Development of a Self-Propelled Capsule Robot for Pipeline Inspection

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***Abstract*—This paper introduces a current research project carried out in the Robert Gordon University for developing the prototype of the vibro-impact capsule robot for pipeline inspection. The project aims to address the technical bottlenecks which have been encountered by current pipeline technologies with a particular focus on oil industry. In order to verify the concept, a dummy capsule prototype with a diameter of 80 mm is designed and manufactured for testing in a 2.5 meter long section of 140 mm nominal diameter clear PVCu pipe with a flow velocity up to 0.3 m/s. By using the experimental test bed, the prototype of the capsule system can be tested at various flow rates, and the experimental results could be used for comparing with CFD simulation results for optimization.**

Keywords—Capsule robot; pipeline inspection; vibro-impact; self-propelled; prototype design

I. INTRODUCTION

The inspection and maintenance of pipelines is an ongoing challenge that many industries face, particularly in the oil and gas industry. The use of in-line intelligent pipeline inspection devices which are called "Smart Pigs" [1][2] is usually the preferred method of inspection to determine the condition of oil pipelines. A large proportion of pipelines are, however, installed in such remote and hostile environments that 'pigging' is highly challenging. The current method of "pigging" relies solely on product flow. These inspection devices are forced through a pipeline by the pressure of the product flow acting on them. However, localised environment issues within pipeline such as excessive corrosion, debris or blockage can cause product flow to reduce, thus causing modern pigging technologies failure. Moreover, the movement of these devices, such as direction and speed, is limited by the product flow which constrains inspection performance. Facilities must also exist to launch the equipment at one end of the pipeline and to receive it at the other end. Therefore, it can be seen that an inspection robot capable of self-propelled bi-directional travel in a pipeline could have great benefits in certain circumstances.

This paper sketches the ongoing research project in the Robert Gordon University for developing the prototype of the vibro-impact capsule robot [3][4][5][6] for pipeline inspection. The encapsulated mobile robots driven by autogenous internal force have been the subject of active scientific research in recent years, e.g. [7][8][9]. The virtue of such robots is that no external driving mechanism is required so that they can move independently in harsh environments. As shown in Figure 1, Liu *et al.* [3] proposed that the rectilinear motion of a system can be obtained through overcoming external resistance described as dry friction force using a periodically driven internal mass interacting with the main body of the system. A proof-of-concept experimental verification of the vibro-impact capsule system was presented by Liu *et al.* [6]. The conducted bifurcation analysis indicates that the behaviour of the system is mainly periodic and that a fine tuning of the control parameters, e.g. frequency and amplitude of excitation, stiffness ratio, can significantly improve the performance of the system.

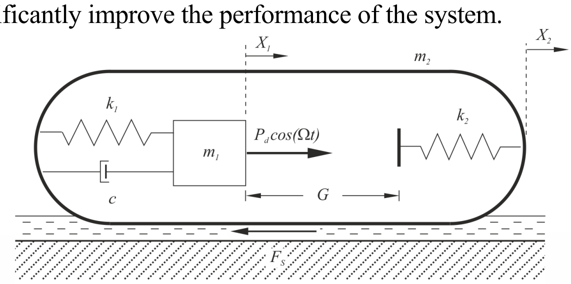

Figure 1 Physical model of the vibro-impact capsule system [3]

The rest of this paper is organized as follows. In Section 2, the proof-of-concept experimental apparatus is introduced. In Section 3, the prototype design of the vibro-impact capsule system is studied. In Section 4, the experimental test bed which will be used for testing the capsule prototype in a fluid environment is described. Finally, some concluding remarks are drawn in Section 5.

II. PROOF-OF-CONCEPT TEST BED

Experimental investigations of the vibro-impact capsule system for proof of concept have been undertaken by Liu *et al.* [6] with the setup presented in Figure 2(a), and the schematics of the experimental setup is shown in Figure 2(b). The capsule system consists of a linear DC servomotor mounted on a base frame holding a support spring with an adjustable stiffness k_2. The motor has a movable internal rod controlled by a motion controller for conducting harmonic excitation with desired frequency and amplitude, Ω and P_d. Once the motor is switched on, there is a resistance force keeping the rod in place, which nonlinearly depends on the displacement and velocity of the rod. Assuming that this force could be linearised around the capsule working point, it could be characterised by constant coefficients k_1 and c for the displacement and velocity, respectively. A gap, G exists between the rod and the support spring, and the rod contacts with the support spring when their relative displacement is equal to zero. The absolute displacement of the rod is X_1, and the absolute displacement of the base frame is X_2 which was measured by a linear variable differential transformer (LVDT) displacement transducer. The relative displacement of the rod and the base frame, $X_1 - X_2$ was measured through the motor using the motion controller. The acceleration of the rod, X_1 was obtained using an accelerometer mounted directly on the rod. The signals from these devices were captured and observed in real-time using the data acquisition system.

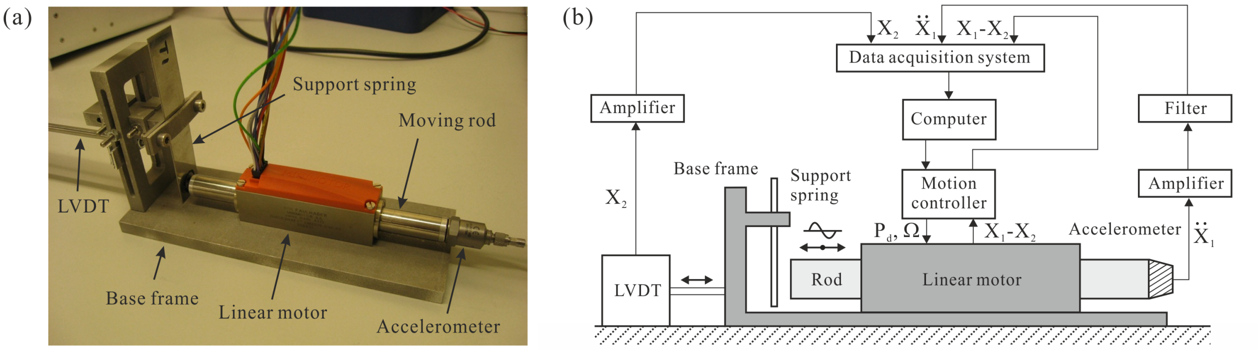

Figure 2 (a) Photograph and (b) schematics of the experimental set-up showing the novel experimental rig where the internal impacts are controlled by the stiffness of the cantilever beam [6]

III. Capsule Design

Based on the experimental study presented by Liu *et al.* [6], a prototype capsule as shown in Figure 3 has been developed to investigate the potential for the vibro-impact system to be used to power pipeline inspection capsule. The necessary driving force that must be generated by the vibro-impact system was calculated for the prototype based on the assumption that the capsule is running in air and on a smooth horizontal surface. The capsule prototype was manufactured by 3D printing using plastics. Based on the total weight of 0.5 kg, the gravitational force generated by the capsule is 4.9 N. Assuming a coefficient of friction to be 0.3 for plastic on plastic contact, the friction force that the capsule must overcome is therefore 1.47 N.

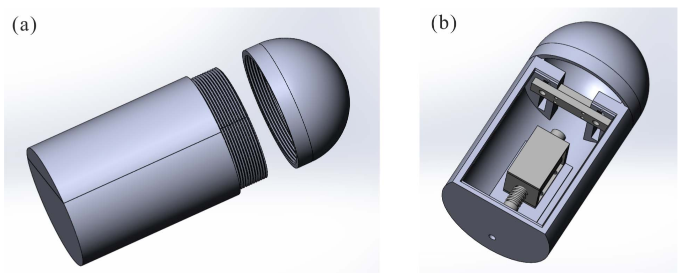

Figure 3 Prototype design of the vibro-impact capsule system

The impact necessary to drive the capsule is provided by a large 10mm-throw Push-type solenoid produced by Adafruit. It has an operational range of 9-24 Volts and a coil resistance of 43 ohms. Control of the solenoid is handled using the open-source prototyping platform Arduino. The Arduino software has been used to program an Arduino board to provide actuation pulses to the solenoid. This approach allows the actuation frequency to be controlled through the programme uploaded to the board. The Arduino board is powered using a USB connection and can only pass 40mA from a pin. To handle the higher power demand for the solenoid the output from the Arduino board is connected to the base leg of a TIP120 transistor through a 1KΩ resistor. When actuated by the Arduino board the transistor connects the solenoid to two 9V batteries set in series. The control circuit for the vibro-impact capsule system is shown in Figure 4. In the current prototype, the solenoid is housed in the capsule while the control system is all located externally and connected to the capsule with the power cables. This allows the capsule to be compact and lightweight, although it will be preferable for future prototypes to be wireless.

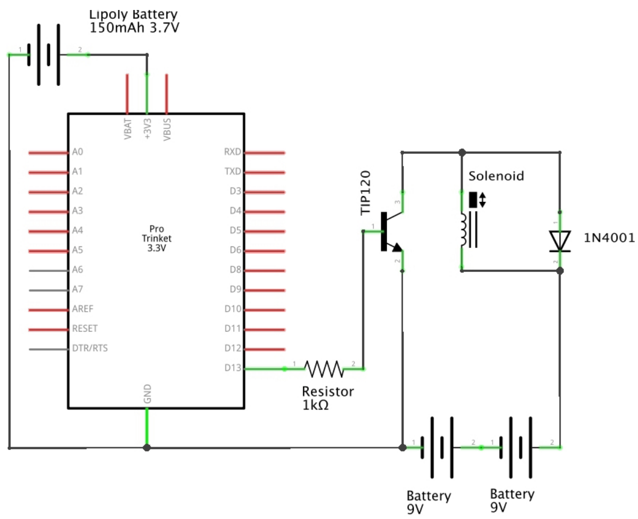

Figure 4 Prototype control circuit

As shown in Figure 5, the capsule body with a diameter of 80 mm has been designed as a basic cylinder shape with one hemispherical end. The hemispherical end is threaded onto the cylindrical section securing the two parts of this section together. The support spring is clamped into the housing in a way that its length, and therefore stiffness, can be varied.

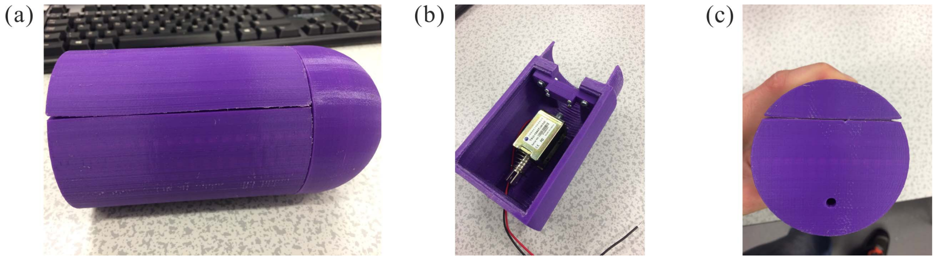

Figure 5 Capsule prototype

IV. EXPERIMENTAL TEST BED DESIGN

Experimental investigation of the vibro-impact capsule system performance is to be carried out. An experimental test bed has been designed to allow the capsule to be tested against the flow in a water pipe with a flow velocity up to 0.4 m/s. The aim of testing is to identify the dynamic characteristics of the capsule operating in a water-filled pipe. The stability of the capsule is to be assessed, the maximum velocity attained by the capsule is to be measured and the maximum flow rate in which the capsule can function is to be identified. A number of capsule design variations are to be tested and the results compared with those obtained through CFD analysis during the optimisation process.

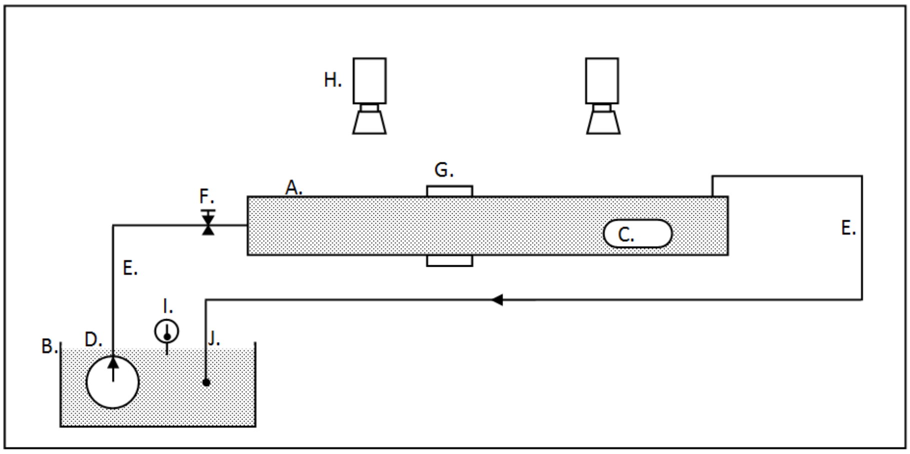

Figure 6 Test Bed Schematic Diagram: A – Test Pipe, B – Pool, C – Vibro-Impact Capsule, D – Submersible Electric Pump, E – 3” Flexible Hose, F – Ball Valve, G – Ultrasonic Flow Meter, H – Video Cameras, I – Temperature Probe, J – Return to pool

As illustrated in Figure 6, the test setup consists of the test pipe (A), a 2.5m long section of 140 mm nominal diameter clear PVCu pipe in which the capsule will run. Water from a ground level pool (B) is circulated through the test pipe and back into the pool using a submersible electric pump (D) connected to the test pipe using 3” flexible hoses (E).

The flexible hoses are connected to removable end caps, the downstream one of which is removed to allow the capsule to be loaded into the pipe. Once the capsule has been loaded into the pipe the capsule stopper is inserted behind it. This is a cross piece designed to stop the capsule being forced into the downstream end of the pipe, blocking the exit hose and risking damage to the power cables. The power cables needed for the prototype capsule are fed through a vertical 20 mm pipe which is connected at the downstream end of the test pipe, the power cables then exit through a rubber seal and are connected to the control unit

The flow rate is controlled by a manually operated ball valve (F) located before the entrance to the test pipe. The flow rate is monitored using a Micronics Portaflow 330 ultrasonic flow meter (G) attached to the outside of the test pipe. This is calibrated to the pipe material and dimensions and also to the water temperature, which is recorded throughout each experiment using a temperature probe (I).

The clear test pipe allows the motion of the capsule in the pipe to be recorded using video cameras (H) positioned next to the pipe. This approach allows the average capsule velocity to be determined from the time taken for the capsule to pass distance marks on the pipe. It also allows motion characteristics such as tilting, spinning or bouncing to be captured and replayed for analysis.

The test pipe shown in Figure 7 has been designed such that it can be filled completely with water, leaving no air-gap at the top of the pipe, regardless of flow rate. Any air trapped in the system can be bled through the cable outlet pipe. By filling the system using the pump and then closing the ball valve before switching the pump off, the water can be locked into the test pipe so that the capsule can be tested in still water as well as against a flow rate. Testing using this experimental test bed will give validation to the CFD simulation results and allow the potential for industrial vibro-impact capsule inspection tools to be assessed.

V. EXPERIMANTAL RESULTS

Experimental investigation of the vibro-impact capsule system was carried out to identify the dynamic characteristics of the capsule operating in dry friction environment. The following section presents capsule performance under variations of the system parameters such as stiffness of the support spring and the frequency of excitation.

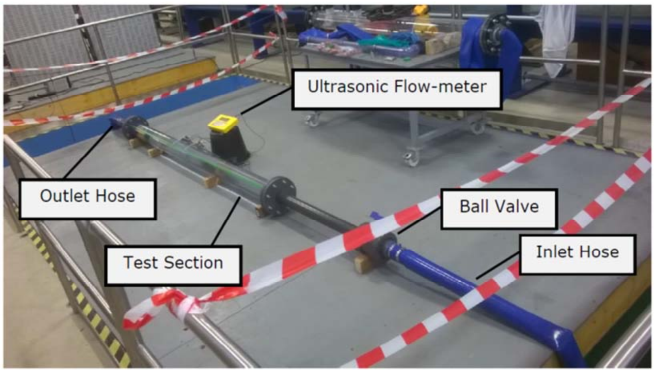

Figure 7 Photograph of the experimental test rig

During the experiments dynamic response of the system was also tested using different stiffness of support spring. The variation of spring stiffness was achieved by changing its length. As can be seen from Figure 8(a), at low frequency f=5Hz capsule's speed is decreasing as the stiffness of the spring is increasing. However, at higher frequencies of excitation 10-25Hz the results are opposite. Consequently, increase of spring stiffness results in increase of capsule's speed.

Investigation of the system response to different frequencies of excitation was performed in the frequency range [5,30] Hz. and using a softest support spring k=221 kN/m. Fig. 8 presents the results using time histories of the capsule displacement.

It can be seen from the Fig. 8 (a), (b), (c), (d), (e) that in frequency range [5,25] Hz no backward motion is observed during the experiment. Comparing the progression of the system, it was clear that increase the frequency of the excitation from 5 to 15 Hz leading to increase of capsule's speed. At 15 Hz capsule moves with the highest progression rate. However, as the frequency of excitation exceeds 15 Hz the speed of displacement starts to decrease, Fig.8 (d), (e).

Once, the excitation frequency reaches 30 Hz the capsule starts to move backward, Fig. 8 (f). Analysis of the system has shown that at this frequency the rod of the solenoid does not hit the support spring, because in this case actuation time of the

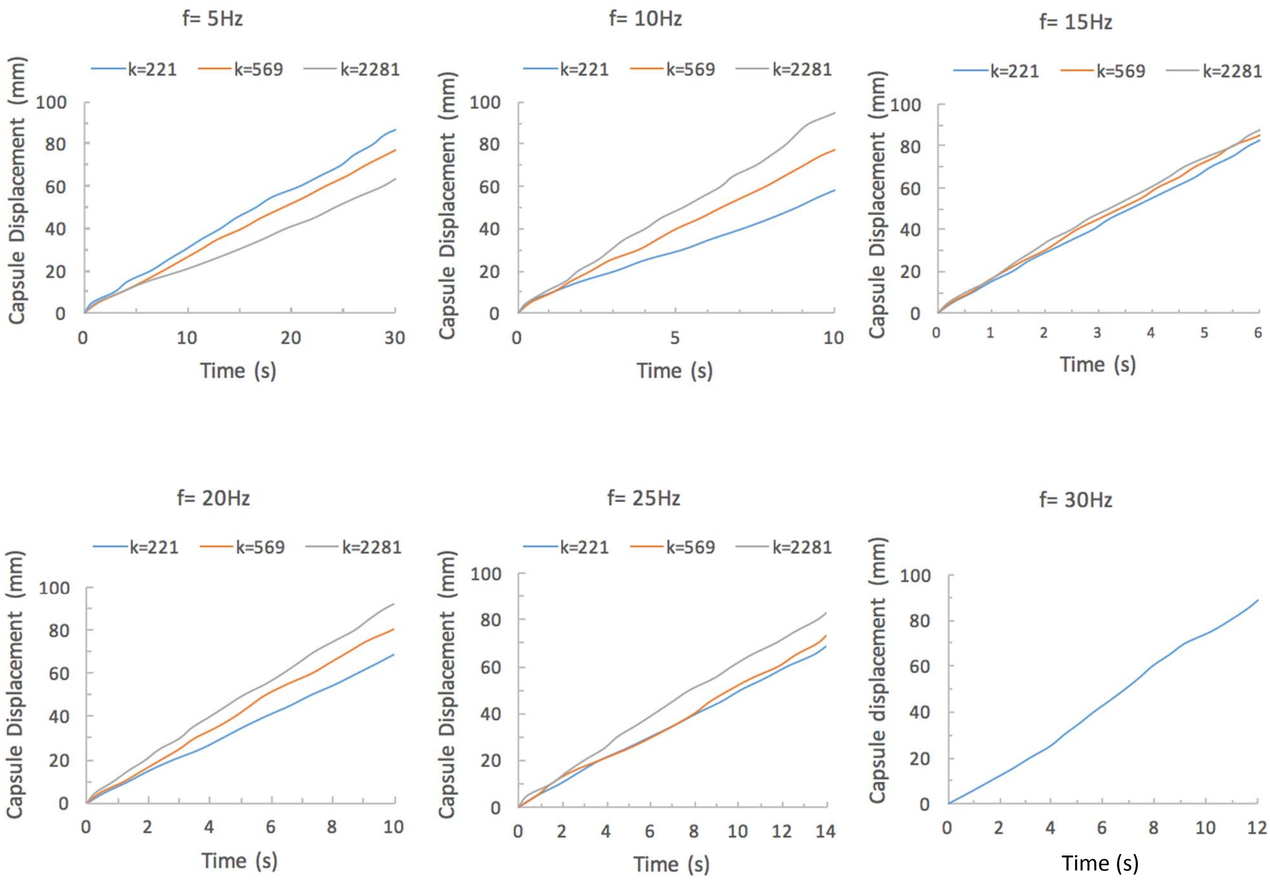

Figure 8 Time histories of capsule displacements

solenoid is not enough to complete full stroke. Therefore, backward motion of the capsule produced due to impact between the rod and solenoid's frame.

VI. Concluding Remarks

A current research project in the Robert Gordon University for developing the prototype of the vibro-impact capsule robot for pipeline inspection has been introduced in this paper. The project aims to address the technical bottlenecks in pipeline inspection by developing a self-propelled capsule robot. In order to verify the concept, a dummy capsule prototype with a diameter of 80 mm has been designed and manufactured for testing in a 2.5m long section of 140 mm nominal diameter clear PVCu pipe with a flow velocity up to 0.3 m/s. By using the experimental test bed, the prototype of the capsule system can be tested at various flow rates, and the experimental results could be used for comparing with CFD simulation results for optimization.

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