Design and Experiment of Negative Impedance Converter for Impedance Cancellation of Electromagnetic Moving Coil Geophone

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Abstract. Negative impedance converter is an important theory in circuit design and has been widely used in engineering technology, such as network reactive power compensation, positive impedance elimination, antenna design and so on. Based on the analysis of the circuit principle of a common negative impedance converter, the improved circuit is analysed and simulated. The improved circuit is applied to the impedance design of moving-coil geophone. After experiments with this improved circuit, the expected results have been achieved. The goal of bandwidth expansion has been achieved preliminarily.

1. Introduction

As the particularity of its measuring object, the general geophone is mostly developed basing on the inertial law. And its structural model can be expressed by a mass-spring suspension system, which is actually not a linear system. So, with the mathematical analysis of the model, in order to make the mass move as slightly as possible near the equilibrium position to improve system linearity as well as to expand the bandwidth, we need a feedback damping force, which can be realized by various feedback circuits designing, but using of the negative impedance converter (NIC) is another clever way. In this paper, we analyse the principle of a commonly used negative impedance circuit and the selection of parameters is also discussed. After the simulation verifying the feasibility of this scheme, the circuit we build performance good in the experiment and achieves the design goal of reducing distortion and widening frequency band for the geophone.

2. The principle of NIC and a common realization circuit

Negative impedance converter refers to a two-port network whose electrical characteristics when looked from outside presents as a negative impedance (Fig. 1), as the meanwhile according to the type of input control signal, it can be divided into voltage-controlled impedance converter and current-controlled impedance converter.

Therefore, in another aspect, when it is connected to the circuit, NIC can be regarded as a negative power source to provide energy to the circuit as: a voltage controlled current source or a current controlled voltage source. Individual electronic components rarely exhibit negative impedance characteristics. Commonly active devices such as operational amplifiers are used to form negative impedance networks. A common ideal negative impedance converter circuit is shown below (Fig. 1).

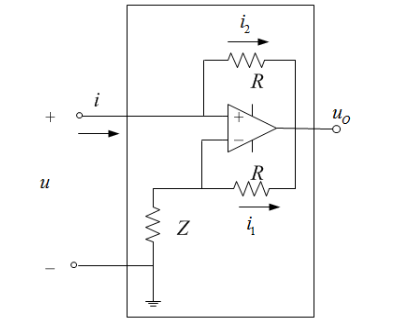

Figure 1. Schematic diagram of a common ideal NIC circuit

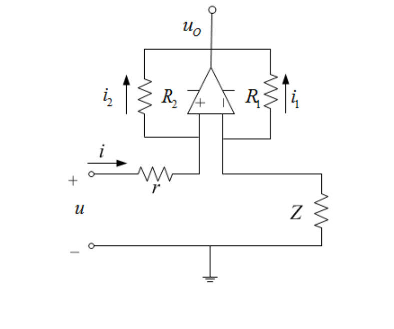

Figure 2. The actual circuit model of such NIC

Circuit analysis based on ideal amplifier conditions: "False Break" and "False Short"

$$\because \ u_+ = u_- = u \ , i_+ = i_- = 0 \tag{1}$$

$$\therefore \ i_1 = i_2 \tag{2}$$

$$\therefore \ i = i_2 = i_1 = -\frac{u}{Z} \tag{3}$$

So in this basic negative impedance circuit, the input impedance is -*Z* which is decided by grounding impedance in Fig. 1. The schematic diagram shows that under ideal conditions, the feedback resistance of positive terminals and negative terminals is symmetrical. However, in the actual circuit construction, it is difficult to achieve the complete symmetry of resistance, then the input impedance of the circuit is -*kZ* with a proportional coefficient *k*, in which *k* equals to the ratio of two resistance values.

3. Stability analysis of NIC

The positive feedback exists in this NIC op-amp circuit. It is necessary to make the positive feedback gain less than the negative feedback gain, so that the whole circuit is a negative feedback system thus to ensure circuit stability. Apart from two approximate symmetrical feedback resistors, the input signal is connected at one end of the two input terminals and the grounding load impedance is connected at the other end, as shown in Figure 2.

According to the operational amplifier principle.

$$u_o = A_V \cdot (u_+ - u_-) \tag{4}$$

The internal resistance of the input signal should be considered.

$$u_+ = \frac{r}{R_2 + r}(u_o - u) + u \tag{5}$$

$$u_- = \frac{R_1}{R_1 + Z} u_o \tag{6}$$

So,

$$u_o = A_V\left(\frac{r}{R_2 + r} u_o - \frac{R_1}{R_1 + Z} u_o + \frac{R_2}{R_2 + r} u\right) \tag{7}$$

In which A_v is the open-loop gain factor of op-amp, generally more than 100db, *R* is the internal resistance of signal source. The feedback block diagram of the circuit can be drawn as shown in Fig. 3.

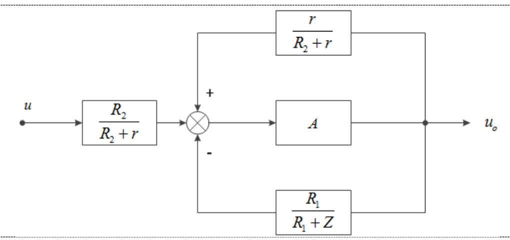

Figure 3. Feedback block diagram of the improved NIC circuit

Obviously positive feedback gain is $\frac{r}{R_2+r}$ and the negative feedback gain is $\frac{R_1}{R_1+Z}$, therefore as long as makes the impedance Z larger than the internal resistance of the input signal, the circuit can ensure stability. Correspondingly, when the input signal is connected to the negative input, the impedance Z should be smaller than the internal resistance of the signal, that is, the load of the negative end should always be greater than the positive end.

4. Application of Internal Resistance Cancellation for Moving Coil Geophone

Moving-coil geophone in constant magnetic field, as the principle of electromagnetic induction, besides exporting voltage proportional to the speed, its motion will also be hindered by the force proportional to the loop current. In order to improve linearity and frequency bandwidth of the geophone, it is hoped that the coil will be in force balance and remain in the centre position. Therefore, the NIC characteristic feeding current controlled by the voltage can be used to apply a damping force to the moving ring proportional to moving speed. Connecting a NIC to the geophone, the geophone can be considered as input voltage signal to the negative impedance circuit, and which is approximately a servo control system taking the coil speed as the object.

5. Analysis of the improved experimental circuit

The NIC circuit used in the experiment is shown in Fig. 4.

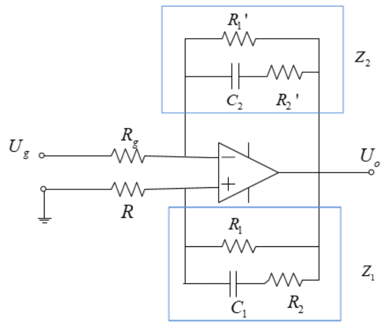

Figure 4. Circuit design schematic of the improved experimental circuit actually used in experiment

Where, U_g is the output voltage of the geophone, R_g is the inner resistance of the geophone, the impedance of the positive feedback path is Z_1, the impedance of the negative feedback path is Z_2, R is the load resistance and R_2 is the capacitive protection resistance. Ideally, the two feedback paths are symmetrical $Z_1 = Z_2 = Z$. The transfer function can be written as

$$\frac{U_O(s)}{U_g(s)} = -\frac{R(s)+Z(s)}{R_g(s)-R(s)} \tag{8}$$

For this circuit the input impedance is -*R*. Amplitude-frequency characteristics are determined by Laplace transform function of impedance *Z*, which can be considered as a system included an inertial part plus a differential part.

$$Z(s) = R_1 \frac{CR_2 s + 1}{(R_1 + R_2)Cs + 1} \tag{9}$$

As the Amplitude-frequency curve shown in Fig. 5, the corner frequency of the system is the corner frequency of the inertial part $\frac{1}{C(R_1 + R_2)}$, in which the capacitance *C* mainly determines the upper cut-off frequency.

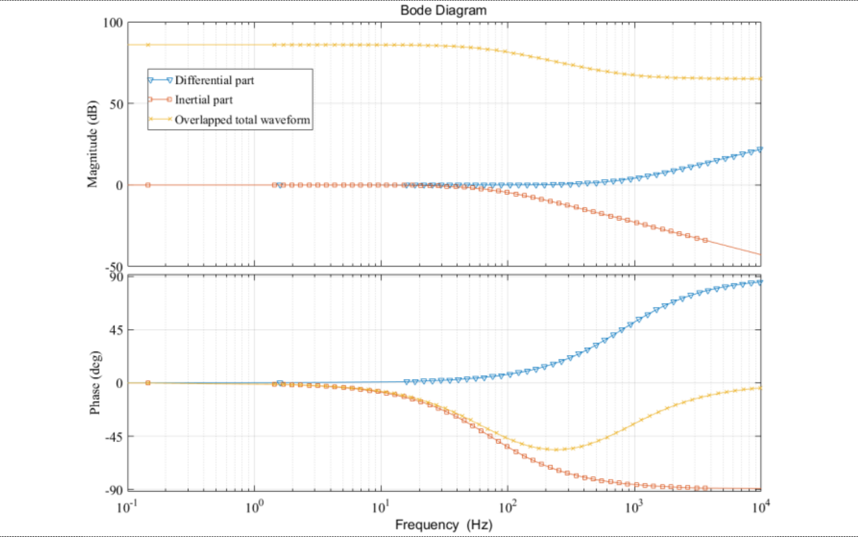

Figure 5. The amplitude-frequency curve of $Z(s)$

The resistance asymmetry in practical circuits is also discussed. The transfer function now is

$$\frac{U_o}{U_g} = \frac{(R_1 + 1)}{(R_1' - R_1)} \frac{R_1'}{R} \cdot \frac{1 + R_1 C/(R_1 + 1)s}{(\frac{1}{R} - \frac{1}{R_g})\frac{R_1' R}{R_1' - R_1}{}_1 Cs + 1} \tag{10}$$

Shows that when R_1' is greater than R_1 the higher cut-off frequency increases, while when R_1' is smaller than R_1, the lower cut-off frequency decreases.

6. Experiments and results

Operational amplifier uses OP07, select component parameters *C*=0.001uf, load resistance *R* part is connected to a ZX25A precision resistance box with resistance range of 0.01-11111.10Ω.

6.1Negative resistance characteristic experiments

A signal generator with an internal resistance of 50Ω in series with a 198Ω (measured value) resistance is used as a signal source outputting sinusoidal signal with RMS of 100 *mV* and frequency of 1Hz. Results have been shown in Table 1, which shows that considering the factors of measurement and calculation errors and environmental disturbance, the negative resistance provided by the NIC circuit is quite accurate.

Table 1. Real negative external resistance of NIC with different resistance values of resistance box

R (Ω)	Loop current (mA)	Theoretical negative resistance (Ω)	Actual negative resistance (Ω)
150	1.0247	150	150.41

100	0.6768	100	100.25
50	0.5069	50	50.722
175	1.3773	175	175.37

6.2Band expansion experiment for geophone

Because we focus on the low frequency band expansion, the function generator outputs frequency sweep driving current signals with the range of 0.4-15Hz through Howland current pump to simulate the ground motion. A SN-4.5Hz geophone whose natural frequency is 4.5Hz and internal resistance is about 400Ω (measured value) is used to connect the build NIC circuit.

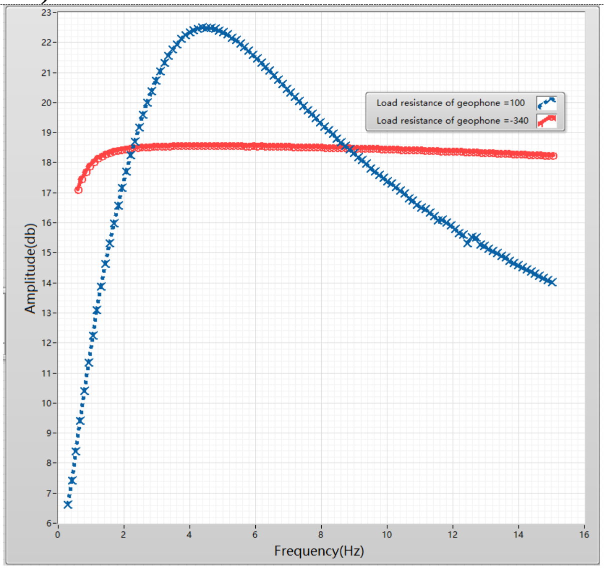

Figure 6. Amplitude curve when geophone connecting with a resistance of 100 (blue). Amplitude curve when geophone connecting with the NIC which equivalent to a resistance of -340 (red)

Comparing with connecting with a resistance of 100Ω, when geophone connect with the NIC equivalent to a resistance of -340Ω, though the sensitivity decrease, its frequency passband low limit extended to 0.58Hz and curve within passband become more flat, as shown in Figure 6.

7. Conclusion

To using of the characteristic of NIC that its output feeding current is controlled by its input voltage linearly, a NIC circuit consisting of an operational amplifier is designed to provide a damping force proportional to the output voltage of the geophone. Based on the analysis of circuit stability and transfer function, the component parameters are determined. Experiment results shows that to extend the frequency bandwidth in this way is reasonable. The expected target is achieved.

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