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Investigation of electrostriction appliance and its application for bionics flapping aircraft

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Abstract: A novel design for an electrostriction appliance derived from the theory and application of electromagnetics is presented. The working principle, that is the application of gravitation and elasticity together to realize the "shrinking" and "extending" effect from the distortion and transforming power into mechanical energy, is briefly explained. The characteristic parameter relationships are established and the experimental research is performed. Experimental results show that this sort of electrostriction appliance can perform well as regards driving force and beeline displacement, and furthermore, its self-weight is smaller. This makes it suitable for beeline drivers with a high application value, especially for the driver of the bionic appliance. In the application of the electrostriction appliance to a bionics-flapping aircraft, the wings can work with a flapping angle in the range of a certain value by controlling the "shrinking" and "extending" of the electrostriction appliance. It can reduce the startup power and the impact load of the driver. The flapping extent of the wings will change when the voltage which is put into the electrostriction appliance varies. This makes it more flexible as the bionics-flapping aircraft realizes different actions of flying.

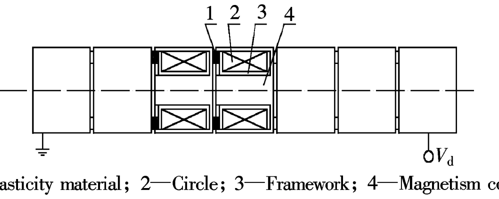
Key words: electrostriction appliance; working principle; bionics-flapping aircraft; flapping-wing movement

There are many modes involved in the driving flapping-wing movement of bionics-flapping aircraft, such as applying RCM[1,2] (reciprocating chemical muscle), adopting micro-electromotor, gear and double-rod[3], applying electrostrictive polymer[4]. A new method of driving is presented that applies electrostriction appliance to the driving flapping-wing movement of bionics-flapping aircraft.

The electrostriction appliance is a novel driver. It can effectively achieve beeline displacement and driving force. It can be designed in several structure forms. In this paper, "pressing spring" mode is employed and the adopted elasticity material is a nonmetal deformable substance.

1 Working Principle of Electrostriction Appliance

When the loop is electrified, a magnetic field will be produced. If two electrified loops are placed with reverse polarities in close proximity to each other, electromagnetism suction will be produced. If an elasticity object is placed between these two loops, "shrink" effect will be engendered. On the other hand, "extend" effect will be engendered if the current is cut off. To augment the suction, a high magnetizer is placed in the loop. And several loops are placed with reverse polarity in close proximity to each other in a line. The goal is to gain larger beeline displacement. The electrostriction appliance expounded in this paper indicates that the beeline driver can engage the "extending" and "shrinking" effect due to the effect of the current to change the mechanical energy from the electric energy, as shown in Fig. 1. If a multilevel electrostriction appliance is applied in driving the flapping activity of a flapping-wing air vehicle, it can be visually named as an "artificial-tendon" because it can "shrink" and "extend" as do the tendons in biology.



1—Elasticity material; 2—Circle; 3—Framework; 4—Magnetism core

Fig. 1 Structure of electrostriction appliance

The concept of the electrostriction appliance comes from the theories and applications of electromagnetism. The gravitation F of the electro-magnet is in inverse ratio with the square of displacement d, as $F \propto 1/d^2$. When F and d satisfy a certain requirement, the electro-magnet always possesses great volume and

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deadweight. This restricts its scope of application.

It is easy to imagine that if the needed displacement is provided by j level of the electro-magnet in series, for example $j = 4$, then the force of every level would enlarge 16 times more than the former one; i. e., four small electro-magnets will replace a big electro-magnet which produces 16 times force more than the small one. The volume and the deadweight of the "4-small-ones" are much smaller than those of the "1-big-one". Furthermore, the difference becomes more prominent as j increases.

In order to expand gravitational action into "shrinking" and "expanding" action, the scheme of coupling of gravitation and elasticity is employed. When gravitation is in effect, the elasticity material shrinks; as it is out of effect, the elasticity material rebounds.

Impulse current is applied in the electrostriction appliance. The requirement for the waveform is not strict, and the frequency is determined by the application condition.

2 Parameter Calculation of Electrostriction Appliance

2.1 Calculation of electrostriction suction

Fig. 2 shows the calculation model of the electrostriction appliance. Where ϕ_c is the diameter of the magnetic core, ϕ_a is the outer diameter of the framework, and ϕ_b is the outer diameter of the magnetizer. Based on $\pi\phi_c^2/4 = \pi\phi_b^2/4 - \pi\phi_a^2/4$, then $\phi_b = \sqrt{\phi_c^2 + \phi_a^2}$. δ is the thickness of the magnetizer's outer loop(m), $\delta = (\phi_b - \phi_a)/2$.

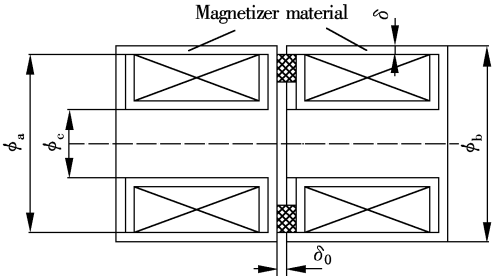

Fig. 2 Calculation model of the electrostriction appliance

The electrostriction suction F_d (N) can be calculated by[5]

$$F_d = \frac{10^7 B_0^2 S_0}{8\pi} \quad (1)$$

where S_0 is the total area of air clearance(m^2), which is twice as big as that of the magnetic core; B_0 is the magnetic induction intensity (T). The approximate expression can be deduced as

$$B_0 = \frac{\Phi}{S_0} \quad (2)$$

where Φ is the magnetism flux. For the electrostriction appliance in Fig. 2, it can be deduced as

$$\Phi = \frac{IN}{R_m + R_0} \quad (3)$$

where I is the prompting current, N is the number of circles of the loop, R_m is the magnetism impedance of the magnetizer, and R_0 is the magnetism impedance of air clearance.

$$R_m = \frac{L}{\mu S} \quad (4)$$

where L is the average length of the magnetism pathway; S is the section area of the magnetism pathway; μ is the magnetism conductance of the magnetizer, $\mu = \mu_r \mu_0$.

$$R_0 = \frac{2\delta_0}{\mu_0 S_0} \quad (5)$$

where δ_0 is the gap of area, i. e. the work clearance or the displacement d of the electro-magnet, which can be as big as the thickness of the elasticity material or less than; μ_0 is the magnetism conductance of area, $\mu_0 = 4\pi \times 10^{-7}$ H/m.

Compared Eq. (4) with Eq. (5), it can be found that for the electrostriction appliance, the magnetism impedance of area satisfies $R_0 \gg R_m$, because high ratio magnetizer is employed and $\mu \gg \mu_0$. To reduce the deducing process, it can be assumed that

$$\Phi = \frac{IN}{R_0} \quad (6)$$

Substituting Eqs. (6), (5) and (2) into Eq. (1), we can get the electrostriction suction,

$$F_d = \frac{10^7 S_0}{32\pi} \frac{I^2 N^2}{\delta_0^2} \mu_0^2 \quad (7)$$

Assuming that $\eta = \frac{10^7 S_0}{32\pi} \mu_0^2$, then

$$F_d = \eta \frac{I^2 N^2}{\delta_0^2} \quad (8)$$

2.2 Analysis of elasticity

For the electrostriction appliance, the rubber circle, which belongs to a deformable non-metal substance, can be selected as elasticity material. As shown in Fig. 3, it has an outer diameter d_2, an inner diameter d_1, and height h. And the distortion quantity is s.

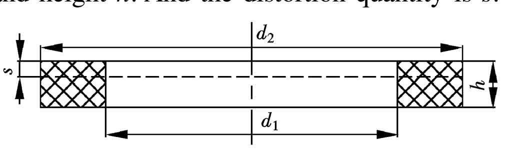

Fig. 3 Rubber circle

When the rubber spring is compressed, the apparent elasticity modulus E_a is in relevance with the geometric shape, which can be expressed as

$$E_a = iG = (3 + kc^2)G \tag{9}$$

where i is the influence coefficient of geometric shape and rigidity, for the rubber circle in Fig. 3, $i = 3 + kc^2$[6]; $k = 10.7 - 0.098H_S$[6], H_S is the Shore hardness; c is the shape coefficient that is equal to the bearing area/freedom area:

$$c = \frac{\frac{\pi}{4}d_2^2 - \frac{\pi}{4}d_1^2}{h(\pi d_2 + \pi d_1)} \tag{10}$$

In Eq. (9) G is the shear module of rubber. The correlation with H_S is[6]

$$G = 0.117e^{0.034H_S} \tag{11}$$

The correlation between the stress σ and the strain ε of the rubber circle in simple distortion such as "extending" or "shrinking" is[6]

$$\sigma = \frac{E_a}{3}[(1+\varepsilon) - (1+\varepsilon)^{-2}] \tag{12}$$

where ε can be obtained as

$$\varepsilon = \frac{s}{h} \tag{13}$$

As shown in Fig. 3, the effect area between the rubber circle and the framework is

$$S = \frac{\pi}{4}(d_2^2 - d_1^2) \tag{14}$$

As a result, the action force F_k between the rubber circle and the framework is

$$F_k = \sigma S = \frac{\pi E_a}{12}(d_2^2 - d_1^2)\left[\left(1+\frac{s}{h}\right) - \left(1+\frac{s}{h}\right)^{-2}\right] \tag{15}$$

The nonlinear rigidity characteristic curve of the rubber circle is shown in Fig. 4. Actually, the elasticity force only needs to overcome the remanence force as well as to achieve comeback. To reduce the rigidity of the rubber circle, the ring-shaped rubber circle, which is usually used, can be processed into several pieces of sector structure.

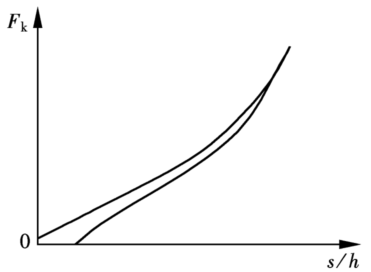

Fig. 4 Rigidity characteristic curve of rubber circle

2.3 Analysis of drive displacement

In Eq. (15), s is the distortion quantity of the rubber circle as well as the distortion quantity between "shrinking" and "extending" of the electrostriction appliance known as the single-level drive displacement.

From the static analysis of the rubber circle, driving force F is the difference between the electromagnetism suction F_d and the elasticity force F_k (while the system is working stably, driving force F is equated with the load).

$$F = F_d - F_k \tag{16}$$

Substituting Eqs. (8) and (15) into Eq. (16), we get the correlation expression between the single-level drive displacement and the correlative parameters of the electrostriction appliance.

If multilevel in series is applied in the electrostriction appliance, then the total driving displacement s_d is

$$s_d = js \tag{17}$$

where j is the number of levels.

The characteristic parameter relationship based on static analysis is established by Eqs. (1) to (17), which can be used in design and analysis for the electrostriction appliance.

2.4 Example

If the diameter of the magnetic core $\phi_c = 4$ mm with the outer diameter of the framework $\phi_a = 10$ mm, and the outer diameter of the magnetizer $\phi_b = 10.77$ mm, the total area of clearance $S_0 = 2\pi\phi_c^2/4 = 25.133$ mm^2.

If the diameter of lead $\phi_d = 0.08$ mm, the resistance of the lead is 277 Ω when the number of the circle $N = 3\,500$. On the basis of the acceptable carrying capacity of the lead we assume that the voltage $U = 24$ V. Then the current passing the lead can be worked out: $I = 0.09$ A. If the clearance $\delta_0 = 0.3$ mm, based on the approximately calculating equation (8), it can be worked out as follows: $\eta = 3.95 \times 10^{-12}$ while the electromagnetism suction $F_d = 4.39$ N.

Because of the magnetism impedance of the magnetizer, the actual value of electromagnetism suction is less than the calculated value. If the electrostriction appliance is applied in the case of flapping-wing air vehicle, the value of the load F is only 1 to 2 N, the electromagnetism suction F_d in this example will be larger than F, and the qualification of start-up will be satisfied. If the rubber circle has a smaller elasticity modulus, then a bigger beeline displacement will be obtained.

Assuming that the magnetism body adopts electrical pure-iron, the consistency of saturation flux $B_s = 2.158$ T, and the diameter of the circle magnetic core

$\phi_c = 4$ mm, and the limit value of electromagnetism suction is

$$F_{\mathrm{dmax}} = \frac{10^7 B_0^2 S_0}{8\pi} = 46.57 \text{ N}$$

From the above calculation, we can see that the value of electromagnetism suction can be adjusted within a wide range according to the concrete application condition.

3 Experimental Research on Electrostriction Appliance

3.1 Design and manufacture of electrostriction appliance

Aim of design: smaller volume, less weight, larger driving force, and greater displacement.

Selecting material of every part: ① The framework material is plastic ABS. In experiment, to make machining easy, the plastic framework is bought and machined. ② The material of the magnetic core we select is electrical pure-iron DT4E. Electrical pure-iron has big magneto conductivity (For general pure-iron $\mu_{\max} = 2 \times 10^4$, while for pure-iron that is very pure $\mu_{\max} = 2.8 \times 10^5$, and for single crystal pure-iron $\mu_{\max} = 4.13 \times 10^6$[7]) and higher saturation magnetic induction value ($B_s = 2.158$ T). It has wide use in relation to direct-current magnetic fields. In experiment, to make machining easy, we decide to buy the magnetic core of type pc30 from the shop. The picture of the framework and the magnetic core is shown in Fig. 5. ③ The elasticity material we choose is NBR 2717 rubber.

Fig. 5 Framework and magnetic core

The facility electrostriction appliance manufactured by hand is shown in Fig. 6.

3.2 Analysis of the experimental result

The experiment was carried out in the unloaded condition. The analysis of the results is as follows:

1) In the experiment, when $\delta_0 = 0.6$ mm, $j = 10$, then we obtain $s_d = 0.2$ mm. The reason why total displacement exists but is tiny is that the magnetic force is small for the circle number being only 300, restricted by the dimensions of the magnetic core.

Fig. 6 Facility electrostriction applicance

2) If the geometric parameters, which affect the magnetic force, have been optimized, greater magnetic force and greater displacement will be obtained and the costs will greatly increase.

3) Because the characteristic parameters of the electrostriction appliance are influenced by several factors, the theoretical calculations are only used as a reference to the design of the electrostriction appliance.

4) For the electrostriction appliance which was developed and manufactured by hand, if we follow correct connections and import the squareness-wave current from both sides of the circle, the magnitude and the frequency of electromagnetism force can be adjusted by changing the frequency of imported voltage and current signal.

4 Feasibility of Applying Electrostriction Appliance to Bionics Flapping Aircraft

In 1992, the American Defense Advanced Research Projects Agency (DARPA) held a meeting about the future military affairs technology. In the meeting, the concept of micro air vehicles (MAVs) was brought forward for the first time. Meanwhile, the weight was restricted to that of an insect or that of a bird[8].

Since the appearance of the concept of MAVs, the relevant research projects received great attention from DARPA and NASA which are military organizations, and great progress has been made. From the research results in existence, micro aircraft can be sorted into three kinds: fixed-wing, spin-wing and bionics flapping.

The research into fixed-wing aircraft and spin-wing aircraft achieves a satisfactory level, but the flying-animal-in-nature without exception adopts the flapping mode to fly. So researchers believe that flapping is the optimal mode in flight in biological evolution. The research concerning flapping aircraft has become the hotspot in this field.

The biological flying mechanism is highly complex. It is almost impossible to design an aircraft entirely imitating the mechanism of biology. So usually we partly anticipate its motion. The basic flapping motion is wing-flapping in a definite angle in an upright plane. The physical model of electrostriction driving wings is shown in Fig. 7(a), and the kinematics diagram is shown in Fig. 7(b). The wing can flap within a range of a definite angle by controlling the electrostriction "shrinking" and "extending".

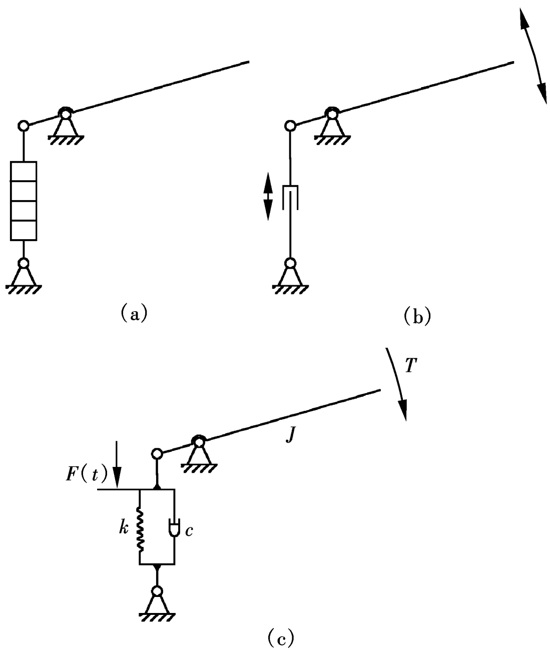

Fig. 7 Electrostriction driving wings. (a) Physical model; (b) Kinematic diagram; (c) Mathematical model

The mathematical model corresponding to the physical model is shown in Fig. 7(c). Therefore, J is the moment of the inertia of the wing. k and c are the equivalent stiffness coefficient and the damp coefficient of the electrostriction, respectively. The system is under the action of electromagnetism force $F(t)$ and the wing is flapped. $F(t)$ is in equilibrium with the resistance torque when the wing is flapping.

When the system starts, the torque is great when $F(t)$ does not need to adopt a big value. Under the condition of $F(t)$ being small, the range of wing flapping is small. Time after time, the energy is cumulated. After that, the range of flapping will become greater. Then the inertia force will be in equilibrium with the elasticity while $F(t)$ is in equilibrium with the resistance. We call this characteristic "soft startup". Compared with "hard startup", it decreases the startup power of the driver and the impact load of the whole system.

When the voltage put on the electrostriction appliance that drives the wings is changing, the range of flapping will also change. Then it will vary the motion of flying, such as turning and overturn. So the system possesses great flexibility.

Compared with other driving modes, the electrostriction appliance develops a new method of driving. For example, its requirement for the environment is less than that of the driving mode that applies RCM, so it is suitable for civil or military applications. If we adopt a micro-electromotor to offer the driving force, something must be added to the system, such as gears and double-rods that drive the wings to flap. Not only is the running efficiency of the rod lower, but the ranges of the left wing and that of the right wing are different which causes an asymmetry of inertia force. And it makes the stability of the whole system poor. Compared to electrostrictive polymers that drive the system, it is more suitable for the larger sized micro-aircraft.

In summary, the merits of adopting electrostriction appliances to driving bionics-flapping aircraft are greater in stability, efficiency, flexibility, the rates of capability with lower cost. And its disadvantage is that it requires larger size. So it is suitable for civil and military applications.

5 Conclusion

The electrostriction appliance is a kind of beeline motion driver. It has wide applications in the future for its simple structure and its facility of manufacture. By reasonable design, especially logical choices of material for every part, such as consideration of "less weight" and "higher magneto-conductivity", this kind of driver will obtain greater beeline displacement and driving force when the preconditions of whole size and weight are lower. It is well-used for imitating the movements of animals in the realm of biology, such as the flapping-wing movement of bionics-flapping aircraft. When applying the electrostriction appliance in the flapping motion of bionics-flapping aircraft, the startup power of the driver and the impact load of the whole system are decreased, a greater flexibility in varying the motion of flying is obtained. In conclusion, a potential worthiness of this application exists.

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电致伸缩器的研制及其在仿生扑翼飞行器中的应用

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摘要:提出了一种源于电磁铁理论和应用的电致伸缩器的新颖构思,简述了电致伸缩器采用引力与弹力互联以形变产生伸缩效应、将电量转化为机械量的工作原理,建立了电致伸缩器的特性参数关系,进行了电致伸缩器的实验研究. 研究表明,这种电致伸缩器能获得较好的驱动力和较大的直线位移且自重较小,是一种具有较高应用价值的直线驱动器,尤其适用于生物器件的驱动. 将电致伸缩器应用于仿生扑翼飞行器,通过控制电致伸缩器的"缩"和"伸",能实现翼在一定角度范围内的上下拍动. 该驱动方式能减小驱动器的启动功率和整个系统的冲击载荷,通过改变驱动两翼的电致伸缩器的电压可使两翼拍动幅值不同从而方便地实现不同的飞行动作.

关键词:电致伸缩器;工作原理;仿生扑翼飞行器;扑翼运动

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