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Dynamic Behavior Analysis of Tiny Robot

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요 약 무선 캡슐 내시경은 소장 질환을 진단하는 등의 어려움을 해결하는 진화 의료 기기로서 중요한 역할을 했다. 그것은 제한된 크기와 기능 때문에 몇 가지 단점이 있다. 가장 큰 장애물은 자기 운동 장애에서 속도 문제를 제공할 수 없다는 점이다. 따라서, 인간의 소화 시스템의 특성을 간단히 내시경 역학의 정보를 얻기 위해, 특히 소장을 소개한다. 조건 추출을 확인하기 위해서 LuGre 모델이라는 새로운 동적 마찰 모델을 도입하고 명확하게 특성 및 모델의 사용을 얻기 위하여 분석한다. 캡슐 내시경의 실제 상황과 관련된 매개 변수의 고려하여 매트랩 시뮬링크는 모델을 작성하는 데 적용하고 기능을 발견 할 수있는 시뮬레이션을 통해 확인하였다.

Abstract The wireless capsule endoscopy played an important role as the evolutionary medical device to solving the difficulties such as diagnosing the intestine diseases. Due to the limited size and functions, it has some drawbacks. The most obstacle thing is the disability of self-motion, it means that it cannot provide the speed problem. Hence, the characteristics of human digestion system is briefly introduced, especially the intestine, to get the information of endoscopy dynamics. Next, in order to make an abstraction of the condition, a new dynamic friction model called LuGre model is introduced and clearly analysed to get the characteristics and the usage of the model. By the consideration of parameters that are tightly related with the real situation of the capsule endoscopy. The Matlab Simulink was applied to build the model and verified by the simulation to discover the features.

Key Words : Endoscopy, dynamic modelling, Tiny Robot, speed control

1. Introduction

As a health care instrument, endoscopy provides the pictures which were taken from inside of human body. However, this little device still has some drawbacks needs to be overcome. One of the significant points is the disability of motion. It relies on human natural peristalsis to passing through digestive system. Therefore, as a result, if healthcare professionals detect some abnormity inside patient's bowel, it is not possible for the capsule endoscopy to stop or slow down at that area to take more images for making a definite diagnosis.

A patient should not eat anything from the midnight before the day of examination. After about ten hours', the capsule endoscope is required to be swallowed. It will be activated instantly. At the same time, patients are supposed to wear a set of antenna array and image recorder to receive images. Patients are forbidden for having anything but clear liquids within the following two hours, and they can start to have food in other two hours. During the whole examination procedure, they

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can move freely with the image receiver and recorder unit [2, 4]. Ordinary, the endoscopy passes through the digestive system in eight hours.

In 2001, a brand-new type of diagnosis in intestine was approved and released. The Given Imaging Ltd, an Israel medical technology company which was emphasized on the visualized diagnostic devices, launched the wireless capsule endoscopy named M2A. It is as large as a regular pill, with a tiny camera on the head of it, and its name was re-branded to PillCam SB(R) in September, 2004. In 2009, the PillCam series was sold one million units [1]. The M2A wireless capsule endoscopy is about the size of a standard vitamin (11mm ×26mm) and weighs less than four grams. It consists of a video camera to record images at the rate of 2 pictures per second. As it could stay inside human body for approximately eight hours after it swallowed, a total of 50,000 images can be captured. All of them are transmitted and saved in an external storage device for further diagnosis. Besides, to enhance the image quality, a series of LED is equipped with the camera. A set of batteries is used as power supply. A radio transmitter and antenna are installed inside the tiny device for transferring data to the storage instantly [2].

Fig. 1. PILLCAM SB 2

Compared to standard gastro scopes and colon scope, it offers a wider range of view inside the entire small bowel. The embedded camera can take high-quality images in the bowels of patients with little discomfort.

With the reference of current research, CHEN et al. designed a new locomotion-steering mechanism system for the capsule endoscopy [5]. It consists of a rotational body and steering head to achieve forward and backward steering movements inside the intestines. On top of that, BOGDAN et al. presented a model with multiple joint robot, which can perform a creeping motion to move forward [6]. As a result, analysis on the feature and usage of the capsule endoscope is very important to ensure that the capsule cannot be equipped with any external components. Otherwise, the anomalous shape of the capsule will hurt human digestive system or cause discomfort for patients.

In next chapter, human digestion system was introduced with his/her organic. Rather simple explanation, not so much close to medical notation, was considered. In Chapter 3, tiny robot system modelling was also provided. Its dynamic behavior was explained through nonlinear dynamic equation. Analysis and simulation were followed in Chapter 4. In which, trials to make slow the speed were applied by change of robot mass and providing friction force change. Finally, conclusions were derived in Chapter 5.

2. Digestion System

To do the research on the capsule robot, it is significant to get through the characteristics of human digestive system and the time spent in each section of digestive process for the capsule endoscopy in the real clinical uses. Human digestive system is about nine meters long and it takes 24 to 72 hours for food and meal to pass through the whole digestion process. It consists of several different sections. The first is the cephalic phase. In this phase, the food, in this case, the endoscopy will be swallowed and go through the esophagus to stomach. The gastric phase is coming; generally, it takes three or four hours for food to finish this phase. During this time, things will be remained in the stomach to have chemical reaction thoroughly with gastrin and gastric acid. [7] The last phase is intestinal phase; in fact, it is the one which this research will be focused on. This is because the capsule endoscopy will stay in the intestine for its most of using time [8], and according to the existing clinical examples, health care professionals use them for diagnosing Crohn's diseases and other bowel diseases mostly. Besides, with the features of the endoscopy shape, it is better to be used for detecting details of human's intestines. According to this case, the research on the capsule endoscopy is based on its analysis inside human intestinal.

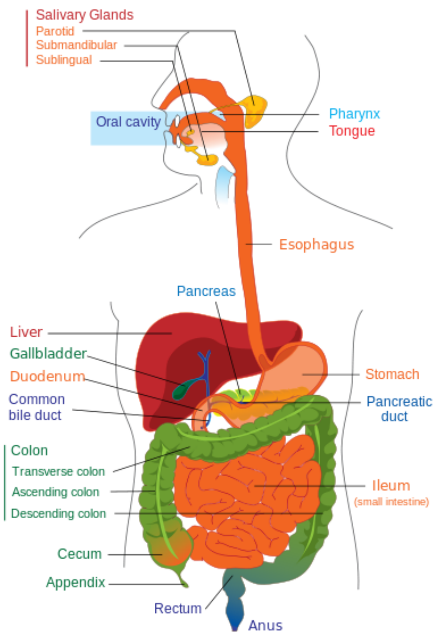

Fig. 2. Human digestion system

After the capsule comes out of the stomach, it enters into small intestine by pyloric sphincter. The small intestine has three parts, the duodenum, jejunum and ileum. From this stage, the food or capsule endoscopy will undergo peristalsis to be moved forward in the small intestine or large intestine. The relating muscles are antagonistic, that is, when one of them is contracting, others are supposed to be relaxed. As a result, the object inside will be squeezed and pushed forward when the circular muscles contract. [7] At the same time, the object will have space to enter in when the intestines are expanded by relaxing circular muscles. Overall, the motion inside the intestines can be treated a stick-slip motion according to its peristalsis characteristics. With this approximation, the LuGre model can be induced to analysis the capsule endoscopy inside the intestines.

3. System Modelling

Principles related with friction model were emphasized in the classical topic in physics. Coulomb found that the friction force is opposite to the direction of velocity but independent of its magnitude, which is generally accepted. However, in Stribeck's experiments, the friction had a slight decline in certain range of increasing velocity. This phenomenon is called the Stribeck effect later on. Now, friction can have an important role to the control system since it has effect on the precision of positioning and pointing systems, which can bring instabilities. To overcome this difference, the Dahl model, is introduced and applied in the aerospace field. At this stage, the Dahl model can describe some properties of friction but the Stribeck effect is excluded. With those ideas, the LuGre model was developed. [9-11]. The LuGre model was considered by the collaboration between control groups in Lund and Grenoble. It is derived from the Dahl model and captures the Stribeck effect. It can be described by the following equations:

$$\frac{dz}{dt}=v-\delta_0\frac{|v|}{g(v)}z=v-h(v) \quad (1)$$

$$F=\delta_0 z+\delta_1 \dot{z}+f(v) \quad (2)$$

In this set of equation, v represents the velocity between the two surfaces. Parameter z is the internal friction state and F is the prediction for the friction.

Compare to the description for the Dahl's model:

$$\frac{dz}{dt} = v - \delta_0 \frac{|v|}{F_c} z \qquad (3)$$

It is clear that the LuGre model will consider the factor of velocity $g(v)$ rather than a simple constant Fc in the Dahl's model. In the second equation, the LuGre model describes the performance for small displacements. In this case, δ_0 is the stiffness and δ_1 I s the micro damping. The $f(v)$ means the viscous friction, and usually equal to $\delta_2 v$. In the steady state, the friction force can beseenas:

$$F_{ss}(v) = g(v)sgn(v) + f(v) \qquad (4)$$

And the reasonable approximation for the $g(v)$ of Stribeck effect is:

$$g(v) = F_c + (F_s - F_c)e^{-|\frac{v}{v_s}|^{\alpha}} \qquad (5)$$

In this case, is the stiction force while F_c represents Coulomb friction force. Therefore, the general curve of the $g(v)$ is like the following Fig. 3 and 4.

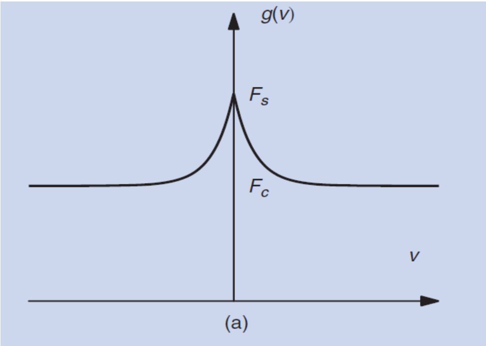

Fig. 3. Function $g(v)$ with Coulomb friction and the Stribeck effect

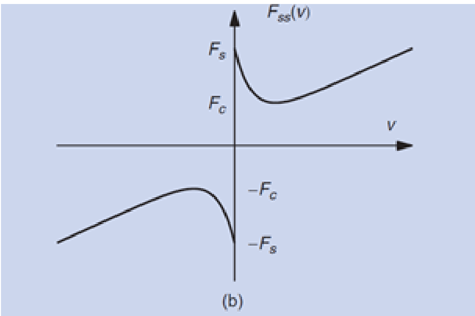

Fig. 4. steady-state function of $F_{ss}(v) = g(v)$ $sgn(v) + f(v)$

On the basis of LuGre model, the stick-slip motion is mainly discussed in this research topic. One of the classical examples for this kind of motion is the spring-mass system. This is just shown in Fig. 5:

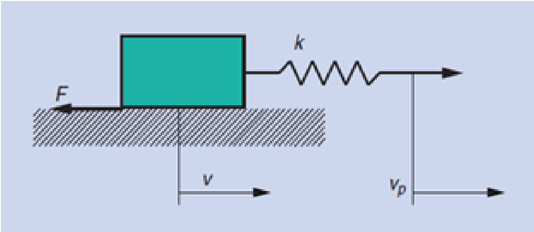

Fig. 5. the spring-mass experiment for the stick-slip

From Fig. 5, the mass is stable when starting pulling the spring. The spring will be elongated at this time. The force with the spring keeps rising until it is larger than the stiction force between mass and surface. After a certain time, the mass will be at rest again and the previous process will repeat. The whole procedure combined with sticks and slips can be modelled for stick-slip motion.

For further discussion, the parameter l is induced for the elongation of the spring. So, $\frac{dl}{dt} = v_p$. In the stick mode, the spring force should be always smaller than stiction force F_s. The parameter k is the spring coefficient and $l_s = F_s/k$. Oppositely, in the sliding mode, the friction force can be treated as Coulomb friction

$$F = -F_c sgn(v) \quad (6)$$

The entire model for the sliding mode is :

$$\frac{dl}{dt} = v_p - v \quad (7)$$

$$m\frac{dv}{dt} = kl - F_c sgn(v) = k(l - l_c sgn(v)) \quad (8)$$

The system varies between slip and stick mode whether v is zero and $|l| > l_s$.

Combining with the general form of the LuGre model, the stick-slip motion can be described as:

$$\dot{l} = v_o - v \quad (9)$$

$$m\dot{v} = kl - F \quad (10)$$

$$\dot{z} = v - \delta_0 \frac{|v|}{g(v)} z = v - h(v) z \quad (11)$$

While the F is the friction force between two surfaces:

$$F = \delta_0 z + \delta_1 \dot{z} + f(v) = \delta_1 v + f(v) + (\delta_0 - \delta_1 h(v)) \quad (12)$$

To be clarifying the parameter z, there is a basic model to describe the phenomenon. Two surfaces make contact each other with asperities, which can be treated as several bristles. The bristles can be deflected just like the spring elongated or suppressed. The deflection increases as the rising of the friction force. However, the bristles will not slip only if the deflection is large enough to bear. In this case, the deflection of the bristles is a random variable which is not clearly described in the LuGre model. Indeed, the parameter z, is the average deflection of the bristles and modelled with the first-order differential equation. [10]

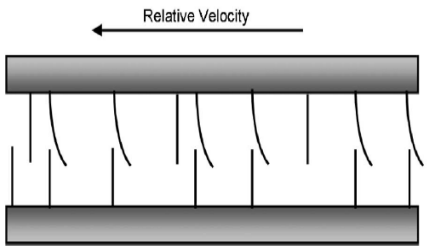

Fig. 6. the bristle model for describing the LuGre model

3.1 Aim and Methodology

In this real case, the aim to research the capsule endoscopy is to reduce its forward speed inside the human intestine. This improvement can make the capsule endoscopy to stay at somewhere inside the intestine for a longer time rather than being pulled forward. As a result, the capsule can take more images than before to help for the diagnosis. With this target and the given LuGre model, the possible solution for this problem can be derived by following steps:

The aim is to reduce the velocity of capsule endoscopy v:

Since in the slipping mode of the LuGre model,

$$v = \dot{l} - v_p \quad (13)$$

$$\dot{v} = \frac{kl - F}{m} \quad (14)$$

Combing the condition inside the human intestine with the mass-spring system for the stick-slip motion, the speed of the capsule resembles the relative speed of the mass. The forward speed to the intestine, which is supposed to be a constant, can be interpreted as the forward speed v_p in that model. The mass of the capsule can corresponded to the parameter m in the LuGre model. The elongation multiplied with the spring coefficient kl, in this case, is also possibly to be a constant because of the characteristics of human digestion.

Therefore, the main ideas to solve this problem are generally to adding mass of the capsule endoscopy or applying an external force. To achieve this, the model should be built and run under the Matlab. So, in the following work, the model for this capsule robot will be simulated to analyse the effect with mass and external applied force.

To testify the effect, a simple block diagram for the LuGre model will be built in the Matlab Simulink. The Matlab Simulink is a powerful application for calculation and simulation. With the assistance of this software, each component of the model can be built and set separately and connected to be simulated.

3.2 Aim and Methodology

At first, the block diagram of the basic LuGre model is supposed to be built. With the model equations, the three equations are designed by users. In total, there are two inputs and two outputs. Besides that, the friction state and its derivative value, z and dz, are inherited as a loop inside the model. To achieve this, the "from" and "goto" links are applied. The following block diagram demonstrates the whole model.

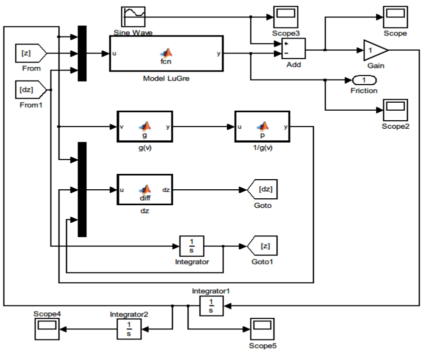

Fig. 7. the general block diagram for LuGre model in Matlab Simulink

The self-defined functions inside the model are quite simple but efficient. The function "fcn", is designed to calculate the value of the friction force between two surfaces. The code for this function is listed in the following blank.

```
function y = fcn(u)
%#codegen
sigma0 = 100000;
sigma1 = sqrt(100000);
sigma2 = 0.4;
y=sigma0 * u(2) + sigma1 * u(3) + sigma2 * u(1);
end
```

As the description mentioned before, the value of the sigma0 is the average bristle stiffness, the sigma1 is the damping coefficient and sigma2 means the viscous friction. The input independent variable u is a 3×1 matrix which stands for average friction state z, its derivative dz and velocity v. The whole function represents the equation (12). The output is the friction force.

The block g(v) means the function which predicting the Stribeck effect. The function and the relating parameters are in the following block.

```
function y = g(v)
%#codegen
fc = 1;
fs = 1.5;
vs = 0.001;
y = fc+(fs-fc)*exp((-v/vs)^2);
end
```

The value of "fc" is the kinetic friction force, while the "fs" is the static friction force. Vs is the Stribeck velocity which is quite small slip one. The result will be take the reciprocal to be calculated the differential of the parameter z.

$$g(v) = F_c + (F_s - F_c)e^{-|\frac{v}{v_s}|^{\alpha}}$$

The "diff" block is aimed at calculating the value of dz with z, velocity and 1/g(v). With the previous blocks provided, the values required are put into the multiplexer and sent to the self-defined block with a 3×1 matrix. The calculation is on the basis of this equation:

$$\dot{z} = v - \delta_0 \frac{|v|}{g(v)} z$$

```
function dz = diff(u)
%#codegen
k = 100000;
dz = u(1)-k*abs (u(1)) * u(2) * u(3);
end
```

After that, the new value of dz will be inherited with the "from" tag of dz and to be calculated at the next time. It works like a feedback loop. As a result, the values of the output will be changed with time rises. Then the response of the system will be evaluated and the motion characteristics will be found.

Table 1. parameters for LuGre model

Parameter	Value	Unit
σ_0	10^5	N/m
σ_1	Sqrt (10^5)	Ns/m
σ_2	0.4	Ns/m
F_c	1	N
F_s	1.5	N
V_s	0.001	m/s

To investigate the situation more clearly, five scopes are set. The scope one is set after the adder, which can present the net force applied on the object. Scope2 is set at the output port of the model LuGre block, which shows the magnitude of friction force. The scope3 is to monitor the applied force on the whole system. In this case, the applied force is set as a sine wave function at first. The fourth and fifth scopes are on the feedback loop of the system. Since the output of the adder is the net force. Due to the equation previously:

$$m\dot{v} = kl - F \tag{15}$$

The acceleration of the object can be calculated only if its mass is known. So, the gain is 1 because of the mass of the object is defined as 1 kilograms in this condition. After integrating once, the velocity of the object can be get, which is exactly the one of input of the "fcn" block. If the result is integrated again, the displacement of the object can be found. Therefore, the functions of these two scopes are to detect the velocity and displacement of the object.

4. Simulation Results

4.1 Original Results

From the block diagram provided, the simulation results can be shown by a variety of scopes directly. The simulation time is 3 seconds and the sine applied force is:

$$f_{applied} = 0.1\sin 12t + 1.25 \tag{16}$$

From the scope 3, the waveform of the applied force is shown clearly with the period of π/6 second and its magnitude is in the range of [1.15, 1.35].

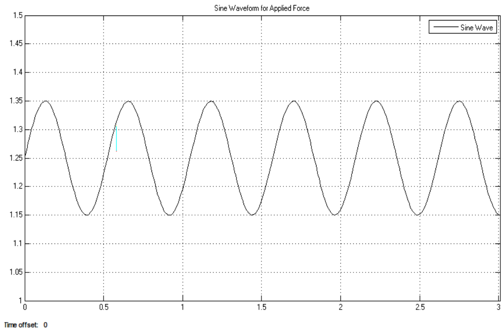

Fig. 8. the output waveform of the applied force

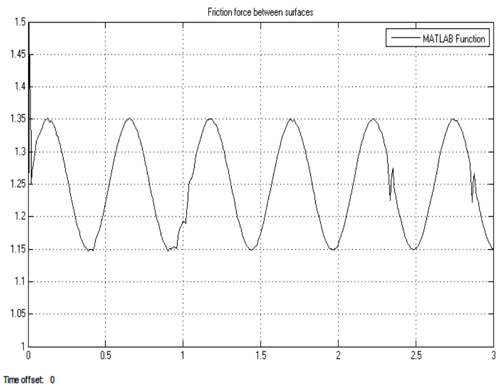

Fig. 9. the friction force between the two surfaces

The scope 2 shows the resultant friction force between two surfaces derived from Stribeck effect. From the graph, there are slight distortion between the applied force and this one, especially at the peak points or bottom ones, which is the net force on the object and its waveform is shown on the scope 1. The graphs of them are in the following.

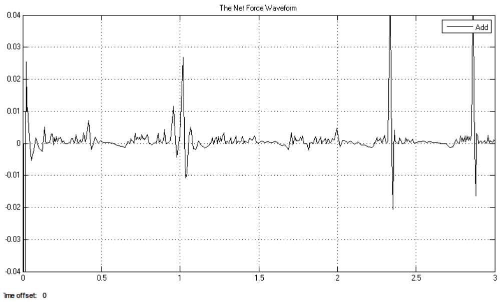

Fig. 10. the net force on the object

The scope 4 and 5 are the description of the object motion, while the scope 4 is the displacement of the object and the scope 5 is the velocity. The waveforms are on the following graph.

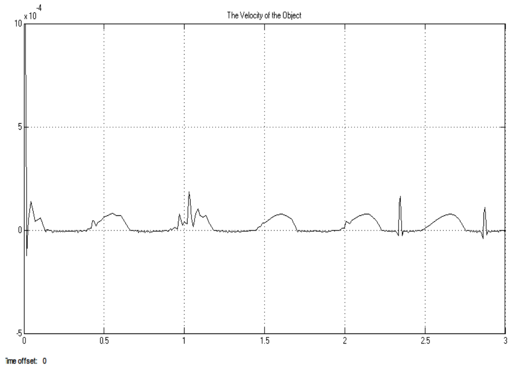

Fig. 11. the velocity wave for mof the object

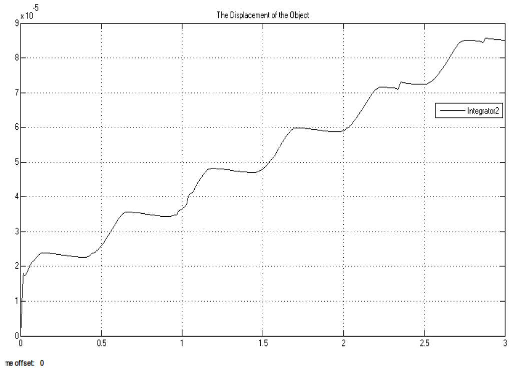

Fig. 12. the Displacement of the object

These two figures are quite important to clarify the stick-slip motion. From the first graph, the object moves at the speed range of $[-1\times10^{-5}, 7.5\times10^{-5}]$ meters per second if the irregular speed is neglected. Generally, the object is supposed to be moved forward as the area under the velocity curve is evidently positive. The next graph, which verifies this assumption, the object moves forward fast at first and then makes slightly backwards in turn. For each period, the object moves forward in a distance of around 1.2×10^{5} meters in total. In all, the motion characteristics can be concluded in the following table.

Table 2. the motion characteristics of the original model

Period	Speed min	Speed max	Displacement	Speed avg.
π /6 second	-1×10^{-5}m/s	7.5×10^{-5}m/s	1.2×10^{-5}m	2.3×10^{-5}m/s

4.2 Implementation

Secondly, according to the given assumption, the change of the object mass will have influences on its motion. In this case, the experimental results will be found by changing the “gain” of the block. As the original value is 1, the new values are set as 1.1, 1.2 until 1.5. The graphs of 1.5 will be shown and the others are concluded inside a new table for comparison.

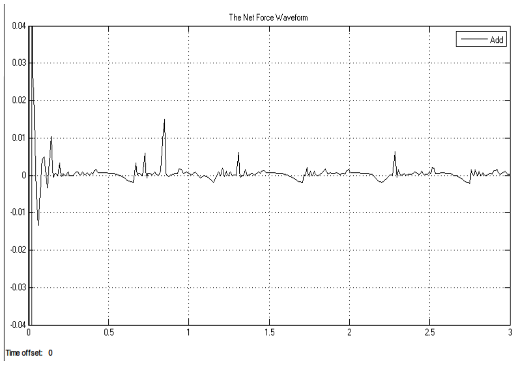

Fig. 13. the net force on the object when mass is 50% larger than original one

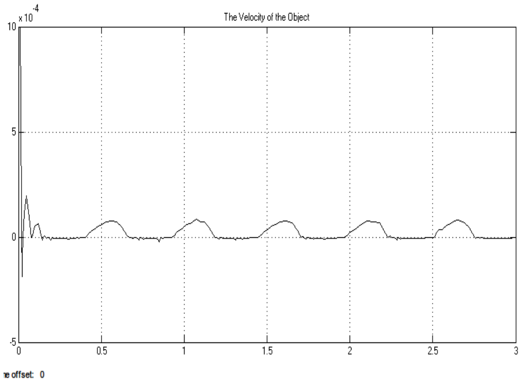

Fig. 14. the velocity for larger mass

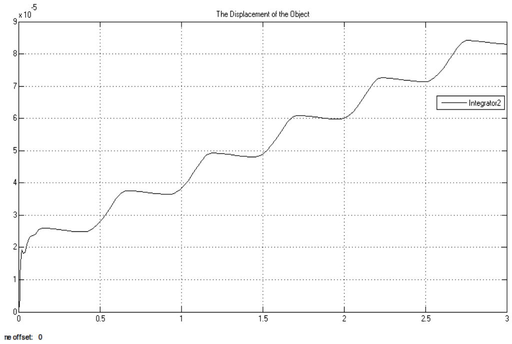

Fig. 15. the Displacement for the larger mass

With reference to the three graphs above, the key statistics for this 150% mass keeps most of the features of the original ones. However, there are still slight differences between these two results. Firstly, the oscillation in the figure 13 is much milder than the one in figure 10, which can cause the smaller acceleration on the mass. Therefore, the top speed of the larger mass is smaller than the standard one but the difference is not as evident as the mass does. After all, during all of the three seconds period, the new one move forward at a distance of 8.3×10−5m, whichisshorterthantheoriginalone,8.5×10−5meters.

It seems that the change in mass does not influence the motion a lot. Then, considering the mass extend to 200%, 300% or even larger. The results will be in the following table.

Table 3. the results of other mass for the model

Mass to Original (%)	Max speed	Overall displacement	Avg. speed
200	7.6×10^{-5}m/s	8.5×10^{-5}m	2.8×10^{-5}m/s
300	7.6×10^{-5}m/s	9.3×10^{-5}m	3.1×10^{-5}m/s
500	7.8×10^{-5}m/s	10.4×10^{-5}m	3.5×10^{-5}m/s
1000	7.7×10^{-5}m/s	11.8×10^{-5}m	3.9×10^{-5}m/s

From the table above, it turns out the results go against the assumption. The average speed of the mass rises as the increment of the mass. Comparing the displacement between these curves, the first period of the displacement varies a lot with the mass. The combined figure below will illustrate the distance of the mass in the first 0.5 second, which is approximately equivalent to the time period.

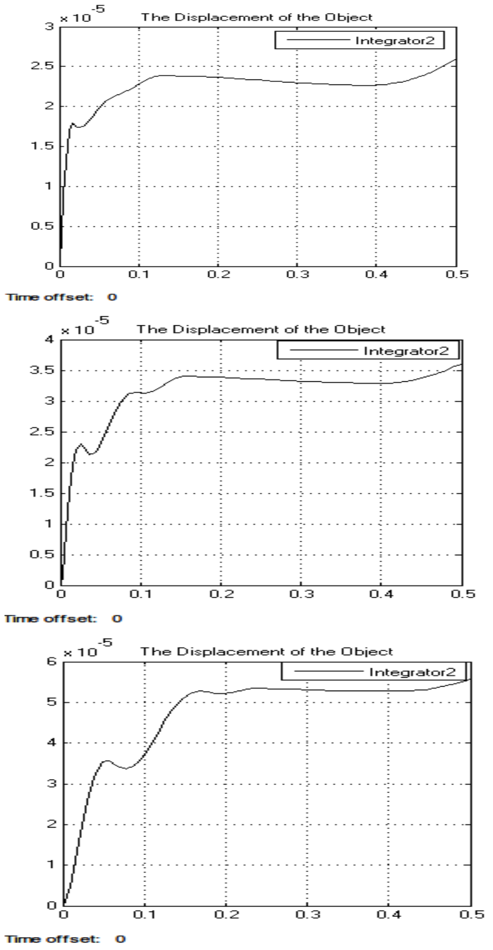

Fig. 16. the displacement of the first time period (0.5 sec for approximation) with the original mass, 300% mass and 1000% mass

From the figures above, the displacement varies a lot due to the mass. The distance of the 1000% mass is the two more times than the original one. Considering this effect, the first-time displacement is supposed to be removed from the overall distance. As a result, the distance and velocity of the mass in the other 2.5 seconds for the mass is in the table below.

Table 4. results for the rest of time

Mass (%)	Distance	Avg. velocity
100	5.9×10^{-5}m	2.4×10^{-5}m/s
200	5.5×10^{-5}m	2.2×10^{-5}m/s
500	5.8×10^{-5}m	2.3×10^{-5}m/s
1000	6.1×10^{-5}m	2.4×10^{-5}m/s

From the table, that the influence of the mass is not clear indeed. For the phenomenon of the first-time displacement, it can be researched in the next stage.

4.3 Implementation II

Besides that, the other idea to affect the performance of the moving mass is to apply the external force on it. To discover this, the original Simulink diagram should be modified a little, as the following figure shows.

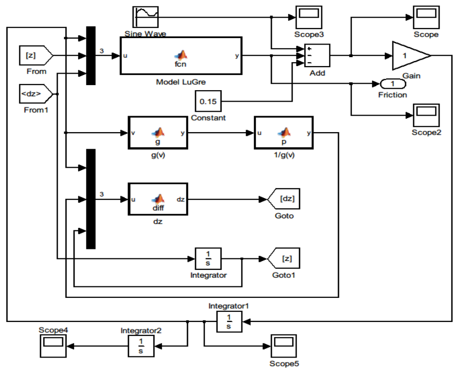

Fig. 17. the test block diagram for external force

It is clear that there is another input added on the adder, which is combined with the friction force and applied force. The rest of the model is remained the same. At first, the value of the force is set as a constant of 0.15N. The results of the system are shown below.

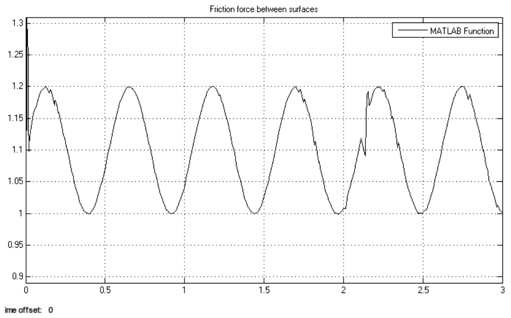

Fig. 18. friction force with the 0.15N external force

Generally, the range of the friction force is around [1, 1.2], which of difference to the original one is exactly 0.15N and the distortion exists compared to the sine wave.

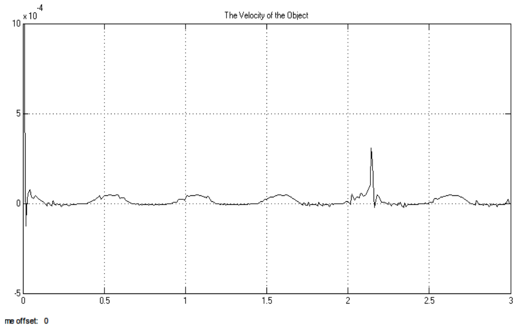

Fig. 19. the velocity with the external force

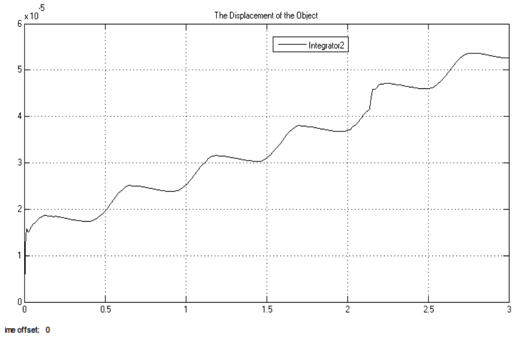

Fig. 20. the displacement with the external force

Using the same way in the previous section, the influence of the external force is listed in the following table.

Table 5. the key results for changing the external force to the mass

External Force (N)	Total Displacement (10^{-5}m)	Displacement in 0.5 sec (10^{-5}m)	Displacement in other periods (10^{-5}m)	Avg. Speed (10^{-5}m/s)
0 (Original)	8.5	2.6	1.2	2.36
0.10	6.0	2.2	0.8	1.52
0.15	5.3	2.0	0.5	1.32
0.25	4.2	1.7	0.5	1.00
0.50	2.4	1.2	0.3	0.48

Comparing the results in the average speed column, the speed decreases sharply with the increment of the external force. Whatever the displacement of every single period, the values are decreased.

4. Conclusions

From the provided results, two ideas for changing the velocity of the mass in the LuGre system are simulated by Matlab Simulink. Generally, the additional mass has little influence on the speed of the mass. In common sense, the magnitude of the sliding friction force is proportional to the mass and the friction coefficient. However, in this case, the force did not extend evidently though the mass was much larger than the standard one. One of the possible reason is the friction coefficient is set too small. Or, according to the results of the first period, the LuGre model may have some special characteristics for the first round of the stick-slip motion. This abnormal situation is supposed to be checked carefully in the further research.

Comparing to that, the additional force will have a very effective impact to decrease the velocity of the mass. This seems a solution to the problem. However, it also has some drawbacks to implement. The most important thing is the energy. Although a little portion of the original applied force will have good improvement, considering the long running time in the real condition and the size of the equipment, the power supply may not have enough energy to complete such a process.

Besides that, the input force of the system is a simple sine wave function. It is the basic function to be simulated. The model was testified perfectly. However, there is still some possibilities for new input types, such as square wave function or triangle wave function to simulate the real condition.

In this research, the capsule endoscopy is the example of the tiny robot system. To investigate this, the features and usage of the real device are discovered in detail, especially the motion characteristics of the human intestine. As a result, the stick-slip motion is the key point to research. Secondly, the friction model named LuGre model is induced to understand the advanced relationship between the velocity and the friction force. The stick-slip motion can be the abstraction of the mass-spring system. The performance of the system is simulated and recorded in the Matlab Simulink. To achieving the aim of reducing the velocity of the mass, two implementations are induced and investigated. The additional mass seems to affect the results not evidently. Comparatively, the additional force in the mass does have apparent effects to slow down the mass. However, the results at this stage is not convincing enough. Other input force or the abnormal facts about the simulation is supposed to be checked in the future.

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