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ELECTROMAGNETIC MINIATURE PUMP USING PERISTALTIC MOTION OF INTERCHANGEABLE FLEXIBLE TUBE

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ABSTRACT

This paper presents an electromagnetic miniature pump using peristaltic motion of an interchangeable flexible tube. Four hinge-type electromagnetic actuators arranged serially in one line pinch a flexible tube and generate peristaltic motion on the tube. In order to reduce electric power consumption, the magnetic latch mechanism using permanent magnets is applied to the actuator drive. As the actuator pinches the outside wall of the interchangeable tube, this pump can deal with any liquids inside the tube. The prototype pump has the flow rate range of 0.1~1cm^3/min and the maximum pressure of 13kPa by a battery drive. This paper shows the electromagnetic design of the actuator using the FEM magnetic field analysis. The optimum drive sequence of the pinching actuators and the experimental result of pump characteristics are reported. Furthermore, feasibility consideration of application to the portable intravenous drip system for medical treatments is carried out.

KEY WORDS

Pump, Electromagnetic Actuator, Power Saving, Flow Control, Latch Mechanism

INTRODUCTION

A pump which pressurizes the fluid inside the elastic tube by pinching it from the outside of the tube is generally applied to the sanitary/medical applications and the chemical analyzers. Due to the existence of an interchangeable tube wall between the fluid and the mechanical parts, it can deal with various kinds of fluid (acid, alkaline,etc.), and can prevent the fluid from contaminating. It also requires no cleaning because the fluid is changed with the interchangeable tube at the same time. The commercialized pumps of that type generally consist of the elastic rubber tube looped along the cylindrical inner wall, and the rollers squeezing the tube as shown in Fig.1. The roller unit is usually driven by a rotary actuator such as an electric motor. In this system, the precise rotational speed control of the rotary actuator in wide speed range from very slow up to high is necessary for the flow rate control. In order to realize the flow rate control in simpler configuration, this paper presents the different pump mechanism from the rotary type. The proposed pump system pinches an elastic tube by means of serially-arranged hinge type electromagnetic actuators and generates the peristaltic pumping motion on the tube by the sequential action of the actuators. Furthermore the power saving drive of the pump system on the condition of the battery drive is described.

CONFIGURATION OF MINITURE PUMP SYSTEM AND ITS APPLICATION

The portable intravenous drip infusion system is specified as the design target application of the proposed pump system. The movable intravenous drip equipment is not generally compact and limits the sphere of activity of the patient. Patient who has the scheduled medication by injection also has same restriction in his daily life. The proposed system shown in Fig.2 consists of the medicine liquid package in the breast pocket, the elastic tube run along the shoulder and arm, and the proposed pump actuator unit with the controller on the upper arm. The medicine liquid is transfused into the body at the forearm just like the conventional intravenous drip infusion. Table 1 indicates the required pump performance of the portable intravenous drip infusion system.

Figure 3 shows the hinge-type electromagnetic actuator used in the proposed pump. The actuator generates the force pinching the elastic tube between the armature and stator when the actuator is activated. The armature is returned by the elastic force of the tube when it is inactivated. It generally wastes electric power to keep the pinching position by continuous energizing of the coil. Therefore, the power consumption becomes large, especially in the drive mode having long interval. For reduction of power consumption, the magnetic latch mechanism using the permanent magnet inserted into the magnetic circuit is adopted to this actuator. The magnetic latch mechanism is common technology but very effective to the power saving drive of electromagnetic ON/OFF actuator [1].

MAGNETIC LATCH MECHANISM

Figure 4 shows an example of the force-displacement characteristics of a solenoid actuator with magnetic latch mechanism. The elasticity of the tube and pressure of the fluid inside the tube are assumed as a spring load. At the non-energized and open position, the actuator keeps open position because the attractive force generated by the permanent magnet is lower than the spring load. Then, the instantaneous energizing to the coil in the same direction as the permanent magnet magnetic field activates the actuator to the closed position (①) because the total attractive force overcomes the spring load. The actuator keeps closed position (②) without energizing. Therefore, no electric power is consumed. The instantaneous energizing to the coil in the counter direction for the permanent magnet magnetic field reduces the total attractive force, and then the actuator is released by the spring load. Because

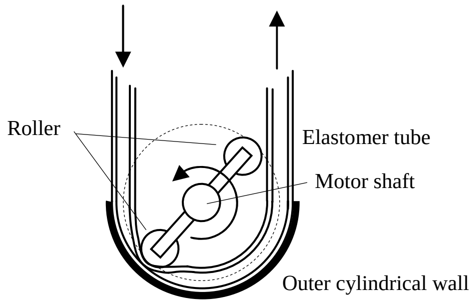

Figure1 Rotary type tube pump

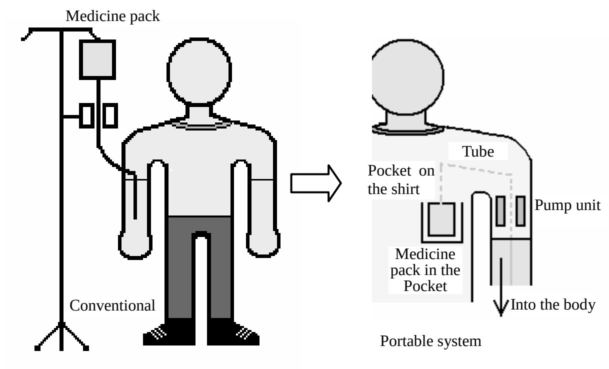

Figure 2 Concept of portable liquid medicine

Table 1 Required specifications of small electromagnetic pump

Pressure (max.)	over 13kPa
Controllable flow rates	0.1 cm^3/min～1.0 cm^3/min
Power source	Rechargeable battery cell (Ni-MH)

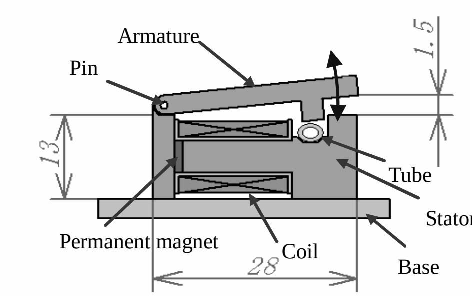

Figure 3 Hinge-type electromagnetic actuator

the instantaneous energizing works as only the trigger of actuator motion, the actuator wastes no electric power at the steady state, which occupies most of the actuator state.
The permanent magnet inserted into the magnetic circuit is exposed to inverse magnetic field to release the actuator. Therefore, permanent magnet material is key factor to the performance of the magnetic latch mechanism. Neodymium magnet (Nd-Fe-B) is applied to the actuator because of its toughness against demagnetization compared with ferrite or Alnico permanent magnets. The size of the permanent magnet is determined by consideration of balance between the required actuator force and the demagnetization effect caused by the energized coil, with the aid of FEM magnetic field analysis.

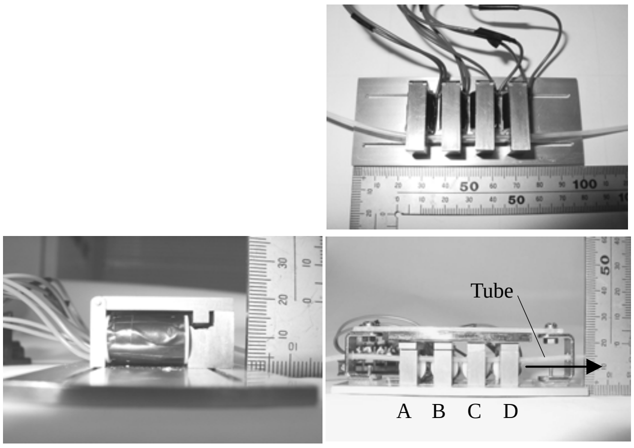

Photo 1 Electromagnetic pump unit

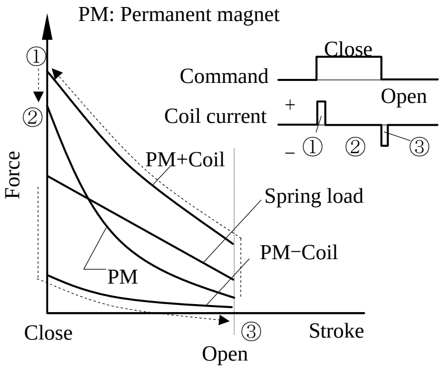

Figure 4 Electromagnetic latch mechanism

DESIGN OF MINITURE PUMP SYSTEM USING HINGE-TYPE ELECTROMAGNETIC ACTUATORS

Photo 1 displays the miniature pump which consists of four serially arranged hinge type actuators shown in Fig. 3. Here, each actuator is indicated as A, B, C and D from the left as shown in the photo. The peristaltic motion is generated on the tube by the sequential action of each actuator as shown in Fig.5. Then, the fluid is delivered from the right to the left in Photo 1.
One cycle of pumping is illustrated in Fig.6. The flow rate is controlled by the modulation of cycle. The closed actuator keeps its position without electric power consumption and acts as a check valve. Counter sequence against the cycle in Fig.6 makes pumping action of counter direction flow. When all the actuators are in open position, the pump unit does not restrict the flow inside the tube.
The maximum discharge pressure of the pump mainly depends on the pinching force of the hinge-type actuator. Figure 7 shows an example of FEM analysis of pinched tube. As the result of FEM deformation analysis, the required pinching force to make no clearance in the tube is estimated 5N for the tested silicone tube with inner tube diameter of 1mm, the wall thickness of 0.5mm under the inner pressure of 13kPa. This simulated force is experimentally confirmed by the leakage test as shown in Fig.8. A silicone tube pressurized at 13kPa is squeezed by a linear actuator, and the pinching stroke

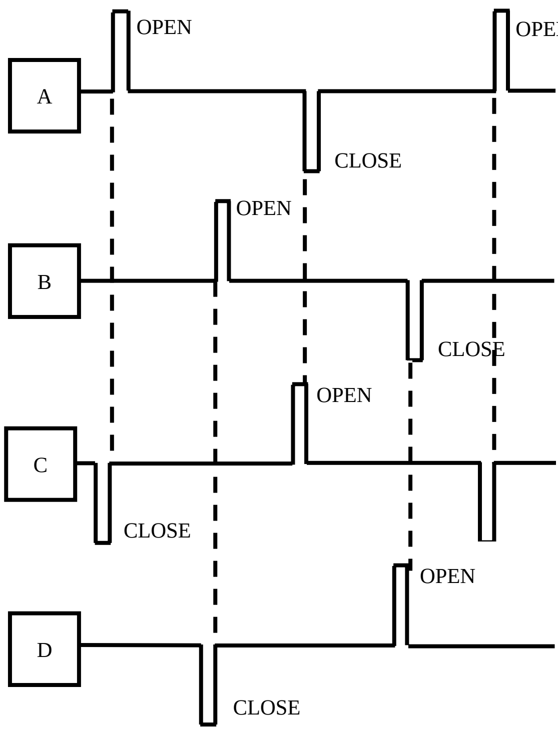

Figure 5 Drive sequence of pump unit

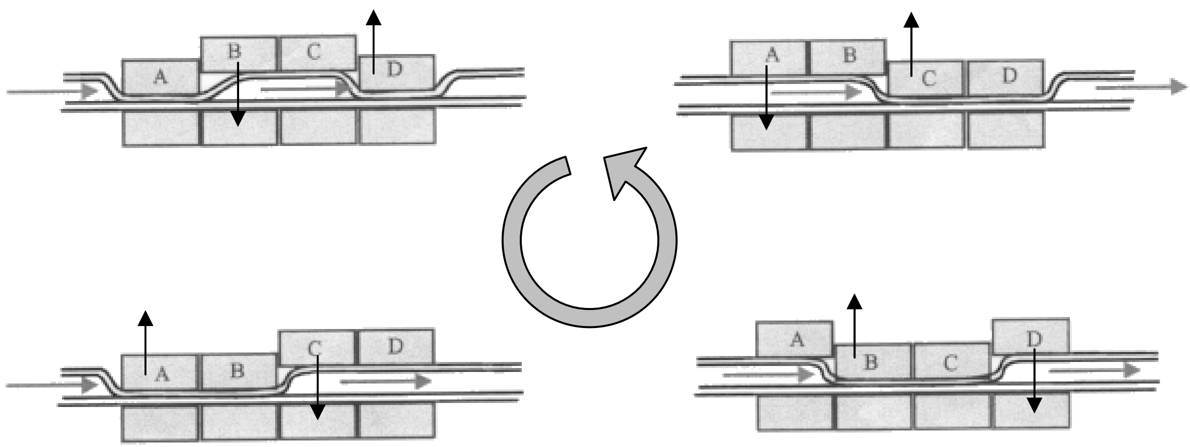

Figure 6 Peristaltic motion of elastic tube generated by the hinge-type electromagnetic actuators

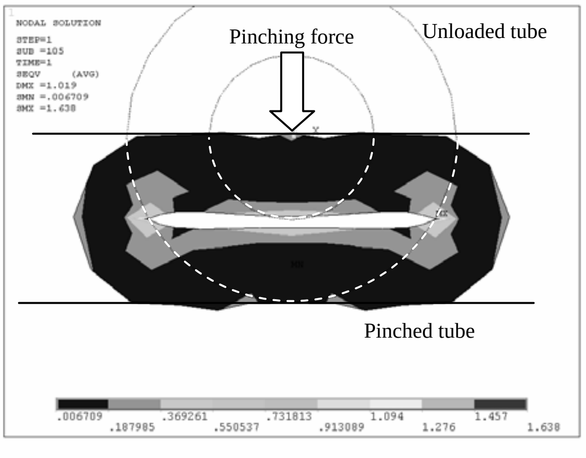

Figure 7 FEM analysis of pinched tube

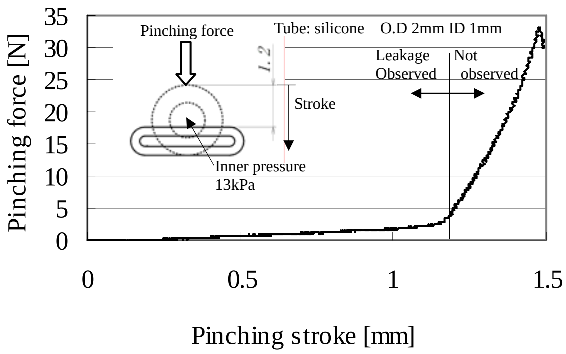

Figure 8 Experiment to determine the pinching force and stroke for no leakage

and force are measured at the same time. The pinched wall of the tested tube is completely adhered at squeezing of 1.2 mm in which the no leakage is observed.

The dimensions of the actuator are determined to realize the required force and stroke against the inner pressure of the tube, using FEM magnetic field analysis. Figure 9 shows the result of the FEM magnetic field analysis of the actuator. For the tested silicone tube, the actuator is required the force over 5N in whole range of the stroke by attraction due to the PM and coil. The shape of actuator and the size of the permanent magnet are optimized to satisfy the force – stroke characteristics shown in Fig.4 [2], [3].

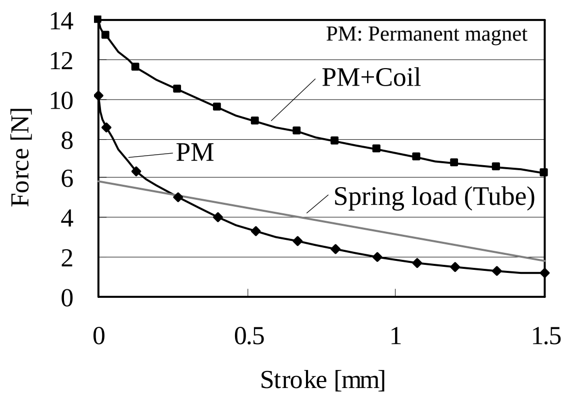

Figure 9 Calculated force-stroke characteristics uisng FEM magnetic field analysis

PERFORMANCE OF THE PROTOTYPE MINITURE PUMP

Figure 10 shows the schematic diagram of a full-bridge electric circuit generally used for the electric driver of solenoid with the latch mechanism. A commercial product IC package having 4 full-bridge circuits inside is applied to the driver of the prototype miniature pump.
Figure 11 shows the flow rate control characteristics of the prototype miniature pump, in which the drive frequency is determined by the reciprocal of the cycle. Tap water is used as working fluid. It is confirmed that the linearity of flow rate control is guaranteed in the range from 0.1 to 1.0 cm^3/min, which satisfies the design requirement in Table 1. In the range above the drive frequency of 3 Hz, the flow rate becomes less than the approximate line representing the linearity. The reason of this divergence is considered that the proportion of releasing time due to the elasticity of the tube in the cycle becomes large, and then the restoration of the tube is not significant.
The maximum discharge pressure of the pump is measured using the testing circuit shown in Fig.12. The pressure in the chamber rises up to the maximum discharge pressure during pumping. Figure 13 gives the

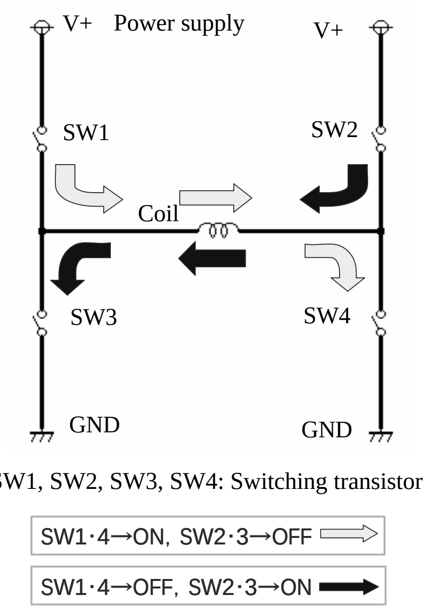

Figure 10 Full-bridge electric circuit for solenoid driver with latch mechanism

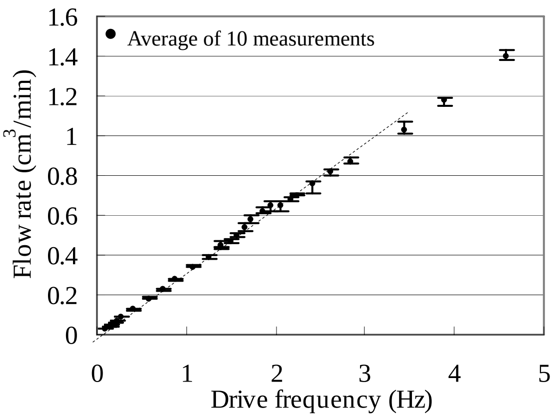

Figure 11 Drive frequency – flow rate characteristics

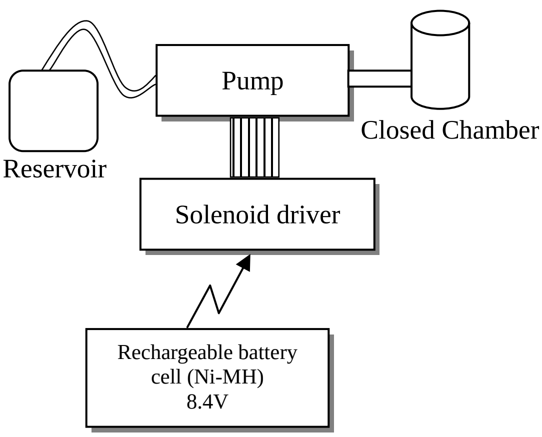

Figure 12 Testing circuit for the maximum discharge pressure measurement

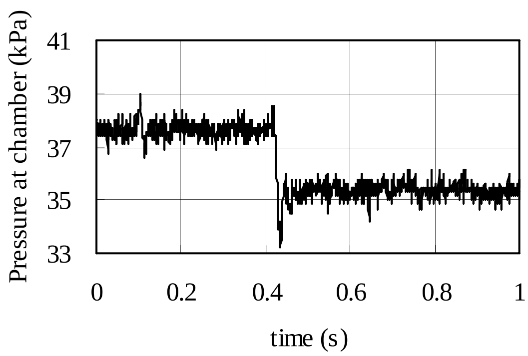

Figure 13 Measurement of the max. discharge pressure

Table 2 Test results of continuous run by full-charged battery(Ni-MH 8.4V)

Drive freq.(Hz)	1.0	2.0	3.0	4.0
Time (hr.)	36	18	12	9

transient pressure in the chamber. The pressure saturates at 38kPa and suddenly falls to 35kPa. At the pressure of around 38kPa, the closing of the actuator becomes unstable because the spring load consisting of the elasticity of the tube and the pressure inside the tube is comparable with the pinching force. Therefore, the maximum discharge pressure is regarded as about 35kPa.

Electric power is supplied from 9V-type Ni-MH rechargeable battery cell (Output voltage: 8.4V) to the solenoid driver. Table 2 shows the continuous run time by full-charged battery. The full-charged battery runs the pump for 12 hours at the drive frequency of 3Hz continuously. It is sufficient performance for the portable intravenous drip infusion system. From the viewpoint of energy balance, the continuous run time is expected to be in inverse proportion to the drive frequency. However, it depends upon the electric performances of driver and controller. If those devices are not designed well, the continuous run time would be considerably reduced, because they continuously consume the electric power even when the actuator is not activated. In order to make the pump durable, the reduction of power consumption at those devices should be achieved.

CONCLUSIONS

The performance of the miniature pump consisting of the interchangeable flexible tube and the hinge-type electromagnetic actuators has been reported. The prototype pump (50mm x 28mm x 15mm) with the silicone tube of 2mm in diameter was manufactured. It covers the flow rate of 1.5cm^3/min and has the maximum discharge pressure of 38kPa by the rechargeable battery cell (Ni-MH 8.4V) drive. The magnetic latch mechanism designed optimally is effective to reduce the electric power consumption. The prototype pump at drive frequency of 3Hz runs for 12 hours continuously by full-charged battery cell. As the pumping action is achieved based on the open-loop sequence control of each actuator, the pump flow rate can be controlled without flow sensors proportionally to the drive frequency of the actuators.

Feasibility consideration of application to the portable intravenous drip system for medical treatments has been carried out. It was confirmed that the prototype pump has sufficient performance for the target system. Furthermore, it will be applicable to the miniature pump system for sanitary/medical applications and the chemical analyzers.

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