OPPOSED TUGGER-PAIR AND TWISTOR-PAIR PNEUMATIC POLYMERIC MECHATRONIC ACTUATORS

Henry M. Paynter, *Professor Emeritus, MIT,* **Rudy Wojtecki**, *Associate Professor, Kent State University*, **Mark Nagurka**, *Associate Professor, Marquette University*, and **Joseph M. Juarez, Jr**., *Member, ASME*

Abstract— Positional control of pneumatic polymeric Tugger and Twistor actuators is directly accomplished simply by modulation of input pressure. Characteristics are based on thermodynamic principles using the enthalpy function H(P,Z) as the fundamental potential dependent on pressure, P, and a positional variable, Z, which is the Tugger stroke or the twist angle of the Twistor. While the derived characteristics have been previously validated for single Tuggers and Twistors, many applications utilize these actuators as antagonistic opposed pairs, featuring flexible open-loop control effected by suitable PC/PLC programming. The objective of this paper is to describe test rigs used to develop and ultimately provide suitable data for typical open loop control applications. This paper is a progress report, with the first part addressing an application to a vibrating suspension platform employing Tugger-pairs at each end. The second part addresses similar position control of a laser pointer attached to two opposed Twistor-pairs arranged in an orthogonal configuration forming a Gimbal-drive, thus demonstrating actuation of a spherical joint..

Index Terms—pneumatics, Tugger, Twistor, Gimbal-drive

I. Introduction

For the last three decades novel forms of polymeric and elastomeric fluid actuators have been produced for application to robotics and other control systems. These devices have unique properties that allow them to compete advantageously with more conventional pistons and vanes. In particular, linear contractile tension actuators, or Tuggers, as well as rotary actuators, or Twistors, have been described and analyzed in several papers (Paynter, 1996a, b; Paynter and Nagurka, 1997; Paynter and Juarez, 1999). These particular papers are all now readily available at the website: www.hankpaynter.com then follow the link "Pneumatic Tug-&-Twist Technology," together with much other collateral information. The devices described here are also covered, in part, by the following US Patents: For Tuggers: USP 4,721,030 and USP 4,751,869; and For Twistors: USP 4,108,050 and USP 4,751,868, details of which are also available at the USPTO website. Interested readers are urged to read this prior background information the better to understand the material presented here.

Like piston-&-cylinder apparatus, Tuggers and Twistors are First Law devices, whose fundamental thermodynamic properties can be derived from a fundamental equation or potential, in the particular form of a generalized enthalpy, H (P, Z) where P is the input internal pressure and Z is an appropriate position variable. For a fluid piston H = P*A*Z with A being the bore area. The resulting displacement volume V = A*Z while the piston force becomes F = P * A. However, comparable but more complex results for Tuggers and Twistors were presented in two of the above-cited papers (Paynter, 1996b; Paynter and Juarez, 1999).

The present paper serves as a progress report on extending these earlier results to cases where Tuggers and Twistors are employed as antagonistic opposed pairs, like animate muscles, to provide simultaneous open-loop position and impedance control. The two cases treated below will ultimately offer novel low-cost and light-weight mechatronic features.

II. TWO OPPOSED TUGGER-PAIRS ON A BEAM

Part one of the paper addresses an application to control a gyrating platform configuration initially modeled as a beam and consisting of two opposed Tugger-Pairs used to demonstrate linear actuation. The analytical setup consists of a beam with a Tugger-Pair actuator at each end of the beam supplied with four independent pressures. The Tugger-Pair actuation pressures on the left side of the beam are labeled P_{LT} (the Left-Top actuator pressure), and P_{LB} (the Left-Bottom actuator pressure); and the Tugger-Pair actuation pressures on the right side of the beam are labeled P_{RT} (the Right-Top actuator pressure), and P_{RB} (the Right-Bottom actuator pressure). A disturbance F(t) applied at an eccentric point on the beam provides the input excitation and pressurized actuators extend and contract as shown in Fig. 1, which together results in a vertical displacement or heave, Y, and pitch angle, W.

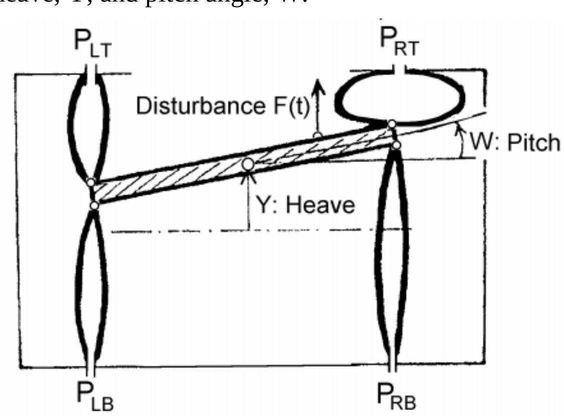


Fig. 1., Two Opposed Tugger-Pairs on a Beam, Exaggerated Deflections

The following analysis represents the open-loop response of this beam application designed to investigate the utility of Tugger-Pair actuators for structural control. The Free-Body Diagram shown in Fig. 2 indicates Tugger forces F_{LT}, F_{LB}, F_{RT}, and F_{RB} with each Tugger capable of applying a force as a function of pressure. The disturbance force, F(t) = B*Sin(C*t) applied at L/2 from the right end of the beam. The beam has a mass, M, a length 2L, and a length-reduced moment of inertia about its center of mass, J = (M*L)/3. Assume angular displacement is small such that F(t) and Tugger forces all act vertically.

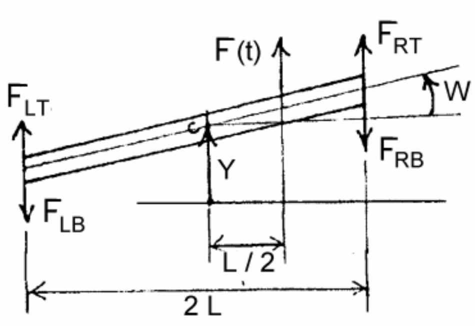


Fig. 2, Beam Free-Body Diagram

The equations of motion, assuming damping, are:
Translation,

$$F_{LT} + F_{RT} - F_{LB} - F_{RB} + F(t) - E*Y' = M*Y'', \quad (1)$$

where E represents an actuator inherent damping term; and
Rotation,

$$- F_{LT} + F_{RT} + F_{LB} - F_{RB} + 0.5*F(t) - E*W' = J*W''. \quad (2)$$

Tugger forces can now be modeled using data from an actual actuator such as Dynacycle Corporation's Dynaflex Model D125, (Paynter, 1996b; Paynter and Nagurka, 1997). The Tugger-Pair approximate characteristics consist of two Dynaflex Model D125s as shown in Fig. 3 below. The abscissa represents the beam translation where Y= 0 is arranged to be half the full stroke for each Tugger as well as the nominal displacement point of the beam. The top Tugger force is then

$$F_T(Y) = Po*Ao*[1 - (Xo + Y)/Lo]. \quad (3)$$

The bottom Tugger force is

$$F_B(Y) = Po*Ao*[1 - (Xo - Y)/Lo]. \quad (4)$$

The nominal pressure being applied, Po is 60 psi. Ao is the maximum effective cross-sectional area at 60 psi (a Dynaflex Model D125 characteristic). For this actuator Lo is 0.3 inches and therefore choosing Xo = 0.15 is now the nominal displacement point Y = 0.

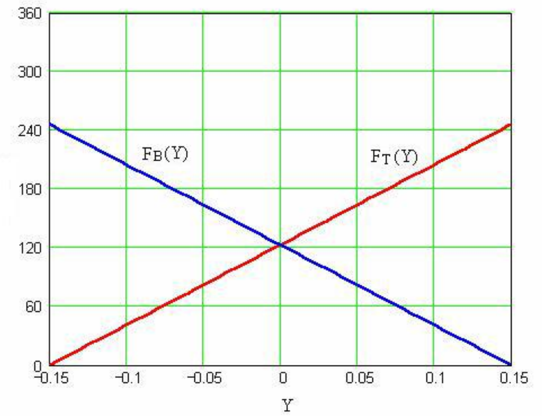


Fig. 3, Tugger-Pair Characteristics using a Dynaflex D125

Equations (3) and (4) may now be used to write the Tugger forces in equations (1) and (2).

$$F_{LT} = Po*Ao*[1 - (Xo + Y_L)/Lo] \quad (5)$$

$$F_{LB} = Po*Ao*[1 - (Xo - Y_L)/Lo] \quad (6)$$

$$F_{RT} = Po*Ao*[1 - (Xo + Y_R)/Lo] \quad (7)$$

$$F_{RB} = Po*Ao*[1 - (Xo - Y_R)/Lo] \quad (8)$$

where again referring to Fig. 2,

$$Y_L = Y - L*Sin(W) \quad (9)$$

$$Y_R = Y + L*Sin(W) \quad (10)$$

Substitute equations (9) and (10) into equations (5) - (8) to obtain F_{LT}, F_{LB}, F_{RT}, F_{RB} = Function (Y, W) for given Po, Ao, Xo, and Lo. Then substitute F_{LT}, F_{LB}, F_{RT}, F_{RB} into equations (1) and (2) to obtain the equations of motion which can be written in State-Space form with
State $\underline{\mathbf{Z}}$ = $[Y\ Y'\ W\ W']^T$ are:

$z_1' = z_2$
$z_2' = [F_{LT} + F_{RT} - F_{LB} - F_{RB} + F(t) - E* z_2]/M$
$z_3' = z_4$
$z_4' = [- F_{LT} + F_{RT} + F_{LB} - F_{RB} + 0.5*F(t) - E*z_4]/J.$

MATHCAD was used to solve for $\underline{\mathbf{Z}}$, with initial conditions for $\underline{\mathbf{Z}} = \underline{\mathbf{0}}$, B = 100 and C = 10 for F(t); and M = 1.0, J = 0.33*M*L, L = 10.0, and E = 4.0., Fig. 4.

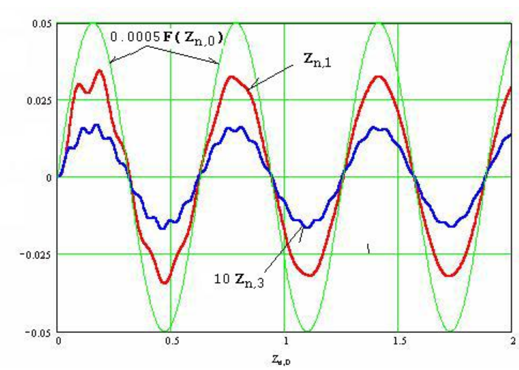


Fig. 4, Solution for Y, W, and input excitation, F(t)

In Fig. 4, F(t) represented as $0.0005*F(Z_{n,0})$ has been scaled down for juxtaposing with the solutions, Y is plotted as $Z_{n,1}$, and W is plotted as $(Z_{n,3})*10$. The Tuggers act as spring and damper systems in this open-loop configuration.

III. TWO OPPOSED CROSSED TWISTOR-PAIRS: GIMBAL-DRIVE INITIAL RESULTS

The second part of this paper addresses positional control of a laser pointer mounted on a device consisting of two opposed Twistor-Pairs in an orthogonal configuration so to form a Gimbal-drive or spherical joint to demonstrate rotary actuation. Two Twistor actuators can be pre-twisted to form the jointed device or Twistor-Pair shown in Fig. 5, where the Twistor-Pair forms the flexural joint and the bidirectional pneumatic actuator. Controllably varying the fluid pressure of each Twistor rotates the member as indicated in Fig. 5. Two such crossed Twistor-Pairs can then provide a fully active flexural spherical joint with open-loop proportional control. Such a Gimbal-drive is shown in Fig. 6., where one Twistor-Pair acts as the first rotary axis (labeled A and B at the two independent pressure ports) and holds another Twistor-Pair in an orthogonal arrangement producing a second rotary axis. A laser pointer mounted on the second axis (labeled C and D at the two independent pressure ports) projects its gimbaled motion onto an X-Y target, Fig. 6. The experimental apparatus shown in Fig. 7 consists of a pressure control panel, the Gimbal-drive with laser pointer (on table center-bottom of figure), and a target grid (on wall left-center of figure) located 4 feet from the laser pointer end. The red helium-neon laser light can be seen in its home position at the origin of the target grid Fig. 8 where each coordinate grid location is 1 millimeter.

Hundreds of pressure and deflection readings including torque measurements have been made using this set-up. A variety of differential pressures were applied to the Twistor-Pairs to achieve a circular pattern shown in Fig. 9 with the eight photos starting from the top and resulting in the coordinates $(X,Y)_n$ = $(21mm,0mm)_1$, $(15mm, 15mm)_2$, $(0mm, 21mm)_3$, $(-15mm, 15mm)_4$, $(-21mm, 0mm)_5$, $(-15mm, -15mm)_6$, $(-21mm, 0mm)_7$, and $(15mm, -15mm)_8$ respectively. The differential pressures are applications of two different control pressures to ports A and B for the X-axis Twistor-Pair and two different control pressures to ports C and D for the Y-axis Twistor-Pair, Fig. 6. Obviously an infinity of differential pressures could result in the laser pointing to the same coordinate, for example coordinate $(-15mm, -15mm)_6$ can be reached using the corresponding common mode pressures (19psi, 16.5psi) or (11psi, 13.5psi), but the differential pressures were in each case 2psi. These different common mode pressures result in varying the stiffness of the Gimbal-drive as these pressures increase. Some additional observations associated with the response of the actuators have been creep dynamics due to the viscoelastic monolithic polymeric Twistors which must now be incorporated into further analysis.

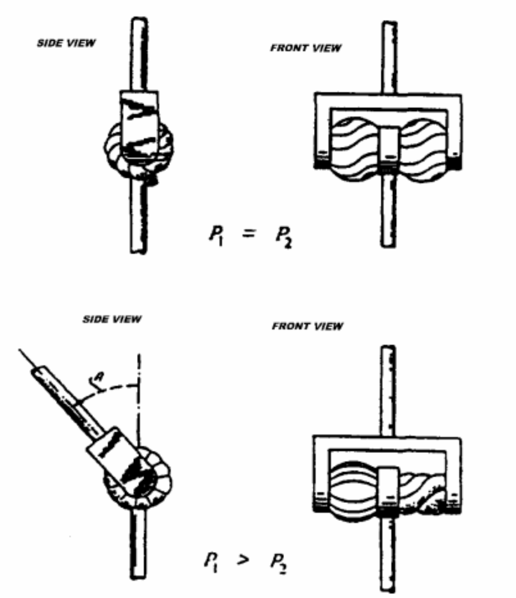


Fig. 5, Deflected Twistor-Pair constituting both flexural joint and proportional actuator

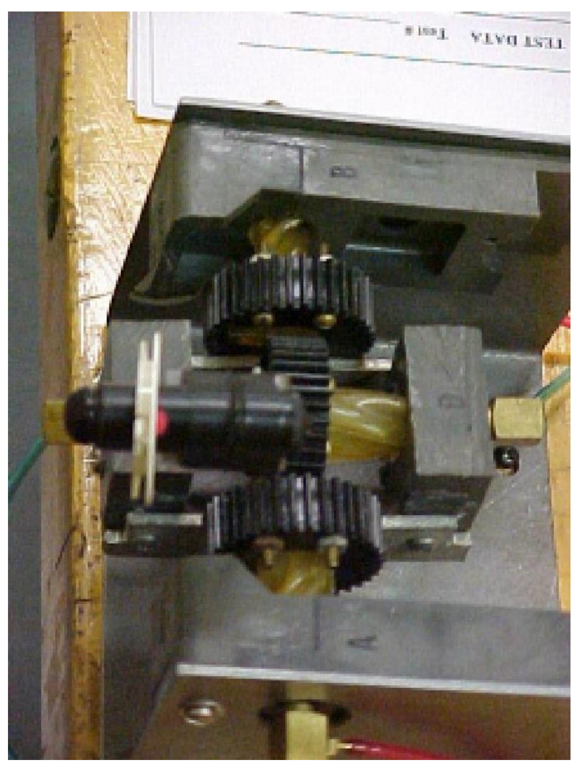


Fig. 6, Two Opposed Twistor-Pairs in an orthogonal configuration forming a Gimbal-drive

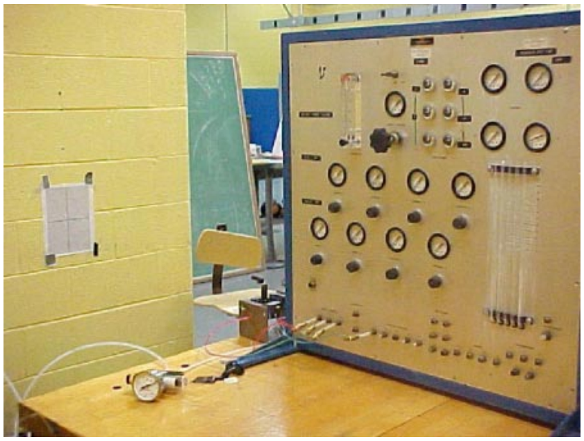


Fig. 7, Experimental Apparatus at Kent State with Pressure Control Panel, Gimbal-drive, and Laser Target Grid

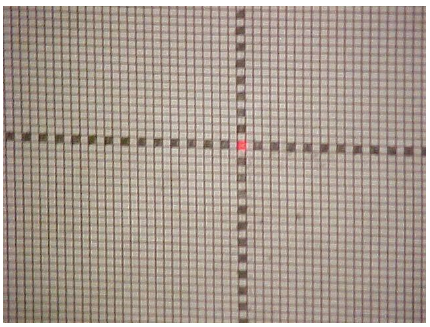
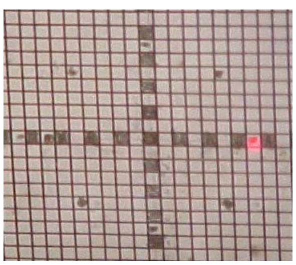


Fig. 8, Laser light in Home Position at Origin of Target Grid



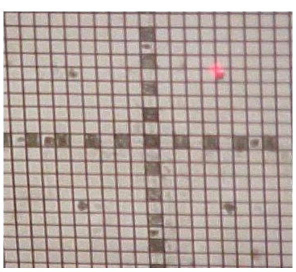
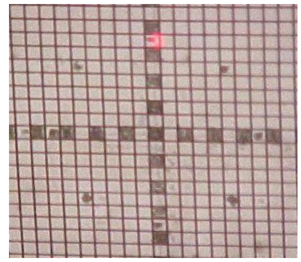
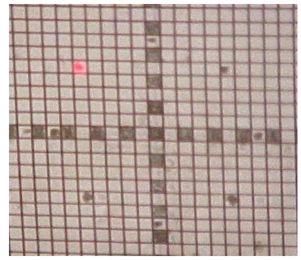
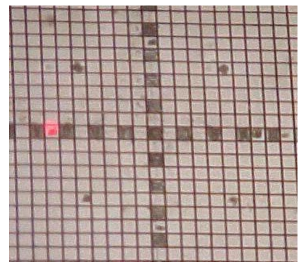
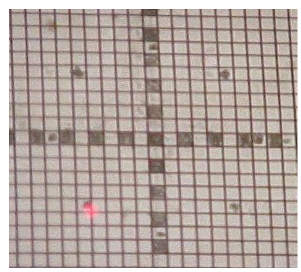


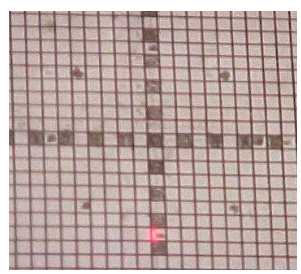
Fig. 9, Eight Photos showing a Laser Drawn Circle in Counter-Clockwise Succession

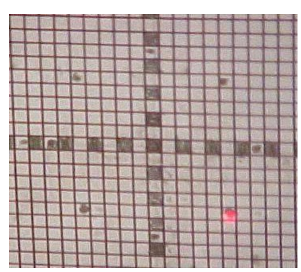












IV. CONCLUSION

As previously mentioned, this paper is a progress and Twistor report on analysis and testing leading ultimately to PC/PLC mechatronic control of Tugger-Pair and Twistor-Pair devices and systems. Part one of this paper demonstrated how to incorporate a Tugger with known characteristics into an analytical design model of a vibrating beam by using opposed Tugger-Pairs at each end of the beam and calculating the open-loop response. Continuing studies will investigate applying common-mode and differential-mode control to the actuators from the sensed deflection of the beam ends. Experimental testing will then validate these analytical designs.

Part two of this paper verified that a practical application could be constructed which contains two opposed Twistor-Pairs forming a Gimbal-drive that is pressure-controlled to conform to a prescribed pattern. Further analysis will be directed to obtaining model equations used to characterize the Gimbal-drive. Such phenomena as the dynamic affects of creep due to the monolithic polymeric actuators and the device's impedance as the common mode pressure changes will also be investigated. Final results will then provide software commands permitting open-loop programming for computer control of such spherical joints.

V. REFERENCES

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