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Examples for Filter Synthesis

E. Hermanis

Laboratory "Vide",
Brivini p/n Jaunjelgava, LV-5134 Latvia, e-mail: evalds.h@apollo.lv

Example with a passive phase driver

It is a classical phase driver circuit with a balanced active load (Fig. 1).

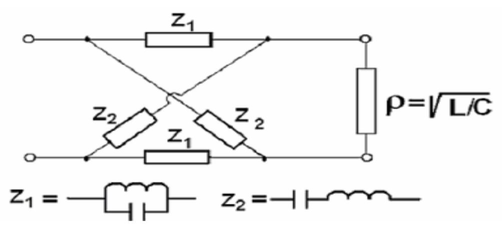

Fig. 1. Lattice link $L_1 = L_2$, $C_1 = C_2$

By active input resistance and in terms of the absence of amplifiers it is differed from phase inverter [1].

The circuit's input resistance is also active and is equal to characteristic resistance.

That let us connect a series of such circuits without separating voltage repeaters. We can get the respective pulse response at the output of each circuit, but the group of all responses can be used as basis function family for the construction of various filters. There are no losses when the signal spreads in the phase driver circuit. These are good preconditions.

The transfer function of such a four-port network is as follows:

$$K(p) = \frac{LCp^2 - \sqrt{LC}\,p + 1}{LCp^2 + \sqrt{LC}\,p + 1}. \tag{1}$$

To simplify the analysis we can select a time constant $\sqrt{LC} = 1$ so that the expression (15) can be written for a set of N-links:

$$K(p) = \left(\frac{p^2 - p + 1}{p^2 + p + 1} \right)^N . \tag{2}$$

By carrying out the inverse Laplace transform we get a family of pulse responses from each link of the circuit.

The pulse response of the first link (N = 1) is matched by this expression:

$$\phi 1 := \left(\frac{2}{3}\sqrt{3}\sin\left(\frac{1}{2}\sqrt{3t}\right) - \cos\left(\frac{1}{2}\sqrt{3t}\right) \right) \cdot e^{(-1/2t)} + \text{Dirac}(t), \tag{3}$$

which contains Dirac's delta function at zero. Considering that a pulse of finite length will function in the input of the filter to be synthesized and that it's voltage will be equal to 0 at the beginning moment, the Dirac's delta function can be ignored. In that case the first four pulse responses are as follows:

$$\begin{cases} \phi 1 = \left(\frac{2}{3}\sqrt{3}\sin\left(\frac{1}{2}\sqrt{3t}\right) - \cos\left(\frac{1}{2}\sqrt{3t}\right) \right) e^{(-1/2t)}; \\ \phi 2 = \left(\frac{28}{9}\sqrt{3} - \frac{4}{3}\sqrt{3t} \right) e^{(1/2t)} - \sin\left(\frac{1}{2}\sqrt{3t}\right) + \\ + \left(\frac{4}{3}t - 4 \right) \cos\left(\frac{1}{2}\sqrt{3t}\right) e^{(-1/2t)}; \\ \phi 3 = \left(\frac{8}{9}\sqrt{3t^2} - \frac{20}{3}\sqrt{3t} + \frac{82}{9}\sqrt{3} \right) e^{(-1/2t)} \sin\left(\frac{1}{2}\sqrt{3t}\right) + \\ + \left(-6 + \frac{4}{3}t \right) \cos\left(\frac{1}{2}\sqrt{3t}\right) e^{(-1/2t)}; \\ \phi 4 = \left(\frac{568}{27}\sqrt{3t} + \frac{128}{27}\sqrt{3t^2} + \frac{1912}{81}\sqrt{3} \right) \cdot \\ \cdot e^{(-1/2t)} \sin\left(\frac{1}{2}\sqrt{3t}\right) + \\ + \left(-\frac{8}{27}t^3 + \frac{32}{9}t^2 e - 8 \right) \cos\left(\frac{1}{2}\sqrt{3t}\right) e^{(-1/2t)}. \end{cases} \tag{4}$$

From these we can derive a Gram matrix **G**, the links of which are

$$g_{j,k} = \int_0^\infty \phi_j(x)\phi_k(x)dx .$$

The matrix has a simple structure. Choosing only 4 links for the beginning of a row we get

$$G=\begin{bmatrix}2 & 2 & 2 & 2\\ 2 & 4 & 4 & 4\\ 2 & 4 & 6 & 6\\ 2 & 4 & 6 & 8\end{bmatrix}. \qquad (5)$$

It is easy to see how the matrix should be composed for any number of links.

Because of specific construction of obtained Gram matrix (5), the trace of the matrix is increasing rapidly as the number of its links grows. Already with only 4 x 4 diagonal matrix elements the sum of elements of the main diagonal is 20. It shows that the chosen basis is not the best from the said perspective.

The inverse matrix has a simple form (three-diagonal) too

$$\frac{1}{G}=\begin{bmatrix}1 & \frac{-1}{2} & 0 & 0\\ \frac{-1}{2} & 1 & \frac{-1}{2} & 0\\ 0 & \frac{-1}{2} & 1 & \frac{-1}{2}\\ 0 & 0 & \frac{-1}{2} & \frac{1}{2}\end{bmatrix}. \qquad (6)$$

The trace is minimal and that is a very important prerequisite.

Since the matrix is three-diagonal the new biorthogonal functions are only a combination of the three primary ones.

$$\psi_k(t)=\phi_k(t)-1/2\left[\phi_{k-1}(t)+\phi_{k+1}(t)\right]. \qquad (7)$$

This shows that the use of the basis $\Psi_k(t)$ would be most purposeful as the trace is minimal and it grows linearly together with the number of links.

The formula let us ascertain the family of the biorthogonal functions easily:

$$\begin{cases}\psi 1=\left(-\frac{8}{9}\sqrt{3}+\frac{2}{3}\sqrt{3t}\right)e^{(-1/2t)}\sin\left(\frac{1}{2}\sqrt{3t}\right)-\\ -\frac{2}{3}e^{(-1/2t)}t\cos\left(\frac{1}{2}\sqrt{3t}\right);\\ \psi 2=\left(-\frac{16}{9}\sqrt{3}+\frac{4}{3}\sqrt{3t}\right)e^{(1/2t)}\sin\left(\frac{1}{2}\sqrt{3t}\right)+\\ +\frac{2}{3}e^{(-1/2t)}t\cos\left(\frac{1}{2}\sqrt{3t}\right);\\ \psi 3=\left(-\frac{40}{27}\sqrt{3t}^2+\frac{122}{27}\sqrt{3t}-\frac{344}{81}t^3\sqrt{3}\right)\cdot\\ \cdot e^{(-1/2t)}\sin\left(\frac{1}{2}\sqrt{3t}\right)+\\ +\left(\frac{118}{27}t+\frac{4}{27}t^3\right)\cos\left(\frac{1}{2}\sqrt{3t}\right)e^{(-1/2t)}.\end{cases} \qquad (8)$$

The basis functions of both families are mutually orthogonal

$$\int_0^\infty \phi_k(x)\psi_j(x)dx=\begin{cases}0, & if\ k\neq j\\ 1, & if\ k=j\end{cases}. \qquad (9)$$

That lets us to calculate the expansion quotients of the function to be approximated with one of them by the other family of functions. By multiplying both sides of the equation (7) by the target function and integrating them in the limits of existence (where it differs from zero significantly) we ascertain the coherence between the quotients

$$b_k=a_k-\frac{1}{2}\left(a_{k-1}+a_{k+1}\right). \qquad (10)$$

Considering the simple expression (10) it is more advantageous to calculate the expansion quotients with the functions from the φ family, thus getting the quotients a_k. However, these preconditions do not necessarily mean that the expansion of the pulse response of the selected filter will converge quickly. Limiting the number of links the systematic error will occur [3 (14)] as it is stated by the Bessels inequality. In concordance with the expression (10) the error energy is as follows:

$$E_{Ny}=\int_0^\infty f_{Ny}^2(t)dt-\sum_{k=1}^{N}a_k\left(a_k-\frac{1}{2}(a_{k-1}+a_{k+1})\right). \qquad (11)$$

where a_k is the expansion quotient of the Nyquist function by the biorthogonal functions of the basis. That facilitates the calculation, because only integrals must be calculated

$$a_k=\int_0^{t_0} f_{Ny}(x)\phi_k(x)dx .$$

The calculation for the raised cosine function

$$Rc := \frac{\sin\left(\frac{\pi\,(t-td)}{T}\right)\cos\left(\frac{\pi\,\alpha\,(t-td)}{T}\right)T}{\pi\,(t-td)\left(1-\frac{4\,\alpha^2\,(t-td)^2}{T^2}\right)} \qquad (12)$$

with the parameters T=1; α=0.5 td=3 with 10 links gives the following quotients:

[0.516; -0.187; -0.228; 0.174; 0.399; 0.257; -0.059; -0.287; -0.306; -0.153]. That lets us to calculate how the approximation energy is increasing depending on the number of links of the circuit. The horizontal line shows the energy of the function to be approximated. We can see that with only 10 links it is far from the desired level. The inequality (13) clearly shows that the approximation energy can only approach the target function's energy and thus the rate of it's increase can only fall.

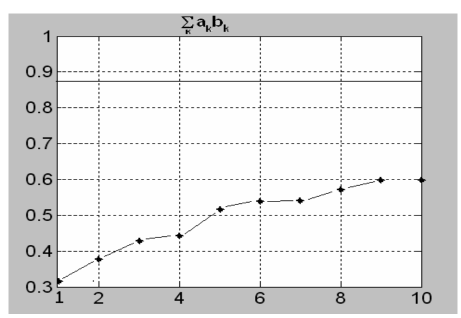

Fig. 3. The energy of approximation depending on the number of links

The difference between energies is too large and 10 links are insufficient for the approximation. Each of the 10 links of the circuit contains 4 oscillation circuits and increasing the number of links may be commercially not profitable.

Therefore, the phase driver circuit must be seen as less suited for the synthesis of the raised cosine function realizing it with separate elements.

An Example of the synthesis of a Filter using Bessel function's orthogonality in the interval [0; ∞)

Links of the LC delay line series can provide an example of such a physically realizable basis.

By putting together a circuit with a sufficient number of LC links (Fig. 2)

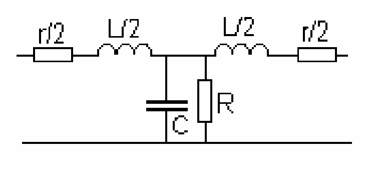

Fig. 2. LCR – link

and choosing the respective condenser's voltage responses to the delta δ -pulse, we get linearly independent pulse responses which would serve as the basis for the synthesis of a filter henceforth. The presence of resistors not only ensures the damping of the signal but also a minimal reflection from the load at the terminal. The reflection cannot be fully eliminated because the perfectly matched load is physically impossible. However, it can be realized approximately as a two-port component that contains reactive elements [2]. Homogeneous LC-circuit is favorable because all of its stage processes can be described with Bessel's functions. Pulse responses in the form of condenser voltages conform with the 1st type of Bessel's functions with the odd indexes that, together with the weight function, are orthogonal within the interval [0; ∞):

$$\int_0^\infty \frac{J_{2k-1}(x)J_{2i-1}(x)}{x}dx = \begin{cases} \dfrac{1}{2(2k-1)}, & if\ k = i, \\ 0, & if\ k \neq i. \end{cases} \quad (13)$$

Since the condenser's output pulse responses contain damped exponential curves that are caused by losses

$$h_k(t) = \omega_0 \exp(-t/\tau) J_{2k-1}(\omega_0 t), \quad (14)$$

Then accordingly to the formula, orthogonality can be ensured by choosing the following as the other function class:

$$g_i(t) = 2(2k-1)\exp(t/\tau) J_{2i-1}(\omega_0 t)/(\omega_0 t), \quad (15)$$

each link of which contains an exponential curve with a positive step. $\omega_0=2/\sqrt{LC}$ and τ=RC=L/r in both formulas. The value of integral does not change, if we multiply (10) both functions ($g_i(t)\times h_k(t)$).

Since all of the Nyquist functions are limited in time, even the fact that $g_i(t)$ are increasing absolutely ($\lim_{t\to\infty}(g_i) = \infty$) does not cause any problems. To ascertain the quotients of the Nyquist function's expansion $h_N(t)$ by functions $h_k(t,)$ we must calculate the integrals.

$$a_k = \frac{2(2k-1)}{\omega_0} \int_0^\infty \frac{h_{Ny}(x)\exp(x/\tau)J_{2k-1}(\omega_0 x)}{x}dx. \quad (16)$$

The convergence of integrals theoretically depends on the type of the Nyquist function $h_N(t)$ The calculation is facilitated by the fact that Nyquist's functions are damping quickly in both directions and thus we can assume that they are perfectly limited.

An example. Let's assume that we must synthesize a filter with a pulse response that is closely similar to the one in the [3 Fig. 4]. It matches up to the length of the symbol T_s=1 at α=0,5. It is known from the Communication theory that the filter's cutoff frequency $f_0 = (1+\alpha)/2T_s$. But, from the circuit we also know the formula for calculating the highest frequency that can spread in the LC circuit. From this we derive an important parameter of the circuit to be synthesized

$$\sqrt{LC} = \frac{2T_s}{\pi(1+\alpha)}, \quad (17)$$

that characterizes the delay per one link of the circuit. Placing in the values we see that $\sqrt{LC}$ = 0,4244 time unities. Since $f_0 = 1/(\pi\sqrt{LC})$, the cyclic frequency in the formulas (28-30) is $\omega_0 = 2/\sqrt{LC}$. In this example ω_0=4, 7124.

The damping of oscillations of basis function $h_k(t)$ is most affected by the time constant τ, in the choice of which we must make a compromise – it is preferable to not to diminish the basis function's amplitudes much, yet at the same time it is important to prevent intense reflection from the load. In this example the time constant is chosen so that it is equal to the length of the interval, respectively 10 time unities as shown in the [3 Fig. 4]. Choosing 10 links for the circuit the maximal mutual delay of pulse responses is 4.244 time unities, which comprises the main part of the Nyquist function's impulse response. Placing in all the data the integral (16) and integrating only in the interval of [0; 10] for each of the Bessel functions parameters ***k*** we get the following weight quotients **a** = [0,0087; 0,0325; -0,0795; 0,1788; 0,6059; 0,5448; 0,2053; 0,0055; - 0,0269]. Suffice to multiply these quotients respectively with $h_k(t)$ and to sum up the results $h_{na} = \sum_{k=1}^{10} a_k h_k(t)$ to get the necessary approximation.

To verify the accuracy of the approximation it is useful to find the expansion of the Nyquist function in the biorthogonal basis. Calculating the integrals for this purpose $b_k = \int_0^{10} h_k(x) h_{Ny}(x) dx$ we get these results:

b = [-0.0035; 0.1219; -0.1563;

-0.3755; 0.2955; 0.9564; 0.7258; 0.2420; -0.0020; -0.0298]. Using Bessel's inequality (10) we calculate the sum $\sum_{k=1}^{10} a_k b_k = 1.1709$ and the integral $\int_0^{10} h_{Ny}^2(x)dx = 1.1711$. The insignificant difference shows that the theoretical model (Bessel function's basis) is suited well for the synthesis of the given filter. From the Fig. 4 we can see that it is enough with 8 links that provide the approximation energy E8 = 1,17; the last 2 links do little to make it more precise.

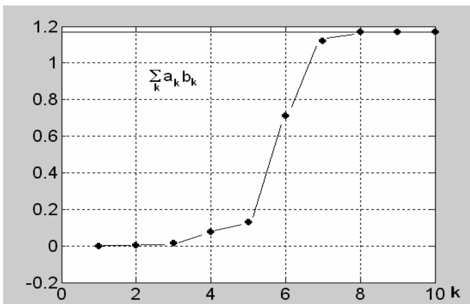

Fig.4. The approximation energy with Bessel's functions

In praxis the use of formulas (28-30) is not recommended, because in a real basis circuit there is tolerance of elements and the reflection from the terminal of the circuit. Actually the pulse responses of the links of the circuit are obtained by measurements and there are deviations from the norm. Therefore the result acquired by using formulas (28-30) will not be satisfying.

The synthesis of a filter by orthogonalizing the line segments of the basis functions

In the theoretical model an ideal matching of line with the load is planned and the tolerance of components is not taken into account. The real filter is a slight perturbation of the ideal model. In praxis both the pulse responses and the responses to the unit pulse $h_k(t)$ are obtained by measurements in a finite interval of time *[t1; t2*]. Assuming that the system should be stable, we can conclude that $h_k(t \geq t2)=0$ un $h_k(t \leq t1)=0$.

If our goal is to find the approximation of the filter's pulse response [3 (Fig. 6)] then we have to choose the pulse responses $h_k(t)$ of the links of the circuit as the basis functions. But, if the goal is to find the filters response to the unit pulse, then the basis functions must be constructed from the reactions of the links of the circuit to these input signals. That means that we must use the raised cosine function [1 (1)] instead of the impulse response [3 (Fig. 6)].

Calculations must be carried out with formulas [3 (12-14)]. First we must construct a square matrix Φ with the following elements:

$$\varphi_{n,k} = \int_{t1}^{t2} h_n(x-t_1)h_k(x-t_1)dx . \qquad (18)$$

Then we calculate the inverse matrix Φ^{-1} with elements $\psi_{i,j}$ and form the class of biorthogonal functions

$$g(x) = \Phi^{-1}h(x) , \qquad (19)$$

where $g(x)$ and $h(x)$ are the vector functions. Then we must find the expansion quotients (spectre) of the filter's pulse response by the pulse functions of the links of the basis circuits.

$$b_k = \int_{t1}^{t2} h_{Ny}(x)g(x)dx . \qquad (20)$$

We get the approximation of the filter's pulse response as a result.

$$\widetilde{h}_{Ny}(x) = \sum_{k=1}^{K} b_k h_k(x). \qquad (21)$$

The conditions of numerical experiments

There are two possibilities to be explored: 1) to calculate the optimal adding quotients for each set of components (this is a very disadvantageous version from the technical point of view, except for the case in which the adding quotients are calculated with an adaptive algorithm);
2) to calculate the quotients by the nominal values of the components independently from the particular tolerance (this is the technological version in which it is more advantageous to use more precise components and not calculate the quotients for each filter separately).
The LCR-circuit was presented as a SIMULINK model. (Fig.5).

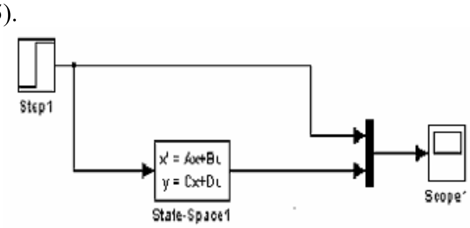

Fig.5. The SIMULINK model of a basis circuit

State-space matrices are chosen in analogy to [2] but at this time they have 10 links instead of 8. The advantage of the model is that the reflection from the load in it is similar to a real experiment and it is also possible to imitate the tolerance of components. A positive difference from the physical experiment is that it is possible to study the influence of each factor separately and thus ascertain the most essential of them.
It is also possible to compare the effect of a reactive load to that of an active load $\rho = \sqrt{L/C}$. Since the signal generator "Step" that's chosen is perfect (Heaviside step), then the circuit's reactions to the δ-pulse are on the right side of the Fig.6 differentiating the acquired step responses (the left side of the Fig.6).
If the step responses were measured we would only see noise on the left side of the Fig. 6, but modeling allows us to avoid measuring so far as the construction's parasitic parameters don't have any significant influence.

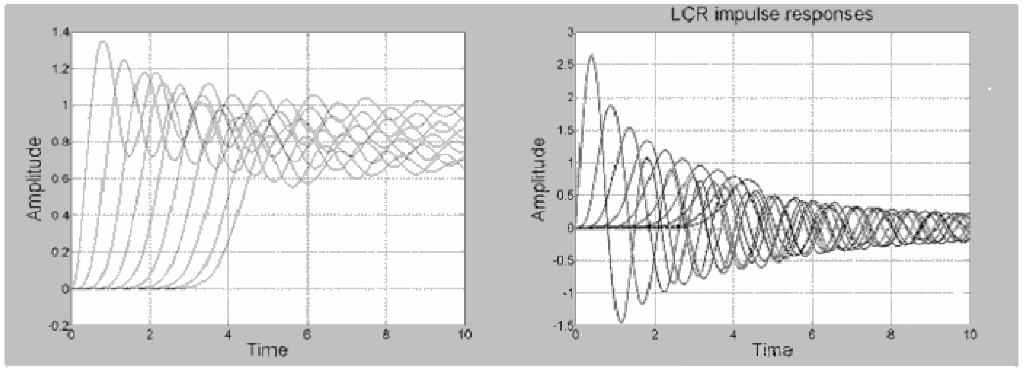

Fig. 6. Step and impulse responses of the RLC links

Since the circuit of the reactive load consists of two links of the circuit with accordingly calculated parameters [2], then the step processes on the respective capacitors (dashed characteristics in Fig. 6) are only slightly different from the step processes of the capacitors of the identical links of the circuit. That lets us to complement the expansion basis with these step processes too, which increases the accuracy of the approximation.

Synthesis using the pulse responses of the links of the basis circuit

Calculating the expansion quotients of the Nyquist function shown in the [3 Fig. 6] we get these results:

a = [-0.0059; 0.0027; 0.0500; -0.0586; -0.2023; 0.0781; 0.5850; 0.6084; 0.2955; 0.0429],
b = [0.0109; -0.0204; 0.1401; -0.0908; -0.4035; 0.1182; 0.8266; 0.7919; 0.3334; 0.0885].

Summing up the products we get $\sum_{k=1}^{10} a_k b_k = 1.1710$.
So the quality of approximation is not inferior to the case with ideal Bessel's functions. Practically the approximation is exact. Another important parameter is the trace of the matrix: Trace **(Φ)=**19.2.

It characterizes the filter's sensitivity to divergences of the weight quotients. Seeing that in praxis the dispersion of the divergence of weight quotients cannot be ascertained, the trace has only a comparative meaning. One can verify it's influence by comparing the synthesis in different bases. In this case L=33 and C=5.458e-3 thus ρ=77.76 ($\rho = \sqrt{L/C}$ the value of ρ does not depend on the units of measurements of L and C we can assume that L=33 µH and C=5.458e-3 µF; we can interpret these values also as nH and nF). In this case the limitation of L and C is $\sqrt{LC}$ = 0.4244 (if we choose to use µH un µF as units of measurement then the value 0.4244 must be interpreted as 0.4244 µs).
Opting for active load for the circuit, reflection can be detected in the step processes. That leads to errors in the approximation, which are more visible on the right side of the Fig. 7.

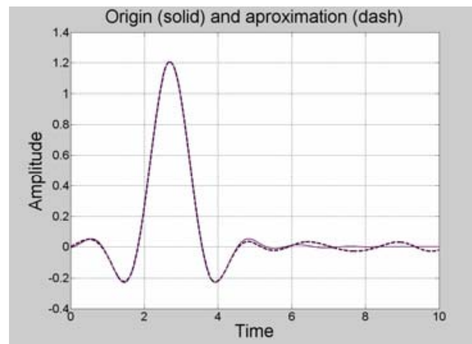

Fig.7. The influence of reflection on the accuracy of the approximation

The values of both of the indicators of quality have changed: $\sum_{k=1}^{10} a_k b_k = 1.1690$ and Trace **(Φ)=**19.4. The value of the systematical error (1.1711-1.1690)/ 1.1711%=0.18%, and the error can be seen visually in Fig. 7. In return the change of the Trace **(Φ)** is so small that its effects would be difficult to detect.

The error energy in the experiments described below is calculated with the following formula:

$$Enerr = \int_{t1}^{t2} (aproximation - ideal)^2 dt \ .$$

Using matched reactive load and components with the nominal dispersion of σ=1% in 100 cycles it was ascertained that the response energy of the synthesized filters response to the unit pulse deflects from the energy of the raised cosine function not more than 0.005 %.

The use of active matched load almost does not affect the result. Even considering the systematical error (which dominates in this case) the error is 0.15 %. The systematic error which occurs with the use of active load of basis circuit suppresses the effect of the difference of Gram matrix traces. These experiments show that a parameter scattering of components of 1% does not affect the quality of the filter considerably.

Trimming each filter's adding quotients we see that results are more precise even at a higher tolerance of components. In a circuit with tolerance of all elements at a level of dispersion of 10% in 100 cycles with reactive matched load the error energy added up to 0.43% of the optimal approximation energy. With a matched active load the respective error energy was 0.53%. Thus if the filter operates in the regime with an adaptive weight quotient trimming algorithm a higher parameter tolerance of components is admissible (up to 10%).

The acquired values characterize the kind of synthesis in which the impulse response is approximated at first and then the response to the unit pulse is calculated.

The synthesis using responses of the links of basis circuit to the unit pulse

There is also a straight way when the basis circuit's responses to the unit pulse are used to approximate the "raised cosine" characteristic. It turns out that in this case Trace **(Φ)** = 7.76 and that has a positive effect on all experiments compared to the synthesis of a filter in which the impulse responses of the links of the circuit are used as the basis.

Without parameter tolerance of components and with active resistance of the load of basis circuit we get these characteristic values: the approximation energy of the raised cosine function $\sum_{k=1}^{10} a_k b_k = 0.8741$ at the raised cosine function energy of $E_{Rc} = 0.8750$ the systematic error is (0.8750-0.8741)/0.8750%= 0.1% .

Individual trimming. Parameter tolerance of components σ=10%.

Adjusting each filter's adding quotients to the reactively matched load of the basis circuit in 100 cycles of experiment the error energy is only 0.22% of the energy of the raised cosine function. If the basis circuit is matched with active wave resistance the error energy is 0.25%.

Without individual trimming and at the parameter scattering of 1% the acquired results show minimal errors. With an active load of the basis circuit the error energy compared to the raised cosine function's energy is only 0.01%, with matched reactive load only 0.005%. These values are calculated not considering the systematical error, which is greater.

Synthesizing the filter by the nominal values of the details it is advisable to the quotients of the filter to be synthesized using a model (i.e. MATLAB Simulink) because in praxis it is impossible to create a filter without tolerance of components. One exception could be the high-frequency region, where the parasitical reactances of details and construction must be taken into account.

Conclusion

The RLC ladder circuit is seen as suitable basis circuit for the synthesis of the Nyquist filter. It is more advantageous to synthesize filters using the responses of the links of the circuit to the unit pulse. It is advisable to use the raised cosine function as the target function for the approximation. It provides less sensitivity to the parameter scattering of the details compared to the use of the impulse responses of the links of the circuit when approximating the filter's impulse response. If we approximate the raised cosine function with at the roll-off factor of 0.5 it is enough with 8 links of the RLC basis circuit. At a lesser value of the roll-off factor the number of links must increase.

The use responses of the phase driver circuits for the synthesis of filters is unprofitable because it requires a relatively high number of links and each of them contains 4 oscillation circuits.

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Analizuojami sėkmingi ir nesėkmingi Naikvisto filtrų laikinės sintezės pavyzdžiai. Akcentuojami du faktoriai: 1) tinkamos sintezės bazinės grandinės parinkimas ir 2) tikslo funkcijų parinkimas. Remiantis šiais faktoriais, nustatoma filtrų kokybė ir sudėtingumas. Il. 7, bibl. 3 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

E. Hermanis. Examples for Filter Synthesis // Electronics and Electrical Engineering. – Kaunas: Technologija, 2006. – No. 1(65). – P. 5–10.

In the article successful and unsuccessful examples of the synthesis of Nyquist filters are shown into time domain. Accent is set to two factors 1) of the selection of adequate basic chain for the synthesis and 2) the selection of objective function. From these factors it will overstate quality and complexity of the filter. Ill. 7, bibl. 3 (in English; summaries in Lithuanian, English and Russian).

Э. Херманис. Примеры синтеза фильтров // Электроника и электротехника. – Каунас: Технология, 2006. – № 1(65). – С.5–10.

Представлены успешные и неуспешные примеры временного синтеза фильтров Найквиста. Акцентируются два аспекта: 1) подбор соответствующей базовой цепи синтеза и 2) выбор функций цели. На основе этих факторов определяется качество и сложность фильтров. Ил. 7, библ. 3 (на английском языке; рефераты на литовском, английском и русском яз.).