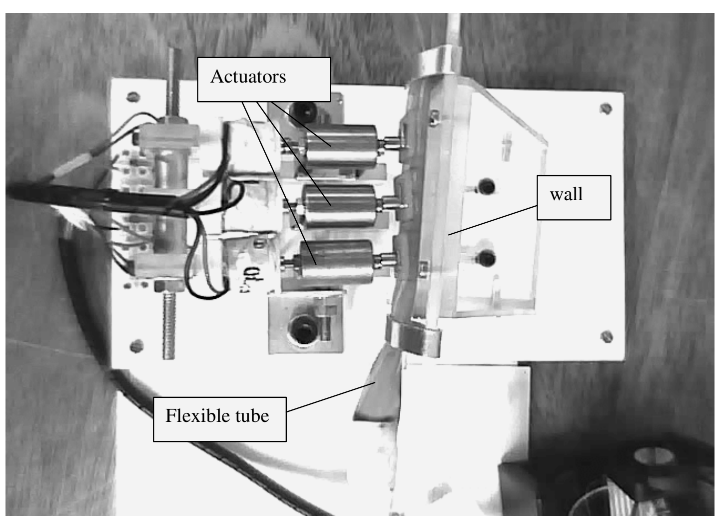


Figure 6 Prototype (top view)

4. PUMPING TESTS

Pumping tests was conducted in the arrangement shown in Fig.7. In the picture, the upstream reservoir is set at the left side of the pump. This pump is set so as to provide positive pressure to the pump. A water column is installed immediately after the pump outlet for measuring the pumping pressure. The average flow rate is measured by measuring the amount of fluid pumped to the downstream reservoir, and measuring the time required to pump this amount of fluid.

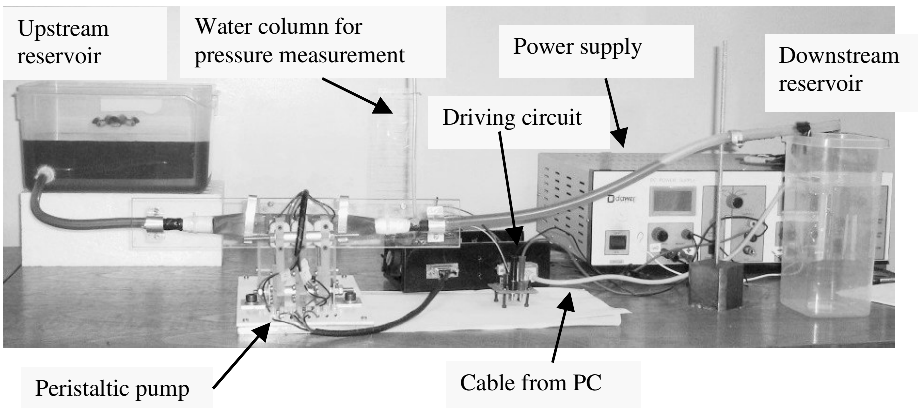


Figure 7 Test set-up

First pumping experiments are executed according to the synchronism described in Fig.2. However, experiments demonstrated that steps 2 and 3, of Fig.2, could be simplified as a single step as shown in Fig.8. Fig.9 and Fig.10, show respectively the flow rate and the pressure obtained in the pump at a variety of driving periods. Values of flow-rate and pressure are obtained repeating the pumping test four times for each driving period. The average values are presented in the graphs. These results prove the validity of the pumping principle. Besides, they showed that a flow-rate of 30.4mL/s and a pressure of 660Pa are achieved with a driving period of 49ms. This period corresponds to a frequency very close to the natural resonance frequency of the oscillatory mechanism. This demonstrated the efficiency of the oscillatory mechanism on amplifying the movement of the actuators.

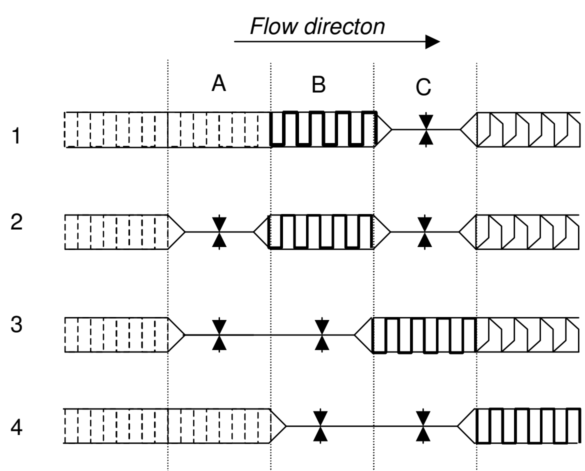


Figure 8 Driving synchronism

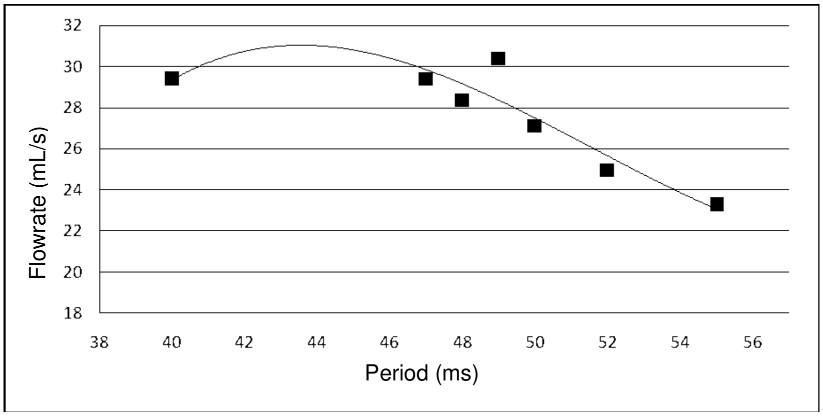


Figure 9 Driving period x flow-rate

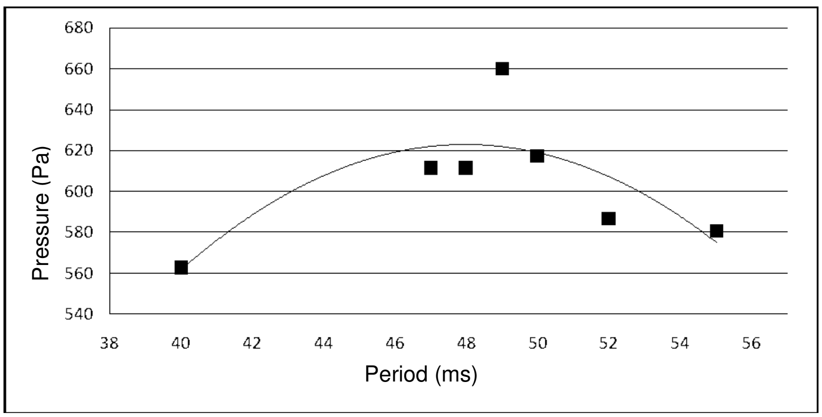
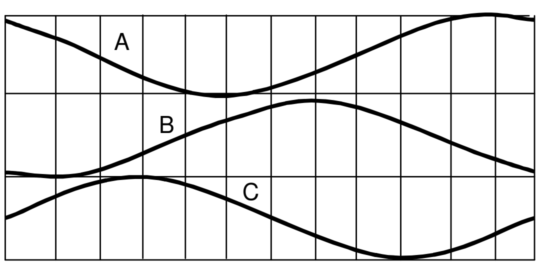
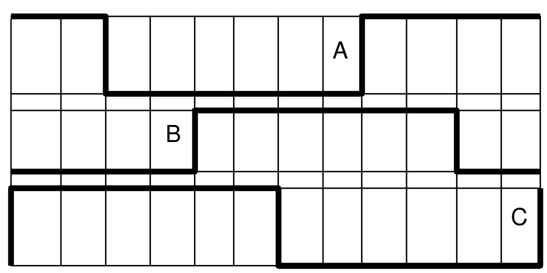


Figure 10 Driving period x pressure

Besides the synchronism described by Fig.8, a three-phase synchronism is also proposed and tested. By driving the actuators in three-phase synchronism, a propagating wave is created in the flexible tube walls, achieving the fluid pumping. The principle of the propagating wave is well known in ultrasonic motors (see for example, Uchino,1998). Since the solenoids used in this work is ON/OFF type, the three-phase signal shown in Fig.11(a) is linearized as shown in Fig.11(b).



(a) Three-phase signal



(b) Linearized three-phase signal

Figure 11 Linearized three-phase synchronism

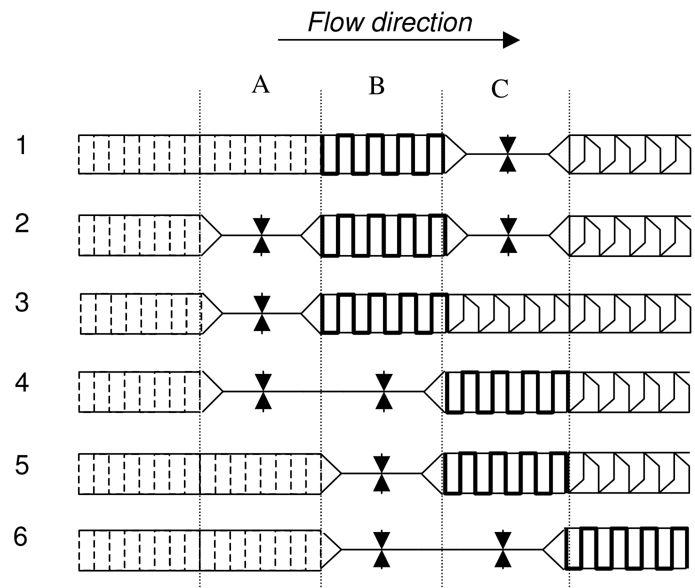


Figure 12 Linearized three-phase synchronism

Figures 12 and 13, show respectively the flow rate and the pressure obtained in the pump at a variety of driving periods. The maximum flow-rate of approximately 30mL/s and a pressure of 400Pa are achieved using a driving period of 60ms. This period corresponds to a frequency lightly inferior to the natural resonance frequency of the oscillatory mechanism. An effective pumping is achieved also in this case and the oscillatory mechanism still demonstrated to be efficient. Compared with the originally presented driving synchronism, the three-phase synchronism resulted in slightly low values of flow-rate and pressure. Results are not shown but three-phase synchronism achieved improved repeatability in the pumping results. This is supposed to occur because of the more perfectly cyclic way each actuator is driven. In the original synchronism (Fig.8), in each pumping cycle composed of 5 steps, the actuators A and B are turned ON twice. However, the actuator C is turned ON, three times. In the three-phase synchronism (Fig.11), in each pumping cycle, all actuators are turned ON, equal number of times: three. This makes the actuator oscillates more uniformly.

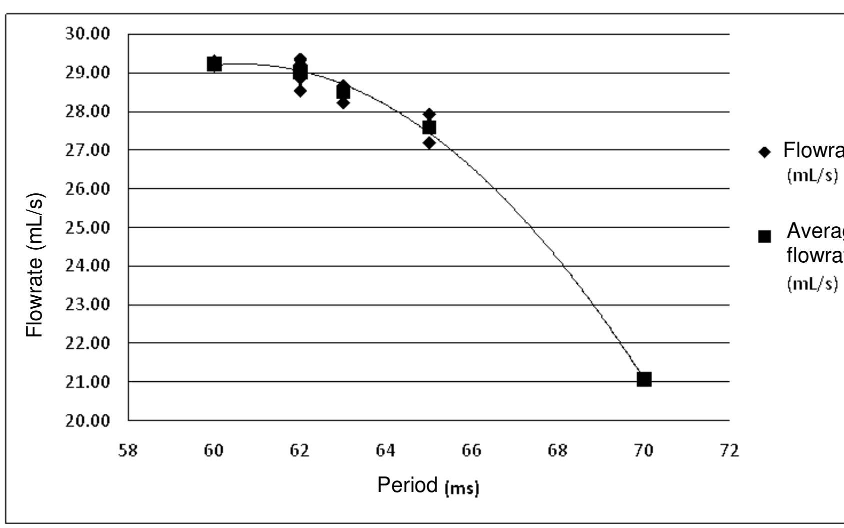


Figure 13 Flow rate x driving period (linearized three-phase synchronism)

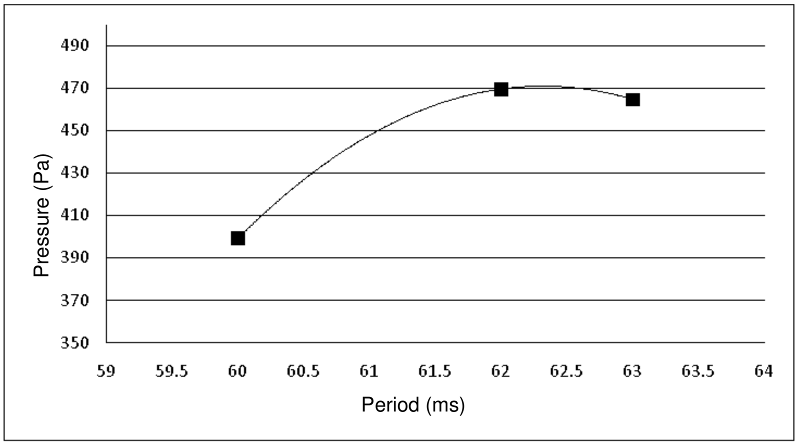


Figure 14 Pressure x driving period (linearized three-phase synchronism)

5. CONCLUSIONS

This work presented a new variation of the peristaltic pump that, instead rollers, uses three solenoid type electromagnetic actuators to compress a flexible tube sequentially, generating the flux of the fluid. A prototype was developed experimentally. This development included an oscillatory mechanical system to be used with the solenoid so as to obtain a large amplitude motions. In the pumping tests, two driving synchronisms are tested: the original and the three-phase synchronism. These synchronisms gave a maximum flow-rate of approximately 30mL/s. Comparing with commercial pumps like Hemopump (blood pump, Wampler,1994) that gives an average flow-rate of 58,3mL/s, the pump presented in this work shows lower capacity. However, it must be considered that this work aimed the validation of the pumping principle and no optimization is executed. Future works includes the development of analytical model for the pump as well as the optimization of the pump constructive and operational parameters aiming maximization of flow-rate and pumping pressure. Moreover, the solenoid actuator and the oscillatory mechanism will be redesigned so as to achieve a more compact pump.

6. ACKNOWLEDGEMENTS

This work reported in this paper is supported by a research fund from The State of São Paulo Research Foundation (FAPESP, BRAZIL, Projeto Temático No. 2006/58773-1).

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