

СУЧАСНА ФІЗИКА

UDC 621 #(621.37/.39; 621.382.2/.3; 621.387)

DOI: <https://doi.org/10.17721/1812-5409.2026/1.36>

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**INFLUENCE OF THE POSITIVE FEEDBACK RESISTOR RESISTANCE
ON THE AMPLITUDE-FREQUENCY RESPONSE OF THE GYRATOR BASED
ON THE OPERATIONAL AMPLIFIER**

You can get rid of the use of inductors in active RLC filters of the second and higher orders by using a gyrator – an RC cell included in the positive feedback circuit of an operational amplifier. This "active inductor" circuit allows you to implement active filters even using microelectronics devices. The purpose of our work is to develop practical recommendations for choosing the value of the feedback resistor resistance in gyrator circuits and to investigate its influence on the amplitude-frequency characteristic of the device.

As a research method, computer modeling was used in the LTSpice software application, during which the main characteristics of the oscillatory LC circuit and the circuit with a gyrator on an LT1006 operational amplifier were compared, and the corresponding amplitude- and phase-frequency characteristics were obtained.

It is shown that the position of a maximum of amplitude-frequency response of the circuit with a gyrator is closer to the resonant frequency of the RLC oscillating circuit, when the resistance value of the coupling resistor is closest to the output resistance of the operational amplifier, but at the same time it must be at least 100 Ohm. To ensure a stable transmission coefficient of the circuit with a gyrator when the resonant frequency changes tenfold, the resistance must be about half the operational amplifier's output resistance, 300 Ω in this case.

Key words: active filter, gyrator, feedback, operational amplifier, amplitude-frequency response.

Classification according to AMS 2020: 94C60.

Introduction

In radio engineering and radio electronics, there is a need to pass and amplify signals only in a certain frequency range, the so-called passband, or to suppress them outside the selected range – in the suppression band. This task is assigned to four-poles (filters), the amplitude-frequency characteristics (AFC) of which are non-zero in the passband and close to zero at its outside (Levytskyi, 2007; Bekh, 2024; Carter, & Mancini, 2018).

Passive second-order RLC filters are more efficient than first-order RC filters, but the latter, in turn, do not contain inductors, the dimensions and other parasitic parameters (resistance, interturn capacitance, etc.) of which increase significantly at low frequencies close to the frequencies of the audio range (Bekh, 2024; Carter, & Mancini, 2018). Another disadvantage of passive RC filters is the attenuation of the useful signal in the passband. This drawback is eliminated by combining passive RC filters with amplifier stages covered by various types of feedback. Such combined filters are called active (Bekh, 2024; Carter, & Mancini, 2018).

The object of the study is the gyrator circuit – an RC cell connected in the positive feedback loop of an operational amplifier (Bekh, 2024; "Old Hack EE", 2022; National Semiconductor Corp, 1980) for a change from the use of inductors in active filters with order higher than two. The voltage across capacitor C in the gyrator circuit causes the voltage and current at the output of the circuit to behave similarly to those values across the inductor. Similar "active inductor" circuits allow implementing active filters in a wide frequency range (up to units of GHz (Kilinc et al., 2025)) even by means of microelectronics, where, however, they are more often implemented on inverting and non-inverting amplifiers included in the feedback loop on separate field-effect transistors (Patel, & Oza, 2018), which complicates the calculation of such circuits due to the need to take into account the steepness and nonlinearity of their transmission characteristics (Patel, & Oza, 2018; Saad, & Garrab, 2025; Kilinc et al., 2025).

The literature (Bekh, 2024; Carter, & Mancini, 2018) provides practical recommendations for choosing the value of the resistance of the feedback resistor R_2 in the gyrator circuit on the operational amplifier (Fig. 1 b) – it should be equal to the minimum load resistance of the operational amplifier. However, the minimum load resistance of the operational amplifier itself is not often included in its passport data. In addition, there is no information about the influence of the value of the resistance R_2 on the frequency properties of the resulting device.

The goal of the study is to develop practical recommendations for choosing the value of the feedback resistor R_2 in the gyrator circuit and to study its influence on the amplitude-frequency characteristic of the device.

Computer simulation in the LTSpice software environment using the LT1006 operational amplifier available in it (Linear Technology, 2007) was chosen as the research method.

1. Modeling Details

Figure 1 shows a schematic of an oscillating circuit with an inductor (Fig. 1 a) and a circuit with a gyrator (Fig. 1 b) based on the LT1006 operational amplifier, whose "inductance" is determined by the circuit elements, together with the operational amplifier, and is equal to the inductance of the circuit's coil.

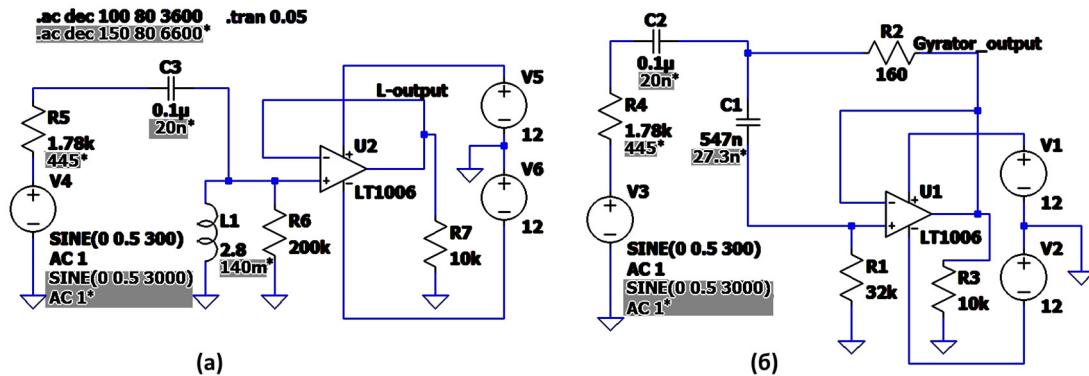


Fig. 1. Schematic of an RLC oscillating circuit with a repeater based on an operational amplifier (output – a "L-output") (a) and a circuit with a gyrator (output – "Gyrator_output") (b). The values of the components without a background correspond to a resonant frequency of approximately 300 Hz, while those with a gray background and an asterisk (*) correspond to – 3 kHz

The resistance of the load resistors (Fig. 1 a and Fig. 1 b) for the LT1006 operational amplifier, as specified in its documentation (Linear Technology, 2007), ranged from 600 Ω to 10 kΩ. A final value of 10 kΩ was selected to eliminate the influence of this parameter.

The circuit with an inductor is loaded by a repeater on the operational amplifier and a resistor connected in parallel to it (Fig. 1 a), which acts as a load resistance even when the operational amplifier's input impedance is very high. Reducing the resistance leads to a decrease in the quality factor of the oscillating circuit, but this changes the results only quantitatively.

The parameters of the gyrator components (Fig. 1 b) were calculated according to the algorithm (Bekh, 2024):

- the resistance of the feedback resistor was selected R_2 ;
- The resistance of the resistor was selected R_1 , such that it satisfies the conditions $R_1 \gg R_2$ (but not more than $200 \cdot R_2$) and $R_1 < 0,1 \cdot R_{BX}$ (where R_{BX} – is the input resistance of the operational amplifier);
- For this resonant frequency f_0 the values of the circuit capacitor C_2 and the capacitor C_1 were selected based on the inductance of the coil L_1 (Fig. 1 a), де – $L_1 = R_1 \cdot R_2 \cdot C_1$, (Fig. 1 b).

The Q-factor of the gyroscope, obtained from the expression (Bekh, 2024):

$$Q = \frac{1}{2} \cdot \sqrt{\frac{R_1}{R_2}},$$

has always been 7,07.

The ranges of parameter variation for the circuit (Fig. 1) elements are listed in Tab. 1. The step size for changing the resistance of the feedback resistor R_2 was 1,5 to 2 times the previous value. This change also determined the values of the parameters R_1 and C_1 . The resonant frequency of the circuit f_0 was 300 Hz in the first stage of the study (the "300 Hz" case in Tab. 1) and 3 kHz in the second stage (the "3 kHz" case in Tab. 1).

During computer simulation using the LTSpice software environment, several frequency response and phase response curves were obtained. They are:

- amplitude-frequency dependences (characteristics) of the transmission coefficient K (in dB) as a function of signal amplitudes (hereinafter referred to as AFCs).
- phase-frequency characteristics, which hereinafter are referred to as phase responses or PFCs or *Phase* (in degrees).

In the frequency response graphs obtained using cursor measurements in LTSpice at the maximum transmission coefficients $K_{0-Gyrator-1}$ and $K_{0-Gyrator-2}$ the resonance frequencies $f_{0-Гіратор-1}$ and $f_{0-Гіратор-2}$, as well as the circuit passbands (at the -3 dB level) were determined; based on these, the Q-factor of the circuit with coils Q_{RLC-1} and Q_{RLC-2} and with gyrators $Q_{Gyrator-1}$ and $Q_{Gyrator-2}$ was calculated. The resistance value of the resistor R_2 was normalized to 1 kΩ to evaluate the relative change in resonant frequencies, the resonant frequency of the circuit with the gyrator was normalized to the frequency of the R5C3L1 oscillating circuit with coils $f_{0-RLC-1}$ and $f_{0-RLC-2}$.

2. Experimental results

Figures 2 and 3 show the frequency response and phase response curves of the circuits under study for the "300 Hz" and "3 kHz" cases, respectively. Noticed that in both cases, the circuit with real inductance (dark solid line) has higher values compared to the same parameter of the circuit with a gyrator (light solid line), while the frequency response behavior of both circuits in the vicinity of the resonant frequency (dotted lines) is similar.

Table 1

Changing the parameters of the RLC oscillating circuit and the gyrator-based circuit for two frequencies

Parameter	Circuit 1 – "300 Hz"		Circuit 2 – "3 kHz"	
Resonant frequency f_0 , Hz (theoretical)	301		3041	
	Minimum	Maximum	Minimum	Maximum
R_1 , kΩ	10	320	8	256
R_2 , Ω	50	1600	40	1280
R_3 , kΩ	10		10	
R_4 , R_5 , kΩ	1,78		0,445	
C_1	5,6 μF	5,47 nF	438 nF	427 pF
C_2 , C_3	0,1 μF		20 nF	
L_1	2,8 H		140 mH	

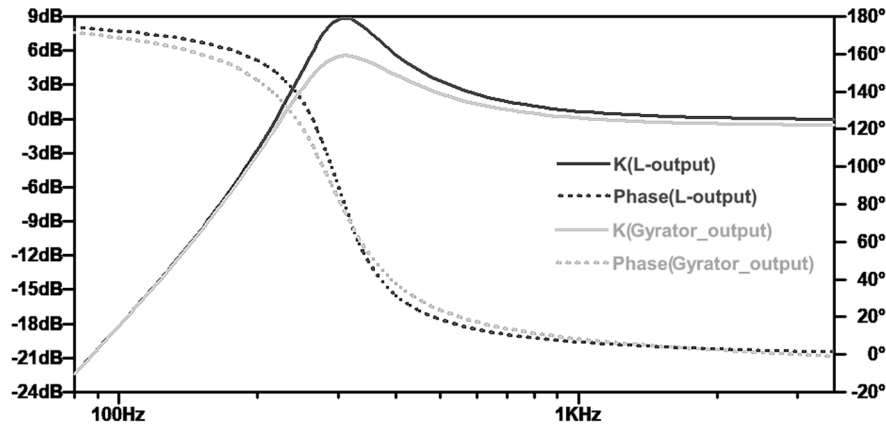


Fig. 2. Amplitude-frequency response (solid lines) and phase responses (dotted lines) plots of an oscillating circuit with an inductor (dark lines) and a circuit with a gyrator (light lines), obtained in LTSpice with a feedback resistor $R_2 = 160 \Omega$ and a resonance frequency of 300 Hz

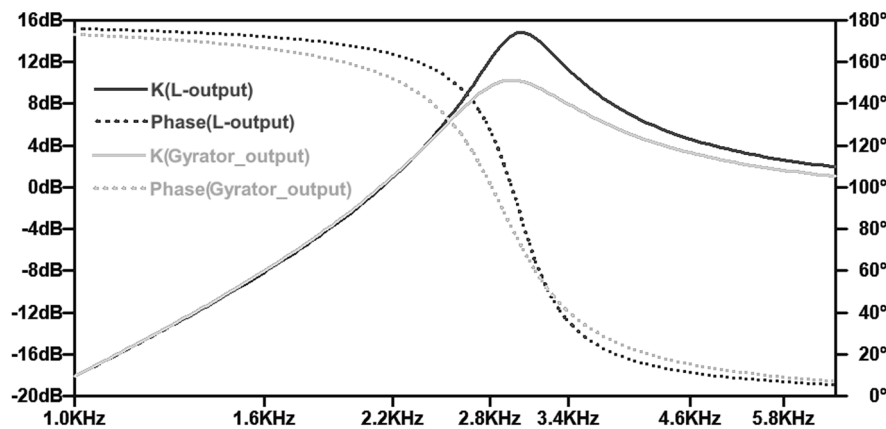


Fig. 3. Amplitude-frequency response (solid lines) and phase responses (dotted lines) plots of an oscillating circuit with an inductor (dark lines) and a circuit with a gyrator (light lines), obtained in LTSpice with a feedback resistor $R_2 = 160 \Omega$ and a resonance frequency of 3 kHz

According to cursor measurements, the resonant frequency of the circuit $R5C3L1$ is $f_{0-RLC-1} = 311,236 \text{ Hz}$ for the "300 Hz" case and $f_{0-RLC-2} = 3041,515 \text{ Hz}$ for the "3 kHz" case.

Figure 4 shows graphs of the relative change in the resonant frequency of a circuit with a gyrator $f_{0-Gyrator-1}$ and $f_{0-Gyrator-2}$ compared to the resonant frequency of a circuit with inductance $f_{0-RLC-1}$ and $f_{0-RLC-2}$ as a function of a resistance of the resistor R_2 for both simulation stages. Measurements showed that the resonant frequency of the circuit with a gyrator $f_{0-Gyrator-1}$ and $f_{0-Gyrator-2}$ can differ from the frequency of the circuit with real inductance in the upward direction up to 12% at resistance of the resistor $R_2 > 300 \Omega$, and the closest values are observed at a resistor resistance of $R_2 = \{200..400\} \Omega$. At a resistance of $R_2 < 100 \Omega$ in the "300 Hz" case, a sharp increase in the resonant frequency of the circuit with the gyrator is observed; at the same time, in the "3 kHz" case at $R_2 < 300 \Omega$, a further decrease in the resonant frequency of the circuit with the gyrator relative to the circuit $R5C3L1$ frequency is observed.

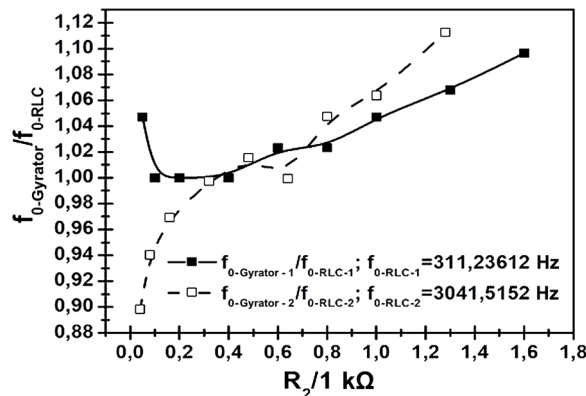


Fig. 4. Graphs showing the relative change in the resonant frequency of a circuit with a gyrator $f_{0-Gyrator-1}$ and $f_{0-Gyrator-2}$ compared to the resonant frequency of a circuit with inductance $f_{0-RLC-1}$ and $f_{0-RLC-2}$ as a function of the resistance of the feedback resistor R_2

Figure 5 shows graphs of the transmission coefficient of the circuit $K_{0-Gyrator-1}$ and $K_{0-Gyrator-2}$ with a gyrator at the resonant frequency as a function of the relative change in the resistance of the feedback resistor R_2 , normalized to the transmission coefficient of the circuit with the coil, which was approximately $K_{0-RLC-1} = 8,908$ dB for the "300 Hz" case and $K_{0-RLC-2} = 14,844$ dB for the "3 kHz" case. Analysis of the graphs showed that for the "300 Hz" case, the maximum transmission coefficient of the circuit with a gyrator is achieved at $R_2 = 400 \Omega$ and does not exceed 0,74 of the transmission coefficient of the circuit with inductance, while for the "3 kHz" case, at $R_2 = 200 \Omega$ it does not exceed 0,7. With a coupling resistance of $R_2 < 100 \Omega$, the transmission coefficient of the circuit with a gyrator decreases rapidly (Fig. 5).

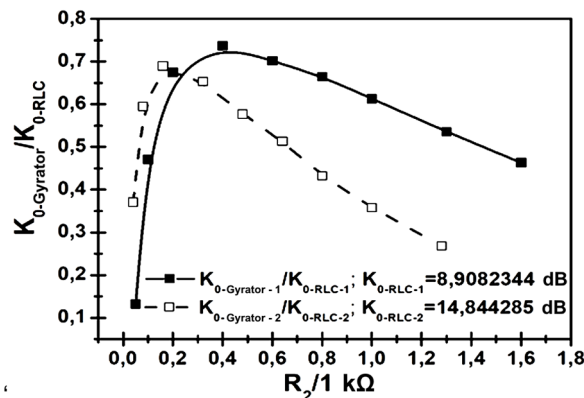


Fig. 5. Graphs showing the dependence of the transmission coefficient $K_{0-Gyrator-1}$ and $K_{0-Gyrator-2}$ on the resonant frequency of the gyrator normalized to the transmission coefficient of the coil-based oscillating circuit relative to the feedback resistor R_2

As is well known, the transmission coefficient of the circuits under study is related to the Q-factor of both the oscillating circuit with a coil and the circuit with a gyrator. Figure 6 shows graphs of the Q-factor of the circuit with a gyrator $Q_{Gyrator-1}$ and $Q_{Gyrator-2}$ normalized to the Q-factor of the RLC circuit with a coil $Q_{RLC-1} = 2,439$ and $Q_{RLC-2} = 5,36$ respectively, as a function of the relative change in the resistance of the feedback resistor R_2 . By comparing the graphs shown in Fig. 5 and Fig. 6, one can see that the dependence of the relative Q-factor of studied circuits with a gyrator mirrors the behavior of the dependence of their transmission coefficients, albeit with slightly lower values.

In conclusion, it can be stated that the optimal resistance of the feedback resistor R_2 should not exceed the output impedance of the operational amplifier. For the circuits studied in this work, at both values of the resonant frequency, a resistance of 300Ω can be considered optimal, i.e., half of the recommended load resistance for the operational amplifier (Linear Technology, 2007).

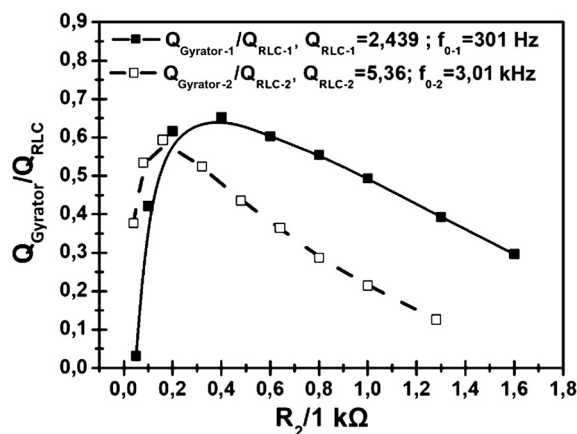


Fig. 6. Graphs showing the dependence of the Q-factor of the circuit with a gyrator ($Q_{Gyrator-1}$ and $Q_{Gyrator-2}$), normalized to the quality factor of the RLC circuit with a coil (Q_{RLC-1} and Q_{RLC-2}), on the relative change in the resistance of the feedback resistor R_2

Discussion and conclusions

To obtain a resonance frequency for a circuit with a gyrator based on the LT1006 operational amplifier that is as close as possible to the resonance frequency of a circuit with an inductor, the resistance of the feedback resistor R_2 , which is part of the gyrator, must be no less than 100Ω , and to ensure a stable gain of the circuit with the oscillator when the resonant frequency changes tenfold, it (R_2) should be approximately half the output impedance of the operational amplifier used (for the LT1006, the resistor R_2 value will be 300Ω). Note that these values depend on the type of operational amplifier, specifically its output resistance, which must be accounted when selecting values of R_2 in practice.

Author's contributions: Ihor Bekh – conceptualization; methodology; development of the theoretical framework; analysis of the results; Roman Bohdanov – analysis of sources; preparation of the literature review; software; collection and verification of empirical data; empirical research and analysis of the results.

Sources of funding. The study was conducted mostly at the authors' own expense. Some financial support was partially provided by Taras Shevchenko National University of Kyiv.

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Отримано редакцією журналу / Received: 27.07.25

Прорецензовано / Revised: 30.03.26

Схвалено до друку / Accepted: 16.04.26

Опубліковано / Published: 05.06.26

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ВПЛИВ ОПОРУ РЕЗИСТОРА ПОЗИТИВНОГО ЗВОРОТНОГО ЗВ'ЯЗКУ НА АМПЛІТУДНО-ЧАСТОТНУ ХАРАКТЕРИСТИКУ ГІРАТОРА НА ОПЕРАЦІЙНОМУ ПІДСИЛЮВАЧІ

Позбутися від використання котушок індуктивності в активних RLC-фільтрах другого та більше порядків можна за допомогою гіратора – RC-комірки, увімкненої в коло позитивного зворотного зв'язку операційного підсилювача. Така схема «активної котушки індуктивності» дає змогу реалізовувати активні фільтри навіть засобами мікроелектроніки.

Метою пропонованого дослідження є розроблення практичних рекомендацій щодо вибору величини опору резистора зворотного зв'язку у схемі гіратора та його впливу на амплітудно-частотну характеристику (АЧХ).

Як метод дослідження було використано комп'ютерне моделювання у програмному застосунку LTSpice, під час якого було порівняно основні характеристики коливального LC-контурів та контуру з гіратором на операційному підсилювачі LT1006 й отримано відповідні амплітудно- та фазово-частотні характеристики.

Показано, що положення максимуму АЧХ контуру з гіратором тим ближче до резонансної частоти RLC контуру, чим опір резистора зв'язку ближчий до вихідного опору операційного підсилювача. Проте він має бути не меншим за 100 Ом, а для забезпечення сталого значення коефіцієнта передачі контуру з гіратором, у разі зміни резонансної частоти у десять разів, має становити близько половини вихідного опору операційного підсилювача, у цьому випадку – 300 Ом.

Ключові слова: активний фільтр, гіратор, зворотний зв'язок, операційний підсилювач, амплітудно-частотна характеристика.

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; in the decision to publish the results.