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Experimental Analysis of a Free-Swimming Water Pipe Leakage Sensor

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ABSTRACT

Every day, millions of litres of water are wasted due to leaks, water that could have been used to help the poor. Leaks must be quickly detected, located, and repaired in most circumstances because the negative impacts linked with their existence might cause major problems. Sensor networks are now widely used for leakage management as a result of recent developments in sensor technology. Researchers have now gone further to embed sensors into the pipeline itself in order to detect, locate, and quantify the size of the leak. As a result, the current article's goal is to propose a new leakage detector shape and evaluate its performance through experiments. A water pipe experiment using a high-speed camera is carried out in the experimental work. All the components of experiment setup are mounted together on the built test rig and test section of the experiment only to be tested to get stable water flow, reasonable reading of digital flowmeter, no leakage of the pipe connection and good lighting to improve the visionary quality for the data collection. Three mobility modules Design 1, Design 2 and Design 3 which were designed and numerically validated by Zaki *et al.,* [14] through his research are tested in this experiment. In order to further enhance the performance of mobility module of Design 3, a new improved design of mobility module, Design 4 is tested in the pipeline to determine the performance when simulated in real pipe conditions to identify pipeline leaking. The mobility module's performance has been improved by design optimization so that it can work in real-world pipe conditions. The basic shape remains the same as the mobility module selected in the last comparison.

1. Introduction

External pipe leaks are usually easily identified with a visual check and the use of various costly instruments. Underground pipes, on the other hand, provide a unique problem in terms of monitoring leaks, and this is where a small in-pipe sensor should come in helpful. Underground drainage caused by leaks can cause issues like building and structure damage, deterioration of building materials, soil erosion, and toxins penetrating from the leaking pipe [1].

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Non-Revenue Water is water that has been generated but has been lost before it reaches the client (NRW). As of 2014, more than 4.27 billion liters of treated water were leaking out of Malaysia's ageing pipe system on a daily basis. It's incredible to think that this much could fill more than 1,700 Olympic-sized swimming pools or meet Perlis' water needs for 53 days [2].

Worst of all, replacing just 1 km of 44000 km of asbestos-cement pipes across the country will cost RM 500,000 [3]. As a result, proper pipeline leakage management is judged to be the most practical alternative that can be implemented in the near future, even though ageing pipe replacement is required.

When water leaks from a water pipeline, it penetrates the layer above the damaged area and emerges on the ground surface. It can also be concealed and only become apparent when the water level rises in the sewer system or pipeline networks. The use of inappropriate pipes, hard contact on the pipes, ground deformations, corrosion or erosion of the inner wall of the pipes, and ageing polymer materials are all common causes of pipeline damage [4]. The aim of this paper, to report the performance of new improved design of mobility module when simulated in real pipe conditions to identify pipeline leaking.

1.1 Free Swimming Leakage Detector Device

SmartBall, a free-swimming untethered acoustic leak detection device is introduced as it has the potential to identify very small leaks and locate them to within a few feet without the need for disruption of the pipeline's operation or installation of costly equipment. SmartBall is spherical and smaller than the pipe bore allowing it to roll silently through the line and achieve the highest responsiveness to small leaks. Figure 1 shows the internal design of SmartBall which is fully sealed porous foam ball envelops a water-tight aluminium ball that is containing sensitive acoustic sensor. It is being released by a piggy trap through a flange opening and propelled by hydraulic force of minimum flow of 0.5 fps. Because the device travelled in the water column and passed directly adjacent to the leak, it clearly and distinctly identified the noise signature created by each leak [5].

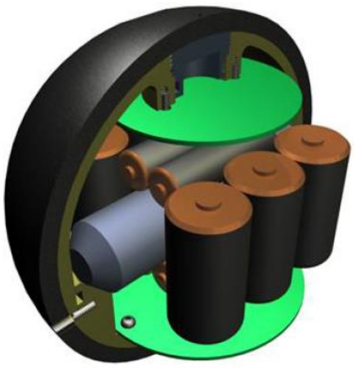

Fig. 1. SmartBall Internal View

Sahara System uses an acoustic sensor to detect water leakage in large diameter pipes with diameter over 200mm and the sensor is mounted on an umbilical cable. For smaller pipes with diameter of 100mm, swept tee or Y branch fitting is used. Leaks are detected by utilizing the GPS and can detect leaks as small as 10litres/hour. The main drawback from the Sahara System is that it is a tethered system hence it is difficult to be controlled and bounded by the maximum distance of 2000m which can be analyzed by the following Figure 2 [6].

Fig. 2. Sahara Pipeline Inspection

Figure 3 shows the PipeDiver which is another recent development in free-swimming leak detection technology. It is used specifically for critically large diameter pipe that is no longer in service but not possible to be removed due to lack of redundancy or operational constraints by the means electromagnetic signals. Meant for large concrete pipe, it can detect the loose or broken wire wraps which directly indicate that the pipe is failing. It can identify and detect all the butterfly valves and bend joints in the pipeline structures. For metallic pipes, the PipeDiver can detect area of abrasive corrosion or any defects [7].

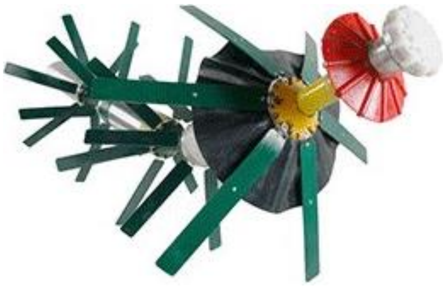

Fig. 3. PipeDiver Sensor Model

Twin Balls Technology is also one of the recent developments in free-swimming leak detection technology. It utilizes two flowing balls with different purposes those are released one after another. The first ball gives acoustic and location data from the sound and GPS sensors which are then be analysed once received by the control system to indicates the size of leak and its location. The second ball then releases to supply the healing gel to the localized leak. The detailed 3-D design on the Twin Balls sensor model is as shown in the Figure 4 [8].

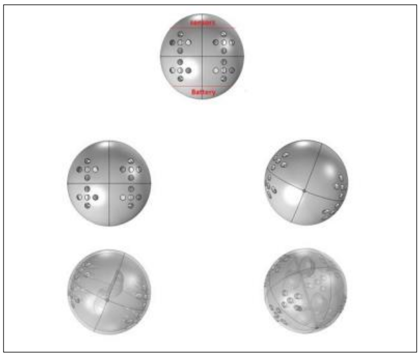

Fig. 4. 3D design of the Twin Balls

An autonomous inspection system which capable of recording exact location and status of the pipe have been designed. It is capable of measuring the relative position of the entry point and the docking station. The basis of the design is wheeled robot 'snake' with segmentation of modules as shown in Figure 5. The redundancy of modules facilitates the accommodation of payload such as the sensors and batteries. While the central module accommodates the rotation joint to control its orientation. The system utilizes a laser projecting camera which detects deformation of circular image and uses ultrasonic microphone to capture the noise from the leak [9].

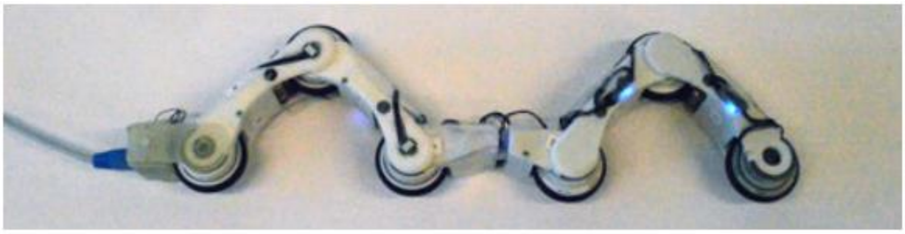

Fig. 5. Robot design with Ethernet as the tether

Evo Series 1.0 is one of the recent developments in the in-line pipeline inspection that uses the ultrasonic technologies. The Dual Diameter tool as portrayed in the Figure 6 can go up to 4m/s of inspection speed and axial resolution of 0.75mm. The inspection includes the detection of defects in the pipeline such as cracks and corrosion [10].

Fig. 6. Dual Diameter tool Evo Series 1.0

Magnetic Flux Leakage (MFL) Pigging is an autonomous leakage detection system with the inspection tool on board such as the computer, sensor, batteries and odometer. Hall sensors and coil picks up the leak signal following the magnetic flux principles. The system is suitable for a high range of inspection distance up to 500km and suitable for carbon steel pipelines with the wall thickness of range 5mm to 25mm. The configuration of the modules in the tool is as shown in the Figure 7 [11].

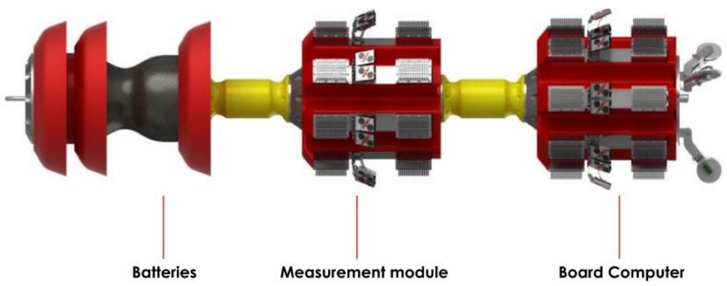

Fig. 7. Magnetic Flux Leakage (MFL) tool

Remote Field Testing (RFT) Technology has developed for pipeline assessment of pipe as narrow as 3" up to 78" where the See Snake tool functions as 'free-swimming' tool for the application of pipes under 56" and functions as tethered mode tool for the application of wider pipes. The range of inspection is 50km and the sensing system is driven by scanning which prioritizes the area for replacement. The assessment of the system includes the wall thickness measurement, graphitic corrosion, cracks and dents. Figure 8 shows the See Snake tool in the application of small diameter pipes [12].

Fig. 8. See snake tool installation

1.2 A Middle East Study of Water Piping Leakage

Water pipeline leakage can be apparent when the water enter penetrates the layer above the damaged location and emerge on the ground surface. It can also be hidden and only become noticeable when the water swells through the sewerage system or the pipeline networks. Some of the most frequently found factors of pipeline damages are the application of improper pipes, hard contact on the pipes, ground deformations, corrosion or erosion of the inner wall of the pipes and ageing polymer materials.

An example of comprehensive leakage review work has been done Al-Dhowalia *et al.,* [13]. The work was done in Saudi Arabia. The studies covered subject assessments of ten representative regions of about 0.25 km2 each. They found that the average leak rate was approximately 1977 L/km/hour (the highest was 9845 L/km/hour). Compared to different water leakages in other part of the world, the water leak at Riyadh metropolis was considered to be one of the highest. An exact evaluation of leakage was done and it was determined that there was a huge difference between new and old residential areas. The 3 oldest regions of the metropolis confirmed leakage stages among 59% and 80%; whereas, the leakage stages of newly evolved regions have been among 1% and 10%.

The exact location of the leakage has been studied also by Al-Dhowalia *et al.,* [13]. It was observed that 80% of the full detected leaks have been withinside the provider connections. It was determined that maximum of the leak factors has been positioned at residence connections because of damages and cracks withinside the connection elements which includes couplings, elbows, valves, and saddle clamps. The reasons for those damages or cracks have been attributed to the negligence of contractors at some point in the setup of pipe fittings residence connections. It was also determined that flawed bedding and backfilling have been the principal elements inflicting pipe connection damage. Improper bedding should impose extra bending on pipes, and therefore expanded the variety of stresses on pipe fittings. In addition, backfilling and bedding sand containing massive and sharp stones ended in scratching and puncturing the pipes and fittings. Furthermore, the cyclic nature of water supplies, stress fluctuations, temperature change, and repeated surges might be contributing elements to the existence of pipe fittings. In fact, many micrographs of fracture surfaces taken from one-of-a-kind failed pipe fittings have been indicative of fatigue failure.

2. Methodology

Upon starting off the experimental work, the apparatus or devices to complete the experiment such as the digital flowmeter, the pump engine, the structure of piping and the use of high-speed camera are searched and studied according to the compatibility to each other. Once the type of model for each of the apparatus and devices have been decided, it is tested and calibrated to reduce the systematic error. After finishing the essential step, all the components of experiment setup are mounted together on the built test rig and test section of the experiment only to be tested to get stable water flow, reasonable reading of digital flowmeter, no leakage of the pipe connection and good lighting to improve the visionary quality for the data collection. If these controlling variables are not achieved, the steps repeated again from square one.

2.1 Design of Experiment

The experiment set up consists of a piping system with test section of one meter clear pipe, a pump engine to speed up the water flow, a water flow meter sensor to measure the mass flow rate of the water flow in the experiment, three testing mobility modules and a high-speed camera system to capture the movement of the mobility module for the calculation of mobility module's relative speed.

The ideas of solving this problem are to build a functioning piping system, create a capsule, as a transporter and sensor to detect the leakage. The very first thing was designed the piping system roughly and came up with few designs of the piping system to make sure the flow in the system is not disturbed. After finalized the design, CAD drawing been proceeded as shown in Figure 9 and Figure 10.

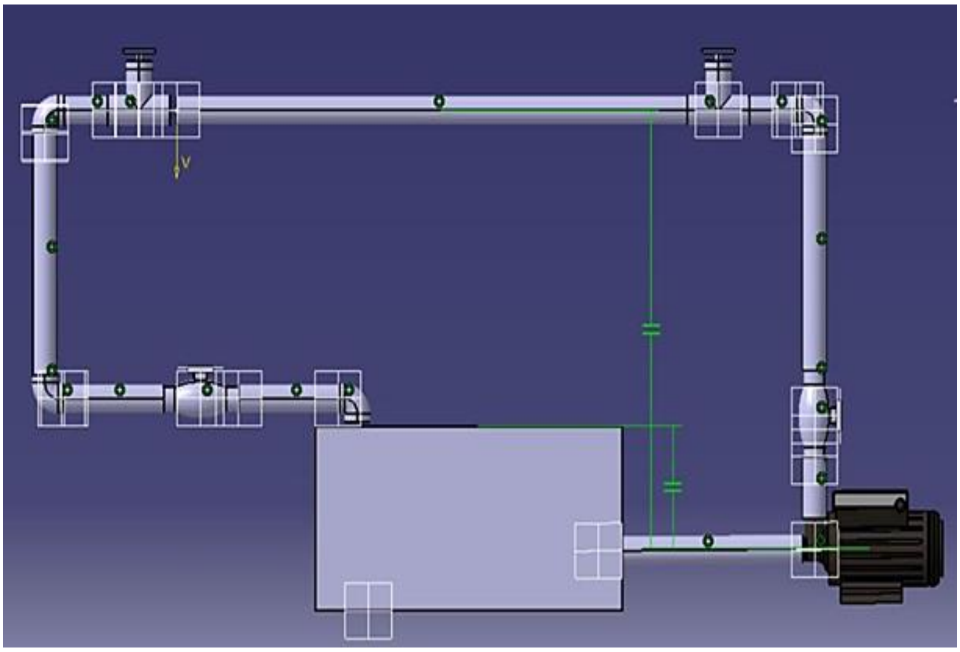

Fig. 9. Side view of the piping system design

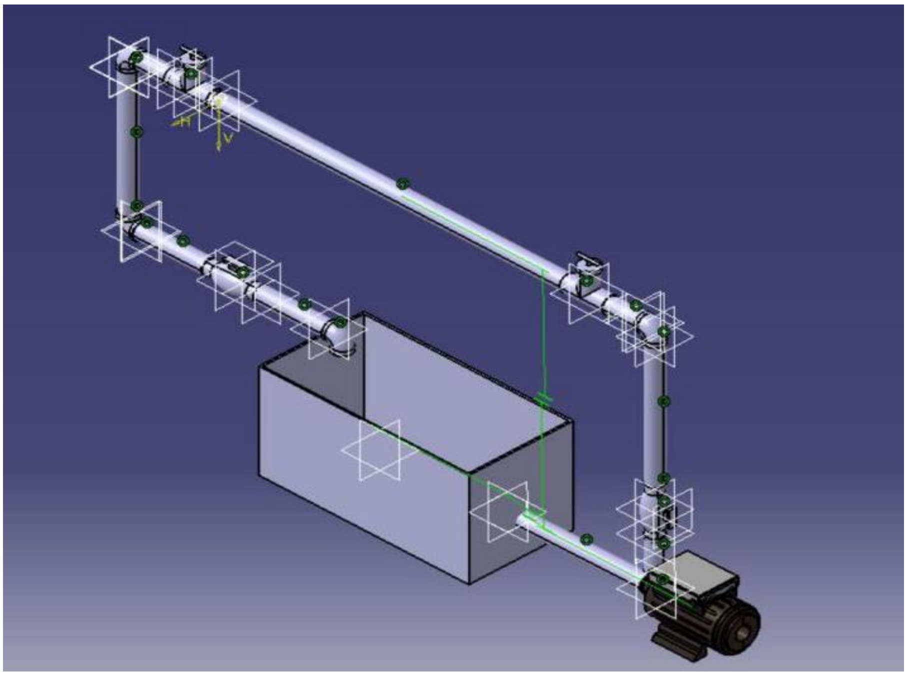

Fig. 10. Isometric view of the piping system design

2.2 Piping System and Test Section

As shown in Figure 11, the piping system structure is placed on a higher platform to let the water flow cycles. The commencing path of the water flow sucked from the reservoir is started off at the outlet of the pump engine with power supply of 1.5hp through a 50mm diameter pipe connection. The pipe is then deflected upwards by an L-joint towards a higher placed test section. A flow meter is placed at the half length of the pipe before it is connected to a 100mm diameter pipe by using a diffuser. An opening valve for mobility module insertion is connected before the test section. A test section which is a transparent acrylic pipe with the length of 2m is laid on a table with dark background for better vision observation of the experiment result. At the end of the test section, a valve for the mobility module withdrawal is placed before the pipe system proceeded with PVC-100mm pipe to be connected to the reservoir.

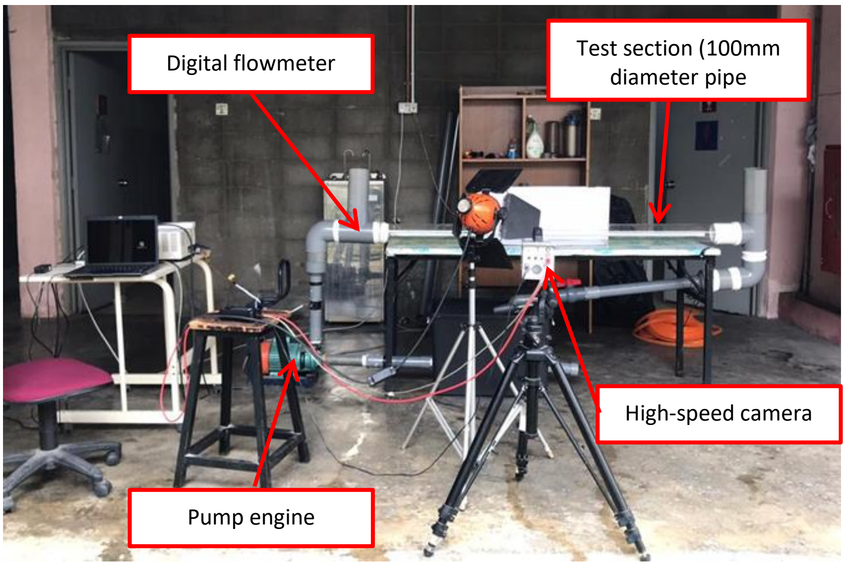

Fig. 11. The experimental setup

2.3 Water Flow Meter Sensor

Water flow meter sensor is used to measure the mass flow rate of the water flow in the piping system. Mass flow rate is an important parameter to ensure the stability of the water flow to control the variable of the experiment so that the performance of the mobility module as a result is more reliable. The actuator and the measurement display of the flowmeter is as shown in the Figure 12, while the 3D CAD of the flowmeter actuator which is turbine-driven is as shown in the Figure 13.

Fig. 12. The flow meter set

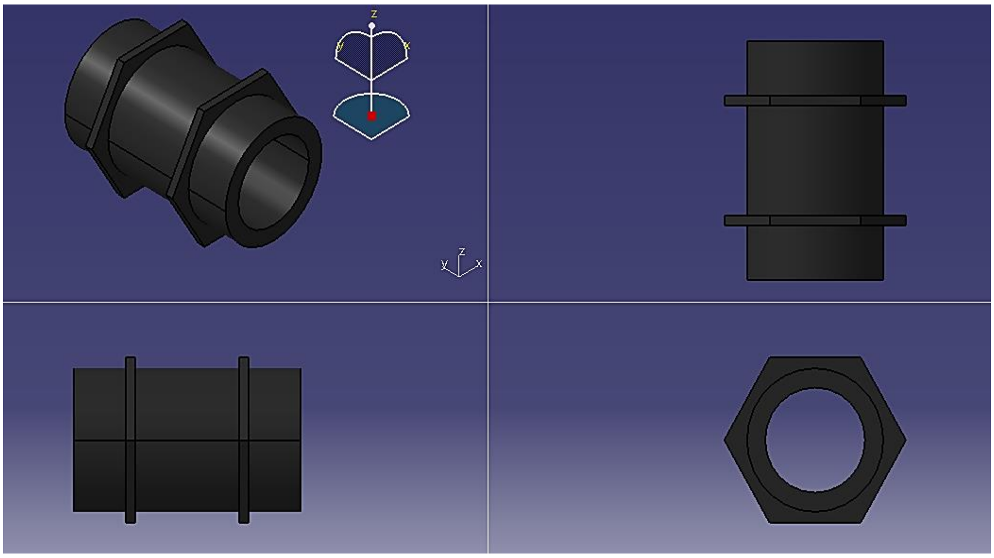

Fig. 13. CAD of flow meter sensor

2.4 High Speed Camera

To capture and record the behavior of all the three mobility modules, a high-speed camera as shown in Figure 14 is used as well as its accompanying software which called the HotShot SC to get the information of the movement of the mobility modules in terms of frames. From the software interface as shown in Figure 15, the value of frame per second of the video recording can be obtained by determining the calibration value. By pinpointing the mobility module due to its instantaneous frame to the total number of frames, the time taken for it to travel a certain distance as well as certain amount of frame can be determined hence enabling the speed calculation. The maximum framing rates is 200 000 fps and it is very sensitive to light. Hence, a spotlight is needed to enhance the lighting for better quality of the HSC video.

Fig. 14. NAC HotShot 512 Sc Digital High-Speed Video Camera

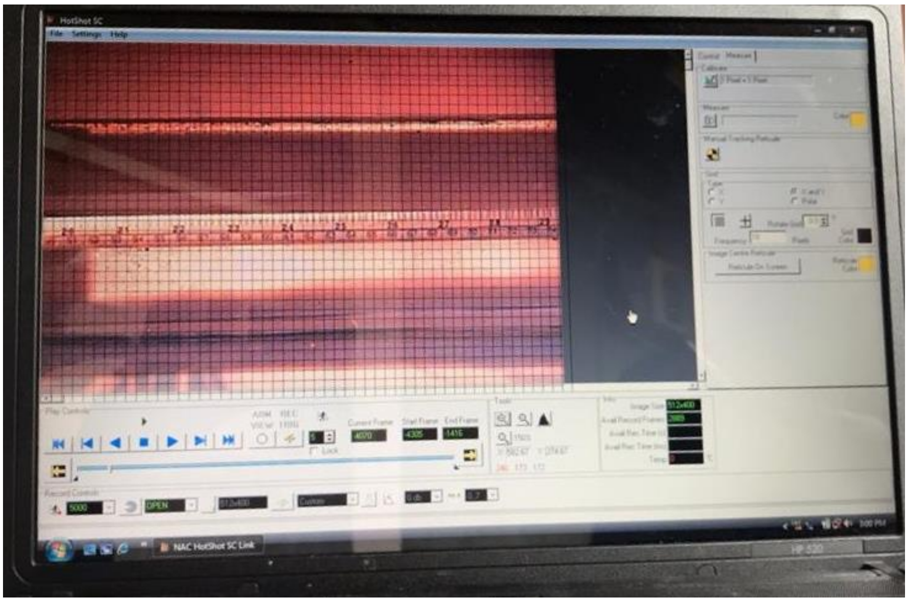

Fig. 15. The NAC HotShot SC software interface which displays the video of movement of the module in a focused section, the value of frame per second, the start frame, current frame and the end frame

The framing rates of the high-speed camera for all the experiment is set to be 5000 fps. It is the most suitable rates to capture the movement mobility modules clearly and accurately. The instantaneous number of frame where the leading point of the module reaches 20cm and 25cm is observed and recorded. The grid helps to enhance the accuracy of pinpointing the position of the mobility modules.

2.5 Calculation

Calculation of speed of water flow

Power supplied to the pump engine = V×I

where
V= 220V of nominal socket and I=5A
Torque = (60 ×Engine power)/(2π×Engine RPM)

where
Engine power=1.5hp/1100W and Engine RPM=500
Mechanical work of the pump engine = torque(τ)×angular velocity(ω)
Linear velocity of water flow = radius(R)×angular velocity(ω)

Calculation of speed of mobility module

Total number of frames travelled = frame at 20^th cm-frame at 25^th cm

Time taken for the module to travel = (total number of frame travelled)/(frame per second)

Speed of module = (distance travelled by the module)/(time taken for the module to travel)

2.6 Design Concept of the Mobility Module

The aim of this design study is to produce a shape with the following features

i. Minimum resistance within all other design constraints, thus decreasing its relative speed and increasing stability.
ii. Minimum flow noise especially over the exterior of the sensor design.
iii. A spacious interior for placing of sensing, power and data acquisition devices for a given small volume.

Table 1
Conceptual Matrix

Features	Concept 1	Concept 2	Concept 3
Material	Metal	Membrane	Plastic
Speed	Variable	Variable	Variable
Mechanism/technique	Acoustic	Transcient-based	Suction force
Location	Inside the pipeline	Inside the pipeline	Inside the pipeline
Basic shape	Sphere	Cone	Cone

Based on the conceptual matrix done prior to the design of the mobility module, the hydrodynamic characteristics of each of the mobility module can be predicted by applying some hydrodynamic investigation on the theoretical as well as by simulating the working environment of the mobility module via simulation software.

Based on the previous research which is investigating the hydrodynamics characteristics of each module in the simulation-wise, the experimental behavior of the mobility module can be predicted. From the simulation it is known that Design 3 has the most stable behavior and the smoothest flow around it. By meaning, there is less separation occurs at the boundary of the module hence the module is not going to be tumbled because of turbulence. Referring to the previous research, it is also predicted that the fins of Design 3 will keep the module stays afloat hence reducing the disturbance of the sensing system to improve the accuracy of the leak detection. The maximum speed for the mobility module when simulated in a moving water are 3.306 m/s, 2.629 m/s and 2.947 m/s relatively for Design 1, Design 2 and Design 3 relatively. The speed for each of the design is going to be validated in this research.

2.7 Mobility Modules

Three mobility modules which were designed and numerically validated by Zaki *et al.,* [14] through his research are tested in this experiment. The designs are distinguished and described to acknowledge the hydrodynamics properties of each design and flow properties of the design in the test section. Figure 16 show the top view and the front view of the ABS plastic 3D printed mobility modules. Figure 17 - 19 show the CAD of Design 1, Design 2 and Design 3 with their dimensions.

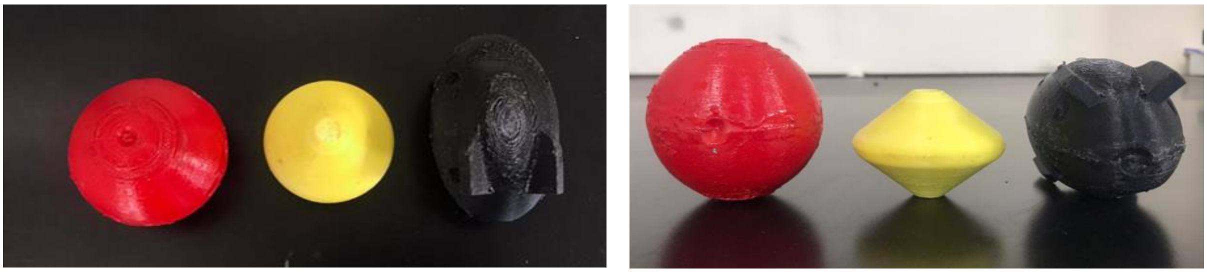

Fig. 16. Top view and front view of mobility modules

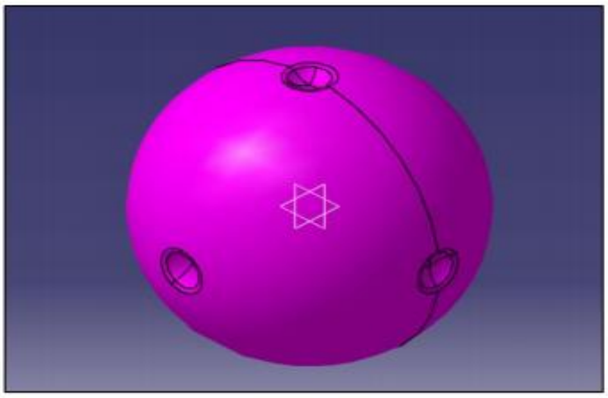

Fig. 17. CAD of Design 1 with diameter of 60mm

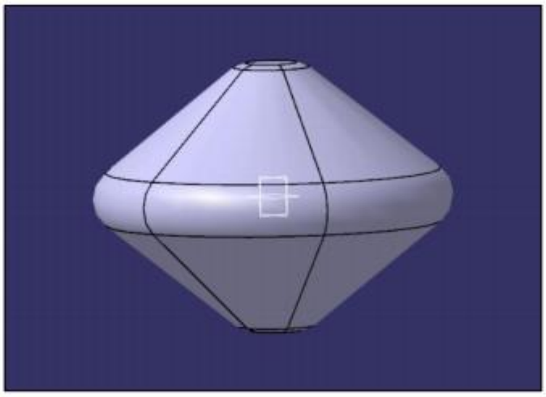

Fig. 18. CAD of Design 2 with L=60 and H=50mm

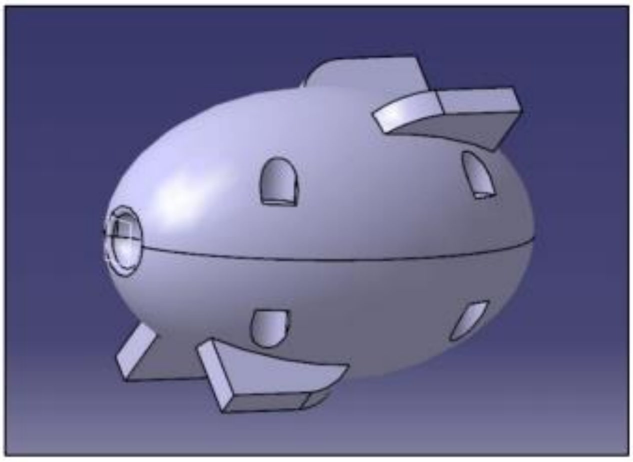

Fig. 19. CAD of Design 3 with L=80mm and H=50mm

3. Results

3.1 Improvement Design of the Mobility Module

In order to further enhance the performance of mobility module of Design 3, a new improved design of mobility module, Design 4 is tested in the pipeline to determine the performance quality in the real-life condition. Design 4 is inspired by torpedo shape which has a good stability quality when travelling in water. The performances of Design 4 are expected to be the best among the mobility modules. The speed of the new design is determined and calculated while the attitude behavior and stability are observed. Figure 20 shows the CAD of Design 4 and Figure 21 shows the 2D drawing of the new design of the mobility module.

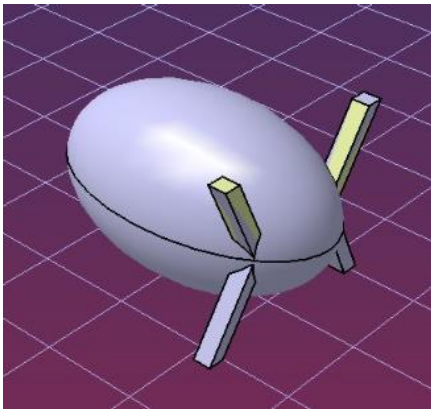

Fig. 20. CAD of Design 4 with L=80mm and H=50mm

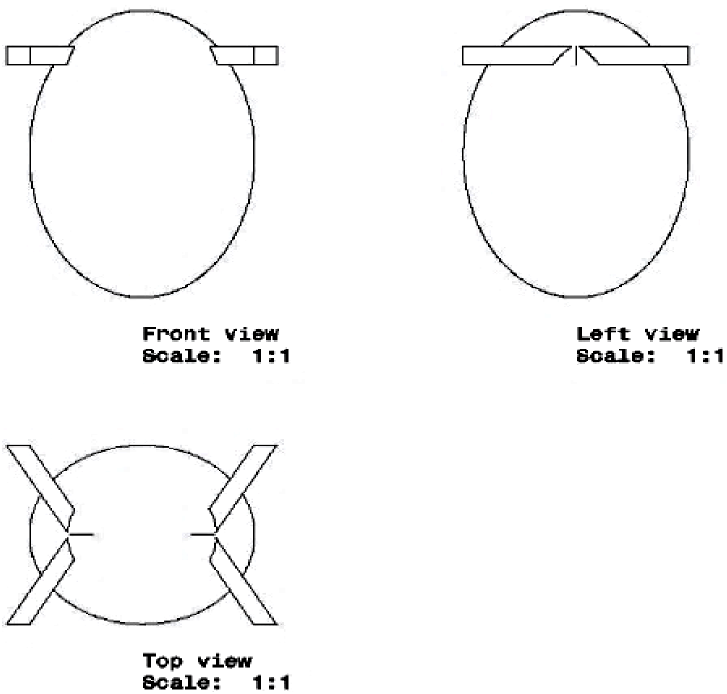

Fig. 21. 2D drawing of the new design of the mobility module

3.2 Relative Speed of Mobility Modules

Table 2 and Table 3 show the observation data of the flowmeter when the experiments were taken out. Figure 22 shows the voltage supply transformer were set at 150V. The reading of the flowmeter as shown in Figure 23 is recorded when the water has filled up the clear pipe 100% and there is no air bubbles formation. It indicates the water flow is stable corresponding to the power supply input that has been set. The average flow rate reading is calculated to increase the accuracy of the flow rate measurement.

Table 2
Tabulation of data extracted from HotShot Sc for Design 1 and Design 2

Voltage supply (V)	Design 1			Design 2		
	Flow rate (LPM)	Frame at 20th cm	Frame at 25th cm	Flow rate (LPM)	Frame at 20th cm	Frame at 25th cm
130	6.77	2596	1291	6.61	4581	3398
140	7.14	4070	2761	7.19	6476	5378
150	7.46	5140	3835	7.56	5673	4646

Table 3
Tabulation of data extracted from HotShot Sc for Design 3 and Design 4

Voltage supply (V)	Design 3			Design 4		
	Flow rate (LPM)	Frame at 20th cm	Frame at 25th cm	Flow rate (LPM)	Frame at 20th cm	Frame at 25th cm
130	6.66	5194	3943	6.68	4782	3580
140	6.97	5579	4470	7.35	6713	5512
150	7.42	6766	5694	7.76	5653	4490

The observation data collected from the high-speed camera 512 Sc through the accompanying software HotShot Sc are also shown. The software displays the video of the movement of the module taken in a 5000fps speed which is in a slow motion. The instantaneous position can be detected since the video can be paused and dragged. An accurate position can be seen in the video where as a ruler was mounted on the 1.5m clear pipe. The test section area from the position of 20cm to 25cm was fitted in the HSC type video. A reference point of each of the mobility modules was set hence is detected with the guidance of the ruler monitored in the HotShot Sc software. The position of the reference point of the mobility module is recorded when it reaches 20cm by taking its relative number of frames to its total number of frames of the whole video. The second position of the reference point of the mobility module is recorded at 25cm and once again its relative number of frames to the overall number of frames of the HSC video.

Fig. 22. Voltage supply transformer at 150V

Fig. 23. Flowmeter reading during stable flow at 150V voltage supply

Table 4 and 5 show the calculated values from the data collected which led to the value of speed of the mobility module. The time taken for the mobility module to travel in the fixed 0.05m distance can be calculated by calculating the total number of frames travelled for the fixed distance.

Table 4
Tabulation of calculated data for Design 1 and Design 2

Voltage	Design 1			Design 2		
supply (V)	Total frame	Time taken	Speed (m/s)	Total frame	Time taken	Speed (m/s)
130	1305	0.261	0.19157	1183	0.2366	0.21132
140	1309	0.2618	0.19098	1098	0.2196	0.22768
150	1305	0.261	0.19157	1027	0.2054	0.24342

Table 5
Tabulation of calculated data for Design 3 and Design 4

Voltage	Design 3			Design 4		
supply (V)	Total frame	Time taken	Speed (m/s)	Total frame	Time taken	Speed (m/s)
130	1251	0.2502	0.19984	1202	0.2404	0.20798
140	1109	0.2218	0.22543	1201	0.2402	0.20816
150	1072	0.2144	0.23321	1163	0.2326	0.21496

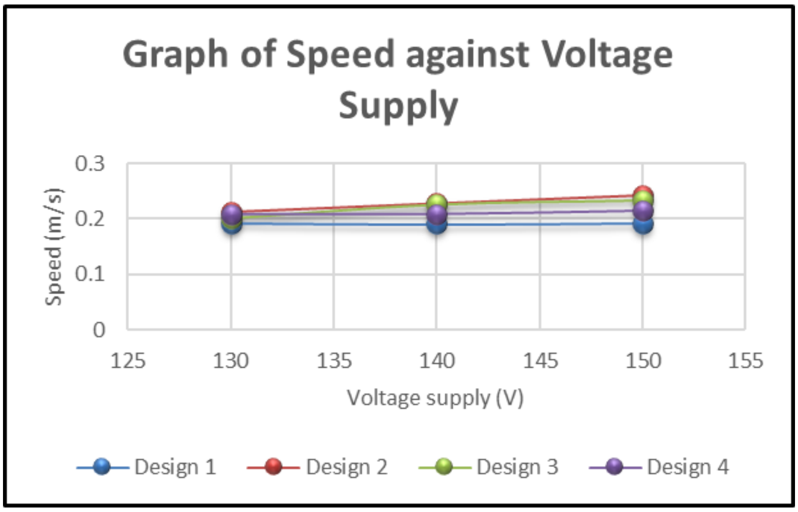

Fig. 24. Pump engine speed against voltage supply(V) of mobility modules(m/s) of Design 1, Design 2, Design 3 and Design 4

Table 6
The velocity of water according to the voltage supply

Voltage supply (V)	Power (W)	Torque (Nm)	Angular velocity (w)	Linear velocity (m/s)
130	650	21	30.95	30.95R
140	700	21	33.33	33.33R
150	750	21	35.71	35.71R

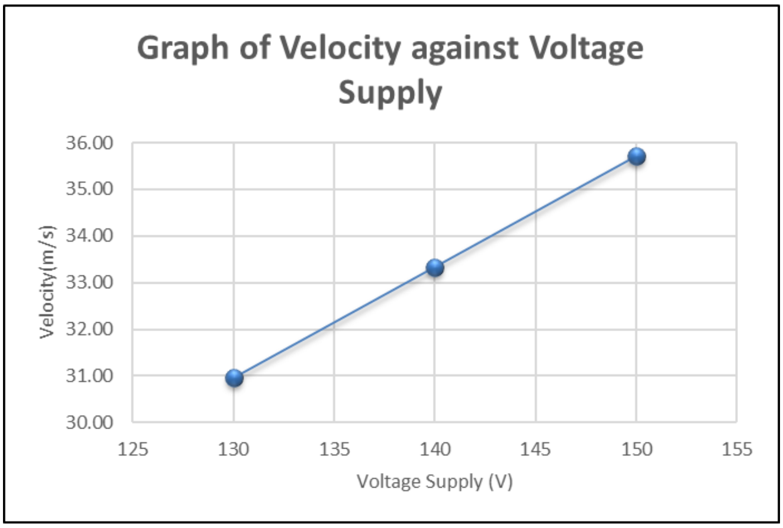

Fig. 25. Velocity against voltage supply (V) of the water flow (m/s)

It can be observed the speed of the mobility module increases with the increment of voltage supplied to the pump engine based on Figure 25. When the voltage supply is added in to the pump engine, the pump engine consumed power as the voltage multiplied with the current flowing through the connection. The more the voltage value supplied, the more power is consumed by the pump engine to produce work to the flowing medium which is water. The power generated by the pump engine is directly proportional to the linear velocity of the water in the impeller of pump engine's radius function. Hence, increasing the voltage supply of the transformer to the pump engine will increase the power consumed by the pump engine hence producing more power for a faster flow of water in the pipe system.

In comparison based on the Figure 24, it can be concluded that Design 1 has the lowest relative speed among the three-mobility module. This is because Design 1 module has the most resistance and produce the most noise to the water flow because of its blunt spherical edge. The blunt leading-edge area where is also the stagnation point of the water flow and the module experiences separation of flow hence increasing the drag to the mobility module. This occurrence will also increase the noise because of the turbulence in the flow. The presence of noise in the system is the major drawback for a clean data collection of the sensing module hence also the overall mission performance. The interior of the mobility module Design 1 is not suitable for component configuration as it is spherical-shelled. The speed of the mobility module also affects the accuracy of the detection of leakage localization and sizing because the slower the module, the more data can be collected.

After finishing the experiment runs, it is prominent that mobility module of Design 2 has the fastest relative speed to the water based on the trend shown in the Figure 24. It is because of the double-conical shape of the module which creates wakes at the center edge of the cone hence making the module unstable and wobble in the water flow. Because of the wakes, the module rotates on its own axis and glides forward along with the water flow path hence making it moves faster. It has the least resistance towards the water flow because of its sharp center edge hence also reducing the drag force on the module. The noise occurrence is taking place majorly as the wakes are created as well turbulence at the hind region of the module. The interior space of the module is limited because of the ineffective geometry when the double-cones is shelled.

Mobility module of Design 3 which has the basic shape of an ovoid and fairings mounted at the leading and trailing edge of the hull has a slower relative speed compared to Design 2 but faster than Design 1 based on the trend of curves in the Figure 24. The hydrodynamic cone elliptical edge of the module minimizes the water flow resistance on the module. There is no separation of flow occurs at the contact point of water at the leading edge of the module. The water flow flowing pass through the module is remained laminar and no turbulence occur. On top of that, least amount of noise is created around the module and laminar flow is sustained in the pipeline. The space and volume inside the ovoid-shelled module is efficiently adequate to allocate the sensor and micro-processing components for the complete mission accomplishment.

From the speed overview referring to the Figure 24, the mobility module of Design 4 is slower than the Design 3. The elongation of the appendages at the tail of the mobility module of Design 4 as compared to Design 3 explained the increase in drag hence also drop in its speed when travelling throughout the pipeline. This will advantage the sensing system of the module because it can gather as much acoustical data to be interpreted to enhance the accuracy of the sensing system. Due to the significant reduce in the speed, it caused the resistance of the module to the water flow is minimized hence the stability of the module will be increased. Flow noise over the exterior of the mobility module also will be minimized meaning that there is no formation of vortices or wakes that can cause irregularity in the stability of the mobility module. Design 4 has the same interior volume as Design 3 as the hull shape is the same which is spacious for the allocation of the microprocessor, power storage and sensing system of the Internal Flow Leakage Sensor.

3.3 Attitude and Stability of the Mobility Module

Based on the observation recorded in the Table 7, Design 1 swims unstably through the test section while maintaining its position at the top altitude of the inner pipe like shown in Figure 26. It floats its weight hence making contact with the upper wall of the pipe along the movement with the water flow. Because of the impact of contact, the module will become wobbly and shaking in the water pipe hence inducing instability such as rolling and yawing. The spherical-shelled module case has the least density considering its mass-to-volume ratio where it making the module unnecessarily spacious and less dense. Because of the design whereas only dimples allocated to increase the drag and no fairings or appendages attached to act as the attitude control, it tends to turn and roll over. This movement will bring disadvantages to the sensing and processing module of the Internal Flow Leakage Sensor as it will create complication to the algorithms of the programmed. Mobility module of Design 1 behaviors do not fit the design requirements of the mobility module because of the lack in the performance as compared to the desired performance.

Table 7
Attitude and stability of the module in the pipe during the experiment

Module	Position in the pipe	Stability
Design 1	At the top	Unstable
Design 2	At the bottom	Unstable
Design 3	In the middle	Stable
Design 4	In the middle	Stable

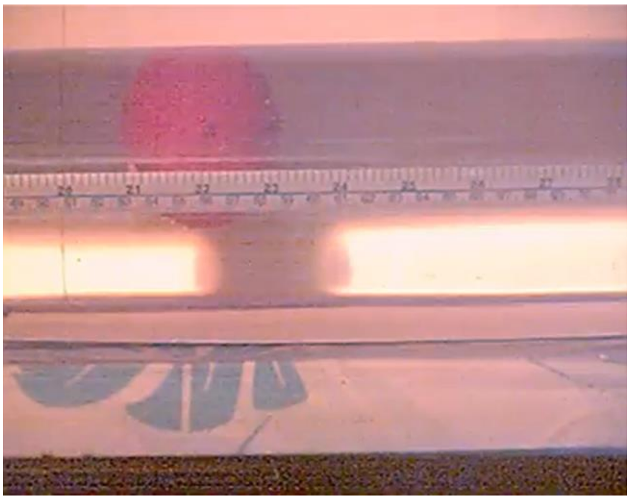

Fig. 26. The position of mobility module Design 1 in the pipe at 130V powered flow

Based on the Table 7, mobility module of Design 2 positioned at the bottom of the vertical radius of the inner pipe and is unstable in behavior throughout the test section. Because of it compacted-double coned shape, which has large mass-to-volume ratio, it resides at the bottom while moving along with the water flow in the pipeline as shown in Figure 27. The attitude behavior of mobility module of Design 2 is quite unstable due to the contact of it with the bottom wall of the pipeline. The contact occurrence between the mobility module causes impact hence making the module to vibrate and shook. This movement meanwhile induces instability when hit by the water flow hence making it turns like a bay-blade in the water pipeline. The double conical shape of the mobility module does not enhance the performance since it turns a lot when the water flow gets heavier.

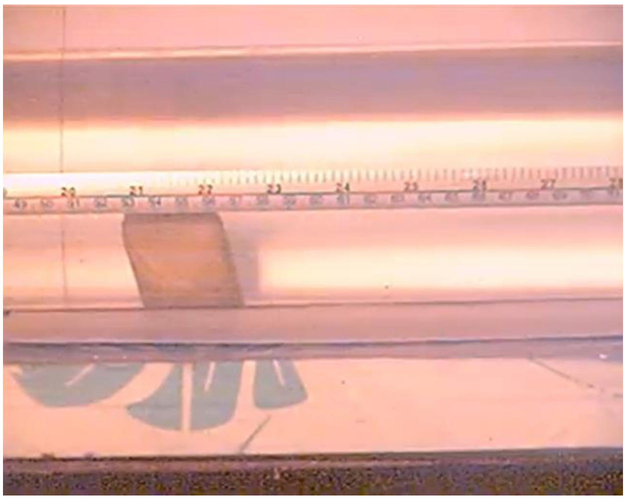

Fig. 27. The position of mobility module Design 2 in the pipe at 130V powered flow

Mobility module of Design 3 stays in between of the pipe as shown in Figure 28 while it moves throughout the pipeline and has a fair stable behavior in the pipe system. It is able to half afloat in the internal fluid flow is because of its design where it has two complimenting fairings at the opposite edges of the module hull to balance the body on its center of gravity apart from balancing its center of gravity by putting some weight in the ovoid shell of the module. Because of the absence of contact to the internal wall of the pipe that could cause unnecessary vibration to the system, it swims without undergoing rotations on its own. It is also does not turn and roll over because of the presence of fairings which act as the attitude control to restrict the module from rotating around its own axis when hit by the water flow. The mobility module does change it position in the radius of the pipe because of a slight pitching instability. Regardless, the heading of the module remains stable and consistent from point where it is released until to the point it is retrieved in the test section which is an important aspect in the sensing and processing modules of the leakage detection system.

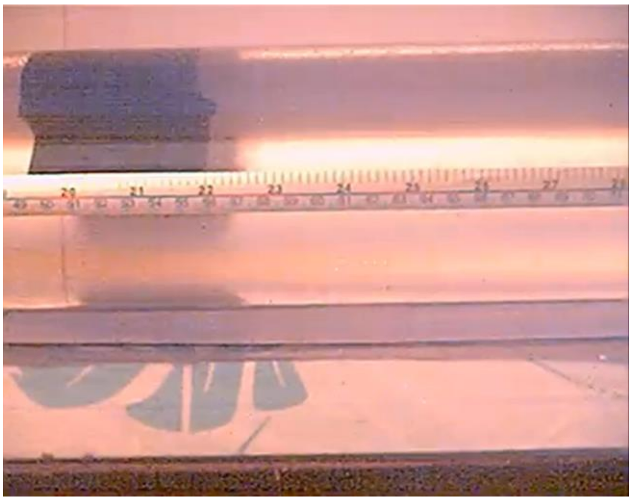

Fig. 28. The position of mobility module Design 3 in the pipe at 130V powered flow

Based on the observation from Figure 29, Design 4 also swims swiftly throughout the pipeline while floating somewhere in the middle of the pipeline diameter while maintaining its heading. It does not roll or tumble as there is no irregularity of flow around the exterior of the module such as vortices and wakes which will cause disturbance to the flow causing the module to experience some torques. While the attitude behavior replicates of Design 3, Design 4 somewhat undergoes a little instability which it is slight pitching. Design 4 module seems to lose its constant horizontal position where it is tilted up and down occasionally. The reason of this instability attitude is because of the lack of symmetry in the designation in compensation to reduce its relative speed. Though, the instability does not cause much damage hence can be ignored as the angle of variation is insignificant.

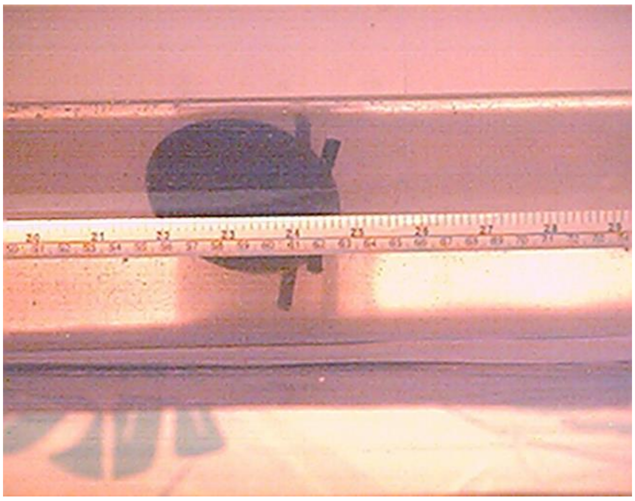

Fig. 29. The position of mobility module Design 4 in the pipe at 130V powered flow

3.4 Performance Assessment of the Mobility Module

From the morphological and Pugh matrices as in Table 8 and Table 9, mobility module of Design 4 has fitted most of the design requirement and has the most preferable performance. It is travelling with a slow speed regardless of the pump engine voltage supply hence it will be beneficial for the data processing of the leakage sensor system in the mobility modules. Design 4 also floats in between the pipe without touching the upper or lower walls of the pipe hence will reduce the noise interference in the leakage sensing system. Vibration from the contact between the mobility module and the pipe wall will create another acoustical input which will disturb the sensing system. Other than that, Design 4 also have good behavior performance and the best stability in which it does not roll, stumble or yawing but slightly pitch while moving forward along with the water flow.

Table 8
Morphological Matrix

Module	Design 1	Design 2	Design 3	Design 4
Speed	Slow	Fast	Medium	Medium
Position in the pipe	At the top	At the bottom	In the middle	In the middle
Stability	Unstable	Unstable	Stable	Stable

Table 9
Pugh Matrix

Module	Design 1	Design 2	Design 3	Design 4
Speed	+++	-	+	++
Position in the pipe	-	-	+	+
Stability	-	-	+	+

where
+ = desirable
- = undesirable

4. Summary

Following a thorough examination of water pipe leaking, it can be concluded that water pipe leakage is a major issue that persists today in every region of the globe. It is a severe issue that must be resolved or at the very least minimized in order to save millions of dollars/ringgits. The most common among the others in detecting water pipe leaking is the free moving leakage sensor. It does, however, require a significant amount of work and adjustment. One of the enhancements is the shape of the aerodynamics. This aerodynamics form is critical for ensuring the sensor's smooth and uninterrupted motion along the pipelines. Hence, the current work will focus on the aerodynamics shape of the free moving leakage sensor.

The performance of the leakage sensor is being determined in this study by experimental work proposed by earlier researchers. A water pipe experiment using a high-speed camera is carried out in the experimental work. There is no doubt that there is still a research gap in establishing the optimal design of the free moving leakage sensor. As a result, the current article will aim to close the gap.

5. Conclusions

In conclusion, the objectives of this research have been accomplished. Mobility module of Design 4 has been designed and developed base on the aerodynamics performance of the earlier design mobility module. The design hydrodynamics performance also been investigated via experimental work to validate it has a preferable performance when simulated in the real pipe condition to detect leakage in the pipeline. Post-assessment of the mobility modules, an optimized design has been created out to further improve the performance of the mobility module to be working in the real pipe condition. The basic shape is fixed as the same as the mobility module that has been chosen in the previous comparison.

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