

DYNAMIC MODELLING OF MULTI SECTION BIONIC MANIPULATOR: APPLICATION TO ROBOTINO-XT

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ABSTRACT

This paper deals with the Bond Graph dynamic modeling of a multi section bionic manipulator applied to Bionic Handling Assistant robot (BHA). This bio-inspired flexible manipulator is comprised of two bending sections, one rotating section and one compliant gripper. Each bending section is comprised of three bellows, which are actuated pneumatically. To simulate the bellows behavior, differential equation for a pipe conveying fluid has been obtained and finite element representation of the mathematical model is carried out. This finite element approach has been linked to the bond graph modeling approach. Similarly remaining of the bellows have been modeled and are linked to each other by putting suitable boundary conditions to obtain the dynamic model of the manipulator as a whole. Thus, this model can be used to design an adequate control for the whole BHA robot. This model will be validated through simulation and experimental tests.

Keywords: Bionic Manipulator modeling, FE Bond Graph Model, Pneumatic actuator bond graph

1. INTRODUCTION

Bionic engineering started growing last decade, by finding the best correlation between biological and mechanical motions. According to the considered missions (Siciliano and Khatib 2009), with the biological inspired robots, the mechanism that is patterned after principles found in humans or nature is being reproduced. It also refers to artificial devices implanted into humans, replacing or extending normal human functions with certain accuracy. Two classifications of bionic robots have been done by Trivedi et.al (2008) with large spectrum of applications, one concerns the soft robots such as Pneumatic Artificial Muscle robots (PAM), and the other concerns the hard robots with soft capabilities such as Multi-Section Backbones Tubes robots (MSBT). Bionic Handling Assistant (BHA) from Festo (2011) can also be classified in the latter category. It is 3-sections pneumatically actuated with 3 backbones tubes per section. The flexibility of this bellow is provided by the Polyamide material fabricated by Rapid Prototyping

method and gives a great maneuverability of 11 Degrees of Freedom (DOF).

To carry out dynamic modeling of such kind of manipulator, the various sections of manipulator arm need to be studied in detail. Numerous papers deal with various aspects of bellows, such as stresses due to internal pressure and axial deflection, dynamic analysis and static analysis and fatigue life estimations.

Andersson (1964, 1965) derived correction factors relating the behavior of the bellows convection to that of a simple strip beam. This approach had subsequently been the basis of standards and other publications presenting formulae for hand-calculation for bellows.

The most comprehensive and widely accepted text on bellows design is however the Standards of the Expansion Joint Manufacturers Association (1998). The EJMA standards are found to comply better with experience, and are therefore recommended everywhere. Ting-Xin et al. (1990) and Osweiler (1989) did comparisons of the EJMA standards with finite element. The EJMA organization itself has also conducted research to verify the standards.

This paper presents the dynamic model of a single section of multi-section bionic manipulator for the 'Bionic Handling Assistant' robot of Festo called Robotino XT. This robot is omni directional mobile robot with bionic manipulator as shown in Figure 1. (Festo, 2011).

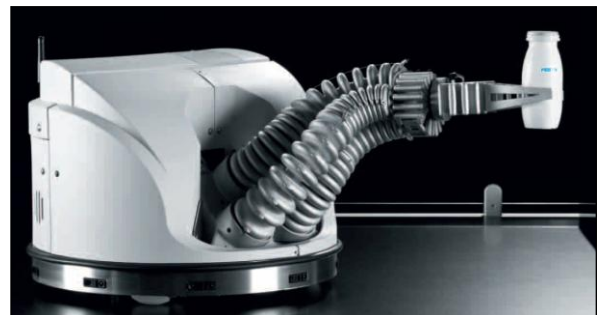


Figure 1: Robotino XT Robot

2. VARIOUS SECTIONS OF MANIPULATOR ARM

Robotino XT shown in Figure 1 (Festo, 2011), is a combination of a mobile Omni directional robot called

Robotino and a small version of the 'Bionic Handling Assistant' (BHA) mounted on it. This small bionic trunk has 8 degrees of freedom (DOF) and can be divided in several parts as shown in Fig. 2: two bending parts, a rotation part, and a compliant gripper. Each bending part is composed of three flexible backbone tubes, while the rotation part is actuated by two flexible backbone tubes in form of arc. The gripper works with the same principle of the rotation part in another plane. The backbone tubes are actuated with compressed air, where the position and the orientation are controlled by differentiating the pressures.

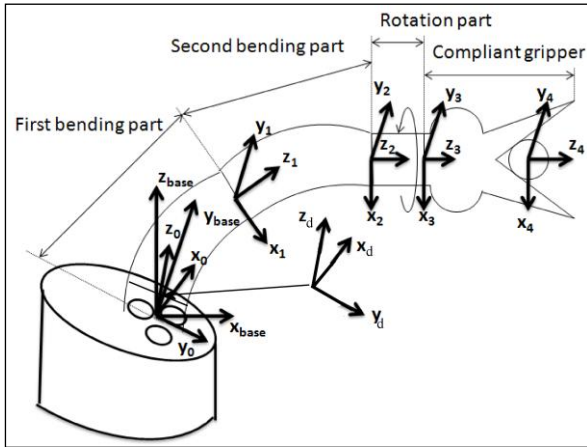


Figure 2: Model of the Manipulator arm

3. DYNAMIC MODELLING OF BELLOWS

To carry out dynamic modeling of the manipulator arm, the different sections of the arm were taken into account and studied thoroughly. Now, the bending sections are made up of bellows. According to Borman et al. (2000), special geometry of the bellows makes it very flexible in overall bending but very stiff against radial deflections. This means that significant transverse deflections and rotations of cross-sections perpendicular to the bellows axis can take place, with oval ring remaining negligible. Thus, although being far from a beam in appearance, a beam representation of the bellows should be relevant. Thus, each bellow has been modeled as a fictitious pipe, through which fluid is flowing.

3.1. Assumptions

Assumptions that have been taken while modeling the bellow as a beam are as follows:

- Plane sections originally normal to the longitudinal axis of the beam remain plane and normal to the deformed longitudinal axis upon bending.
- The beam is just undergoing deformation due to bending.
- The strains in the longitudinal, radial and torsional directions are assumed to be negligible.

- The effect of shear deformation on the dynamic response of the beam is ignored.
- The material is assumed to be isotropic and elastic.

3.2. Mathematical Model

The differential equation governing the bending vibrations of the bellow can be obtained from the general differential equation for bending vibration of pipe conveying fluid, given by Broman et al. (2011)

$$E_p I_p \frac{\partial^4 w}{\partial x^4} + (\rho_p A_p + \rho_f A_f) \frac{\partial^2 w}{\partial t^2} - \rho_p A_p (1 + \alpha \frac{E_p}{G_p}) \frac{\partial^4 w}{\partial x^2 \partial t^2} + 2\rho_f A_f V \frac{\partial^2 w}{\partial t \partial x} + (p\pi R_m^2 + \rho_f A_f V^2) \frac{\partial^2 w}{\partial x^2} = F \quad (1)$$

Where E_p is the young's modulus of elasticity of the pipe, I_p is the area moment of inertia for the pipe cross-section, w is the transverse displacement, x is the length of the pipe, ρ_p is the density of the pipe material, A_p is the area of cross section of the pipe, ρ_f is the density of the fluid, which is flowing inside the pipe, A_f is the flow area, t is the time, α is the shear coefficient, G_p is the polar modulus of elasticity of pipe, V is the flow velocity, F is the transverse force acting on the pipe.

The influence of shear deformation on bending of bellows is assumed to be very small (Morishita et al., 1989). Thus the shear coefficient can be neglected from Equation (1). Thus the equation reduces to:

$$E_p I_p \frac{\partial^4 w}{\partial x^4} + (\rho_p A_p + \rho_f A_f) \frac{\partial^2 w}{\partial t^2} - \rho_p A_p \frac{\partial^4 w}{\partial x^2 \partial t^2} + 2\rho_f A_f V \frac{\partial^2 w}{\partial t \partial x} + (p\pi R_m^2 + \rho_f A_f V^2) \frac{\partial^2 w}{\partial x^2} = F \quad (2)$$

To obtain the mathematical formulation of this model by FEM, first step is to convert the equation (2) into its weak formulation. We consider a beam element, whose two consecutive nodes are x_e and x_{e+1} . Each node has two degrees of freedom associated with it. Thus we obtain as follows:

$$\int_{x_e}^{x_{e+1}} v [E_p I_p \frac{\partial^4 w}{\partial x^4} + (\rho_p A_p + \rho_f A_f) \frac{\partial^2 w}{\partial t^2} - \rho_p I_p \frac{\partial^4 w}{\partial x^2 \partial t^2} + 2\rho_f A_f V \frac{\partial^2 w}{\partial t \partial x} + (p\pi R_m^2 + \rho_f A_f V^2) \frac{\partial^2 w}{\partial x^2} - F] \quad (3)$$

In the above equation, v is the weight function. Simplifying the equation (3), we obtain:

$$\begin{aligned}
& \int_{x_e}^{x_{e+1}} \frac{\partial^2 v}{\partial x^2} \cdot E_p I_p \frac{\partial^2 w}{\partial x^2} + \int_{x_e}^{x_{e+1}} v \frac{\partial^2 w}{\partial x^2} (p\pi R_m^2 + \rho_f A_f V^2) \\
& + \int_{x_e}^{x_{e+1}} v [(\rho_p A_p + \rho_f A_f) \frac{\partial^2 w}{\partial t^2} - \int_{x_e}^{x_{e+1}} v \cdot \rho_p I_p \frac{\partial^4 w}{\partial x^2 \partial t^2} \\
& + \int_{x_e}^{x_{e+1}} v [2\rho_f A_f V \frac{\partial^2 w}{\partial t \partial x}] = \frac{\partial v}{\partial x} \{E_p I_p \frac{\partial^2 w}{\partial x^2}\}_{x_e}^{x_{e+1}} \\
& - v [E_p I_p \frac{\partial^3 w}{\partial x^3}]_{x_e}^{x_{e+1}} \quad (4)
\end{aligned}$$

So the stiffness matrix [K] can be obtained from the following part of the equation (4)

$$\int_{x_e}^{x_{e+1}} \frac{\partial^2 v}{\partial x^2} \cdot E_p I_p \frac{\partial^2 w}{\partial x^2} + \int_{x_e}^{x_{e+1}} v \cdot \frac{\partial^2 w}{\partial x^2} (p\pi R_m^2 + \rho_f A_f V^2) \quad (5)$$

The Mass Matrix [M] can be obtained from part of equation (4), given as

$$\int_{x_e}^{x_{e+1}} v [(\rho_p A_p + \rho_f A_f) \frac{\partial^2 w}{\partial t^2} - \int_{x_e}^{x_{e+1}} v \cdot \rho_p I_p \frac{\partial^4 w}{\partial x^2 \partial t^2} \quad (6)$$

The damping matrix can be identified as:

$$\int_{x_e}^{x_{e+1}} v [2\rho_f A_f V \frac{\partial^2 w}{\partial t \partial x}] \quad (7)$$

Now for the model of the form [M]{X}+[K]{X} = F we have ignored the damping effect and also we have assumed mass matrix as the lumped mass matrix. For the lumped mass matrix, the inertial effects in transverse as well as the rotary degree of freedom have been considered. Thus, mass matrix is as follows:

$$[M] = \frac{\rho_p A_p l}{2} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & l^2/12 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & l^2/12 \end{bmatrix} \quad (8)$$

In equation (8), l is the length of one beam element. To obtain the stiffness matrix, we have considered Equation (4) and have written the weight function, v as ϕ_i and the dependent variable, w as ϕ_j where ϕ_i and ϕ_j are the shape functions for the beam element and w_j are the various degrees of freedom of a beam element.

Thus, $[K_{ij}]$ matrix can be obtained from the following expression:

$$\begin{aligned}
K_{ij} = & \int_{x_e}^{x_{e+1}} \frac{\partial^2 \phi_i}{\partial x^2} \frac{\partial^2 \phi_j}{\partial x^2} E_p I_p w_j + \int_{x_e}^{x_{e+1}} \phi_i \frac{\partial^2 \phi_j}{\partial x^2} \\
& (p\pi R_m^2 + \rho_f A_f V^2) w_j \quad (9)
\end{aligned}$$

If h_e is the length of single beam element, then shape functions of the beam element are as follows:

$$\begin{aligned}
\phi_1 &= 1 - 3\left(\frac{\bar{x}}{h_e}\right) + 2\left(\frac{\bar{x}}{h_e}\right)^3 \\
\phi_2 &= -\bar{x}\left(1 - \frac{\bar{x}}{h_e}\right)^2 \\
\phi_3 &= 3\left(\frac{\bar{x}}{h_e}\right)^2 - 2\left(\frac{\bar{x}}{h_e}\right)^3 \\
\phi_4 &= -\bar{x}\left[\left(\frac{\bar{x}}{h_e}\right)^2 - \left(\frac{\bar{x}}{h_e}\right)\right] \quad (10)
\end{aligned}$$

The stiffness matrix thus obtained is:

$$\begin{aligned}
[K] = & \frac{EI}{l^3} \begin{bmatrix} 12 & -6h_e & -12 & -6h_e \\ -6h_e & 4h_e^2 & 6h_e & 2h_e^2 \\ -12 & 6h_e & 12 & 6h_e \\ -6h_e & 2h_e^2 & 6h_e & 4h_e^2 \end{bmatrix} + \\
& \frac{p\pi R_m^2 + \rho_f A_f V^2}{30h_e} \begin{bmatrix} \frac{6}{5h_e} & \frac{11}{10} & \frac{6}{5h_e} & \frac{1}{10} \\ \frac{1}{10} & \frac{-2h_e}{15} & \frac{1}{10} & \frac{h_e}{30} \\ \frac{6}{5h_e} & \frac{1}{10} & \frac{6}{5h_e} & \frac{11}{10} \\ \frac{1}{10} & \frac{h_e}{30} & \frac{1}{10} & \frac{-2h_e}{15} \end{bmatrix} \quad (11)
\end{aligned}$$

4. DYNAMIC MODELLING OF MANIPULATOR ARM

Three bellows have been fixed onto a plate to form a bending section as explained in Fig. 2. Two such bending sections together form the manipulator arm of the Robotino XT. Thus, by putting suitable initial and boundary conditions, the dynamic model can be modeled as shown in Fig. 3. The various parameters considered for simulation are shown in Table 1.

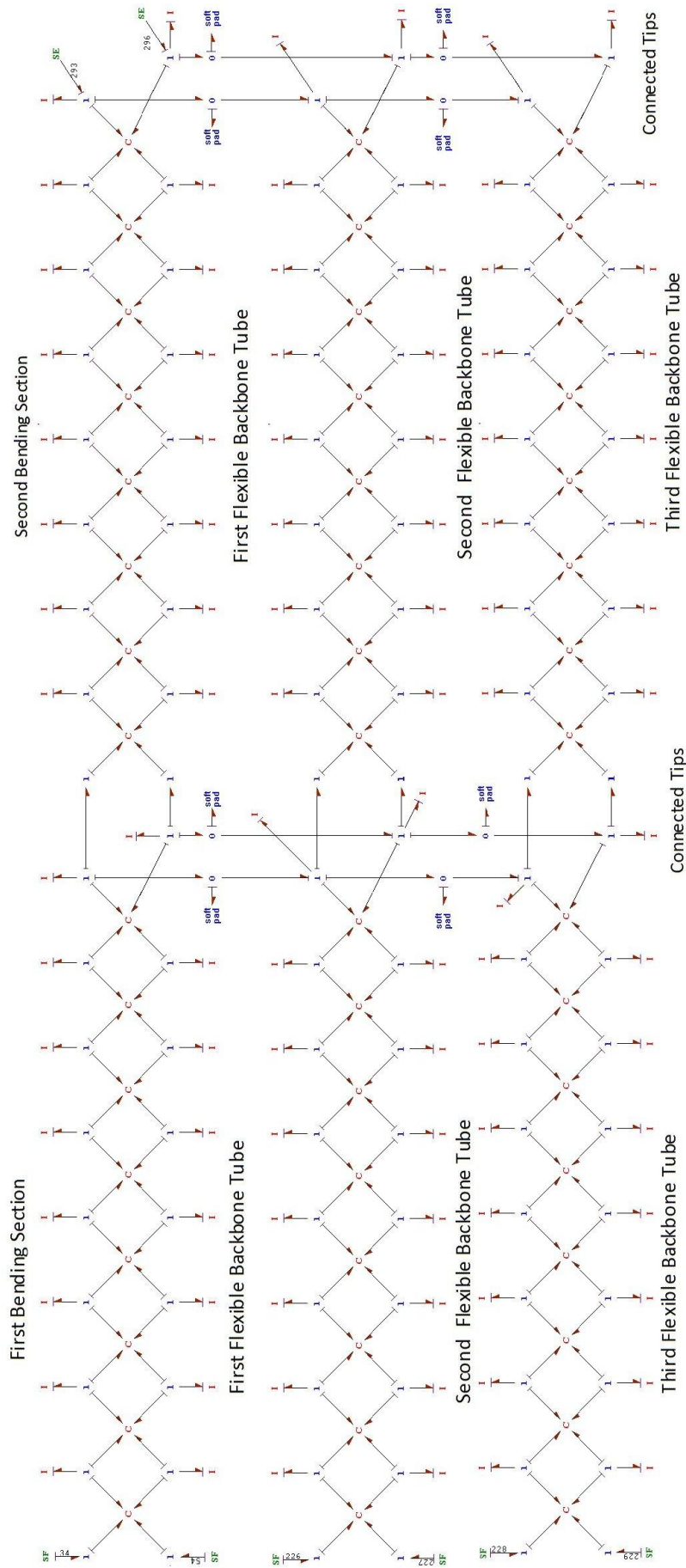


Fig. 3: Bond Graph model of the Manipulator Arm

Table 1: Parameters for modeling of manipulator arm

Parameters	Symbol	Value	Units
Young's Modulus of Elasticity of equivalent pipe	E	1,55,000	N/m ²
Mean Radius of the equivalent pipe	R _M	0.0341	m
Wall thickness of the equivalent pipe	SP	0.0007	m
Mass per unit length	M	1.643	Kg/m
Density of fluid	ρ_f	1.225	Kg/m ³
Length of equivalent pipe	L	0.1014	m
Pressure in the first bellow of first bending section	PA1	500	N/m ²
Velocity of flow in the first bellow of first bending section	V	6	m/sec
Transverse force acting on the tip of first bending section	F _{verti1}	4	N
Pressure of the fluid in third bellow of first bending section	PA2	600	N/m ²
Velocity of the fluid in second bellow of first bending section	V ₂	6.4	m/sec
Pressure of the fluid in third bellow of first bending section	PA3	800	N/m ²
Velocity of fluid in third bellow of first bending section	V ₃	6.8	m/sec
Pressure of fluid in first bellow of second bending section	PB1	500	N/m ²
Velocity of fluid in first bellow of second bending section	V ₄	6	m/sec
Pressure of the fluid in the second bellow of second bending section	PB2	700	N/m ²
Velocity of the fluid in second bellow of second bending section	V ₅	7.0	m/sec
Pressure of the fluid in the second bellow of second bending section	PB3	900	N/m ²
Velocity of the fluid in third bellow of second bending section	V ₆	7.4	m/sec
Transverse Force acting on the tip of the second bending section	F _{verti2}	-4	N

Thus the bond graph consists of six Rayleigh Beam elements. In the model, the end tips of bellows of first bending section are connected to starting points of the corresponding bellows of second bending section. Also, the bellows of each section are connected to each other.

Under the influence of parameters stated above, the behavior of the tip is shown in Figure 4. Figure 5 (a) - (c) shows the animation frames for the motion of the six flexible backbones.

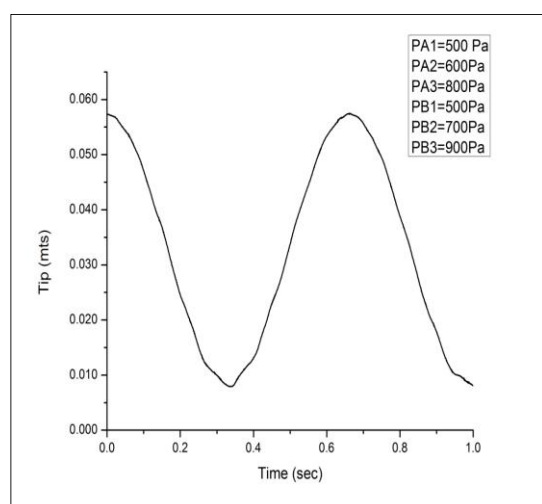


Figure 4: Tip response of manipulator arm

In the above graph, PA1, PA2, PA3 are the pressures of the fluid in first bending section and PB1, PB2, PB3 are the pressures of fluid in the bellows of second bending section.

Also, the following frames describe the positions of the various nodes of the modeled beam elements.

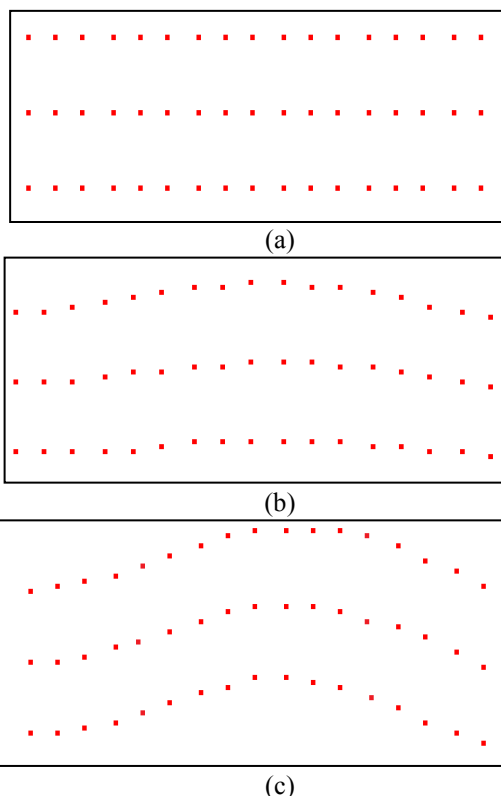


Figure 5: (a), (b) and (c): Animation frames for motion of six backbones

In Fig. 5, nodes of six Rayleigh beams have been shown. Each beam is divided into nine elements, thus having nine nodes into it. Here only one such cycle of vibration has been shown. One cycle is assumed to be of 0.60 seconds. Simulation results have been carried out for 1s.

5. CONCLUSION

The compressed air is flowing in each bellow of both the bending sections with different velocities and different pressures, giving rise to different stiffness. This different stiffness of bellows give rise to a powerful movement. To obtain the dynamic model of the manipulator arm, geometry of bellow is studied in detail and is found that the differential equation governing the bending vibrations of the bellow can be obtained from the general differential equation for bending vibrations of a pipe conveying fluid. To simulate the bellow behavior, finite element representation of differential equation is done and stiffness matrix can be derived. This FE approach can be linked to bond graph modeling approach to obtain the dynamic model of manipulator arm as a whole. Once the dynamic model of this class of bionic manipulator has been synthesized, it can be used to design an adequate control for the whole Bionic Handling Assistant.

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