Testing of a Mechatronic Inspection System’s Prototype

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Abstract: The aim of the paper is to investigate some of the most important parameters of an inspection mechatronic system and to test the developed prototype for validation purpose. In the introduction of the paper some important details about the inspection mechatronic systems are presented. In the second part the developed prototype along with the test conditions are presented. In the third chapter theoretical aspects about the locomotion of the system inside pipelines are discussed. Test condition and results are presented in chapter four and five of the paper.

Keywords: pipeline inspection, mechatronic system, prototype, test, validation.

1. INTRODUCTION

In the mining, gas and petroleum industries, maintenance and inspection represents a big concerning. Accidents and high-priced full pipeline replacements can be avoided by the use of a mechatronic system for in-pipe inspection that can give visual and sensorial data about the status of portions of the pipeline. Inspection and exploration mechatronic systems represent a challenging domain in the field of Mechatronics because of the hazardous and limited workspace in which the developed systems have to adapt and also because of the reduced ability to monitor and acquire data about the inspected environment. The locomotion of different inspection and exploration robot designs has been addressed by many researchers (Hirose, S., et al., 1999, Horodinca, M., et al. 2002, Kwon, Y., et al. 2002, Carbone, G. et al. 2009, Choi and Roh, 2007, Li, P., et al. 2007, Schempf, H., et al. 2010). This paper presents some details about the main parameters, a short presentation of the prototype and the test made to determine the traction force of the prototype in different pipe conditions.

2. PRESENTATION OF THE DEVELOPED PROTOTYPE

The developed prototype design is modular, composed of three modules (2 active modules and one passive). The active module contains the actuator and is responsible for the driving function of the prototype. It is composed of 6 slider-crank mechanisms placed at 120° angles around the central axle. This structure can adapt more easily to the variation of the pipe's diameter. In Fig.1 the 3D design of the prototype along with a image of the developed prototype are presented. The wheels of the active module are pressed against the inner surface of the inspected pipe using two compression springs placed one on each side of the module’s central axle. This constructive solution has the advantage to adapt independently to the pipe diameter variations. One of the problems encountered in the design of this module was the actuator’s size that has made the crank mechanisms not identical. Also two different sized springs were used.

Fig. 1. The 3D design and prototype of the active module.

The passive module has the task of transporting the electronic equipment and the batteries that power the actuators. It has a cylindrical shape and six wheels, three at each end of the module, placed at 120° angles around the longitudinal axis. The axle of each individual wheel is mounted in a fork-like clamping system which is placed on a rod with a compression spring that allows the wheel to slide along an axis perpendicular on the longitudinal axis of the module. In this way the module can cross sections of pipe with different diameters. The 3D model and the prototype of the passive module are presented in Fig. 2:

Fig. 2. The 3D design and prototype of the passive module.

The developed mechatronic inspection system prototype is presented in Fig. 3.
The prototype is able to inspect pipes with the interior diameter ranged between Ø130 and Ø200 mm. It weights 1980 g and has a length of 856 mm (Tătar, M.O, et al. 2009, Tătar, M.O, et al. 2010). The force exerted on the inner pipe walls for all prototypes is generated with the help of a compression spring. The connection element between the modules is a universal joint that helps the modules to orientate in the limited workspace. The cable influence on the movement inside the pipe was not taken in consideration because the robotic system has the capability to be autonomous energetically. At the preliminary tests at normal laboratory conditions the recorded system’s speed inside a pipe with Ø160 mm in diameter was 150 mm/s at a supply voltage of 6V. A wireless mini-camera with a protection case with rollers is mounted in the front of the prototype for inspection purposes.

3. THEORETICAL ASPECTS

One of the most important issues in the design of a mechatronic system for in-pipe inspection is to obtain the necessary traction force to pull instrumentation as well as the system’s modules. Especially in vertical pipelines, it is desirable to keep adequate wall pressing forces in order to ensure sufficient traction forces. Excessive forces dissipate power and can damage the system and at insufficient forces the system can fall down (Zhang, Y., at. al. 2007).

Scheme representing the forces and torques distribution on a planar section of the mechatronic system’s active module mechanism is presented in figure 4.

The following annotation were made: \( F_r \) as the friction force between the wheel and the pipe wall, \( F_r = \mu \cdot F_g \), where \( F_g \) is the reaction force between the wheel and the pipe wall; \( M_f \) as the rolling friction torque \( M_f = s \cdot F_g \), where \( s \) is the rolling friction coefficient; \( \mu \) as the slip friction coefficient, \( \mu_r \) as the rolling friction torque \( M_f \), \( \omega \) as the robot’s speed \( v = \omega R \), \( G \) as the weight force of the active module, \( m \) as the actual mass of the active module, \( M_{RM} \) represents the resistant reduced torque of the actuator’s axle, \( \omega_{m} \) represents the friction torque in the wheel bearing and has the expression (Alutei, A., et al. 2010):

\[
M_{f} = \frac{\mu \cdot d \cdot F_{g}}{2}
\]

The bearing friction from the mechanism was neglected. Considering that the wheel does not slip on the pipeline interior surfaces, the traction force is direct proportional to the friction coefficient and the pressing force between the wheel and the pipeline surface. The coefficient of friction depends on the material of wheel and the surface condition of the pipe.

In conditions of pure rolling, the motor output power \( P_m \) is presented as a function of traction force \( F_{traction} \) wheels speed \( v_w = \omega_1 \cdot r_{wheel} \), transmission efficiency \( \eta \) and the variation of the motor torque \( M_m \). The transmission ratio \( i \) is given as follows:

\[
i = \frac{n_m}{n_{RM}} = \frac{\omega_m}{\omega_{RM}} = \frac{Z_3}{Z_1} = \frac{v}{r} \cdot \frac{r_{wheel}}{z_1}
\]

where \( n_m / n_{RM} \) represents the rotation speed / the angular velocity of the actuator’s axle and \( n_m / n_{RM} \) represents the rotation speed / the angular velocity of the active wheel.

The traction force for the whole active module is:

\[
F_t = 3 \cdot \frac{\eta P_m}{v_w} = 3 \cdot \frac{\eta P_m}{R_0} = 3 \cdot \frac{\eta M_m}{r_{wheel}}
\]

Considering the transmission efficiency \( \eta = 0.98 \), the transmission ratio \( i = 38 \), a friction coefficient of 0.2, the motor wheel with a radius \( r_{wheel} = 25 \) mm and the torque value at the actuator’s axle registered at 6V and 0.34 A supply voltage is \( M_m = 1.768 \cdot 10^{-3} \)Nm, the calculated traction force of the system on horizontal pipes is 7.86 N.

4. THE TEST CONDITIONS AND SCHEME OF THE EXPERIMENTAL SETUP

To verify the traction force of the inspection mechatronic system in pipelines, two repeated tests in two similar horizontal pipelines with an interior diameter of Ø160 mm and with two different conditions inside the pipe were made.
One of the pipes contained oil on the interior diameter’s surface and the other pipe the conditions were normal. The purpose of the test is to determine the traction forces of the mechatronic system and to identify the influence of slippage on the traction force. To measure the traction force of the mechatronic system Xplorer GLX digital measure device was used. As the Xplorer GLX data sheet suggested, the device represents a data collection, graphing, and analysis tool designed for science experiments. The Xplorer GLX supports up to four sensors simultaneously, in addition to two temperature probes and a voltage probe connected directly to specialized ports. The force sensor connects to an interface and records force in the range of -50 N to +50 N at a rate of up to 1000 samples per second and have an accuracy of 1% and resolution of 0.03 N. One of the advantages of this sensor type is that only the forces in the direction of the sensor are measured, the side forces being minimized. According to the scheme illustrated in figure 5, we can test the system’s actual traction force with a force sensor connected to the Xplorer GLX measuring device which recorded and displayed the measured values. The peak of the traction force is recorded when the driving wheels are starting to slip on the interior wall of the pipe. The pull cord was an inextensible shank constrained at the margins using a rotational joint.

\[ \text{Fig. 5. Testing scheme for the determination of the traction force of the active module} \]

5. TEST RESULTS AND DISCUSSION

The first set of measurements were conducted on Ø160 mm PVC pipes with oil on the surface of the inside diameter. The recorded values at a supply source for the actuator of 6V are given in figure 6.

The measured values given in figure 6 show the variation of the traction force in an interval of 60 s. The maximum value was recorded when the system had been connected at the power supply and represents an overgrowth corresponding with the current and torque overgrowth of the actuator shock response. The peak traction force is recorded when the drive wheels slip on the surface of pipe wall. The variation is cyclic because of the two states of measurements. In the first cycle the robot advances until it reaches the maximum traction force and until the slippage appears.

After the robot starts to slip inside the pipe, because of the manufacturing and assembly errors summed with the lower friction forces involved, a relaxation cycle appears and the traction force reaches its minimum value. The maximum value obtained according with the graph from figure 6 is 4.8 N and the minimum value obtained is 2.9 N.

\[ \text{Fig. 6. Variation of the active module’s traction force in the first test} \]

In the figure 7 the test took place in the same conditions, the difference being that the PVC pipe had no oil on the inside diameter.

The results presented in figure 7 show a maximum value for the traction force of 10.4 N and a minimum value of 6.6 N. A difference of 4 N between the two graphs revealed the effect that the slippage between the system’s motor wheels and the inside of the pipe has on the traction force. In normal conditions the system performed in the interval predicted by the calculus. The small variations recorded between the peaks were the perturbations inflicted by the manufacturing and assembly summed errors.

\[ \text{Fig. 7. Variation of the active module’s traction force in the second test} \]

The image taken at the test of the prototype.
Tests for the mechatronic system’s capability to travel in elbow portions of the pipe were conducted. In figure 9 images taken from the test are presented. Due to the independent pair of mechanisms designed, the active wheel of the robot maintained continuous contact with the pipe’s wall.

Fig. 8. Images from the test for the determination of the mechatronic system’s capability to travel in elbow portions.

The inspection mechatronic system presented in the paper is not energetically autonomous, being powered through wires. By using wires, the main advantages are that the power flow is permanent and the system can easily recover after power losses. Another advantage is that the system is lighter without having to transport an energy source. However, the main disadvantage is that the wires are creating additional friction force, which is greater as the travelled distance increases. Another important disadvantage is that the wires make the passing of the systems trough numerous elbows more difficult.

The experimental result shows that the inspection system can provide a sufficient traction force in pipelines with different portions and conditions and also proves that the presented theoretical analysis is valid.

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7. CONCLUSIONS

This paper presents specific tests of a developed mechatronic system for inspection tasks. The structure of the modular mechatronic system consists of active and passive modules connected with universal joints. The systems have the advantage of versatility, adaptability, usage of lightweight robust modules, low energy consumption, low cost of fabrication. These modular systems can be used for the inspection and exploration of pipes with inner diameters ranged between Ø130 and Ø200 mm. For inspecting the inside of the pipes, the modular systems are equipped with a wireless video mini-camera, housed in a protection system.

REFERENCES


