Estudos Tecnológicos em Engenharia, 10(2):57-63, julho-dezembro 2014

Dynamic response analysis of the electro-pneumatic module of a continuous positive airway pressure in newborns using Bond Graph modeling

Análise de resposta dinâmica do módulo eletro-pneumático da pressão positiva contínua na via aérea modelado por *Bond Graph*

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Abstract. Continuous Positive Airway Pressure is a ventilation system noninvasive complex currently applied in particular in neonatology. In this context, the parameters must have a controlled setting, since it will have an impact on the survival of premature infants with very low birth weight - which require constant control. The aim of this paper was to propose a mathematical model for the electro-pneumatic module of a Continuous Positive Airway Pressure in newborns system (Neo CPAP) with an interest in quickly check the influence of a particular change parameter on the performance of subsystems. The methodology used to analyze the variables was the mathematical modeling by IDOV technique (validate, identify, design, optimize). This approach leads to an adequate shape for obtaining the physical behavior and characterization of the studied system. The joint system accomplishes results that CPAP function is obtained; research has shown that, by adopting a specific purpose, one can create a better understanding of Assistive Technology and its parameters and how to control it.

Keywords: CPAP, modelling, Bond Graph.

Resumo. O Continuous Positive Airway Pressure (CPAP) é um sistema de ventilação não invasiva complexo, atualmente aplicado particularmente em neonatologia. Nesse contexto, os parâmetros devem ser controlados, pois terão um impacto sobre a sobrevivência de prematuros com muito baixo peso ao nascer – que requerem um controle constante. O objetivo deste artigo foi propor um modelo matemático para o Módulo de eletro-pneumático de um sistema CPAP em recém-nascidos (Neo-CPAP) com o interesse em verificar rapidamente a influência de uma determinada alteração de parâmetro sobre o desempenho dos subsistemas. A metodologia utilizada para análise das variáveis foi a da modelagem matemática pela técnica IDOV (validar, identificar, projetar, otimizar). Tal abordagem leva a uma modelagem adequada para a obtenção do comportamento físico e da caracterização do sistema estudado. O conjunto de resultados do sistema que realiza a função CPAP foi obtido; a pesquisa mostrou que, através da adoção de um propósito específico, pode-se criar uma melhor compreensão da Tecnologia Assistiva e de seus parâmetros e de como controlá-los.

Palavras-chave: CPAP, modelagem, Grafo de Ligação.

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Introduction

The Continuous Positive Airway Pressure for Newborns (Neo-CPAP) device is used to maintain the airway at a pressure above the ambient throughout the breathing, and thus preventing the complete removal of the inspired gas, while maintaining high stability. This technique was applied in cases of hyaline membrane disease in 1971, in which the use of this treatment was able to maintain a normal spontaneous breathing rate with excellent results (Lima *et al.*, 2004). Currently its application occurs mainly among newborns of very low weight, since this technique provides increased functional residual capacity (FRC), pulmonary compliance (PC) and especially the reduction of intrapulmonary deviation, in which an improper deviation occurs in the ventilation-perfusion ratio (V/Q), besides the reduction of oxygen diffusion (Kamper, 1999). In a study conducted by Mayor (2010), a chronology of the equipment evolution is presented. The results show delimitations of characteristic functions of operation, handling, consolidated and strongly validated applications (Bonassa, 2000; Borges *et al.*, 2003; Carvalho, 2000; Carvalho e Bonassa, 2000; Postiaux, 2004). However, mathematical models of this dispositive are rare and they are often models that use phenomenological laws for obtaining the constitutive relations of the basic elements of the pneumatic system. To overcome this limitation, a study was elaborated to obtain a mathematical model of the electro-pneumatic structure of the developed prototype Neo-CPAP. The theory used in this study is Bond Graph (BG), a graphing tool developed by H. M. Paytner in 1959 used to describe the physical interactions between physical systems, mechanical, hydraulic, electrical, pneumatic quantities, among others (Rodrigues, 2009). Bond Graph is meant to represent the exchange of energy among components of a physical system and the compression of the interaction among the components. In general, as literature provides, pneumatic systems are fluid systems that have multiple subsystems with non-linearities, such as compressibility of the air, holes, friction and losses (Garcia, 2009; Guenther *et al.*, 2006). According to Von Linsingen (2001), a hydraulic system is a device by which an input of energy is converted and conditioned into useful mechanical energy. In this context, electro-pneumatic system of Neo-CPAP fits because it is a fluid power system.

This article aimed at modeling and representing the Electro-pneumatic Module for subsystems which are analogous to mechanical equivalent circuits. Obtaining a representation of State Model -Space used in control theory that provides the ability to rapidly determine the effect of a given change parameters such as controllability, poles and stability in performance subsystems.

Description of the electro-pneumatic module of Neo-CPAP

The input variables are compressed air and oxygen (O_2); the output variable is the air that reaches the patient. The system works in such a way that proportional valves begin to adjust the flow of mixed air at the moment the equipment is connected. The flow is maintained according to the set value on the control panel of the equipment. The gas passing through proportional valves of compressed air and oxygen is directed to the mixer, homogenizing the mixture. At the output of the machine there is a flow sensor that measures the pressure with which the gas reaches the patient. This pressure is limited according to the setting of the Pressure Positive Expiratory at the end of Phase (PEEP). Finally, any excess of gas is vented to atmosphere through the exhalation valve.

A. O_2/Compressed air channel

The channel for the entry of O_2 corresponds to a tube connected to a one-way valve in order to allow flow in one direction and blocking the flow in the opposite direction. For this reason, there is a pressure regulating valve of oxygen, which keeps the pressure stabilized at work set value and a proportional valve that controls the flow of O_2. The compressed air channel operates similarly to the O_2 channel subsystem. Figure 1 shows a pneumatic circuit that comprises.

The channel of O_2 with the structure of three types of valves. Its operation is based on the application of a modulated flow and pressure to the air channel of the patient.

B. Air channel of the patient

This subsystem has tubes with T-connector, representing a star connection. It is composed by a main branch and a branch of fusion to the main application. Furthermore, there is a safety valve called PSV (Pressure Safety

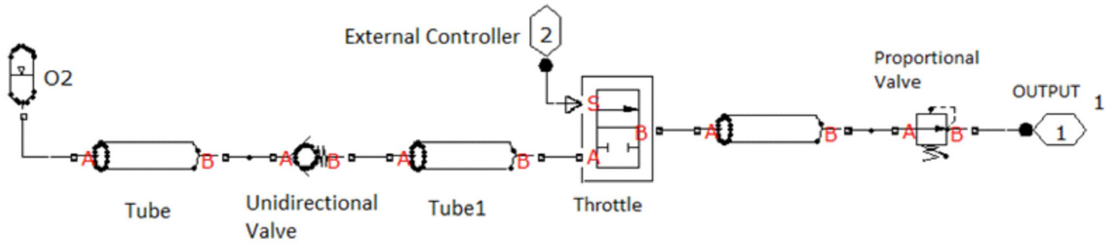


Figure 1. System that composes the O_2 channel.

and Relief Valve) that is an automatic pressure relief device to avoid excessive pressure. The PSV provides pressure relief before the system is broken up by pressure rise. It is a 3-way valve, in which the three ports are A, A1 and B. A is input, B is output and A1 controls the differential pressure (p_c). In other words, p_c is the minimum differential pressure valve to open A1 port and keep it open until normal pressure value is achieved.

This differential pressure has the control function described in Equation 1.

$$p_c = p_A - p_{A1} \quad (1)$$

Methods

A. Simplifying hypotheses and adopted parameters

The simplifying hypotheses are: (i) Localized losses of load caused by restrictions on the horizontal line, (ii) Valves with a linear behavior to open and close in relation to pressure, (iii) Horizontal tube, (iv) Non-turbulent flow, (v) Vibrations were neglected; (vi) Incompressible fluid and constant areas; (vii) Bottlenecks in the valves only, and (viii) A linear model was adopted ignoring the nonlinearities of valves, tubes and fittings. Furthermore, the Channel of Compressed Air has in its structure the same elements shown in Figure 2 (air channel of the patient, safety valve and exhalation valve). However, for this subsystem it was considered: (a) Model of flow following the equation of state of an ideal gas as a criterion (Equation 2) where 'p' is the pressure [Pa], 'V' is the volume [m3], 'm' is the mass of gas [kg]; 'R' is a constant that depends on the ideal gas [Nm / kg K], 'T' is the absolute temperature [K].

$$pV = mRT \quad (2)$$

(b) Features of the model: (i) Model with isothermal behavior, (ii) Model of a perfect gas; (iii) Absence of condensate; (iv) Unidimensional flow, (v) Variables pressure and temperature are homogeneous in the volume.

B. Parameters

In the analysis of the parameters that compose the system, the basic elements of the pneumatic system are resistance (R), inertance (I) and capacitance (C). In Bond Graph theory, resistors (R) are characterized by a constitutive relationship between stress *e(t)* and flow *f(t)*; resistors dissipate energy as the product between *e(t)* and *f(t)* is always positive. In the case of pneumatic systems, the resistance is the relationship between pressure and output V' (q_m = flow). The capacitance (C), which is storage elements or energy suppliers, is characterized by the constitutive relation of stress with the integral variable displacement (*q(t)*). Normally, the stored potential energy is a state function, and displacement is a state variable for the capacitor. In the case of pneumatic systems, the capacitance represents the compliance as a relation between mass and pressure. Finally, the inertance (I) has the ability to accumulate energy in form of kinetic energy. Moreover, the inertance relates the variable power flow '*f*' to the amount of movement integral variable (Karnopp *et al.*, 2000). Table 1 shows the parameters that compose the system.

Results

To obtain the model via Bond Graph it is necessary to specify the study system based on the physical model considering simplifying hypotheses, inputs and outputs. The adopted hypotheses introduced erros in the system. The absence of condensation is necessary and sufficient condition for the CPAP system.

The absence of condensation is a condition that results from isothermia. Moreover, it is necessary to apply the method of integrated equation by assuming unidimensional flow as simplifier (Garcia, 2009). However, according to the literature, the flow cannot be unidimensional due to the viscous effects produced by a turbulent velocity profile (Garcia, 2009). Thus, a future study is also needed in order to remove these hypotheses for the purpose of improving the model.

The BG model of the subsystems of Figures 1 and 2 were made in the simulation software 20-sim (Rodrigues, 2009). The achievement of this system is given by the application following the change in the physical model for the analogue model. This application was supported by the graphical tool Bond Graph.

The mathematical equations in the state-space model form were obtained from the analogue model (Rodrigues, 2009; Gawthrop e Smith, 1996). The BG diagram obtained is composed by four groups of basic elements: one port passive elements (Inertance or Inductance, Capacitance, and Resistance), two one port active elements, (Sources of Stress and Flow), two basic two port elements (Transformer and Spinner) and two junctions (1 and 0) (Rodrigues, 2009). The classification of this system was considered to be a parametric modeling with concentrated parameters, linear, SISO, time-invariant, continuous-time and deterministic (Garcia, 2009).

Figure 3 shows the BG diagram of the subsystem 1 in several physical domains. The subsystem 1 corresponds to the air channel.

Mathematical modeling of the CPAP system was obtained after the preparation of BG diagram and the execution of systematic procedures to obtain the equations of the system in the state-space form according to the algorithm for the construction of the BG.

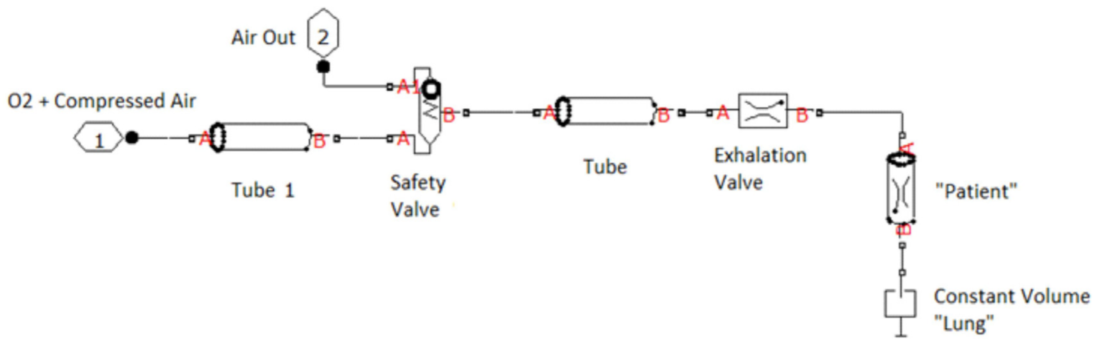


Figure 2. System representing the air channel of the patient.

Table 1. Analog of the real variables by Bond Graph technique.

Parameter	Description	Analogous System	Bond Graph
LT_i (i=1,2,...n)	Tube length	Fluidic inductance and resistance in series.	R and R at a junction 1, common mass flow (common flow).
dT_i (i=1,2,...n)	Tube diameter	Energy dissipation of the flow.	Composes the value of R and I.
O_2	Power flow to feed the system	Power flow	Sf
O_2 + Compressed air	Power flow to feed the system	Power flow	Sf

Continues

Table 1. Continuation.

Parameter	Description	Analogous System	Bond Graph
Unidirectional valve	Allows flow in one direction and blocks it in the opposite direction.	P is the pressure differential across the valve between the ports pA and pB allowing the flow always in p>0.	R at a junction 1.
Throttle	Imposes a control on two hydraulic connections. These connections correspond to the inlet opening (A), output (B) and signal (S).	Resistance as a function of the external signal. The formula that describes: C_d = discharge coefficient	R at a junction 1.
Proportional valve	The input force is produced by a proportional solenoid. The force is proportional to the intensity of electric current flowing through the solenoid.	Resistance as a function of the external signal.	R at a junction 1.
Exhalation valve	Modulates the pressure due to the flow.	Inertance having a relationship with the dynamic range of the volume.	I at a junction 1, common flow.
Safety valve	Releases the high pressure of the system.	Capacitance which has a proportional relationship with volume.	C at a junction 0, common pressure (common effort).
Patient	Natural breathing resistance. For example, trachea.	A variation Pp in patient pressure generates a resistance value R which will cause a mass air flow into the lungs and produce a variation Po in internal pressure.	R at a junction 1.
Lung	Has a positive volume pressure.	Reservoir pressure – mass capacitance.	C at a junction 1.

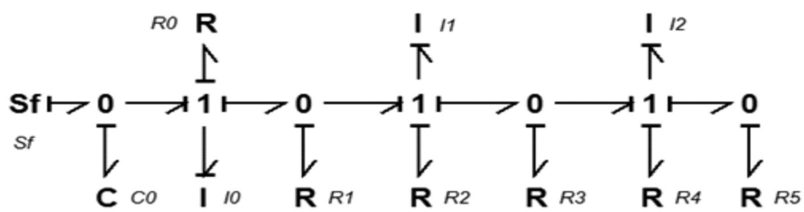


Figure 3. BG diagram representation of the subsystem 1.

The equation for this system is given by:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix}=\begin{pmatrix}0 & -\frac{1}{I0} & 0 & 0\\ \frac{1}{C0} & -\left(\frac{R0+R1}{I0}\right) & \frac{R1}{I1} & 0\\ 0 & \frac{R1}{I0} & -\left(\frac{R1+R2+R3}{I1}\right) & -\frac{R3}{I2}\\ 0 & 0 & \frac{R3}{I1} & -\left(\frac{R3+R4+R5}{I2}\right)\end{pmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}+\begin{bmatrix}1\\ 0\\ 0\\ 0\end{bmatrix}Sf$$

(3)

This equation represents the System of Equations in State-Space form =A.X+B.u.

Likewise, Figure 4 shows the diagram that represents the subsystem 2 in various fields of the BG.

The elements that compose the BG subsystem 2 are the capacitances and inertance system. The equation for this system is given by:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\end{bmatrix}=\begin{pmatrix}0 & 0 & -\frac{1}{I0} & 0 & 0\\ \frac{1}{C0} & -\left(\frac{R0+R1}{I0}\right) & \frac{R1}{I1} & 0 & 0\\ 0 & \frac{R1}{I0} & -\left(\frac{R1+R2+R3}{I1}\right) & \frac{R3}{I2} & 0\\ 0 & 0 & \frac{R3}{I1} & -\left(\frac{R3+R4}{I2}\right) & -\frac{1}{C1}\\ 0 & 0 & 0 & \frac{1}{I2} & 0\end{pmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix}+\begin{bmatrix}1\\ 0\\ 0\\ 0\end{bmatrix}Sf$$

(4)

The simulation of the system was performed by fixing the elements of the tubes in constant values, which are R_0, I_0, I_1, R_2, I_2, and R_4. As a variation of the inlet pressure occurs from 90Pa to 25Pa, the values of R1, R3, and R5 had a relation of proportion. It means that, for a pressure of 100%, R1 = 100, R3 = 44.45 represents 44.45% of the pressure and R5 = 27.78 represents 27.78% of the pressure.

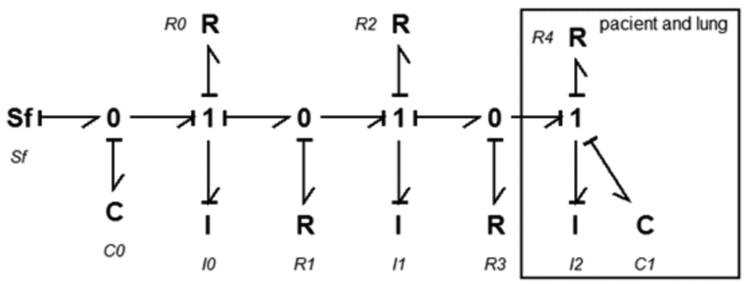
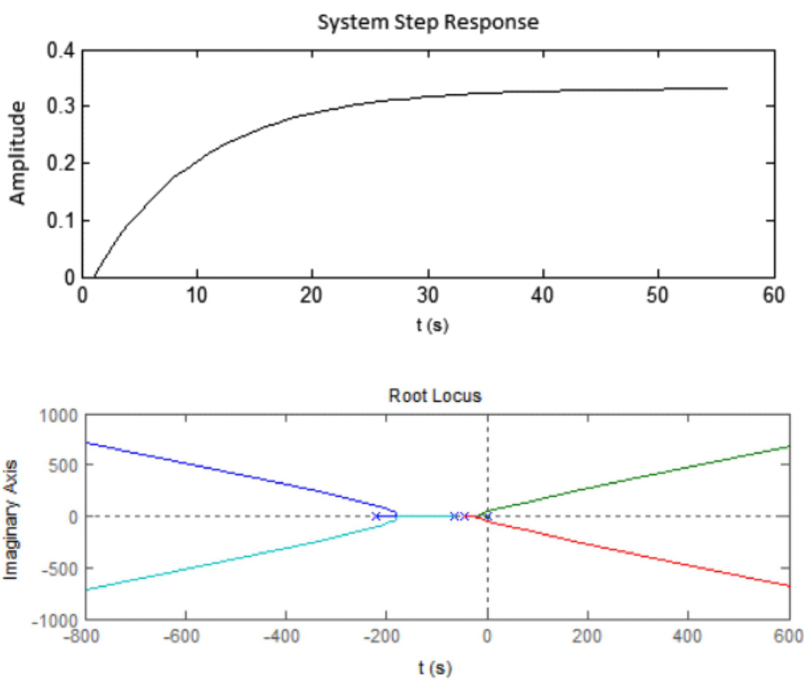


Figure 4. Graphical Representation of the Circuit Air System + Air Channel of the Patient.



(a)

(b)

Figure 5. (a) Step response of the system model; (b) Root locus plot of the system model.

According to the simulation, there is an error in the system that is not stabilized at 1 Pa. Another important factor is that the response time is very high, which implies the need to introduce a controller in the system.

Conclusion

The modularity of the proposed procedure should contribute towards the use of complex bio-inspired systems. Finally, the proposed model serves as a relevant application in bio-inspired systems that demonstrates the potential benefits of the exact feedback linearization methodology, which has proved very suitable for modeling the dynamic behavior of modular systems (in this case, device medical) interacting with various components and nonlinearities. A code was written in Matlab to analyze the basic dynamics simulation of the model system, its response to the unit step input and its response in the root locus. In the system studied, the process of energy conversion in different and equal domains occurs constantly, but with a change in the nominal value of the variable. Thus, it is necessary the use of transducer, such as valves receiving a rated voltage as the input variable, and offer a variation in gas flow that runs as a result. Dynamic changes resulting from the introduction of the constants are observed in the state space matrices A of the system when compared with the system without alteration. It is noticed that the introduction of the constants in I_0 element introduce a phase lag. This CPAP model may be an effective solution for public and private health units in order to facilitate medical care at remote health units, making it available at a relatively low cost, thus promoting healthcare in poor communities. To realize further developments in bio-inspired system, it is still necessary to consider some specific aspects of this technique for the description of such systems, such as the description of nonlinear fields in more elements – typical of this type of system. Furthermore, new studies should explore how this technique can help in developing organic controllers.

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Submetido: 22/06/2014
Aceito: 16/04/2015