OPAMP Performance Test of LPC5536

By TIC

1. Introduction to OPAMP

LPC5536 contains three individual instances of the OPAMP module (OPAMP0, OPAMP1, OPAMP2) with the low noise mode and high speed mode. The resistance gains of positive and negative terminals in OPAMP are programable.

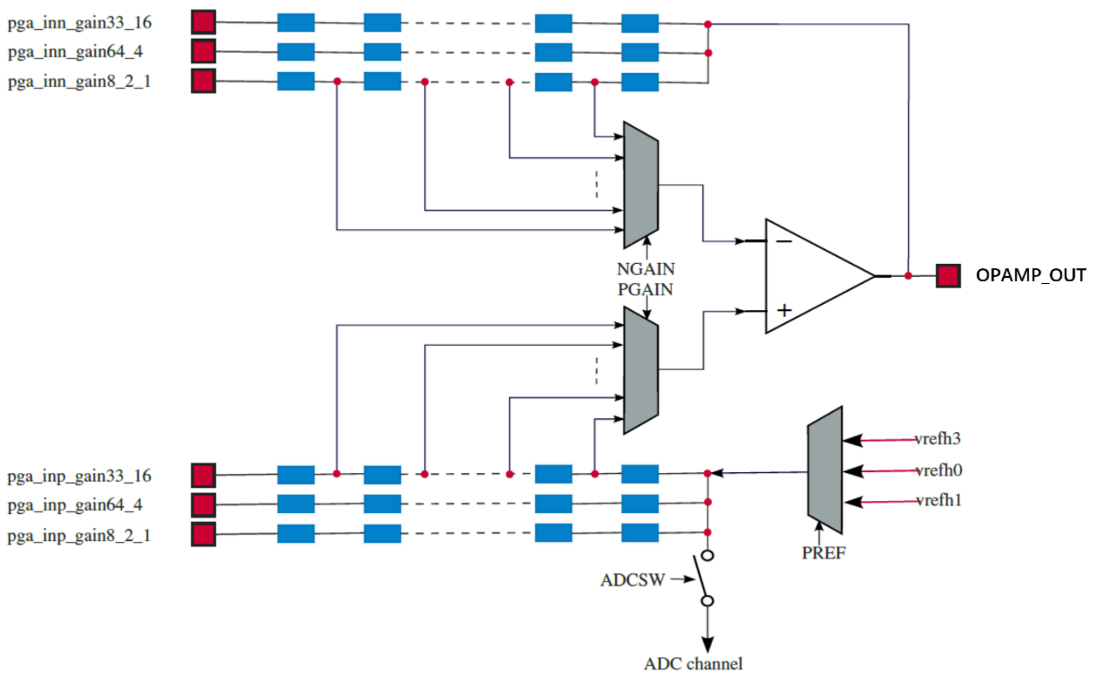

Figure 1. LPC5536-OPAMP block diagram

The LPC5536-OPAMP block diagram is shown in Figure 1. The signal input from positive and negative pins are fed into the amplifier through Internal Resistance Matrix.

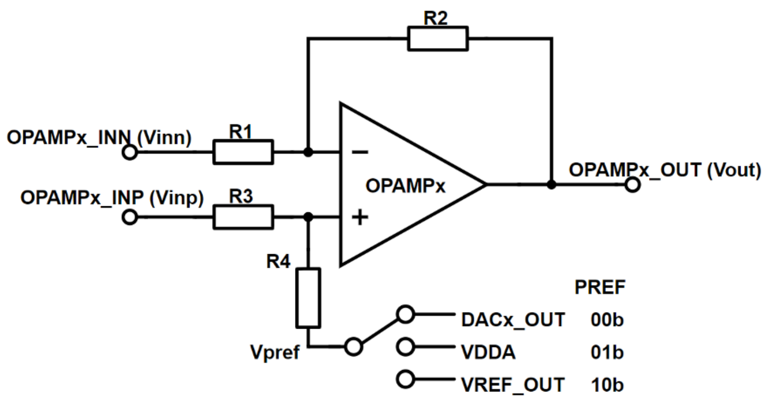

Figure 2. LPC5536-OPAMP equivalent circuit

As shown in Figure 2, Internal Resistance Matrix is equivalent to resistors R1, R2, R3, R4. The programmable gains PGAIN, NGAIN actually represent the resistance ratio of Internal Resistance Matrix.

$$PGAIN = \frac{R4}{R3}, NGAIN = \frac{R2}{R1} \tag{1-1}$$

By setting the value of PGAIN and NGAIN, users can control Internal Resistance Matrix connected to positive and negative terminals of the amplifier so as to amplify in different magnifications. PGAIN and NGAIN options include 1X, 2X, 4X, 8X, 16X, 33X, 64X.

The positive reference voltage options include DACx_OUT, VDDA, and VREF_OUT. PREF in OPAMP_CTR register is used to select the input of the positive reference voltage connection.

- 00b：Connect DAC output to the positive reference voltage (OPAMP0-DAC0, OPAMP1-DAC1, OPAMP2-DAC2)；
- 01b：VDDA；
- 10b：VREF module output VREF_OUT. The output is ranging from 1 to 2.1V.

2. Usage of LPC5536-OPAMP

As shown in Figure2, note that the voltage of output pin OPAMPx_OUT is V_{out}, the voltage of positive and negative input pins OPAMPx_INP0 and OPAMPx_INN are V_{inp} and V_{inn} respectively, and the positive voltage is V_{pref}.

The register setting and board connection are given below in follower, non-inverting, and differential mode. For more information about the usage of OPAMP, refer to the application note: [AN13508] OPAMP Usage on LPC553x/LPC55S3x.

2.1 Follower OPAMP

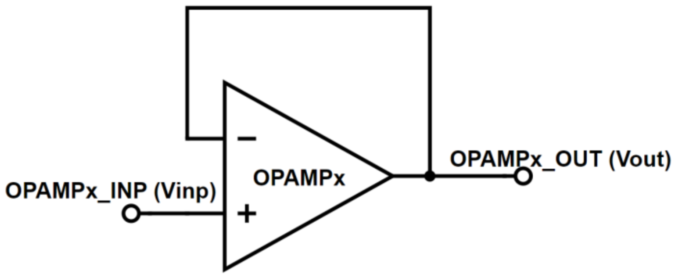

Figure 3. Using OPAMP as follower

To make OPAMP work in Buffer mode, Set register OPAMP_CTR bits [26-24] NGAIN=000b, and thus Internal Resistance Matrix is not connected to negative terminal of OPAMP. Set OPAMP_CRT register bits [18-17] PREF=10b, and disable VREF module (default status). Then, PREF stays in the high impedance state. In this case, the output formula of follower mode is:

$$V_{out} = V_{inp} \quad (2\text{-}1)$$

2.2 Non-inverting OPAMP

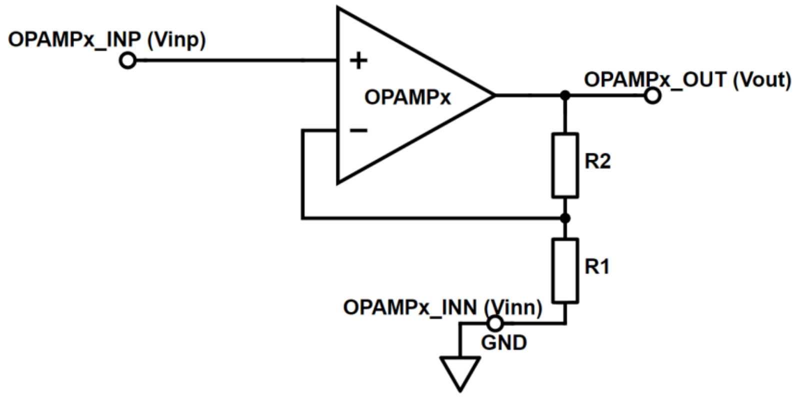

Figure 4. Using OPAMP as non-inverting amplifier

Set register OPAMP_CTR bits [18-17] PREF=10b, and disable VREF module (default status). Then, PREF stays in the high impedance state.Connect negative input to ground, $V_{inn} = 0$, and OPAMP work in non-inverting mode. The output formula of non-inverting mode is:

$$V_{out} = (NGAIN + 1)V_{inp} \tag{2-2}$$

2.3 Differential OPAMP

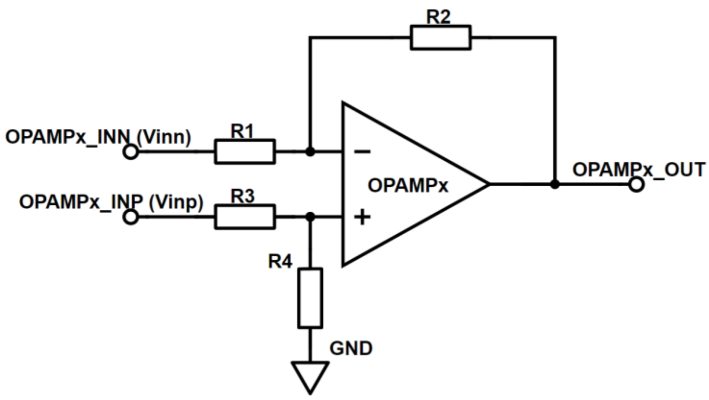

Figure 5. Using OPAMP as differential amplifier

Set register OPAMP_CTR bits [18-17] PREF=01b so as to connect DACx_OUT to the positive reference voltage. Configure DACx to output 0 voltage to make $V_{pref} = 0$. In this case, the output formula of differential mode is:

$$V_{out} = \frac{NGAIN+1}{1+\frac{1}{PGAIN}} V_{inp} - NGAIN * V_{inn} \tag{2-3}$$

When PGAIN=NGAIN, the output formula can be simplified as:

$$V_{out} = PGAIN(V_{inp} - V_{inn}) = NGAIN(V_{inp} - V_{inn}) \tag{2-4}$$

3. Test Preparation of LPC5536-EVK

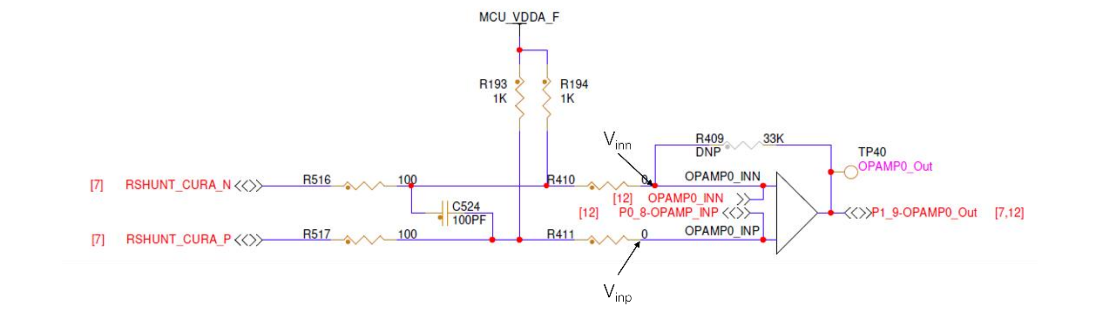

Figure 6. LPC5536-EVK-OPAMP0 schematic diagram

As shown in Figure 6, users can't directly connect the input signal to pins OPAMP0_INN and OPAMP0_INP on LPC5536-EVK. Only through RSHUNT_CURA_P and RSHUNT_CURA_N (J13-1 and J13-3 on EVK) can users input the signal. Because of the current-limiting resistors R516/R517 and the pull-up resistors R193/R194, the actual voltage is different from the voltage of the input signal. **To eliminate this error, we need replace the current-limiting resistors R516/R517 with short circuit and remove the pull-up resistors R193/R194, referring to Figure 7.**

The output of OPAMP0 can be measured at TP40 OPAMP0_OUT in the middle of the board or at J7-AN of the mikroBUS. The position of test point on the board refers to Figure7.

In this test, the positive input and negative input are fed into OPAMP through RSHUNT_CURA_P and RSHUNT_CURA_N, and the ouput of OPMAP is measured at J7-AN of the mikroBUS.

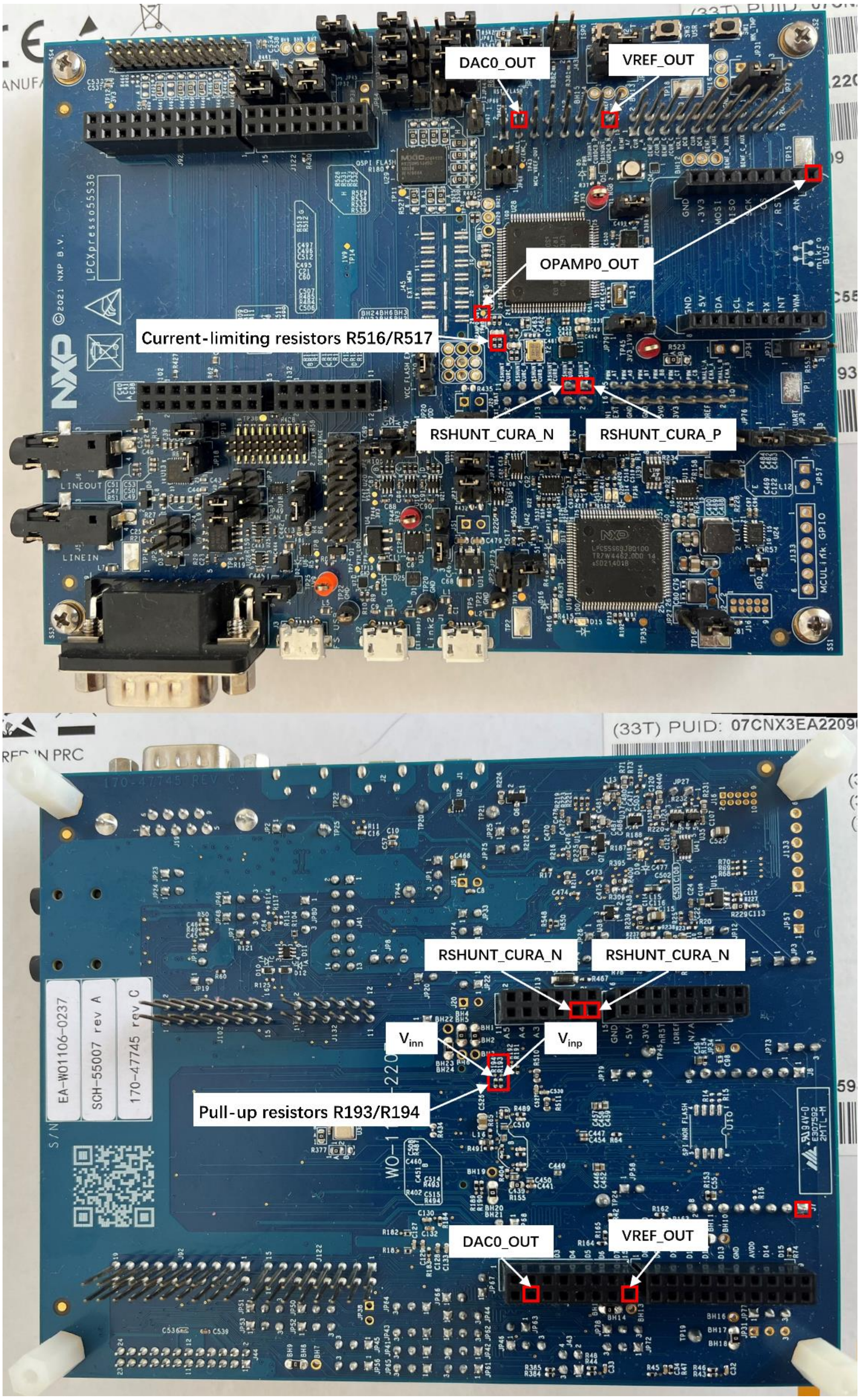

Figure 7. LPC5536-EVK

4. Test Result

In this chapter, we test the follower mode, non-inverting mode and differential mode of OPAMP, and compare the output accuracy of LPC5536-OPAMP in non-inverting mode and differential mode.

Test environment :

- Software：

MCUXpresso 11.6.0

SDK_2_10_2_LPCXpresso5536

- Hardware：

LPCXpresso5536-EVK

Signal Generator HP 33120A

Multimeter

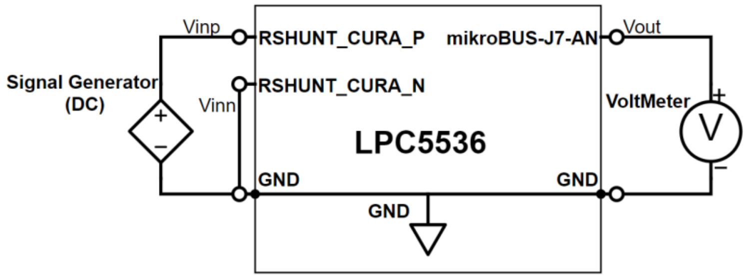

Figure 8. Test board connection

4.1 Follower Test

As described in Section 2.1, configure OPAMP_CTR register and control the positive input. Measure the voltage of the output pin OPAMPx_OUT. Code reference is shown in Figure 9.

```
OPAMP_GetDefaultConfig(&config);
config.posGain = kOPAMP_PosGainNonInvert1X;
config.negGain = kOPAMP_NegGainBufferMode;
config.posRefVoltage = kOPAMP_PosRefVoltVrefh1;//Vrefh0-VDDA Vrefh1-VREFOUT Vrefh3-DAC
config.enable        = true;

OPAMP_Init(DEMO_OPAMP_BASEADDR, &config);
```

OPAMP in Buffer mode by setting NGAIN

Select VREF_OUT as PREF and disable VREF module (default status). Then, Vpref is in the high impedance state.

Figure 9.Configuration code of follower OPAMP

As shown in Figure 10, voltage transmission characteristic shows that LPC5536-OPAMP module has a good performance on voltage following, and the output error is close to 0.

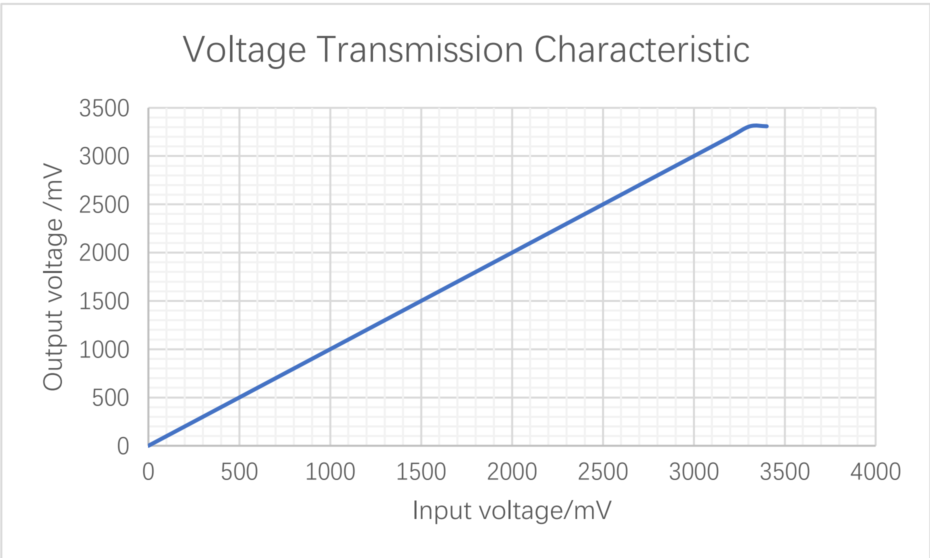

Figure 10. Voltage transmission characteristic of LPC5536-OPAMP follower mode

4.2 Non-inverting Test

As described in Section 2.2, configure register OPAMP_CTR, connect the pin RSHUNT_CURA_N to ground, and change the input voltage through RSHUNT_CURA_P. Measure the output voltage of the pin OPAMPx_OUT when NGAIN is equal to 1X, 4X, 16X, 33X, 64X. According to the non-inverting **Formula (2-2)**, the non-inverting magnification is 2X, 5X, 17X, 34X and 65X respectively. Code reference is shown in Figure 11.

```
OPAMP_GetDefaultConfig(&config);
config.posGain = kOPAMP_PosGainNonInvert1X;
config.negGain = kOPAMP_NegGainInvert1X;
config.posRefVoltage = kOPAMP_PosRefVoltVrefh1;//Vrefh0-VDDA Vrefh1-VREFOUT Vrefh3-DAC
config.enable        = true;

OPAMP_Init(DEMO_OPAMP_BASEADDR, &config);
```

Set NGAIN=1X, 4X, 16X, 33X, 64X

Select VREF_OUT as PREF and disable VREF module (default status). Then, Vpref is in the high impedance state.

Figure 11. Configuration code of non-inverting mode

As shown in Figure 10, MCX OPAMP module has good linearity in working range.

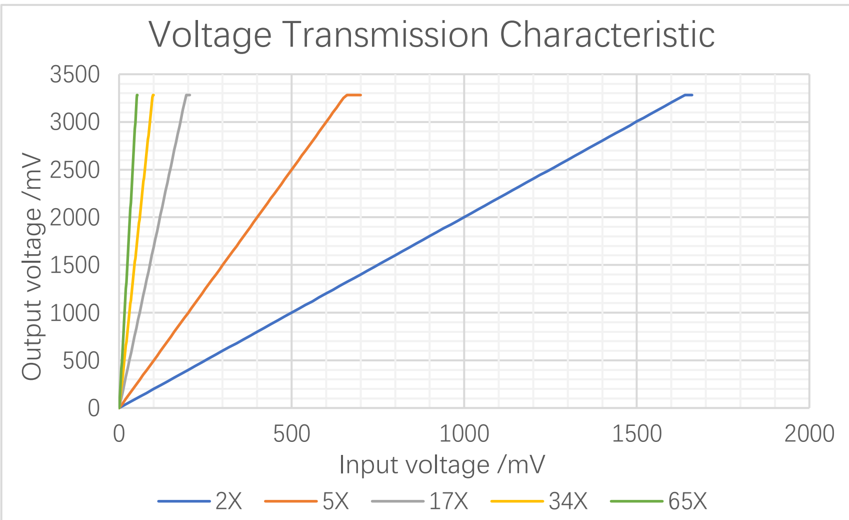

Figure 12. Voltage transmission characteristic of LPC5536-OPAMP non-inverting mode

According to the test data, the OPAMP error is analyzed and calculated in the following.

4.2.1 Error Analysis

According to **Formula (2-2)** in Section 2.2, an ideal OPAMP in non-inverting mode has an output as following.

$$V_{ideal} = (NGAIN + 1)V_{inp} \tag{4-1}$$

However, since there is a very small input offset voltage at the input side, and meanwhile there is a gain error in NGAIN, the real output voltage is

$$V_{real} = (NGAIN + 1 + E_{GAIN})(V_{inp} + V_{io}) \tag{4-2}$$

$$V_{real} = (NGAIN + 1 + E_{GAIN})V_{inp} + (NGAIN + 1 + E_{GAIN})V_{io} \tag{4-3}$$

Suppose the difference between the real output value measured and the calculated ideal value is output error V_{out_error}.

$$\boldsymbol{V_{error} = V_{real} - V_{ideal}} \tag{4-4}$$

The input offset voltage and gain error of Internal Resistance Matrix are two static errors that we are concerned about, which influence the precision of OPAMP output directly. Generally speaking, the input offset voltage can be determined by measuring the zero bias voltage in follower mode. However, because of the voltage limit of pin OPAMP_OUT, the

OPAMP output voltage is always greater than 0, and it is impossible to measure the input offset voltage when it is a negative bias. On the other side, since the input offset voltage is quite small, measuring it directly requires a high precision of measuring equipment.

Here, we estimate the gain error and input offset voltage of OPAMP by fitting straight lines from non-inverting test data.

Suppose input voltage V_{inp} is $\boldsymbol{x^T} = \{x_1, x_2, \ldots, x_i, \ldots, x_n\}$, and the corresponding output voltage measured V_{out_real} is $\boldsymbol{y^T} = \{y_1, y_2, \ldots, y_i, \ldots, y_n\}$. The fitted linear output formula is:

$$y = \hat{k}x + \hat{b} \qquad \mathbf{(4-5)}$$

With the ordinary least squares, get the Parameters to be estimated $\hat{k}, \hat{b}$:

$$\hat{k} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2} \qquad (4-6)$$

$$\hat{b} = \frac{\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i}{n\sum x_i^2 - (\sum x_i)^2} \qquad (4-7)$$

Then, get the gain error to be estimated $\hat{E}_{GAIN}$:

$$\boldsymbol{\hat{E}_{GAIN} = \hat{k} - NGAIN - 1} \qquad \mathbf{(4-8)}$$

Suppose the output offset error is $\hat{E}_0$.

$$\boldsymbol{\hat{E}_0 = \hat{b}} \qquad \mathbf{(4-9)}$$

Then, get the input offset voltage to be estimated.

$$\boldsymbol{\hat{V}_{io} = \frac{\hat{E}_0}{NGAIN + 1 + \hat{E}_{GAIN}}} \qquad \mathbf{(4-10)}$$

As shown in Figure 13, the intercept of the fitted straight line is the output offset error $\hat{E}_0$, and the slope difference between fitted straight line and ideal straight line is the gain error $\hat{E}_{GAIN}$.

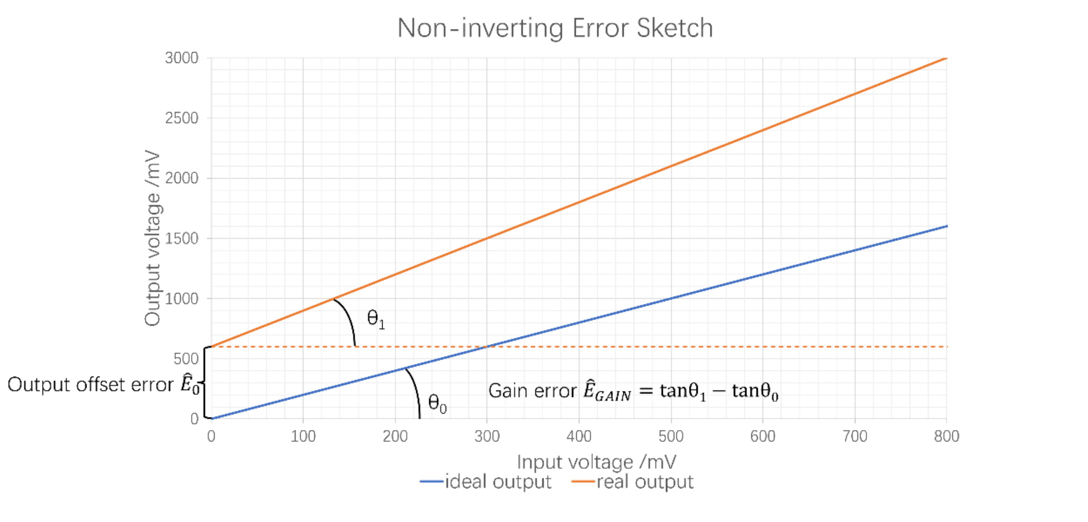

图 13. Non-inverting with gain error and offset error

The formulas for each error are given in this section. Specifically, during testing, we record the input V_{inp}, and the output V_{out_real} for each set of tests, which is noted as $\boldsymbol{x^T}$ and $\boldsymbol{y^T}$. Then, calculate $\hat{k}, \hat{b}$ of the fitted straight line parameters, and finally get the gain error, output offset error, and input offset voltage of OPAMP.

4.2.2 Gain Error and Output Offset Error

Based on **Formula(4-8)**, the gain error of LPC5536-OPAMP under different NGAIN settings are shown in Figure 14. The main factor of gain error is the resistance error of Internal

Resistance Matrix. The diagram indicates that the larger the magnification, the larger the absolute value of the gain error. The largest relative gain error is -0.9% when NGAIN is equal to 64.

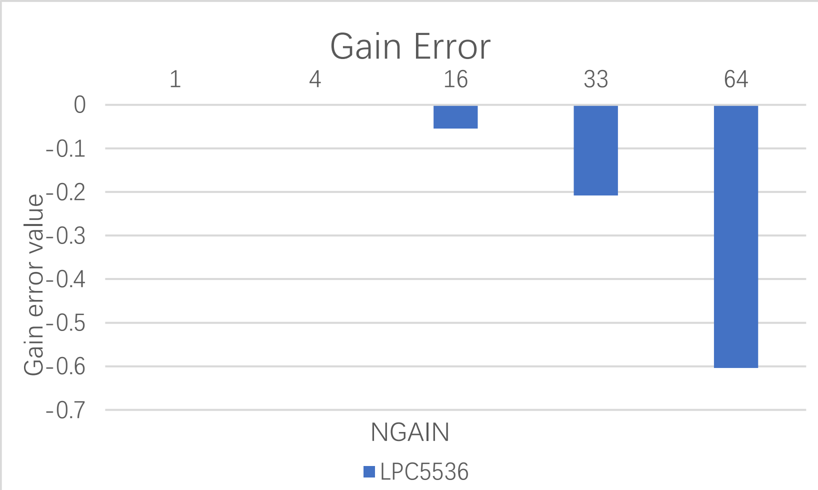

Figure 14. Gain error

According to **Formula (4-9)**, the output offset errors of LPC5536-OPAMP under different NGAIN Settings are calculated and shown in Figure 15. In the non-inverting mode, the input offset voltage of OPAMP is amplified, causing a bigger output offset error. The larger the magnification, the larger the absolute value of the output offset error. The largest output offset error happens in magnification of 65X, which is -37.5mV. According to **Formula (4-10)**, the input offset voltage of LPC5536 is about -0.65mV.

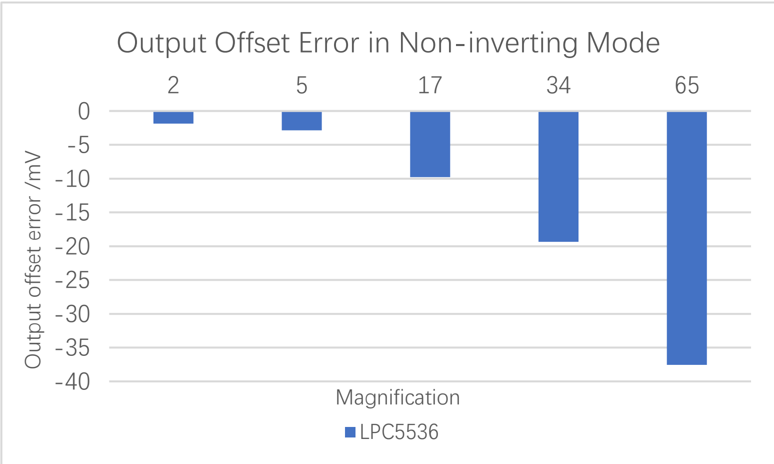

Figure 15. Output offset error

4.2.3 OPAMP Output Error

According to **Formula (4-4)**, the error variation curve of non-inverting is shown in Figure 16. LPC5536-OPAMP has high accuracy at low magnification.When OPAMP works at a large magnification, affected by the input offset voltage, the output error increases a lot. As shown in Figure 16, when NGAIN=64X, which means the magnification of 65X, the output error of LPC5536-OPAMP reaches a maximum of -68mV.

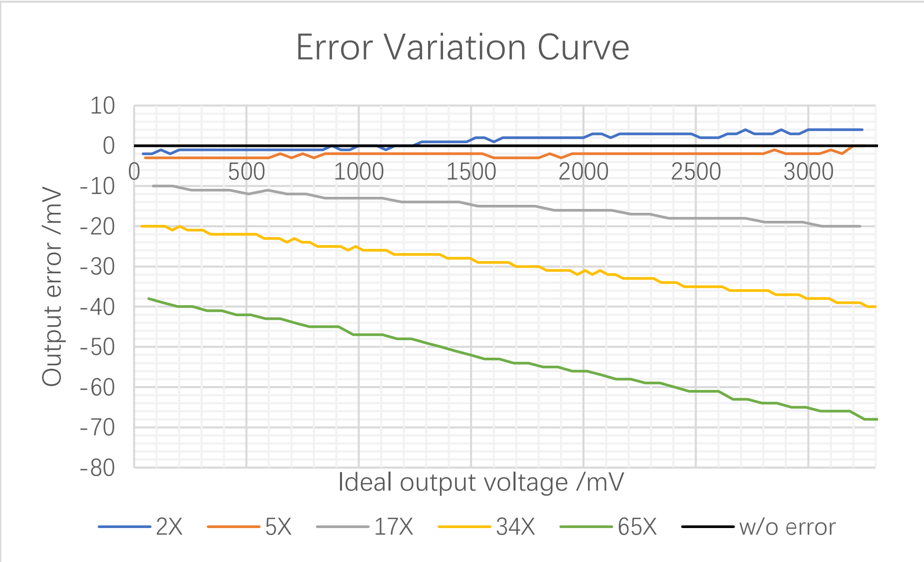

Figure 16. Error variation curve

4.4 Differential Test

As described in Section 2.3, configure register OPAMP_CTR, connect the pin RSHUNT_CURA_N to ground, change the input voltage of the pin RSHUNT_CURA_P, set PGAIN and NGAIN to the same value of 4X, 8X, 16X, 33X, 64X, and then measure the output of the pin OPAMP0_OUT. In this test, $V_{inn} = 0$, according to **Formula (2-3)**, the magnifications of the positive input are 4X, 8X, 16X, 33X, 64X.Code for initializing OPAMP refers to Figure 17.

```
OPAMP_GetDefaultConfig(&config);
config.posGain = kOPAMP_PosGainNonInvert64X;
config.negGain = kOPAMP_NegGainInvert64X;
config.posRefVoltage = kOPAMP_PosRefVoltVrefh0;//Vrefh0-VDDA Vrefh1-VREFOUT Vrefh3-DAC
config.enable        = true;
OPAMP_Init(DEMO_OPAMP_BASEADDR, &config);
```

Set PGAIN=NGAIN=4X, 8X, 16X, 33X, 64X

Select DAC_OUT as PREF

Figure 17. Conifuguration code of differential mode

Code for initializing DAC refers to Figure 18, which make DAC output 0.

```
void DEMO_InitDAC(void)
{
    dac_config_t dacConfig;
    DAC_GetDefaultConfig(&dacConfig);
    dacConfig.referenceVoltageSource = DEMO_DAC_VREF;
    DAC_Init(DEMO_DAC_BASEADDR, &dacConfig);
    DAC_Enable(DEMO_DAC_BASEADDR, true);
    DAC_SetData(DEMO_DAC_BASEADDR, 0);
}
```

Set DAC output 0.
Then Vpref=0.

Figure 18. Conifuguration code of DAC

As shown in Figure 19, MCX-OPAMP has a good linearity in work range.

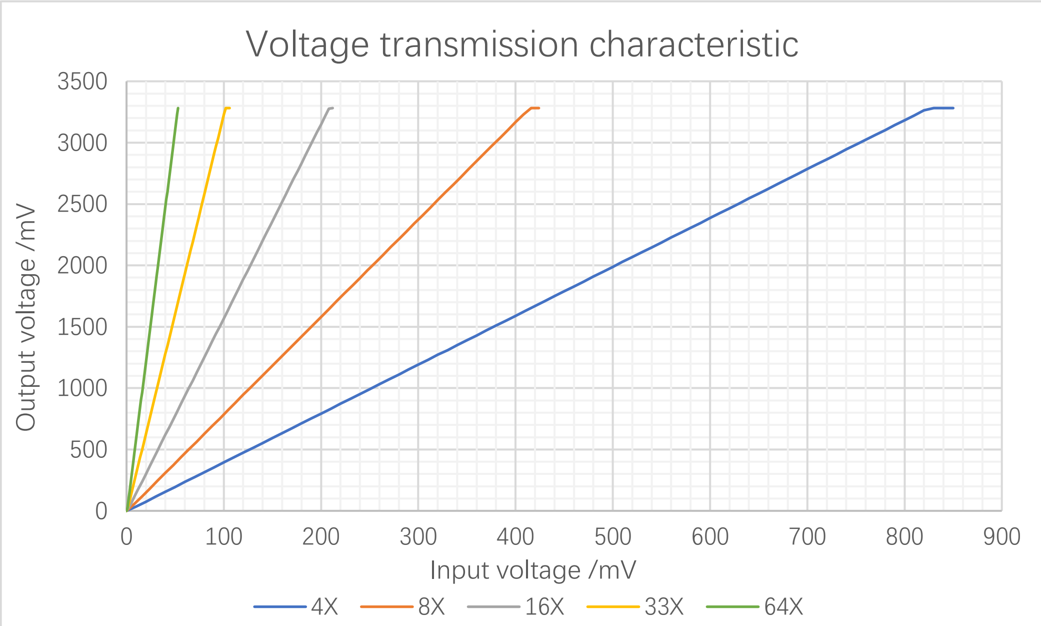

Figure 19. Voltage transmission characteristic of LPC5536-OPAMP differential mode

Figure 20 shows that the output error of LPC5536-OPAMP also increases as the magnification increases in differential mode.

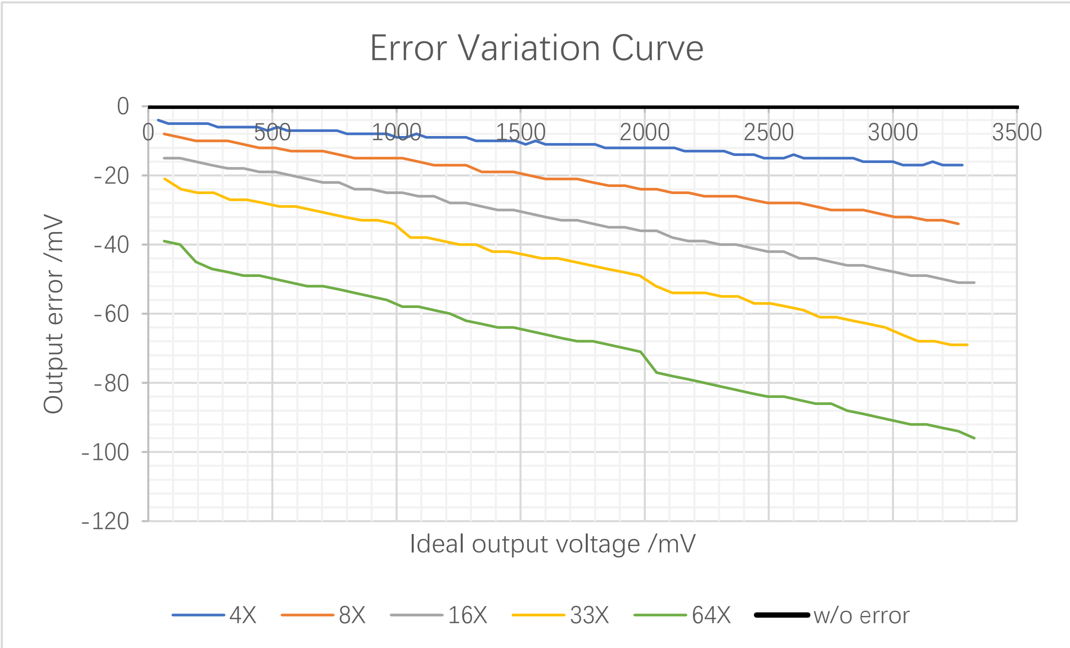

Figure 20. Error variation curve

5. Conclusion

The OPAMP performance test indicates that the precision of LPC5536-OPAMP matches the description in the product data sheet. The gain error is less than 5%, and the input offset voltage is less than 5mV, which can meet the presicion need to a certain extent. It is worth mentioning that the output error of LPC5536-OPAMP is very small at low magnification. For example, the full-range error is just single-digit mV at the magnifications of 2X and 5X in non-inverting mode. For scenarios requiring higher precision, users can connect the external high-precision resistors to achieve higher output precision.

Contents