AUDIO INVERTING AMPLIFIER

The first sketches of this circuit appeared about twenty years ago when I started to develop an all-discrete audio preamplifier. I had a good example of building such things - D. Self's preamplifier described in Wireless World (June 1979). Its basic amplifying stage contained some improvements in comparison with a classic one, as a result, the preamplifier characteristics were notably better than typical at that time.

Mr.Self soon switched over to using the NE5534 op-amplifier whose high performance in audio applications seems unsurpassed even now, twenty years after (I confidently measure its distortion not exceeding 0,0002% in the whole audio range, with a 2V output signal applied to a 2kΩ load).

In the meantime, I was experimenting with my audio inverting amplifier until reaching, in the early 90s, the ultimate both in its characteristics, simplicity and sounding. Just the amplifier's sounding advantageously distinguishes it from the ones built on op-amplifiers. I however didn't mention this feature when describing the configuration as a circuit idea in Electronics World (September 1992), the represented there were only its objective measurement characteristics.

I have comprehensive measurement data obtained both with the help of my VK-1,2 instruments and when simulating the circuit with the Multisim10 software, these data being practically the same that confirms their high reliability. Of course, the audio inverting amplifier deserves detailed ventilation and further I would like to give its analysis.

Employing a minimum of components (4 transistors, 4 resistors and 3 capacitors) this discrete amplifying block has a transparent and rational structure that ensures a very small degradation of the audio signal passing through it. It contains the only one stage of voltage amplification, a cascode on Q1, Q2, while its output stage (the emitter follower Q3 fed with the current source Q4) performs subsequent current amplification (see Fig.1).

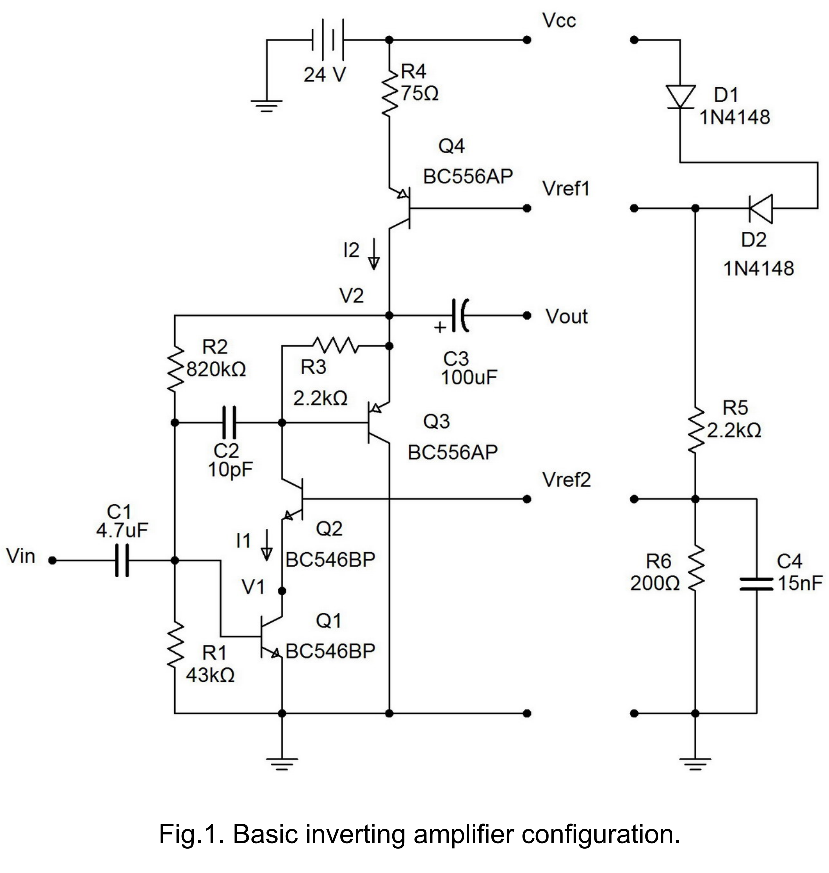


Fig.1. Basic inverting amplifier configuration.

To make the circuit correctly operate when handling the audio AC signals, proper DC conditions must be established. Quiescent currents I_1, I_2 of the input and output stages and DC voltages V_1, V_2 at their critical points (the collector of Q1 and the emitter of Q3) are easily and almost independently set with the help of four resistors (R1-R4) and two reference voltages V_{REF1}, V_{REF2} derived from a simple network (D1, D2, R5, R6). These references can be common for several such amplifying blocks.

Given that in normal operation conditions the emitter-base potential of a transistor lies within 0,6-0,65V, being slightly affected by its collector current, and that the base current is negligible in comparison with the collector current (I_C/I_B=B>200 for BC546, BC556), the main DC relationships for the circuit are fairly straightforward.

With the chosen in Fig.1 resistor values, they yield:

$$I_1 = \frac{V_{BE3}}{R3} = \frac{0,65}{2,2} = 0,3mA \qquad \text{All resistors – in k}\Omega$$

$$I_2 = \frac{2V_D - V_{BE4}}{R4} = \frac{2\times 0,65 - 0,65}{0,075} = 8,7mA$$

$$V_1 = V_{REF2} - V_{BE2} = (V_{CC} - 2V_D)\frac{R6}{R5 + R6} - V_{BE2} = 22,7\frac{0,2}{2,2 + 0,2} - 0,6 = 1,3V$$

$$V_2 = V_{BE1}\frac{R2 + R1}{R1} = 0,6\frac{820 + 43}{43} = 12V$$

The calculated values are close to those of measured, they are optimal for the circuit best AC performance - minimum noise and distortion and maximum slew rate of the output. To reduce limitations in achieving a maximum possible signal swing at this output, V_1 is lowered to 1,3V without any detriment to an audio AC signal at this point because the signals at the collector and the base of Q1 are practically the same and don't exceed some millivolts.

Temperature stability of the chosen quiescent currents and voltages depends mostly on the emitter-base potential of the involved transistors or V_D of diodes. A 1^{o}C rise of temperature causes a 2,1mV decrease of this potential, so for the assumed, say, 20^{o}C temperature variation, the instability of V_{BE} will be 42mV or 7% relative to 0,6V. Such percent drift of the circuit DC conditions is quite tolerable.

To make the circuit work as a linear amplifier with a fixed gain, two additional resistors R_{IN} and R_{FB} should be introduced (see Fig.2). They form the shunt negative feedback which determines the circuit main AC characteristics – its input resistance R_{IN} and closed-loop gain $A = - R_{FB}/R_{IN}$, where " - " means that the amplifier inverts the input signal phase. The chosen in Fig.2 values give R_{IN}= 4,3kΩ and A = - 22/4,3= - 5. The measured DC voltages at all operating points of the circuit are listed in Table 1.

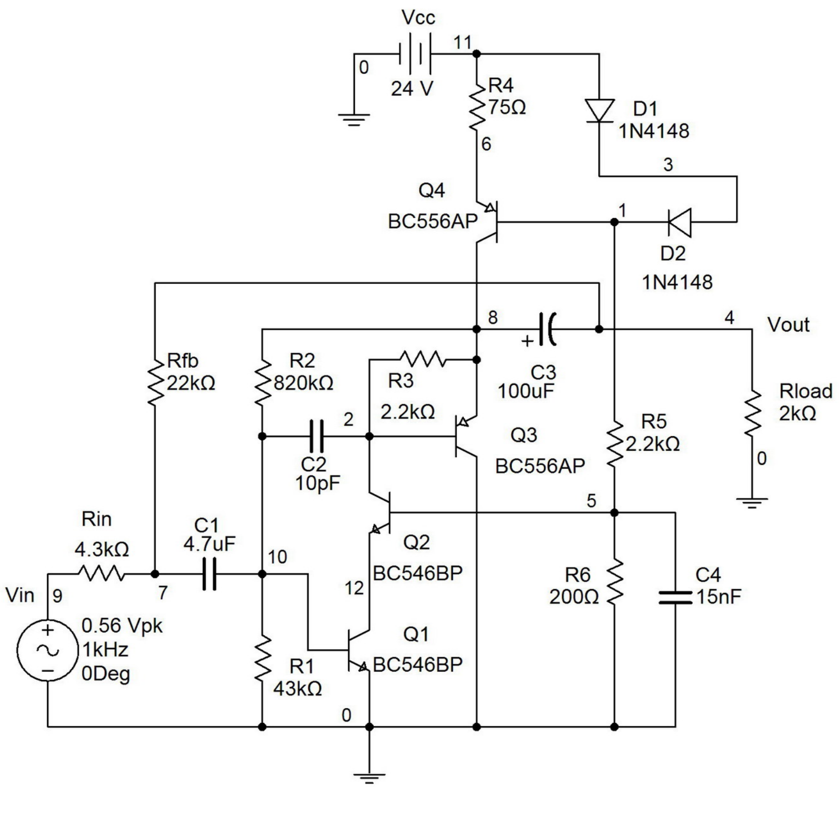


Fig.2. Inverting amplifier with feedback.

DC Operating Point	Voltage (V)
4	0.00000
6	23.35603
2	12.78413
3	23.32658
7	0.00000
11	24.00000
9	0.00000
5	1.88752
8	13.48451
10	0.61179
1	22.65316
12	1.27907

Table 1. DC operating points of the inverting amplifier.

The base of Q1 is the point of comparing the input and output (feedback) signals applied to it via R_{IN} and R_{FB} correspondingly. The resulting AC signal at this point of the so-called virtual earth is very small:

$$V_{IN0} = V_{OUT}/A_0, \quad \text{here } A_0 \text{ - open-loop gain.}$$

This signal doesn't exceed 1-2mV, it modulates the emitter-base potential which is high enough (0,6-0,65V) to cause any notable non-linearity. The explaining that circuit fragment is depicted in Fig.3.

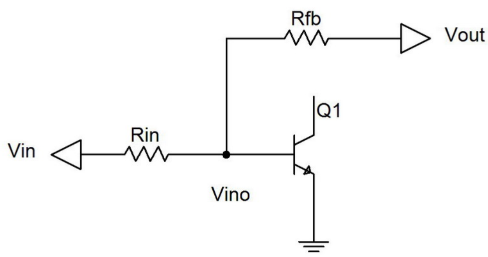


Fig.3. AC equivalent input circuitry of the inverting amplifier.

In a typical differential amplifier with the series negative feedback, the input and feedback signals are applied to different points - to the bases of a long-tail pair Q1, Q2 (see Fig.4).

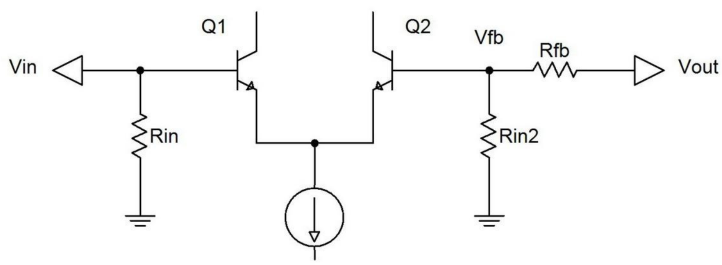


Fig.4. AC equivalent input circuitry of the differential amplifier.

Comparing of these signals isn't here so accurate as in the inverting amplifier and just non-ideal matching of the two emitter-base potentials seems to be responsible for the audio signal degradation. The more sensitive this amplifier, the more serious the signal degradation and more subjectively preferable for its handling appears to be the inverting amplifier which delivers more details of naturalness to the output signal and hence to the sound we hear. This conclusion is rather intuitive because it isn't confirmed by the most sensitive distortion measurements with the help of stationary test signals, it however can be easily confirmed when subjectively testing the inverting and differential amplifiers with the help of our ears.

The two circuits' comparison is most demonstrative when using them in the MM-head preamplifier necessary for vinyl disc reproduction. The signal this preamplifier copes with is small in magnitude (about 5mV) but rich of the so-called “live” content, just what we all dream to enjoy. For clean experiment, all the measurement characteristics of the inverting and differential preamplifiers should be maintained equal (gain, frequency responses) and exemplary (ultra-low distortion and high output slew rate).

After such preparation, the following listening evaluation doesn't require much time to convince everybody in the inverting amplifier's capability to reproduce all that has been recorded - sounds and even silence, both being just “live” sounds and “live” silence, this impression doesn't become less strong in the presence of a slightly higher noise inherent to this preamplifier.

In general, my audio inverting amplifier should be used in all the stages of audio amplification, correction and conversion to ensure the output signal isn't spoiled by any casual circuitry. The only exception may be done for a power amplifier, particularly if using my own VK-5 70W-amplifier. Such stages as preamplifiers with a fixed gain, mixers and tone controls are widely used in audio just in the inverting amplifier topology and here I wasn't so original, building them on my discrete inverting amplifier. To use the circuit in my noise reducer and low-voltage power amplifier was a puzzling task indeed, that required novel design solutions in the realization of low-pass filters and bridged amplifiers.

The amplifier is excellently simulated by the Multisim10 software which offers a powerful set of tools and virtual instruments for all conceivable kinds of circuit analysis. It's reasonable to start testing with the basic inverting configuration, the scheme to be entered to the program is shown in Fig.5.

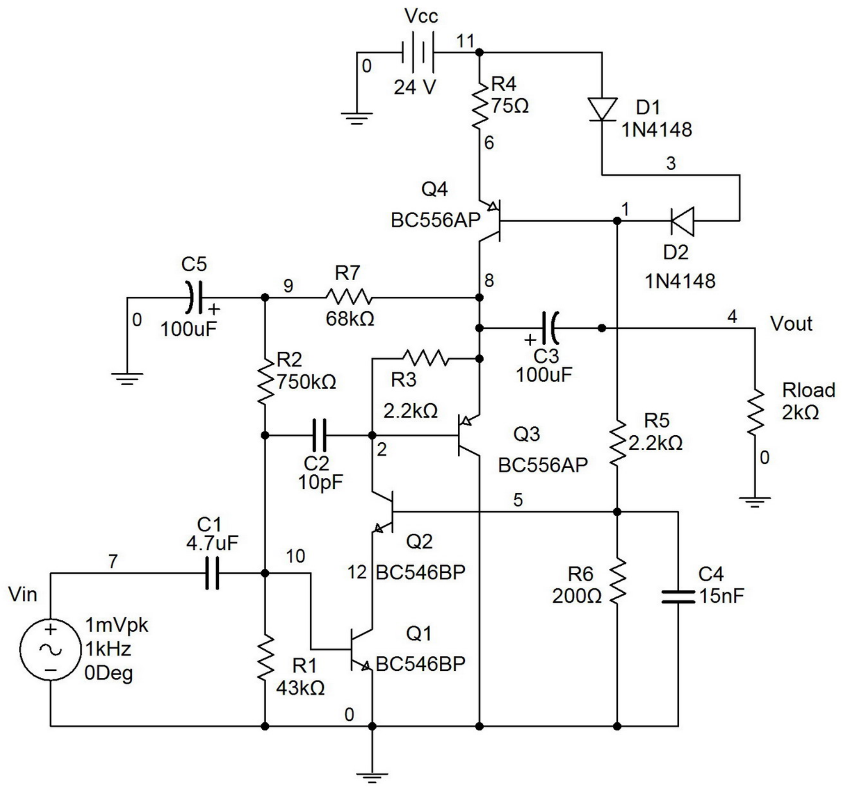


Fig.5. Inverting amplifier without feedback.

Here the biasing resistor to the base of Q1 is split into R2 and R7, their common point being AC grounded via C5 to prevent the AC negative feedback. The main characteristics of the circuit are an open-loop gain A_0 (see Fig.6) and open-loop distortion measured on a 2kΩ load (Fig.7-8).

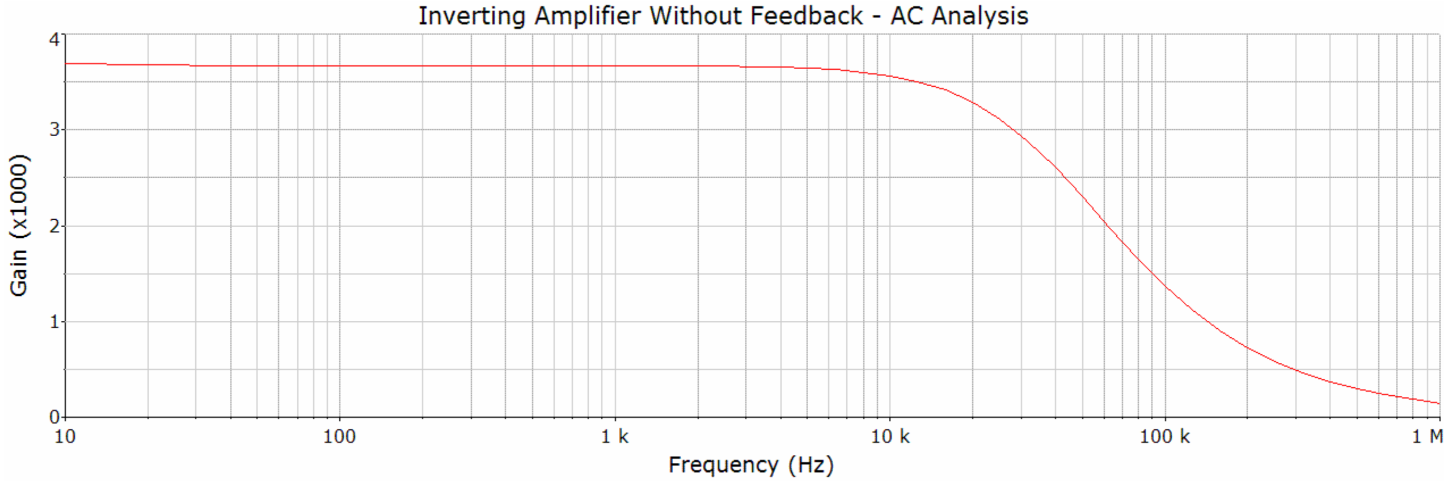


Fig.6. Inverting amplifier open-loop gain.

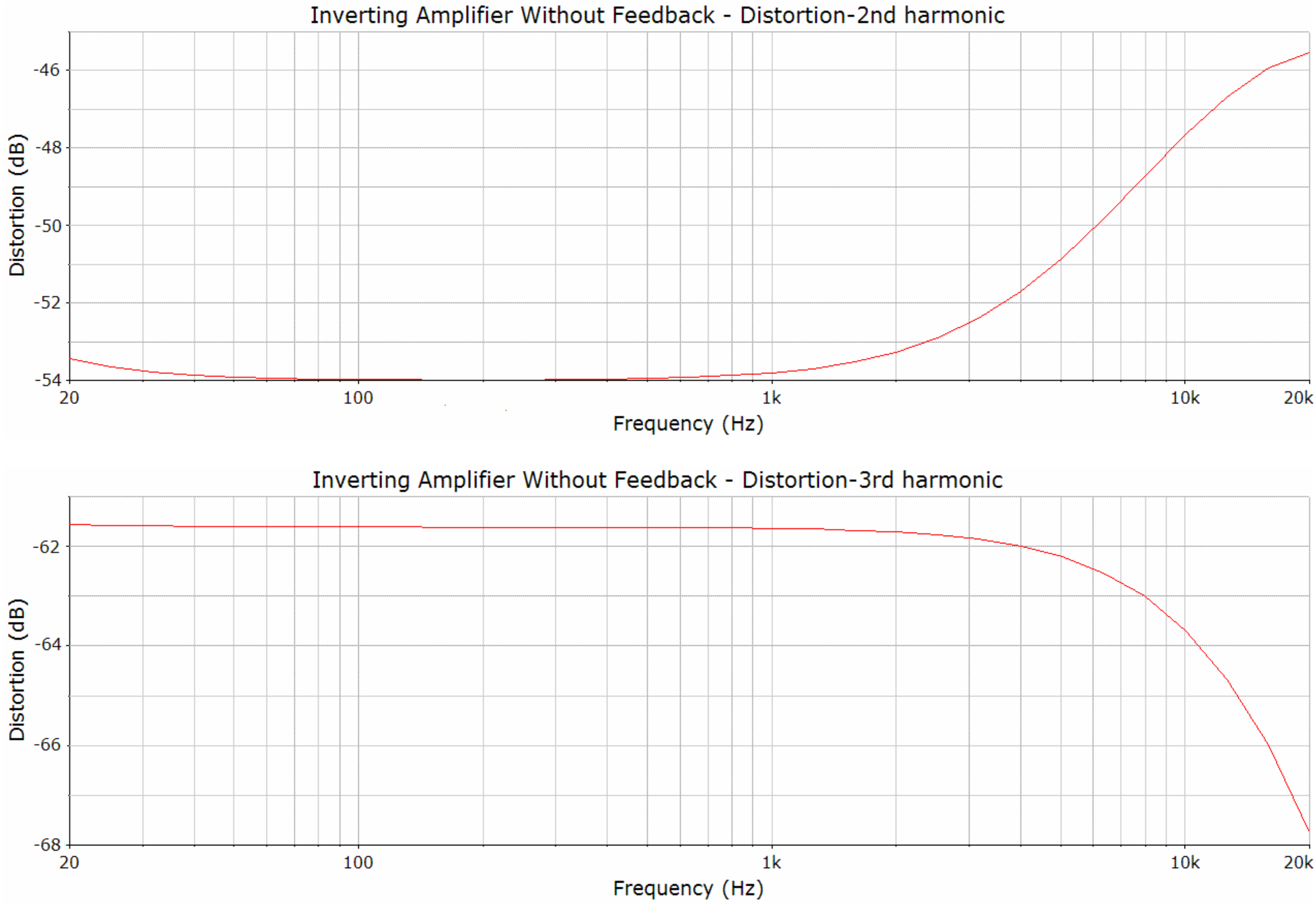


Fig.7-8. Inverting amplifier distortion.

According to the above, the inverting amplifier features an open-loop gain of more than 3000 in the whole audio 20Hz-20kHz range (still 160 at 1MHz), its 2V output signal, applied to a 2kΩ load, has open-loop total harmonic distortion (THD_0) within -(54-46)dB or 0,2-0,5%. This 2V signal is a maximum operational output of the majority of audio preamplifiers and I usually set it when making the circuit analysis. However, the amplifier's headroom allows to produce at its output up to 7V, this signal being on the verge of clipping and having THD of about 1,5%, with the same load.

Testing of the inverting amplifier with feedback is performed on the example of the circuit Fig.2. After entering it to the simulation program, an input signal of 0,4V should be chosen to give the desired 2V output, the set closed-loop gain A= -5 is typical for most audio applications. The obtained amplitude-frequency response is shown in Fig.9. Note that the circuit closed-loop bandwidth extends up to 700kHz (at the level of -3dB) and the amplifier remains absolutely high-frequency

(HF) stable not only in this case, but always and with any amount of the applied negative feedback, the correction capacitor C2=10pF guarantees that.

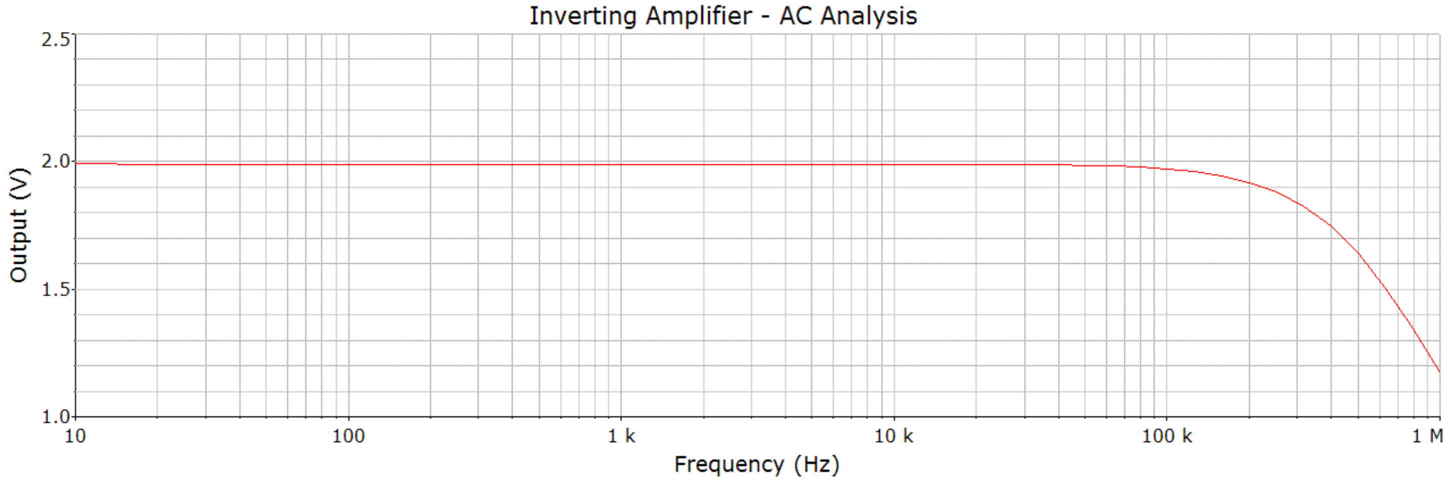
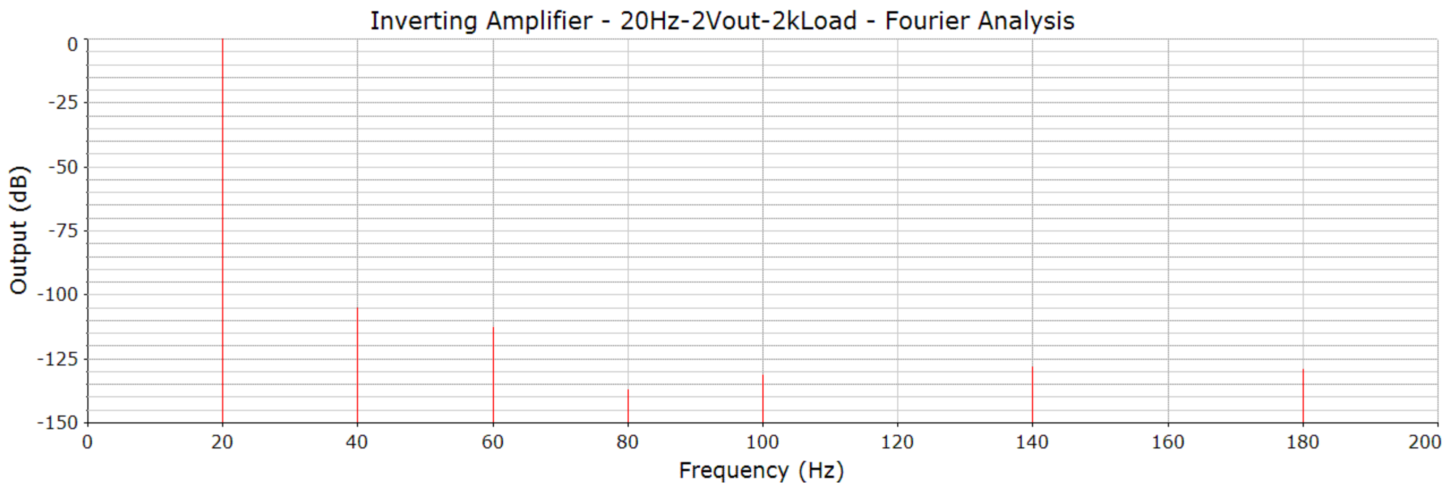


Fig.9. AC analysis of the inverting amplifier with feedback.

The amplifier closed-loop distortion can be obtained from its open-loop distortion by reducing the latter in A_0/A times, this parameter is called the feedback amount and in our case it exceeds 3000/5= 600 in the whole audio frequency range. The calculated closed-loop distortion is:

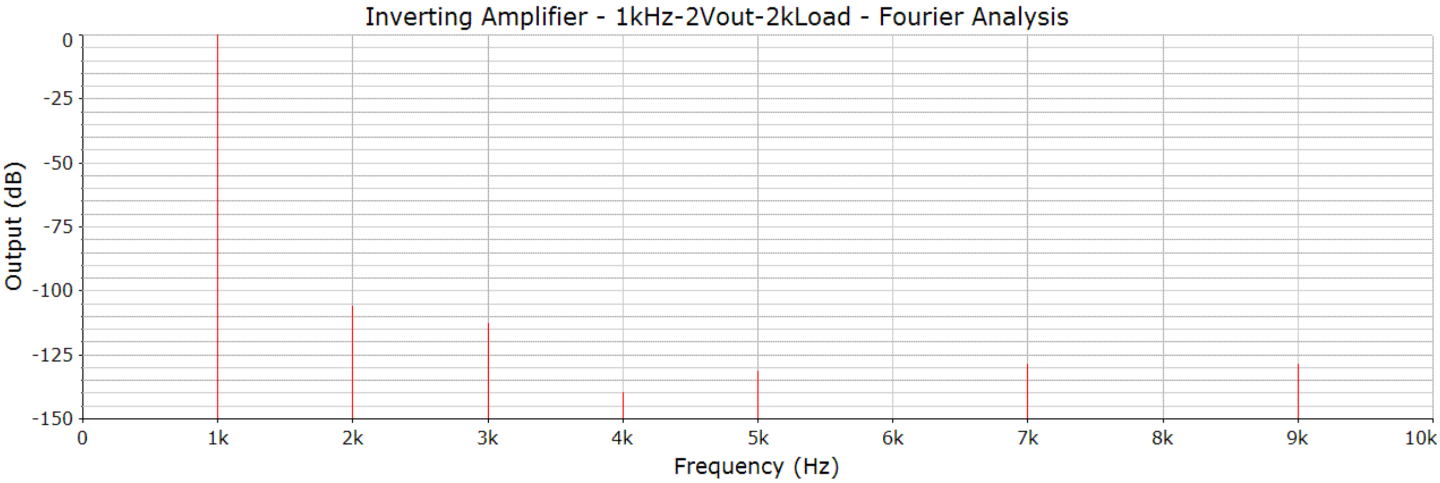
$$THD = THD_0/600 = (0,2\text{-}0,5)/600 = 0,0004\text{-}0,0008\%.$$

To get corresponding experimental data, the simulation program should be run again and it will perform spectrum analysis of the inverting amplifier output at the lowest, mid and highest frequencies of the audio range. The result is produced in two forms (see Fig.10-12).



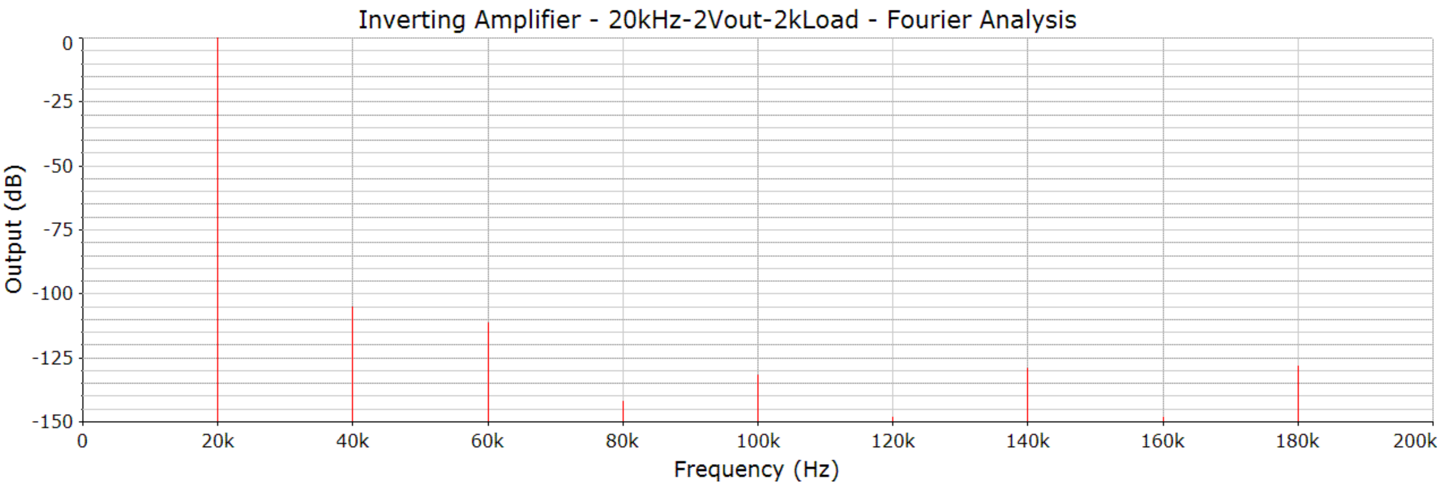
Fourier analysis for V(4)
DC component: 1.52405e-005
No. Harmonics: 9
THD: 0.000589041 %

Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
1	20	2.78536	-178.41	1	0
2	40	1.49377e-005	109.489	5.36295e-006	287.895
3	60	6.57452e-006	179.138	2.36039e-006	357.545
4	80	3.96918e-007	-88.129	1.42502e-007	90.2774
5	100	7.55299e-007	-18.768	2.71168e-007	159.639
6	120	7.29604e-008	-91.379	2.61943e-008	87.0275
7	140	1.04901e-006	-22.936	3.76615e-007	155.471
8	160	7.39985e-008	-85.993	2.6567e-008	92.4131
9	180	9.9344e-007	167.986	3.56666e-007	346.392



Fourier analysis for V(4)
DC component: 0.00164668
No. Harmonics: 9
THD: 0.000561612 %

Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
1	1000	2.78325	179.952	1	0
2	2000	1.41207e-005	92.8367	5.07344e-006	-87.115
3	3000	6.49583e-006	179.5	2.3339e-006	-0.45142
4	4000	2.83698e-007	-84.835	1.0193e-007	-264.79
5	5000	7.52972e-007	-11.578	2.70537e-007	-191.53
6	6000	4.24929e-008	66.3009	1.52673e-008	-113.65
7	7000	1.02167e-006	-15.303	3.67076e-007	-195.25
8	8000	3.79413e-008	75.1607	1.3632e-008	-104.79
9	9000	1.02318e-006	160.334	3.67619e-007	-19.617



Fourier analysis for V(4)
DC component: 5.59006e-005
No. Harmonics: 9
THD: 0.000623027 %

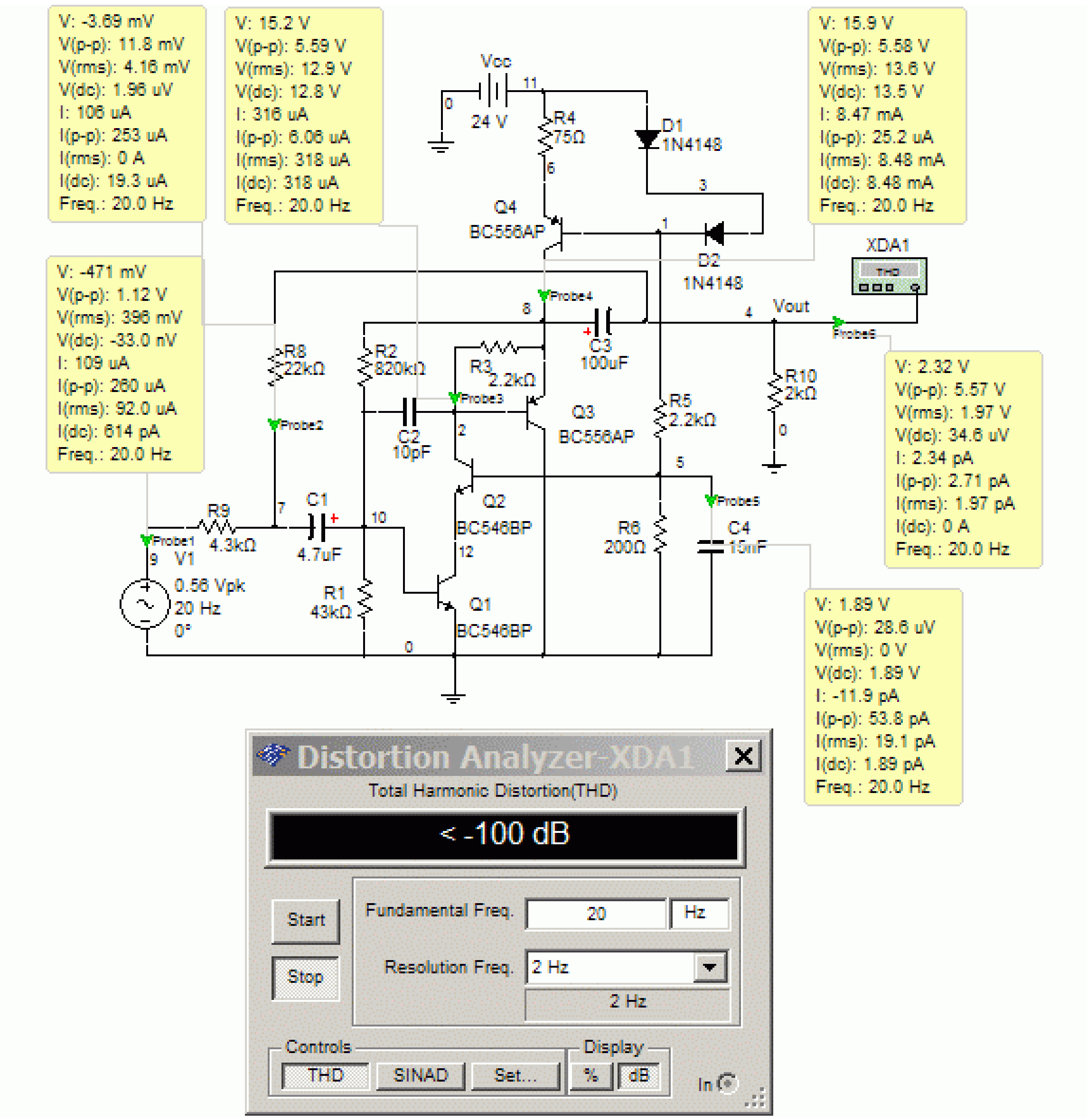
Harmonic	Frequency	Magnitude	Phase	Norm. Mag	Norm. Phase
1	20000	2.78221	178.398	1	0
2	40000	1.55042e-005	153.695	5.57262e-006	-24.702
3	60000	7.57613e-006	-156.61	2.72306e-006	-335.01
4	80000	2.17417e-007	-119.67	7.81455e-008	-298.06
5	100000	7.06811e-007	-5.949	2.54046e-007	-184.35
6	120000	1.08815e-007	98.1637	3.91108e-008	-80.234
7	140000	9.76638e-007	-10.29	3.51029e-007	-188.69
8	160000	1.07373e-007	101.577	3.85927e-008	-76.821
9	180000	1.07863e-006	156.004	3.87688e-007	-22.393

Fig.10-12. Fourier analysis of the inverting amplifier with feedback.

For each frequency, the represented are the first harmonic being the amplifier output signal itself, and the harmonics of numbers from 2 up to 9 being distortion components of the output, their sum is closed-loop total harmonic distortion.

These experimental values lie within 0,0005-0,0008% that corresponds very well to the values calculated above and confirms a remarkable property of the inverting amplifier circuitry - all distortion occurs at the very output (the emitter follower Q3 fed with the current source Q4). The input stage doesn't generate distortion at all, otherwise the presence of this distortion couldn't be effectively reduced by the feedback and would be registered. Fig.10-12 show graphical pictures of the conducted spectrum analysis at the most important frequencies 20Hz, 1kHz and 20kHz.

Screenshots of the interactively simulated amplifier circuit are represented in Fig.13-14. The virtual distortion analyzer monitors the amplifier output, there are also measurement probes placed at some critical points of the circuit and giving detailed time-varying information about characteristics of the simulation process (voltage, current, frequency). The analyzer readings are THD< -100dB at both test frequencies 20Hz and 20kHz, that confirms the results of the circuit Fourier analysis.



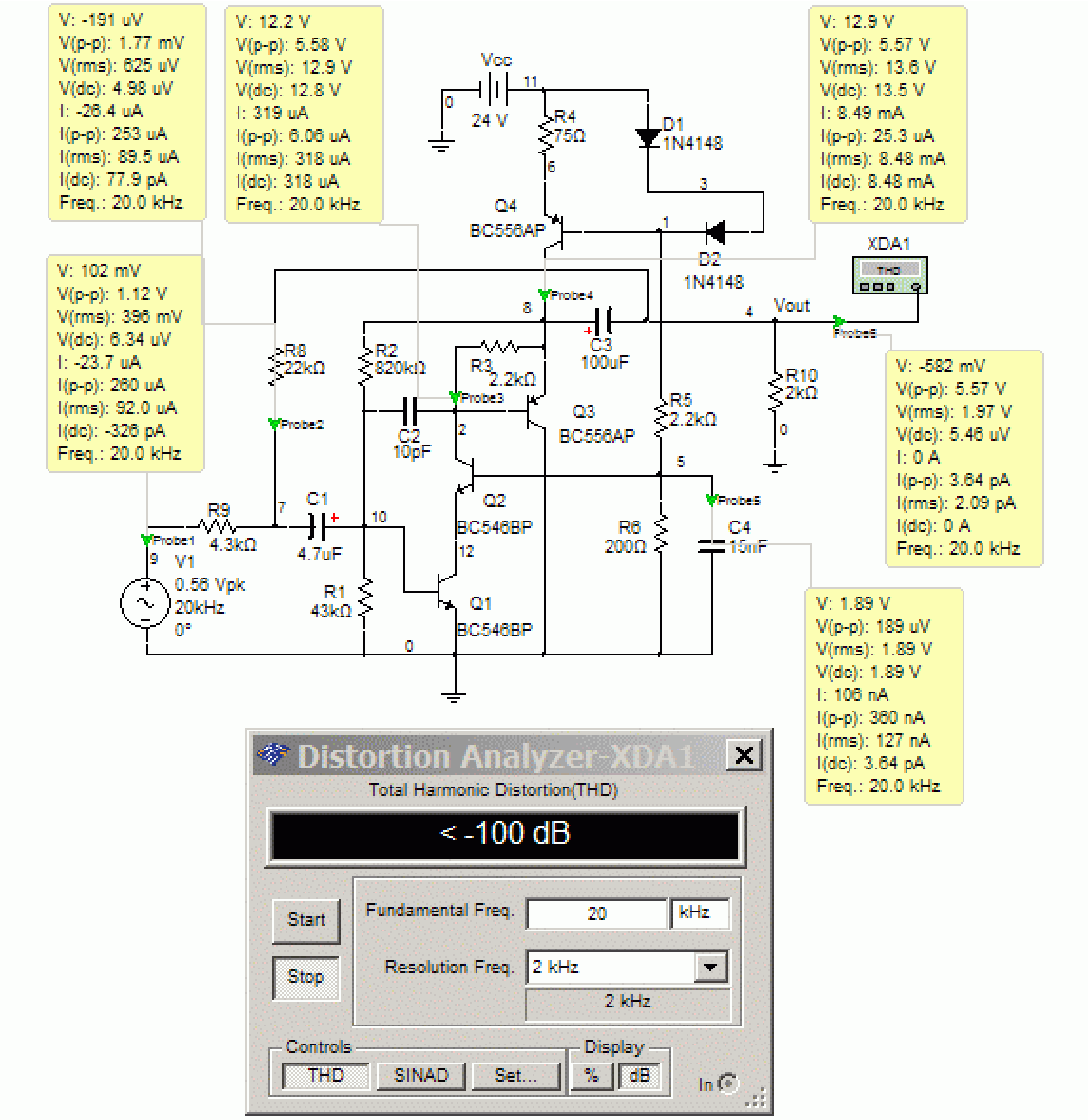


Fig.13-14. Simulation of the inverting amplifier circuit at 20Hz and 20kHz.

Recently, I've developed the unprecedented in its reliability and accuracy method of measuring distortion with the help of my virtual VK-2 distortion meter which can perform the fully transparent interactive distortion measurements of fantastic sensitivity - below -170dB (0.0000003%) within 20Hz-20kHz, the automatic process of -175dB suppression of the fundamental frequency taking less than 3sec.

On the virtual oscilloscope screen you can see the extracted "live" distortion harmonics of an amplifier or oscillator whose circuit is entered to the simulation program which contains already the VK-2 distortion meter circuit. Amplified by +80dB the exact RMS sum of these harmonics is measured confidently because it is free of any swamping noise and any added distortion being unavoidable in real distortion or spectrum analysis. The Multisim oscillator and the VK-2 virtual meter don't create distortion and noise by definition, this trick allows to investigate the linearity just of the device under test with the help of the classic, most right method - by removing the fundamental frequency from the analyzed signal. The accuracy of measuring the residual distortion harmonics can be easily verified by applying their calibrated amounts, say -120dB, to the meter's input and analyzing its output, this accuracy being better than 0.5dB at all audio frequencies.

The test scheme of Fig.15 contains the inverting amplifier with a gain of -5, it is fed from the Multisim 10 non-distorting generator and its 2V-16kHz output drives a 2.2kohm load. This voltage is then normalized at 1V level and applied to the input of the active rejection filter block consisting of an input twin-T notch network, a high-performance discrete amplifier (K=100), a 100kHz low-pass filter and at last the system of fine automatic tuning of the rejection filter, its Q-factor is chosen Q=2 and it carries out more than -170dB suppression of the fundamental frequency within 20Hz-20kHz. The following then output amplifier (K=100) brings the total gain of the residuals to +80dB for measuring them by an ordinary

RMS voltmeter, observing on the virtual oscilloscope screen and using them in the filter tuning.

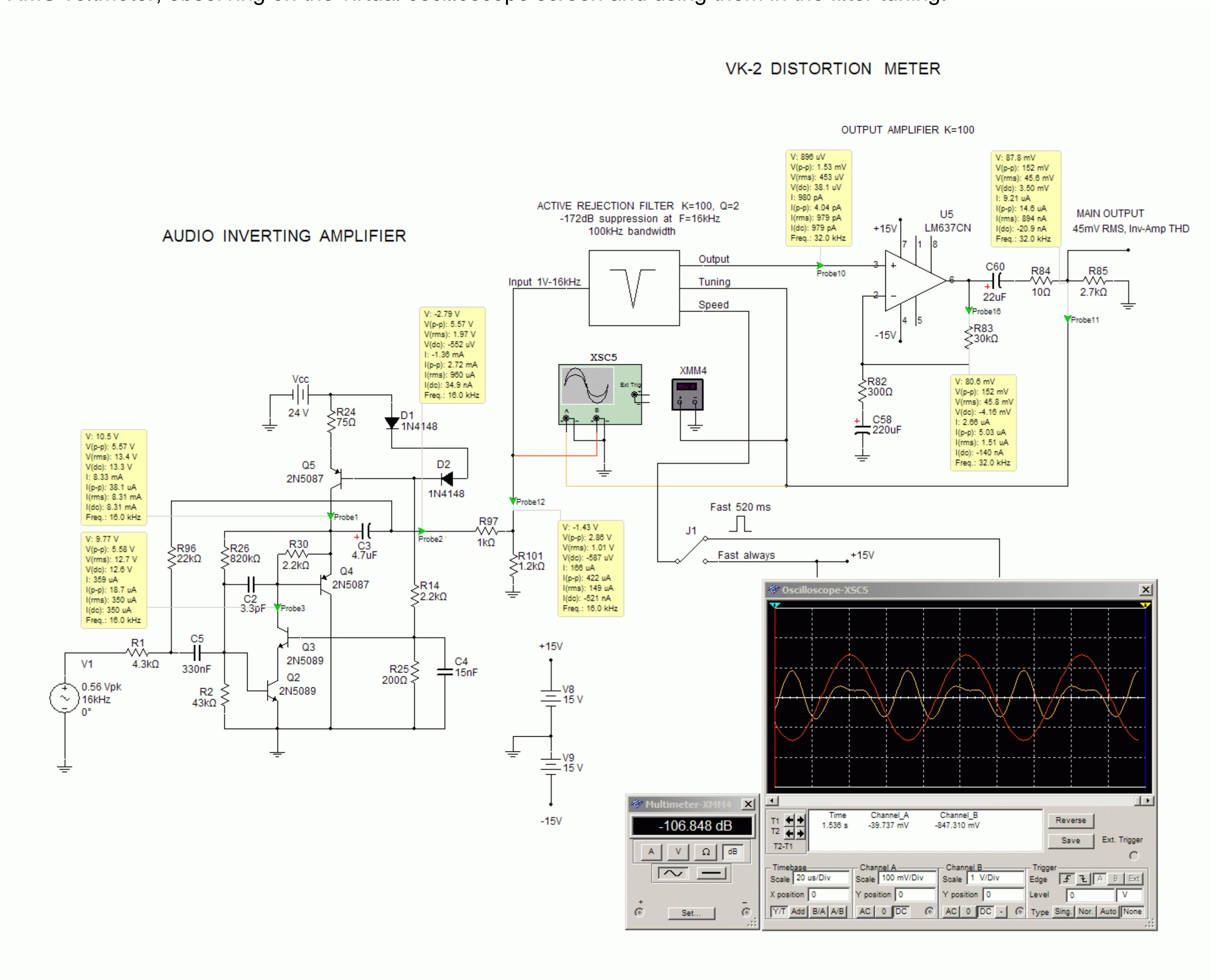


Fig.15. VK-2 distortion measurement of the inverting amplifier at 16kHz.

The whole process of measuring distortion takes 1.54sec, its result appears at the VK-2 meter output, and the measured distortion is shown on the screen and registered by an AC millivoltmeter, its RMS value being in this case 45mV/10000=4.5μV or -107dB relative to the 1V input. As can be seen, this distortion is mainly the second harmonic.

The similar procedure was conducted and for a 1kHz test frequency, the obtained in 1.94sec RMS value of extracted distortion is 42mV/10000=4.2μV or -108dB relative to the 1V input, it appears to be the second 2kHz harmonic (see Fig.16). The described measurement method is transparent and very accurate, the above distortion figures are absolutely reliable and they are close to the results of Fourier analysis performed earlier (see Fig.10-12).

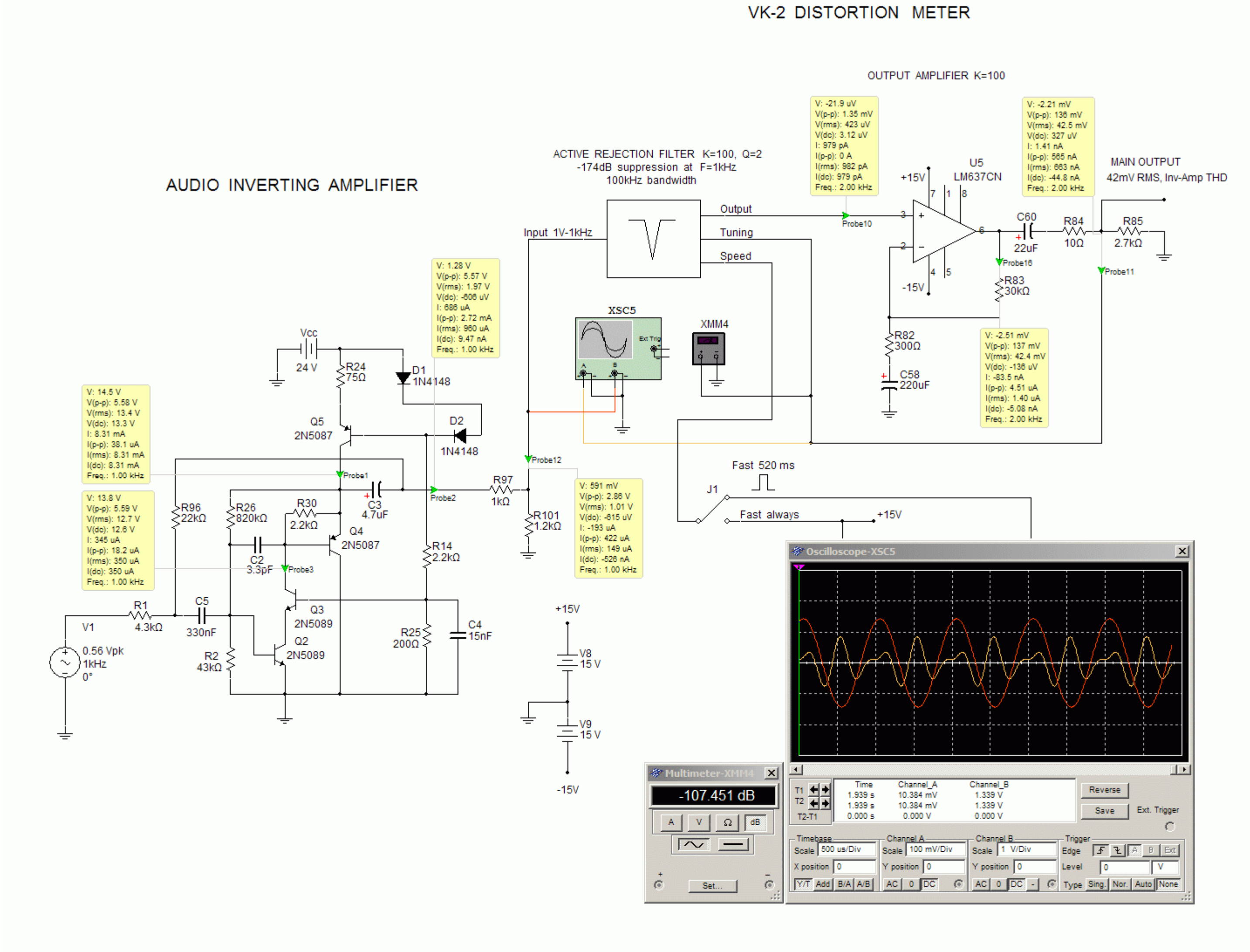


Fig.16. VK-2 distortion measurement of the inverting amplifier at 1kHz.

Virtual testing of the amplifier circuit Fig.2 is concluded by its transient analysis, the resulting 10V-100kHz square-wave output is depicted in Fig.17. It can be easily seen that slew-rate of this output is 20V/μsec.

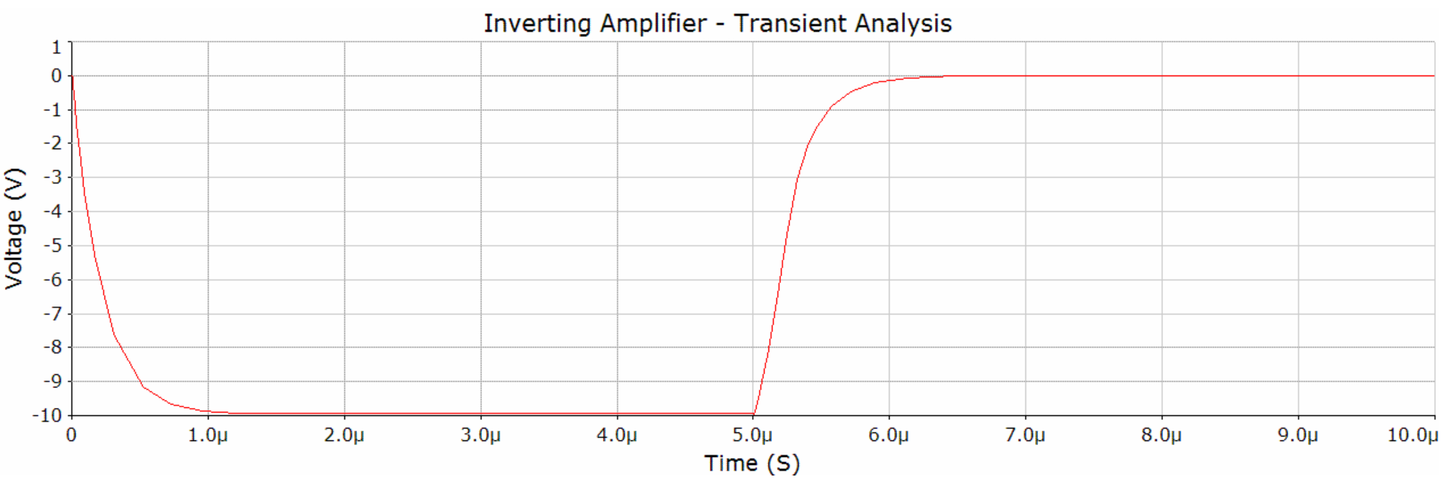


Fig.17. Transient analysis of the inverting amplifier with feedback.

Noise performance of the inverting amplifier might be close to the ultimate if it depended only on its input transistor Q1 (see Fig.1). Indeed, this single transistor works in very auspicious conditions: the grounded emitter, low collector voltage and an optimum collector current, all that ensures extremely low unweighted input noise generated by this transistor - 280nV over the audio 20Hz-20kHz bandwidth.

Moreover, in some special applications, for example in a MC-cartridge preamplifier, the input transistor is represented as the parallel connection of four identical devices to reduce the transistor's base resistance and achieve an unbelievable signal-to-noise ratio of -141dB, the output signal being 0.775mV RMS.

However, in most widespread applications of the inverting amplifier, the main source of noise is the passive circuitry preceding the base of the input transistor and performing various functions, setting the closed-loop gain for example. Thermal noise of the resistor R_{IN}= 4,3kΩ (see Fig.2), calculated according to the Johnson-Nyquist formula

$V_{NOISE} = \sqrt{4kTR\Delta F}$, is 1,17μV over a 20kHz bandwidth, i.e. 4 times higher than 0,28μV contributed by the input transistor Q1. The less the value of resistor R_{IN}, the less the noise it produces, but this also leads to reducing the amplifier input impedance which, on the contrary, should be maintained as high as possible. Finding a compromise between low noise and high input impedance is therefore a problem inherent to the inverting amplifier, but it seems to be the only its weak point.

Concrete audio applications of the inverting amplifier are the subjects of separate articles, most of these applications are concentrated in my VK-6-LiveSound audio system which produces the distortionless sound of unprecedented clarity and naturalness. Here I make only the circuit presentation, so everyone can try to use it at own discretion.

I have explored so far the circuit as a complete all-sufficient amplifying block whose main feature is class-A operation on its output and hence very low produced distortion, all this in combination with its ability of live sound reproduction. But the output linearity can be further considerably improved by using the inverting amplifier as a part of the operational amplifier in which the added input differential stage increases an open-loop gain and widens the amplifier's functionality, the subjective audio characteristics not being considered here of prime importance. Such a discrete amplifier was designed for special ultra-low distortion applications in my VK-1 audio oscillator and VK-2 distortion meter and there it delivers a 2V output into a 300Ω load with less than 0,00003% distortion in the whole 20Hz-20kHz frequency range.

And at last, about subjective evaluation of the audio equipment built on the inverting amplifier circuitry.
Most impressive is of course direct evaluation of the sound obtained from an ordinary vinyl disc. The circuitry used in the MC- or MM-cartridge preamplifier allows to retrieve and bring to our ears the whole “live” content that was recorded on the disc. These “live” sounds invariably strike any listener because the reproduced musical panorama features the details never heard before, a human voice being at all of the ultimate naturalness. However, it is direct analogue audio reproduction which can be demonstrated only for a limited number of people.

I didn’t expect much when I converted the analogue signals produced by my audio equipment to a digital format with the help of my computer’s 96kHz/24bit soundcard and Sound Forge 9 software. But it was a revelation for me that the obtained wav-files and then home-made CDs, unlike commercial CDs, completely preserve the “live” content of original recordings made on master-tapes or vinyl discs (LPs). The “live” sounds appear to be of such great vitality that even subsequent mp3 conversion can not “kill” them. Now I have several hundreds of my LP rips made in wav format, there are recordings of rock, classic and jazz music.

To demonstrate their quality, I’ve prepared my LP rip sample which can be downloaded. For comparison, I offer also to download a typical rip of the same song, made with the help of an ordinary audio equipment. Alternate playing of these two audio files from the same chosen point in Sound Forge 9 allows to clearly hear the difference in sounding - not in level or tone balance, but just in "live" content. Of course, all should be reproduced via decent audio equipment and acoustics to enjoy the sound in full degree.

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