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A Sperm-Based Autonomous Micro-Robot: First Step

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Abstract: The weakness of sperm motility arouses the interest of many researchers due to its effect on the success of fertilization cases in couples. In recent years, this has led to the emergence of new technologies such as controllable micro-motor systems which still under evolution. The previous works that concerned with the design of micro-motors in assisting of sperm for moving or change their direction, were not autonomous-based systems. Further, it is worth noting, designing an autonomous micro-robot that emulates sperm in size and behavior is a difficult challenge. Therefore, this paper presents the first step in designing this micro-robot, by drawing the physical structure of micro-robot based on figuring the biological structure of sperm and its behavior to complete the fertilization process. While the main objective is to design a Micro-actuator system, based on the piezoelectric technique for generating a forward thrust force of the micro-robot. The simulation of the proposed design has been conducted by the Solidworks platform and MATLAB, to examine the performance of the micro-actuator system, in which the results describe the requirement for achieving an actuation system.

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Keywords: Micro-Robot, Sperm, Piezoelectric Actuators, Micro-actuator, Fertilization Process.

1. INTRODUCTION

Recently, the studies conducted by fertility specialists and documented by the World Health Organization have proven that men have a bad quality of semen are unable to succeed in the reproductive process even in the case of frequent sex for long period. During these decades, the specialists highlight the decreases in semen quality in males Miyamoto et al. (2012). Several studies provided evidence that the reduction of the number of sperms in semen, the number of healthy sperm, and the ratio of sperm motility due to deforming is continued Feki et al. (2009). If the movement (motility) or shape (morphology) of the sperm is abnormal, the sperm may not be able to reach and penetrate the female egg to inject DNA into it. Artificial fertilization methods such as vitro fertilization and artificial insemination consider as a solution for the problem of infertility in men. It is worth noting, the fact that these methods do not solve all the problems of fertilization failure, in addition to its low success rate. One successful fertilization process may take several times of attempts, while these processes are stressful and costly for couples. Moreover, the problems of deformities of sperm and the weak motility of sperm are affecting artificial fertilization processes too Henkel et al. (2005).

Recently, there has been a quantum leap in the evolution of nanoscience led to the emergence of new fields for the manufacture of nano-motors and micro-robots that emulating the size of cells within organisms. These motors and robots face many challenges to achieve locomotion in the environment inside organisms. These challenges are the high density of the medium, viscosity, and the presence of obstacles. Besides, the physical components of the motor or robot must be assembled within a small size commensurate with the application like achieving locomotion tasks Guix et al. (2014), Hogg (2014), Williams et al. (2014).

Some fabrication techniques have been demonstrated for small robots in fluids like those that micro-machines based on magnetic fields Guix et al. (2014) or based on changing the chemicals in the machine's environment Guix et al. (2014), Hogg (2014), or Nano-biosystem by bold experiments to control cells as biorobots Williams et al. (2014). In Medina-Sánchez et al. (2016), researchers have invented a micro-motor that can enhance the ability of sperm to swim which improves man's fertility. The micro-robot is a small metal spiral that its size enough to cover the tail of the sperm. Using a rotating magnetic field, the metal spiral is used as a motor to drive the sperm to the egg. The sperm can then fertilize the egg, and the micro-motor can simply slip off the sperm. In Magdanz et al. (2013), a micro-bio-robot has been proposed which includes a microtube used as a micro-motor which is driven and controlled by external magnetic fields. Khalil et al. (2018) have proposed a micro-robot known as soft robotic sperm includes a head made from magnetic material and an ultra-thin flexible flagellum. In these micro-motors, the motion control achieved from outside of the sperm environment (outside of a woman's body) by magnetic fields, so there is no autonomous locomotion achieved by micro-motors. Also, this micro-motors helps sperm to move or redirect its motion, while the problem of poor fertilization may be due to the biological deformation of the sperm.

Micro-organisms can be considered as a source for inspiration to design and implementation of micro-robots, and many research is dealing with the design of robots and mini-robots based on swimming animals or crustaceans. Also, some of these researches deal with the design and implementation of

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robots and mini-robots that swimming in the water and rely on piezoelectric technology Rashid et al. (2016), but these robots have not emulated the size and behavior of sperm and swim in a liquid such as semen.

In this paper, a sperm-based autonomous micro-robot has been proposed which a physical structure of proposed has been drawn. While the main objective of this paper is concerned with the proposed piezoelectric actuator which is used to generating thrust force for the micro-robot. The performance evaluation has been performed for the proposed actuator. Solidworks platform and MATLAB are employed for simulating the proposed system to validate the ability of micro-actuator to generating forward motion.

2. MICRO-ROBOT DESIGN

Sperm is the male reproductive cell and is derived from the Greek word (σπέρμα) Sperma (meaning "seed"). Sperm cells cannot be divided and have a limited life span, but after fusion with egg cells during fertilization, a new organism begins developing, starting as a totipotent zygote. The human sperm cell is haploid so that its 23 chromosomes can join the 23 chromosomes of the female egg to form a diploid cell. In humans, sperm develops in the testicles and is released from the penis. A mature human sperm cell has a snake-like structure, which its length is 55 µm while the width is 10 µm as shown in Fig. 1-a, which, has the following parts Gaffney et al. (2011).

Head: It is spherical consisting of a large nucleus and a dome-shaped acrosome present on the nucleus. The nucleus contains genetic information and half numbers of chromosomes. The acrosome releases a hyaluronidase enzyme, which destroys the hyaluronic acid of the ovum and enters into the ovum.

Mid piece: It is a tubular structure, in which mitochondria are spirally arranged. The middle piece is called the powerhouse of sperm because it gives energy to the sperm to swim in the female genital tract.

Tail: It arises from the middle piece and it is the end part of the sperm as shown in Fig. 1-a. It contains axial filaments. The tail helps the sperm to swim in the female genital tract. It is the main part of sperm to move.

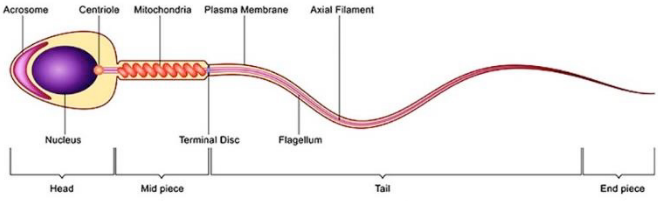
The proposed micro-robot structure is shown in Fig. 1-b. The design is inspired by the real structure of the physical sperm, in which the micro-robot includes three main parts as follows:

Head: It must contain the biological features of the natural sperm head and should be able to destroy the hyaluronic acid of the ovum and enters into the ovum to perform fertility (see Fig. 1-b).

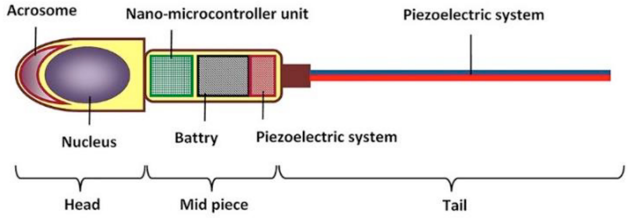
Mid piece: As mentioned above in real sperm, the middle piece is called the powerhouse of sperm because it gives energy to the sperm to swim in the female genital tract. In the proposed design, this part will be the central controller unit, which contains a nano-microcontroller unit and power supply as shown in Fig. 1-b.

Tail: This part compound by a piezoelectric system to generate forward thrust force for the micro-robot swimming process.

The designing and implementing a micro-robot like precise sperm and can carry out sperm tasks to perform the fertilization process is a huge challenge and cannot be accomplished in one go. To overcome the challenges of achieving this micro-robot, the researching task will be divided into three parts, according to the proposed design of the robot (head, mid piece, and tail). Each part will be presented for a series of research in various disciplines as future works to overcome the difficulties of designing the internal structure of each part and carrying out functions with high performance. In this paper, the micro-piezoelectric actuator will be proposed for micro-robot to achieve the function of the sperm tail that is concerned with generating thrust force.



a. Human sperm cell



b. Micro-robot sperm cell

Figure 1. Sperm cell structure.

2.1 Flagellum of the human sperm

Natural reproduction depends on sperm motion; which sperm must move for thousands of its body lengths in the complex female reproductive path to reach the ovum Gaffney et al. (2011). During this journey, the behavior of sperm takes several motility modes (motile, non-motile, or hyper-activated) and motion patterns (typical, helical, hyper-helical, hyper-activated, or chiral ribbons) Su et al. (2012). Sperm used flagellum to generate these swimming patterns while the path of the female reproductive tract represented by geometrical, physiological, chemical, and rheological stimuli Zabeo et al. (2019).

The sperm flagellum is motile as a waveform due to molecular motors, this leading to sperm swimming in semen. The flagellum is divided into two parts; the first part is the passive element, in which the flagellum is connected to the head. Although this part has very little motion and difficult to notice, however, it is considered responsible for the start of the movement, in addition to the bending direction of sperm flagellum. The second part is the active element, in which the active force is generated along the flagellum not only in the connection point with the head. This active force arises from outer and inner flagellum dynein motors Gaffney et al. (2011).

In literature, the microorganisms such as sperm are live in low Reynolds number fluidic regime, for example, the Re<<1. Due to the resistivity in low Reynolds number flow (e.g. Stokes flow). The efficacy of swimming microorganisms in nature differs from those of the biggest size such as fish. The microorganism swimming mechanism such as sperm, creates a traveling wave, propagating in the reverse direction of the microorganism locomotion. So, the optimal swimming mechanism for a microsystem is flagellum swimming by creating a planar or helical traveling wave in an elastic tail Zabeo et al. (2019). Therefore, a piezoelectric actuator based on a flapping mechanism will be proposed to generating thrust force for the micro-robot.

Furthermore, sperm activity is affected by the viscosity of semen due to the reduction velocity in the region of high viscosity. The natural value of viscosity is 20 mPa.s, at this value, the Sperm swim at the normal velocity represented by 60 ± 10% µm/s. In the cases of the region with high viscosity, the velocity must be decreased to compensate for the thrust force while at low viscosity the velocity unchanged to avoid uncertainty in the system behavior. If the viscosity of semen increased to more than 100 (>= 100 mPa.s) then the Sperm velocity must reduce to less than 5 µm/s (<=5 µm/s) Owen et al. (2005).

2.2 Dynamics of micro-robot

In general, the motion of micro-robots is under dominate of inertia and viscous force. For moving a micro-robot has length *L* and motion velocity *v*, the Reynolds number *Re* is defined as

$$Re = \frac{Inertia}{Viscous\ force} = \frac{\rho v L}{\mu} \tag{1}$$

where ρ, and μ, are the density, and dynamic viscosity of the medium, respectively Naser et al. (2019a), Naser et al. (2019b).

The dynamic model of micro-robot can be described by Newton's second law equation that the forward force *F* acting upon a micro-robot equal the derivative of its momentum to the time t. If the mass m of the micro-robot is constant, the equation is as follow

$$m\frac{dv}{dt} = F \tag{2}$$

where *v* denotes the velocity of the micro-robot. Here, the forward force is the different outcome of the thrust force F_{th} and drag force F_d. Equation (2) is described as Naser et al. (2021)

$$m\frac{dv}{dt} = F_{th} - F_d \tag{3}$$

Concerning the proposed design of micro-robot that shown in Fig. 1-b, the head can be considered as a spherical object has a diameter of D_h, So the drag force is defined as

$$F_d = C_D(0.5\rho v^2)(0.25\pi D_h^2) \tag{4}$$

where C_D is the drag coefficient, which is a function of the Reynolds number Naser et al. (2020). The relationship between C_D and *Re* for a micro-robot can be experimentally approximated by Schlichting (1955)

$$C_D = \frac{24}{Re} \quad Re < 1, Stokes\ flow \tag{5}$$

Due to micro-robot has very low Reynolds number (see Fig. 2), the drag force is evaluated from (1), (4), and (5) as follows:

$$F_d = 3\pi\mu D_h v\ (Stokes\ law) \tag{6}$$

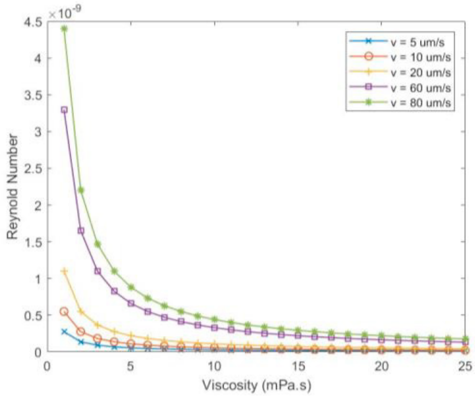


Figure 2. Reynold number vs viscosity for different values of motion velocity.

Now, the dynamic model of micro-robot can be express as

$$m\frac{dv}{dt} = F_{th} - 3\pi\mu D_h v \tag{7}$$

In the case of constant thrust force, the solution of the differential equation can be evaluated for a finite change in velocity from v_o at $t = 0$ to v_F at an arbitrary time *t*

$$v(t) = (v_o - v_F)e^{-\frac{t}{\tau}} + v_F \tag{8}$$

The velocity v_F can be evaluated as

$$v_F = \frac{F_{th}}{3\pi\mu D_h} \tag{9}$$

and the relaxation time τ is

$$\tau = \frac{m}{3\pi\mu D_h} = \frac{\frac{\pi}{6}D_h^3\rho_h}{3\pi\mu D_h} = \frac{D_h^2\rho_h}{18\mu} \tag{10}$$

where ρ_h is the density of the micro-robot head.

The expended power by the flagellum has been evaluated, which is the power that used to overcoming viscous forces plus the elastic deformation power. The power vs the viscous force is evaluated to validate the increased viscosity effectuate. So, the expended power expressed as Machin (1958)

$$P_e = 0.5LC_D\mu(Aw)^2 \tag{11}$$

For Reynolds (*Re*<<1) the expended power is written as

$$P_e = \frac{12}{\rho v}(\mu A w)^2 \tag{12}$$

where *A* is the amplitude of the flagellum wave, and *w* is the angular velocity of flagellum.

Unlike available regular size motors, a micro-robot should have good performance concerning the viscous drag overcomes inertia condition, i.e., Reynolds numbers (*Re* << 1).

2.3 Piezoelectric actuator of micro-robot

The motion of micro-robot like sperm mainly depends on the micro-actuator represented by a piezoelectric system that produces nano-position movement. The control system of piezoelectric actuators is a hot topic in recent years due to the nonlinear behavior of piezoelectric, which can reduce the accuracy of the manipulation, even causing the instability of the whole system. The mathematical modeling and control approaches have been used to solve the problem of the nonlinear response of the piezoelectric actuator Uchino (2003).

The ability of piezoelectric materials for the reversing the process in the form of direct effects such as the conversion of electric potential to mechanical strain, in which the most typical use of piezoelectric materials by bending mode through the utilization of the ‘‘31-mode’’ with uniform electrodes as shown in Fig. 3. So, 31-mode in bending is widely studied for the dynamic actuation for decades Leadenham et al. (2015). The macro-fiber composite (MFC) technology has been developed by researchers at the NASA Langley Research Center High et al. (2003). The MFC technology is superior over monolithic piezoelectric by increasing the flexibility, improved actuation authority, and anisotropic behavior. The advantages of MFC led to many applications including vibration control Browning et al. (2009), bio-inspired locomotion Cen et al. (2013), flapping-wing structures Bilgen et al. (2020), and in-air/underwater dynamic actuation Cha et al. (2016). Furthermore, the bimorph characteristics includes of multiple piezoelectric and flexible plates compounded together for a large bending equal to several hundred of µm, and relatively low response time in ms Uchino (2003).

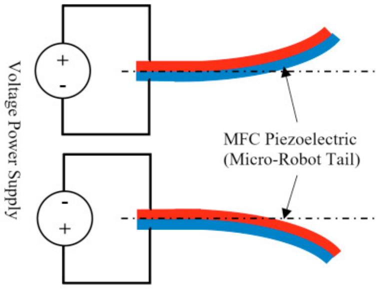


Figure 3. Micro-actuator based on MFC piezoelectric.

There are five important parameters determine the properties of piezoelectric, which are Strain Constant, Voltage Constant, Electromechanical Coupling Factor, Mechanical Quality Factor, and Acoustic Impedance for more information about these parameters can be found in Rashid et al. (2020), Ikeda, (1984).

3. SIMULATION OF PROPOSED MICRO-ROBOT

In this paper, MATLAB has been used to simulate the proposed micro-robot within the environment that seems similar to the man's semen with respect to density and viscosity. In the first step, the response of the tail actuator will be studied, in addition, the thrust force and expended power of the micro-actuator will be evaluated. Further, the motion of the micro-robot model will be studied by the Solidworks platform for different frequencies of tail flapping. Therefore, a basin has been designed with micro dimensions that suit this test which, its dimensions are (40 um x 100 um x 40 um), while the properties of the liquid are (density is 1 g/ml, viscosity is 5 mPa.s – 100 mPa.s) Owen et al. (2005) as shown in Fig. 4.

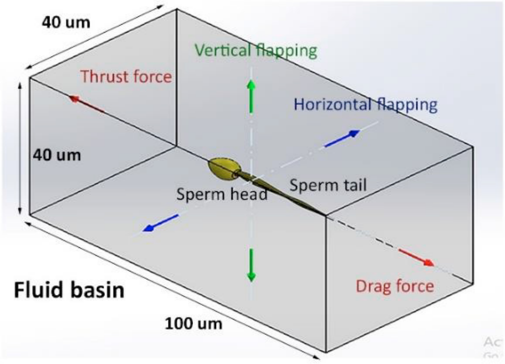


Figure 4. The micro-robot environment.

Figure 5 shows the output response of micro-actuator for several values of viscosity in order to observe the effects of viscosity on the micro-robot velocity, in which the velocity of micro-robot decreased with increasing values of viscosity. So, the micro-actuator must overcome the reduction of the velocity during the motion of the micro-robot inside the environment has dynamic viscosity such as semen Owen et al. (2005). Further, the rising time of the velocity response is increased with increasing viscosity of the semen, so, the micro-robot needs more time to achieve the steady-state value.

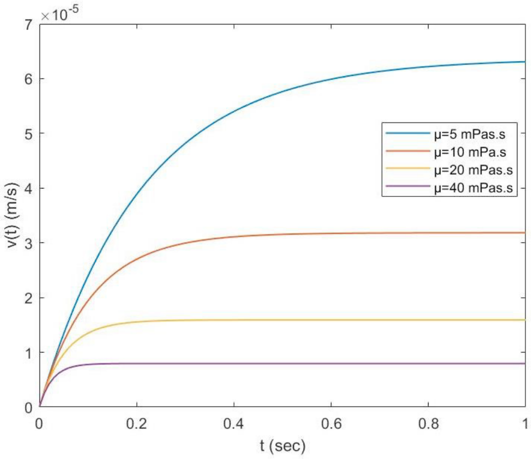


Figure 5. The micro-actuator response of velocity versus several values of viscosity.

As mentioned above, the viscosity is reducing the micro-robot velocity, therefore, to compensate this reduction in velocity, the thrust force should be increased as shown in Fig. 6. This challenge directly effecting on the expended power, in which, the frequency and amplitude of micro-actuator should be increased, in this case the expended power will be increased too as shown in Fig. 7.

The micro-robot has been simulated by Solidworks platform under liquid environment similar to semen. The frequency of micro-actuator flapping has been changed from 1 Hz to 10 Hz as shown in Fig. 8, while the results show the micro-robot velocity is increased due to increasing the value of frequency.

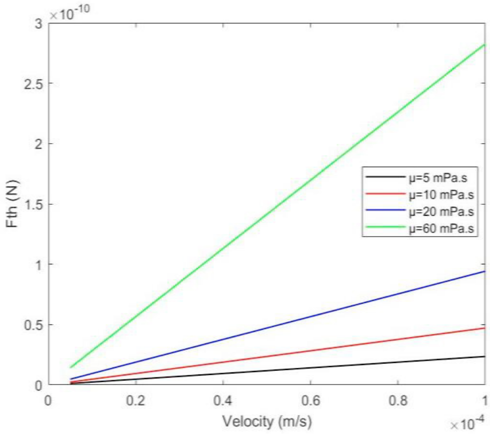


Figure 6. Thrust force vs velocity for different values of viscosity.

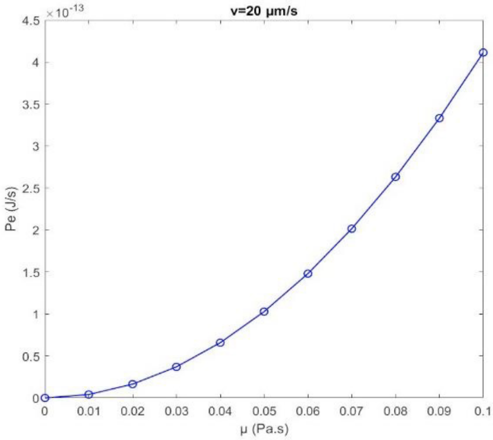


Figure 7. The expended power vs viscosity.

4. CONCLUSIONS

In this paper, a proposed design of the micro-robot prototype has been introduced, in which the micro-actuator system has been suggested and experimentally simulated to validate the success of this system. The results showed the velocity is decreased with increasing the semen viscosity, further, increasing the response rising time for arrival to the steady-state response. The thrust force has been evaluated with respect to viscosity, which the results showed, in case of increasing viscosity, the thrust force should be increased to achieve constant velocity. On the other hand, the expended power will be increased because increasing thrust force is achieved by increasing the amplitude or the frequency of the micro-actuator flapping. Further, the results of Solidworks simulation showed that the micro-robot velocity is increased with increasing frequency of tail flapping.

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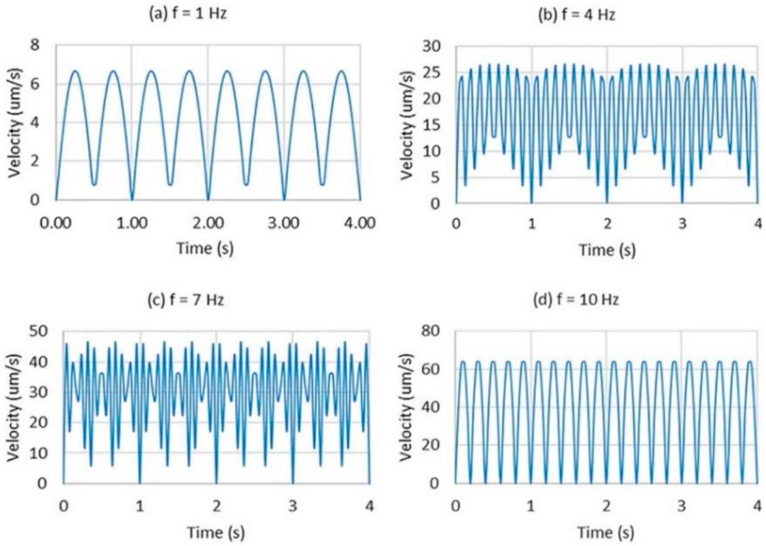

Figure 8. Micro-robot velocity with respect to tail frequency.

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