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THE FREQUENCY-LOCKED LOOP SYSTEM OF THE NARROW-BAND FOLLOW-UP VOLTAGE-CONTROLLED OSCILLATOR FILTER

This paper proposes an astatic frequency-locked loop with the improved noise immunity and dynamic accuracy compared with the static frequency-locked loop. Improved noise immunity has been achieved through radiopulse spectrum conversion of an input harmonic signal. It allows reducing the self-tuning band of the narrow-band voltage-controlled oscillator follow-up filter, implemented on the basis of the developed frequency-locked loop, by several orders of magnitude. Simple analytic expressions for estimating the improvement of noise immunity and dynamic accuracy of the developed system are given allowing to compare it with the static frequency-locked loop of the voltage-controlled oscillator. An implementation of the harmonic signal spectrum radio pulse converter on the basis of present hardware components is proposed.

Keywords: *frequency-locked loop; IF amplifier; voltage-controlled oscillator; low-pass filter; mixer; frequency.*

Introduction

Frequency-locked loop (FLL) systems are widely used in various radio receivers, in frequency-modulated signal demodulators with frequency feedback, for voltage-controlled oscillator (VCO) frequency control, for narrow-band follow-up filtering of continuous quasi-harmonic signals with variable frequency, observed under various noisy disturbances, etc.

By now, statistical theory of radio signals reception and procession is well-developed, including filtering of radio signals with variable frequency, and, in particular, Doppler signals observed under additive normal noise [1 – 3]. Many efficient practical realizations of the FLL systems has already been proposed, which are used as narrow-band filters with VCO forced frequency turning [4, 5].

The main advantage of the narrow band filters, implemented using VCO FLL, is a wide acquisition sweep of the variable frequency signal, which does not depend on the parameters of the low-pass filter circuits included into the oscillator control loop.

However, the abovementioned advantage of the FLL system over the follow-up systems with PLL is linked to their main disadvantage – low immunity of the poor accuracy of the frequency mismatch in the stable mode between the input frequency and output filtering signal.

Current applied problems on application of FLL systems as narrow-band filters has predefined their future development towards the improvement of noise immunity and dynamic accuracy.

This report describes the theoretical and practical results obtained by the authors allowing to improve noise immunity and dynamic accuracy of the static FLL system. This goal is achieved by improving its astatism order and substantial broadening of the IF filter bandwidth, included into the narrow-band filter servoloop.

Main part

1. Brief theoretical description of the noise immunity and dynamic accuracy of the static FLL system.

Block diagram of the static FLL system, used in a narrow-band tracking filter is given in Fig. 1.

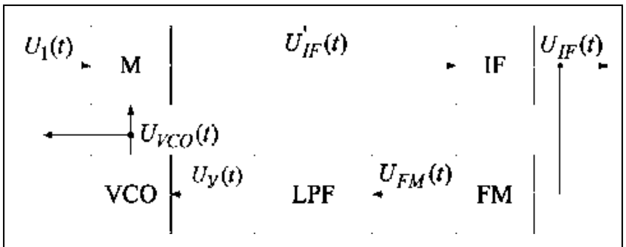

Fig. 1. Static FLL System Block Diagram:
M denotes mixer; VCO is voltage-controlled oscillator; IF is IF amplifier; FM is FM discriminator;
LPF is low-pass filter

The static FLL operates as follows:

The input signal $U_1(t)$ with frequency $\omega_s(t)$ is fed to one of the mixer (M) inputs. To the other mixer input the signal $U_{VCO}(t)$ of the voltage-controlled oscillator (VCO) with frequency $\omega_{VCO}(t)$ is fed. At the output the mixer forms the output signal $U'_{IF}(t)$ of the intermediate frequency $\omega_{IF}(t) = \omega_s(t) - \omega_{VCO}(t)$. This output signal is amplified by IF amplifier and as voltage is fed to the FM discriminator (FM-d) with zero frequency $\omega_0 = \omega_{IF}$.

The FM discriminator generates voltage $U_{FM}(t)$, which is proportional to the intermediate frequency deviation $\Delta\omega_{IF}(t)$ from its nominal value $U_{FM}(t) = k_{FM}\,\Delta\omega_{IF}(t)$, $\Delta\omega_{IF}(t) = \omega_{IF}(t) - \omega_{IF0}$, where k_{FM} is FM discriminator conversion efficiency. Control voltage $U_{VCO}(t)$ with by VCO frequency retuning is formed after low-pass filtering. This signal influences $\omega_{VCO}(t)$ frequency so that $\Delta\omega_{IF}(t)$ is reducing.

In the steady stable tracking mode the frequency deviation $\omega_{VCO}(t)$ contains information on the input signal deviation $\omega_s(t)$, for example, by means of Doppler. On the other hand, the described FLL system could be considered as IF stabilization system at level ω_{IF0}.

The analysis of the FLL system noise immunity is a quite complicated mathematical problem. Therefore most of the works, devoted to this problem consider only the impact of the signal and noise on the FM discriminator. Here we use the research results on noise immunity analysis described in [6].

Let us assume that input signal of FLL represents additive mixture of harmonic signal and white noise; IF amplifier has two-stages and low-pass filter is a first-order filter. Then the estimation variance of the filtering frequency $\omega_{VCO}(t)$ on the VCO output is calculated by the following formula:

$$\sigma_\omega^2 = \left[\frac{\alpha\gamma k_2}{\alpha(k_2+1)+\gamma}\right]^2 \cdot \left(\frac{\sigma}{A_{mc}}\right)^2, \tag{1}$$

where $\alpha = 1/T$;

$T = RC$ is LPF const, $\gamma \simeq 5\Delta f$;

Δf is IF amplifier bandpass;

k_2 is FLL open-loop transfer function;

$(\sigma / A_{mc})^2$ is power signal-to-noise ratio;

A_{mc} is signal amplitude;

σ is noise power rms value.

It follows from (1) that σ_ω^2 is proportional to γ i.e. IF amplifier has narrower bandwidth, and smaller signal-to-noise ratio.

Dynamic error of the static FLL system is determined in a steady state by error ratio $\Delta\omega_{IF\,st}(t) = \Delta\omega_{IF\,i}(t)/k_2$, where $\Delta\omega_i$ is initial detuning $\Delta\omega_{IF\,i}(t) = \Delta\omega_s(t) - \Delta\omega_{VCO}(t)$. This error is unavoidable, because k_2 is limited by the FLL system stability. The described system shortcomings makes their use in the precision tracking hardware undesirable.

2. The proposed FLL system implementing the narrow-band tracking filtering with improved noise immunity and dynamic error.

Fig. 2 displays the block diagram of the developed FLL system, used in narrow-band tracking filter.

Below we describe the operating principle of the proposed system.

The input signal of the RPSC is harmonic signal $U_{inp}(t) = U_0 \cos\omega_s t$, where U_0 is amplitude, ω_s is frequency. Radio pulse spectrum converter (RPSC) generates the sequence of coherent radio pulses of the

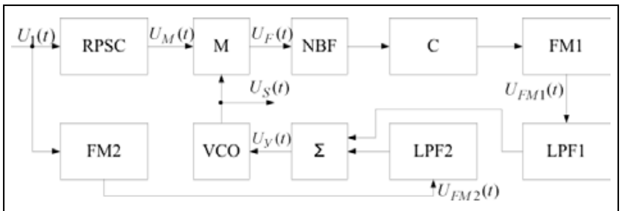

Fig. 2. The Developed FLL System Block Diagram: RPSC is radio pulse spectrum converter; M is mixer; NBF is narrow-band filter; C is clipper; FM1, FM2 is FM-detector 1, FM-detector 2; LPF1, LPF2 is low-pass filters; Σ is summator; VCO is voltage-controlled oscillator

standard amplitude U_0, pulse width τ, and period T. Analytically, this sequence can be represented as:

$$\psi(t) = U_0 \sum_{n=-\infty}^{\infty} \cos\left[\omega_s(t-nT)+\varphi_{0,n}\right]$$

$$\text{at } nT < t \le nT+\tau, \tag{2}$$

$$0 \text{ at } nT+\tau < t \le (n+1)T,$$

where $\varphi_{0,n}$ is initial phase, n is radio pulse.

For a coherent radio pulse sequence:

$$\varphi_{0,n} = \omega_0 nT.$$

The spectrum of this radio pulse sequence can be represented as:

$$S(\omega) = \sum_{n=0}^{\infty} U_n \cos(\omega_s + n\Omega)t, \tag{3}$$

where $\Omega = 2\pi/T$; n is integer number;

U_n is amplitudes of spectrum harmonics $S(\omega)$.

$$U_n = \frac{\tau}{T}\frac{\sin n\Omega\tau/2}{n\Omega\tau/2}. \tag{4}$$

Spectrum envelope and spectrum harmonics have very tight connection. Spectrum carrier frequency ω_s is in the envelope maxima.

Input frequency deviation ω_s translates the spectrum envelope and harmonics along the frequency axis.

Formed in this manner spectrum inputs one of the mixer inlets. The VCO output signal is fed to the second input of the mixer, which frequency is $\omega_{VCO}(t) = \omega_s(t)$. The spectrum of the latter signal is close to quasi-harmonic with one spectral component $S_{VCO}(\omega) = U_{VCO}\cos\omega_{VCO} t$.

Mixer M output signal $U_M(t)$ is a sequence of radio pulses with carrier frequency $F = n\Omega$, that is constant given constant n and Ω parameters of the radio pulse spectrum converter. Having constant frequency F, the band of the low-pass filter of the FLL IF amplifier could be narrowed improving noise immunity. The gain of the proposed scheme could be calculated by the ratio of the IF amplifier and NBF frequency passbands.

$$\chi = \Delta\omega_{IF}/\Delta\omega_{NBF}. \tag{5}$$

In order to calculate the energy loss during the spectral conversion the ratio τ/T should be used at the harmonic n equals 0,9. The conclusion follows form the analysis of the formula (3).

Hereafter the operation of the FLL system circuit on the band NBF, C, FM-detector 1, FM-detector 2, LP filter 1, summator, doesn't differ from the operation of the frequency control system.

Dynamic error reduction $\Delta\omega_{IF\,st}(t)$ in case of step change of $\Delta\omega_s(t)$ and limitation in case of linear change $\Delta\omega_s(t) = \Delta\omega_i + \alpha_1 t$, where α_1 is input frequency deviation rate of the developed FLL system, is achieved through the implementation of the direct control channel of the oscillator frequency, so called the forced retuning channel.

As seen from the block diagram given in Figure 2 the forced retuning contains the FM-detector 2 and Low-pass filter 2.

The application of such exposure method on the VCO transforms static FLL system into an astatic system of the first order [4].

However, as shown in [4], at step change of the input frequency $\Delta\omega_s(t) = \Delta\omega_i$ steady-state error is $\Delta\omega_{NBF\,st}(t) = 0$.

In case of linear change of the input frequency

$$\Delta\omega_{NBF\,st}(t) = \frac{(T_{FM} + T_{VCO})}{1 + k_2}, \qquad (6)$$

where $T_{FM2} = T_{LPF2}$;

T_{VCO} is response time setting of the VCO stationary operation.

3. Summary of the possible RPSC implementation

Block diagram of radio pulse converter of harmonic signal is given in Fig. 3.

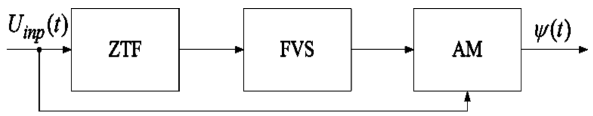

Fig. 3. RPSC block diagram:
ZTF is zero transient former; FVS is former of the video impulse sequence with the given ratio τ / T;
AM is amplitude modulator

The developed RPSC system operates as follows:

The harmonic signal $U_{inp}(t)$ is applied at the input. ZTF performs two-side signal clipping and differentiation. Subsequently, there is unipolar sequence (positive or negative) of the short pulses of the same amplitude at the low-pass filter output. Frequency of the pulse train equals the input frequency $U_{inp}(t)$. The former of the video impulse sequence with the required ratio τ / T could be implemented on the off-the-shelf chip of the counters/dividers with decoder [7]. Amplitude modulator forms radio pulse width τ, and period T with carrier frequency equal to input frequency. Amplitude modulator could be implemented based on the operating amplifier [8].

Conclusion

The main results obtained in the study are as follows.

The VCO FLL system with the astatism of the first order has been developed. This system is implemented based on of the variable-frequency oscillator forced frequency control. It provides zero dynamic deviation at frequency hopping $\Delta\omega_s(t)$ of the input signal and finite dynamic deviation when input frequency changes according to the linear low. In the latter case, dynamic deviation depends on the total time delay of the VCO settling time and low-pass filter in the forced retuning circuit.

Improved noise immunity of the developed FLL is achieved by using radio pulse conversion of the input harmonic signal spectrum. This solution provides substantially smaller in $50 \div 100$ times bandlimitedness of the closed control circuit in comparison to the control circuit of the static FLL.

Quite simple variant of the radio pulse converter implementation on the basis of the present hardware components has been proposed.

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СИСТЕМА ЧАСТОТНОГО АВТОПІДСТРОЮВАННЯ КЕРОВАНОГО ГЕНЕРАТОРА ВУЗЬКОСМУГОВОГО СТЕЖАЧОГО ФІЛЬТРА

В.В. Печенін, К.О. Щербина, О.В. Войтенко

Розроблена і досліджена астатична система частотного автопідстроювання з поліпшеною завадостійкістю і динамічною точністю в порівнянні зі статичною частотною автопідстройкою. Підвищення завадостійкості досягнуто за рахунок трансформаційного радіоімпульсного перетворення спектра вхідного гармонійного сигналу, що дозволило зменшити в кілька десятків разів смугу контуру ланцюга автопідстроювання керованого генератора вузькосмугового стежачого фільтра, реалізованого на основі розробленої схеми частотного автопідстроювання. Приведені прості аналітичні вирази, що дозволяють оцінити виграш в завадостійкості та динамічній точності розробленої системи частотної автопоідстройки в порівнянні зі статичною системою частотного автопідстроювання керованого генератора. Наведено варіант практичної реалізації радіоімпульсного перетворювача спектра гармонійного сигналу на основі існуючої елементної бази.

Ключові слова: *автопідстроювання частоти; підсилювач проміжної частоти; керований генератор; фільтр нижніх частот; змішувач; частота.*

СИСТЕМА ЧАСТОТНОЙ АВТОПОДСТРОЙКИ УПРАВЛЯЕМОГО ГЕНЕРАТОРА УЗКОПОЛОСНОГО СЛЕДЯЩЕГО ФИЛЬТРА

В.В. Печенин, К.А. Щербина, О.В. Войтенко

Разработана и исследована астатическая система частотной автоподстройки с улучшенной помехоустойчивостью и динамической точностью по сравнению со статической ЧАП. Повышение помехоустойчивости достигнуто за счет применения радиоимпульсного преобразования спектра входного гармонического сигнала, что позволило уменьшить в несколько десятков раз полосу контура цепи автоподстройки управляемого генератора узкополосного следящего фильтра, реализованного на основе разработанной схемы ЧАП. Приведены простые аналитические выражения, позволяющие оценить выигрыш в помехоустойчивости и динамической точности разработанной системы ЧАП по сравнению со статической системой частотной автоподстройки управляемого генератора. Приведен вариант практической реализации радиоимпульсного преобразователя спектра гармонического сигнала на основе существующей элементной базы.

Ключевые слова: *автоподстройка частоты; усилитель промежуточной частоты; управляемый генератор; фильтр нижних частот; смеситель; частота.*