Feedback and Control of Micropumps

by

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ABSTRACT

This research program relates to feedback and control of micro-electromechanical system (MEMS) components, which may include reaction chambers, pumps, valves mixers, heaters, diffusers, nozzles, channels, fluidic interconnections and others that may be integrated in a microfluidic system and applied to medical and chemical diagnostic devices, and any devices requiring liquid-or gas-filled chambers for operation. For the purpose of this study, a micropump constructed from no-moving parts (NMP) valves, driven by a piezoelectric element membrane and bonded to a flexible diaphragm is characterized by a Laser Interferometer. In order to predict the pump's performance, a non-contact displacement measurement fibre optic interferometer is used which, when applied, dynamically characterises the pump's open loop parameters. It is intended that the steady-state parameters be mapped into the closed-loop control elements, based on continuous measurement and adaptive compensation so that the pump performance criteria are always satisfied.

1. Introduction

Micro-electro-mechanical system (MEMS) technology is most suitable for the fabrication and integration of microfluidic systems, which offer a unique solution to chemical and biochemical analysis and synthesis. The integrated microfluidic systems may be constructed from any number of microfluidic components and on top of a regular circuit substrate. There are many benefits in miniaturization of these biomedical systems, including substantial saving in time taken to do the analysis, cost of analysis and space utilization for the equipment performing the analysis. Ultimately, it is desirable to provide systems capable of performing a variety of different fluidic operations integrated in a single system (Forster *et al.,* 1995). To achieve this, it is imperative that reliable and accurate monitoring and control of the parameters for any of the fluidic elements within the microfluidic system be implemented. Typically, a microsystem will comprise of components categorised as microsensors or detectors, which detect any changes within the system environment, intelligent electronics capable of making decisions based on the changes indicated by the sensors and microactuators capable of altering the system environment according to the directives from the intelligent electronics.

Using MEMS technology, it is the purpose of this research to characterise the dynamic performance of one of the microfluidic components, in this case a piezoelectric- driven micropump. In order to identify potential causes of failure and optimise for its parametric limitations, in both electrical and mechanical elements of a microstructure, it is imperative that a suitable measuring system is integrated without impeding pump performance.

This paper describes the use of a non-contact fibre optic based interferometer for measuring the dynamic displacement of a micropump applied externally to the MEMS structure. This approach ensures that the optimum displacement of the piezoelectric actuator membrane is maintained for any given gas or liquid being pumped through the micropump's valves and chambers.

2. Industrial Implications

Microfluidic systems are emerging not necessarily from industrial demand but from the technologies that enable the fabrication of such microcomponents (Forster *et al,* 1995). The application targets for a micropump range from medical, biological, and pharmaceutical to chemical, where miniaturization increases portability, reduces cost, increases accuracy, reduces the amount of chemical or biological samples required for analysis, and also speeds up the measurement time. Reduction in size also implies reduction in quantity, so micro based processing plants are best suited for distributed processing of materials at the immediate point-of-use In biomedical applications, an implantable micropump can be fabricated to accurately and on demand, administer the amount of medicine required as the regulation of flow rates can be controlled precisely through integrated electronics.

Traditionally, feedback and control systems do not necessarily translate well into the microsystem domain. Numerous factors come into play in terms of characteristics and performance of such systems (Gerlach *et al.,* 1995) and hence there is a need to investigate a range of problems in order to understand the methods and technologies that will be required to produce viable systems.

3. Methodology

This research investigates the characterization of a micropump using a variety of detecting methods, depending upon the specific operation that is being performed. An optical detection system is used as a sensor for the measurement of the piezoelectric membrane displacement. A study of the dynamic actuating properties such as actuating currents, frequencies and duty cycles is undertaken to optimise the actuating performance of a micropump in a microfluidic system.

The detectors and actuators may exist as separate units for the purpose of this study, but ultimately the preferred option is to integrate them into a single self-contained unit. This paper examines the integration processes from the aspect of miniaturization, performance optimisation, monitoring and controlling methods, which can be synthesized to form an efficient and reliable closed loop system. The integrated system facilitates connection of the instrument with the computer by a way of a single or multiple ports accommodating for transmission of information between the controller, detector and the computer. In addition, direct monitoring of the drivers associated with controlling the microactuators based on the decision making intelligent electronics is also made possible via optically isolated ports (Figure 1).

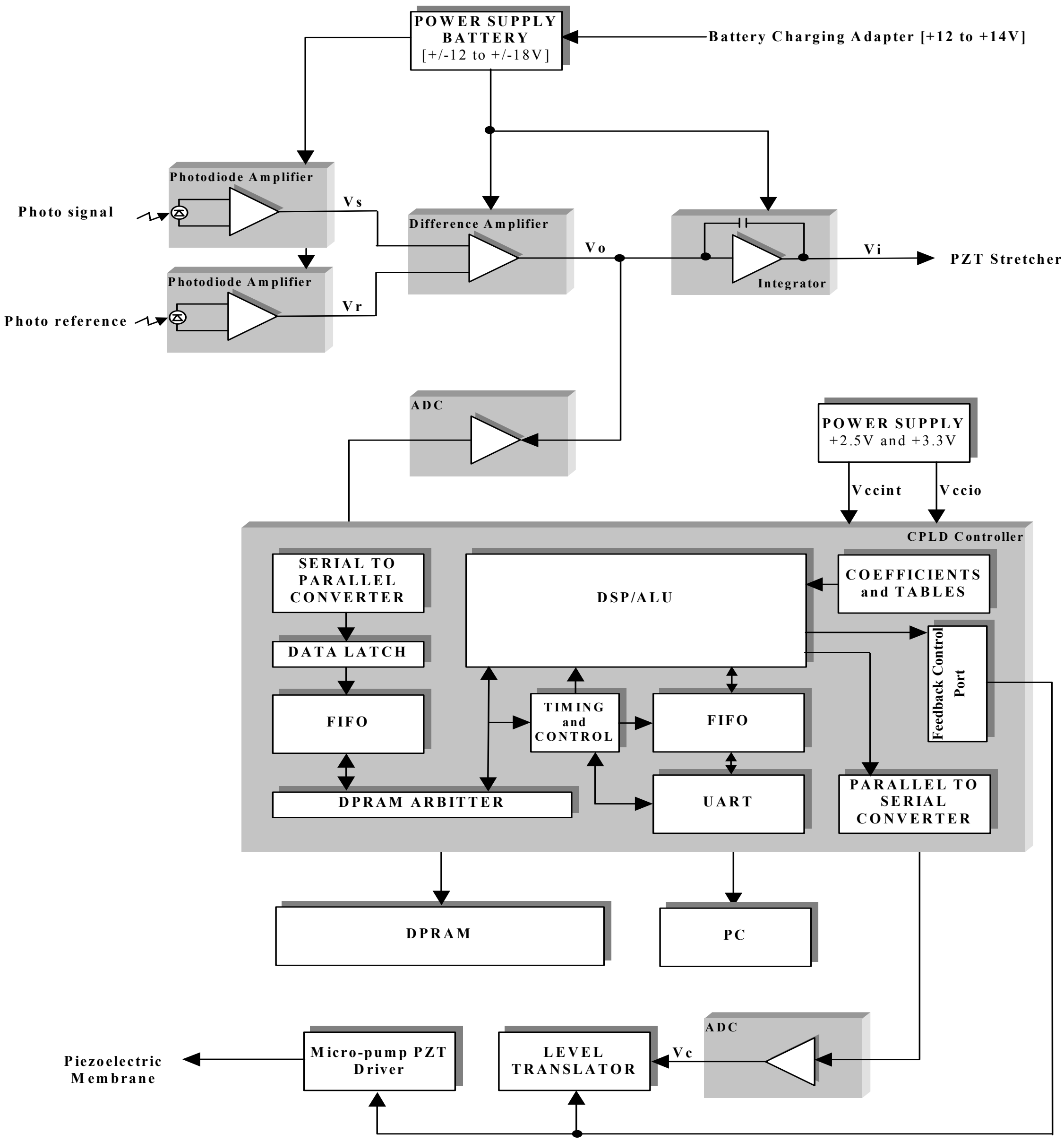


Figure 1 System Block Diagram

It is envisaged that the outcome from this study will provide the basis for the design and development of a non-contact high bandwidth in system interferometer. This will be used as the sensor for the dynamic measurement of a micropump, interfaced with hybrid or polymer infused electronic components capable of controlling actuating currents, frequency and duty cycles in a closed loop environment. Closed loop actuators are ideal for applications requiring high linearity, long-term position stability, repeatability and accuracy and when used in conjunction with a position measuring sensor and microelectronic circuits, they form an intelligent and reliable microfluidic component control system.

4. Micropump Closed Loop Considerations

4.1 Overview

The micropump characterisation takes into account the structural, mechanical, chemical and electrical parameters that are susceptible to steady-state variations attributable to electrical noise, temperature, vibrations, inductance, capacitance and chemical reactions. In a closed loop control system the performance is measured by its steady-state error, gain and phase margins, which are essentially the criteria for optimality. The performance and reliability of a micropump is only as good as its feedback compensation, which maximises or minimises the performance index that is unknown until the completion of the optimising process. Figure 2 illustrates a simple adaptive control system for a micropump of varying parameters that are continuously measured and then compensated so that the system performance criteria are always satisfied.

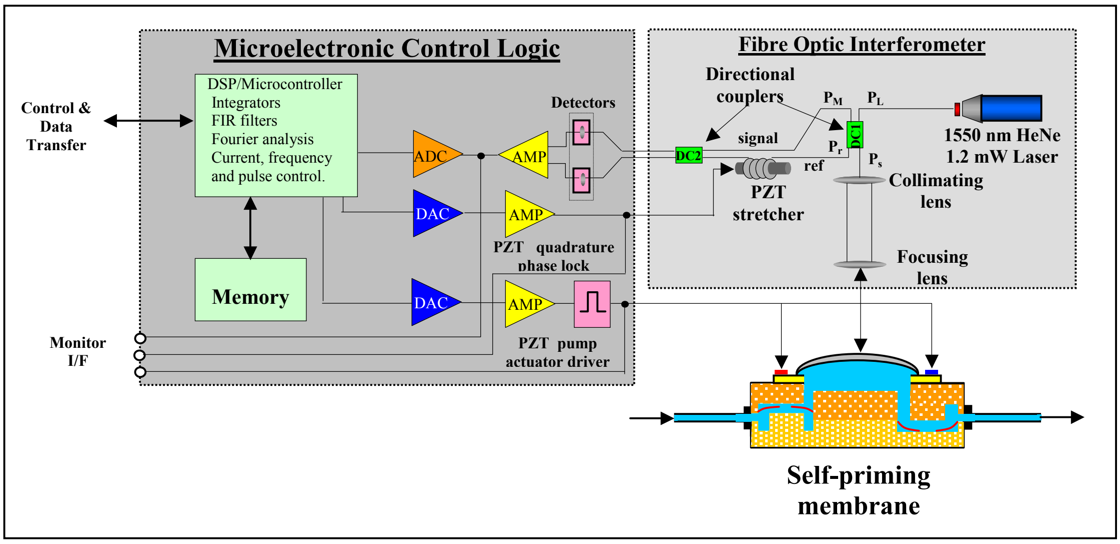


Figure 2 - Micropump feedback control system

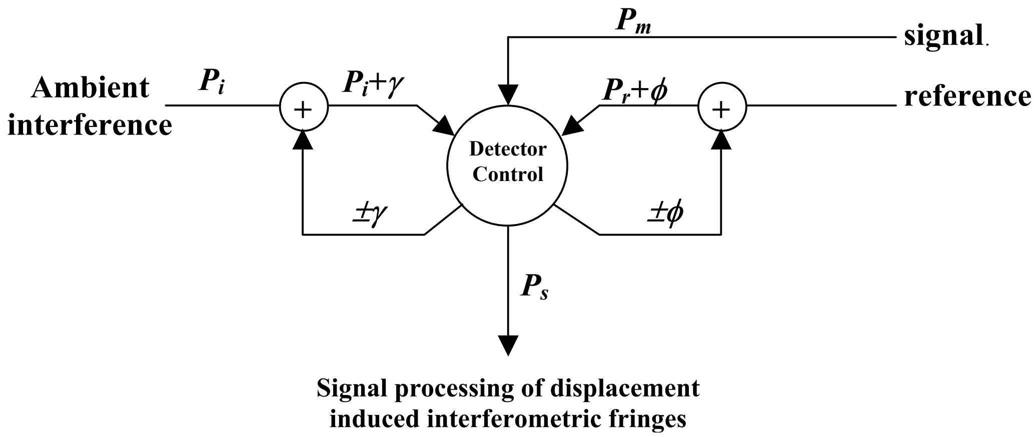
When considering a closed loop system for a micropump it is imperative that the design parameters chosen closely match the ideal responses to minimise the performance index or the error between the actual and ideal response.

4.2 Closed Loop Controlling Elements and Parameters

(i) Fibre optic interferometer (sensor)

The closed loop (feedback) control system for a micropump is composed of three components, a piezoelectric actuator, fibre optic interferometer (sensor), and control logic.

The fibre optic interferometer requires feedback compensation for the low-drift induced phase changes in order to precisely lock the interferometer at the quadrature point (Davis *et al.,* 1999). The compensation factor can be expressed as a function of the error where the controlling element is a phase shifter (Figure 3).



ϕ = phase error
γ = fotonic interference error
P_m = fringe modulation due to displacement
P_i = ambient interference
P_s = desired value of output

Figure 3 - Interferometer detector closed-loop feedback path

Equally, ambient interference at the input to the photo-detector may be sufficiently high to induce a fringe pattern distortion, which needs to be minimized or eliminated all together as it may produce additional patterns that would be processed as valid fringes and therefore producing erroneous results.

(ii) Piezoelectric Actuator

The micropump piezoelectric actuator controlling elements are amplifiers, frequency generators, phase shifters noise cancellers, and pulse width modulators and filters, each of which is capable of affecting the controlled output to the actuator.

(iii) Control Logic

The control logic is composed of microelectronic circuits capable of manipulating the parameters of the controlling elements described in the previous two sections. The intelligence for the control logic is to be implemented in the form of a digital signal processor (DSP). Additional sensors may also be included in the closed-loop, such as thermistors, accelerometers, piezoresistors, capacitive or flow rate sensors, keeping in mind that they should not impede the overall system performance.

Figure 4 shows a basic block diagram of an adaptive control system that can be used to optimize the performance of a micropump. All of the parameters, which are known to vary with time in the block labeled "Parameter optimization", are continuously measured at the input ***c(t)*** and output ***d(t)*** of the piezoelectric actuator block in order to identify the parameters requiring adjustment in the control elements block to satisfy system specifications. Included in the Parameter optimization block are the fibre optic interferometer parameters not shown as a separate feedback path.

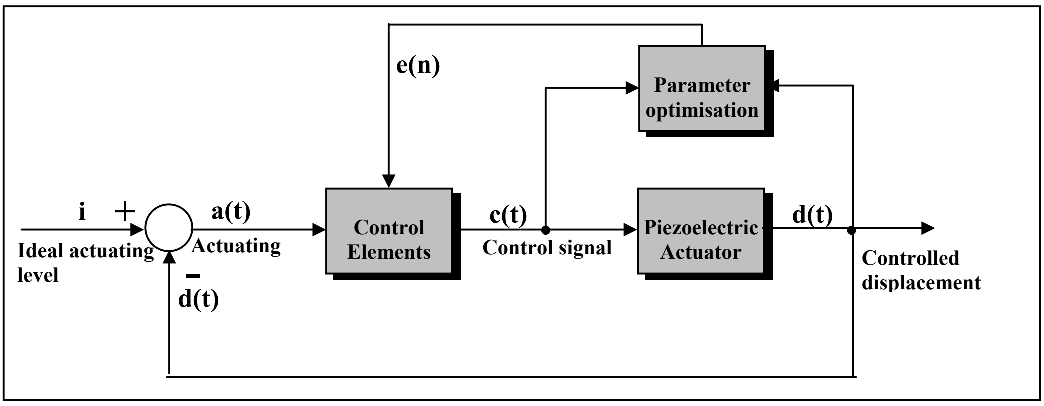


Figure 4 - Block diagram of an adaptive micropump control system

Most, if not all, of the signal processing is included in the Parameter optimisation block, passing only the error signal *e(t)* to the control elements block where the appropriate elements are modified and output to the piezoelectric actuator block fully optimised.

(iv) Fully integrated system

Figure 5 is a schematic of how a complete and fully integrated micropump feedback closed-loop system would physically appear, as derived from the preliminary investigation using the experimentation and methodology outline in the preceding sections.

The interferometer section will be constructed using inorganic polymer glass, miniaturised using specialised techniques and linked using fibre optic tubing appropriately attenuated to meet the required specifications. The optics will be sealed and isolated in an epoxy resin with a high temperature coefficient to minimise low frequency drifts. The sensing electronics (photo detectors) will be included as a separate layer, based on hybrid technology and linked to the controlling electronics through a number of optically isolated channels to minimise noise. The sensing, controlling and actuating elements are split across three different planes, each configured as a layer encapsulated within its own epoxy resin.

The actuating electronics will be isolated to greater than 2 kV from other layers as the PZT driver produces a pulse ≥ 400 V dc. A power cell (single lithium) is sealed and located away from the high voltage inverter transformer and is only enabled during pumping. The size of a complete feedback closed-loop system, including the micropump should be no larger than L70mm x W40mm x H25mm in the first release of the integrated prototype.

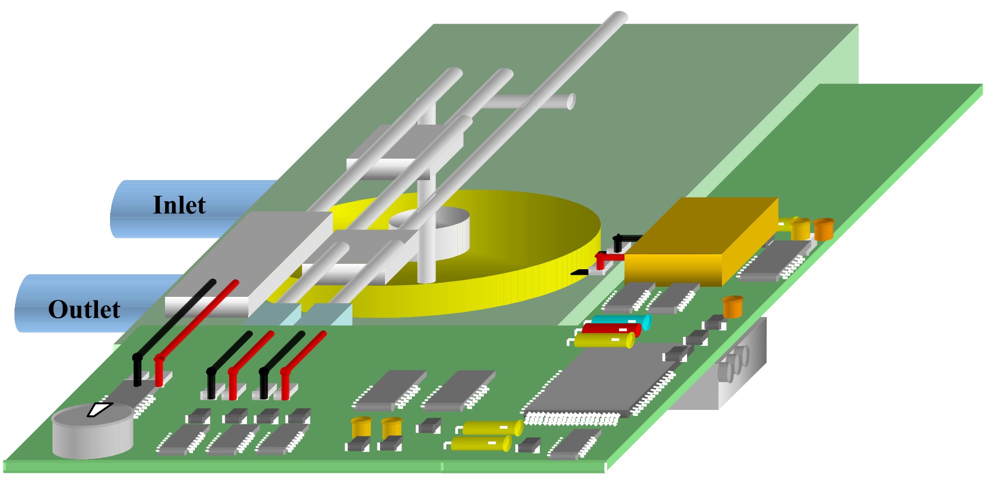


Figure 5- Integrated micropump system utilizing an adaptive closed loop feedback control

5. Results and Discussions

For the purpose of calibration and verification of the electronics described in the methods section, the initial tests were performed using piezoelectric buzzer (audio transducer, driven by a sine-wave of varying frequency. Figure 6 represents a plot of data derived from a single transition of a sinusoid with a frequency of ***10 Hz***.

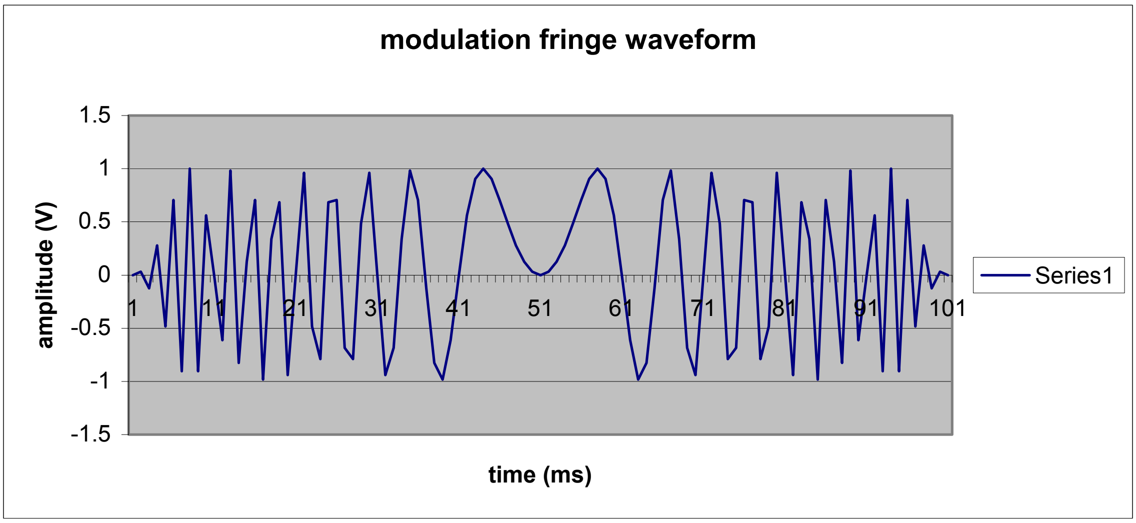


Figure 6 - Typical fringe pattern for displacement

By differentiating across the generated fringes and extrapolating the maximum and minimum points (Figure 7), we can plot the rate of increase ***dV*** with respect to ***t***, where ***dV/dt*** is the differential coefficient of amplitude ***V*** with respect to ***t***. The turning points were determined using the $dV/dt = 0 = \tan\ \theta$, and the subsequent frequency interpolated from the distribution of minimum and maximum peaks.

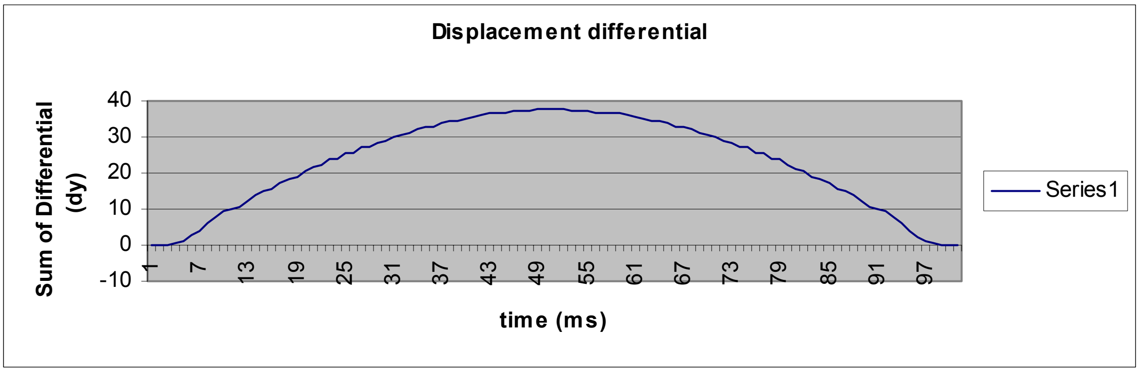


Figure 7 - Sum of differentials |dv/dt|

The displacement of the diaphragm is measured by the number of fringes multiplied by the wavelength of the source (Figure 8). During the positive transition of the applied PZT potential, a sudden change in frequency is used as a trigger point for the initialisation of the displacement signal-processing (DSP) algorithm.

The DSP algorithm is averaged over a number of samples to filter out the high frequency noise modulated by the fringe coefficients. The averaging distribution factor is determined from the amplitude of noise carried by the fringe sinusoids. This is an adaptive function calibrated during the manufacturing process that can vary within a predetermined parameterised coefficients range (FIR filter taps).

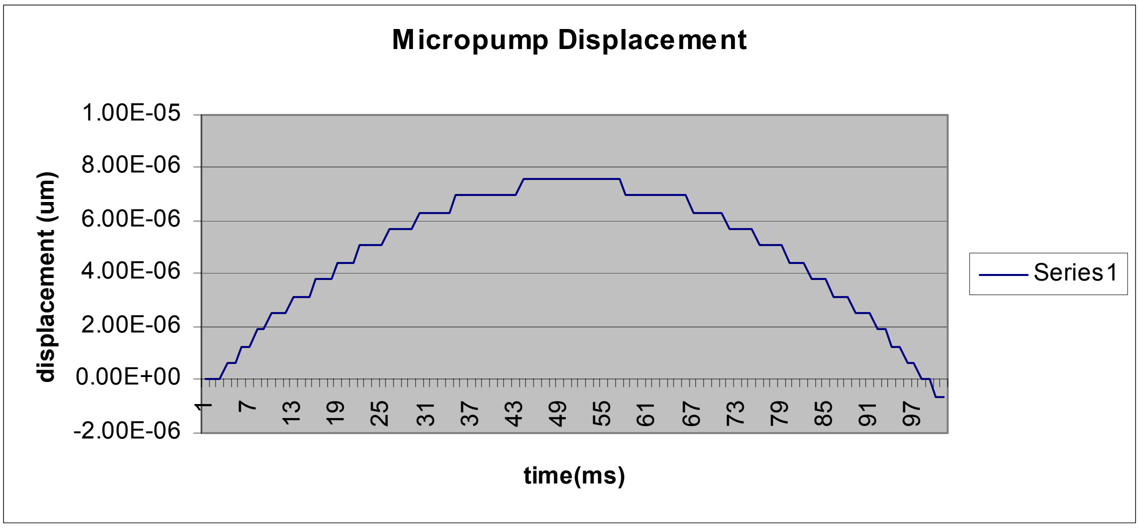


Figure 8 - Micropump displacement based on the 632.8 nm modulation fringes

Figure 8 represents a positive excitation fringe pattern for the displacement of the micropump diaphragm when pumping water. Note the low frequency preceding the high frequency fringe sinusoids that is used as a signature for the beginning of the diaphragm displacement; it has a distinct and incomplete cycle transient function, indicating a sudden change in the diaphragm position. The difficulty is in determining the direction of the displacement since the excitation pulse generates a similar transient function for both the positive and negative transition. It is possible to modify the excitation pulse that would produce two distinct fringe transitions of differing, but fixed frequencies that can be used as trigger points indicating the direction of diaphragm movement.

Figure 9 illustrates the trigger points for the detection of the direction in which the diaphragm is moving. During the application of the actuation pulse, the positive transition slope is ramped up in two stages. The first stage ramp is inclined at an angle ($0 < \theta \leq 5°$) that produces fringe modulation equal to ***Asin ωt,*** while the second ramp completes the actuation pulse at a much greater angle ($80° \leq \theta < 90°$). The negative transition slope is also ramped down in two stages, where the first is inclined at an angle equal to twice the positive transition slope first ramp that will produce fringe modulations equal to ***Asin 2ωt,*** and the second equal to ($90° < \theta \leq 100°$).

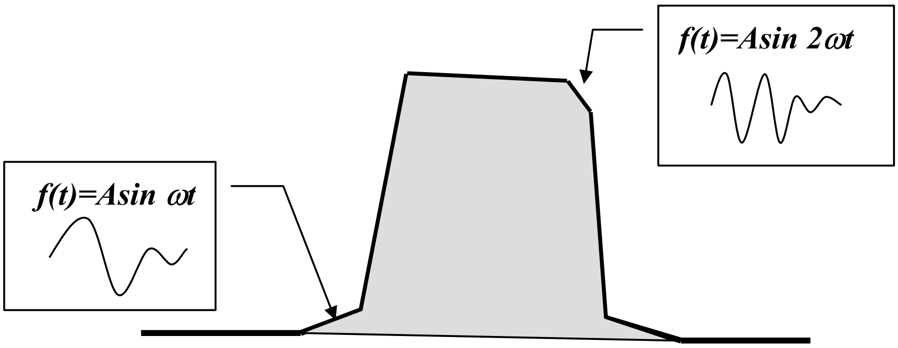


Figure 9 - PZT actuation pulse with direction synchronisation slopes

It was shown that the elements controlling the actuation slope parameters must be dynamically configurable in order to limit the bandwidth within acceptable boundaries for optimum amplifier performance. The boundary limitations are pre-programmed into the coefficient tables and used adaptively for characterisation of the displacement under different pumping fluids of varying viscosity. Ultimately, the bandwidth limitations may result in lower ramping rates and subsequently lower pumping rates, but a fundamentally more stable and accurate pumping medium.

6. Conclusion

In summary, the objective of this research is to identify and parameterise the steady-state dynamic variables during the displacement measurement of the piezoelectric actuator, using a fibre optic interferometer. It is intended for the parameterised evoked potentials (elicited by the fibre optic interferometer) to be sampled, accumulated and processed, identifying control elements that may be applied in an adaptive closed-loop environment.

For the purpose of this research, a fully functional and experimentally optimised electronic modules have been developed incorporating high bandwidth photo-detector amplifiers, high speed analog to digital converters, digital signal processing unit and a high voltage inverter for feedback control of the piezoelectric membrane actuator.

It is conceivable that all of the digital signal processing elements may be implemented in a single, system on a programmable chip device (SOPC), such as the complex programmable logic device (CPLD), most commonly known as the field programmable logic array (FPGA). This would allow for dynamic re-programmability implementation on demand, beneficial for applications requiring control logic (functional) changes without having to modify the physical layout or structure of the system.

It was demonstrated by this research that it is possible to produce an adaptive closed-loop system model based on the characterisation of a micropump using a fibre optic interferometer. This phase may be considered as proof of concept that opened a path towards total system integration for a micropump.

7. Acknowledgements

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