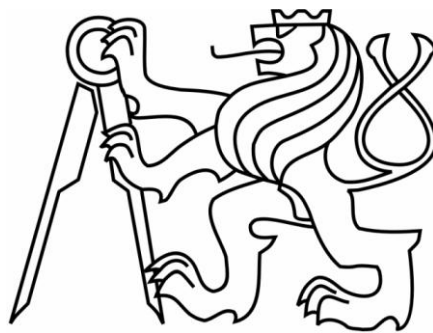Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Circuit Theory

Optimized design of ARC filters using Differential

Evolutionary Algorithms

Master thesis

2013   Developer: Bc. Jiří Barchánek

Project leader: Doc.Ing. Pravoslav Martinek, CSc.

České vysoké učení technické v Praze
Fakulta elektrotechnická

katedra mikroelektroniky

ZADÁNÍ DIPLOMOVÉ PRÁCE

Student: **Bc. Jiří Barchánek**

Studijní program: KME
Obor: Elektronika

Název tématu: **Optimalizovaný návrh ARC filtrů na bázi evolučních algoritmů**
.

Pokyny pro vypracování:

1. Ověřte možnosti využití diferenčních evolučních algoritmů pro návrh vybraných typů selektivních funkčních bloků 2.řádu.
2. Sestavte návrhový algoritmus, implementujte ho v programu MAPLE a ověřte jeho funkci na konkrétních příkladech.
3. Navrhněte úpravy základního algoritmu tak, aby bylo možno respektovat reálné vlastnosti aktivních prvků a minimalizovat rozptyl hodnot parametrů pasivních prvků.
4. Ověřte efektivnost algoritmu a možnosti zrychlení výpočtů vhodnou volbou řídicích parametrů algoritmu, případně využitím pomocné optimalizační procedury.

Seznam odborné literatury:

[1] Corne, D., Dorigo, M., Glover, F. New Ideas in Optimization, Mc Graw Hill,1999.
[2] Zelinka, I. Umělá inteligence v problémech globální optimalizace. BEN, Praha, 2002.
[3] Martinek, P., Boreš, P., Hospodka, J. Elektrické filtry. Vydavatelství ČVUT, Praha, 2003.

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Platnost zadání: 28. 2. 2015

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V Praze dne 28. 8. 2013

Acknowledgment

Here I would like to thank those who helped me bring this work to a successful end. I want to thank them for their willingness and patience, because it wasn't easy and without their help it would be much more difficult. Namely, I would like to thank doc. Ing. Pravoslavu Martinkovi CSc for the time I spent in the consultation and for his valuable advice and suggestions.

Affidavit

I declare that I have my master thesis "Optimized design of ARC filters using Differential Evolutionary Algorithms" developed independently with the assistance of the consultant and used only the literature, which I mention in the "References" attached to the thesis. I also declare that I have no objection to lending, publishing and recovery work in accordance with § 60 Zákona č. 121/2000 Sb., o autorských záležitostech, if Department of Circuit Theory will agree to.

Signature...................

Annotation

This thesis concerns the design of active RC filters with respect to the real parameters of the components using a differential evolutionary algorithm. The implementation of the algorithm was made in Maple software. The aim is to verify the usefulness of the procedure (algorithm) to find out the advantages and disadvantages of using this algorithm in the design of circuits.

Table of content

Chapter 1

Introduction to the problem

This thesis is dealing with issue of optimization methods and their usage in development of active RC filter structures. Whole work is continuation of my bachelor thesis [4]. So the point is to make the optimization algorithm works on chosen filter structure. After that, results are compared with ideal design. Ideal design is created by using equations from literature for [3] and [5]. Design created by optimization algorithm will be strict, with considering of real parameters of used structure. The biggest role here will have frequency dependence of operational amplifier gain. Frequency dependence adds another pole to transfer function and it makes ideal design ineffective.

The work is divided into chapters. At the start there is basic introduction. Chapter 2 is all about used filter structure and its parameters. Chapter 3 is dealing with description of used algorithm and problems with its implementation. Last two chapters are about results and their conclusion.

1.1 Active RC filter

Filter is an important part in many electronic designs. Its main function is to limit frequency band. We got several types of filters like low pass (cuts off high frequencies), high pass (cuts off low frequencies), band pass (creates pass band) and special group of elliptical filters. Examples of frequency response of each type of filter can be find on figures 1.1 - 1.4 (frequency is represented by scaled frequency ω). Main parameters of filter are transfer, slope and cut-off frequency ω_0. Those parameters are represented by filter's transfer function. Transfer function is showing us, how the filter behaves in frequency domain. There are several types of approximation of filter from given values. Difference between them is their shape in pass band and stop band. We use four types of approximations: Chebyshev, Butterworth, inverse Chebyshev and Cauer. For example Chebyshev approximation has ripple in pass band and smooth tran in stop band on the other hand Butterworth approximation is smooth in pass band and stop band. Another important parameters of filter are quality factor Q and multiple constant k. Quality factor Q shows us how close are poles of the transfer function to real or imaginary axis. Multiple constant k indicates how many times the module of transfer function will increase. Filters can be divided into few groups according to their

structure. Main groups into which they are divided are passive/active and digital/analogue. This thesis is focused on active analogue filters more about other types can be found in [3] and [5].
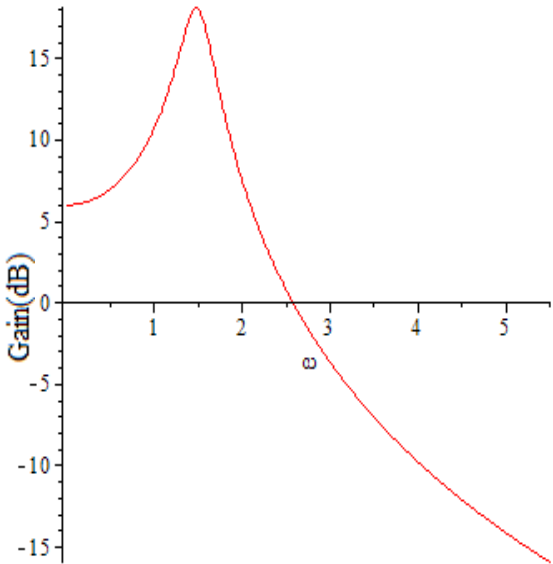
Figure 1.1: Low-pass filter
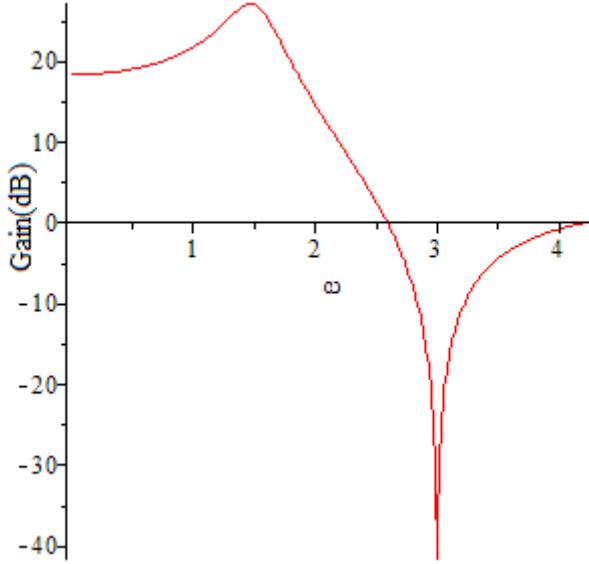
Figure 1.2: Elliptic low-pass filter
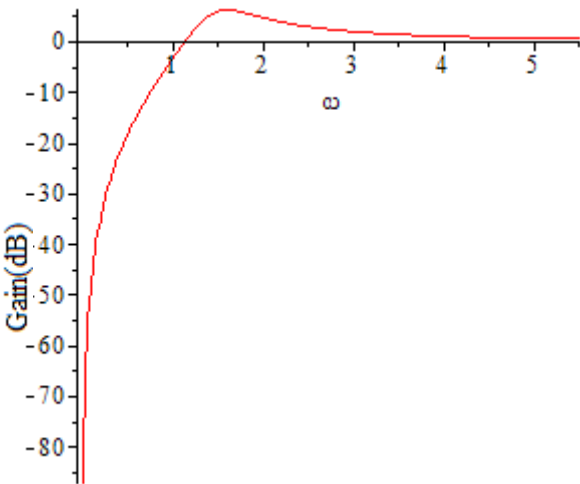
Figure 1.3: High-pass filter
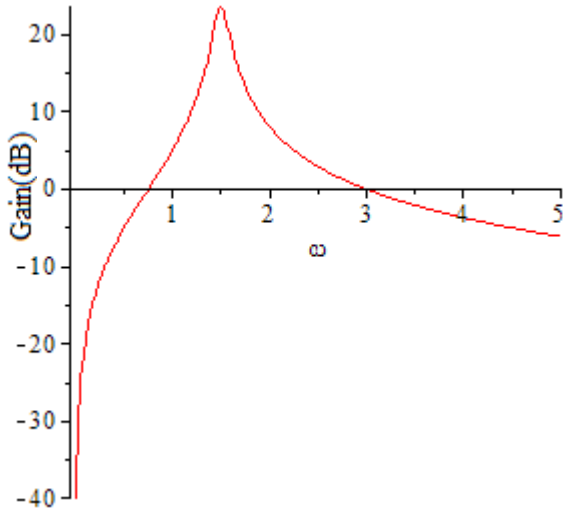
Figure 1.4: Band-pass filter

Active filter always contains some active element. In the beginning they were built from discrete transistors, but after advancement in the field of electronics first operational amplifiers started to appear and transistors were replaced by operational amplifiers. Their advantage over passive filters is in better management of low frequencies and they are less sensitive on values of components. Structure of active filter contains an active element and

passive elements represented by capacitors and resistors. For right function active filter needs external power source. There are three approaches in active filter design. First is cascade synthesis where circuit of higher order is represented with blocks of lesser order. Next one is design based on LC prototype. And last is straight synthesis. The exact approach used in this thesis will be described in chapter 2. Biggest problem with design of active filter are real parameters of circuit elements namely their gain frequency dependence. This is most evident in the case of operational amplifier.

An operational amplifier is a DC coupled high gain electronic voltage amplifier. Operational amplifiers are widely used in modern electronic devices. Their construction is based on transistors. First models were constructed from bipolar transistors, but now they are constructed from unipolar transistors MOSFET. Ideal operational amplifier can be characterized like voltage controlled voltage source with infinite gain, whose input resistance is infinite and output resistance is zero. In reality gain can't be infinite. The main point of this project is dealing with frequency dependence of operational amplifier gain. Frequency dependence is a reason, why we can't use active filters unlimited over whole frequency domain. At the point where frequency dependence starts to show, gain of the operational amplifier begins to drop. In design it's necessary to take this into account. If ours cut-off frequency is much lower than transition frequency (frequency limit of operational amplifier) it's possible to make design without correction for frequency dependence. But when design gets closer to transition frequency, correction has to be done. There is possibility to make correction straight from definition in [3], but that works correctly only for cut-off frequency forty times lower than transition frequency. So here, with frequencies even closer to transition, is place for modern optimization methods. Operational amplifier's got more real parameters we have to look after for example: input voltage and current offset and output noise. But their correction is much easier than correction of frequency dependence. More about operational can be found in [3] or [5]. Description of frequency dependence problem will continue in next chapters.

1.2 Modern optimization algorithms

Thanks to computer revolution we can use modern optimization methods based on series of complex calculations. Those algorithms mostly use stochastic or deterministic methods and their combination. Stochastic algorithms are trying to find the solution of the problem by randomly generating possible solutions and comparing them with a task. This can be effective

only with small amount of solutions, because with high amount of solutions this method will be very slow. Next types are the deterministic algorithms, which are progressing by cutting off impossible solutions and step by step they are getting to final solution. Those algorithms are effective only with right implementation of problem. In more complex cases this can be really a problem. With their combination we get complex method, which uses procedures from both. We can call them hybrid algorithms. By right combination of previous two methods we get very effective algorithm that can be used effectively to solve many difficult tasks. Today we have got many types of those algorithms for example: ant colony optimization algorithms, particle swarm optimization, scatter search algorithms and evolutionary algorithms. Algorithm used in this thesis is based on one of those hybrid algorithms and it's called differential evolutionary algorithm from now on evolution algorithm. Detailed description of this algorithm will be in following chapters. There are other types of algorithms based on this combination but they are not subject of this thesis. More about modern optimization algorithms can be found in [1] [2].

Chapter 2

Tow-Thomas filter structure

Circuit, which has been chosen for this project is Tow-Thomas structure with three operational amplifiers. This circuit represents active filter of second order and is able to create three types of filter transfer functions. The main advantage of this circuit is ability to create different transfer function without big interferences into circuit structure. This circuit also shows good susceptibility parameters. Possible transfer functions for this circuit are low pass filter, band pass filter and elliptical section of low pass filter (realisation of high pass filter is also possible but it´s not used in this work). As stated before this circuit contains three operational amplifiers, first of them has got role of summing amplifier and integrator, second is integrator and the last just negates output of second amplifier. The schematic of modified Tow-Thomas circuit is on figure 2.1.
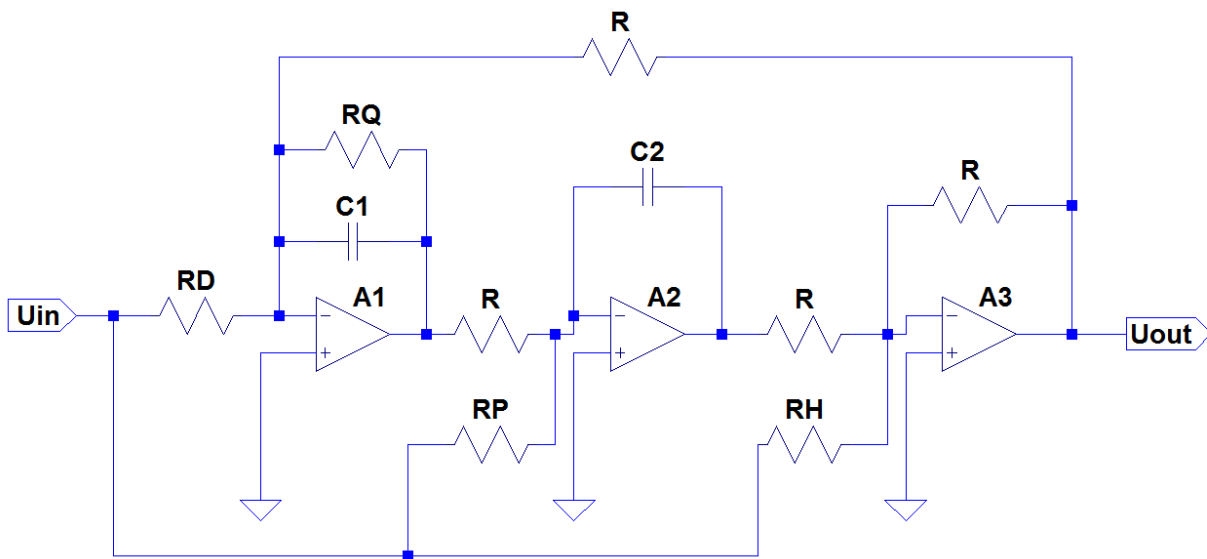
Figure 2.1: Tow-Thomas circuit

Tow-Thomas structure used in this project is modification of basic structure. Modified structure has got three additional resistors. By adding or removing those resistors we easily choose which transfer function we want to use. Resistors used for setting each type of transfer function are resistor RD, RP and RH. Resistor RD is always plugged and it creates coefficient of absolute term of transfer function numerator. Resistor RP creates linear term and resistor RH creates quadratic term of transfer function numerator. General biquadratic transfer function for this modified structure can be derived in this form (2.1).

$$H(p) = \frac{U_0}{U_1} = -\frac{p^2\frac{R}{R_H}+p\frac{1}{RC}\left(\frac{R^2}{R_Q R_H}-\frac{R}{R_P}\right)+\frac{1}{R^2 C^2}\left(\frac{R}{R_D}-\frac{R^2}{R_D R_P}\right)}{p^2+p\frac{1}{R_Q C}+\frac{1}{R^2 C^2}} \qquad (2.1)$$

From equation (2.1) can be easily see that resistor R_D, R_P and R_H are participating in creation of numerator of transfer function. Denominator is created by the rest of circuit components.

Low pass filter is realised only with resistor R_D because this resistor is responsible for absolute term of numerator of low pass filter transfer function (2.2). For band pass filter we have to add resistor R_P to create linear term for numerator of band pass filter transfer function (2.3). Transfer function of elliptical filter (2.4) contains two cut off frequencies ω_0 and ω_N and uses different approximation of transfer function, while previous two filters use Chebyshev approximation, elliptic filter uses Cauer approximation. That's why resistors R_D, R_P and R_H in elliptical filter circuit need to be connected to create needed terms for transfer function numerator. In (2.5) can be seen transfer function of the high-pass filter. Further implementation wasn't realised.

$$H(p) = \frac{H_0\omega_0^2}{p^2+\frac{\omega_0}{Q}p+\omega_0^2} \qquad (2.2)$$

$$H(p) = \frac{H_0 p\frac{\omega_0}{Q}}{p^2+\frac{\omega_0}{Q}p+\omega_0^2} \qquad (2.3)$$

$$H(p) = \frac{H_0(p^2+\omega_N^2)}{p^2+\frac{\omega_0}{Q}p+\omega_0^2} \qquad (2.4)$$

$$H(p) = \frac{p^2}{p^2+\frac{\omega_0}{Q}p+\omega_0^2} \qquad (2.5)$$

2.1 Ideal filter design

Ideal filter design is design without considering of real parameters of used parts. Ideal filter based on Tow-Thomas structure can be designed with simple equations. Those equations can be found in literature [5] or we can derive them from circuit schematic. In most cases we got goal parameters of filter (ω, Q, k) and we are looking for values of circuit resistors, other

parameters like amplifier gain and value of capacitors we set. Scaled frequency ω can be used instead of frequency f, this problem is described in next paragraph.

Equations for low pass filter are the simplest, with only three unknown values of resistors. Value of resistor R is obtained from first equation (2.6), value of resistor R_Q is obtained from second equation (2.6) and value of resistor R_Q is obtained from third equation (2.6). According to (2.1) equations for R and RQ remain same for all designs, because they are used in creating of transfer function denominator, which is same for all types of transfer functions.

$$R = \frac{1}{fC}, \quad R_Q = RQ, \quad R_D = \frac{R}{k} \tag{2.6}$$

Band-pass filter design uses different equation (2.7) for value of R_D and there is also new equation (2.7) for resistor R_P.

$$R_D = \frac{R_Q R_P}{R}, \quad R_P = \frac{R_Q}{k} \tag{2.7}$$

Equations for elliptical low pass filter resistors R_H and R_P are in (2.8) and for resistor R_D in (2.9).

$$R_P = R_H Q, \quad R_H = \frac{R}{k} \tag{2.8}$$

$$R_D = \frac{R_P R_Q R_H}{k \omega_N^2 R_Q R_P R + R_H R} \tag{2.9}$$

2.2 Frequency scaled filter design

Frequency scaled design of filter means that real value of frequency f is transferred to scaled value ω. If scaled frequency is used in design, values of all circuit components will be in scaled format. Working with scaled parameters has got two major advantages. First of all it's not necessary to work with high values of frequency in orders of MHz, because it's possible to transfer values of frequency to the order of units. Another advantage is possibility to use one scaled design for more real designs. That's because scaled parameters are evaluative with relative value of real parameters. Result of frequency scaling is frequency ω and can be obtained from this equation (2.10) where f is real frequency and f_N is scaling

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frequency. In case of this project only values which we need to evaluate from scaled form are values of resistors. All other values are set or will be given with real design. Equation (2.11) is example of calculation of real value of resistor, where C is real capacitor and R_N is scaled value of resistor.

$$\omega = \frac{f}{f_N} \quad \rightarrow \quad f_N = \frac{f}{\omega} \tag{2.10}$$

$$R = \frac{R_N}{2\pi f_N C} \tag{2.11}$$

2.3 Circuit stability and frequency dependence

Every operational amplifier has limited bandwidth where it can work. Effect which occurs in this band is called frequency dependence of operational amplifiers gain. Frequency dependence of operational amplifier gain reduces gain of the amplifier. The edge of GBW (gain-bandwidth) is called transition frequency f_T, at this amplifiers gain has value of 1. Frequency dependence could also make whole circuit unstable. For every operational amplifier in circuit frequency dependence adds a parasite pole in transfer function. Tow-Thomas circuit used in this project has got three amplifiers so his transfer function will have three parasite poles. Example of how this transfer function could look like is here (2.12). Note that this is not real transfer function, because real transfer function with frequency dependence is much more complicated.

$$H(p) = -\frac{A(p^3+p^2+p)\left(p^2\frac{R}{R_H}+p\frac{1}{RC}\left(\frac{R^2}{R_Q R_H}-\frac{R}{R_P}\right)+\frac{1}{R^2C^2}\left(\frac{R}{R_D}-\frac{R^2}{R_D R_P}\right)\right)}{A(p^3-p^2-p)\left(p^2+p\frac{1}{R_Q C}+\frac{1}{R^2C^2}\right)} \tag{2.12}$$

It is possible to correct effect of frequency dependence with help of equations (2.13) for cut-off frequency ω_0 and (2.14) for quality factor Q. More about those equations can be found in literature [3] and [5]. Corrected ω_0 and Q are used as new default parameters for design. Correction of quality factor is only needed when equation (2.15) is higher than zero. Those equations work pretty well on designs with small influence of frequency dependence. Their efficiency will be described in following chapters.

$$\omega_{0correct} \approx \omega_{0a} + \frac{2+k_i}{2}\frac{\omega_{0a}^2}{\omega_t} \tag{2.13}$$

$$Q_{correct} \approx \frac{Q_0}{1 - 4Q_0\frac{\omega_0}{\omega_t}} \qquad (2.14)$$

As stated before frequency dependence also could cause instability of circuit. That's caused by summation of phase errors of real integrators which can lead to interruption of feedback stability of whole loop. Instability effect can be corrected by frequency correction. If the correction is needed can be decided with use this equation (2.15).

$$1 - 4Q_0\frac{\omega_0}{\omega_t} > 0 \qquad (2.15)$$

If result of equation is higher than zero then correction isn't needed otherwise correction has to be done. Correction can be done by adding correction capacitor C_K or correction resistor R_K into circuit (figure 2.2). Value of those components can be calculated from equation (2.16). When correction resistor is chosen we also have to reduce value of integrator's resistor by value of R_K.
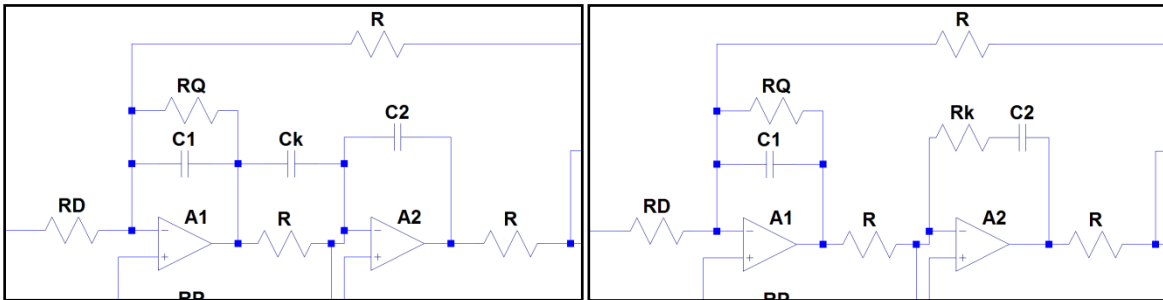

Figure 2.2: Example of connection of C_K and R_K to the circuit

$$R_k = \frac{4}{\omega_t C} , \quad C_k = \frac{4}{\omega_t R} \qquad (2.16)$$

Chapter 3

Differential evolutionary algorithm

From numerous optimization algorithms was chosen differential evolutionary algorithm for realization of this project. As stated before there are many types of optimization algorithms which differ in method's procedure. Differential evolutionary algorithm comes from the group of hybrid algorithms so it has got random part and deterministic part. Random part serves as generator of possible solutions. Those solutions are compared with ideal solutions we want to achieve. And deterministic part trying to compare each solution and creates new solutions by using methods known from nature evolution. Best solutions are taken and one or more their members are submitted for hybridization. If the solution after hybridizations is better than previous then it proceeds to new generation. Principle of how choosing new vectors works is on figure 3.1.
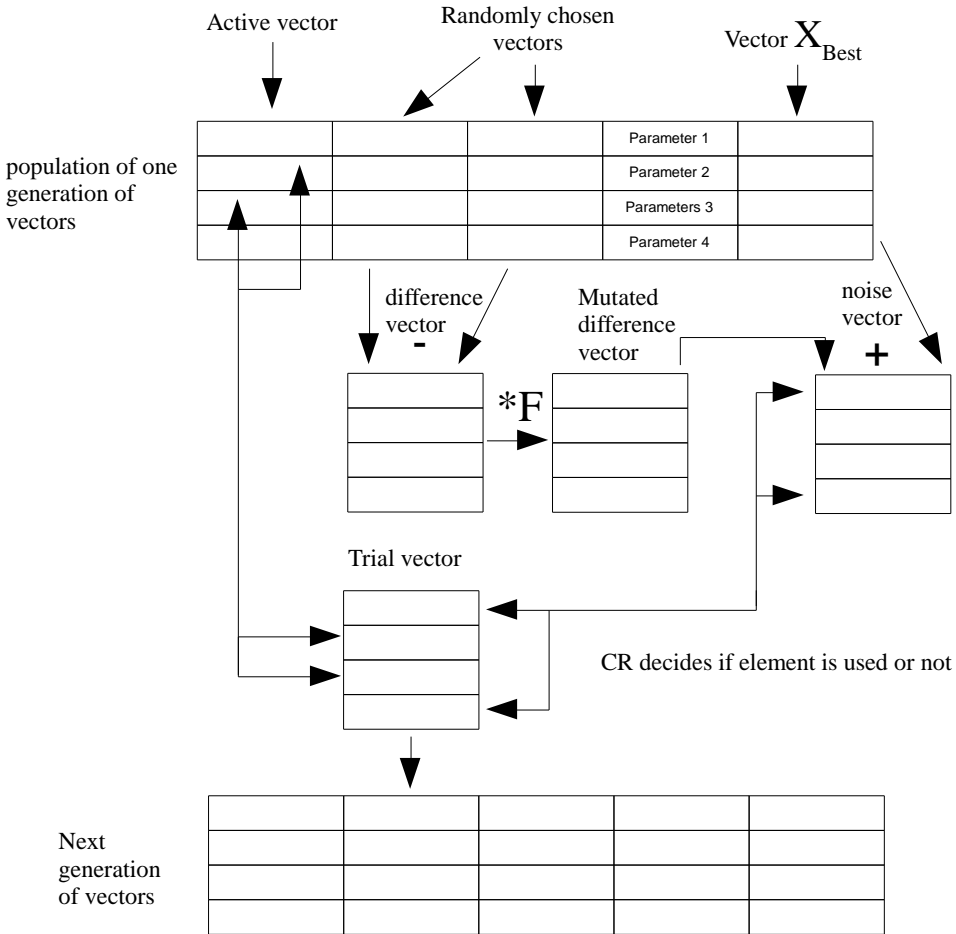

Figure 3.1: Principle of differential evolution

Differential evolutionary algorithms use generations of solutions where each generation is based on previous generation of solution. So if the algorithm's settings are right, then every new population represents better set of solutions. As comparison element is used a fitness function. Fitness function represents sum of individual divergences so lesser the value of fitness function represents better solution. The Divergence value is based on comparison of requested parameters of design with the parameters which we get from algorithm. So with bad setting of deltas (divergences) algorithm can't even start or when starts won't work well. Following paragraphs will continue with a description of an exact application of algorithm.

3.1 Application of algorithm on active filter structure

As a simulation interface for algorithm in this project was chosen MAPLE software. MAPLE is mathematical software which can work with symbolic equations. This is very useful in this type of project, where symbolic transfer functions are used.

This optimization uses comparing of two frequency responses for creating of fitness function. One of those frequency responses is ideal frequency response calculated from (2.1-2.5). From those equations can be easily seen that this function is second degree. Another frequency response is calculated by MAPLE from circuit schematics. Transfer function used in creating of this frequency response is modified with frequency dependence of operational amplifiers. So as stated before frequency dependence adds parasite poles to transfer function, so in this case transfer function will be fifth grade. So algorithm is trying to match second grade transfer function to fifth grade by comparing their frequency response characteristics. Example of how this comparison looks like is on figure 3.2. Both functions from figure 3.1 has same filter parameters (band-pass $\omega=1{,}5$, $Q=4$, $k=2$, $\omega_T=45$).

$$Hi := -\frac{0.75\,s}{s^2 + 0.375\,s + 2.25}$$

$$Hbestu := \frac{-0.00029067649615\,s^3 - 0.02036086393\,s^2 - 0.3112961721\,s - 0.0001055036744}{0.000008762409563\,s^5 + 0.001028802084\,s^4 + 0.03869175084\,s^3 + 0.4610136692\,s^2 + 0.2528720545\,s + 0.9999999998}$$

Figure 3.2: Transfer functions of ideal and "real" band pass filter ($\omega=1{,}5$, $Q=4$, $k=2$, $\omega_T=45$)

MAPLE software works gradually, so whole algorithm is divided in few main blocks. First block is representation of design goals. In this case the easiest way to represent the filter parameters is through its transfer function. With use of a MAPLE graphical functions ideal

frequency response is created. Samples on different frequencies are taken to approximate frequency response of desired transfer function. Those samples will be later in creation of fitness function as references.

Next block is about definition of circuit structure. Here is used library created at Czech Technical University especially for definition of circuits in MAPLE. Library name is Syrup, the entering of circuit is based on same principle like in spice programs. It means that the circuit nodes are numbered and individual parts are placed between numbers of nodes. After completation of circuit, two nodes are chosen as an input and an output. Ratio of those two namely the output/input creates transfer of circuit. To get right form of transfer function needed for optimization few more operations has to be done. Like the simplification of transfer function. Because transfer function is quite large, this may rise calculation times. Another more important step is application of frequency dependence. Frequency dependence is described by this equation (3.1). As stated before frequency dependence adds additional poles to transfer function. In this case it means quite an enlargement in size of transfer function, slower computer may have a problems with this enormous equation. With this form of transfer function it is possible to continue to next step and that step is the optimization.

$$A(p) = \frac{A_0}{1 + \frac{pA_0}{\omega_T}} \tag{3.1}$$

After getting all needed information optimization can start. At the start of optimization block there is the declaration of input parameters of differential evolution algorithm. Those parameters need to be declared before start and set right for smooth run of the algorithm. Here is a list of the important ones:

NP - This is number of elements in population. Basically speaking higher is better, more combinations can be done in one population. Bad side is with high amount of elements calculation speed slows down.

G – Number of generations used for optimization. For this parameter also applies higher is better. But it is not necessary for this number to be really high, because optimal solution can come sooner than all generations are used. Optimal number of generations can be easily found by trial and error after few optimizations of one design.

NF - Number of unknown parameters. Vector of unknown parameters is created with help of this number. Basically this number sets dimension of vectors.

M_h, M_d - Range of values used in the random generating of vectors in population. With wider range values optimization takes more time or optimization could fail, because it gets into the

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local extreme. Before the start of optimization there is also check for stability of circuit by equation (2.9). If the check fails then different version of algorithm must be used, the version with compensation capacity or resistor. Also values of capacitor are set to C = 1, it is a normalized value of capacity. This setting of capacitor value is used in all simulations. Next step is creating fitness function by substituting the values from vector into the symbolic transfer function. After that it is possible to create frequency response of circuit and this frequency response can be compared with ideal frequency response, declared at the start of algorithm. Result of their comparison is difference of both functions. Difference is calculated by this equation (3.2). Fitness function is sum of those differences. Ideal solution will have zero value of fitness function. So the ideal solution from the best vector should same frequency response as ideal frequency response. Figure 3.3 is example of the MAPLE code for creation fitness function.   Differential evolutionary algorithm has few possible choices how to mutate or hybridize vectors of solutions. Whole process is controlled by this equation (3.3), which is mandatory in creation of new vectors. There are also two mutation parameters. First of them is mutation factor F and second one is CR the threshold of hybridization. Example how the evolutionary algorithm generates new vectors with use of constants C and F can be seen on figure 3.1.

```
>  fitval:= proc(XP)
    global  R1, R2, Href, Ndo:
     local i, j, delta, PP1, Htest:
      for i to NF do R||i:= XP[i]; od:
       Htest:= [seq(abs(subs(s=I*om,Hufz)),om=dataom)];
       for i from 1 to Ndo do delta[i]:= evalf(Htest[i]/Href[i] -1) od:
     add(evalf(1e7*abs(delta[i])^2),i=1..Ndo);
    end:
```

Figure 3.3: Example of creation of fitness function in MAPLE

$$delta[x] = \frac{H_{TEST}}{H_{REF}} - 1 \tag{3.2}$$

$$v = x_{best}^{G} + F(x_{r2}^{G} - x_{r3}^{G}) \tag{3.3}$$

Algorithm ends when reaches required number of generations or when fitness functions value reaches requested level. The result of optimization is vector x_{best} which contains values of optimized parameters. At the end of optimization there is test of those

values. Test itself is a comparison of ideal frequency response and frequency response created by circuit with optimized parameters of components. Detailed description of differential evolution can be found in literature [2][6] and [7].

3.2 Low-pass filter and band-pass filter optimization

For optimization of low-pass filter is used setting of circuit described in previous chapter. Input ideal transfer function has form (2.2). Ideal frequency response is created from this transfer function. Samples used for creating of fitness function are taken in range from $\omega=$ 0 to $\omega=$ 3.5 with the spread about thirteen samples thought the range. Samples are spread with more focus on the surrounding of cut-off frequency. Exact placing of samples may vary in different designs. Unknown parameters of circuit are resistors R, RQ and RD, all other parameters are set. So the vector used for optimizations will have three elements. There are three versions of algorithm for optimization of low-pass filter. One version is for circuit which doesn't need stabilization and other two are with stabilization component added to the circuit. As described before if design doesn't pass stability test, compensation component has to be added to the circuit. No other element is added to the vector, because their values (2.9) come from already used components.

Realization of optimization of band pass filter is quite similar to low pass. For sampling there is a difference in range. First sample is taken from $\omega = 0.3$, because frequency response starts from zero Y axis and according to (3.2) this cause the error in creating of difference. Circuit itself got additional resistor R_P in compare with the low-pass structure. So vector of unknown parameters got four elements. Another difference is the setting of output of this circuit. As an output is used node after second operational amplifier. Rest of the algorithm is same as a low-pass design.

3.3 Elliptical low-pass filter optimization

Realization of optimization of elliptical low pass filter is more complicated than previous two designs. This structure has got five unknown parameters (additional resistor RH) this means that calculation time will be longer. This circuit transfer function is much more sensitive on changes of values. This mean that little change in the value of resistors can cause big change in transfer function. Another problem is creating of zero point, because value of transfer in that point should be zero. It is the same problem with equation (3.2) for band pass

design. But it is different here, it is not effective to use few samples around the point. Point must be sampled very strictly, in order to get the lowest possible value of transfer. Samples very close to zero on Y axis also cause very high value of fitness function and that is a problem mainly at the start of optimization. Those facts together make optimization falls into local extreme very often. So the solution for this problem is to do more optimizations. That mean that first optimization will have minimal requirements for frequency dependence and depth of zero point. Second optimization will use values from x_{best} of previous optimization as a starting x_{best}, but this time requirements for frequency dependence will be higher. And the last optimization will have different sampling to create low value at zero point. Number of needed optimization may vary with difficulty of required design, but important thing is each optimization starts from values of previous. When stability correction is needed process is same. Optimization starts with normal version and when the stability test won't pass with given requirements, the optimization version is switched to corrected version. If frequency requirement values were close in both designs, then this switch won't cause trouble.

Chapter 4

Results

Results of optimization algorithms were tested by two methods and were compared with other solutions from different design methods. The comparation of results was made for scaled and real parameters. For the scaled comparing was used MAPLE software. And for simulation of real circuit with values gathered from optimization was used LTSpice software. In next paragraphs will be described results of all designs optimized with evolutionary algorithm.

4.1 Distribution of results

Results of each design are divided into three main groups, those groups are: designs without stabilization, designs with capacity correction and designs with resistor correction. Each design is compared in scaled form and real form.

Special MAPLE program was created for comparison of scaled forms, this program shows comparing of the ideal frequency response to the frequency responses created by other design methods. This program uses same process of creating ideal transfer function and creating of circuit as used in optimization programs. Transfer function is gathered by same process as in optimization. The unknown parameters are substituted by results of each method. Point is to get results of all methods into one graph. There are four traces in each graph. First of them is ideal frequency response and serves as a reference. Second is ideal design created by equations from paragraph 2.1. Third trace is corrected ideal design created with equations from paragraph 2.1 and 2.3. Last trace shows frequency response achieved with evolution algorithm. There are also table of results and frequency response created by LTspice. There are two types of tables for each filter type, one is for design without compensation and other for compensated design. Tables contain results of corrected ideal design and results of optimization by algorithm. LTspice graph is there for showing that optimized values work also in different simulation.

4.2 Results for low pass filter

First block of results shows results for low pass filter with designs that doesn't need stability compensation. There are several types of designs with different parameters of transfer function to show how algorithm can deal with them. Each design was made for two transition frequencies of operational amplifiers to show how values changes when this frequency rises. Results can be found in table 1. From table can be easily seen that quite differ. It mostly depends on how close is transition frequency to cut-off frequency. The biggest difference is in value of R_Q, which is because of quality factor correction (2.14). This correction uses exact equation that doesn't work in every situation, evolutionary instead uses individual approach to every problem. In the figure 4.1 can be seen frequency responses for each design approach. Parameters of ideal transfer function from fig 4.1 are $\omega_0=1,5$, $Q=8$, $k=4$ and $\omega_T=55$. Blue line is ideal frequency response and in this case results of evolutionary algorithm practically overlap this line, results of algorithm have red line. Black line represents ideal design which is absolutely off limits. Green line is corrected ideal design which is quite good but thanks to high value of R_Q it doesn't match over cut off frequency. On figure 4.2 there is test of values from evolutionary algorithm onh real frequency with use of LTspice. Cut off frequency of this design is 45 kHz.

Low-pass filter									
goal				Classic design			DE algorithm		
ω_0	Q	k	ω_T	R	R_Q	R_D	R	R_Q	R_D
1,5	4	2	30	0,60606	12,12121	0,30303	0,58833	1,26791	0,29147
1,5	8	4	55	0,61625	38,73549	0,15406	0,60886	2,56867	0,15165
1,5	10	1	65	0,64436	83,76704	0,64436	0,64033	3,36910	0,63851
1,5	1	1	15	0,57971	0,96618	0,57971	0,49193	0,31004	0,48497
2	6	6	55	0,43651	20,57823	0,07275	0,42512	1,28798	0,07054
1,5	4	2	45	0,62500	5,35714	0,31250	0,61636	1,58207	0,30679
1,5	8	4	70	0,62640	15,94468	0,15660	0,62133	2,94208	0,15496
1,5	10	1	80	0,64843	25,93718	0,64843	0,64534	3,73978	0,64408
1,5	1	1	30	0,62016	0,77519	0,62016	0,59708	0,47744	0,59380
2	6	6	70	0,44872	8,56643	0,07479	0,44118	1,51279	0,07332

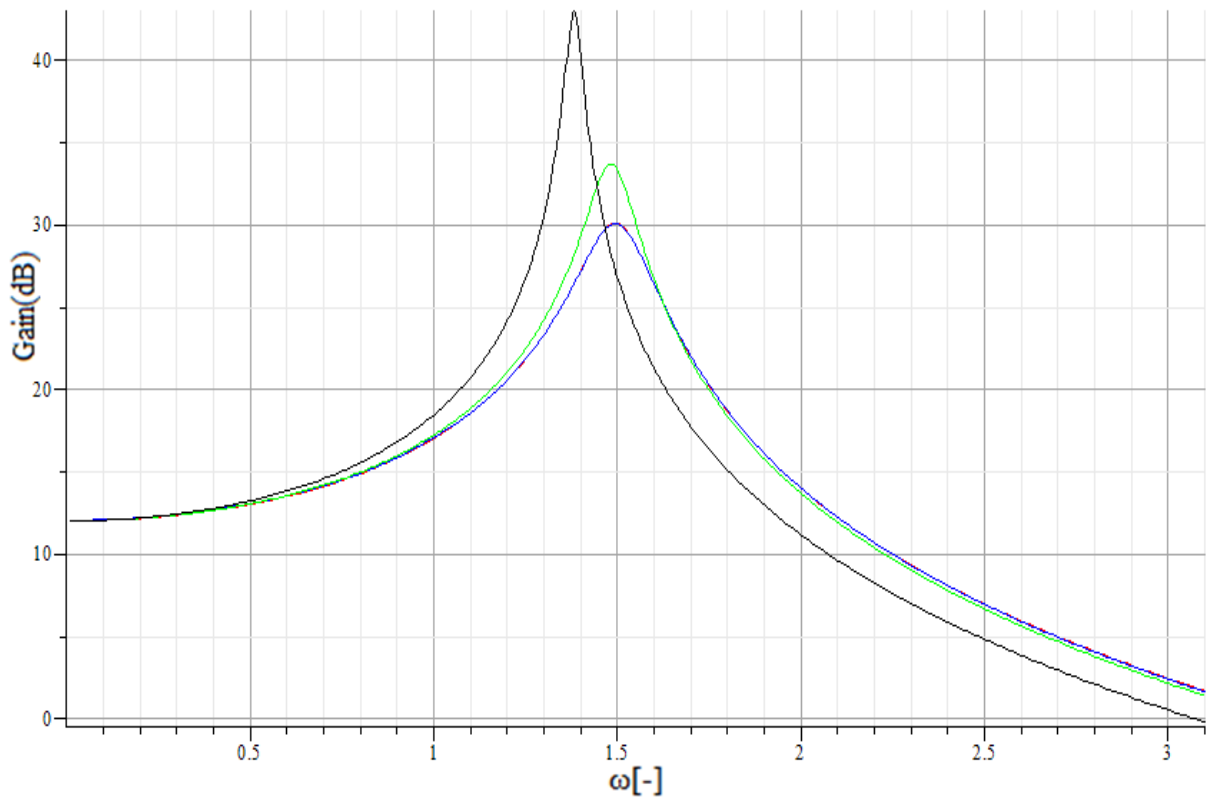*Table 1: Results for low-pass filter*

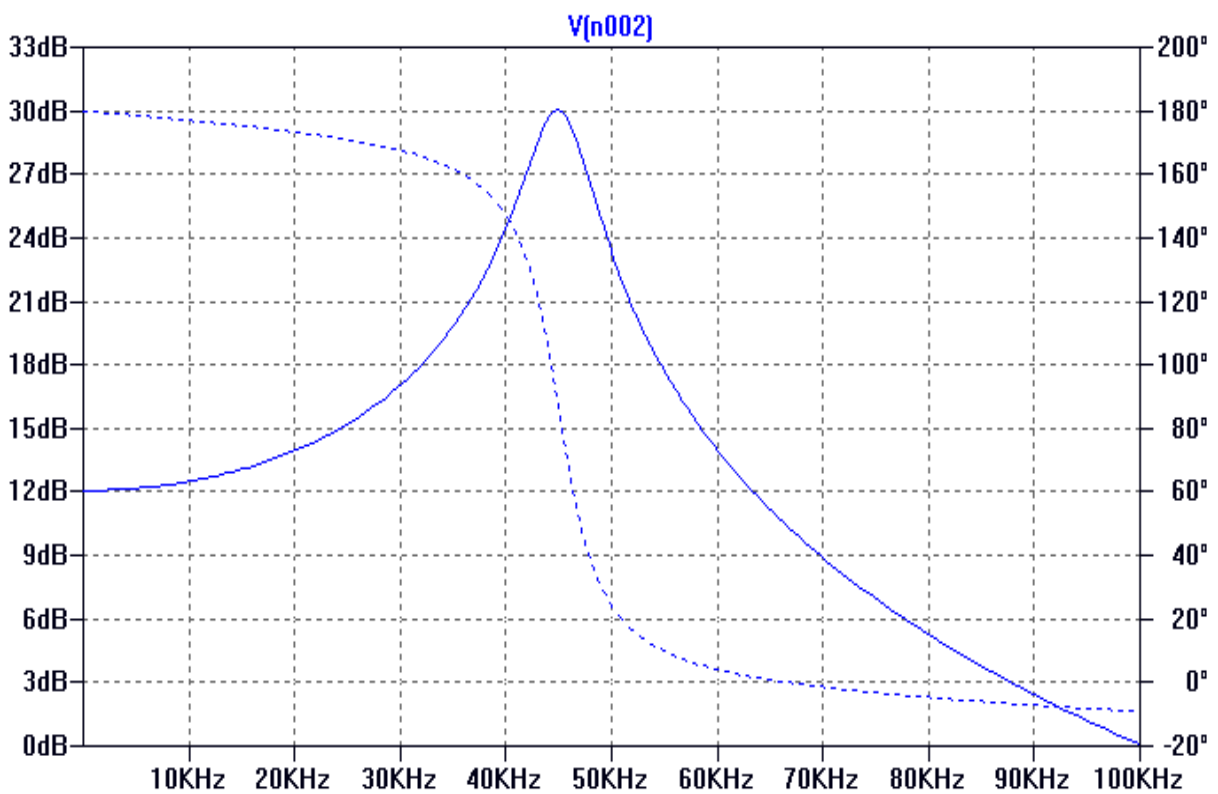*Figure 4.1: Frequency responses low-pass filter ($\omega_0=1,5$, $Q=8$, $k=4$ and $\omega_T=55$)*

Figure 4.2: Frequency response of real frequency design for low-pass filter ($\omega_0=1,5$, $Q=8$,
$k=4$ and $\omega_T=55$)

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4.3 Results for low-pass filter with stability compensation

Results of compensated designs of low-pass filter are in table 2. As stated before there are two possibilities of stability compensation, one with resistor R_k and other with capacity C_k. In the table 2 there are only designs with C_k, but results for R_k can be seen in further pictures. Designs in table 2 were made for low values of transition frequency ω_T, that is because compensation is only needed when ω_T is low or Q is high. Description of this problem is in chapter 2.3. In case of low-pass filter corrected design work pretty well, differences are much lower than in design without compensation. That is mostly because corrected designs are more suited for circuit with capacity compensation. In the figure 4.3 can be seen frequency response for design with capacity compensation. Filter parameters of this design are $\omega_0=1,5$, Q=2 , k=2 and transition frequency is $\omega_T=15$. From this figure can be seen that ideal design is out of limits (black line). Corrected design (green line) works quite well with only difference in maximum gain. Results of evolutionary algorithm (red line) mostly overlap the ideal frequency response (blue line) with small difference in slope in stop-band. In the figure 4.4 there is comparison of frequency responses of designs with resistor compensation. Parameters of filter are same as before. In this case both ideal and corrected designs are unusable. For evolutionary algorithm result are quite same as before. In the figure 4.5 and 4.6 can be seen results applied to circuit with real frequency. Both designs here work very well.

Low-pass capacity compensation									
goal				classic design			DE algorithm		
ω_0	Q	k	ω_T	R	R_Q	R_D	R	R_Q	R_D
1,5	4	2	15	0,55556	2,22222	0,27778	0,55630	1,92128	0,28683
1,5	8	4	20	0,54422	4,35374	0,13605	0,53486	3,87403	0,13719
1,5	10	1	25	0,61162	6,11621	0,61162	0,61249	5,78318	0,62348
2,5	12	2	20	0,32000	3,84000	0,16000	0,31792	2,21939	0,16512
2	6	6	20	0,35714	2,14286	0,05952	0,33744	1,60498	0,05858
1,5	4	2	20	0,57971	2,31884	0,28986	0,58005	2,14273	0,29603
1,5	8	4	30	0,57971	4,63768	0,14493	0,57412	4,45339	0,14537
1,5	10	1	30	0,62016	6,20155	0,62016	0,62038	6,03076	0,62840
2,5	12	2	30	0,34286	4,11429	0,17143	0,34199	3,27661	0,17496
2	6	6	25	0,37879	2,27273	0,06313	0,36445	1,89316	0,06260

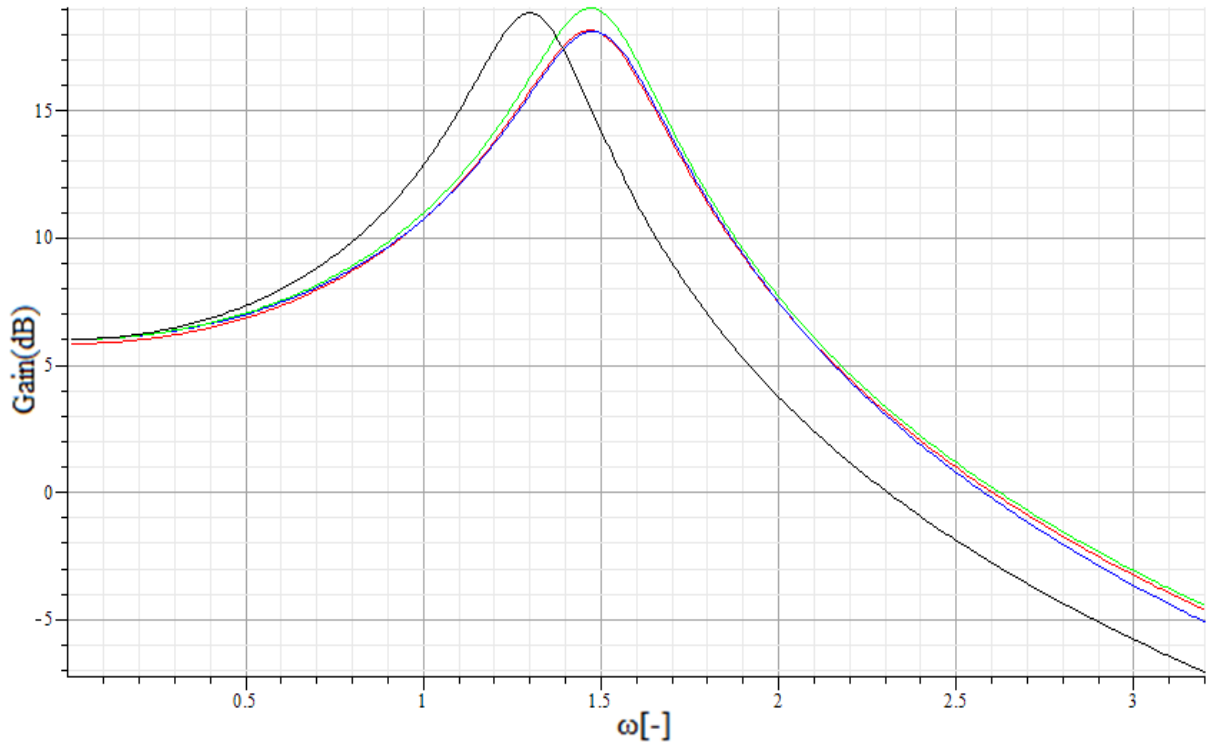*Table 2: Results for low-pass filter with capacity compensation*

Figure 4.3: Frequency responses low-pass filter (ω_0=1,5 , Q=4 , k=2 and ω_T=15) with capacity compensation

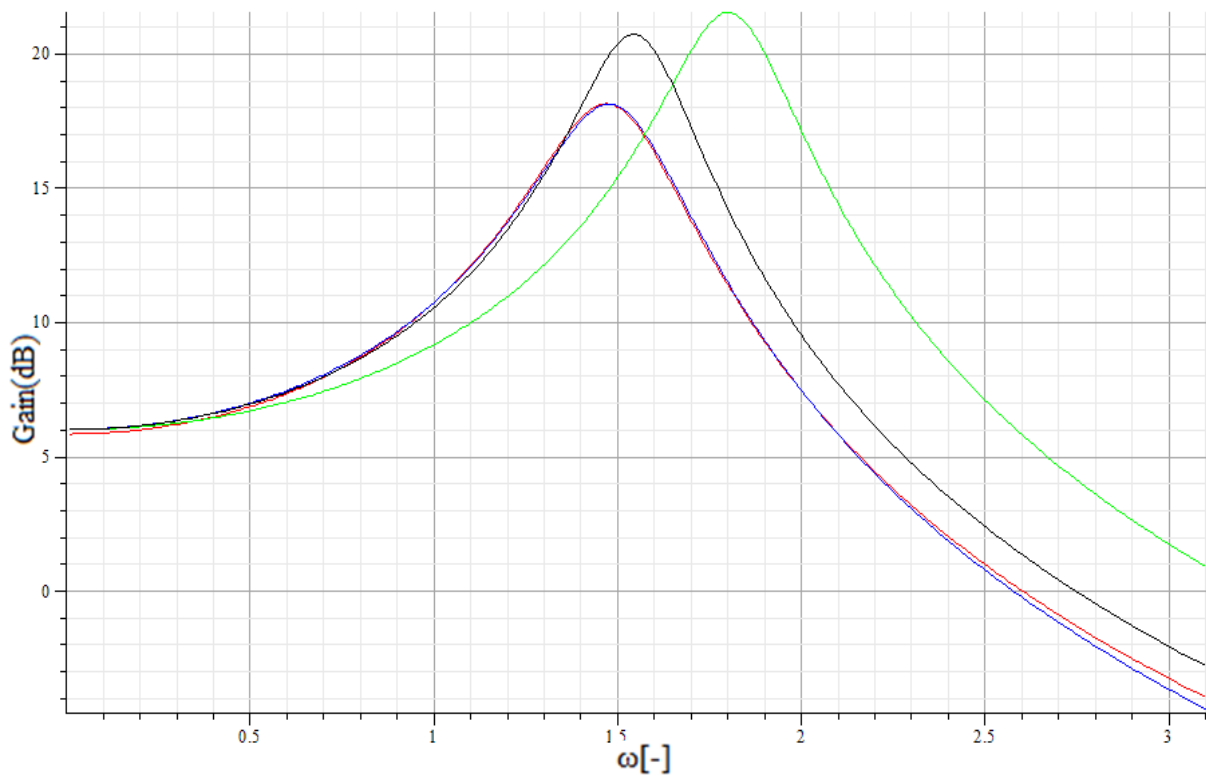*Figure 4.4: Frequency responses low-pass filter (ω_0=1,5 , Q=4 , k=2 and ω_T=15) with resistor compensation*
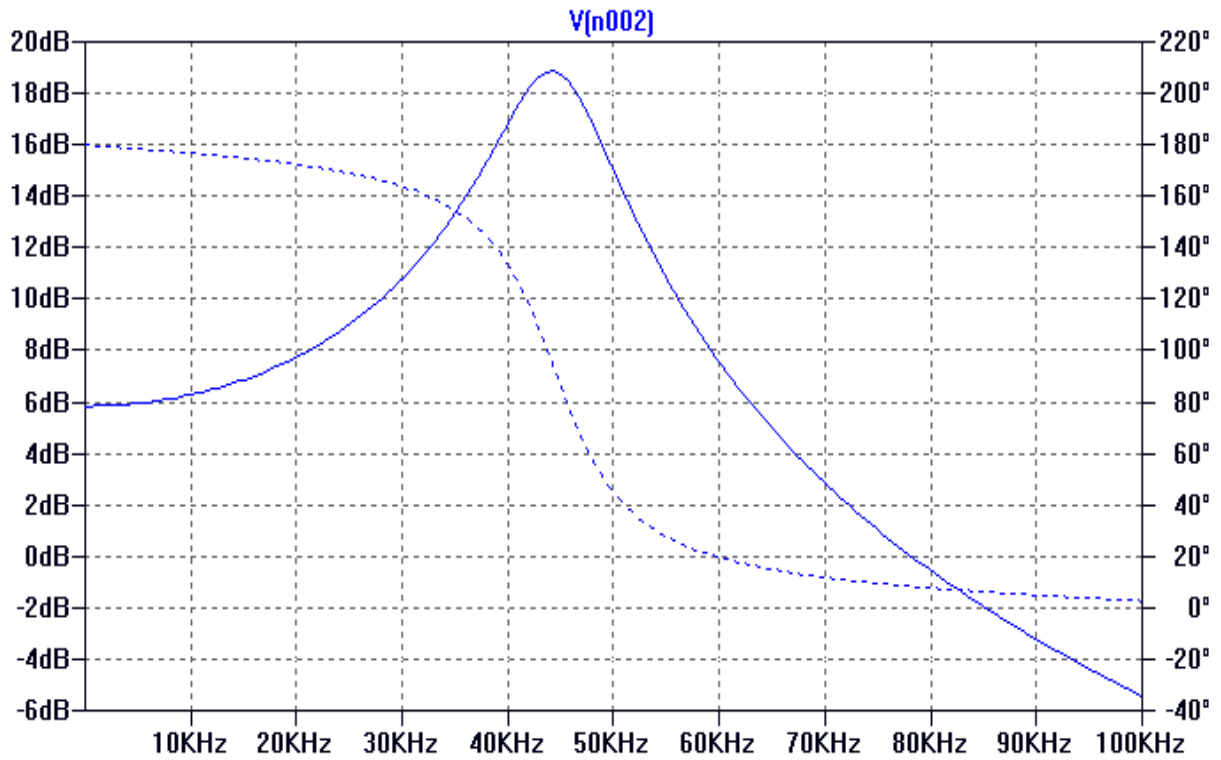
24

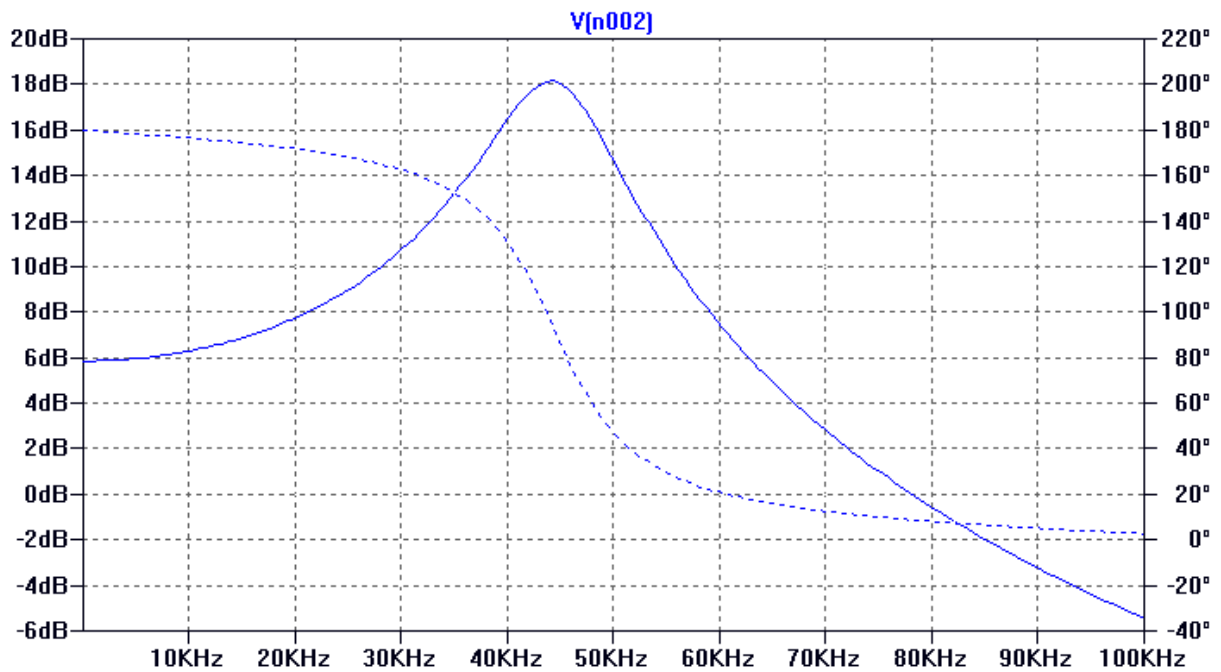*Figure 4.5: Frequency response real low-pass filter (ω₀=1,5 , Q=4 , k=2 and ω_T=15) with*

capacity compensation

Figure 4.6: Frequency response real low-pass filter (ω₀=1,5 , Q=4 , k=2 and ω_T=15) with

resistor compensation

4.4 Results for band pass filter

Another group of results are results of band-pass filter designs. Results are shown in same form as before. In table 3 there are numeric results. From the table can be seen that values from corrected design quite differ from values from evolutionary algorithm. That's again because of Q correction. According to (2.14) parameters of those filter designs are close to edge of stability so correction that is based on same equation as stability check doesn't work correctly. Parameters for ideal filter in figure 4.7 are ω_0=1,5 , Q=10 , k=1 and ω_T=65. From figure 4.7 can be seen that frequency response of corrected design (green line) has correct cut-off frequency, but gain is about 20dB lower than it should be. For other results, the ideal design (black line) also doesn't fit right. Its gain is too high and cut-off frequency is slightly lower. Ideal frequency response (blue line) and frequency response of evolutionary algorithm design (red line) overlap each other. In the figure 4.8 there is frequency response of real frequency design created from values from evolutionary algorithm. This frequency response matches ideal frequency response, cut-off frequency is 45kHz.

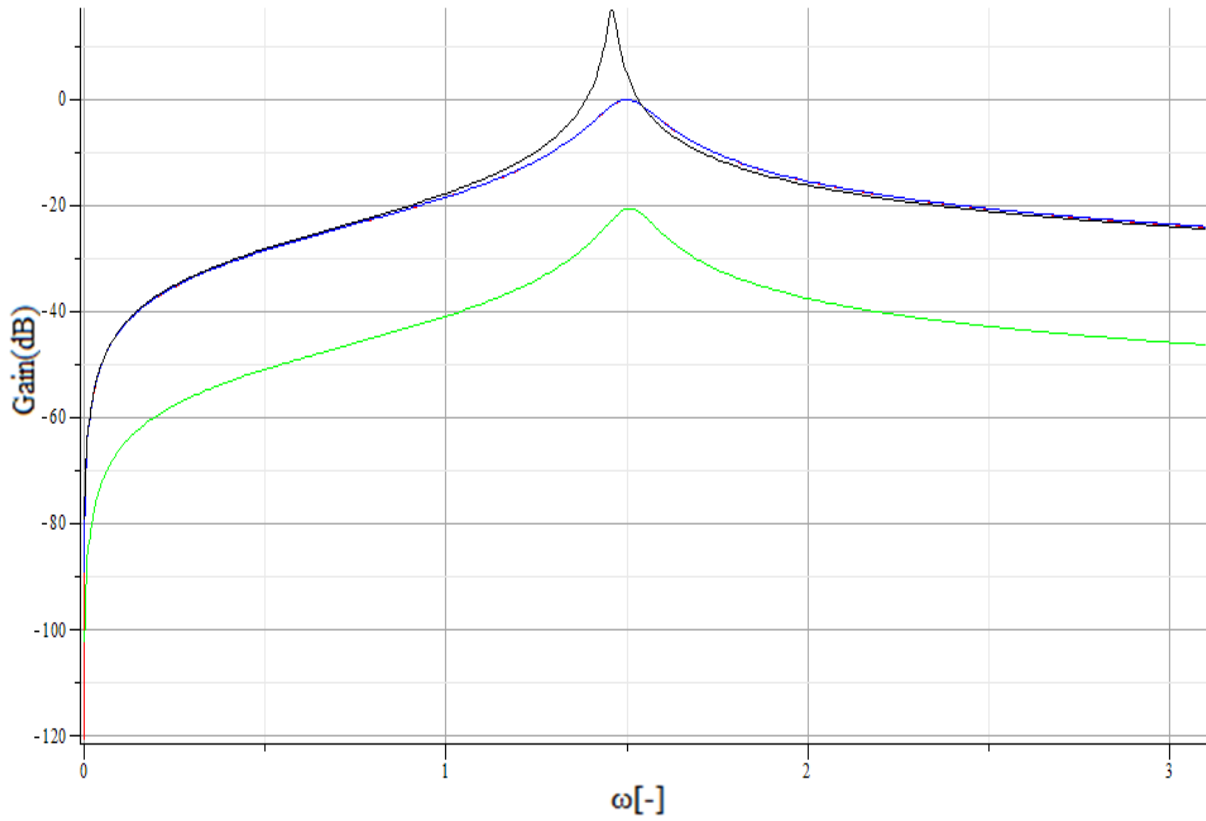| Band-pass											
goal				classic design				DE algorithm			
ω_0	Q	k	ω_T	R	R_Q	R_D	R_P	R	R_Q	R_D	R_P
1,5	4	2	30	0,606	12,121	121,212	6,061	0,612	1,391	2,974	1,312
1,5	8	4	55	0,616	38,735	608,701	9,684	0,639	2,800	5,555	1,274
1,5	10	1	65	0,644	83,767	10889,7	83,767	0,647	3,431	34,121	6,479
1,5	1	1	15	0,580	0,966	1,610	0,966	0,476	0,326	0,355	0,522
2	6	6	55	0,437	20,578	161,686	3,430	0,465	1,547	1,527	0,461
1,5	4	2	45	0,625	5,357	22,959	2,679	0,632	1,679	3,588	1,357
1,5	8	4	70	0,626	15,945	101,466	3,986	0,645	3,135	6,218	1,288
1,5	10	1	80	0,648	25,937	1037,49	25,937	0,651	3,790	37,668	6,517
1,5	1	1	30	0,620	0,775	0,969	0,775	0,586	0,485	0,506	0,613
2	6	6	70	0,449	8,566	27,257	1,428	0,474	1,740	1,719	0,470

Table 3: Results for band-pass filter designs

Figure 4.7: Frequency responses band-pass filter (ω_0=1,5 , Q=10 , k=1 and ω_T=65)

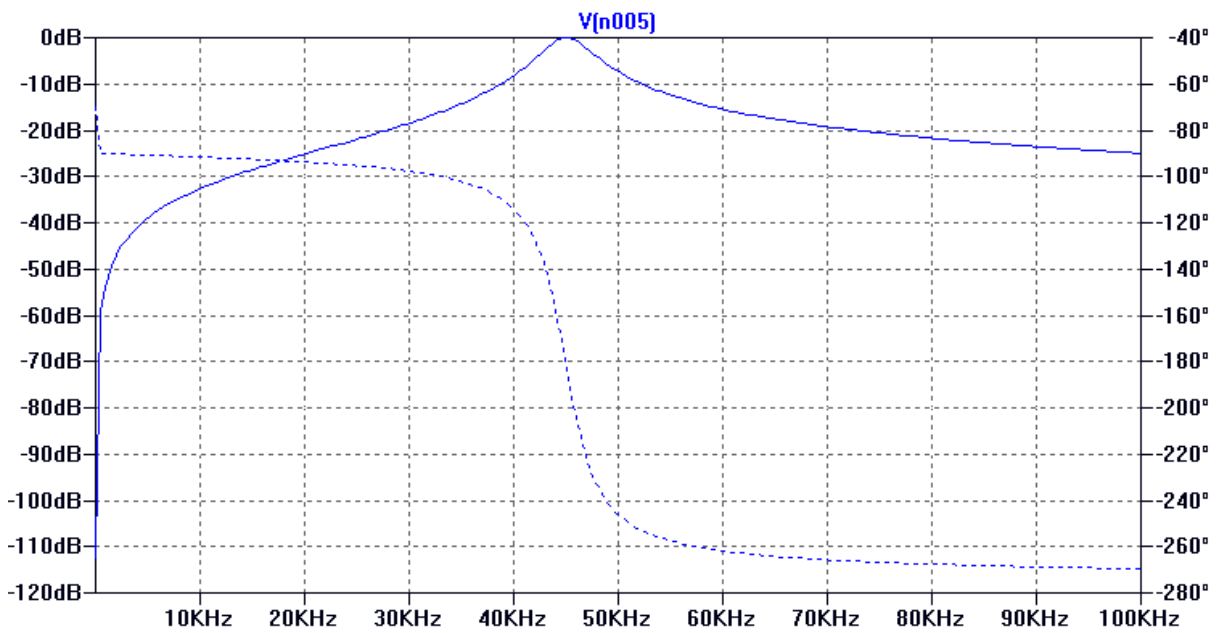*Figure 4.8: Frequency responses band-pass filter (ω_0=1,5 , Q=10 , k=1 and ω_T=65)*

4.5 Results for band pass filters with stability compensation

Results for these designs are displayed in the table 4. From the table can be seen that results doesn't differ so much. All designs here were made for low values of transition frequency. Frequency responses for filter design with parameters $\omega_0=1,5$, $Q=8$, $k=4$ and $\omega_T=15$ are displayed in the figure 4.9. Frequency response of ideal (black line) and corrected (green line) design doesn't match ideal frequency response (blue line). In the case of corrected design it is because of low value of transition frequency. At low values like this transfer function starts to be sensitive for small changes in values. Frequency response of evolutionary algorithm is overlapping ideal frequency response with small difference in higher stop-band frequencies. In the figure 4.10 there is an example of frequency responses for same design but with resistor compensation. Here have the ideal and corrected design even bigger difference to ideal frequency response than in design with capacity compensation. Design from evolutionary algorithm (red line) show also small differences to ideal frequency response, mostly at the lowest frequencies, where design with resistor compensation cannot manage low value of ideal frequency response gain. Figures 4.11 and 4.12 show designs made on real frequencies. Designs behave same as on scaled frequencies.

Band-pass capacity compensation											
Goal				classic design				DE algorithm			
ω_0	Q	k	ω_T	R	R_Q	R_D	R_P	R	R_Q	R_D	R_P
1,5	4	2	15	0,556	2,222	4,444	1,111	0,588	2,202	3,959	1,066
1,5	8	4	15	0,513	4,103	8,205	1,026	0,592	4,018	7,440	1,111
1,5	10	1	15	0,58	5,797	57,971	5,797	0,608	4,615	43,636	5,833
1,5	1	1	15	0,58	0,58	0,58	0,58	0,513	0,517	0,364	0,362
2	6	6	15	0,326	1,957	1,957	0,326	0,403	2,072	1,751	0,347
1,5	4	2	20	0,58	2,319	4,638	1,159	0,607	2,378	4,415	1,133
1,5	8	4	20	0,544	4,354	8,707	1,088	0,609	4,556	8,637	1,167
1,5	10	1	20	0,599	5,993	59,925	5,993	0,621	5,427	52,36	6,056
1,5	1	1	20	0,599	0,599	0,599	0,599	0,556	0,561	0,436	0,434
2	6	6	20	0,357	2,143	2,143	0,357	0,427	2,432	2,178	0,388

Table 4: Results for band-pass filter with capacity compensation

Figure 4.9: Frequency responses band-pass filter (ω_0=1,5 , Q=8 , k=4 and ω_T=15) with capacity compensation

Figure 4.10: Frequency responses band-pass filter (ω_0=1,5 , Q=8 , k=4 and ω_T=15) with resistor compensation
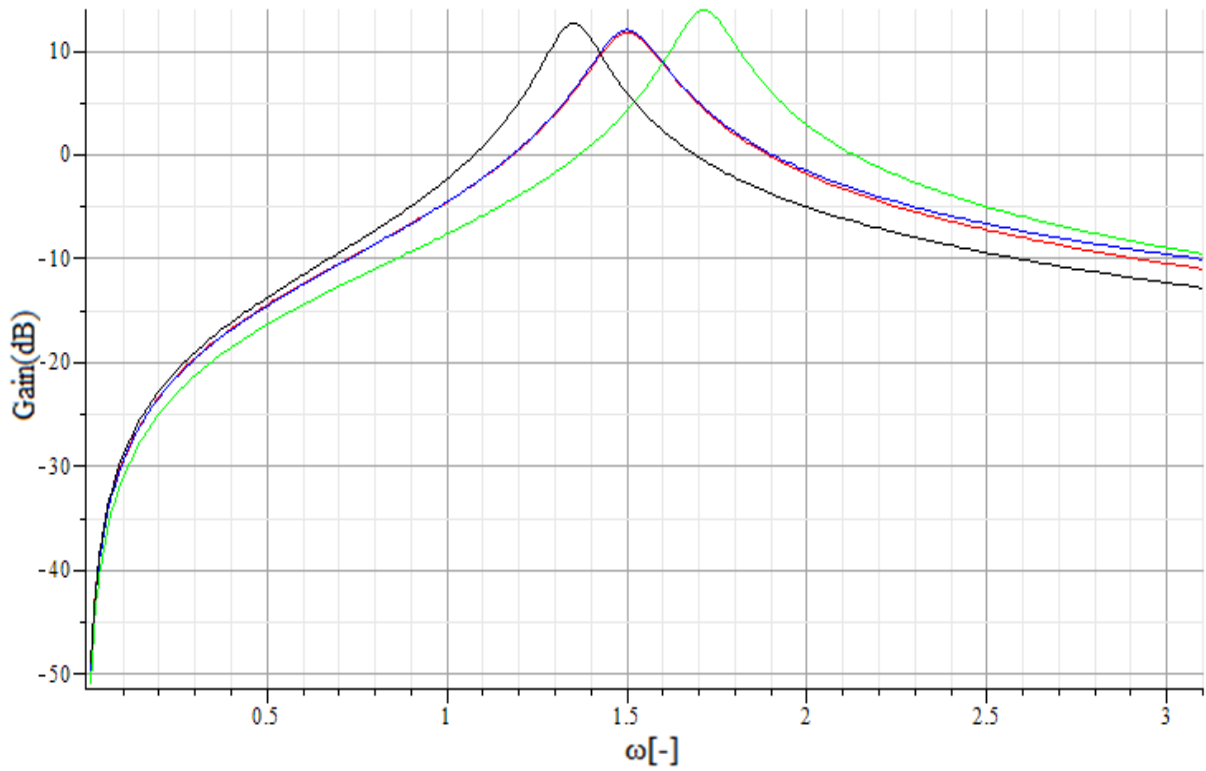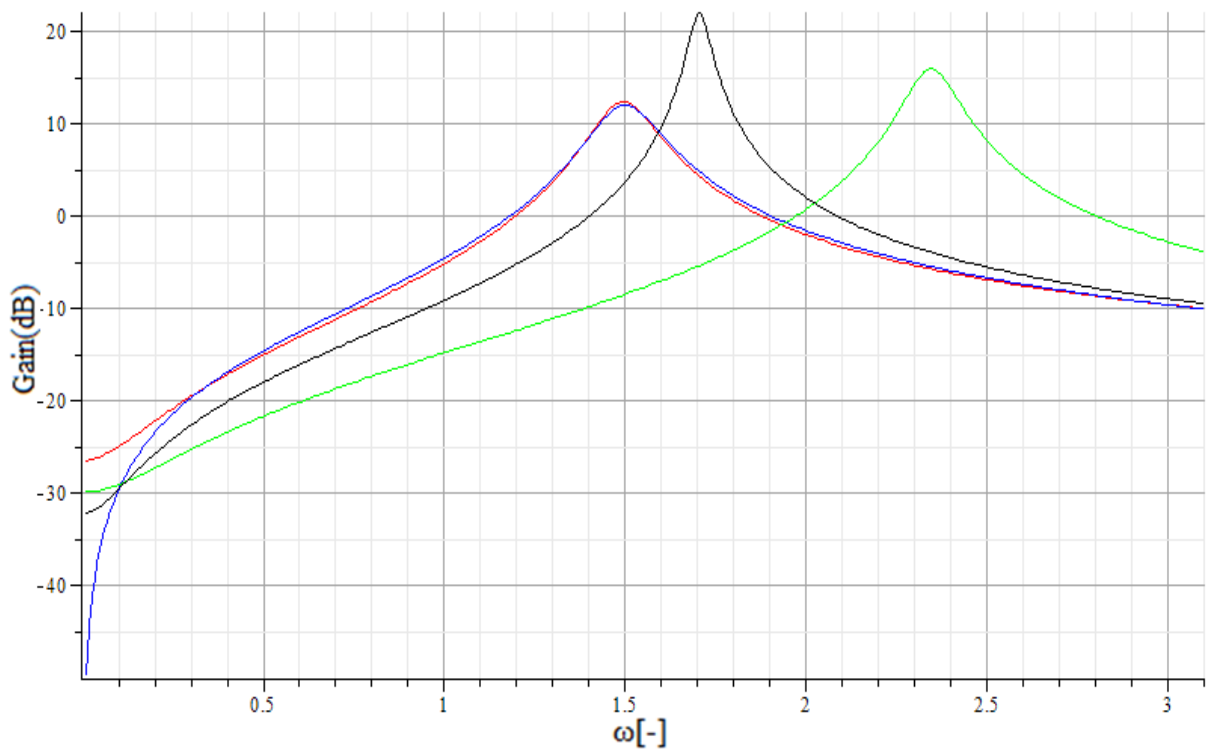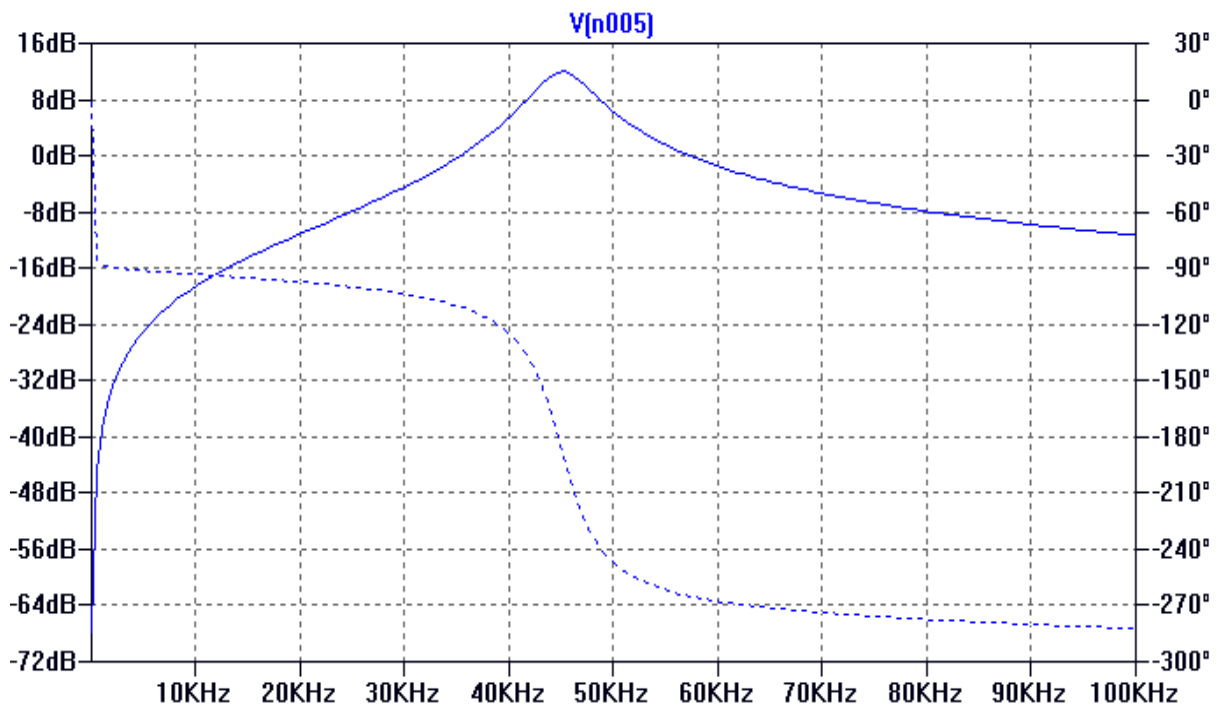
Figure 4.11: Frequency responses band-pass filter ($\omega_0=1,5$, $Q=8$, $k=4$ and $\omega_T=15$) with capacity compensation
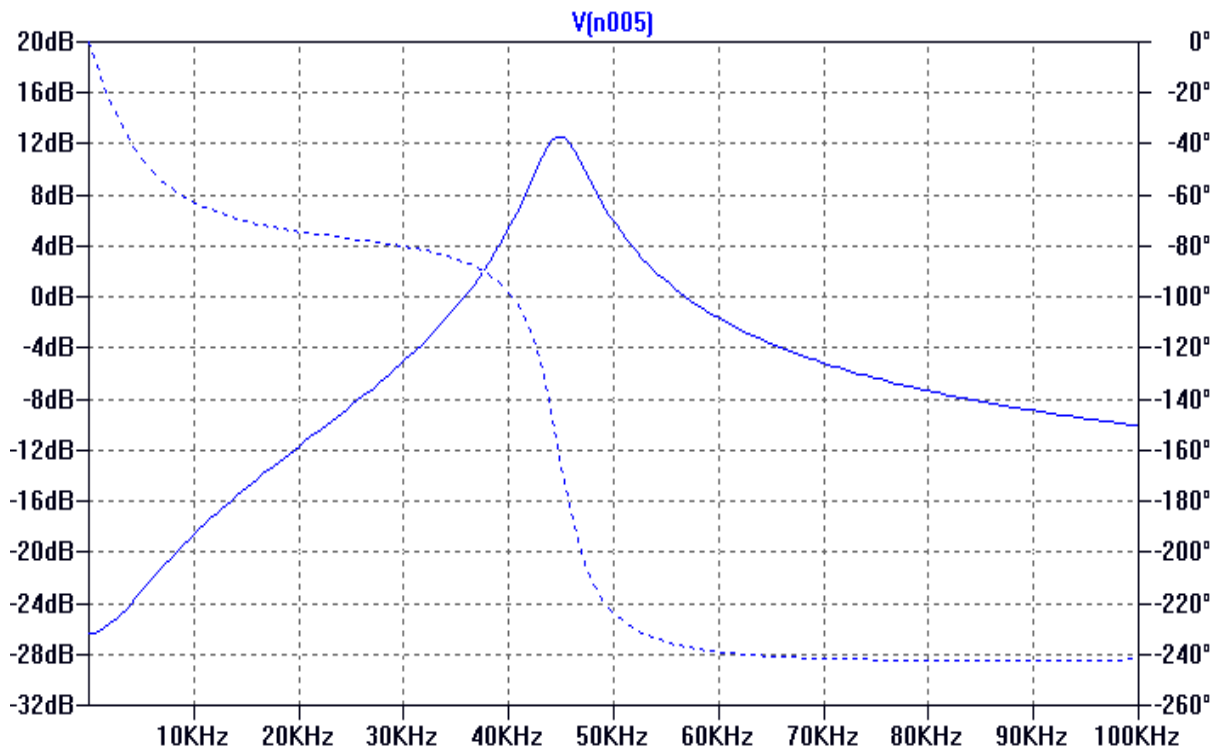

Figure 4.12: Frequency responses band-pass filter ($\omega_0=1,5$, $Q=8$, $k=4$ and $\omega_T=15$) with resistor compensation

4.6 Results for elliptic low pass filter

   Results for designs of elliptical low pass filter can be seen in table 5. Results of both designs show a lot of differences. That is because design of elliptical low pass filter is complicated and very sensitive on frequency dependence of used operational amplifiers. Frequency responses for filter design with parameters $\omega_0=2$, $Q=6$, $k=3$, $\omega_N=2,5$ and $\omega_T=55$ are shown in the figure 4.13. Frequency responses of ideal (black line) and corrected (green line) design don't match ideal frequency response (blue line). Frequency response of evolutionary algorithm design (red line) matches ideal frequency response in almost all points with exception in zero gain point. Here evolutionary algorithm gain value stops at -42dB and fails to match -62dB of ideal filter. In the figure 4.14 can be seen frequency response of real frequency design made by evolutionary algorithm. Design was made for same parameters as design from previous figure. Real frequency design matches scaled design perfectly.
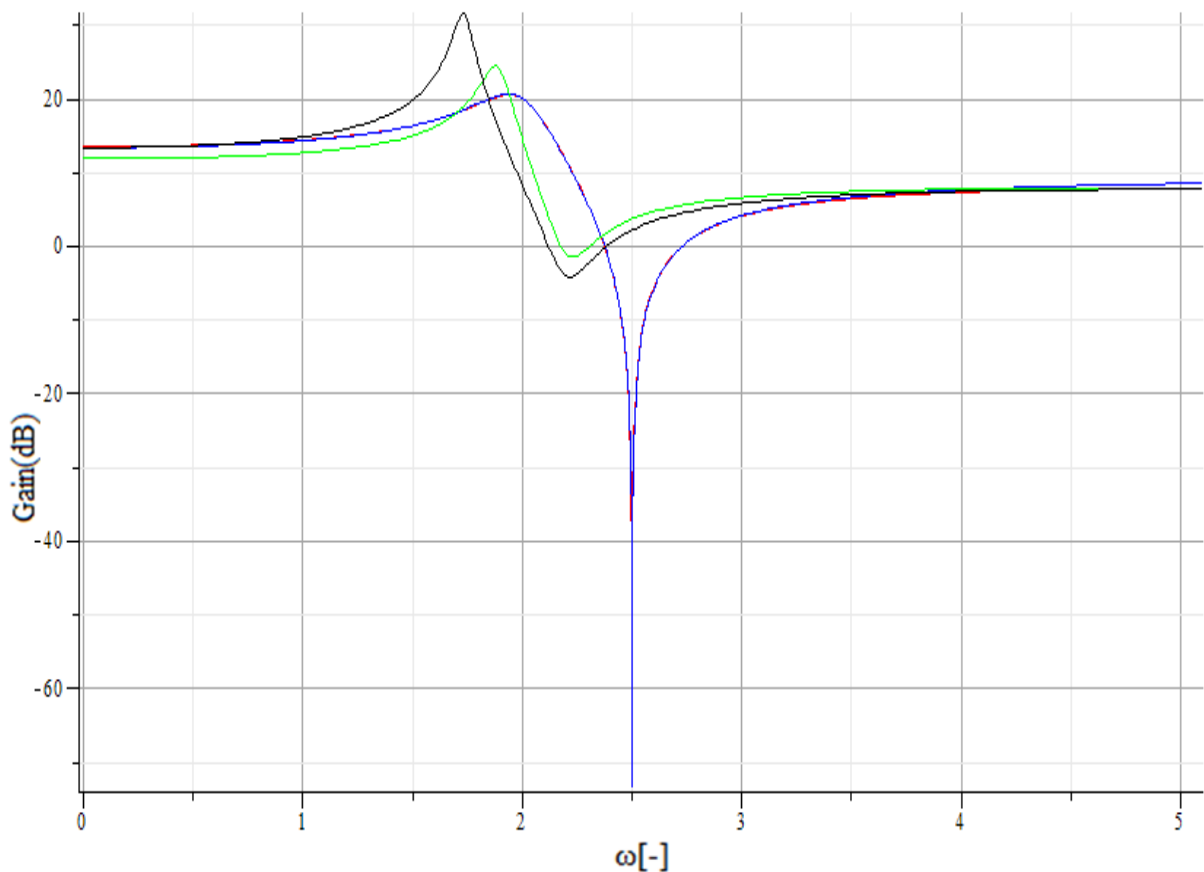

Figure 4.13: Frequency response elliptic low-pass filter ($\omega_0=2$, $Q=6$, $k=3$, $\omega_N=2,5$ and $\omega_T=55$)

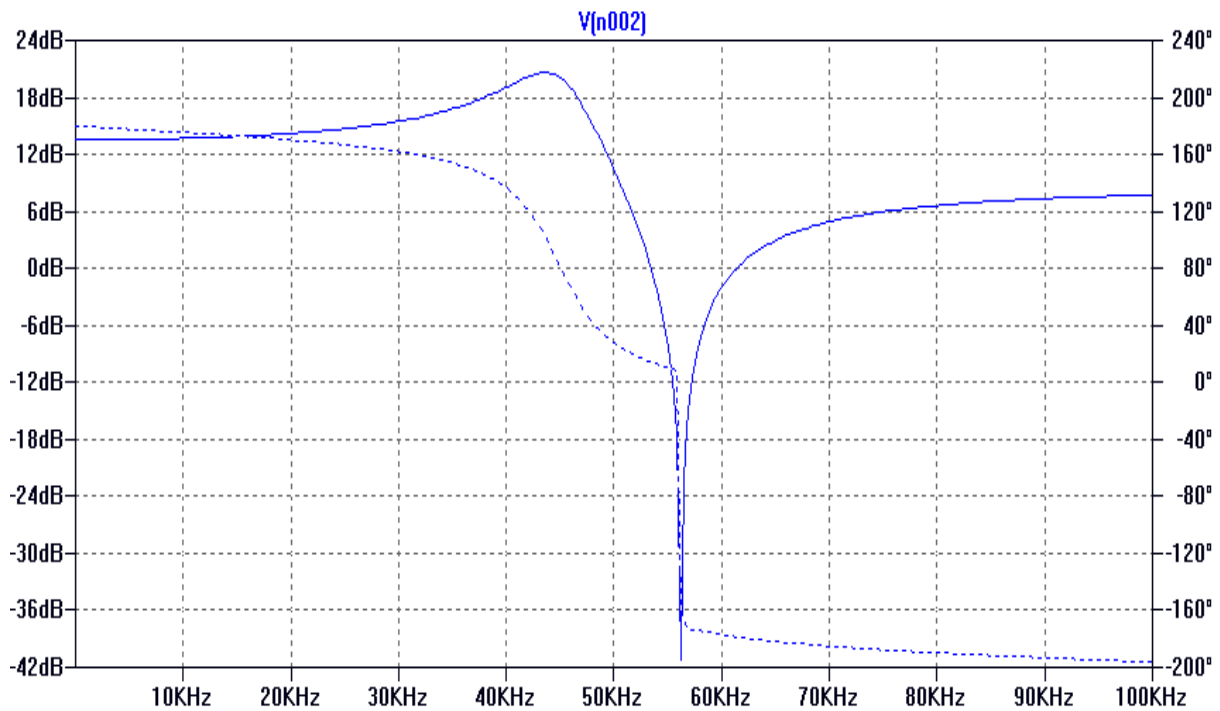| Elliptic low-pass									
Goal					Classic design				
ω_0	Q	k	ω_T	ω_N	R	R_Q	R_D	R_P	R_H
1,5	6	2	40	2	0,6202	37,2093	0,2015	18,6047	0,3101
1,5	8	4	55	2	0,6162	38,7355	0,1014	9,6839	0,1541
1,5	10	1	65	2	0,6444	83,7670	0,3880	83,7670	0,6444
2	12	2	105	3	0,4817	67,4312	0,1153	33,7156	0,2408
2	6	3	55	2,5	0,4583	21,6071	0,1163	7,2024	0,1528
1,5	6	2	55	2	0,6322	10,9800	0,1973	5,4900	0,3161
1,5	8	4	70	2	0,6264	15,9447	0,0997	3,9862	0,1566
1,5	10	1	80	2	0,6484	25,9372	0,3854	25,9372	0,6484
2	12	2	120	3	0,4839	29,0323	0,1148	14,5161	0,2419
2	6	3	70	2,5	0,4667	8,9091	0,1141	2,9697	0,1556
Goal					DE algorithm				
ω_0	Q	k	ω_T	ω_N	R	R_Q	R_D	R_P	R_H
1,5	6	2	40	2	0,5698	1,3712	0,1483	1,0357	0,2701
1,5	8	4	55	2	0,5525	1,4664	0,0722	0,5229	0,1291
1,5	10	1	65	2	0,6310	2,9169	0,3476	4,6026	0,6228
2	12	2	105	3	0,4641	2,3652	0,1018	1,9479	0,2292
2	6	3	55	2,5	0,4117	0,9285	0,0794	0,4390	0,1291
1,5	6	2	55	2	0,6002	1,7578	0,1600	1,2583	0,2915
1,5	8	4	70	2	0,5811	1,8493	0,0776	0,6377	0,1391
1,5	10	1	80	2	0,6380	3,2993	0,3528	4,9271	0,6319
2	12	2	120	3	0,4687	2,5912	0,1030	2,0483	0,2320
2	6	3	70	2,5	0,4344	1,1495	0,0860	0,5279	0,1393

Table 5: Results for elliptic low-pass filter

Figure 4.14: Frequency response elliptic low-pass filter ($\omega_0=2$, $Q=6$, $k=3$, $\omega_N=2,5$ and $\omega_T=55$)

4.7 Results for elliptical low pass filter with stability compensation

Last result block are results for elliptic filter with stability compensation. Results for these designs can be seen in table 6. Table contains results for designs with capacity compensation. Difference between the results of both designs is big. That is because results were made for designs close to transition frequency. In the figure 4.15 can be seen frequency responses for filter with parameters $\omega_0=1,5$, $Q=6$, $k=6$, $\omega_N=2$ and $\omega_T=25$. Designs shown in figure 4.15 are using capacity compensation. Frequency responses of ideal (black line) and corrected design (green line) presented in figure don't match ideal frequency response (blue line). Frequency response of evolutionary algorithm design (red line) matches ideal frequency response with exception in zero gain point where is 10dB higher. In the figure 4.16 there are frequency responses for designs with resistor compensation. In this case corrected design and ideal design fails again. Evolutionary algorithm design also doesn't work perfectly with 40dB difference in zero gain point. In the figures 4.17 and 4.18 there are frequency responses of evolutionary algorithm designs on real frequencies. Both designs match frequency scaled designs.

Elliptical low-pass compensation C									
Goal					Classic design				
ω_0	Q	k	ω_T	ω_N	R	R_Q	R_D	R_P	R_H
1,5	6	2	20	2	0,57971	3,47826	0,21126	1,73913	0,28986
1,5	8	4	25	2	0,56497	4,51977	0,10929	1,12994	0,14124
1,5	10	1	30	2	0,62016	6,20155	0,40052	6,20155	0,62016
2	12	2	35	3	0,44872	5,38462	0,12334	2,69231	0,22436
2	6	3	35	2,5	0,43750	2,62500	0,11914	0,87500	0,14583
1,5	6	2	25	2	0,59524	3,57143	0,20596	1,78571	0,29762
1,5	8	4	30	2	0,57971	4,63768	0,10657	1,15942	0,14493
1,5	10	1	35	2	0,62640	6,26398	0,39658	6,26398	0,62640
2	12	2	40	3	0,45455	5,45455	0,12177	2,72727	0,22727
2	6	3	40	2,5	0,44444	2,66667	0,11736	0,88889	0,14815
Goal					DE algorithm				
ω_0	Q	k	ω_T	ω_N	R	R_Q	R_D	R_P	R_H
1,5	6	2	20	2	0,46224	1,16501	0,10883	0,33082	0,21343
1,5	8	4	25	2	0,43327	3,15988	0,05682	0,38983	0,09183
1,5	10	1	30	2	0,54372	1,62698	0,13715	0,53103	0,26222
2	12	2	35	3	0,38958	1,89032	0,08173	0,48847	0,18516
2	6	3	35	2,5	0,36625	1,07735	0,07159	0,23029	0,11599
1,5	6	2	25	2	0,51359	1,43070	0,12646	0,44490	0,24386
1,5	8	4	30	2	0,54905	2,17518	0,07220	0,37499	0,13161
1,5	10	1	35	2	0,56370	1,77854	0,14431	0,59840	0,27442
2	12	2	40	3	0,40249	2,15600	0,08480	0,45466	0,19435
2	6	3	40	2,5	0,38877	1,21393	0,07802	0,29426	0,12425

Table 6: Results for elliptic low-pass filter with capacity compensation of stability

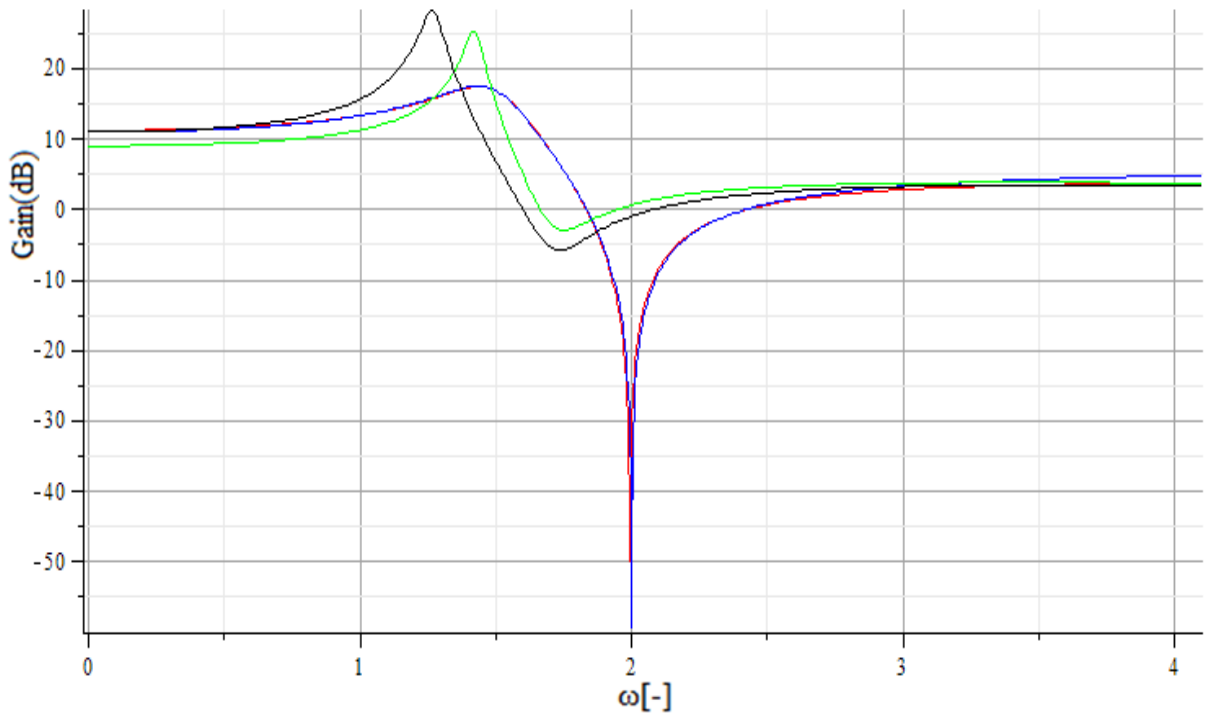*Figure 4.15: Frequency response elliptic low-pass filter (ω_0=1,5, Q=6, k=2, ω_N=2 and ω_T=25) with capacity compensation*
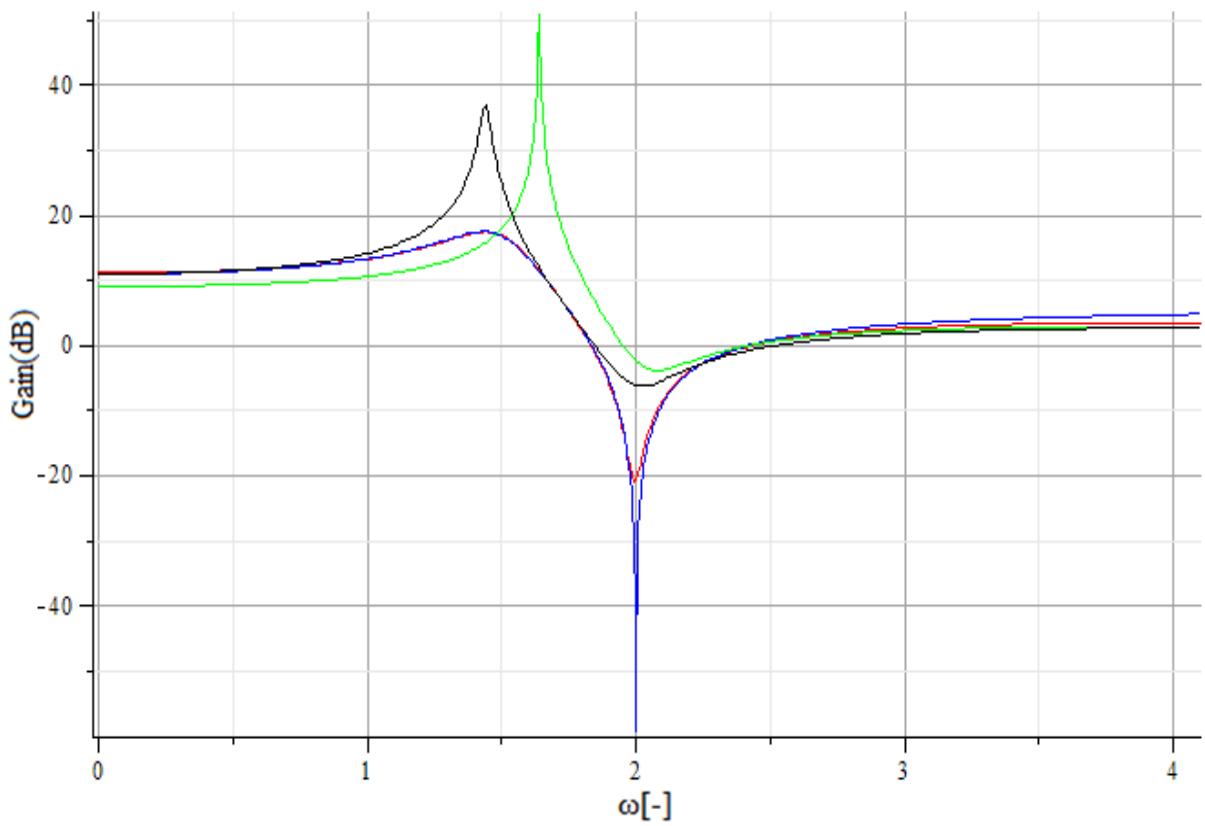

Figure 4.16: Frequency response elliptic low-pass filter (ω_0=1,5, Q=6, k=2, ω_N=2 and ω_T=25) with resistor compensation
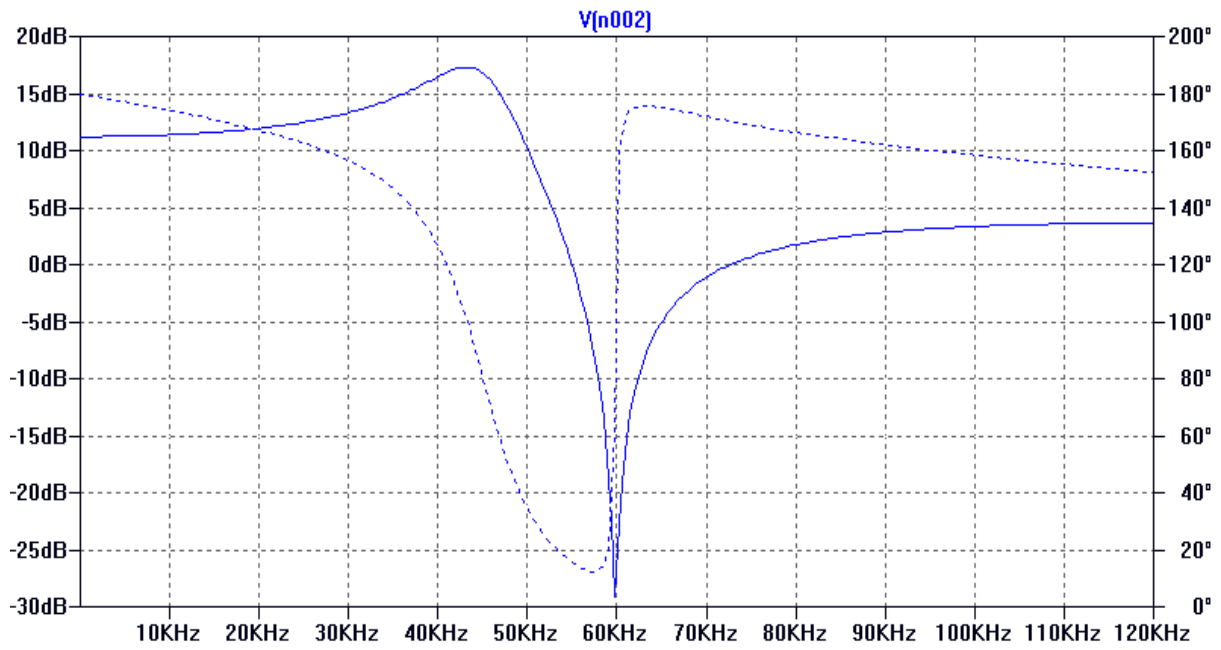
Figure 4.17: Frequency response elliptic low-pass filter ($\omega_0=1,5$, $Q=6$, $k=2$, $\omega_N=2$ and $\omega_T=25$) with capacity compensation
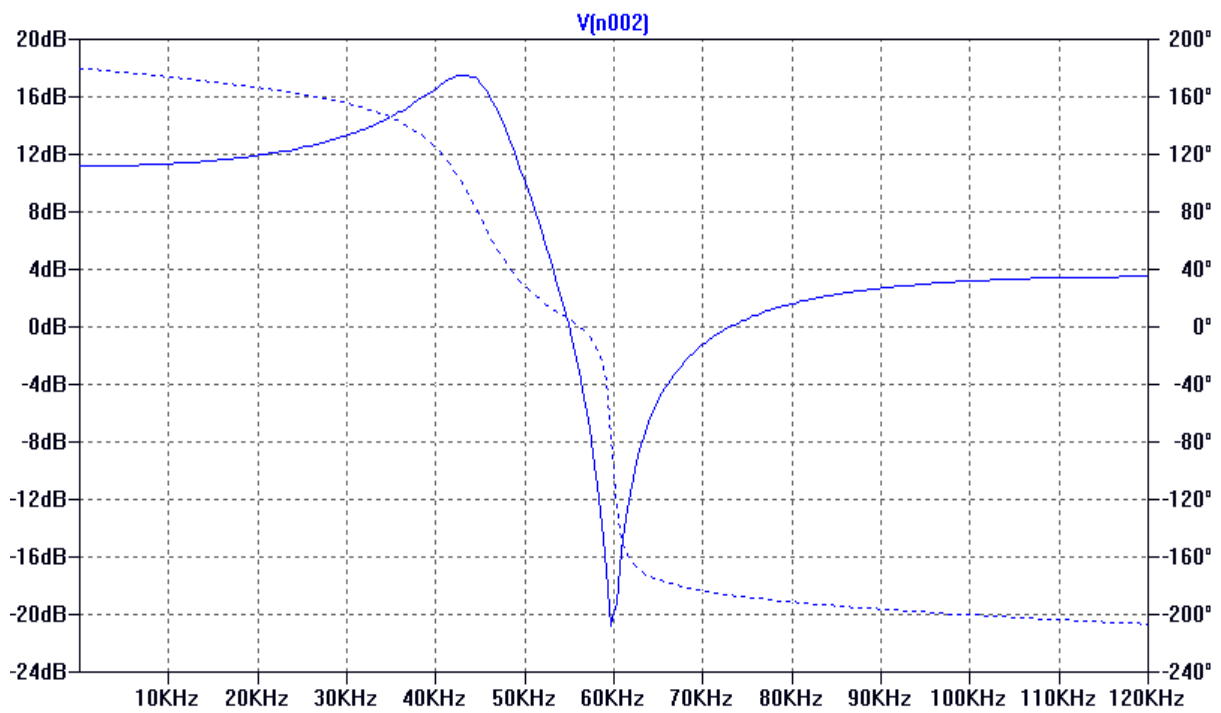

Figure 4.18: Frequency response elliptic low-pass filter ($\omega_0=1,5$, $Q=6$, $k=2$, $\omega_N=2$ and $\omega_T=25$) with resistor compensation

Chapter 5

Conclusion

Purpose of this work was to verify usage of evolutionary algorithms in active RC filter design. Tow-Thomas filter was chosen as a testing circuit. This structure gives us options to realize different types of filters. For testing were chosen three types of filter: low-pass filter, ban-pass filter and elliptic low-pass. So this project was divided into three main areas. Each area deals with different filter type and its implementation. Designs of each type of types of filter show different problem which has to be solved.

First type of filter designed in this project is low-pass filter. Low-pass filter has the easiest implementation on Tow-Thomas filter structure. Thanks to this fact implementation was mostly without problems. In previous chapter were shown the results of implementation of this filter type. Results were compared to ideal and corrected designs. Ideal filter design proves to be ineffective for designs at the of GBW of operational amplifier. This type of design can only work, when frequency dependence of amplifiers gain doesn't have effect so cut-off frequencies are much lower than transition frequency f_T (about two hundred times lower). Corrected ideal design has better results than basic ideal design but also has problem, when cut-off frequency closing to the end of GBW. Corrected design works well when cut-off frequency is about seventy times higher than transition frequency. There is also a problem with stability of circuit because of that two other types of design were made, one for capacity compensation and other for resistor compensation. Corrected ideal design shows that it works much better with capacity compensation then with resistor. That is mostly because this type o compensation adds only capacitor to the circuit but in case of resistor compensation you also have to change value of integrator resistor. Circuit works near edge of GBW and it is more sensitive on changes in circuit parts values. Evolutionary algorithm results show almost perfect solutions in all designs. Evolutionary algorithm proves to work correctly even on cut-off frequencies only ten times higher than transition frequency. In the case of designs with compensation, evolutionary algorithm shows also good results. Both types of compensation give almost same result. Calculation times of optimization are about one minute on modern computer so design of this o filter can be really fast.

Second type of filter realised in this project is band-pass filter. In design we have to count with more resistors it causes slight more difficult design than with low-pass filter. Results show that corrected design works quite bad in case of band-pass filter. This can be

seen in table 3 and on the frequency response in figure 4.7. Reason why corrected design doesn't work well with those designs lies in quality factor correction. This type of correction works well when design isn't made close to limit of stability. In this case most designs were and correction was trying to rise value of corrected Q higher than needed. Thanks to that this design has correct cut-off frequency but much lower gain. Ideal design fails again because designs were made at the place where frequency dependence of gain has greater effect. When designs are made for filter that needs stability compensation corrected and ideal designs have also unusable result. Results of evolution algorithm show that evolutionary algorithm works fine with minimal differences in its frequency response to ideal frequency response. Capacity compensation works better in designs with stability compensation with only slight difference in upper stop-band. Resistor compensation has problem with matching zero gain at zero frequency. This could cause problem in some designs with higher multiple constant. Calculation times for this type of filter optimization by evolutionary algorithm are about 1-2 minutes.

Last type of filter realised in this project is elliptic low-pass filter. Designs for this type of filter were the most complicated. Circuit structure has connected all resistors for creating of numerator of transfer function. This fact raises number of circuit values which needs to be calculated. Ideal design for this type of circuit is usable only when cut-off frequency is about one thousand times lower then transition frequency. Whole circuit is very sensitive on changes in part values. Corrected design is also unusable when cut-off frequency is close to transition frequency. Corrected design can work quite well on cut-off frequencies two hundred times lower than transition frequency. Situation is same in designs with stability compensation as in designs without. Evolutionary algorithm works well on elliptic filter structures only problem is matching exact value of zero transfer point. This can be managed by repeating of optimization with more precise sampling of zero transfer point. It can't be done from the start because of complicated transfer function of this filter type. Designs must be done in a sequence with start on higher values of transition frequency. This process takes quite a lot of time, because optimization is robust in this case. Optimization takes about 5 minutes. When more optimizations are needed to be made in a row this time could rise to 20 minutes and more for one design. Designs with stability compensation have acceptable results when capacity compensation is used. Design made by evolutionary algorithm shown in figure 4.16 shows that optimization with resistor compensation has problem with matching zero transfer point.

Evolutionary algorithms prove that they can manage designs of active RC filters much better than classic design methods. Classical design methods are still useful. There will be still designs with low influence of frequency dependence of amplifiers gain. Main advantages of classic design are their speed and easy implementation. When more complicated design needs to be made we can take evolutionary algorithms. They are really precise even when cut-off frequency is near transition frequency. In case of low-pass filter optimization and band-pass filter optimization calculation times aren't that high. Elliptic filter design take more time and sometimes even few try and catch attempts to be finished. For most cases designs with capacity compensations proves to be more precise. Only problem with evolutionary algorithms is quite complicated implementation and more complicated design couldn't work fast on older computers. Evolutionary algorithms are new effective method of designing active filter structures and should be considered in future filter design. They usage in internet applications like Syntfil used by CTU in Prague, won't be effective for now, because of long optimization times. But they can be easily used in more complex design software.

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