# Automated Synthesis of Mechanical Vibration Absorbers Using Genetic Programming

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**Abstract**

Conceptual innovation in mechanical engineering design has been extremely challenging compared to the wide applications of automated design systems in digital circuits. This paper presents an automated methodology for open-ended synthesis of mechanical vibration absorbers based on genetic programming (GP) and bond graphs (GPBG). It is shown that our automated design system can automatically evolve passive vibration absorbers that are close to, equal, or much better than the standard passive vibration absorbers invented in 1912. A variety of other vibration absorbers with competitive performance are also evolved automatically using a desktop PC in less than 10 hours.

*Key words:* Automated design, conceptual design, bond graphs, genetic programming, evolutionary design
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# 1 Introduction

It is well known that innovation in conceptual design in mechanical engineering is extremely difficult, and progress has been slow. For example, the vibration absorber technology widely used in automobiles was invented a century ago[1] while the research in this field is still under-exploited and remains to be very productive [2]. The widespread and critical application of vibration absorbers in structural control[3][4], space structuresBruner:1992, vehicle suspension[5], high-speed trains[6], and helicopter vibration[7] make it an important domain in which to develop automated approaches to facilitate creation of innovative solutions.

There are three primary types of vibration absorbers [8]. The earliest class of vibration absorbers is passive absorbers, which do not require any additional source of power to work. A further extension to this model is semi-passive or adaptive-passive vibration absorbers, in which the controlled frequency range can be controlled or adapted in response to a changing environment by tuning the parameters of one or more components. The latest class of vibration absorbers is the active absorbers, which are based on modern control theory. Much progress has been reported on design of novel, patented or patent-pending active or semi-active absorbers; however, such progress is dependent on the talent and insights of the researchers involved.

We are trying, instead, to answer this question: can the Darwinian invention machine [9] based on evolutionary computation-or, more specifically, genetic programming-be used to speed up the rate of mechanical innovation? Since 1997, it has been demonstrated that genetic programming can generate human-competitive designs in a variety of domains including analog circuits[10], quantum circuits[11], and mechanical linkage mechanisms[12]. Compared to electrical circuits, distributed mechanical systems are more difficult to model. However, many mechanical systems can be effectively modeled and formalized to study their dynamic behaviors using current modeling tools such as bond graphs[13], which are widely used for multi-domain engineering systems.

In our previous work, an automated synthesis framework based on genetic programming and bond graphs (GPBG) was used to successfully evolve a variety of mechatronic systems[14,15]. In this paper, we want to demonstrate that the genetic-programming-based GPBG system can be used to duplicate significant innovations in passive vibration absorber design. In addition, control systems have been shown to be synthesized effectively using genetic programming [16]. We project that one would be able to evolve novel semi-active or active vibration absorbers by combining the GPBG framework with control system evolution demonstrated by Koza et al.'s work.

The remaining of this paper is organized as follows. Section 2 reviews some representative vibration absorber designs as well as previous work on automated synthesis of electrical circuits, mechatronic systems, and mechanisms. Section 3 defines the vibration absorber design problem and presents our GPBG framework for their automated synthesis. The experiments and an analysis of results are then introduced in Section 4. Finally, Section5 concludes this paper with a discussion of planned future work.

## 2    Related Work

The invention history of vibration absorbers has spanned almost a century. The first vibration absorber was invented and patented by H. Frahm in 1911 [1]. As shown in Figure 1, his passive vibration absorber attaches a mass to a primary vibrating system through a damper and spring. By tuning the damping coefficient and the absorber stiffness of the spring, one can dramatically reduce the magnitude of vibration in response to a specified frequency of excitatory vibration. The limitation of these passive vibration absorbers is that they work well only at that specified frequency. If the frequency of the excitatory vibration changes, the vibration absorber will become ineffective or even become harmful due to the "de-tuning" phenomenon. A natural solution to this problem is to add an active controller to the whole system, as shown in Figure 1(b). The benefits of active vibration absorbers are that they can track a change in frequency of the excitation source and that they work for a wide frequency band. They are especially useful for vibration sources of unknown characteristics. The shortcoming of active controllers is that the combined system could suffer from control-induced instability and from large control effort requirements, making them inapplicable in many industrial applications [8]. The third type of vibration absorber, as shown in Figure 1(c), combines the advantages of passive and active absorbers by integrating a tuning control mechanism with tunable passive devices, such as variable rate damping and stiffness [17][18]. These adaptive passive vibration absorbers are welcomed by industry due to their low energy requirements and low cost. There are several good reviews available for further details [19] [8].

There has recently been significant conceptual progress in design of vibration absorbers. Most of it relates to design of active controllers. Olgac and Holm-Hansen [20] proposed a novel delayed resonant vibration absorber, which uses only a time-delayed feedback of the absorber mass displacement as the input signal for the control system. This patented absorber [21] can effectively suppress discrete frequencies. Olgac et al. [22] later introduced an even more interesting dual frequency fixed delayed resonator (DFFDR), which can effectively remove disturbances of two discrete frequencies. This DFFDR challenged the traditional understanding of the single mass/single natural frequency para-

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digm. Filipovic and Schroder [2] extended the concept of delayed resonator and developed the bandpass vibration absorber (patent pending), also using only the local feedback force without measuring the displacement of the primary system. This bandpass absorber can absorb all disturbances in a given frequency band. These developments imply that there is great potential for applying GP-based automated synthesis in this domain for improved designs.
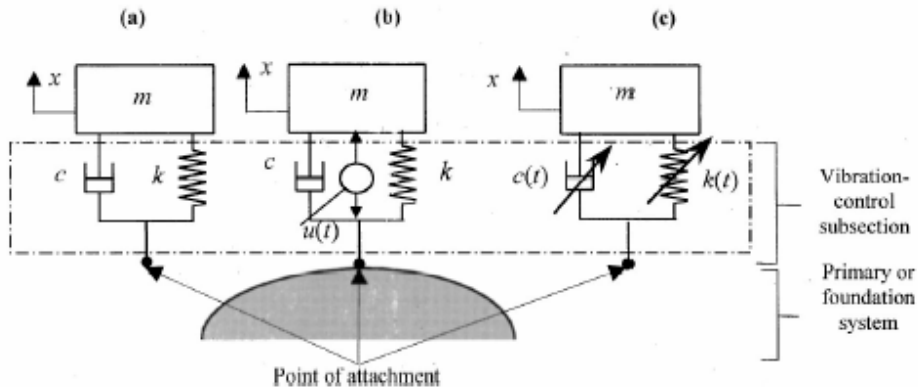


Fig. 1. A typical primary structure equipped with three versions of vibration control systems(absorbers): (a) passive, (b) active, and (c) semi-active configuration

Vibration absorbers are a class of dynamic systems, and can be modeled as analog circuits, block diagrams, bond graphs, etc. One special characteristic of these particular dynamic systems is that the building blocks usually have a fixed number interface ports and may not be connected arbitrarily. Automated synthesis of dynamic systems has been investigated intensively in the past ten years. Most of that work is related to analog circuit synthesis, as pioneered by Koza and his colleagues[9][10]. Their work in automated analog circuit synthesis, including low-pass, high-pass, and asymmetric band-pass filters, is described in [23] [9]. Lohn and Colombano [24] proposed a linear representation approach to evolve analog circuits. Ando and Iba [25] suggested another simple linear genome method to evolve low-pass and band-pass filters with small numbers ($<$50) of components. Controllers, or dynamic systems represented as block diagrams have also been synthesized automatically using genetic programming by Koza et al. [16]. This work has led to the invention of a patentable controller having better performance than a standard PID controller.

Instead of using electrical circuits and block diagrams in our previous work, we developed a GP-based framework for automated synthesis of mechatronic systems using bond graphs as the modeling scheme. The so-called GPBG approach has been applied to automated synthesis of analog filters [14], redesign of an old-fashioned mechanical printer [15] and pump [26], automated synthesis of MEMS systems[27], and synthesis of robust analog filter circuits [28]. However, no attempt has been made to duplicate or compare with designs invented by experts.

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# 3 Mechanical Vibration Absorber Synthesis Using Bond Graphs and Genetic Programming

In this section, we define a vibration absorber synthesis problem and present an improved methodology for open-ended computational synthesis of multi-domain dynamic systems based on bond graphs [13] and genetic programming–the GPBG approach = Genetic Programming+Bond Graphs. Compared to the basic GPBG approach introduced in [29], methodological improvements have been made several aspects, including the following two. First, a new GP function set was developed to improve on the basic set approach used in [30]. This new approach is able to preserve the topology search flexibility of the basic method while greatly reducing the redundancy in evolved solutions. The second improvement is the parameter evolution method. Our previous approach used a numeric subtree to evolve each parameter, while here a special parameter mutation operator is used to evolve the parameters for each topology.

## 3.1 Problem Definition: Synthesis of Passive Vibration Absorbers

In this paper, we are mainly interested in synthesizing passive vibration absorbers to reduce the vibration response of primary systems of various configurations. Figure 2 shows a primary system and its corresponding bond graph model. The design task is to attach some new components to the primary system such that the frequency response at the excitation frequency $\omega$ be minimized. Figure 3 shows the first vibration absorber, invented by H. Frahm in 1911, and its bond graph model. The frequency response of the stand-alone primary system and the primary system with vibration absorber is shown in Figure 4. It can be seen that the vibration absorber can significant quench the response of the primary systems at the excitation frequency. An advanced version of the vibration absorber synthesis problem is to minimize the sum of the frequency responses at two excitation frequencies (dual-frequency vibration absorber) or a frequency band to be minimized, corresponding to the band-vibration absorber described in [2].

## 3.2 Bond Graphs

The bond graph is a multi-domain modeling tool for analysis and design of dynamic systems, especially hybrid multi-domain systems, including mechanical, electrical, pneumatic, hydraulic, etc., components [13]. One advantage of using bond graphs for open-ended design exploration is that the complex loops typical in electric circuit schematics can be transformed into tree-like structures
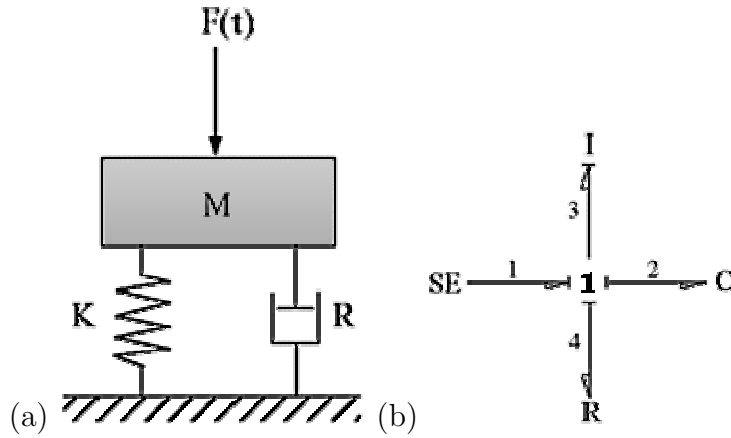
Fig. 2. The bond graph structure of a primary system and its bond graph model (a) The primary system under perturbation of excitation force F(t); (b)The bond graph model of the embryo system.
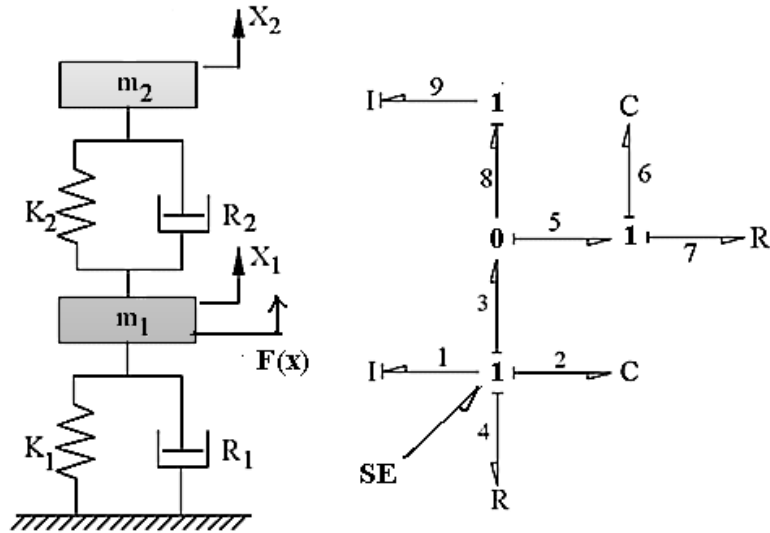


Fig. 3. The bond graph structure of the first patented vibration absorber and its bond graph model.

by the bond graph's 1-junction (serial connection) and 0-junction (parallel connection) concepts, which tend to be easier to evolve in general. Another advantage is that the multi-domain nature of bond graph modeling facilitates evolution of mechatronic systems. Many researchers have explored the bond graph as a tool for dynamic system design, for example [31]. Details of notation and methods of system analysis related to the bond graph representation can be found in [13]. Figure 2 illustrates a small bond graph that represents the accompanying electrical system. Fig. 6 shows the complex bond graph model of a low-pass filter. A typical simple bond graph model is composed of (using notation from electrical systems): inductors (I), resistors (R), capacitors (C), transformers (TF), gyrators (GY), 0-Junctions (J0), 1-junctions (J1), sources of effort (SE), and sources of flow (SF). In this paper, we are only concerned
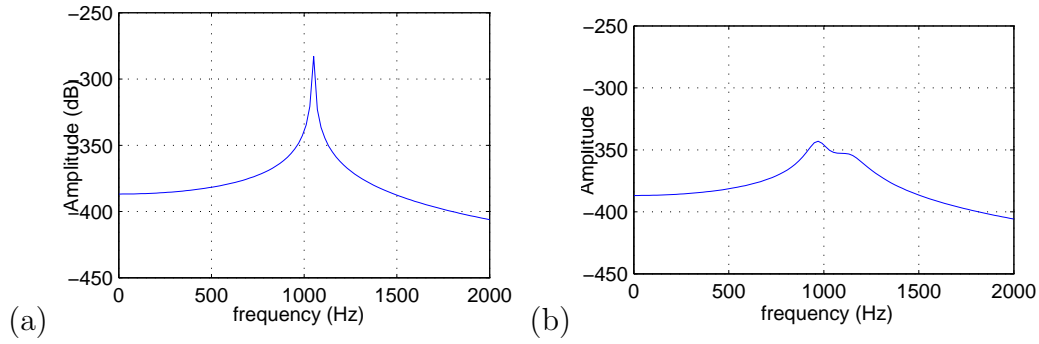
Fig. 4. Frequency responses of the primary system under perturbation of excitation force F(t), without and with vibration absorber. (a) without vibration absorber (b) with a vibration absorber.

with linear dynamic systems represented as bond graphs, which are composed of inductors (I), resistors (R), capacitors (C), sources of effort (SE) (as input signals), and sources of flow (SF) as output signal access points.
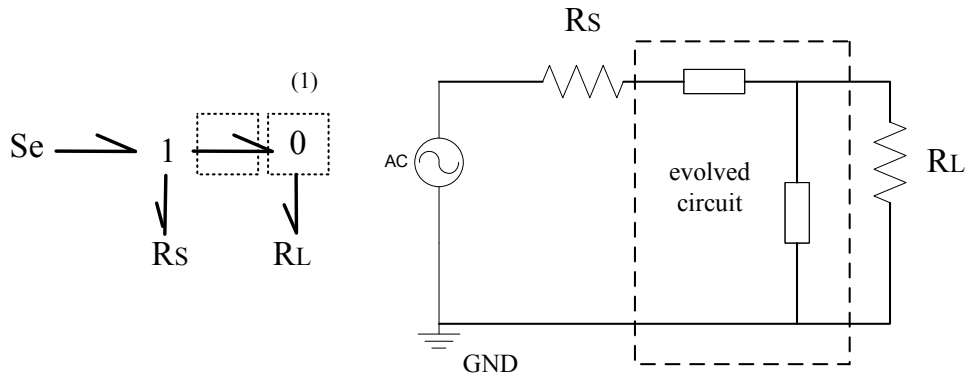


Fig. 5. A bond graph and its equivalent electrical circuit. The dotted boxes in the left bond graph indicate modifiable sites at which further topological manipulations can be applied (to be explained in next section)
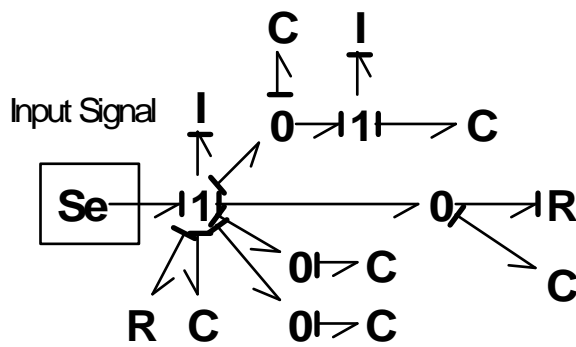


Fig. 6. The bond graph structure of a vibration absorber with 7 components exclusive of the embryo components. (Component sizing values are omitted in the figure for simplicity.)

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## 3.3 Evolving Dynamic Systems Using Bond Graphs and Genetic Programming: the GPBG framework

The problem of automated synthesis of bond graphs involves two basic searches: the search for a good topology and the search for good parameters for each topology, in order to be able to evaluate its performance. Based on Koza's work [9] on automated synthesis of electronic circuits, we created a developmental GP system for synthesizing mechatronic systems represented as bond graphs[29]. This GPBG framework enables us to do simultaneous topology and parameter search. It includes the following major components: 1) an embryo bond graph with modifiable sites at which further topological operations can be applied to grow the embryo into a functional system, 2) a GP function set, composed of a set of topology manipulation and other primitive instructions which will be assembled into a GP tree by the evolutionary process (execution of this GP program leads to topological and parametric manipulation of the developing embryo bond graph), and 3) a fitness function to evaluate the performance of candidate solutions.

Choosing a good function set for bond graph synthesis is not easy. In our earliest work [30], a basic GP function set was used for evolutionary synthesis of analog filters. In that approach, the GP functions for topological operation included {Insert_J0/J1, Add_C/I/R, and Replace_C/I/R}, which allowed evolution of a large variety of bond graph topologies. The shortcoming of this approach is that it tended to evolve redundant and sometimes causally ill-posed bond graphs [32]. Later, we used a causally well-posed modular GP function set to evolve more concise bond graphs with much less redundancy [33]. However, that encoding had a strong bias toward a chain-type topology and thus may have limited the scope of topology search [34]. In this paper, we have improved the basic function set in [30] and developed the following hybrid function set approach to reduce redundancy while enjoying the flexibility of topological exploration:

```
F={ Insert_J0E, Insert_J1E, Add_C/I/R, EndNode, EndBond, ERC}
```

where the Insert_J0E, Insert_J1E functions insert a new 0/1-junction into a bond while attaching at least one and at most three elements (from among C/I/R). EndNode and EndBond terminate the development (further topology manipulation) at junction modifiable sites and bond modifiable sites, respectively; ERC represents a real number (Ephemeral Random Constant) that can be changed by Gaussian mutation. In addition, the number and type of elements attached to the inserted junctions are controlled by three "flag" bits. A flag mutation operator is used to evolve these flag bits, each representing the presence or absence of the corresponding C/I/R component. Compared with the basic set approach, this hybrid approach can effectively avoid adding many

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bare (and redundant) junctions. At the same time, Add_C/I/R still provides the flexibility needed for broad topology search. For any of the three C/I/R components attached to each junction, there is a corresponding parameter to represent the component's value, which is evolved by a Gaussian mutation operator in the modified genetic programming system used here. This is different from our previous work in which the "classical" numeric subtree approach was used to evolve parameters of components. Fig. 9 shows a GP tree that develops an embryo bond graph into a complete bond graph solution. Our comparison experiments [34] showed that this function set was more effective on both an eigenvalue and an analog filter test problem, so the new set was used in this paper.
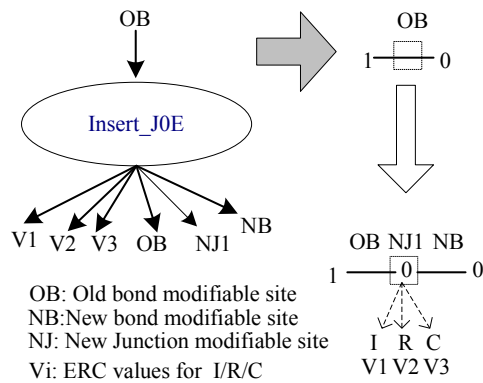


OB: Old bond modifiable site
NB: New bond modifiable site
NJ: New Junction modifiable site
Vi: ERC values for I/R/C

Fig. 7. The Insert_J0E GP function inserts a new junction into a bond along with a certain number of attached components



OJ: old junction modifiable site
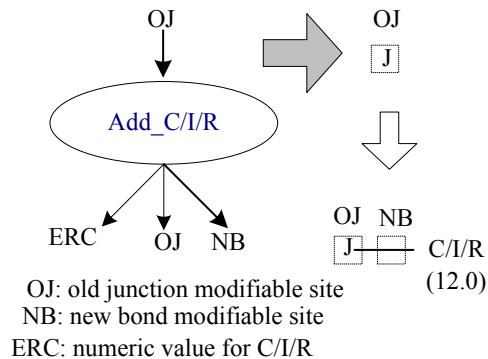NB: new bond modifiable site
ERC: numeric value for C/I/R

Fig. 8. The Add_C/I/R GP function adds a C/I/R component to a junction

## 3.4 Evolving Vibration Absorbers

In this paper, we are interested in evolving three types of vibration absorbers. The vibration absorbers of each type are evolved with several different configurations such as the maximum number of masses to be used, the starting
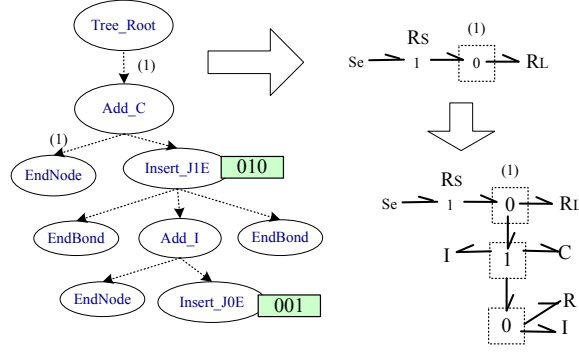
Fig. 9. An example of a GP tree, composed of topology operators applied to an embryo, generating a bond graph after depth-first execution (numeric ERC nodes are omitted). Note that the 010 and 001 are the flag bits showing the presence of absence of attached C/I/R components

embryo and its modifiable site, and the maximum number of components. The synthesis problems include the following.

*Single frequency vibration absorber*

In this problem, we want to see if the GPBG system can reinvent the first patented vibration absorber, shown in Figure 3. The design problem is extracted from **??**. The parameters of the primary system are as follows:

$m_p = 5.77$ kg; $k_p$=251.132 *1e6 N/m; $c_p$= 192.92 kg/s.

The parameters of the standard passive absorber solution is the following:

$m_a = 0.227$ kg; $k_a$=9.81e6 N/m; $c_a$= 355.6 kg/s

We used the bond graph embryos in Figure2 for this problem. The modifiable site is the 1-junction. We could also have different function sets for this GP-based synthesis. Since it is not physically realistic to have many masses attached to the primary structures, we limit the maximum number of masses to 2 in all the experiments.

In this problem, the synthesis objective is to synthesize a vibration absorber such that the frequency response

$$f_{raw} = |TF(j\omega)|_{\omega=\omega_0} \tag{1}$$

of the primary system mass (displacement) at the frequency $\omega$ of excitation force $f = f_0 * sin\omega t$ is minimized. The normalized fitness is defined as:

$$f_{norm} = \frac{NORM}{NORM + f_{raw}} \qquad (2)$$

where NORM is a normalization term aimed at adjusting the $f_{norm}$ into the range of [0,1]. This process transforms the minimization of deviation from target frequency response into a maximization of fitness process as used in our GP system. Since tournament selection is used as the selection operator, the normalization term can be an arbitrary positive number. For both lowpass and highpass filter problems, NORM is set to 10, which gives a fitness range within [0, 1].

According to Equ.1, we need to calculate the frequency response between $\frac{X_1(s)}{F(s)}$ where $X_1$ is the displacement of the primary mass. However, we can only extract from a bond graph the source effort signal $\dot{X}(s)$. We use the following procedure to get the $f_{raw}$:

1)calculate A, B, C, D matrices from a given bond graph;
2)convert A, B, C, D into transfer function $TF_{raw}$;
3)$TF_{norm} = TF_{raw} * 1/s$ is equal to $\frac{X_1(s)}{F(s)}$;
4)convert $TF_{norm}$ back to A', B', C', D' matrices and simulate its frequency response with Matlab.

*Dual frequency vibration absorber*

This problem is borrowed from Olgac et al. [22]'s patented vibration absorber. In this problem, the primary system parameters and corresponding standard passive absorber parameters used in [22] are as follows:

$$m_p = 7.756 \text{ kg}; \ k_p=62,000 \text{ N/m}; \ c_p= 2,500 \text{ kg/s}.$$

$$m_a = 4 \text{ kg}; \ k_a=722,470 \text{ N/m}; \ c_a= 1513.2 \text{ kg/s}$$

The excitation force is

$$f = f_1 * sin\omega_1 t + f_2 sin\omega_2 t$$

where $\omega_1 = 25Hz$ and $\omega_2 = 70Hz$.

The raw fitness in this case is defined as:

$$f_{raw} = |TF(j\omega)|_{\omega=\omega_1} + |TF(j\omega)|_{\omega=\omega_2} \qquad (3)$$

and the normalized fitness is defined in Equ. 2. Since, in this paper, only passive vibration absorbers are evolved, we are not aiming at outperforming the dual frequency absorber invented by Olgac et al. [22], but at determining how well a passive absorber can approximate the performance of the active absorbers for this problem.

*Bandpass frequency vibration absorber*

This problem is taken from the patent-pending vibration absorber invented by Filipovic and Schroder [2]. Their active absorber with a local feedback force has the capability to absorb all disturbance in a given frequency band rather than only at discrete frequencies as do most other vibration absorbers. In this problem, we are interested in testing how closely the evolved passive absorbers can approximate the performance of the invention.

The parameters of the primary system are the following:

$$m_p = 20,000 \text{ kg}; \ k_p = 25,300,000 \text{ N/m}; \ c_p = 39,700 \text{ kg/s}.$$

The natural frequency is thus $\omega_n = 35.7$ rad/s. Filipovic and Schroder [2]'s absorber sets the following parameters for the corresponding passive absorber:

$$m_a = 5,00 \text{ kg}; \ k_a = 632,500 \text{ N/m}; \ c_a = 4,900 \text{ kg/s}$$

with the natural frequency $\omega_a = \omega_n$. The excitation force frequency bandwidth is $bw = 10 rad/s$ and the center frequency is $wo = 35 rad/s$.

To evolve a bandpass vibration absorber, we sum the frequency responses at 12 logarithmically distributed sampling frequencies in the frequency band.

*3.5 Modified Developmental Genetic Programming*

Compared to the GP systems used in [9], our GP system is configured in a little different way in the following respects:

- A flag bit mutation operator is introduced to evolve the configuration of C/I/R elements attached to a junction.
- A subtree-swapping operator is used to exchange non-overlapping subtrees of the same individual (GP tree). In such operations, two type-compatible nodes are randomly selected such that the two subtrees do not overlap, and then a normal crossover operation is applied. This operator does not add or remove components, but reconfiguring the connections among existing components or subcomponents was found to enable better topology search.

- An ERC mutation operator is developed to evolve the parameter values for all C/I/R components. Instead of evolving a numeric subtree for each parameter, a Gaussian perturbation method, as is commonly used in evolution strategies [35], is used to evolve parameters. In each generation, some individuals are selected for parameter mutation. For each such selected individual, half of its parameters are randomly selected to be mutated by adding to the current values a Gaussian perturbation noise with mean 0 and standard deviation 1. These two parameters are determined based on the component value determination process. In our GP system, a mapping process is used to transform an ERC value to the actual component value, following the approach described in [9]. This mapping process is used to constrain the component values into reasonable numeric ranges. The exponential numeric mapping means that a small change in ERC value can lead to large component value modification. We found that our parameter search method had the benefit of reducing the sizes of high-performance GP trees.
- Elitism is used throughout the evolution process.

In this paper, a standard strongly-typed multi-population generational GP enhanced with the above features is used to evolve analog filters represented as bond graphs. The running parameters are specified in Section 4.

## 4 Experiments and Results

One of the biggest obstacles to develop a GP-based automated synthesis system is to build a good fitness evaluator. Instead of using the sophisticated SPICE simulation program as used in many analog filter synthesis projects [23] [25], the frequency response of a bond graph can be simulated in a more convenient way: first a state equation of a bond graph is derived automatically from the model, which generates the A, B, C, D matrices. These state space models can then be simulated on Linux PCs using C++ simulation code generated from Matlab compiler 3.0.

### 4.1 Experimental Settings

Compared to the evolutionary synthesis of electrical circuits, a mechanical vibration absorber usually has a much smaller number of components. So the topological and parameter search space is thus greatly decreased. Most of the experiments are finished in less than an hour. Some of them just cost a few minutes. Here we set the maximum number of components to be 7. Other standard GP parameters are summarized in Table 4.1.

Table 1
Experimental parameters for vibration absorber synthesis

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| No. of subpopulations | 5 | Tournament Selection Size | 7 |
| Sub population size | 400 | pCrossover | 0.4 |
| Maximum evaluation | 100000 | pMutationStandard | 0.05 |
| Migration Interval | 5 gen | MutateMaxDepth | 3 |
| Migration Size | 40 | pMutationParameter | 0.3 |
| Init.MaxDepth | 3 | pSwitchBit | 0.2 |
| Init.MinDepth | 2 | pSwapSubtree | 0.05 |
| StronglyTyped | True | TreeMaxDepth | 7 |

## 4.2   Results

### 4.2.1   Single-frequency vibration absorber

Figure 10 shows an evolved single frequency vibration absorber and its frequency response compared to the responses of the primary structure without any absorber and with standard passive absorber invented in 1912. It is very interesting that the frequency response of the evolved vibration absorber has a very deep spike at the excitation frequency to minimize the frequency response at that single frequency. If the excitation frequency is relatively constant with little shifting, our evolved absorber will achieve better performance at that specific frequency. Another observation of the evolved design is that it does not contain any damper but a single mass and four springs which can be reduced to 3 springs (C in the figure).

### 4.2.2   Dual-frequency vibration absorber

In this problem, the two excitation frequencies are 25Hz and 75Hz respectively. Very interesting, GP system again evolved an absorber at 25Hz with greatly reduced response while the frequency response at 75Hz is worse than the standard passive absorber (Figure 11). Compared to the solution in the previous problem, a damper is used in this dual-frequency vibration absorber. We also checked the parameter values of the evolved solution. The mass value is 3.93 kg, the damper ratio is 1499.58, both are in very reasonable range. The sizing values of other three springs are also easy to realize. However, the shortcoming of our evolved VA is that the frequency response at 75Hz is not damped well, partially caused by our definition of the fitness function which simply minimizes the average the frequency responses at these two frequen-
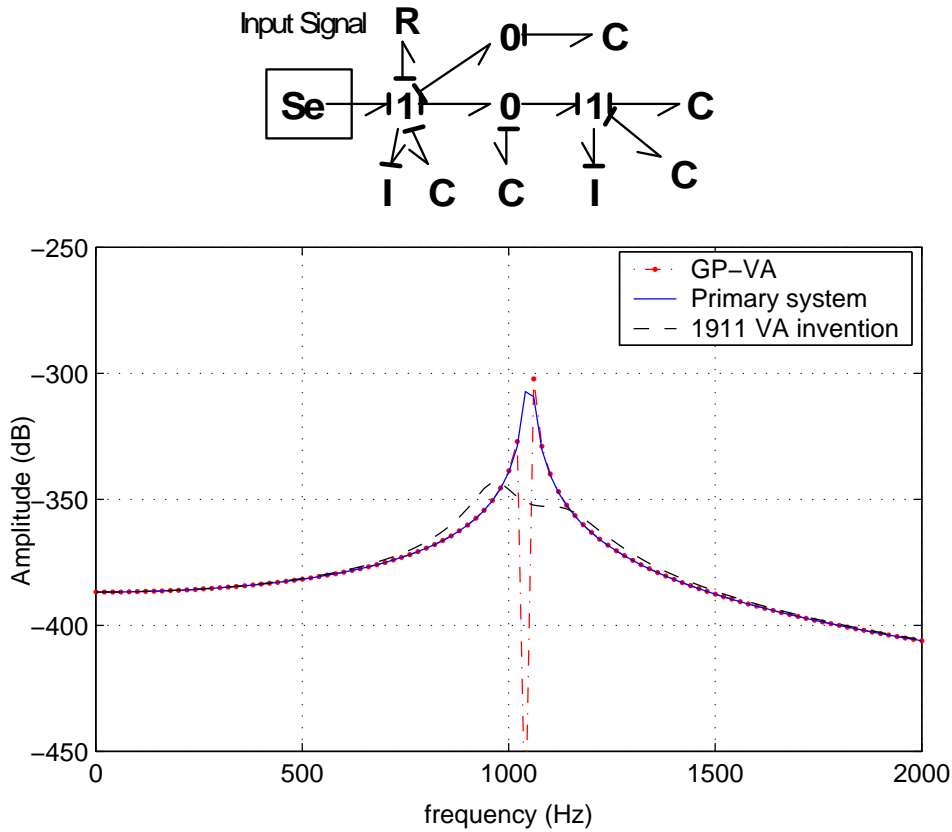
Fig. 10. The evolved single-frequency vibration absorber and its performance compared to standard vibration absorber.

cies. In this aspect, our vibration absorber is much better than the standard one.

### 4.2.3 Bandpass vibration absorber

Figure 6 and 12 show the evolved bandpass vibration absorber. It consists of one damper, one mass and five springs. The parameters of this VA are relatively easy to realize although we did not put the parameter constraints during the evolution. The mass of the PVA is 10 kg, the damper ratio is 5994.39 kg/s. The spring parameters are all within realizable range. In this problem, the target frequency band is from 4.77Hz to 6.37Hz. As we can see from the figure, the evolved VA has much lower frequency responses across all the band area. Compared to the standard passive absorber, our solution is significantly better using only passive components. However, we also find that this solution is not as good as the active bandpass absorber proposed by Filipovic and Schroder [2]. Their active VA is able to almost completely damp any frequency response within the target band area. This discrepancy suggests the necessity and promise of introducing synthesis of both controllers and passive vibration absorbers simultaneously.
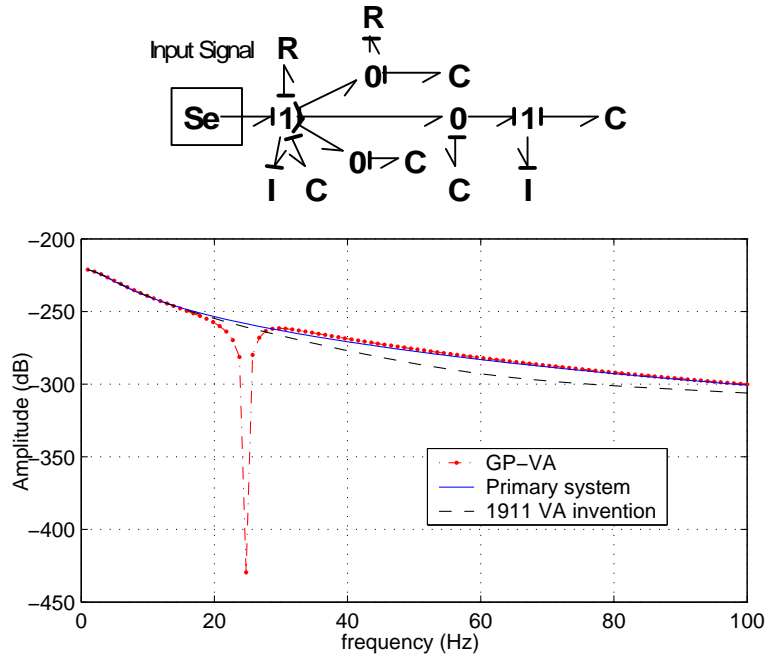
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Fig. 11. The evolved dual-frequency vibration absorber and its performance compared to standard vibration absorber.
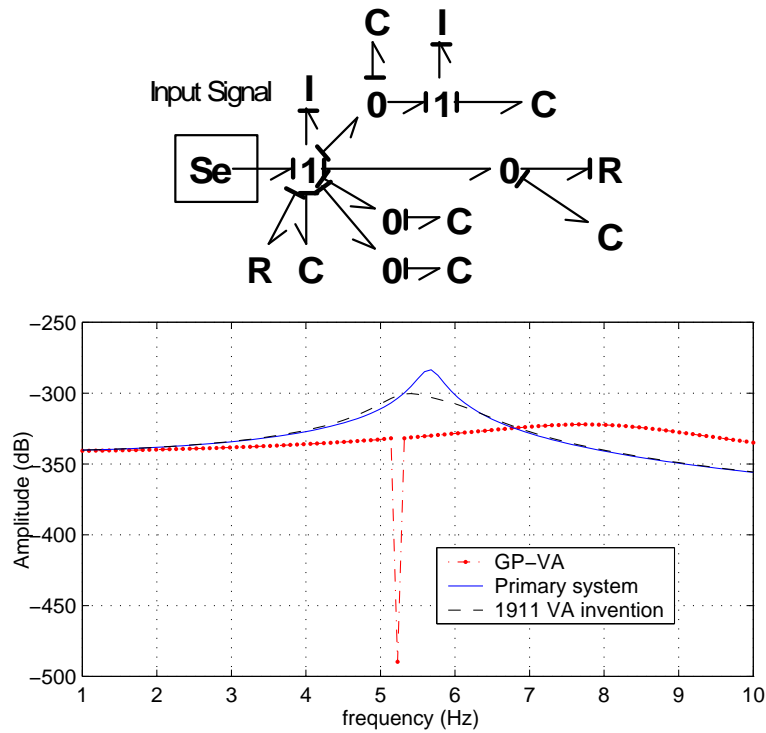
Fig. 12. The performance of the evolved bandpass vibration absorber compared to the standard vibration absorber.

*4.3   Discussion*

# 5   Conclusions

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In this paper, we present a genetic-programming-based method for automated synthesis of passive mechanical vibration absorbers. Using this system, we have

re-discovered the first patented vibration absorber and evolved some new absorbers. Due to the ingenuity inherent in the Darwinian evolutionary process, these solutions can be very useful in inspiring new approaches by design engineers. However, our current system is not able to evolve controllers, which would be necessary to allow synthesis of semi-active and active vibration absorbers. Since both mechatronic system synthesis based on bond graphs [26] and controller synthesis based on block diagrams [16] have been shown to be very successful, we are now trying to combine these two system capabilities, and we hope to rediscover delayed response vibration absorbers, dual frequency vibration absorbers and to evolve conceptually novel vibration absorbers. Considering the importance and extensiveness of application of these devices, it appears very promising to explore this application domain further.

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