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Evolutionary Design for Multi-domain Engineering System - Air Pump Redesign

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Abstract

This paper introduces design method for air pump system using bond graph and genetic programming to maximize outflow subject to a constraint specifying maximum power consumption. The air pump system is a mixed domain system which includes electromagnetic, mechanical and pneumatic elements. Therefore an appropriate approach for a better system for synthesis is required. Bond graphs are domain independent, allow free composition, and are efficient for classification and analysis of models. Genetic programming is well recognized as a powerful tool for open-ended search. The combination of these two powerful methods, BG/GP, was tested for redesign of air pump system.

Key Words : Evolutionary Design, Multi-domain, Bond Graph, Genetic Programming, Air Pump

1. Introduction

A multi-domain dynamic system includes a mixture of, for example, electrical, mechanical, hydraulic, pneumatic, and/or thermal components. Multi-domain dynamic system design differs from conventional design of electronic circuits, mechanical systems, and fluid power systems in part because of the need to integrate several types of energy behavior as part of the basic design[1]. Multi-domain design is difficult because such systems tend to be complex and most current simulation tools operate over only a single domain.

The air pump system[2,3] is an good example of mixed-energy domain system. Because it includes electric, electromagnetic, mechanical and pneumatic elements, an unified approach is required to design. Bond graphs[4-7]. allow us to capture the energy behavior underlying the physical aspects (as opposed to the information aspects) of mechatronic systems in a uniformly effective way across domains. They enable the analysis of multi-energy-domain systems with a unified inter-domain tool.

As an evolutionary design approach for multi-domain system, the Bond Graph / Genetic Programming (BG/GP) design methodology[8] has been developed to overcome limitations of single-domain design approaches and enable open-ended search automatically, based on the combination of these two powerful tools and tested and worked efficiently for a few applications[8-10].

In this paper, BG/GP is applied to air pump design which is consist of mixed-energy domain elements to maximize outflow subject to a constraint specifying maximum power consumption. Section 2 explains Bond Graph and the air pump system. Section 3 describes the Bond Graph / Genetic Programming approach. Section 4 and 5 describes redesign problem of the air pump system and presents design results. Section 6 concludes the paper.

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2. Unified Approach for Mixed-energy Domain System

2.1 Bond graph

Bond graph modeling is a powerful method that enables a unified approach to the analysis, synthesis and evaluation of dynamic system. It represents the common energy processes of multi-domain systems - electrical, mechanical, fluid, and thermal systems - in one graphical notation[4-7]. Bond graphs consist of elements and bonds. There are several types of elements, each of which performs analogous roles across energy domains. The first type -- C, I, and R elements -- are passive one-port elements that contain no sources of power, and represent capacitors, inductors, and resistors (in the electrical domain). The second type, Se and Sf, are active one-port elements that are sources of power, and that represent effort sources and flow sources, respectively (for example, sources of voltage or current, respectively, in the electrical domain). The third type, TF and GY, are two-port elements, and represent transformers and gyrators, respectively. Power is conserved in these elements. A fourth type, denoted as 0 and 1 on bond graphs, represents junctions, which are three-port (or more) elements. They served to interconnect other elements into subsystems or system models. Some example bond graph models are shown below. Figure 1 consists of Se , 1-junction, C, I, and R elements, and that same bond graph represents either a mechanical mass, spring and damper system (left), or an RLC electric circuit (right). Se corresponds with force in mechanical systems, voltage in electrical systems. The 1-junction implies a common velocity for 1) the force source, 2) the end of the spring, 3) the end of the damper, and 4) the mass in the mechanical system, and implies that the current in the RLC loop is common. The R, I, and C represent the damper, inertia (of the mass), and spring in the mechanical system, or the resistor, inductor, and capacitor in the electrical circuit.

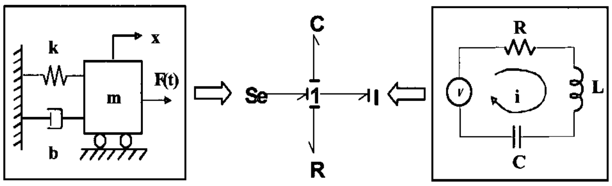

Fig. 1 The same bond graph model for two different domains

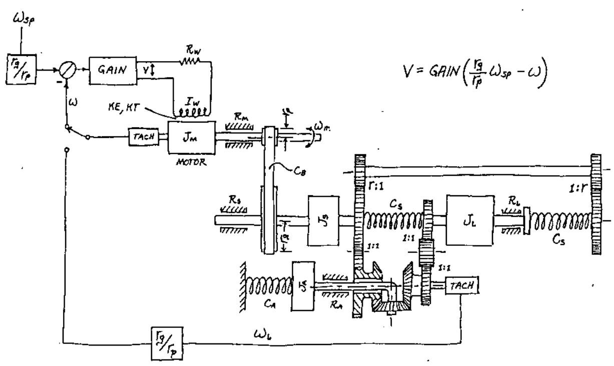

Fig. 2. Schematic diagram of an example mechatronic system - the printer drive

Figure 2 shows a drive system for a printer that involves a drive shaft and a load, with important physical properties modeled. The input is the driving torque generated through the belt coupling back to the motor. Figure 1 shows examples of single-domain systems, while Figure 2 represents a mixed-domain system.

Besides the basic R, I and C elements, two-port elements TF and GY are used in the printer drive system in Figure 3. Transformers TF relate efforts to efforts and flows to flows, while gyrators GY relate the effort at one port to the flow at the other. In this model, TF corresponds to a gear ratio or signal ratio, while GY relates gain to voltage or current in a motor to mechanical rotation.

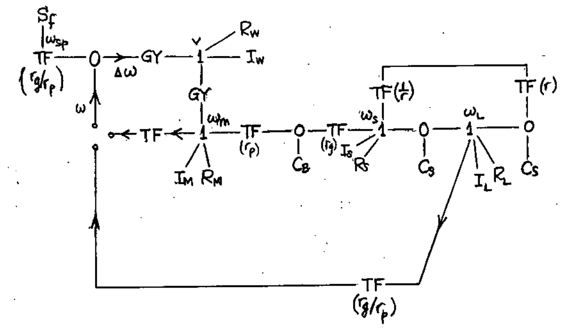

Fig. 3. Bond graph model for printer drive of Figure 2

2.2 Air Pump System

The air pump system includes electric, electromagnetic, mechanical and pneumatic element. A schematic of the air pump is presented in Figure 4. It is a vibratory pump in which an electromagnetic circuit drives a small permanent magnet attached to a pivoted lever that, in turn, drives a rubber bellows pump. The bellows pump has rubber check valves and delivers a small flow of air. The basic structure of the air pump consists of the cascaded arrangement of three coupled subsystems: the electromagnetic actuator, the lever, and the air bellows.

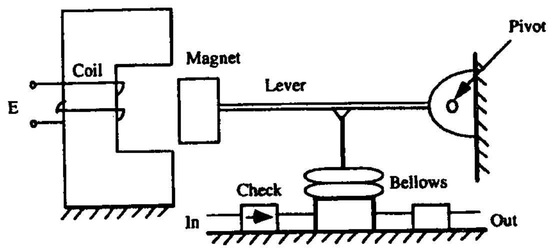

Fig. 4 Schematic of air pump model

Multi-domain system design differs from conventional design of electronic circuits, mechanical systems, and fluid power systems in part because of the need to integrate several types of energy behavior as part of the basic design. In order to automate design of multi-domain systems, such as mechatronic systems, a new approach is required[8-10]

3. Bond Graph / Genetic Programming Design Process

The approach described here includes the potential advantages of both bond graphs and genetic programming, with a powerful synergistic effect for automated, multi-domain, and topologically open-ended design. Especially Genetic Programming[11,12] is more powerful to allow generation of essentially unbounded topologies.

The overall procedure is shown in Figure 5. The designer sets the design context by specifying an embryo bond graph model (i.e., driver and load ports in any number (required for the objective function to be defined), and if desired, any other fixed "plant" which the search process is not allowed to alter). Parameters for the GP search process must be set to control both the generation phase (yielding an initial population of candidate solutions in the form of GP trees) and the evolution phase. At each stage of evolution, each of the candidates is evaluated and assigned a fitness value. The evolution phase is guided by the statistics of the selection and evolution operators. The evolution process terminates when fitness or effort conditions are met. The result is reported as a bond graph (or set of them) with the highest fitness rating(s).

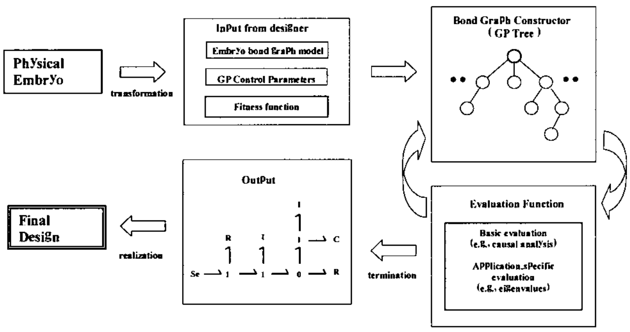

Fig. 5 The BG/GP design procedure

The BG/GP system used GP functions and terminals for bond graph construction as follows. There are four types of functions: add functions that can be applied only to a junction and which add a C, I, or R element; insert functions that can be applied to a bond and which insert a 0-junction or 1-junction into the bond; replace functions that can be applied to a node and which can change the type of element and corresponding parameter values for C, I, or R elements; and arithmetic functions that perform arithmetic operations and can be used to determine the numerical values associated with components (Table 1). Details of function definition and GP process are illustrated in [8].

4. Air Pump Redesign

The bond graph model and related parameters for the original air pump is shown in Figure 6. The average peak value of outflow for the original air pump is approximately 2×10-4 m3/sec, as depicted in Figure 7. The ultimate objective of the pump redesign is to maximize outflow subject to a constraint specifying maximum power consumption.

A genetic algorithm is used to vary bond graph models[3]. This approach adopts a variational design method, which means they make a complete bond graph model first, then simply change the bond graph configuration using a GA, yielding new design alternatives. They obtained an improved design of the air pump system using GA approach, but it is only 13.6% better than original one. Their goal is just to provide a wider range of possible designs, within a topologically limited search space.

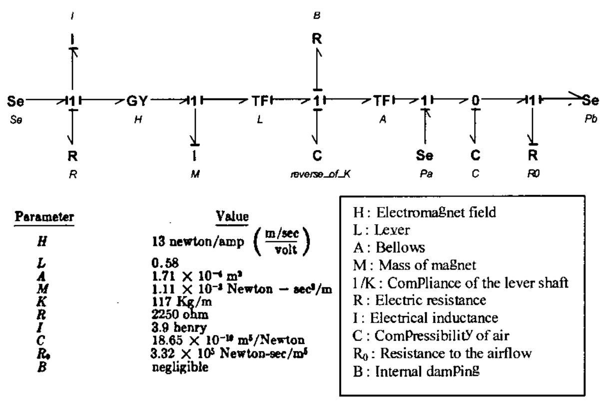

Fig. 6 Bond graph model of original air pump mode

The embryo model for the air pump redesign is shown in Figure 8, with the modifiable sites highlighted as dotted rectangles. The fitness function will consist of a positive term for pump outflow and a negative term for power consumption that is clamped at 0 so long as power is less than the constraint constant. However, in order to better understand the tradeoffs between power consumption and outflow in this problem, we began using a simple multi-objective formulation of the problem, in which weighting factors influence the tradeoff between 1/power consumption and outflow.

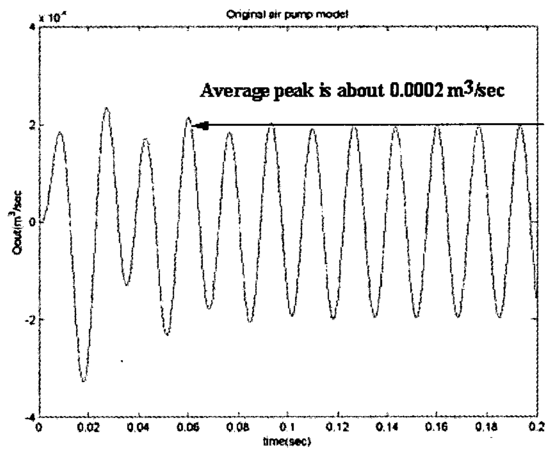

Fig. 7 Outflow of original air pump model

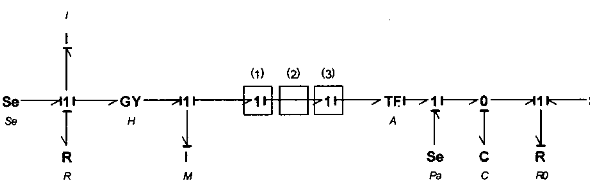

Fig. 8 The embryo model

Following GP functions are used to evolve a bond graph model for air pump design(Table 1).

Table 1. GP terminals and functions

Name	#Args	Description
add_C	4	Add a C element to a junction
add_I	4	Add an I element to a junction
add_R	4	Add an R element to a junction
insert_J0	3	Insert a 0-junction in a bond
insert_J1	3	Insert a 1-junction in a bond
insert_TF	3	Insert a Transformer in a bond
insert_GY	3	Insert a Gyrator in a bond
replace_C	2	Replace the current element with a C element
replace_I	2	Replace the current element with an I element
replace_R	2	Replace the current element with an R element
+	2	Add two ERCs
-	2	Subtract two ERCs
enda	0	End terminal for add element
endi	0	End terminal for insert junction
endr	0	End terminal for replace element
erc	0	Ephemeral random constant (ERC)

5. Experiments and Analysis

Lilgp[13] is used to generate bond graph models. These examples were run on a single Pentium IV 2.8 GHz PC. The GP parameters were as shown below.

Number of generations: 500
Subpopulation : 15
Population size: 200
Initial population: half_and_half
Initial depth: 3-6
Max depth: 15
Selection: tournament (size=7)
Crossover: 0.9
Mutation: 0.1

Two competing design candidates with different topologies are provided, with their performances, in Figures 9-14, from the initial power/outflow tradeoff study. We can see from the output flow responses that they are all higher than those of the original model.

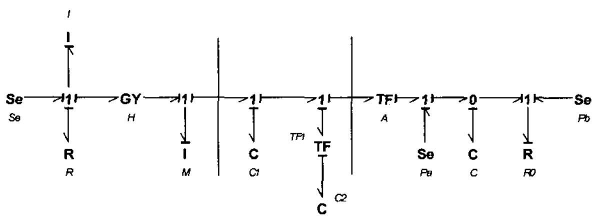

Fig. 9 Bond Graph model of a design variant 1 for air pump

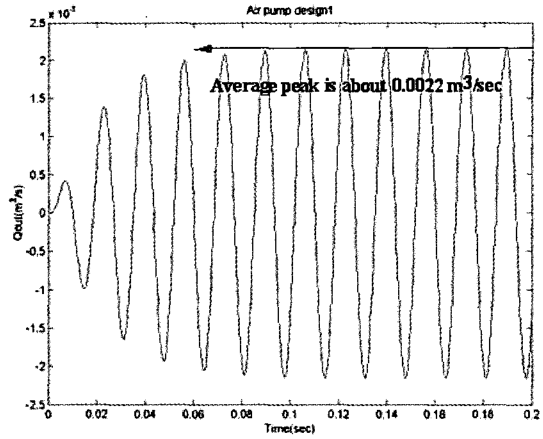

Fig. 10 Outflow of a design variant 1 for air pump

Design variant 1 is represented in Figure 9. Three new components (two C, one TF), between the two dashed lines highlighted, were added at modifiable sites. Figure 10 displays outflow of design variant 1. The average peak value of outflow is approximately 2.210-3 m3/sec and it is almost 9 times better than the original model, however, the power consumption is also somewhat higher than in the original design. Physical realization of design variant 1 is shown in Figure 11.

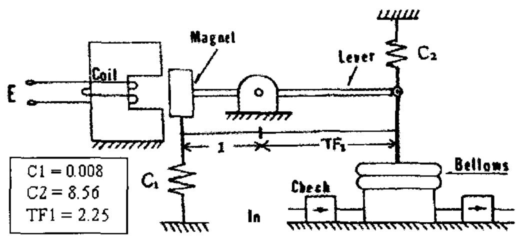

Fig. 11 Physical realization of a design variant 1

In design variant 2, one C and two TFs were added at modifiable sites (Figure 12). Figure 13 displays outflow of design variant 2.

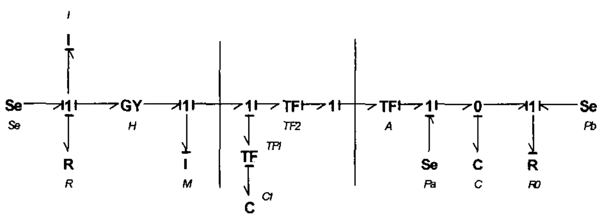

Fig. 12 Bond Graph model of a design variant 2 for air pump

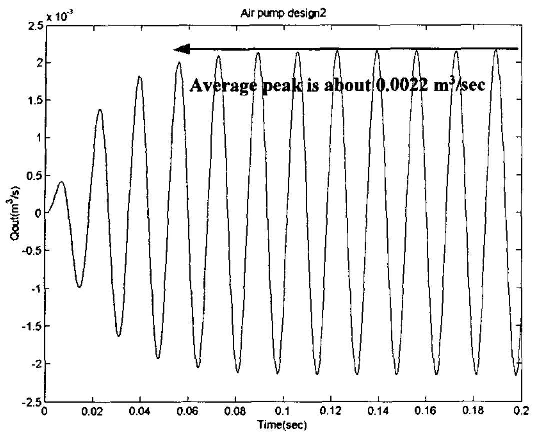

Fig. 13 Outflow of a design variant 2 for air pump

The outflow value is the same as for design variant 1. However, the total power value is 590.45(0<t<0.2) for design variant 1 and 598.22 for design variant 2. This shows that design variant 2 performs slightly less well than design variant 1, but only one C element has been added, rather than the two Cs of design 2, so there is a cost/performance tradeoff available that the designer might wish to make in either direction. Physical realization of design variant 2 is shown in Figure 14.

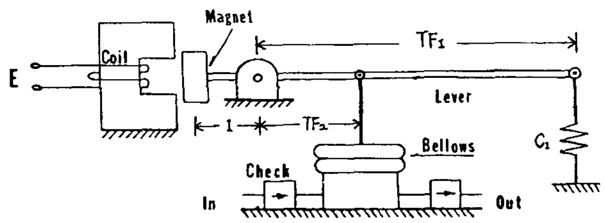

Fig. 14 Physical realization of a design variant 2

6. Conclusion

This paper has introduced a conceptual design of air pump system using BG/GP design method. The domain of air pump system includes electromagnetic and pneumatic fields. The modeling, analysis and synthesis are performed by a unified approach.

In order to design a mixed-energy domain system efficiently, The combination of bond graph and genetic programming, BG/GP design methodology was adopted. Bond graphs are domain independent, allow free composition, and are efficient for classification and analysis of models. Genetic programming is well recognized as a powerful tool for open-ended search.

Two competing design candidates with different topologies for air pump system are obtained. We can see from the output flow responses that they are all higher than those of the original model. The average peak value of outflow is approximately 2.210-3 m3/sec and it is almost 9 times better than the original model, however, the power consumption is also somewhat higher than in the original design.

This tends to support BG/GP design method will improve the efficiency of design for mixed-energy domain system. This, in turn, offers promise that much more complex multi-domain systems with more complex performance specifications can be designed efficiently. The next step in the pump redesign process will be to specify a maximum power constraint and then seek designs that maximize the outflow produced subject to that power constraint. Further study will aim at refinement of bond-graph/genetic programming design methodology, and at demonstration of its applicability to design of more complex systems.

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