Design and numerical simulation of a self-adaptive variable-diameter robot for in-pipe non-destructive inspection

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Abstract. This paper presents a design method and numerical simulation result of an smart in-pipe inspection robot with capability of adjusting its diameter to adapt to pipelines of non-constant inner diameter insensitive to non-smooth imperfect inner surface due to corrosion or erosion. A variable-diameter component consisting of a motor, gear wheels, a screw and nut drive system and a bar linkage is introduced to achieve this self-adaption. Moreover this paper presents a force-balance analysis by virtual displacement principle relating the normal force and internal spring force and conducts a numerical simulation of dynamic process of a 3D mechanical model across diameter-varying sections in horizontal, vertical manners and records transient inner spring force. The paper has significant reference merit for engineering application to ensure safe operation of pipelines.

1. Introduction

With the rapid development of petrochemical industry, pipelines play an increasingly important role in transmitting various fluids such as crude oil, natural gas and other hazardous contents. However long-time service makes the piping structures vulnerable to potential failure such as blasting, local buckling due to internal pressures, excessive moments or thermal loads, so that thorough inspections should be conducted to evaluate the integrity and safeguard the in-situ operations every few years. The traditional inspection methods involve complicated and costly excavation and random sampling of the structures and destroy locally the integrity of piping system, thus it is often followed by costly and time delaying repair. Thus the non-destructive in-pipe inspection conducted by walking robots in automatic or manually controlled manner is deemed meaningful to reduce the manual effort, avoid unnecessary repair process, maintain the integrity and increase the speed of the inspection to reduce economic cost, such that precaution and subsequent measures can be taken to fix the seriously damaged components by repair or replacement. From this perspective, the robots have significant advantages over human inspectors in in-situ inspection, clearing and routine maintenance, so in-pipe inspection robots have wide application prospect.

The technology of in-pipe inspection robots evolving for many years can be classified into pig type(passively driven by pressure difference), wheeled type, crawler type, snake type, inchworm type(suitable for very small diameter pipe) etc.[1]. The travel problem across long pipes with turns or elbows has been under investigation widely, for example, Roh et al.[2, 3] developed an in-pipe robot for
inspection of pipelines with nominal 8-inch inner diameter, adopted a differential driving mechanism and introduced the clutches in transmitting driving power to the wheels to save energy. Park et al.[4] present a normal-force control technique to enhance the crossing ability of vehicles for various pipeline inclinations. Ismail et al.[5] presented a detailed overview of the development of in-pipe inspection. However there is a lack of the research on active diameter-varying robots and we thus developed an inspection robot able to adapt to changes in diameters and presented a numerical simulation of internal spring forces crossing the diameter varying sections.

2. Structural design and Force balance analysis
Fig. 1(a) presents the schematic of the robot kinematics and Fig. 1(b) gives 3D model of the vehicle. The robot is mainly composed of a main body, two motors and one caterpillar unit. The diameter-varying unit consists of a diameter varying motor and gear drive mechanism to transfer torsion to the screw nut drive system made of a screw bar and a nut. The nut then is connected to a bar linkage to change the configuration of the caterpillar unit. The bar linkage is composed of two bars Bar1 and Bar 2 and one central spring. The introduction of spring is essential since it inserts some flexibility to the system and makes the robot adapt to small variations in pipe diameter, surface unevenness due to welded seam, corroded pits. The caterpillar unit is pressed against the inner wall of the pipe by linkage with length $L_2$. The motor drives the gear wheels and rotates the screw bar, thus in turn making nuts travel horizontally pulling or pushing the linkage $L_4$ and maintaining some contact normal forces between inner wall and caterpillar wheels and thus in return creating friction force necessary for driving robot to move forward. The relationship between the spring force $F_s$ and normal force $N_s$ or friction force $F_t$ can be obtained through virtual displacement principle.

From Fig. 1(a), considering the caterpillar unit and two bars of length $L_2$ as an ideally constrained objects.

The virtual work done by forces $N_s, F_s, F_t$ is zero: $F_s \cos \alpha (-\delta x_b) + F_s \sin \alpha \delta y_b + F_t \delta x_b - N_s \delta y_b = 0$.

The geometric restraints yield:

$$x_b = L_2 \cos \beta + L_3 / 2$$
$$y_b = L_2 \sin \beta + H_2$$
$$\delta x_b = -L_2 \sin \beta \delta \beta$$
$$\delta y_b = L_2 \cos \beta \delta \beta$$

From which we obtain $(F_s L_2 \cos \alpha \sin \beta + F_s \sin \alpha L_2 \cos \beta - F_t L_2 \sin \beta - N_s L_2 \cos \beta) \delta \beta = 0$.

Thus due to arbitrariness of $\delta \beta$, it yields $N_s = (\cos \alpha \tan \beta + \sin \alpha) F_s / (\mu \tan \beta + 1)$ where $\mu = F_t / N_s$ is the coefficient of friction. This relation correlates the normal force to spring forces and thus the increase of $F_s$ leads to increased normal forces. Fig. 2 presents the schematic of the driving system and diameter active variation component, the three caterpillar units are connected to one driving motor by a set of gear wheels.

**Figure 1.** Schematic of robot kinematics
3. Numerical simulations
The 3D model was built by using software Solidworks and then dynamic simulation of travelling across a pipe segment of two diameters DN250 and DN200 is presented in Fig. 3.

From 3D model in Fig. 1(b), there are three springs in the precompressed diameter-varying unit (see Fig. 2), the spring forces reflect the normal forces exerted on inner wall to create friction. The Fig. 3(a) reflect the variation of spring forces during a horizontal walking (see Fig. 3(d)). Initially the pipe is DN250 larger than DN200 of the central segment. As the robot starts to walk, the three spring forces are around 10N and at time 1s, the diameter is changed to smaller value and in this process the normal force between inner wall and wheels is becoming large so that subsequently the spring is sensing this change and the spring forces are increasing to a high level about 65N. Then the diameter-varying motor drives the screw-nut unit to pull the bar linkage backward and by this way the size of the robot is reduced to adapt to the smaller diameter segment. After this is accomplished, the spring forces are lowered and remain constant crossing the DN200 segment at a level about 30N. Fig. 3(b) shows the complete process of downward travel across DN250, DN200, DN250 segments in sequence. The response of spring force during the travel is similar to that of horizontal walking and initially the forces are small in DN250 pipe segment and then the forces increase to a high level about 50N and then after active adjustment of linkages the forces are reduced and the forces increase again at the time around 22s to 50N and then the forces decrease to about 30N. Fig. 3(c) shows the variation of spring forces when the vehicle is moving upward.

It is evident that the spring forces remain nearly constant through constant diameter segment and the spring forces increase when a change of diameter occurs and are lowered to a small value again after crossing this tapered section.

![Figure 2. Driving system and diameter-variation component](image)

4. Conclusion
The in-pipe inspection robots are in demand for non-destructive inspection to replace traditional time costly and technically difficult manual inspection of long pipelines. This paper presents an introduction to a variable diameter in-pipe inspection robot which is adaptive to the pipes with diameter changes and insensitive to the small geometric imperfections due to corroded pits, welded seam etc. by introducing spring-based self-adaptive pre-compressed diameter-varying unit. Once the robot encounters a tapered section, actively the motor drives the screw-nut system to pull back crawler wheels from or push forward against the inner wall. Through the virtual displacement principle, we established the mathematical relationship between the normal force and inner spring forces. Thus the spring forces can be used to predict the effective normal forces between wheels and inner wall and this process is simulated for three walking cases including one horizontal walking case, two vertical walking cases. The spring forces keep...
almost constant across constant diameter segment and the forces increase to a high level when diameter-varying unit is active to move the wheels after which process the forces decrease to a small value again. This paper is meaningful reference for further development of in-pipe inspection robotics.

Figure 3. Numerical simulation of robots crossing diameter-varying section and spring forces

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