Analog Circuit Design with Variable Length Chromosomes

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Abstract- This paper proposes a system of evolving analog circuit based on a variable length chromosomes. It should confirm the system's robustness, circuit scalability, and effieciency on time and memory comsumption. Methods featured here are chromosomes of component list, multi-objective evolution, and two-stage evolution. Set of experiments are shown in this paper. First experiment reconfirms the robustness supplied by the evolutionary method. Second compares several types of chromosome implementation. There are also experiments to evaluate the two-stage and scaling method.

1 Introduction

This paper descrbes the system of analog circuit evolution using variable length chromosomes. The feature of this system will be verified through set of simulated circuit evolution experiment.

There are reasons why evolutional method was introduced to circuit design problems. One is to utilize the creative ability of evolutionary method to derive a new function or topology. Another ability of evolutional method, in this case GA, is adaptation through adjustment of parameters.

The second factor is very useful in the field of analog circuit design because one of the main disturbance in manufacturing analog circuit is the error of the component values. The values components such as resistors and capacitors regularly differ from expected or specified values. They are also subject to the influence of environmental effect such as temprature.

The countermeasures for these variations such as redundant implementation or linear adaptive filters require complicated method and much human experience.

We expect to solve the problem on robustness presented above and add efficiency to analog circuit design using the Evolutionary Analog Circuit, which we so call the system. It includes the linear chromosomes implementation which can also make possible the circuit scalability and multi-stage evolution. We also expect to implement this on Evolvable Hardware(here after EHW) to acquire much robustness.

In EHW only the response of the circuit is evaluated and variance in value of the each componets are absorbed through repetive set of adjustment in topology and parameters and evaluation of the resoponse in the genetic algorithm. In this manner robustness against variance in components is achieved.

There are many types of impementation proposed in evolution of analog circuit. For example Genetic Programming uses tree-type chromosomes and synthesize a circuit creating program. In GA, there are matrix and linear program implementation of analog circuit and succeeded in designing several passive filters.

In the study of EHW, several

Based upon these conventional method, we used methods shown below to feature automatic circuit design and manufacture, topology and parameter evolution, and adequate circuit scaling.

- List based chromosomes.
- Two stages of evolution.
- <u>Complexed</u> fitness.

Furthermore these experiments will evaluate the above method.

- Noise and error absorption.
- Comparison with GP.
- Size reduction

2 Variance in Analog Circuit Component

One of the largest defects of analog system is inaccuracy. When analog circuit is implemented as an integrated circuit, circuit component values inevitably differ from designed specification. This is caused by error in component producing process or number of environmental factors such as temprature. This is a quite large obstacle for designing and manufacturing precision analog device. To realize a strict specification for analog device, complicated and empirical designing process is required.

3 System Architecure

In the EHW anlalog circuit evolution, The topology and values of circuit components are adjusted through genetic operation and GA will evaluate each of the circuit and find the closest response with avalilable component.

The system of Evolutionary Analog Circuit is composed as shown in Fig.1.

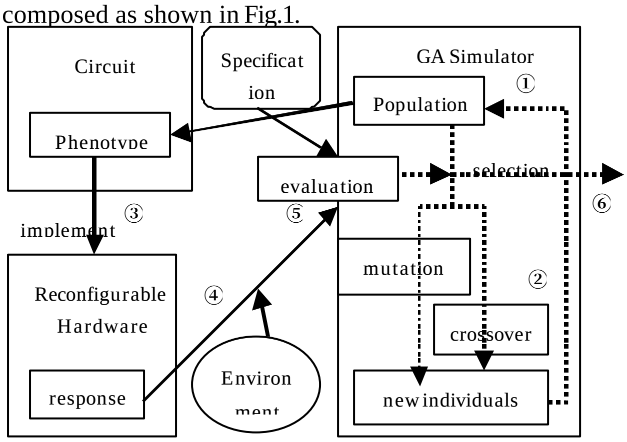


Fig.1:Structure of Evolutionary Analog Circuit

It consists of reconfigurable hardware and GA simulator. Hardwares are resistors and capacitors with programmable value and topology. Circuit evolution follow these steps.

1. Prepare initial population
2. Adustment by genetic operation
3. Implementation of the phenotype
4. Response of the hardware containing noise
5. Response is evaluated based on the objective spec.
6. Inferior individuals are excluded from the group.
7. Return to 2.

These are basic steps for genetic algorithms. Through repetition of adjustment and feedback precise specification is acquired.

4 GA Simulator

This section describes the details of the GA simulator.

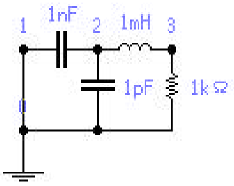
4.1 Chromosomes Implementation

There have been several chromosome representaion proposed for circuit structure. In the Genetic Programming, tree-representation is used and J.R.Koza evolved a circuit creating program for series of complicated circuits. GP is said to have advantage over GA in deriving new topology. Its defects are voluminous memory consumption and convergence time.

Matrix representation for circuit structure is proposed by Kitamura et al. and they succeeded in evolving several analog filters. Its defects are that it requires preliminary knowledge on objective circuit size and complexity.

Linear circuit creating program implementation was used by J.D.Lohn in analog circuit synthesis in [13].

Our chromosome implementation is list representation. This chromosome consisits from list of components in circuit and is variable in length. The chromosomes is shown in Fig.2.



N,0,1,0	C,1,2,1nF	R,0,3,1kΩ	L,2,3,1mH	C,0,2,1pF

Fig.2:Chromosome Implementation

The components are described with type, value, and location. In describing the location of the component we used MessyGA method which is proposed by Goldberg to prevent GA from falling into local solution. Zebulum also used this representation in synthesis of active filters.

Each gene holds an allele for type, location and value parameter. Location is described by pair of integers which represent the nodes in the circuit which the component is connected to. Allele for components' type are R, C, L, N,O which represent resisitors, capacitors reactance, short circuit, open circuit.

4.2 Fitness

Each individual is evaluated based on the deviation between the ideal and actual response by frequency. The fitness function is defined as below.

$$fitness = \frac{1}{K}\sum_{f}^{K}\left|F_f - R_f\right|^2 \quad \cdots \textbf{eq.1}$$

This fitness is the mean of squared deviation between ideal gain F_f and obtained gain R_f at frequency f. The chromosomes with lower fitness are selected to reproduce according to roullette wheel selection. We also used Evolutionary Strategy($\mu+\lambda$)-ES.

4.3 Structure and Parameter Evolution

GA features strong global seach and quick convergence to quasi-optimal solution. On the other hand, stochastic search of GA can be inefficient from quasi-optimal to optimal solution.

In the case of electric circuit evolution from scrach requires two different tasks, which are finding the rough pattern of the filter and adjusting precisely to specification. The first task is acquiring sufficient topology or circuit structure and the second is finely tuning the parameters.

Though in our chromosome representation, both structure and parameters of the components are configurable, we thought it was in efficient to evolve them simultaneously.

In first stage acquiring the proper topology, parameter adjustment with relatively smaller affect on circuit response would be less important to topology alternation. And in final stages of evolution where precise adjustment is required altering topology would be ineffective. We divided the evolution into two stages. In first stage, main objective is to acquire proper topology or structure and parameters will not be a variable. In the second stage, realizing precise specification will be the objective and use the acquired topology as fixed structure.

In the first stage or the structural stage, chromosomes shown in Fig.2 is used. In second stage, or the parameter stage, array of *s* value is used as chromosome. The components are adjusted according to Eq.3. The *s* are real numbers from 1 to –1. Range of modification is kept small for applicability in reconfigurable analog components of EHW.

$$Adjval = Val \times 10^{s} \cdots \textbf{eq. 2}$$

Limiting the variables in each stage results in better fitness, faster convergence, and less memory consumption. Section 6.2 describe the experiment on this method.

4.4 Selective Pressure on Circuit Size

One of the problems in Genetic Programming and GA with variable length chromosomes is development of introns. At certain point in evolution, introns bloat up to huge amount and makes the search awfully inefficient. Details on effect of the introns is described in [7].

In electric circuits, they appear as set of components connected to ground. These introns are crucial to EHW application for it result in consuming large amount of hardware resources.

There can be several measures to eliminate the this introns, but we chose to simply put selective pressure on circuit size. The fitness is adjusted as shown in Eq.4, where *E* is the evaluation of the response and *P* is the penalty for circuit size. *P* is defined as in Eq.(5) where N is the number of components in the circuit and represent the size factor, and T is the modulus to control the intensity of the pressure.

$$fitness = E + P \cdots \textbf{eq. 3}$$

$$P = N \cdot T \cdots \textbf{eq. 4}$$

Since introns have no affect on the circuit response, circuits with introns will be subject to elimination by the size factor.

This selective pressure has its defects when applied too excessively or too early. Eliminating too much introns is said to make crossover operation semantically too destructive, and there are danger of abandoning diversity and eliminating useful schema at early stage of evolution.

T can control the intensity of the pressure by setting the order of P and E in Eq.4. At the early stage of evolution, the term E should be predominant. As the evolution progress and value of E decrease, selective pressure P should gain influence and unnecessary large circuits are eliminated or modified to proper size.

T has to be set according to priority of circuit size and required accuracy, and finding the proper T value is left for future work. We used empirical values for the following experiments in section 8.

5 Robustness Against Variance

The design methods for many passive filters are well established. Yet, analog filters used in many devices are hard to manufacture. As we mentioned before, this is because the components value vary from value specified in designing process.

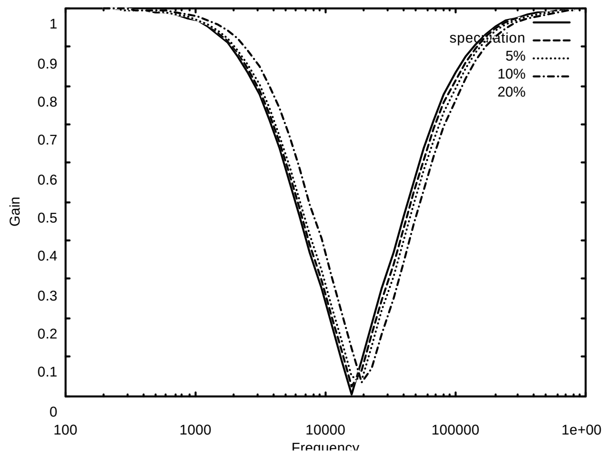


Fig. 3:Ideal and Actual Response of the Band Elimination Filter

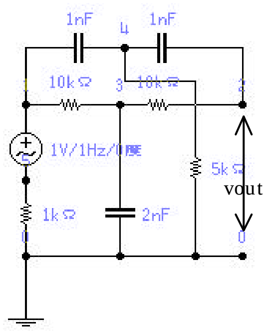


Fig. 4:Band Elimination Circuit Design

For example, solid line in Fig. 3 shows the response of band eliminator filter designed as Fig. 4. However, when the circuit is manufactured from real components, because the components' values vary from specification, response would not be identical to the solid line.

The analog components like resistors and capacitors could contain errors up to 20% of the specified value, and dotted and broken lines in Fig. 3 shows the response when each components in circuit of Fig. 4 randomly contained errors within 20%,10%,5% of the designed values.

These difference caused by the errors are fatal in manufactureing precise analog devices.We conducted a filter synthesis experiment under such condition where components' values are not exactly as specified, to show how Evolutionary Analog Circuit can accomodate with such errors.

5.1 Specification

The goal response is the band eliminating response shown as solid line in Fig. 3. The central frequency of the stop band is 16kHz. The components used to compose this circuit are shown in Table 2

. But each components value are not exact and contain errors upto certain maxima for each of the experiment. We set the maximum errors to 5, 10, and 20% and conducted 5 runs for each case respectively. Result is shown in Table 1.

Noise	Sample circuit	200th generation	400th generation
5%	0.000242971	1.73174e-05	2.53538e-08
10%	0.00121551	1.54782e-05	1.48567e-07
20%	0.00521907	2.17895e-05	1.35741e-07

Table 1:Fitness of Band Elimination Filter

In EHW, circuit ismodified according to the whole response of the circuit, and not by the value of each component. Thus errors in each component will be absorbed through topology and parameter modification of the components as a whole.

6 Comparison with Other Representation

In this section we show several filter synthesis using list chromosomes along with other representations. To compare the result, we used similar objective function and GA parameters.

6.1 Specification

The experiment described here under is based on "Synthesis of an Asymmetric Bandpass Filter" in Chap.31 of [4].

The objective is to acquire an asymmetric bandpass filter described in [4] and [12] as difficult to design because its specifications are both stringent and highly asymmetric.

The ideal and allowable characteristics are defined as shown in Fig.3. Solid line labeled *ideal* indicates the bounds of ideal characteristics and the broken line labeled allowable indicates the allowable range. The circuit behavior is observed at 101 frequencies in the interval between 10kHz and 200kHz in equal increments on a logarithm scale. The fitness is defined as in Eq.6.

$$F = \sum_{0}^{100} \left[W_i \left(d\left(f_i \right) \right) \cdot d\left(f_i \right) \right] \cdots \textbf{eq. 5}$$

Weight W_i is calculated from the difference between the response and the goal response with each observation point, and the total product of the weight W_i and the difference d becomes the fitness. Weight in the pass-band is 10 if allowable, 100 if else. In the stop-band, weight is 1if allowable, 10 if not. Detailed description is found in [4]. The parameters of the GA are shown in Table 2.

	Population	Generation	Crossover rate	Mutation rate
List-based	2000	400	0.99	0.001
GP **[4]**	640000	200	0.9	0.01

Table 2:GA Parameters

6.2 Result

The acquired circuit response is shown in Fig. 5.

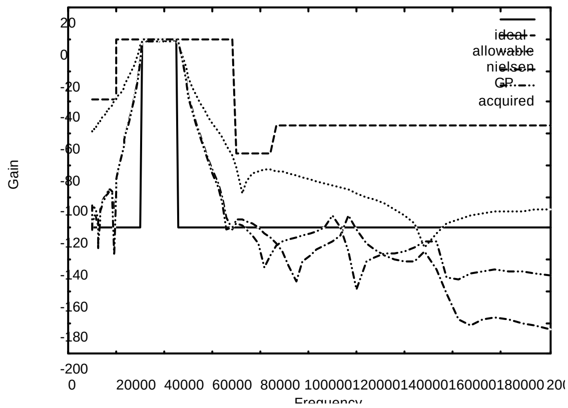


Fig. 5:Acquired Asymmetric Bandpass Filter Response

The best response of the 400th generation is shown as the broken line labeled *acquired*. The dotted line labeled *GP* indicates the response of the circuit obtained in [4]. The fitness of the best individuals was 2037.47 with the *acquired* and 2024.0 with the *GP*. Meanwhile, dotted line of the label *Nielson* shows the response of human designed prototype circuit. The acquired response satisfies the allowable condition in the every region, and obtained better response than the Nieloson's heuristic method. In comparison with GP, we were able to obtain very close response at the pass-band, and equally acceptable characteristic at cut-off region as well.

6.3 Specification

Next experiment is conducted based on [6]. The objective is to acquire an ideal low-pass filter shown in Fig. 6. The pass-band is from 1Hz to 1300Hz and stop-band is from 1300Hz to 100kHz, thus cut-off frequency is at 1300Hz.

The fitness is defined as given in eq.6. $d(f_i)$ is the difference between the goal gain $V_{goal}(f_i)$ and the actual gain $V_{out}(fi)$ at $F+1$ sample frequencies defined as eq.7. The weighted function W is defined by eq.8. The value of W_θ is set to 0.02 in this experiment. For details refer to [6].

$$Fitness = \sum_{i=0}^{F} W(d(f_i), f_i) \cdot d(f_i) \cdots \textbf{eq. 6}$$

$$d(f_i) = \left| V_{goal}(f_i) - V_{out}(f_i) \right| \cdots \textbf{eq. 7}$$

$$W(d(f_i), f_i) = \begin{cases} 1 & for \quad d(f_i) \le W_q \\ 10 & for \quad d(f_i) > W_q \end{cases} \cdots \textbf{eq. 8}$$

$V_{goal}(fi)$ is 1V in the pass-band and 0V in stop-band. Fitness was calculated from total of 78 sample frequencies, 50 from the pass-band and 28 from stop-band. We used the population of 500 individuals, and 200 generations for each run as in [6]. Crossover ratio, mutation ratio, and replacement ratio are the same as in Table 2.

6.4 Result

Fig. 6 shows the response of the best individual of 200th generation. The deviation from specified band remained within W_θ (=0.02V), and its fitness was 1.97615 while the fitness of the best individual obtained in [6] was 2.278. The phenotype of the best individual is shown in Fig. 7.

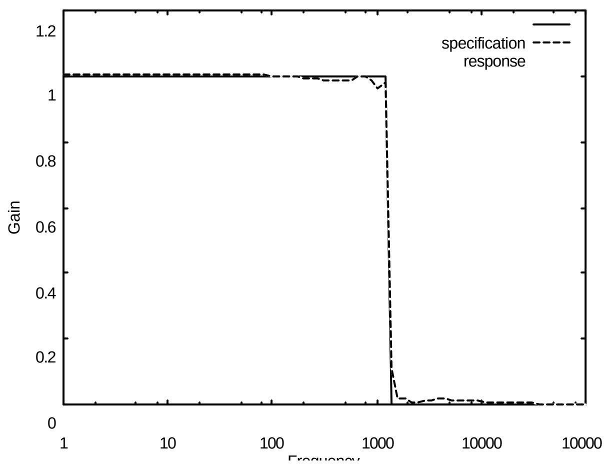


Fig. 6:Specification and Acquired Response of Ideal Lowpass Filter

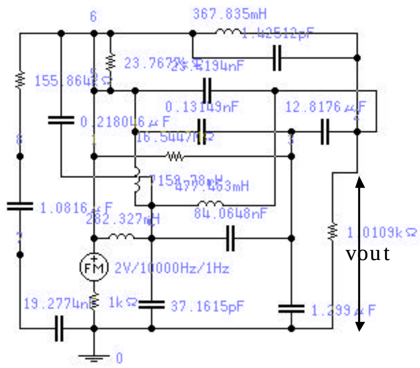


Fig. 7:Aquired Lowpass Filter Circuit

7 2stage Evolution

The experiment in this section divide the evolution into structural and parameter stage.

7.1 Specification

Target response is an ideal high-pass filter depicted as a solid line in Fig. 8. Cut-off frequency is 30kHz, and 14 points were taken at an interval of geometric ratio ranging from 100kHz to 1MHz as the observation points. With the structure evolution phase, the settled values were used as shown in Table 3. GA parameters are as shown in Table 2.

Element types	Values
Resistances	10kΩ,1MΩ
Condensers	1nF,1pF
Coils	100μH,10mH

Table 3:Circuit Components Specification

7.2 Result

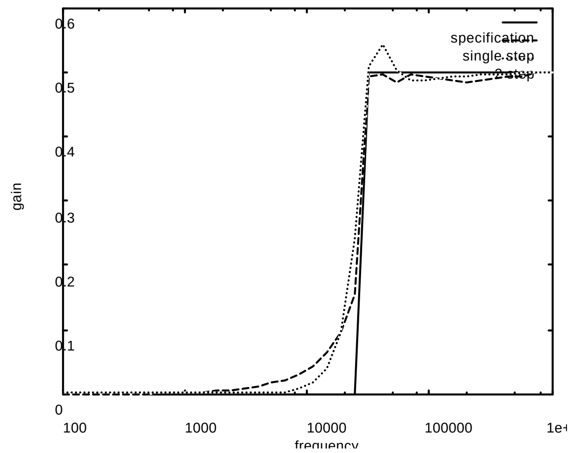


Fig. 8:Specification and Acquired Response of High-pass Filter

Fig. 9 shows the fitness of the best individual by generation. This fitness is average of 3 runs. The broken line labeled *single step* denotes one-stage evolution where topology and parameters are simultaneously evolved. And dotted line labeled *2step* indicates that of 2 stage evolution. An arrow is shown where the parameter evolution starts. The response acquired by each evolution are shown in Fig. 8. The response of single-step evolution is given in broken line labeled *single step* whereas the two-stage evolution is provided by the dotted line labled *2 step*. The fitness is 0.00113213 for two-stage and 0.001955815 for one stage. It is perceived from Fig. 9 while simultaneous evolution converges after 200th generation, two-stage evolution resumes the search by entering the parameter evolution.

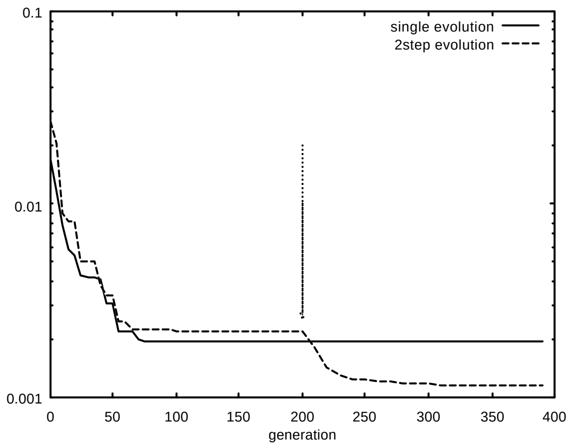


Fig. 9:Fitness by Generation in Highpass Filter Evolution

8 Selective Pressure on Circuit Size

8.1 Specification

We simulated a circuit evolution using the selective pressure referred to in section 4.4. Objective response is the bandpass filter shown in

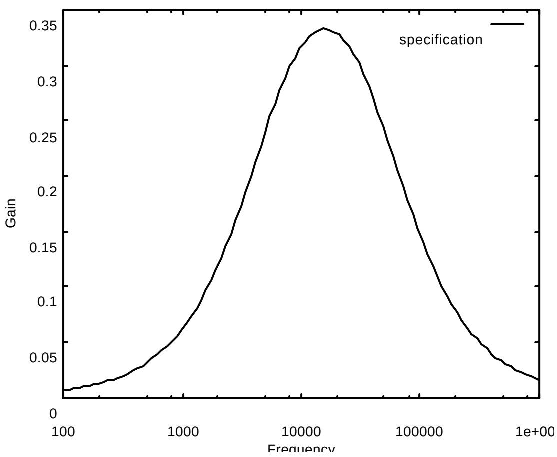


Fig. 10:Objective Bandpass Filter Response

Fitness definition is adusted as in Eq.4, and T modulous is set to 10^{-6}. We conducted 5 runs with 500 population and 200 genererations. Other parameters follows that of Table 2. Only the topology was modified in the course of evolution as circuit size will be fixed in parameter evolution.

8.2 Result

Responses of the best individual at the 40th and 150th generations of a typical trial are shown in Fig. 11. The actual circuit phenotype of each individual is shown in Fig. 14 and Fig. 15. Fitness of the final generation of this run was 6.20766e-11. The fitness and circuit size by generation is shown in Fig. 12 and Fig. 13.

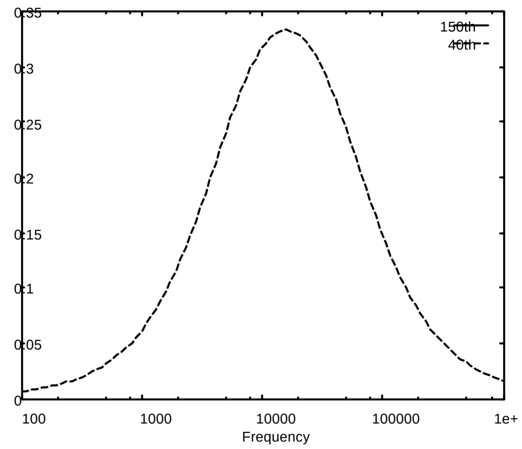


Fig. 11:Response of the Best Individuals from Each Generation

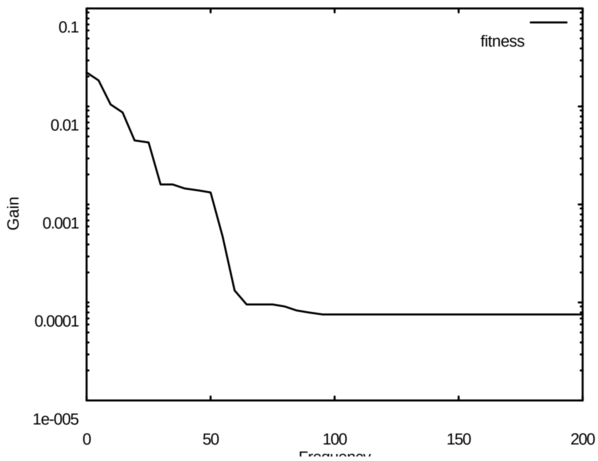


Fig. 12:Fitness by generation

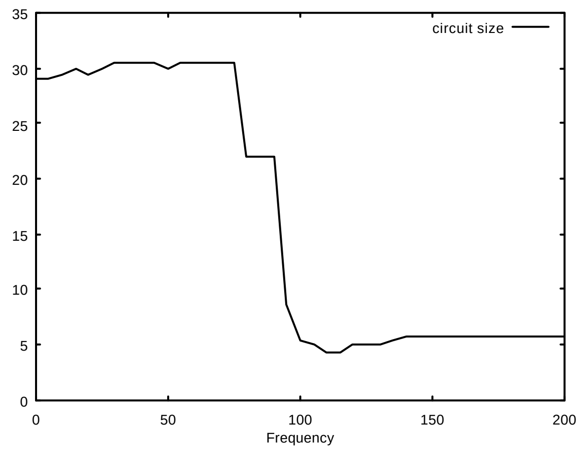


Fig. 13:Circuit Size by Generation

It can be obtained that by the 40th generation, response fullfilled the specification. At 40th generation, while the influence of the pressure is inconsiderable, electrical introns can be seen in Fig. 14, but as can be seen in Fig. 15, those portion are deleted as the evolution progress. Fig. 12 and Fig. 13 shows that adaption in earlier stage of evolution done by aquiring the proper circuit and in the later stage, it is done by getting rid of the unnecessary components.

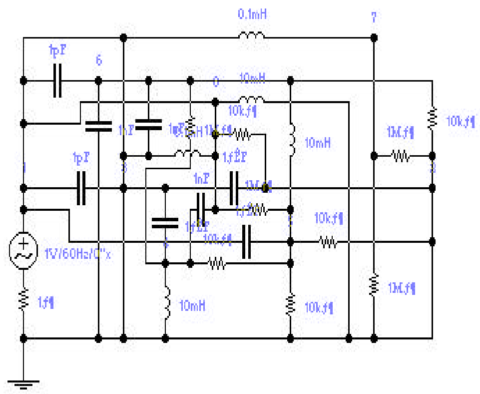


Fig. 14:Best Individual of Generation 40

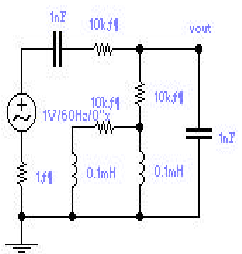


Fig. 15:Best Individual of Generation 150

9 Discussion

9.1 Robustness Against Variation

In experiment shown in section5,

9.2 Comparison with Other Representation

In experiments shown in section6.1, list implementation was able to acquire an circuit with almost equivalent fitness. Generally, GP has the advantage in finding topology and structure. But, in finding circuit structure for the fairly difficult filter shown in section 6.1, list representation was able to achieve equivalent fitness. Meanwhile, using the GA, amount of calculation as in populations and generations can be kept small and memory consumption stays low because of the difference in chromosomes implementation. From this experiment, it can be said that the GA and list representation has the adequecy in circuit design.

9.3 2stage Evolution

In two stages of evolution as we proposed, first stage, or the structural evolution, cause dynamic change in response and fitness, while in later stage, the parameter evolution, response will be altered by smaller degrees to adapt to stringent specification with high accuracy.

Considering the simultaneous evolution of topology and component value, in earlier stage when fitness improve rapidly in primary convergence, effect of parameter being modifiable is so small. In the later stage, topology modification affect too much and newly created circuits do not survive. It also overwhelms the parameter modification and makes it impossible to make little changes.

This 2stage evolution also contributes to lessen the memory consumption by limiting the variables in each stage.

9.4 Pressuring Circuit Size

One empirical part in this system is deciding the T modulus in eq.4. In section 8, we have succeeded in setting the relativity of penalty and response evaluation. Fig. 12 and Fig. 13 shows that in earlier stage of evolution the fitness is improved by acquiring better response, and in later stage, size factor mainly contribute to the fitness improvement. But general way to calculate the T is remained to be studied.

10 Conclusion

In this study, we proposed methods shown below to be used in the implementation of Evolutionary Analog Circuit.

- Component list representation of the circuit.
- 2stage evolution
- Selective pressure on circuit size

These methods were applied to experiments shown in this paper, and result show that these methods are effective for analog EHW. The equipment of the GA system with reconfigurable hardware is to be promoted as a prospect for the future.

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