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Dynamic behaviour of an in-pipe sensor-based platform for soil water monitoring

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ABSTRACT

In this study, the dynamic behaviour of a sensor-based platform that travels through an underground pipeline network is investigated. The platform consists of a soil water sensor, placed on two articulated wheeled bases. In order to improve the maneuverability of the platform within the curved sections of the pipeline, an extension rod between one of the wheeled bases and the soil water sensor was added. Firstly, the behaviour of the platform in a curved section is demonstrated using mathematical modeling and numerical simulation. According to simulation results, the extension rod improves the turning radius ($R_c = 0.26$ m) of the platform significantly. On the other hand, it reduces the clearance ($g = 0.002$ m) between the soil water sensor and the inner sidewall of the curved pipe, affecting at the same time the tractive forces. Next, the vibration effect of the electromechanical devices on the sensor-based platform at low and high speed operation is investigated. The vibration magnitude for the case of high speed operation is almost identical to that for low speed operation, because it is mainly determined by the amplitude of the strongest mode. The platform modal behaviour depends only on the constructional details and is irrelevant to speed and type of excitation.

1. Introduction

Piping systems are mainly used for transporting oils, gases and other chemicals. A number of problems, such as corrosion, cracks, and mechanical damage occur in pipelines, limiting their service ability. Mobile robotic systems can be used for automated inspection of the inner surface of piping systems, using advanced diagnostic techniques, such as, visual inspection, magnetic leakage detection, etc. (Qi et al., 2009). Hirose et al. (1999) presented several types of in-pipe inspection vehicles for ∅25, ∅50, and ∅150 pipes. Roh and Choi (2005) proposed a differential-drive in-pipe robot for moving inside urban gas pipelines. Choi and Ryew (2002) developed a semi-automatic pipeline inspection robot system with active steering mechanism.

Based on their driving mechanism, the pipeline robotic systems can be classified into the following categories: wheel type robot, caterpillar type robot, walking type robot, pig type robot, wall-press type robot, screw type robot, and inchworm type robot (Choi and Roh, 2007). Wheel type is one of the basic in-pipe robots. It is applicable to horizontal pipelines. Salih et al. (2006) presented the design of an omni-directional mobile robot using four custom-made mecanum wheels. All wheels are independently powered. Each mecanum wheel consists of nine rollers. Therefore, it can create force vectors in both x and y directions. Caterpillar is another type of in-pipe robot that has the capability of traversing horizontal, as well as, vertical pipes. Kwon et al. (2007) proposed a mechanism consisted of three pairs of caterpillar, each of which is operated by a DC motor. For the inspection of pipelines carrying oil or other liquids, with a sufficient amount of flow into the pipes, pig type robots must be used. This type of robot is composed of a cylindrical capsule supported by two rubber discs. The rubber discs keep the capsule centered in the pipeline and help build the necessary pressure difference in the fluid to propel the pig along the pipe (Okamoto et al., 1999).

The wall-press type is another popular in-pipe robotic system. The advantage of wall-press type robots lies in the realization of an adaptive (flexible) mechanism for pressing the pipe walls. It solves several crucial technical problems associated with the change in pipe diameter, as well as the presence of vertical pipes and elbows. Zhang and Yan (2007) proposed an in-pipe robot with

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active pipe-diameter adaptability and automatic tractive force adjustment for gas pipeline inspection of varying diameter. It consists of three sets of parallelogram wheeled legs. Each leg has a front and rear driving wheel. The adaptive mechanism is driven by a step motor. This motor drives the rotation of a ballscrew that can push the sets of parallel legs with driving wheels, to come into contact with the surface of the pipeline walls. Also, Choi and Ryew (2002) proposed an alternative type of wheeled leg mechanism that has three wheeled legs spaced 120° around the robot body. The folding and unfolding of the legs is attained by using a pantograph mechanism with sliding base. The wall-press type robots interact with the pipe wall with pressing forces, in order to ensure adequate and stable traction. The wall-pressing mechanism includes suspension links that contract and expand to make the robot flexible, so as to be able to move through the pipe network. It also gives the ability to such robots to climb vertical pipe branches.

Gravalos et al. (2010) presented an innovative sensor-based platform that travels through a subsurface piping system that is capable to monitor the soil water content in real time. This sensor-based platform can be classified as a wall-press type of robotic system. Two-dimensional (2D) and three-dimensional (3D) images of soil moisture were created by using measurements taken from the sensor-based platform described above. The images depict the spatial and temporal soil moisture variability in a meter-scale with high resolution. This information is critical for precise crop irrigation management and also for hydro-geophysical model validation (Gravalos et al., 2013).

This paper is organized as follows. Firstly, the kinematics (geometry of motion) of an in-pipe mobile platform moving in curved pipes is described using mathematical expressions. A numerical simulation of the dynamic behaviour of the sensor-based platform follows. Finally, the actual vibration levels in all three axes are recorded and their spectra are calculated using the Welch power spectrum method.

2. Materials and methods

2.1. Design of the sensor-based platform

A schematic illustration of the prototype sensor-based platform that traveled through the sub-surface access tubes and monitored the soil moisture content is shown in Fig. 1. It was composed of a modified commercial soil moisture sensor (Diviner 2000, Sentek Pty Ltd, Stepney South Australia), placed on two articulated wheeled bases. The total length of the sensor-based platform is 235 mm and its outer diameter may be varied from 48 mm up to 54 mm. The active device is a soil water sensor placed on wheeled bases. The wheeled bases are linked via universal joints. In order to work correctly, they must have equal input and output angles. Also, the forks must be assembled so that they will always be in the same plane. The body of the wheeled bases is circular in shape, and it serves to support the driving and sliding wheels. The driving wheels are supported via bumper suspensions. The suspension system allows motion only along the vertical direction and relies its function on flexible members (compression springs), to hold the bumper loosely in place.

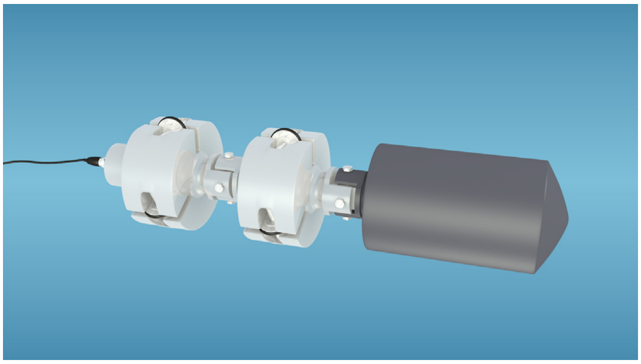

Fig. 1. A schematic illustration of the prototype sensor-based platform.

The deflection of the bumper suspension gives foldable characteristics to the driving wheels, which maintain steady contact with the pipeline walls. The wall-pressing wheels are an advantageous feature of the design, because each wheeled base can move independently of the other. This way, whether it is for straight or curved pipelines, the mobile platform is always guided to the direction of the pipes. Two motors are engaged in the platform movement. These are high quality DC motors that are installed close to the driving wheel parts. The driving power is transmitted to the wheel by a motor shaft. The motor voltage is varied from 0.5 V to 3 V with a typical rotational speed of 500 rpm. Each wheel module uses elastic "O" rings with a high friction coefficient. The high degree of adhesion between the sliding wheels and the pipeline walls, results in improved platform movement. The mobile platform is able to hold firmly onto the inside surface of the pipeline and move smoothly along the piping system. In addition to this, the platform is more stable and the distribution of load on the wheel modules is more uniform. The mechanics of the driving wheels of the mobile platform were described in detail in reference Gravalos et al. (2012).

2.2. Kinematics of the sensor-based platform when moving in a curved pipe

Due to the relation between its length and width, this sensor-based platform cannot pass through right angle elbow runs. Thus, the curved section at the end of each pipe is a very important feature in order for each segment of the platform (both wheeled bases and soil water sensor) to traverse the curvatures successfully (Fig. 2). Furthermore, the turning radius R_c determines the required minimum distance between the straight sections of pipeline and consequently affects the number and location of soil water measurements conducted in the field.

In the following paragraphs a kinematic analysis is performed as shown in Fig. 3. From the kinematics point of view, a crucial variable for the sensor-based platform is the turning radius (radius of curvature), defining the trajectory of motion. Depending on the situation, we can derive an equation to determine the exact value of the turning radius R_c (m) between the second wheeled base and soil water sensor (Gravalos et al., 2012).

$$R_c = \frac{\frac{k_2}{\cos u_2} + k_1}{\tan u_2} \quad (\mathrm{m}) \tag{1}$$

From Eq. (1) R_c depends on the distances k_1 (m), k_2 (m) of the platform segments and the input or output angle u_2 (deg) of the joint. The equation can be applied to the curved paths following each straight line segment of the pipeline. In addition, we accordingly derive Eq. (2) to determine the turning radius R_c (m) between the first and second wheeled bases.

$$R_c = \frac{\frac{k_1}{\cos u_1} + k_1}{\tan u_1} \quad (\mathrm{m}) \tag{2}$$

where k_1 (m) is the distance defined by the imaginary axis passing through the centers of the wheeled base and joint. Again, u_1 (deg) is the input or output angle of the joint.

In order to improve the maneuverability of the sensor-based platform, we added an extension rod between the second wheeled