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Modeling of a Reciprocating Air Compressor using Energetic Macroscopic Representation

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ABSTRACT

This article introduces the energetic macroscopic representation (EMR) nonlinear modeling of a reciprocating air compressor. EMR has been introduced recently for research dev electromechanical systems. It is based on action reaction principle, which organizes the subsystems according to the integral causality. The graphical modeling readability, modularity, structural and functional characteristics. The EMR is the first step toward m control structure development. The air compressor system containing slider-crank mechanism, cylinder head and valves, is divided into multitude simple subsystems. Each subsystem describes an elementary step of energy conversion, several of these blocks may occur in a single module. Calcu principles: mass and energy balance. Models are developed for different subsystems, whi final overall EMR system. The EMR modeling presented here allows the complementary multi-physics modeling of an highlights the interactions of the electromechanical, thermodynamical, h occur simultaneously in an air compressor.

1. INTRODUCTION

Reciprocating compressors are some of the most important machines used throughout various industries. Due to its importance considerable efforts has been devoted by many researchers toward the d models for computer simulation of this type of machine. Hamilton (1974) (See refs which give a representative description of this type of work.)
In general, a cycle of operation of a high speed positive displacement compressor is a com complicated phenomenon, interacting and taking place in a short period of time

As regards the graphical models, their interest is double: firstly used during the modeling itself and secondly as the easiest transfer of knowledge (Brown, 2010) to the other users
In some literature graphical models of compressor are found (Engja, 1985 and Karnopp, 2000). They are based on the same equations and theoretical backgrounds than the previ highlights the understanding of the behavior to a significant extent. To describe the modeling of the thermodynamic system (Thomas, 2001) uses Bond Graph approach. Using the same Karnopp (2000) to proposes an overall picture of the considered system. Bond Graph is a versatile graphical tool describe complex systems, Energetic Macroscopic Representation (EMR) h modularity and readability, EMR reveals the structural and functional cha agreement with physical (e.g. integral causality) (Hissel, 2008). Both Bond Graphs and EMR are obvi model multiphysical systems, but there are nevertheless different features between Bouscayrol based on energy and data flow and uses a uniform representatio while with the latter specific pictograms are used to each power component incre As a matter of fact, it shows the different physical domains crossed by discriminate between the accumulation of potential and kinetic energies whereas EMR does

make any difference. Furthermore, in Bond Graphs, all subsystems are us derivative relationships which violate the causality principle. The EMR oriented towards control. Then any derivative relationship is avoided and some pe concatenation rules can be applied (Bouscayrol, 2005). EMR has been developed since 2000 to analyze systems from a macroscopic point of view; it allows the control design thanks to its control fea Control Structure (MCS) deduced from EMR using inversion rules. The Structure (PCS) by applying simplification rules leads to a control and an energy managemen time.

Therefore, a complex system of several energy sources and several ene modelled by the EMR tool with a clear readability. Moreover, the control of implemented, thanks to the appropriate control tools.

As in other graphical representation methodologies, the product of the action (the ca and reaction pair) is the instantaneous power exchange (Chen, 2009) between the elo connected. Though EMR has been developed firstly to describe electromechanical systems (Chen, 2008), it possible to extend it to new energy domains. Expanded to electrochemica domains, EMR has allowed describing many devices such as fuel cells, electromechanical system electrical vehicles or hybrid systems.

Until now, modelling of the air compressor using EMR is scarce. This paper is organized as follows. In Section 2 some basic knowledge on EMR and some general considerations regarding EMR are pneumatic appl problems. Then, each physical phenomenon taken into account is described an In Section 3, the air compressor behavior including the elements: slider-crank mechanism, cylinder-piston assembly and valves is described. The model is then detailed, putting together all EMR subpa compressor Energetic Macroscopic Representation. Finally, this proposed model is tested (Section 4) on simulation results and the comparison with. Final remarks are devoted to the discussion of the ob

2. EMR DESCRIPTION

2.1 Short Presentation of the Graphic Modelling Tool

As mentioned before, EMR is used for modelling the multi-physic compressor. The product of an act variable with the corresponding reaction variable always provides the instanta power. Thus, it has been possible by Chen (2007, 2009) to extend EMR beyond its initial aims in order t describe multi-physic systems. The EMR model inversion element by elemen control structure; it is called the Maximum Control Structure (MCS) an theoretical), all the values are measurable. In practice, it is not always the cas (PCS) can be deduced from the MCS by applying simplification rules, more details, please refe Bouscayrol (2010) and Chen (2007, 2009). In this paper, only the EMR model part is presented. Table 1 presents the generalized EMR pictograms used in the presented model.

Table 1: Extended Energetic Macroscopic Representation blocs

Energetic Macroscopic Representation (EMR) blocs		
Pair of action a		Two parallel blac pointing in opposi
Source of ener		Light green oval wi rim
Energy convers Same domain		Orange square wi
Energy convers Different doma		Orange circle wit
Energy accumul		Orange rectangle and red diagona
Coupling device (d energy) Same doma		Overlapping orange squa red rim
Thermo-fluidic causali and four variables and liquid)		Orange squares w

2. Adaptation of EMR to a fluidic system

The EMR methodology is based on the assumption that every energy exchange can be describe and one reaction parameter. However, Chrenko (2009) argues that in case of a multiport this does n true all the time.

2.1. Causality between action and reaction parameter: As in other graphic representation met product of the causal parameter pair (here called action and reaction pai blocks (Bouscayrol, 2005). This principal is reasonable as long as there is a relation betw leading to the power. This relation has not necessarily to be a product. T -EMR, in analogy to pseudo-Bond Graph (Thoma, 1993) gives the possibility to handle the parame more freely. For example, Chrenko (2009) uses pressure and mass flow $\dot{m}$ or either Temperature and Enthalpy flow $\dot{H}$ as parameters of EMR.

2.2. Representation of multiports: The basic ideas of EMR contain the fact that all syste small parts, which follow either a simple conversion, a Kirchhoff law or a first order diffe form. For most systems this subdivision can be obtained. However, in s

domains cannot be detached, they can only be described in matrix form. In this case the energetic dom
gas flows cannot be detached. The element has two parameter pairs. According to Thoma
(2006), such an element can be called multiport in EMR analogy to Bond Graph.
Chrenko (2009) proposes that, as the equation cannot be separated into the two energet
both parameter pairs is used, see Figure 1.

Figure 1. Representation of a multiport in EMR.

3. DESCRIPTION OF AIR COMPRESSOR BEHAVIOR

A schematic of the compressor in question is shown in Fig. 2. For modeling purposes the compressor is div
three subsystems, namely:

A. slider-crank mechanism,
B. cylinder head,
C. valves,

Each subsystem is modeled independently and then the submodels are combined to the complete model of th
system.

Figure 2: Compressor schematic

3.1 Slider-crank mechanism

The slider-crank relationship, m(θ), was derived as:

$$m(\theta) = \left[R\sin(\theta) - \frac{R^2 \sin(\theta)\cos(\theta)}{\left(L^2 - R^2\sin^2(\theta)\right)^{1/2}} \right] \quad (1)$$

This transformer modulus shows the relationship between crank speed Ω, and the piston speed V, as well as the
torque Γ, and piston force F.

$$m(\theta) = \frac{\partial V}{\partial w} = \frac{\partial t}{F} \qquad (2)$$

Figure 3: Crank and piston mechanism

Plus, the relation between the volume change and piston displacement is:

$$\dot{V} = -A_p \dot{q} \qquad (3)$$

One may represent the device by the EMR of Figure 3.

Figure 4: EMR of Crank and piston mechanism

3.2 Cylinder head

Considering the cylinder head volume as a control volume that can transport mass a out port, but flow can go in either direction at either port. Finally we ca volume expansion. Notice that we assume that one pressure, one temperature, one entire internal volume of the control volume.

Writing the mass and energy equations for the mentioned control volume, w

$$\frac{d}{dt}E = h_i \dot{m}_i - h_e \dot{m}_e - p\frac{dV}{dt} - \dot{Q} \qquad (4)$$

$$\frac{d}{dt}m = \dot{m}_i - \dot{m}_e \qquad (5)$$

Here E is the internal energy of the control volume, and we assume that the g Even though the EMR representation is not a true one, but as the causalit and therefore accepts flow input on all arrows. It then integrates these flows E, m, and V. And finally the accumulator operates on these variables through approp outputs P and T. The constitutive relations are

$$T = \frac{1}{c_v}\frac{E}{m} \qquad (6)$$

$$T = \frac{mRT}{V} = \frac{mR}{V}\frac{1}{c_v}\frac{E}{m} = \left(\frac{R}{c_v}\right)\frac{E}{V} \qquad (7)$$

Thus, $\dot{E}_i$, $\dot{m}$ and $\dot{V}$ are prescribed (causally), then the thermodynamic via the accumulator constitutive laws. Considering the principals described in section 2 The EMF cylinder head is shown in Figure. 5.

The rate of heat transfer between the gas and the cylinder head wall is mo

$$\dot{E}_w = H_c A_c (T_w - T_c) \quad (8)$$

Where is the overall heat transfer coefficient, the cylinder control volume the surface area, temperature and the instantaneous gas temperature. Regarding the heat transfer, may be that given by Eichelberg (1939)

$$H_c = 2.4\sqrt{7P_c T_c}\sqrt[3]{V_{pr}} \quad (9)$$

Where and are instantaneous cylinder gas pressure and temperature, the mean piston velocity.

Figure 5: EMR of Cylinder head

3.3 Suction and discharge valves

The valves are assumed to be treated instantaneously as a simple orifice of effective cross-sectional area, A isentropic flow. The mass flow rate through the valve as a function of valve area, temperature and downstream pressure, can be computed using the well known relation

$$\dot{m}_v = A_v\, p_u \sqrt{\frac{2k}{(k-1)R_u T_u}}\sqrt{(p_r)^{2/k} - (p_r)^{(k+1)/k}}, \quad (10)$$

Where is the ratio of specific heats and is the ideal gas constant.

And for

$$p_r \le p_{r\,crit} = \left(\frac{2}{k+1}\right)^{k/(k-1)}, \quad (11)$$

The flow is choked. And the mass flow is independent of the downstream pressu

The transported energy $\dot{E}_h$ associated with the mass flow $\dot{m}$ is then

$$\dot{E}_h = c_p T_u \dot{m} \quad (12)$$

Considering the principals described in section 2, the EMR representation of the valve is sh

Figure 6: EMR of Valves

3.4 Complete EMR Model

The three previously developed submodels are assembled to form the model shown in Figure 7. This compleme
EMR displays in one simple diagram the mechanical interaction of the single stag
The basic lumping process and the system structure EMR are clearly analysed and indicated. T
direction and causalities. The advantages of the EMR techniques are clearly illustrated in
complicated mechanical machines can be modelled by building blocks using a gener
Finally the modulation for the inlet and the exhaust are specified by a logic exp
For example:, for

If "e 180° and "d , = (13)

Otherwise, = 0

This will keep the inlet open as long as pressure inside the cylinder is less than the atm
logic can be defined for exhaust valve.

The equations mentioned until now can be delivered to any explicit equati
we have used MATLAB Simulink for simulation. An integration algorithm will m
step to next.

Figure 7: Complete EMR system

4. SIMULATION RESULTS

The model equations were programmed in Matlab Simulink® environment for simulation.
Figures 8 and 9 show pressure and temperature in compressor cyli Figure 10 and 11, show mass and volume in the compressor cylinder.

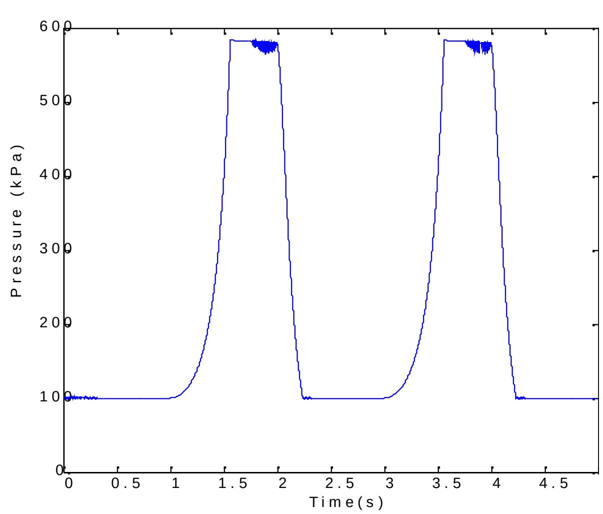


Figure 8: Simulated Pressure in the cylinder.

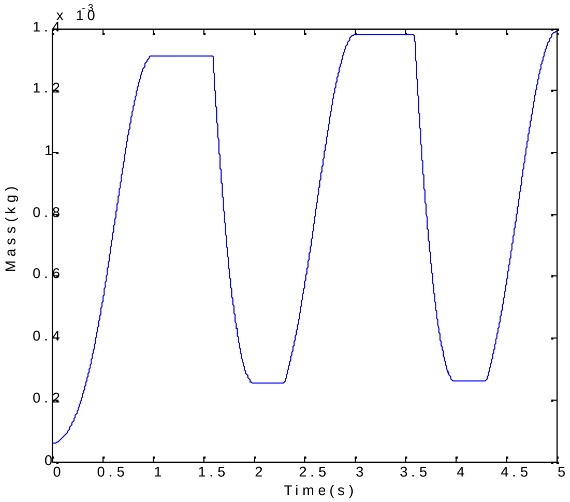
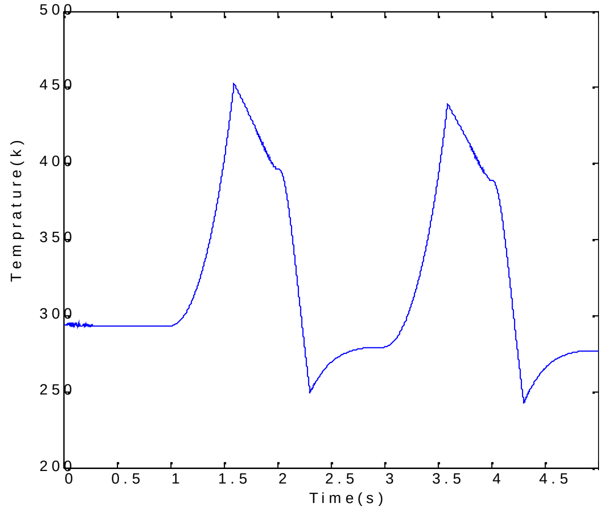


Figure 10: Simulated mass in the cylinde



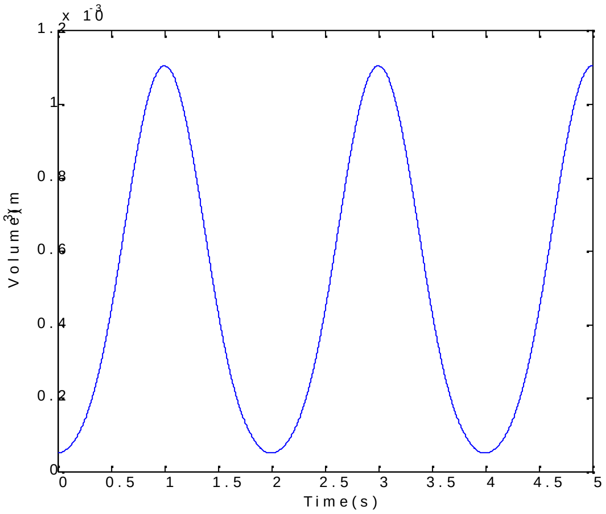


Figure 11: Simulated volume of the cylinc

Figure 9: Simulated Temperature in the cylinder.

To see if the developed model of the complex thermodynamic processes adequately describes the mechanism phenomenon, we have compared the developed model to FEM model by COMSOL Multiphysics. The procedure of Element modeling is described by the author in (Haidar and Barta 2011). The p-V indicator diagram of both models has been shown in the Figure 12. There is a good agreement. The slight difference in the results comes from the difference in accuracy of the heat transfe in defining the nature of valves.

Since the FEM model is more complicated, it can better predict the heat transfer of the cylinder body.

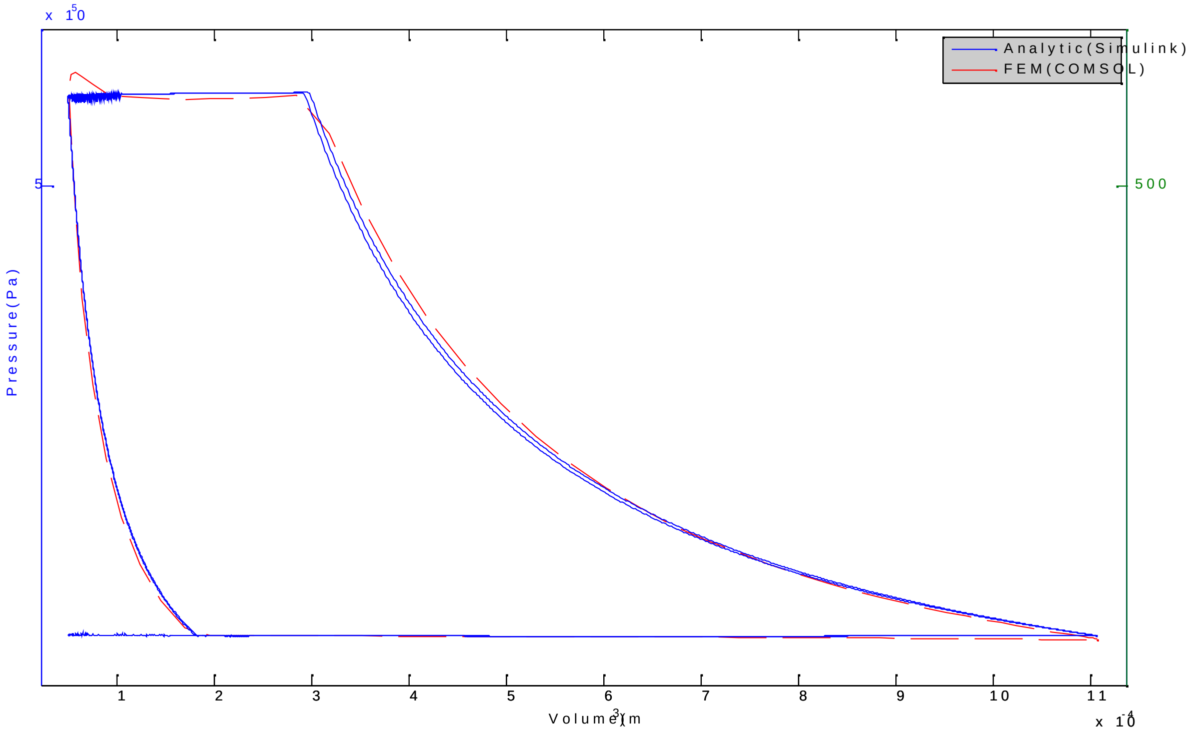


Figure 12. P-V diagram of FEM and analytical model.

5. CONCLUSIONS

In this paper the pseudo EMR approach for a reciprocating compressor is presented. It is
that pseudo EMRs are a very powerful tool for modeling of convective (open) thermodyna
Pseudo EMR in combination with EMR have pushed physical modeling forward. The number of
complex machines or systems which can be modeled in EMR technique greatly straightforward m
enhanced. Besides, the rather simple model developed here shows a good agreement
computationally expensive Finite Element Model.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

$\dot{m}$	Mass flow	(kg/s)	Subscripts	
$\dot{E}$	Enthalpy flow	(J/K)	s	suction
$\dot{V}$	Volume flow	($m^3/$)	i	inlet
T	Temperature	(k)	e	exit
p	Pressure	(Pa)	E	Exhaust
ω	Rotational speed	(Hz)		
τ	Torque	(N.m)		
A	Surface area	(m^2)		
c_p	Isobaric Heat Capacity	(N.m/kg.K)		

k	Heat capacity ratio	(-)
J_ω	Flywheel rotary Inertia	(kgm^2)
R	crank radius	(m)
L	connecting rod length	(m)

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