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Electromagnetic worm-like locomotion system for in-pipe robots: novel design of magnetic subsystem

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Abstract. This paper describes a magnetic subsystem of an electromagnetic worm-like locomotion system (WLLS) with coupled electromagnets. WLLS simple-design consists of two elastically connected ring-like segments that form two magnetically coupled electromagnetic actuators. The actuators generate longitudinal and transverse displacements which lead to locomotion due to synchronized changes of inertial, normal pressure, and friction forces. In present paper, analysis of the magnetic circuit of the WLLS had been performed. From symmetry and general consideration of magnetic system effectiveness, a novel design of the coupled magnetic circuits had been developed. The novel WLLS has two-force component electromagnetic actuators that produce the transverse and longitudinal forces. The novel design of the electromagnetic WLLS is able to move an in-pipe robots and should have better specific pulling force.

1. Introduction

The in-pipe robots are widely used in petroleum, gas, power, agriculture and other industries [1-5]. The mobile apparatuses and robots that can move without legs, wheels, caterpillars, and others, attract much attention in recent years [6-11]. The robot legless locomotion could be obtained due to the motion of internal bodies and asymmetrical interaction of the external casing with the environment [6, 8]. This legless robots for in-pipe locomotion can be carried out by various principles [6, 10]. The locomotion principle based on periodically changed normal pressure forces allows to obtain large specific tractive forces for in-pipe robots [8, 9, 12, 13]. This is particular type of vibration-driven locomotion systems.

The physical principle for generating internal forces may be very different. Mostly, there are inertial, pneumatic, electrodynamic and electromagnetic actuators. The electromagnetic actuators are widely used in the in-pipe robots, for example [2, 11, 12, 14]. Ordinarily the electromagnetic forces have only a longitudinal component, so the changing normal pressure force is created either by mechanical actuators or additional independent electromagnets [13]. In the electromagnetic WLLS [14], the complex electromagnet is used for generating the both force components. The complex electromagnet is formed from two coupled magnetic circuits.

Design and principle of operation of the electromagnetic WLLS were presented in [14]. It was taken that all electric and magnetic quantities, and consequently the electromagnetic forces, varies by the harmonic law. The magnetic subsystem in [14] had been considered oversimplified.

On the other side, electromagnets are used in wide range of technologies, for example, in magnetic catchers in oil refinery industry [15], hand instruments [16, 17], seismic technologies [18], and so on. Theory and methods for evaluation of the electromagnets is well known and are used in all cases [19, 20].

In present paper, we will analyze qualitatively the WLLS magnetic subsystem only. From analysis of the magnetic subsystem, we will obtain the simpler and more effective novel design of the WLLS with the coupled electromagnets [21].

2. Magnetic subsystem analysis

2.1. The WLLS and its magnetic subsystem

The schematic drawing of the vibration-driven WLLS is shown in figure 1 [14]. The WLLS comprised from one vibrating and one contact ring-like segments. The segments are connected each other by elastic links (springs) and could move in a pipe in relation each to other.

Only the contact segment interacts with the pipe wall with a force that have two components: a normal pressure force and a friction force. Due to these forces, the center of mass could be moved [6, 8]. However, to ensure this movement, it is necessary that the forces provide simultaneously both relative oscillations of the segments and changes of the normal pressure force, and hence the friction force [14]. These are achieved by the internal forces – the magnetic forces, which has two components due to an appropriate configuration of the magnetic flux paths.

The magnetic subsystem that includes the exciting coils and the ferromagnetic parts of the segments forms an electromagnetic actuator.
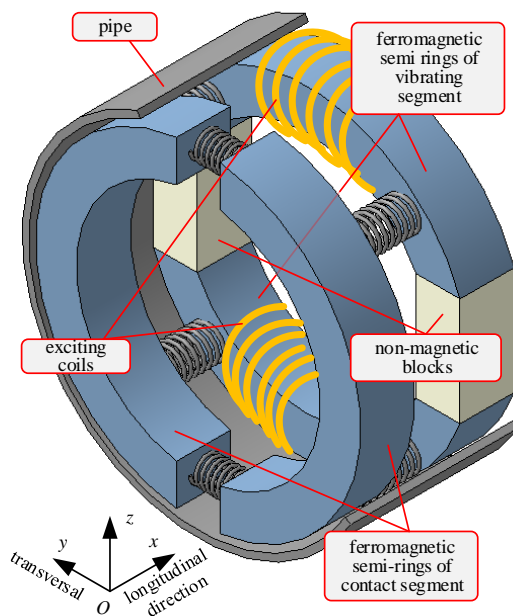

Figure 1. The Magnetic Circuit of the WLLS from [14].

Because each segment consists of two ferromagnetic semi-rings, the four ferromagnetic semi-rings forms a branched magnetic circuit. The exciting coils are winded on the semi-rings of the vibrating segment. Note that the coils may have different numbers and places than is shown on figure 1, but this leads to the same results. The coils are connected with a power supply that provides current pulses with a required magnitude, frequency, and direction.

Magnetic flux path includes not only the ferromagnetic semi-rings, but also transverse air-gaps between the semi-rings and longitudinal air-gaps between the segments. The air-gaps of the contact

segment are misaligned on $90°$ with the air-gaps of the vibrating segment. The last air-gaps filled with rigid non-magnetic blocks that prevent from relative oscillations of the semi-rings in the vibrating segment. On the other hand, the non-magnetic blocks also should 'block or stop' the magnetic fluxes and turn it into the ferromagnetic semi-rings of the contact segment. For this sake, the length of the non-magnetic blocks should be large enough to get more reluctance than the resulting reluctance of alternative flux paths that are mainly formed from two longitudinal air-gaps and the transverse air-gap in the contact segment. Exact ratios can be obtained from the magnetic circuit analysis.
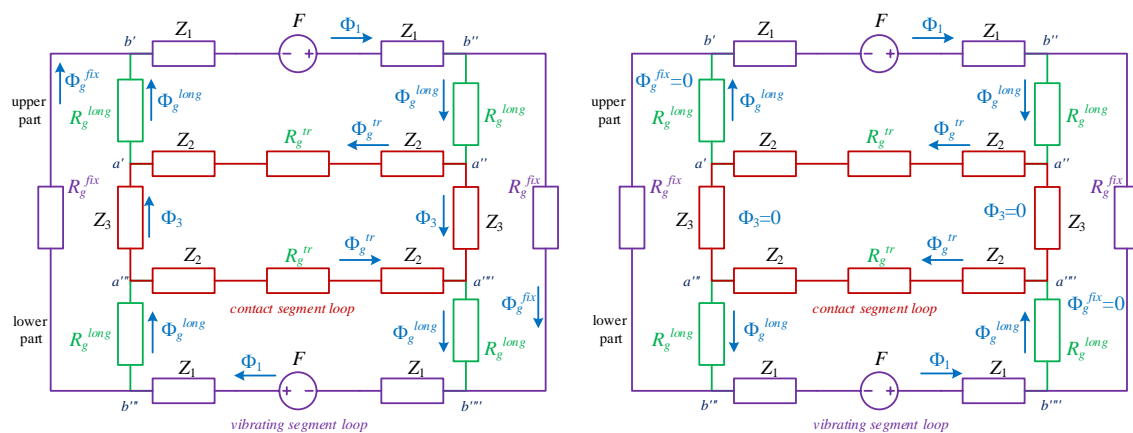
2.2. Magnetic circuit

To find the magnetic forces, we need compute magnetic fields and the fluxes. This can be made by a finite-element software with high accuracy [17]. Only this method is suitable when the electromagnet has large air-gaps and an open magnetic circuit [15]. However, for our purpose, we can use the method of the magnetic equivalent circuits that should have reasonably accuracy while calculations can be kept simple [19, 20].

Due to similarity of magnetic circuit designs, we use the same approach as in [22]. But there are a few differences:

- the winding that are the magnetomotive force (MMF) sources are concentrated on both segments of the magnetic circuit, but are not embraced by the ferromagnetic segments as in [22];
- the magnetic system is asymmetric in the longitudinal direction (the transverse gap in the contact segment is less than the transverse gap in the vibrating segment);
- the magnetic system is symmetric relative to the horizontal plane.

The equivalent circuit of the WLLS magnetic subsystem is obtained as linked magnetic reluctances which corresponds to the flux path parts. The equivalent circuit is formed from two loops that correspond to the vibrating and contact segments. From other side, there are two symmetrical chains corresponding to the lower and upper parts of the magnetic subsystem. These chains are connected by reluctances corresponding to the non-magnetic blocks and ferromagnetic parts of the contact segment. There are the two coils that create the MMF either in the same direction (figure 2, a) or in opposite directions (figure 2, b). In both cases, we have the symmetrical structure with symmetric distribution of the fluxes.

The symmetry of the circuit allows to assume that the symmetrical reluctances have the same value, and the fluxes in symmetrical branches are the same. This was used in figure 2.

a) The MMFs have the same directions.   b) The MMFs have the opposite directions.

Figure 2. Magnetic equivalent circuit.

2.3. Analysis and simplification of magnetic circuit

The equations to determine the fluxes can be obtained from the circuit by the Kirchhoff's laws.

For the equivalent circuit that is shown on figure 2, a, we can write

$$\Phi_1 = \Phi_g^{long} + \Phi_g^{fix}$$

$$\Phi_3 = \Phi_g^{long} - \Phi_g^{tr}$$

$$\Phi_1 2Z_1 + \Phi_g^{long} 2R_g^{long} + \Phi_g^{tr}(2Z_2 + R_g^{tr}) = F$$

$$\Phi_3 2Z_3 - \Phi_g^{tr} 2(2Z_2 + R_g^{tr}) = 0$$

$$\Phi_g^{fix} R_g^{fix} - \Phi_g^{long} 2R_g^{long} - \Phi_3 Z_3 = 0$$

All fluxes in the magnetic subsystem may be derived from this system of equations. Note, that if we assume that for ferromagnetic material $\mu = \infty$, then the flux $\Phi_g^{tr} = 0$ and hence the transverse magnetic force is zero. Actually the $\mu \neq \infty$ and then the flux $\Phi_g^{tr} \geq 0$. Hence, for increasing the transverse flux and the force, it is necessary to increase the reluctance Z_3. This could be achieved by embedding of two non-magnetic blocks in the contact segment, just against the non-magnetic blocks of the vibrating segment. The same could be obtained with respect to the branches with the fluxes Φ_g^{fix}. Ideally, the non-magnetic blocks fully 'block' the fluxes – $\Phi_3 = 0$ and $\Phi_g^{fix} = 0$. In this case, we can break the branches $a'a'''$, $a''a'''$, $b'b'''$, and $b''b'''$. Thus we had obtained the magnetic circuit like two independent loops for the upper and lower parts (one loop is shown on figure 3). Such ideal flux distribution is not really achieved in the magnetic circuits (figure 2, a), and hence, for the WLLS in figure 1. However, using the magnetic circuit in figure 3, we can propose another, more efficient magnetic subsystem that generates the two-component electromagnetic forces.
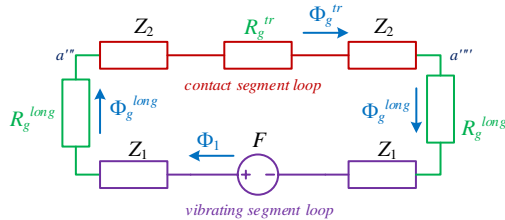

Figure 3. Simple magnetic circuit.

Another way to achieve the ideal flux distribution is to change the direction one of the MMF (figure 2, b). In this case, from the magnetic circuit on figure 2, b we can obtain for the nodes a', a'', a''', and a''''

$$\Phi_3 = \pm\left(\Phi_g^{long} - \Phi_g^{tr}\right)$$

From this equation, it follows that $\Phi_3 = 0$. Similarly, we obtain the expression $\Phi_g^{fix} = 0$. In this case, we obtain a simple system of equations for the circuit shown on figure 3

$$\Phi_1 = \Phi_g^{long} = \Phi_g^{tr}$$

$$\Phi_1\left(2Z_1 + 2R_g^{long} + 2Z_2 + R_g^{tr}\right) = F$$

Thus, from a general model of the magnetic subsystem, we had obtained simpler configuration of the magnetic circuit. This circuit matches to a novel WLLS design which has less weight, since less ferromagnetic parts are used, and the leakage fluxes are significantly reduced. This novel design of the WLLS is presented in the next section.

3. Novel design of WLLS magnetic subsystem

The magnetic subsystem of the novel electromagnetic WLLS for in-pipe robots contains (see figure 4) [21]:

- a ferromagnetic U-shaped core 1;
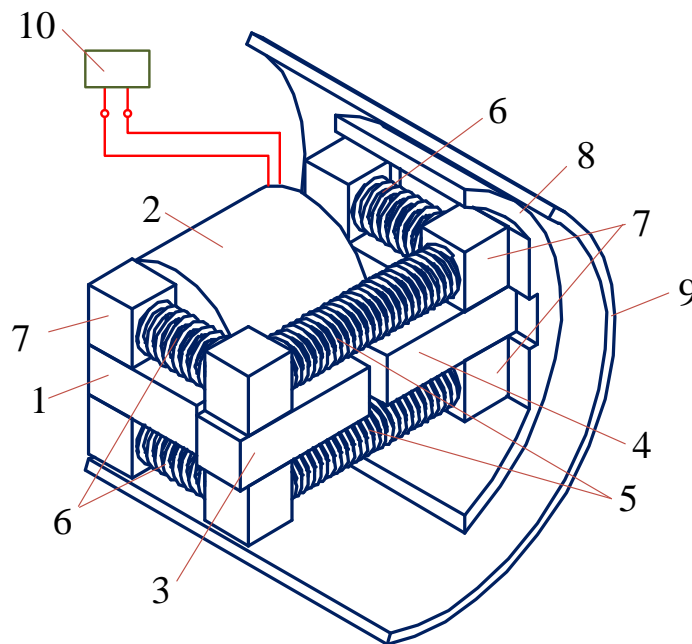- a coil with a winding 2;
- two ferromagnetic armatures 3 and 4.

Figure 4. Novel Design of the WLLS.
1 – U-shaped core; 2 – coil with winding; 3 – left armature; 4 – right armature; 5 – transverse elastic elements (springs); 6 – longitudinal elastic elements (springs); 7 – holders; 8 – friction pads; 9 – pipe; 10 – control system.

The WLLS based on this magnetic circuit is shown on figure 4. The control system 10 supply winding 2 with electric power. The control system is fixed on the same base with the U-shaped core.

The two armatures are interconnected by means of transverse elastic elements (springs) 5 and with the U-shaped core by means of longitudinal elastic elements (springs) 6 as shown on figure 4. The ends of the elastic elements are fixed on the U-shaped core and the armatures by means of holders 7. The friction pads 8, one of the pads is not shown in figure 4, are attached to the ends of both armatures. The pad shape is matching to the shape of the pipe 9. The U-shaped core is the analogue of the vibrating segment for the WLLS on figure 1. The armatures are the analogue of the contact segment on figure 1. There are two operation stages in the WLLS: the installation/uninstalling and the locomotion. Installation in or uninstalling from a pipe. To install the novel WLLS into a pipeline, the control system supplies a constant direct voltage to the winding. Consequently, the armatures attracts to each other and to the core. The voltage magnitude is such that the transverse elastic elements fully contract and the WLLS freely enters into the pipe. Then, the WLLS is inserted into the pipe with the core forward. Further, the voltage is removed and the springs are decompressed. However, the transverse springs not fully decompressed due to the appropriate selection of their length. This preload of the transverse elastic elements is necessary for fixing the system, as well as for its locomotion [14].

The uninstalling of the WLLS is performed in the same way. The locomotion. After installation in the pipeline, the control system applies a periodically rectangular voltage pulses to the winding. When voltage is applied to the winding, an electric current increases, which leads to the appearance and increase of the magnetic flux that passing through the core, the moving armatures and the air gaps between them. Thus, the magnetic flux leads to the generation of electromagnetic force, which has two components – longitudinal and transverse.

When voltage and current are rising, the longitudinal force component tends to reduce the longitudinal air gap, and the transverse force component – the transverse gap. The transverse component of the electromagnetic force compresses the transverse elastic elements, so that the normal pressure force to the pipe surface decreases, which reduces the friction force. At the same time, the longitudinal force component attracts the armatures and the core to each other, the longitudinal elastic elements contract. The core is almost not affected by external forces, and the armatures are affected by a reduced value of the friction force that directed against its movement ('back' or towards armatures on figure 4). The friction force quickly reaches zero, so that the centre of mass remains almost in place. In general, during this time interval, the centre of mass slightly shifts back by the minimum friction force action.

Further, the voltage and current in the winding are reduced, which leads to decompression of the transverse and longitudinal elastic elements. When the transverse elastic elements are decompressed, the normal pressure force from the friction pads to the inner pipe surface increases, and, consequently, the friction force also increases. The longitudinal elastic elements push away the core and the armatures from each other. Armatures are acted upon by a frictional force that directed against its movement, i.e. in the direction of the core. Thus, in this time interval, the centre of mass under the action of a single external force shifts with the core displacement ('forward' or towards the U-shaped core on figure 4). Since the friction force has maximal value, the forward movement is more significant than backward displacement during the current rise. The locomotion system gains a step. Then the voltage and current increase in magnitude again and the cycle repeats.

Thus, the principle of movement of the novel WLLS is based on periodic change in the normal pressure force of the friction pads to the pipe surface [8]. The locomotion cycle, and hence, dynamic model completely coincides with the model of the WLLS in [14]. However, the novel WLLS provides the in-pipe robot locomotion through the pipeline with greater traction forces due to less leakage fluxes.

4. Conclusion

In the present paper, we have analysed the magnetic circuit of the electromagnetic locomotion system. The magnetic subsystem, as we have showed, of the electromagnetic WLLS can be improved in the following ways:

- the use of the additional non-magnetic blocks in the contact segment instead of the ferromagnetic ones;
- the exciting of windings so that it creates the MMF with opposite directions;
- simplification of the magnetic subsystem to the more effective magnetic circuit with less leakage fluxes.

From the analysis of the magnetic circuit, it follows that it is more rational to use the novel design with less leakage fluxes. This design is similar to a magnetic circuit of clapping electromagnets with an additional gap in the armature. This gap divides the armature on two parts. This gap allows the relative motion of these two armatures in the transverse direction.

Based on this magnetic circuit, a simpler design of the worm-like locomotion system is proposed. The model of dynamics can be used as for the previous design [14]. However, in further work, it is necessary to develop mathematical model that allows determining the magnetic forces. It can be done with analytical analysis of magnetic subsystem by magnetic equivalent circuit method or more accurately with finite-element software.

The more complex and functional in-pipe robots could be built as a multi-module system on the base of the proposed WLLS. Besides, the principle of the proposed WLLS can be realized for locomotion along any rails or on surfaces.

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