Study of a Pneumatic Robot Utilizing a BTA (Bourdon Tube Actuator)

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ABSTRACT

The Pneumatic BTA (Bourdon Tube Actuator) is a stickslipless actuator which utilize a pair of spiral bourdon tubes as a functional element and obtains displacement by air pressure. Compared with an electric motor and so on, the BTA is smaller and lighter; moreover, it generates a high torque and accurate positioning.

Before now it has been difficult for a cylindrical type pneumatic actuator to control accurate positioning because of sliding friction. Our laboratory developed a three-axis driving robot with 4-bar linkage utilizing a pneumatic BTA. We obtained oscillating of ± 15 degrees and minimum sensitivity 0.6×10^{-2} degree. A pneumatic BTA robot system makes possible minute action and accurate positioning.

KEY WORD

Torque and position controlled actuator, Pneumatic Robot, Stickslipless actuator

1. Introduction

BTA stands for "bourdon tube actuator," a rotary oscillating actuator that uses spiral bourdon tube to convert air pressure into an angular displacement.

Among its features:

- It has a high weight torque ratio
- It has a small coefficient of friction, because structurally it has no sliding surface.
- It is leakless and is suitable for clean operation.
- It is capable of rotary oscillating operation at low speed without using a speed reduction mechanism as in a geared motor.

Actuators are divided broadly into those that operate by energy conversion and those that operate by functional elements. A BTA has elements of both types, be-

cause it converts pressure into angular displacement, and the material and shape of its bourdon tubes directly affect its characteristics.

Used in this study was a spiral bourdon tube having a built-in air-pressure gauge.

We analyzed its pressure and displacement characteristics and derived calculation formulas that approximate its characteristics and are needed for BTA design. We also developed a positioning control system using this BTA that yields an angular resolution (0.6×10^{-2} deg) not available with conventional pneumatic actuators and a response of approximately 2.0 Hz.

In the laboratory we developed a pneumatic robot system using this actuator and built a three-axis driving robot. In this study we describe its functions and the system.

2. Basic Structure of The BTA¹⁾

In the BTA, two bourdon tubes positioning in the opposite direction, connected by a common rotation shaft. The inner end of each bourdon tube is connected to the common rotation shaft, and the outer end is anchored to the case. Pneumatic pressure is applied through the stationary part at the outer end. Here the pressure of the bourdon tubes is denoted by P_A and P_B . With this simple structure, the rotation of the output rotation shaft is obtained from the pressure difference ($P_A - P_B$) between the two bourdon tubes.

In a BTA, the characteristics of each individual unit vary slightly from the bourdon tube manufacturing process, but they are averaged by being made to oppose each other as in Figure 1. The angular displacement of the BTA common rotation shaft is detected by a resolver, allowing the angular displacement to be determined.

3. Calculation of Rotation Displacement Angle and Torque

The Wolf theorem²⁾ is used for calculating the rotation displacement angle and torque of a BTA. In a BTA, a pair of spiral bourdon tubes, which have a flat-oval cross-section, is used as the driving element, as in Figure 1. Denoting the supplied pressure by P_A and P_B , the rotation displacement angle by θ_{BTA} and the torque by T_{BTA} , according to the Wolf theorem the change in the bending radius ΔR_A and torque T_A with respect to bourdon tube A are given by

$$\Delta R_A = \frac{a^3 K_3}{Eh^3(1 + \lambda^2 K_1)} P_A R \quad (1)$$

$$T_A = \frac{a^6 K_4}{Rh^2(1 + \lambda^2 K_2)} P_A \quad (2)$$

and the change in the bending radius ΔR_B and torque T_B with respect to bourdon tube B are given by

$$\Delta R_B = \frac{a^3 K_3}{Eh^3(1 + \lambda^2 K_1)} P_B R \quad (3)$$

$$T_B = \frac{a^6 K_4}{Rh^2(1 + \lambda^2 K_2)} P_B \quad (4)$$

Fig. 1 Basic structure of BTA

Table. 1 Specifications of Bourdon Tube

Material	SUS 316 TP
Shape of Cross Section	FLAT-OVAL
The Number of Windings	3.25
Pressure	0 ~ 3(100%) (Kg/cm ²)
Displacement of angle	22.5(deg) (100%)

K_1, K_2, K_3 , and K_4 are constants determined by the tube cross-section and its long-short radius ratio and are determined by approximating the flat-oval cross-section with an approximation ellipse. These constants are important in calculating the rotation displacement angle and torque of a BTA. In the formulas here, the symbols of Figure 2 are as follows.

E : modulus of longitudinal elasticity

θ : angle between two cross-sections perpendicular of tube

$2a, 2b$: Major or Minor axis of the cross-section in regard to a neutral surface of wall

λ : a^2/Rh

ΔR : changing of radius after the pressure is put upon the tube

h : thickness of tube wall

T : torque

The amount of movement S_A, S_B of the tip of each bourdon tube is expressed as follows.

$$S_A = \sqrt{2(1 - \cos\theta) - 2\theta \sin\theta + \theta^2} \times R_A \quad (5)$$

$$S_B = \sqrt{2(1 - \cos\theta) - 2\theta \sin\theta + \theta^2} \times R_B \quad (6)$$

Fig. 2 BTA dimensions

The amount of movement S_A, S_B of the tip of a bourdon tube is the amount of displacement of the bourdon tube that is connected to the rotation shaft of the BTA, so R is constant, and converting S_A, S_B to the rotation angle displacement θ_A, θ_B (deg) of the bourdon tubes yields the following.

$$\theta_A = \frac{360}{2\pi R} \sqrt{2(1 - \cos \theta) - 2\theta \sin \theta + \theta^2} \times \frac{a^3 K_3 P_A R}{Eh^3(1 + \lambda^2 K_1)} \quad (7)$$

$$\theta_B = \frac{360}{2\pi R} \sqrt{2(1 - \cos \theta) - 2\theta \sin \theta + \theta^2} \times \frac{a^3 K_3 P_B R}{Eh^3(1 + \lambda^2 K_1)} \quad (8)$$

From this, the rotation displacement angle θ_{BTA} of the BTA, taking the reaction of Bourdon tubes A and B into account, is

$$\theta_{BTA} = \mu \times \frac{\theta_A - \theta_B}{2} \quad (9)$$

where μ is a coefficient that depends on the material of the bourdon tubes and the precision of its machining. Similarly, the torque T_{BTA} of the BTA is as follows.

$$T_{BTA} = \frac{T_A + T_B}{2} (Kgf \cdot cm) \quad (10)$$

Figure 3 shows the output rotation torque T (Kgf · cm) with respect to the rotation displacement angle α of the BTA. The torque varies linearly with changes in the rotation displacement angle α (deg). Figure 4 shows, for bourdon tubes A and B, the relationship between the pressure P (Kgf/cm²) and rotation displacement angle α and the set pressure P_1 with respect to the applied pressure P_2 , as measured optically using laser spot triangulation. For the theoretical value in the diagram, the above-determined theoretical formula (9) is used, and coefficient μ is 1. In this diagram too, the angle varies linearly with the pressure.

4. Structure of BTA Robot

We built in laboratory a three-axis driving robot using three of these BTAs. The purpose is cause letters to be written on minute particles as the first step. For this purpose, a four-bar linkage is adopted, and the hand part is a mechanism that always moves parallel to the X-Y plane.

Fig.3 Characteristics angle / torque

In Y-direction changes with respect to a coordinate system as shown in the diagram, displacement is obtained by driving the Y-axis BTA, and the hand part is moved from P to P' parallel to the X-Y plane by making ABCD in Figure 5 (a) into a parallelogram. Similarly for changes in the X direction, displacement is obtained by driving the X-axis BTA with respect to coordinate system as shown in Figure 5(a), and by making EFGH in Figure 5 (b) into a parallelogram, the hand part is moved parallel from P to P'.

P. For changes in Z direction, that is, changes in the height of the hand part, the hand tip part is displaced from P to P' by driving the two-axis BTA. Denoting the angle of the respective BTAs by θ_x , θ_y , θ_z , this is expressed as follows.

Fig. 4 Static characteristics of rotational angle and pressure

$$\theta_x = \sin^{-1} \frac{X - dX}{L \cos \theta_y} \quad (11)$$

$$\theta_y = \sin^{-1} \frac{Y}{L} \quad (12)$$

$$dX = M - M \cos \theta_z \quad (13)$$

5. BTA Robot System

Figure 6 is appearance of the BTA robot, Figure 7 is its block diagram. The BTA robot control system includes a host computer (PC9821), R/D converter, compressor, electric-air regulator, the robot itself, a resolver, a dryer, and a lubricator. A 12-bit D/A converter board and 8255 board are built into the expansion slots of the host computer, the pressure signal to the electric-air regulators D/A converted, the actually obtained rotation angle is detected by the brushless resolver, R/D conversion is performed, and it is fed into the computer. The actually obtained rotation angle displacement ϕ_i is calculated by R/D-converting the resolver signal, and it is compared with the input displacement angle θ_s . Then feedback is done so that $\phi_i = \theta_s$.

Fig. 5 Mechanisms of BTA robot

Fig. 6 Appearance of BTA robot

Fig. 7 Block diagram of BTA control system

The output signal of the personal computer can be output with a resolution of 1.22×10^{-3} , so the output then can be controlled with a resolution of 1.22×10^{-3} (Kg/cm^2). Actually it is constrained by the resolution of the electric-air regulator and is 0.6×10^{-3} (Kg/cm^2). Figure 8 presents the frequency response of the BTA control system. It shows that it can track closely up to about 2 Hz. The output control valve used in this system is an off-the-shelf electric-air regulator. Since the frequency response of this electric-air regulator is 2 Hz, the frequency response of BTA control system depends to a great extent on this electric-air regulator. Because of this, an improvement in the dynamic characteristics of the electric-air regulator improves the dynamic characteristics of the BTA control system.

Fig. 8 Bode diagram of BTA control system

6. Relationship of Tip Displacement and Pressure

Figure 9 shows the result of measuring with a cathetometer the movement of the BTA robot hand's tip end when the pressure is varied from 0 to 5 (Kg/cm^2) based on the coordinate system of Figure 5. When this is done the pressure of the other bourdon tube is kept constant at 0 (Kg/cm^2). On each axis the amount of movement is symmetrical in the positive and negative directions, a nonlinear curve described, and hysteresis is observed. The reason for this is thought to be that because (1) applied BTA of measuring Bourdon Tube could not obtain the torque for the purpose and (2) the bourdon tube is an elastic body, insufficient rigidity is obtained at pressure of 0-5 (Kg/cm^2), so because of the structure of the BTA robot there are interactions with the weight of the link parts, directly or by friction. The results shown in Figure 4 are for a single BTA, no load is applied to the rotation shaft, and the changes linear, but from these results too it can be inferred that the weight of the link parts and friction play a large role.

Fig. 9 Displacement-pressure curves for the end effector of robotics

Near 0 (Kg/cm^2) there is a big difference in the amount of movement between the case when pressure is reduced. This difference is attributed to the fact that a certain pressure is needed for operating the exhaust valve in the back pressure chamber of the solenoid nozzle, and when the pressure increases, the pressure needed for operating this is near 0 (Kg/cm^2), and this effect becomes apparent.

7. Conclusion

To compensate for the characteristics of compression fluid, which are a drawback of pneumatic actuators, it is possible to take the average of two bourdon tubes by opposing them to each other. Because there is no stick-slip, there is no need to use lubrication oil, and because a

BTA angle resolution of 0.6×10^{-2} degree is obtained, improvement in the dynamic characteristics of electric-air regulator can be expected, as well as three-axis driving robots made for the purpose of fine operations, such as in bio-technology, based on use at higher pressure.

Reference

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