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Asymmetric Baxter- King filter

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***Abstract.* This paper proposes an extension of the Baxter-King symmetric band pass filter to an asymmetric case. It turns out the optimal correction scheme of the ideal filter weights is the same as in the symmetric version – cut the ideal filter at the appropriate length and add a constant to all filter weights to ensure zero weight on zero frequency. Since the symmetric Baxter-King filter is unable to extract the band of frequencies at the ends of the series, the extension to an asymmetric filter is useful whenever the real time estimation is needed. The developed filter can be used in any field of science where it is necessary to extract a band of frequencies from a signal.**

***Keywords*: asymmetric filter, band pass filter, real time estimation, Christiano-Fitzgerald filter.**

I. INTRODUCTION

Scientists in various fields might encounter a necessity to extract a particular band of frequencies from a given signal. The ideal filter that would perfectly do the job is of infinite length in both directions, thus putting limitation to its practical use. There are various proposals of optimally approximating the ideal filter to a finite-length filter. One such filter was proposed by Baxter and King (1999) in economics literature to extract business cycle frequencies, but general enough to extract any band of frequencies of interest. It minimizes the squared distance between the frequency response function of the ideal filter and the approximating filter subject to constraints that the filter is to be symmetric and put zero weight on zero frequency (corresponds to a wave of infinite length).

Although Baxter and King (1999) proposes fixed-length symmetric filter, some programs, e.g. Grocer for Scilab, offer a varying-length variant of the Baxter-King filter, since the underlying theories of both varying- and fixed-length filters are the same. Baxter and King (1999) impose symmetry of the filter to, according to authors, ensure there is no phase shift. However, as this paper shows, symmetry of a filter does not ensure the absence of phase shifts, since finite-length filters put nonzero weight on unwanted frequencies that may introduce phase shifts. Given the latter, one might argue that the longer the approximating filter the better, since its length is closer to the length of the ideal filter. Thus, one might be willing to prefer varying-length symmetric filter to the fixed-length symmetric filter.

Another limitation to the original Baxter-King filter is its symmetry. The symmetry of a filter implies that the ends of the signal cannot be estimated without extending the ends with forecasts and backcasts. Since the latter may not be appropriate or desirable in many applications, the implication of a symmetric filter is that it cannot be applied in real time. However, in many instances, the end of the signal is the most important part of the whole series since it contains the most recent observations. Thus, there is necessity to build a filter that would be able to extract the desired signal also at the ends of the series. There are many filters out there that are asymmetric. For example, one is Christiano-Fitzgerald filter. Many such filters, including the latter, rely on specific assumption about the stochastic process of the incoming signal. Baxter-King filter does not assume, at least explicitly, a specific process for an incoming signal.

This paper deals with the construction of a filter to be applicable in real time and which would be in line with the original Baxter-King minimization problem. Thus, the paper proposes an extension of the Baxter-King symmetric band pass filter to an asymmetric Baxter-King filter by retaining the original Baxter and King (1999) minimization problem but relaxing the constraint on the symmetry. It turns out the optimal correction scheme of the ideal filter weights for the asymmetric Baxter-King filter matches the one for the symmetric Baxter-King filter, which is cutting the ideal filter at the appropriate length and adding a constant to all filter weights to ensure zero weight on zero frequency.

A question arises: when the asymmetric Baxter-King filter is superior to the symmetric Baxter-King filter. Since the symmetric Baxter-King filter is unable to extract a signal at the ends of series, and since the asymmetric Baxter-King filter contains the symmetric filter as a special case – the latter can easily be obtained by putting constraints to the length and symmetry of the filter – the extension to an asymmetric filter is useful whenever the real time estimation is needed, and should be considered whenever the original Baxter-King filter is considered, since it can be no worse than the symmetric Baxter-King filter. The developed filter can be used in any field of science where it is necessary to extract a band of frequencies from a signal in real time.

Another question is: when the asymmetric Baxter-King filter is superior to its closest competitor, the default specification of Christiano-Fitzgerald filter (see Christiano and Fitzgerald, 2003). The default Christiano-Fitzgerald filter is optimized for a series that follows a random walk process. Thus, the asymmetric Baxter-King filter might be superior to the default Christiano-Fitzgerald filter when the random walk process poorly approximates the process of a signal, with the latter being stationary. Further work would be useful to be carried out to find proper conditions when the asymmetric Baxter-King filter is superior to the default specification of Christiano-Fitzgerald filter.

The structure of the paper is as follows. Section II describes the estimation of the asymmetric Baxter-King filter. Section III presents an illustrative example with a sample series, extracted signals with fixed- and varying-length symmetric Baxter-King filter, asymmetric Baxter-King filter, and its closest competitor, the default specification of Christiano-

Fitzgerald filter. Finally, Section IV presents Scilab code for the asymmetric Baxter-King filter.

II. The filter

Consider the following orthogonal decomposition of the stochastic process, x_t:

$$x_t = y_t + \tilde{x}_t. \quad (1)$$

The process, y_t, has power only in frequencies belonging to the interval $\{(a_1, a_2) \cup (-a_2, -a_1)\} \subset (-\pi, \pi)$, where $0 < a_1 \le a_2 \le \pi$. The process, $\tilde{x}_t$, has power only in the complement of this interval in $(-\pi, \pi)$. By the spectral representation theorem,

$$y_t = b(L)x_t, \quad (2)$$

where the ideal band pass filter, $b(L)$, has the following structure:

$$b(L) = \sum_{h=-\infty}^{\infty} b_h L^h, \quad L^h x_t = x_{t-h}, \quad (3)$$

where

$$b_h = \frac{\sin(ha_2) - \sin(ha_1)}{\pi h}, \quad h = \pm 1, \pm 2, \ldots$$

$$b_0 = \frac{a_2 - a_1}{\pi}, \quad a_1 = \frac{2\pi}{p_u}, \quad a_2 = \frac{2\pi}{p_l}, \quad (4)$$

and $p_u, p_l \in [1, \infty)$ define the upper and lower bounds of the wave length of interest. With b_h's specified as in (4), the frequency response function of the ideal filter at frequency ω is

$$\beta(\omega) = 1, \quad \text{for } \omega \in (a_1, a_2) \cup (-a_2, -a_1)$$
$$= 0, \quad \text{otherwise.} \quad (5)$$

Baxter and King (1999) have proposed to obtain a symmetric, fixed length approximation to the ideal filter, (3) and (4), by minimizing

$$Q = \int_{-\pi}^{\pi} \delta(\omega)\delta(-\omega)d\omega$$

s.t.

$$\hat{\beta}(0) = \sum_{k=-K}^{K} \hat{b}_k = 0$$

$$\hat{b}_k = \hat{b}_{-k}, \quad (6)$$

where $\delta(\omega) = \beta(\omega) - \hat{\beta}(\omega)$ is the discrepancy between the frequency response functions of the exact and approximate filters at frequency ω, and the constraint $\hat{\beta}(0) = 0$ is to ensure zero weight on the trend frequency, in line with the assumption $a_1 > 0$. The solution to (6) is a truncation of the ideal filter symmetrically at length K, and an addition of a constant $(-\sum_{k=-K}^{K} b_k)/(2K+1)$ to all filter weights to ensure $\hat{\beta}(0) = 0$.

A natural extension of the Baxter and King (1999) filter is to allow the approximate filter to be asymmetric. In order to optimally approximate an ideal symmetric linear filter in a Baxter-King sense, the problem is to minimize

$$Q = \int_{-\pi}^{\pi} \delta(\omega)\delta(-\omega)d\omega$$

s.t.

$$\hat{\beta}(0) = \sum_{h=-p}^{f} \hat{b}_h = 0. \quad (7)$$

To solve (7), form the Lagrangian

$$\mathrm{L} = Q - \lambda\hat{\beta}(0) \quad (8)$$

with first order conditions (FOCs):

$$\frac{\partial \mathrm{L}}{\partial \hat{b}_h} = \frac{\partial Q}{\partial \hat{b}_h} - \lambda = 0$$

$$\frac{\partial \mathrm{L}}{\partial \lambda} = -\hat{\beta}(0) = 0. \quad (9)$$

Begin by noting that

$$\frac{\partial}{\partial \hat{b}_h}[\delta(\omega)\delta(-\omega)] = \frac{\partial \delta(\omega)}{\partial \hat{b}_h}\delta(-\omega) + \delta(\omega)\frac{\partial \delta(-\omega)}{\partial \hat{b}_h}. \quad (10)$$

Since the frequency response function of the approximating filter is $\hat{\beta}(\omega) = \sum_{h=-p}^{f} \hat{b}_h e^{-i\omega h}$, it follows that

$$\frac{\partial \delta(\omega)}{\partial \hat{b}_h} = -e^{-i\omega h}. \quad (11)$$

(11) implies

$$\frac{\partial Q}{\partial \hat{b}_h} = -\int_{-\pi}^{\pi} [e^{-i\omega h}\delta(-\omega) + \delta(\omega)e^{i\omega h}]d\omega. \quad (12)$$

By the property $\int_{-\pi}^{\pi}[f(\omega) + f(-\omega)]d\omega = 2\int_{-\pi}^{\pi} f(\omega)d\omega$ (since $\int_{-\pi}^{\pi} f(\omega)d\omega = \int_{0}^{\pi} f(\omega)d\omega + \int_{-\pi}^{0} f(\omega)d\omega = \int_{0}^{\pi}[f(\omega) + f(-\omega)]d\omega$ is real, then $\int_{-\pi}^{\pi} f(\omega)d\omega = \int_{-\pi}^{\pi} f(-\omega)d\omega$, and the property follows), (12) becomes

$$\frac{\partial Q}{\partial \hat{b}_h} = -2\int_{-\pi}^{\pi} \delta(\omega)e^{i\omega h}d\omega. \quad (13)$$

Further, by the property

$$\int_{-\pi}^{\pi} e^{i\omega n}e^{-i\omega m}d\omega = \int_{-\pi}^{\pi} e^{-i\omega(m-n)}d\omega = 0 \quad \text{for } n \ne m$$
$$= 2\pi \quad \text{for } n = m, \quad (14)$$

obtain

$$\int_{-\pi}^{\pi} \delta(\omega)e^{i\omega h}d\omega = \int_{-\pi}^{\pi}\left[\sum_{k=-\infty}^{\infty} b_k e^{-i\omega k} - \sum_{j=-p}^{f} \hat{b}_j e^{-i\omega j}\right]e^{i\omega h}d\omega$$
$$= 2\pi[b_h - \hat{b}_h]. \quad (15)$$

Given (9), (13) and (15), the FOCs are

$$-4\pi[b_h - \hat{b}_h] - \lambda = 0. \quad (16)$$

If there is no constraint on $\hat{\beta}(0)$, the optimal approximate (in Baxter-King sense) filter is simply derived by truncation of the ideal filter's weights. If there is a constraint on $\hat{\beta}(0)$, then λ must be chosen so that the constraint is satisfied. For this purpose, rewrite (16) as

$$\hat{b}_h = b_h + \theta,$$

where $\theta = \lambda / (4\pi)$. In order to have $\hat{\beta}(0) = \sum_{h=-p}^{f} \hat{b}_h = 0$, the required adjustment is

$$\theta = \frac{-\sum_{h=-p}^{f} b_h}{p + f + 1}, \tag{17}$$

which yields the same optimal weight adjustment scheme as in the symmetric Baxter-King filter case.

III. An Illustrative Example

Fig. 1 shows a sample series and two signals extracted by symmetric fixed- and varying-length Baxter-King filters for wave length between 6 and 32 periods, and minimum K=12. Even though Baxter and King (1999) do not discuss the varying-length version of the filter, the code for such filter is implemented in some programs, e.g. in Grocer, an econometrics toolbox for Scilab.

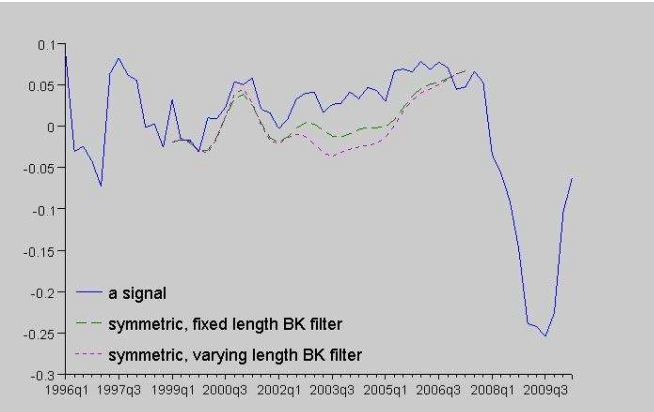

Fig. 1. A sample series and the extracted band of waves of length 6 to 32 periods with symmetric fixed- and varying-length Baxter-King filters, with K=12. The difference between the extracted signals from fixed- and varying-length filters is apparent. The ends of the signal can not be estimated with the symmetric Baxter-King filter.

It can be seen that the two filters give remarkable differences in the extracted signal. Given that the longer the filter, the better an approximation, the varying-length filter should be considered as superior to the fixed-length filter. Also, even though both filters are symmetric, Fig. 1 also shows that their extracted turning point dates do not coincide, which is contrary to Baxter and King (1999) assertion that a symmetric filter does not introduce phase shifts. Fig. 1 illustrates that the symmetry of a filter is not sufficient to guarantee the filter does not produce phase shifts, since finite-length filters give output signals that are contaminated by unwanted frequencies that may introduce phase shifts. In this regard, an argument might be that the length of a filter is more crucial for the quality of the extracted signal than the symmetry.

It can also be seen that the symmetric Baxter-King filter can not estimate the signal at the ends of the series, thus putting limitations to its practical application in real time. Thus, there is a need for a filter that would be able to extract a signal at any point in the sample.

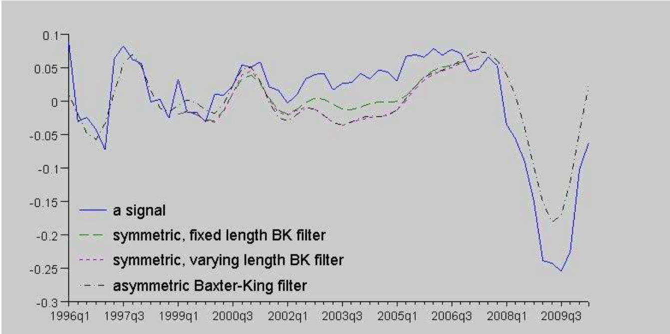

Fig. 2. Asymmetric versus symmetric Baxter-King filters. The asymmetric filter equals the varying-length symmetric filter in the middle of the series where both of them use the whole sample information. Moving from the center of the sample, the varying-length symmetric filter approaches to the fixed-length symmetric filter, while the asymmetric filter always uses the whole sample information, and becomes one-sided at the ends of the sample. The asymmetric filter is able to estimate the desired signal in real time.

Fig. 2 shows the extracted signal from asymmetric Baxter-King filter in comparison to the symmetric case. In the middle of the sample, the asymmetric filter is identical to the varying-length symmetric filter, where they both use all the sample information and are symmetric. Using as many data points as possible is crucial for the extracted signal' s quality; therefore, it is apparent that varying-length symmetric filter is superior to the fixed-length filter.

Moving away from the midpoint of the sample, the varying-length symmetric filter approaches the fixed-length symmetric filter, since the usable number of data points is constrained by the shortest distance to the end of the series, whereas the asymmetric filter uses all the data in the sample at any point, and becomes one-sided at the ends of the series. The merits of the asymmetric Baxter-King filter is apparent – it delivers the extracted signal for all data points in the sample and, thus, can be used in real time estimation.

Two questions arise: i) when the asymmetric Baxter-King filter is superior to the symmetric one, and ii) when the asymmetric Baxter-King filter is superior to its closest competitor, Christiano-Fitzgerald filter.

The answer to the first question is simple. Since the asymmetric Baxter-King filter includes the symmetric Baxter-King filter as a special case – the latter can be obtained by imposing restrictions to the length and symmetry of the former

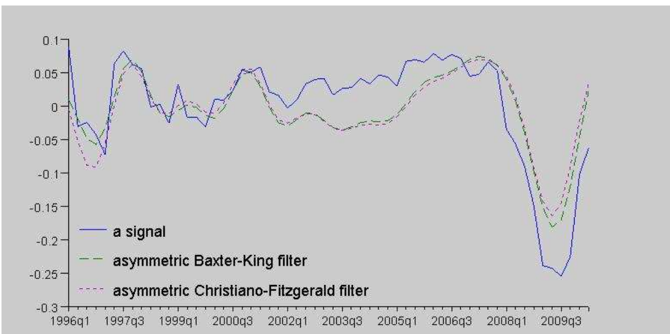

Fig. 3. A sample series, the extracted band of frequencies from the asymmetric Baxter-King filter and the default (random walk) specification of the Christiano-Fitzgerald filter. Both extracted signals are similar with apparently close to identical turning point datation.

– the asymmetric Baxter-King filter should be considered whenever the symmetric Baxter-King filter is considered.

Fig. 3 plots a sample series, the extracted signal for wave length between 6 and 32 periods by using asymmetric Baxter-King filter as well as the default (random walk) specification of the asymmetric Christiano-Fitzgerald filter. It can be seen that, for the particular sample series, both filters extract a similar output signal with apparently close to identical turning point dates.

The default Christiano-Fitzgerald filter is optimized for a series that follows a random walk process. Thus, the asymmetric Baxter-King filter might be superior to the default Christiano-Fitzgerald filter when the random walk process poorly approximates the process of a signal, with the latter being stationary. Further work must be carried out to find proper conditions when the asymmetric Baxter-King filter is superior to the default specification of Christiano-Fitzgerald filter.

IV. Program Code

This section presents the Scilab code for the asymmetric Baxter-King filter.

Scilab is free and open source alternative to Matlab and is available at http://www.scilab.org/.

```
function [fy,AA]=bkfilterasy(y,pl,pu)
//-------------------------------------------------
// All rights reserved
// Adapted by Ginters Buss from
// Eric Dubois (http://dubois.ensae.net/grocer.html)
// who adapted and extended from Terry Fitzgerald
//-------------------------------------------------
// PURPOSE: computes asymmetric Baxter-King filter
// ------------------------------------------------
// INPUT:
// * y = a real (nx1) input vector
// * pl = minimum period of oscillation of desired
// component
// * pu = maximum period of oscillation of desired
// component
//   (2<=pl<pu<infinity).
// -------------------------------------------------
// OUPTUT:
// * fy = vector (nx1) containing filtered data
// * AA = filtering matrix
// --------------------------------------------------
// --------------------------------------------------

b = 2*%pi/pl;
a = 2*%pi/pu;
[T,nvars] = size(y);
if T<5 then
   warning('# of observations < 5');
end
if pu<=pl then
  error('pu must be larger than pl');
end
if pl<2 then
  warning('pl less than 2 , reset to 2');
  pl = 2;
end
//   compute "ideal" Bs
j = 1:2*T;
B = [(b-a)/%pi,(sin(j*b)-sin(j*a)) ./ (j*%pi)]';
//==============================================
AA = zeros(T,T);
for i = 1:T
  AA(i,i:T) = B(1:T-i+1)';
end

AA(1,1) = AA(T,T);
//  Use symmetry to construct bottom 'half' of AA
%v2 = triu(AA,1);
%v2 = %v2(:,$:-1:1);
AA = AA+%v2($:-1:1,:);
AA=AA-kron(sum(AA,2)./T,ones(1,T));
//==============================================
// compute filtered time series using selected
// filter matrix AA
fy = AA*y;
endfunction
```

V. Conclusions

Scientists in various fields might encounter a necessity to extract a particular band of frequencies from a given signal. The ideal filter that would perfectly do the job is of infinite length in both directions, thus putting limitation to its practical use. There are various proposals of optimally approximating the ideal filter to a finite-length filter. One such filter was proposed by Baxter and King (1999) in economics literature to extract business cycle frequencies, but general enough to extract any band of frequencies of interest. It minimizes the squared distance between the frequency response function of the ideal filter and the approximating filter subject to constraints that the filter is to be symmetric and put zero weight on zero frequency (corresponds to a wave of infinite length).

The limitation to the original Baxter-King filter is its symmetry. The symmetry of a filter implies that the ends of the signal cannot be estimated without extending the ends with forecasts and backcasts. Since the latter may not be appropriate or desirable in many applications, the implication of a symmetric filter is that it cannot be applied in real time. However, in many instances, the end of the signal is the most important part of the whole series since it contains the most recent observations. Thus, there is necessity to build a filter that would be able to extract the desired signal also at the ends of the series. There are many filters out there that are asymmetric. For example, one is Christiano-Fitzgerald filter. Many such filters, including the latter, rely on specific assumption about the stochastic process of the incoming signal. Baxter-King filter does not assume, at least explicitly, a specific process for an incoming signal.

This paper deals with the construction of a filter to be applicable in real time and which would be in line with the original Baxter-King minimization problem. Thus, the paper proposes an extension of the Baxter-King symmetric band pass filter to an asymmetric Baxter-King filter by retaining the original Baxter and King (1999) minimization problem but relaxing the constraint on the symmetry. It turns out the optimal correction scheme of the ideal filter weights for the asymmetric Baxter-King filter matches the one for the symmetric Baxter-King filter, which is cutting the ideal filter at the appropriate length and adding a constant to all filter weights to ensure zero weight on zero frequency.

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The paper includes Scilab code for the asymmetric Baxter-King filter for not for profit use.

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Ginters Bušs. Asimetrisks Beksteres-Kinga filtrs
Zinātnieki dažādās nozarēs var saskarties ar nepieciešamību iegūt konkrētu frekvenču joslu dotam signālam. Ideāls filtrs, kas perfekti izfiltrētu nepieciešamās frekvences, ir bezgalīgi garš uz abām pusēm, tādējādi tas nav pielietojams praksē. Literatūrā ir pieejami dažādi risinājumi, lai tuvinātu galīga garuma filtru ideālam filtram. Vienu šādu risinājumu piedāvā Bekstere un Kings (1999) ekonomikas literatūrā, lai iegūtu biznesa cikla novērtējumu, taču šis filtrs ir pietiekami vispārīgs, lai iegūtu jebkādu interesējošo frekvenču joslu. Šis filtrs minimizē kvadrātisko attālumu starp ideālā un tuvinātā filtru frekvences atbildes funkcijām ar ierobežojumiem, ka filtrs ir simetrisks un ka tas liek nulles svaru uz nulles frekvenci (kas atbilst bezgalīga garuma vilnim).
Ir programmas, kas piedāvā mainīga garuma variantu simetriskam Beksteres-Kinga (BK) filtram; lai gan šādu gadījumu Bekstere un Kings (1999) neapskata, tā pamatā ir tā pati minimizēšanas problēma, kas sākotnējam fiksēta-garuma simetriskam BK filtram. Bekstere un Kings (1999) uzspiež filtra simetriju, lai nepieļautu fāzu nobīdes. Taču šis darbs ilustrē, ka filtra simetrija nav pietiekama īpašība, lai nepieļautu fāzu nobīdes, jo galīga garuma filtri liek nenulles svaru uz nevēlamām frekvencēm, kas var radīt fāzu nobīdes.. Vēl viens oriģinālā BK filtra ierobežojums ir tas, ka filtra simetrijas dēļ netiek iegūts signāla novērtējums rindas galos, ja netiek izmantotas nākotnes un pagātnes prognozes. Tā kā prognozes varētu būt nepiemērotas vai nevēlamas daudzos pielietojumos, simetrisks filtrs nevar būt pielietojams reālā laikā, lai gan daudzreiz tieši signāla pēdējie novērojumi ir paši būtiskākie, jo tie satur pašu jaunāko informāciju. Līdz ar to, ir nepieciešams izstrādāt filtru, kas spētu novērtēt signālu reālā laikā.Šis pētījums izstrādā BK tipa filtru, ko var lietot reālā laikā. Tas piedāvā vispārināt simetrisko BK joslas filtru uz tā asimetrisku variantu, paturot oriģinālo Beksteres un Kinga (1999) minimizēšanas problēmu, no tās izslēdzot simetrijas ierobežojumu. Rezultāti rāda, ka optimālā korekcijas shēma asimetrijas gadījumā ir tāda pati, kā simetriskajam filtram – nogriezt ideālā filtra galus attiecīgajos garumos un pievienot konstanti visiem filtra svariem, lai nodrošinātu nulles svaru nulles frekvencei.

Гинтерс Буш. Асимметричный Бакстер-Кинг фильтр
Ученые в различных областях могут возникнуть в необходимости извлечь конкретный диапазон частот от данного сигнала. Идеальный фильтр, который идеально сделал работу, является бесконечной длины в обоих направлениях, положив тем самым ограничения на его практическое использование. Есть различные предложения для оптимального приближения идеального фильтра с фильтром с конечной длины. Один из таких фильтров был предложен от Бакстер и Кинг (1999) в экономической литературе для извлечения частот бизнес-цикла, но достаточно обший для извлечения какой-либо полосы частот. Бакстер-Кинг (БК) фильтр минимизирует квадрат расстояния между функции частотной характеристики идеального фильтра и фильтра приближения при наличии ограничений, что фильтр должен быть симметричным и положить нулевой вес на частоте нуля.Бакстер и Кинг положили симметрию фильтра для обеспечения отсутствии сдвига фаз. Однако, как показывает эта статья, симметрия фильтра не обеспечивает отсутствию фазовых сдвигов, так как фильтры с конечной длины загрязненные нежелательными частотами, которые могут ввести фазовых сдвигов. Учитывая последнее, можно утверждать, что длиннее аппроксимация фильтра, тем лучше, так как длина ближе к длину идеального фильтра.Еще одно ограничение у оригинального БК фильтра является симметрия. От симметрии фильтра следует, что концы сигнала не может быть оценены без расширения конца с прогнозами. Так как последнее не может быть желательным во многих приложениях, следствием симметричного фильтра является, что он не может быть применен в режиме реального время. Однако, во многих случаях конец сигнала является наиболее важной частью серии так как он содержит последние замечания. Таким образом надо построить фильтр, который будет в состоянии извлеч сигнал на концах ряда.Эта статья посвящена строительству фильтра для использования в режиме реального время. В это статье предлагается расширение БК симметричного фильтра с асимметричным БК фильтром, сохранив оригинальную Бакстер и Кинг задачу минимизации но расслабляя ограничение на симметрию. Оптимальная схема коррекции весов идеального фильтра соответствует тому же для симметричного фильтра, который режет идеального фильтра на соответствующей длины и добавляет константу для все веса фильтра для обеспечения нулевого веса на частоте нуля.