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Optimization of Multiple Micro Pumps to Maximize the Flow Rate and Minimize the Flow Pulsation

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Abstract

In recent years, micro pump plays a significant role in many fields, specifically in chemical, medical, and thermal managements. Since there are distinct requirements in each field, several types of micro pumps have been designed to meet those requirements. Fluid flow from these micro-pumps is delivered in a series of small discrete volumes, which make up a pulsating flow. In order to reduce the pulsating flow, the multiple micro-pumps should be actuated in parallel. Thus, in the present work, two piezo-electrical diaphragm type micro-pumps are operated in parallel with a microcontroller based sequential switching to maximize the flow rate and minimize the flow pulsation. Micro-pumps are switched in different phase shifts to study the flow pattern. The flow pulsation is measured in terms of pressure pulsation using pressure transducer. Flow pulsations are recorded for various drive frequencies in the range of 10 Hz to 40 Hz and for peak-to-peak drive voltage in range of 100 - 250 V. It is observed that the flow pulsation for both micro pumps is minimum at higher frequencies and lower drive voltages. Also the flow rate of combined micro pumps with and without offset is precisely measured and reported in the paper.

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Keywords: Micro-pump; flow rate; flow pulsation; frequency; microcontrollerl; sequential switching

1. Introduction

Fluid power technology is gaining tremendous applications in modern manufacturing system. Most of the modern tools are driven through the fluid power system. It is very difficult to identify a single component not being powered by fluid power system. In one or the other stages of its manufacturing it uses a fluid power. A current trend is to

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develop and study the miniaturized fluid power components- micro pumps and micro actuators used for various micro fluidic applications. Micro pumps are the essential components in micro-fluidic system analysis, which has been emerged as a popular area of research and development. These micro pumps assure a precise flow rate to control many micro actuators to do the useful miniature work. Micro pumps, which have the advantage of small size and configurable dimension, are gradually becoming one of the solutions for electronic heat dissipation. Also micro pumps finds promising applications in analytical chemistry, medical treatment, pharmacy, bioengineering, fuel drop generator for automobile heaters, micro metering valves for fuel injection system etc. There are several types of actuation approaches in developing micro pumps, such as electromagnetic [1, 2], piezoelectric [3, 4], shape memory alloy [5], electrostatic [6], and thermo pneumatic [7] devices. Most of actuations are complicated in structure and have high energy consumption. However, piezoelectric actuation has notable advantages that are relatively simple component and low energy consumption.

2. Literature Review

The working principles of various Micro-Electromechanical Systems (MEMS) like- micro sensor, (acoustic, biomedical, bio sensor, chemical sensor, optical sensor, thermal sensor), various micro actuation principles (thermal sources, shape memory alloys, piezoelectric crystals, electrostatic forces) and main practical application devices micro valves, piezoelectric crystals, micro motors, micro pumps, micro accelerometer and many micro fluidic devices are elaborated [8, 9, 10]. A very first document about a miniaturized micro pump is appeared in patent submitted by Thomas and Bassman [11], which dates back to 1975. The device was designed for implantation into the human body and comprised of a solenoid connected to a variable pumping chamber which actuated by opposed piezoelectric disc benders. The micro-pump designed was a peristaltic pump consisting of three active valves actuated by piezoelectric disc. The device primarily developed for use in controlled insulin delivery system. Schamueller et al. [12] reported a piezoelectrically actuated silicon membrane micro-pump with passive valves. The fabrication of the micro-pump was based on double sided processing of silicon and bulk KOH etching. The size of the micro pump was 12 mm × 12 mm and the height including the Piezoelectric Zirconate Titanate (PZT) disc was 0.85 mm. A flow rate 1500 µl/min and a back pressure of 1 kPa were achieved with ethanol as the pumping medium. In case of air as the pumping medium, a maximum flow rate of 690 µl/min was measured. Geipel et al. [13] reported for the first time a novel design of micro-pump with back flow pressure independent flow rate for low rate requirements such as required in drug delivery applications. The concept was based on piezoelectrically actuated diaphragms to achieve flow rate in the range of 1 – 50 µl/min.

A high performance piezoelectric actuated cantilever valve micro-pump for drug delivery application was investigated by Junwu et al. [14]. The output valves of the micropump were improved in design by the cantilever valves. The micro-pump with shorter cantilever valves obtained higher flow rate of 3500 µl/min. and back pressure of 27 kPa. The same micro pump with larger cantilever valves obtained a flow rate of 3000 µl/min. Van Lintel et al. [15] reported a first attempt to fabricate silicon micro-pump based on piezoelectric actuation; The reciprocating displacement type micro-pump comprised of a pump chamber, a thin glass pump membrane actuated by piezoelectric disc and passive silicon check valves to direct the flow. The piezoelectric disc was attached by means of cyano acrylic adhesive. It was the first reported work on successfully fabricated micro-pump using micromachining technologies. Koch et al. [16] proposed a typical piezoelectric micro-pump based on deformation of a screen-printed PZT on the silicon chip. Outlet and inlet valves were formed in the two lower layers and membrane actuator formed the top layer. The dimensions of the silicon membrane were 8 mm × 4 mm × 0.07 mm. Flow rate of up to 120 µl/min. was achieved.

A maximum back pressure of 2 kPa was measured when a supply voltage of 600 V at 200 Hz across a 100 µm thick piezoelectric layer was applied. The micro-pump design was suitable to be applied in medical applications as cheap disposable micro-pump for drug delivery such as insulin or ethanol as the pumping medium. When air was used as pumping medium, a maximum flow rate of 690 µl/min was observed.

Ma et al. [17] presented the development of a novel PZT insulin micro-pump integrated with micro-needle array for transversal drug delivery. Geipel et al. [18] presented novel medical implant based on bidirectional micro-pump for artificial system. In this paper an attempt has been made to study the flow rate and pressure drop, when micro-pumps are connected in parallel.

3. Experimentation

Experimental setup has been fabricated by connecting two micro-pumps in parallel with sequential switching to maximize the flow rate, with minimum degree of flow pulsation. The experimental setup consists of micro pumps, pressure transducer, regulated power supply, Digital Storage Oscilloscope (DSO), electronic circuits. Table 1 shows the specification of the micro-pump and pressure transducer used for the experiments. The calibration of micro pumps and pressure transducer is very much essential to predict its performance accuracy, hence the following section will elaborate calibrations of micro pump and pressure transducer.

Table. 1. Specification of Micro Pump and Pressure Transducer.

S. No	Micro Pump	Specification
1	Pump type	Piezoelectric diaphragm pump
2	Maximum flow rate	30 ml/min for square wave, 20 ml/min for sine wave
3	Maximum pressure	35 kPa
4	Suction pressure	-1.0 kPa
5	Drive voltage(Vpp)	60-250 V
6	Drive frequency	10-60 Hz
7	Overall dimensions	(33x33x5.5) mm
8	Inlet /Outlet pipes	Ø 1.8 - 2.8 mm 5.0 mm length
9	Weight	9 gm
S. No	**Pressure Transducer**	**Specification**
1	Pressure	0-250 kPa
2	Supply voltage	4.85-5.35 V
3	Sensitivity	18.8 mV/kPa

3.1. Calibration of micro pumps

Fig. 1 shows the calibration curves of pump flow rate vs. drive frequency at various drive voltage. For 100 Vpp it shows nearly double the flow rate for pump 1 with respect to pump 2. Similarly, the pump 1 gives maximum flow rate as 25 ml/min and pump 2 as 17 ml/min for 250 Vpp.

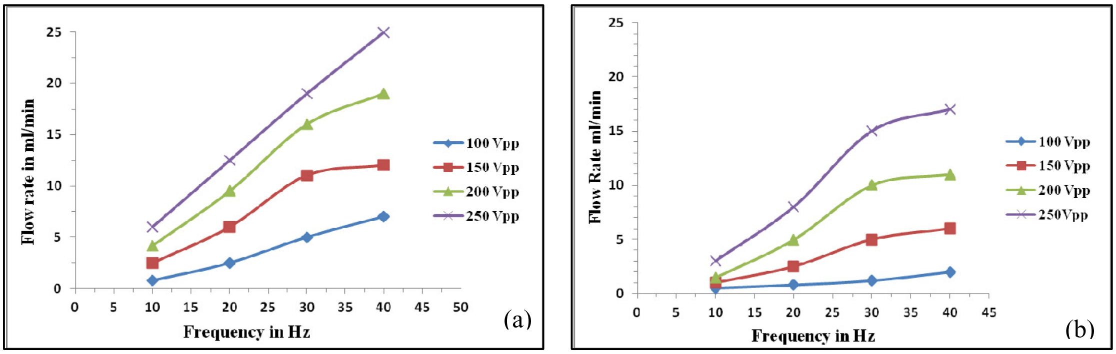

Fig. 1. Calibrations of Micro pumps flow rate Vs drive frequency at various drive voltage Vpp (a) Micro pump 1 (b) Micro pump 2.

3.2. Calibration of pressure transducer

The pressure perturbation during the operation of micro pumps is quantified as degree of pulsation. The pressure transducer is calibrated before conducting the experiments. Fig 2 (a) and (b) shows the photographic view of the calibration setup and voltage vs. pressure calibration curve of the pressure transducer respectively.

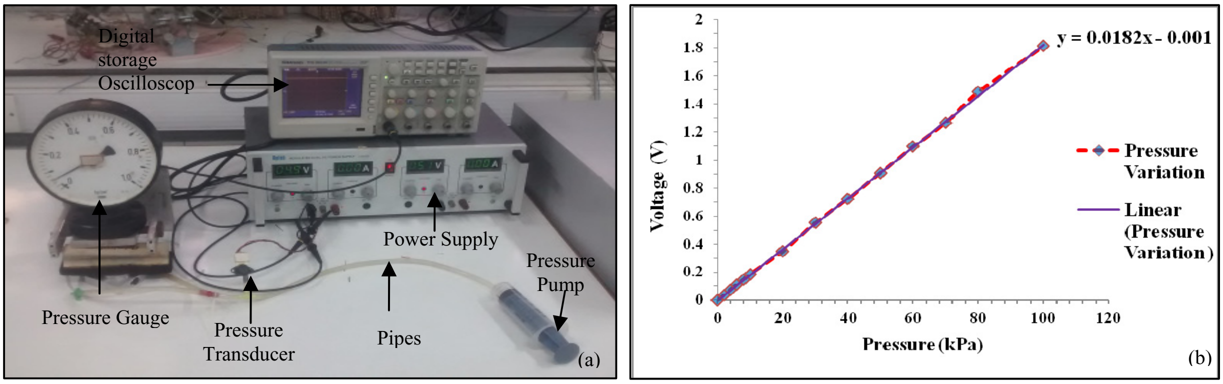

Fig. 2. Calibration of pressure transducer (a) photographic view of the calibration setup (b) voltage Vs pressure curves.

When the pressure was increased to 1 bar the range of voltage is 1.812 V. From this data it shows when increase in pressure, the transducer output voltage increases linearly. So the pressure transducer sensitivity is 18.24 mV/kPa.

4. Experimental setup

Fig. 3 shows the block diagram of the experimental setup used for predicting the flow behavior when connecting two pumps in sequence. A regulated DC power source (0-5 V) is used to provide voltage to the microcontroller and piezoelectric driver boards. Microcontroller generates the frequency signal which can be varied in the range of 0-50 Hz with the help of potentiometer. Desired frequency signal from the microcontroller output is fed to the piezoelectric driver board. This frequency signal from microcontroller has an amplitude range of (0-5 V) which needs to be amplified to the operating range 100-250 V for the micro pumps. The amplification of frequency signal is done through piezoelectric driver board. Piezoelectric driver circuit provides the output of frequency range is 0-50 Hz and drive voltage range 100-250 V. The same is given as an input to the micro pumps. Based on the received input signal from driver board the diaphragm deflects, which changes the area of cross section of flow through the inlet and outlet of the micro pumps. Fig. 4 shows the photographic view of experimental setup.

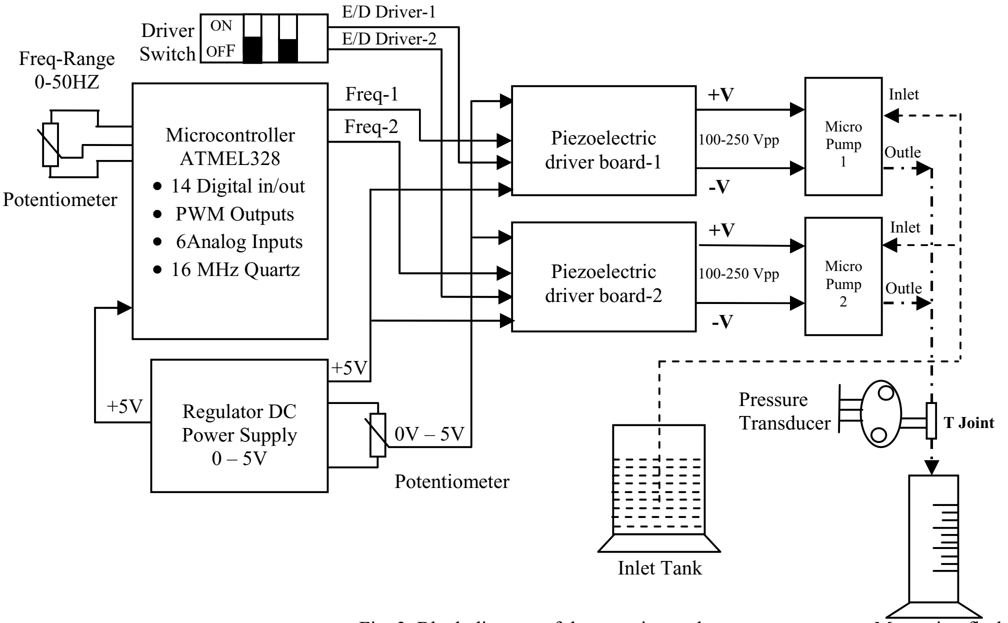

Fig. 3. Block diagram of the experimental setup.

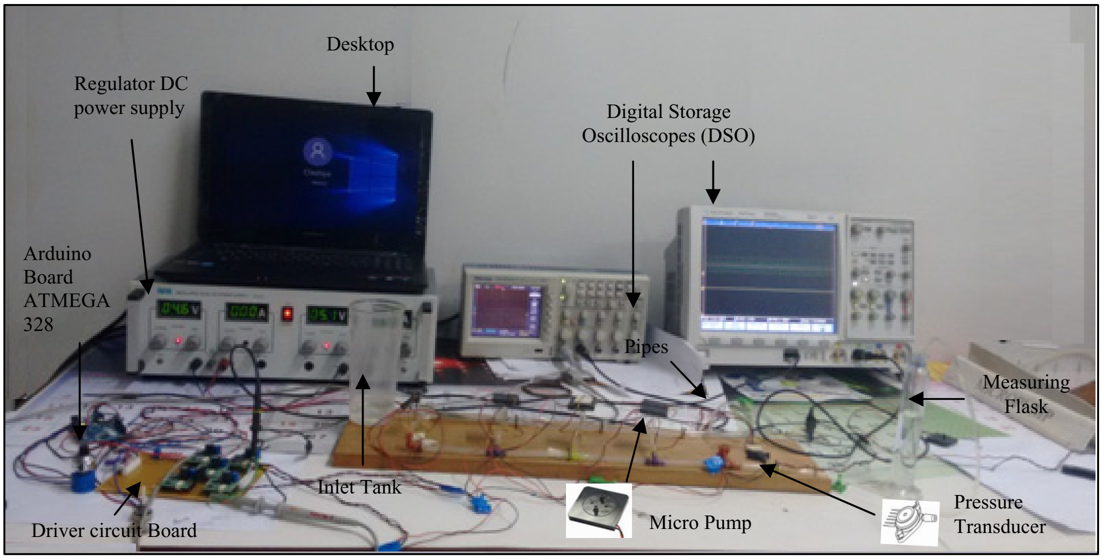

Fig. 4. Photographic view of the experimental setup.

4. 1. Design of experiments

Taguchi orthogonal experimental design L_{16} has been used to conduct the experiment in order to reduce the run time of the experiments. Table 2 shows the process parameters and their levels selected for the experiment. Taguchi L_{16} experimental design table consist of sixteen rows, wherein each row corresponds to unique combinations of levels of the process parameters.

Table.2 Process parameters and their levels

Process parameter	Levels			
	1	2	3	4
Drive Voltage peak to peak (V)	100	150	200	250
Drive Frequency (Hz)	10	20	30	40

5. Results and discussions

Preliminary experiments were conducted for the two micro pumps separately to know the flow pulsation by varying the frequency and voltage, which are recorded in the pressure transducer in terms of pressure variation in the flow. The pressure variation is directly proportional to the flow pulsation. The experiment was further extended to study the flow pulsation effect for serial switching and parallel switching of two micro pumps connected in parallel. The micro pumps are operated with phase shift or delay time to reduce the flow pulsation. The degree of pulsation is defined as the ratio of amplitude of various voltages to the average flow rate. The degree of flow pulsation is

$$\delta = \left(Q_{\max} - Q_{\min}\right) \div Q_{avg} \quad (1)$$

If two micro pumps are to be driven in order to reduce the pulsation then one is driven with 0˚ phase shift and another is driven with a phase shift of 180˚, like this we can further reduce the flow pulsation by using three pumps then these pumps should be driven with a phase shift of 120˚.

5.1. Effect of degree of flow pulsation of micro pump 1and micro pump 2

Fig. 5 shows the effect of degree of flow pulsation of micro pump 1 and micro pump 2. This is measured from the pressure transducer in terms of pressure variation in the degree of flow pulsation and the output of pressure transducer is connected to DSO in which the pressure pulses are directly recorded. Degree of flow pulsation with respect to drive frequency varies in the range of 10 Hz to 40 Hz and drive voltage range of 100 - 250 Vpp. The degree of flow pulsation is minimum at drive frequency 40 Hz in case of both the pumps and maximum at the drive frequency 10 Hz.

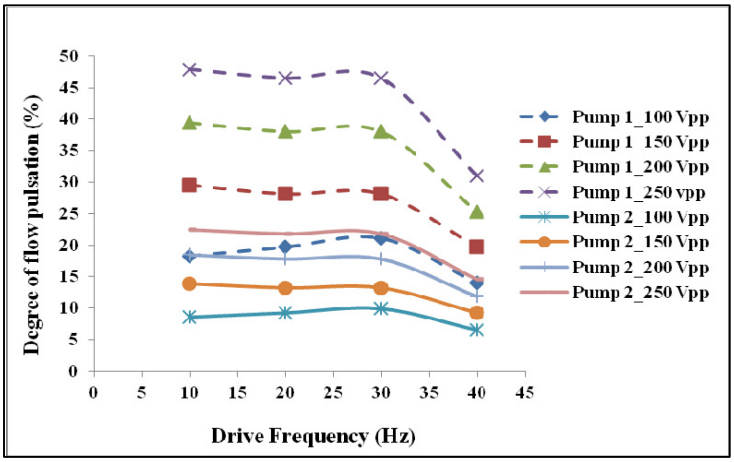

Fig. 5. Degree of pulsation for micro pump 1 and micro pump 2

5. 2 Flow rate of two micro pumps

Table 3. shows the flow rate and degree of flow pulsation measured when two micro pumps are connected in parallel and operate in sequential switching at 0˚ and 180˚ phase shifts. Taguchi L_{16} experimental design is used for conducting the experiments.

Table.3. Flow rate and Degree of flow pulsation when two pumps are operates in phase shift.

S. No	Drive Voltage Vpp (V)	Drive Frequency in (Hz)	Flow rate at 0˚ phase shift (ml/min)	Flow rate at180˚ phase shift (ml/min)	Degree of flow pulsation at 0˚ phase shift (%)	Degree of flow pulsation at180° phase shift (%)
1	100	10	1.2	1	22.5	18.3
2	100	20	3.5	4	25.4	16.9
3	100	30	7	7.8	23.9	19.7
4	100	40	9	9.2	15.5	15.5
5	150	10	3.2	6	38.0	29.6
6	150	20	8.5	7.5	39.4	22.5
7	150	30	15	15	36.6	26.8
8	150	40	18	17	22.5	22.5
9	200	10	6	6	54.9	39.4
10	200	20	14.5	15	57.7	29.6
11	200	30	23	21	50.7	36.6
12	200	40	28	28	32.4	32.4
13	250	10	10	9	71.8	50.7
14	250	20	21	20	73.2	38.0
15	250	30	33	31	64.8	46.5
16	250	40	36	37	42.3	43.7

Fig. 6 shows sequential input signal to drive micro pump driver circuits recorded from the DSO at 0˚ and 180˚ phase shift for pump 1 and pump 2. Sequential input signal is generated from the microcontroller digital output port - channel 8 at frequency 10 Hz, phase shift is 0˚ and channel 7 at frequency 10 Hz, phase shift is 180˚. Fig. 7 shows the degree of flow pulsation when two micro pumps are operated in sequential switching at 10Hz, output in terms of mill volts is recorded the from the DSO.

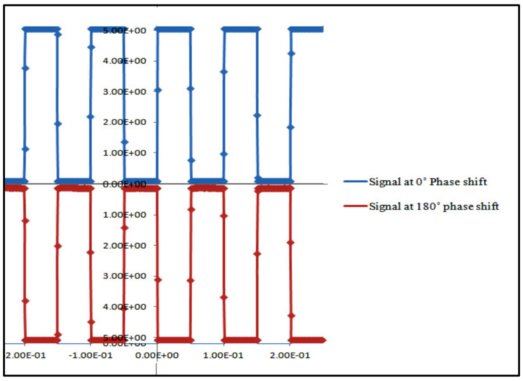

Fig. 6.Sequential input signal to the micro pumps 1 at 0˚ and micro pump 2 at 180˚ phase shift.

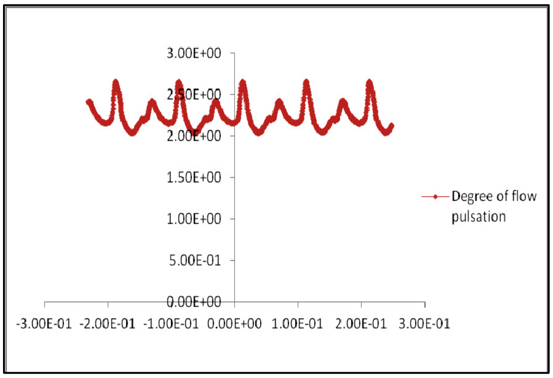

Fig.7. Degree of flow pulsation when two micro pumps are operated in sequential switching at 10Hz.

Fig. 8 shows flow rate vs. drive frequency at various drive voltage curves when two micro-pumps are connected in parallel and operated at phase shift of 0° and phase shift of 180°. It is observed that, the flow rates at 0° and 180° phase shifts are found to be closer to each other at the all values of flow rates. Fig. 9 shows degree of flow pulsation vs. drive frequency at various drive voltages curves when the two micro-pumps are connected and operated in parallel. It is observed that at 0° phase shift, the percentage of degree of flow pulsation at 10 Hz 100 Vpp is 71.8 % and at 180° phase shift (i.e. sequential switching at 180° phase shift) the percentage of degree flow pulsation at 10 Hz 100 Vpp is 50.7 %. From this data it shows that the percentage of degree of flow pulsation with 180° phase shift, will decrease when compare to 0° phase shift.

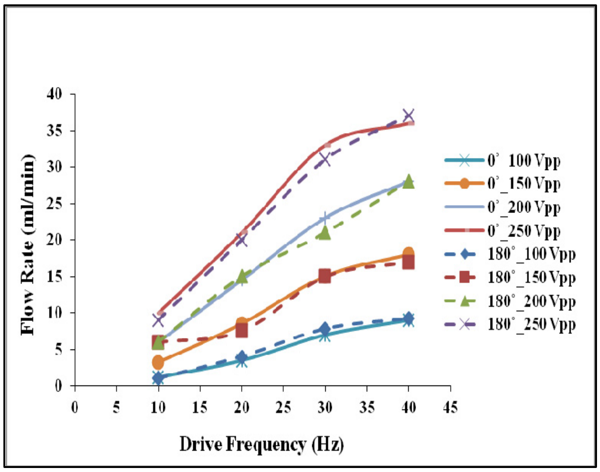

Fig. 8.Flow rate vs. frequency at various drive voltage Vpp for two pumps in 0˚ and 180˚

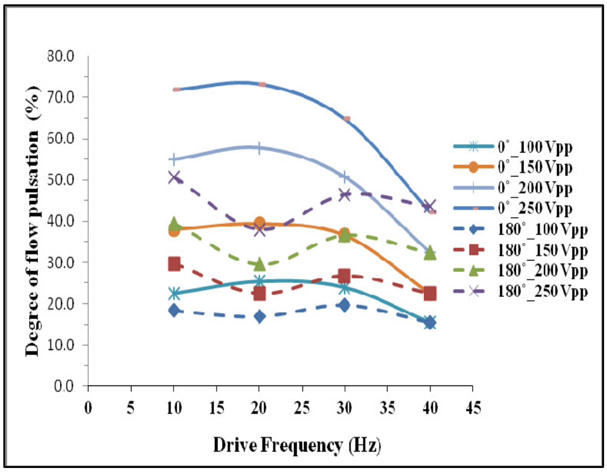

Fig. 9. Degree of flow pulsation vs. frequency at various drive voltage Vpp for two pumps in 0˚ and 180˚

6. Conclusions

- In this paper, an attempt has been made to develop a methodology for driving two micro pumps to maximize the flow rate and minimize the degree of flow pulsation.
- In this connection an experimental setup has been fabricated with electronic circuits to operates two micro pumps in parallel connection and d sequential switching.
- Experiments are conducted to determine the performance of two micro pumps under various operating conditions- varying peak to peak voltage and drive frequency.
- The obtained result reveals the degree of flow pulsation at 0˚ and 180˚ phase shift when driving with 250 Vpp and 20 Hz frequency found to be 73.2 % and 38.0 % and it reveals that reduction in degree of flow pulsation by 35.2 % for 180˚ phase shift.
- The present methodology can be used for drug delivery system in bio medical application.

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