Evolutionary Design for Multi-domain Engineering System - Air Pump

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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 pneumaticelements. 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 for evolution of multi-domain system, BG/GP, was tested for redesign of air pump system.

1. Introduction

Automated design of dynamic systems has been focused widely. Especially, 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 (Coelingh [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, which was introduced in Tay et. al.,[2], 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.

As an evolutionary design approach for multi-domain system, the Bond Graph / Genetic Programming (BG/GP) design methodology[3] 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[3-5].

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 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.

2. Air Pump System

A schematic of the air pump is presented in Figure 1. 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.

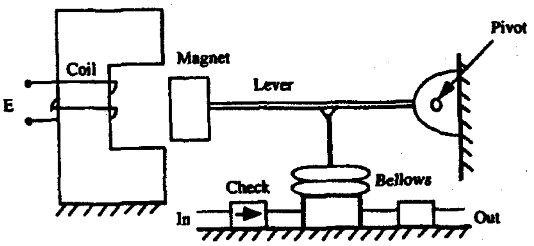


Fig. 1 Schematic of air pump model

3. Unified Approach for Mixed-energy Domain System

3.1 Bond Graph

Bond graph modeling(Figure 2) 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 [6,7].

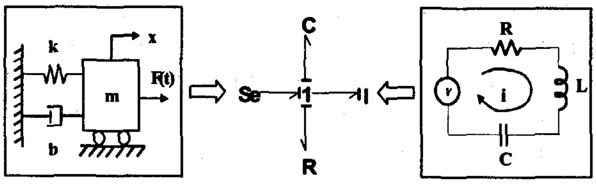


Fig. 2 The same bond graph model for two different domains

Topologically, bond graphs consist of *elements* and *bonds*. Relatively simple systems include passive one-port elements, C, I, and R; active one-port elements, S_e and S_f and two-port elements, TF and GY (transformers and gyrators). These elements can be attached to *0- (or 1-) junctions*, which are multi-port elements, using bonds. The middle of Figure 1 consists of S_e, 1-junction, C, I, and R elements, and that same bond graph represents, for example, either a mechanical mass, spring and damper system (left), or an RLC electrical circuit.

3.2 Bond graph / Genetic Programming design process

The overall procedure is shown in Figure 3. 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).

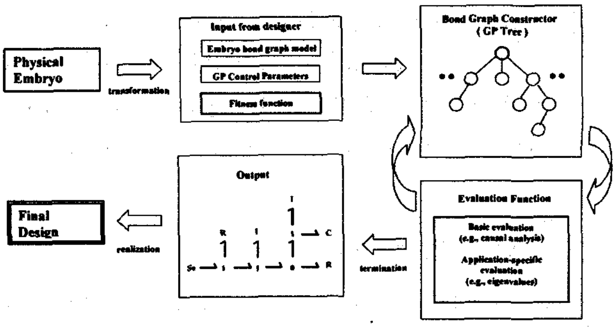


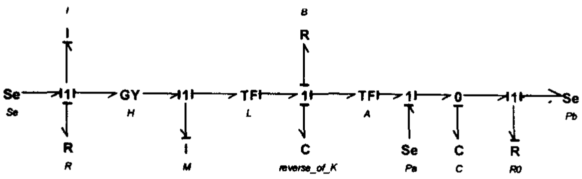
Fig. 3 The BG/GP design procedure

4. Air Pump Redesign

The bond graph model and related parameters for the original air pump is shown in Figure 4. The average peak value of outflow for the original air pump is approximately 2×10^{-4} m^3/sec, as depicted in Figure 5. The ultimate objective of the pump redesign is to maximize outflow subject to a constraint specifying maximum power consumption.

Tay *et al.*[2] use a genetic algorithm to vary bond graph models. 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.



Parameter	Value
H	13 newton/amp $\left(\frac{m/sec}{volt}\right)$
L	0.68
A	1.71×10^{-4} m^2
M	1.11×10^{-3} Newton − sec^2/m
K	117 Kg/m
R	2250 ohm
I	3.9 henry
C	18.85×10^{-10} m^5/Newton
R_0	3.32×10^{6} Newton-sec/m^5
B	negligible

H : Electromagnet field
L : Lever
A : Bellows
M : Mass of magnet
1/K : Compliance of the lever shaft
R : Electric resistance
I : Electrical inductance
C : Compressibility of air
R_0 : Resistance to the airflow
B : Internal damping

Fig. 4 Bond graph model of original air pump mode

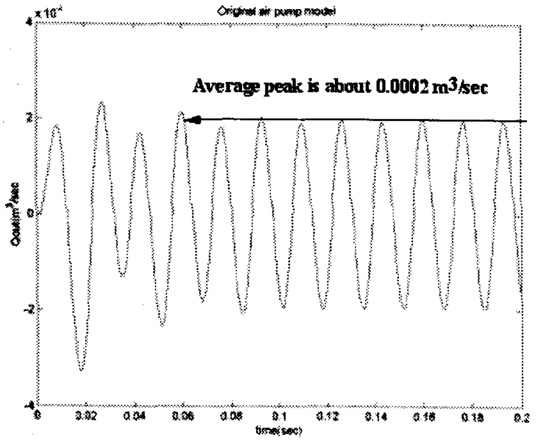


Fig. 5 Outflow of original air pump model

The embryo model for the air pump redesign is shown in Figure 6, 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. Following GP functions are used to evolve a bond graph model for air pump design.

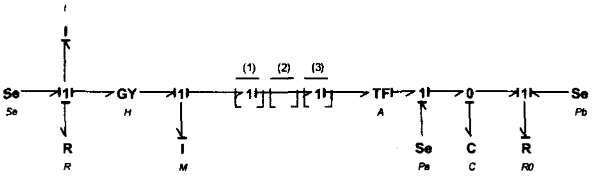


Fig. 6 The embryo model

5. Experiments and Analysis

We used lilgp[8] 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

One of competing design candidates is provided, with it's performances, in Figures 7-9, 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. A design variant is represented in Figure 7. Three new components (two C, one TF), between the two dashed lines highlighted, were added at modifiable sites.

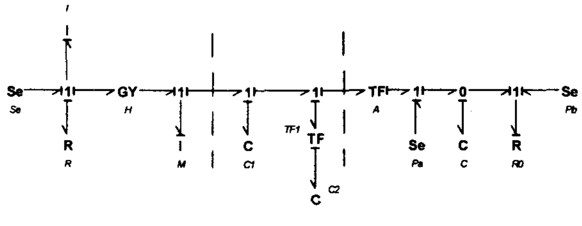


Fig. 7 Bond Graph model of a design variant for air pump

Figure 8 displays outflow of a design variant. The average peak value of outflow is approximately 2.2×10^{3} m^3/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 a design variant is shown in Figure 9.

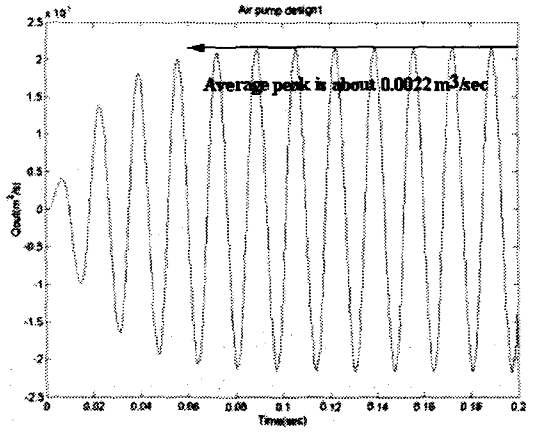


Fig. 8 Outflow of a design variant for air pump

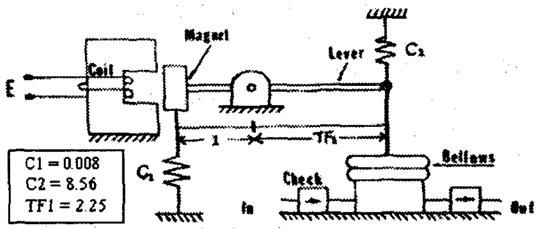


Fig. 9 Physical realization of a design variant

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.

A competing design candidate for air pump system is obtained. We can see from the output flow responses that it is higher than those of the original model. The average peak value of outflow is approximately 2.2×10^{-3} m^3/sec and it is almost 9 times better than the original model.

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.

7. References

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