БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ . BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, 54
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, 54

София . 2004 . Sofia

Replacement of the Damphers by Spring Accumulators in a Pneumatically Driven Link

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1. Description of the cycling motion with spring accumulators and background

The cycling link moving between two points may be realized as a “spring pendulum” where the inertia forces are fully compensated by the spring forces. The motion is self-excited oscillation motion between two points. At the end points, the link is clamped by a proper locking mechanism. This principle allows the use of very small driving force theoretically equal to the friction force. The driving force is applied collinearly to the velocity of the link.

The advantages obtained by this principle are the big velocities and the low energy consumption.

A mechanical arm based on this principle [1] is patented first in Sweden by Riderstrom, (1974). The theoretical basics of oscillators with continuously adding of energy during the cycle are developed in Russia by Korendiasev, Bolotin, Tives and Salamandra (1981) for electro-driven links and in Akinfiev and Krupenin [2] for pneumatically driven manipulators. The theory and basic constructions of pneumatically driven manipulators with adding of the energy at the end of the cycle are developed in 1985 in Bulgaria (Stainov, Konstantinov, Tanev [3]).

2. Strategies of adding the energy

There are two strategies for adding the energy lost during the motion for obtaining self-exciting oscillations between two points:

- Continuously adding energy during the cycle. A constant force equal to or exceeding the friction force is added during the whole road of the link. It can be a small motor directly coupled to the link. To prevent overexcitement, the power of the motor must be controlled. This is suitable for electro-driven links.

- Adding energy at the end of the cycle. At the end of the cycle, the clamp may add the energy necessary for reaching the end position. This is appropriate for pneumatically driven links.

3. Criteria and basic formulae for selection of the spring accumulator

The moving link with mass M, the two clamps and the two springs positioned at the end points A and D are shown schematically in Fig. 1.

The spring turns the moving link into an oscillator (spring-pendulum). Consider that the link is permanently connected to the springs and the point B coincides with point D in the figure ($L_0 = 2L$). The time for reaching the position is half the period of the oscillation T.

Considering that the motion is self-excited oscillation and the lost energy is compensated, the single degree of freedom oscillator with mass M and spring coefficient c has a natural frequency k:

$$k = \sqrt{c/M}.$$

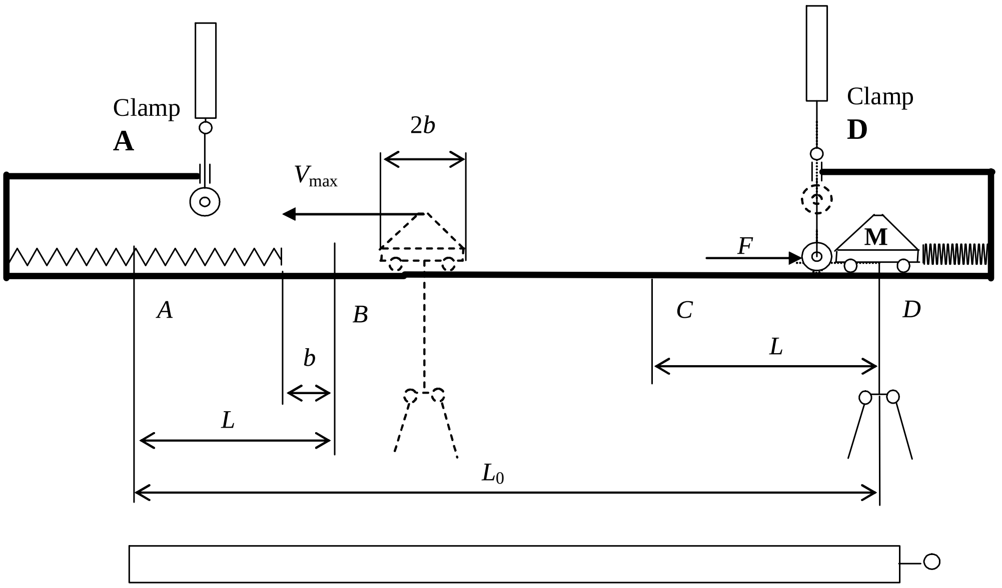

Fig.1. Scheme of the manipulator link with spring accumulators and energy adding clamps. The pneumatic cylinder required for performing the motion L_0 of the link is shown underneath. L_0 is length of the road; M – mass of the moving links; F – maximal spring force; V_{max} – velocity of the inertial travel; L – length of the spring road; $2b$ – width of the locking link

The period T depends on the mass M and on the spring force:

$$T = 2\pi/k.$$

From the above equations the spring coefficient is obtained:

(1) $$c = \frac{4\pi^2 M}{T^2}\ .$$

The equation of the simple oscillations is

$$x(t) = L_0 \cos kt$$

where L_0 is the road of the link between points A and D.

The expression (1) allows for the calculation of the spring constant for a desired period T and mass M in the case when the link is permanently connected to the spring.

When the link is not permanently in contact with the springs ($L_0 > 2L$), as shown in Fig.1, the link between points B and C is moving under the inertia forces and the Coulomb friction. The velocity at point B is:

(2) $$V_{\max} = kL.$$

The inertial motion of the link starts at $t_1 = k\pi/2$ and continues approximately $t_2 = (L_0 - 2L)/\ V_{\max}$.

The half of the period is $\tau = 2t_1 + t_2$.

The angular frequency for this case is

$$k = \frac{\pi L + L_0 - 2L}{L\tau}$$

yields the spring coefficient:

(3) $$c = k^2 M.$$

The maximum spring force at points A and D is:

(4) $$F_{\max} = cL.$$

A scheme of the forces and energy losses during the motion is shown in Fig. 2.

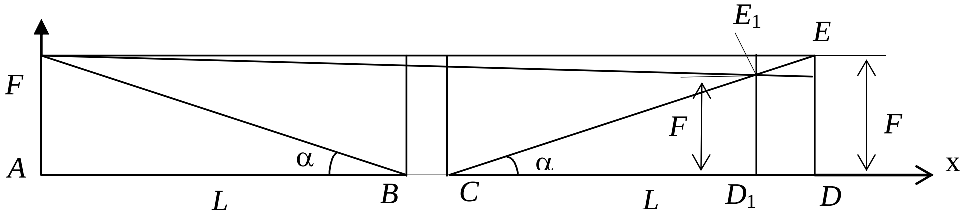

Fig.2. Determination of the force characteristics of the energy adding mechanism: F – maximal spring force; F_1 – the spring force at point D_1

The maximal value of the potential energy of the spring is

(5) $$E_p = (1/2)\ c\ L^2.$$

The lost energy is

(6) $$E_l = mMgL_0.$$

For the existence of self-excited oscillations E_p must be greater than E_l. Hence, for the spring coefficient from equations (5) and (6), the following is obtained:

(7) $$c > \frac{2\mu MgL_0}{L^2}\ .$$

The minimal admissible period $T_{\min}(\mu)$ in relation to the coefficient of friction is shown in Fig.3. The curve shows that this principle is better applicable for smaller periods than for bigger velocities. Knowing the coefficient of friction and the parameters of the oscillating system, equation (7) yields the minimal admissible spring coefficient.

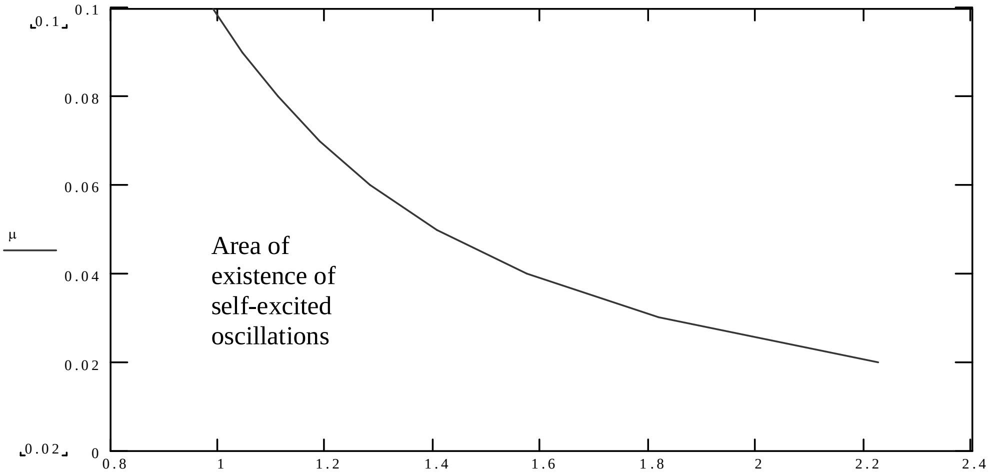

Fig. 3. The minimal admissible period $T_{\min}(\mu)$

4. Basic requirements in the synthesis of the locking mechanism

The locking mechanism holds the movable link into a position, releases the spring force at the beginning of the motion and clamps the link at the end position, adding the lost energy into the spring. Depending on the control strategy, the locking mechanism may add energy also during the acceleration of the link.

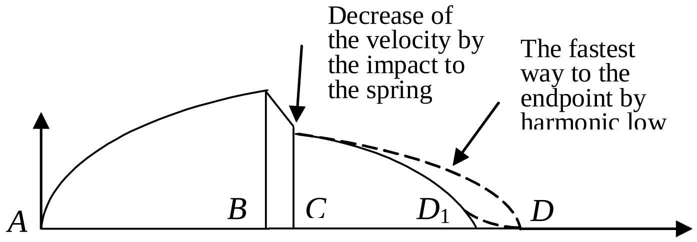

Fig.4. Scheme of the velocity versus the position of the link. When the link reaches point C, the clamp D is released, and pushes it into position.

The locking mechanism on the scheme in Fig.1 is driven by a small cylinder. In the locked position, the locking link is under the maximal spring force F and the mechanism must fixate the link even at zero air pressure. When the moving link reaches point C, the pneumatic cylinder is powered and the locking mechanism grips the link. For reliability of the motion, the force applied to the link at point D_1 must be at least equal to F_1.

If no energy is added, the link will stop at point D_1 before turning back. Hence, the force applied by the locking mechanism at point D_1 must be greater than the spring force F_1.

The clamping may occur between points C and D_1 and must cause minimal impact forces by the accepted variation of the energy losses.

For minimizing the period of the cycle and the acceleration forces, the mechanism should set a harmonic motion to the link at the end position (Fig. 4).

There are some cam and lever mechanisms suitable for this purpose. For the calculation of the locking mechanism the force F_1, the length CD_1 and the velocity at the clamping point B are required.

The surface of the triangle CD_1E_1 is the maximal value of the potential energy minus the lost energy:

$$\frac{CD_1^2 c}{2} = \frac{cL^2}{2} - \mu MgL_0$$

and

$$CD_1 = \sqrt{\frac{cL^2 - 2\mu MgL_0}{c}} \,. \tag{8}$$

The force F_1 is

$$F_1 = cCD_1 = \sqrt{c^2L^2 - 2\mu cL_0 Mg} \,. \tag{9}$$

5. Evaluation of the energy savings using the "spring pendulum"

The evaluation consists in comparison of the energy consumption for different periods T, of a resonant module shown in Fig. 1 and one linear module of traditional design performed by an single pneumatic cylinder as shown in Fig. 5.

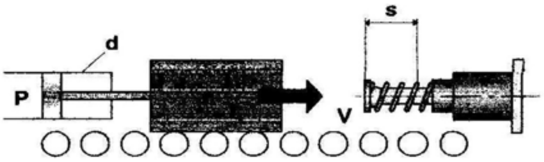

Fig. 5. A scheme of a traditional design of a pmeumatically driven linear module

The input data are:
$2T$ = 0.5, 1, 1.5, 2 s is the periods of the cycle;
L = 1 m is the length of the road;
Q = 90 kg is the mass of the link;
m = 0.05 is the coefficient of friction in the bearings;
l = 0.15 m is the length of the spring of the locking mechanism;
p = 6 bar is the air pressure.

The air consumption for one hour in l/h for both modules is given below:

$2T =$	$Q_2(T)\,\frac{3600}{2T} =$	$Q_1(T)\,\frac{3600}{2T} =$
0.5	7.956×10^4	4.28×10^3
1	9.945×10^3	1.118×10^3
1.5	2.947×10^3	541×981
2	1.243×10^3	359×518

The results in the left column $Q_2(T)$ are for the traditional design and the results in the right column $Q_1(T)$ – for the same system designed as a “spring pendulum”.

It is obvious that the transformation of the link into an oscillator with motorized clamps gives great effect by increasing the frequency of oscillation. The result is calculated for a locking mechanism of a guide-way type.

6. Comment

In conjunction with the advantages, the implementation of the “spring pendulum” has some restrictions:

– The large acceleration at the beginning of the motion, due to the abrupt implementation of the maximal spring force.

– The necessity for leveling of the system in order to obtain equal potential energies at the end points.

– The impossibility to stop the link between the end points at emergency.

The big driving force causes a big reaction force on the base. All elements between the link and the earth are deformed under this force. The abrupt implementation of it causes vibrations and energy losses.

7. Conclusion

The implementation of motorized spring-clamps instead of dampers turns the cyclic-moving link into an oscillator. The reduction of the pressure air consumption, depending on the coefficient of friction and on the period of the cycle may exceed 10 times.

The results published here are a new part of the investigations on self-excited oscillations which have been done at CLMI for more than 15 years.

References

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Замещение демпферов звена с пневматической задвижкой пружинными аккумуляторами

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(Резюме)

Для получения быстрого циклического движения звена, вследствие повышении инерционных сил, требуется значительной мощности двигателя.

В пневматической задвижке это означает большей консумацией сжатого воздуха и применение больших демпферов. Уже известен принцип “пружинного маятника”, у которого инерционные силы впольне скомпенсированны. Ряд конструкции с електро- и пневмозадвижки разработаны в Швеции, России и Болгарии. Результаты показывают, что эти конструкции надежные и обеспечивают значительной (в некоторых случаях надвишающей 10 раз) экономии сжатого воздуха. Цель настоящей статьи является обсуждение предимств этого принципа и основ конструирования и вычисления звенев с пневматической задвижкой.