The F5Pi

F5P Voltage Gain Stage + M2 Output Stage = Perfectly Integrated

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M2 Output Stage in Class AB

Earlier, we published the operating principle of the M2 Output Stage in Class AB, as well as its performance with different MOSFET pairs [1]. With the Toshiba 2SK3497/ 2SJ618 matched pair, the distortion is extremely low even without any feedback [2]. And the bandwidth of this output stage is well over 2MHz. As a power buffer, it is truly amazing.

One can easily build a nice speaker amplifier by combining with a voltage gain stage (VAS). And this has been successfully built by a few, using a high voltage opamp such as OPA551 as VAS. A few feedback schemes have been tried, and many preferred the proposed mixed feedback where the opamp has an inside feedback loop, in addition to an outer loop including the M2OPS [1].

Looking at the datasheet of the OPA551, one can deduce what the key performance parameters are with MFB. The OPA551 on its own should have a THD of about -90dB at 1kHz 15Vrms with a gain of 20. The open loop gain (OLG) is typically 126dB, at 2Hz -3dB. OLG at 1kHz is therefore ~72dB, And at G = 20, NFB at 1kHz = 46dB, reducing to 26dB at 10kHz. It also means that the intrinsic distortion at 1kHz is ~0.6%

F5 Preamp as High-Output Voltage Amplifying Stage (VAS)

But such a nice output stage deserves an equally nice discrete voltage gain stage. If we want to build a discrete frontend to go with the M2OPS, what would be the desirables ?

- Discrete, all-FET, complementary push-pull
- Low intrinsic distortion
- Sufficient gain (say 26dB), and controlled amount (~30dB) of negative feedback
- Capable of driving the M2OPS at low distortion and swing to within 4V of both supply rails

One suitable candidate is Nelson's FE2023. It has good performance and does not have to rely on NOS parts, but it is not complementary push-pull, as the M2OPS is. Another good candidate is the BA3, if you prefer no global negative feedback, and run the M2OPS in open loop, as in the M2.

But some negative feedback will help to lower the output impedance of the M2OPS (~0.4R) and increase damping factor, as those who tested the M2OPS with OPA551 also preferred mixed feedback. So perhaps a lower-bias F5 Preamp (or BA3 with NFB) would make a better frontend ?

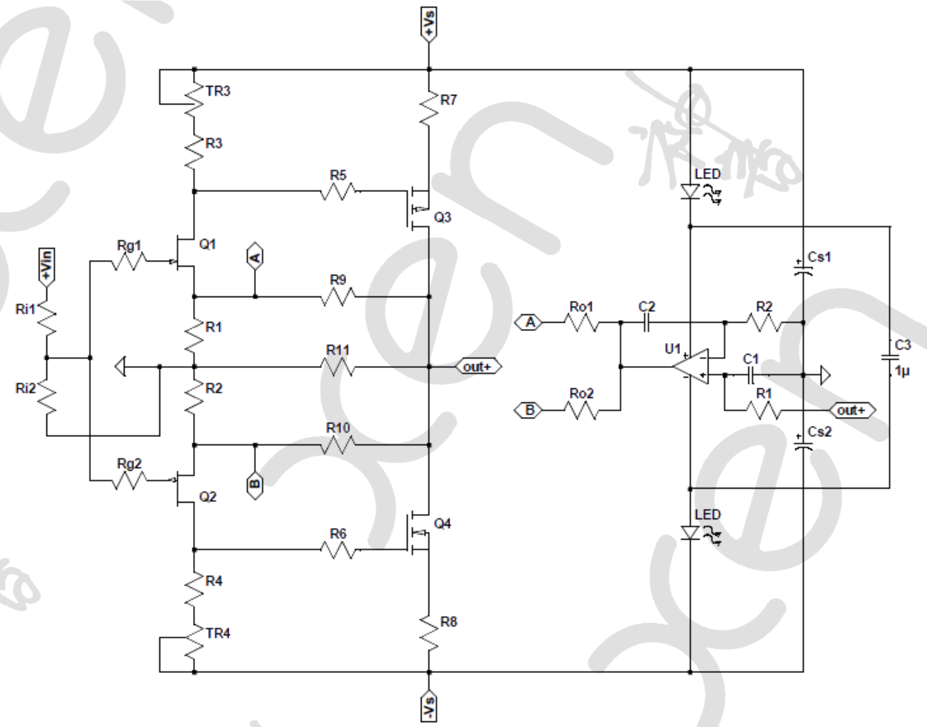
The F5 power amp is actually a transconductance amplifier in open loop. The load itself converts the output current back into voltage before NFB is applied. As such, its performance is load dependent. But speaker impedance is not always constant over the audio band. This can be improved significantly by adding a unity-gain power buffer between the F5 and the load impedance. With the M2OPS at such low distortion and such high bandwidth, the performance of the combined amplifier will be largely determined by the proposed F5 frontend.

There have already been two examples of using the F5 topology in low bias, namely the F5-HA [3] and the F5X Preamp [4]. In April 2015, a circuit for a headphone amp based almost 1:1 on the F5 power amp [5] was published. It was not perfect as a headphone amp for loads down to 32R. However, as a VAS in an integrated amp, the load to the frontend is much lighter. The M2OPS has an input impedance of around 25k, so driving it is not a big issue.

The F5 Preamp shown here is essentially a low-power F5, with output MOSFETs changed to TO220 devices, at a bias of ~80mA. The obvious choice of the input JFETs is the 2SK170 / 2SJ74BL pair, but the source resistor should be limited to not much more than 33R; else the frontend bias is reduced too much. For a gain of 20, the output is loaded by ~350R of the feedback network alone. When used as a stand-alone preamp, bias of the MOSFETs can be increased further for even heavier loads. The similarity to the BA3 means the PCB can be designed to accommodate both.

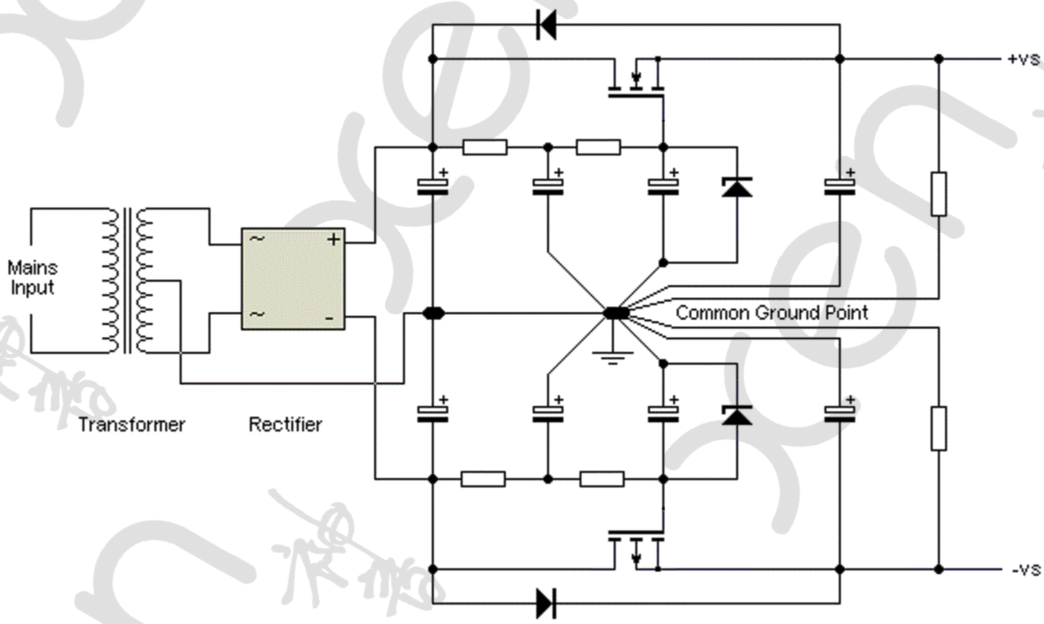
A variety of TO220 complementary MOSFETs can be used after the JFETs. Most obvious choice is Toshiba 2SK2013 / 2SJ313 despite being obsolete. The Onsemi FQP3N30 / 3P20 are also truly complementary, but are also obsolete. IRF610 / 9610 are probably the only pair still active. The Toshiba 2SK2381 / 2SJ407 were used by John Curl in the Parasound A23, but we found that they suffer from thermal hysteresis [6,7].

The F5 Preamp on its own will drive 600R load and can swing at least +/-20V. Bandwidth is >400kHz. Perfect square waves with no overshoot. One can now just connect the F5 Pre output to the M2OPS input in open loop, as in the M2, or include the M2OPS in mixed feedback to increase damping factor. The F5 Preamp has a moderate amount of NFB, around 30dB. When used with the M2OPS in mixed feedback, damping factor is about 200. This can be increased further if so wished, by going to full NFB with the M2OPS.



Power Supply for the M2OPS

It should be obvious that changes in rail voltages will cause DC offsets in the M2OPS on its own. Thus, it is recommended to use power supply with some form of voltage stabilisation. One may consider IC regulator such as LM338, which is capable of up to 5A. Alternative solution can be a simple Cap Multiplier using the same MOSFET pairs, preceded by 2 stages of RC low-pass filter. The schematics below, borrowed from ESP Project 15, serves to illustrate the principle.



Power Supply for the F5 Preamp

The frontend circuit can naturally share the same supply as the M2OPS. For an even quieter supply for the frontend, the same cap multiplier or regulator as the M2OPS can be duplicated but with devices of lower rated current. The frontend will then be much less affected by any transient current draw of the OPS, even when fed from the same transformer secondaries.

Volume Control and Source Select

We want to make this into an integrated amplifier, with volume control and source select in the same enclosure. With a gain of ~26dB, and source signal of 2Vrms, there is no real need for a separate preamp with added distortion. For an integrated amp, the mains transformer is preferably placed at the front, away from the input connectors. But the volume-control and source-selection knobs have to be at the front as well. That points to a relay-based solution to minimise noise pick-up. One solution considered was using an industrial rotary switch to switch individual source-select relays, and something like the Muses 72323 or Maxim DS1882 volume control IC in a form of volume pot as attenuator.

There are a couple of things we do not like with the Muses and the like. It has measurably higher distortion than a pure resistor-based solution. And it does not allow separation between digital and analogue parts of the circuit, as well as between channels. The three power supplies (for digital and for bipolar analogue switches) are also connected to the analogue signal Gnd.

After extensive search on the net, we settled on the logarithmic ladder attenuator, such as that published by Alex Nikitin [8]. There is even a Wiki page on this circuit [9]. Apart from low distortion as in any well-designed resistor attenuator, it has the advantage that it can be operated from a minimalistic binary up-down counter using pure logic without any MCU's. This can be done either with two push buttons, or an encoder with some simple glue logic. When using encoder with built-in push button, the push button can be used to trigger the volume change after turning the knob to the desired new level. This will avoid relays clicking through multiple attenuation levels when adjusting the knob. Only the push action triggers the relay switching after setting the new volume level, as indicated synchronously by a 2-digit LED display. A possible architecture is described in Appendix A.

Alternatively, if one wants to have other features such as remote control, the well-engineered RelaiXedPassive [10]. by Jos van Eijndhoven is very appealing. It is worth noting that an earlier version has become a Tentlabs product. He also has a webpage explaining different switched attenuator topology in detail [11]. The attenuator network is essentially the same as that of Nikitin.

An example of the original design was built, and it worked faultlessly. But it was felt that a few areas could do with some improvements. Instead of using a 5V SMPS in the original version to drive both the digital circuits and the relays, it was decided to power the relays with a separate auxiliary PSU, which can also be used to supply other auxiliaries, such as a speaker protection circuit. The relay coils, in close proximity to the micro-loaded relay signal contacts, can then be free from any disturbances from any digital circuits. 10 channels of optocouplers form the switching interface between the relay drivers and the control circuit, isolating the digital and relay coil supplies completely. This applies equally to the attenuator as to the source selector. The original relay driver board has to be redesigned, but the front-panel controller board can remain unchanged. For best channel separation, the left and right channel relay boards are completely separate and supplied by separate power supplies.

In addition, instead of using one contact of the DPDT Omron G6K relays for each channel, both contacts are used only for one channel in parallel. This is particularly important for so-called microload, despite the use of gold-plated contacts and sealed construction [12,13]. It also allows maximum channel separation.

The source code of the RelaiXedPassive is published [16], which means those skilled in the art can adapt it for their own requirements. The original design uses one encoder to operate both volume control (rotation) and channel indexing (push-button). To be compatible with the said logic-based two-knob design, one encoder can be used for volume control, while a second one is for source selection. As we did not venture into changing the source code, the second encoder is used just as a push button for source select. In both cases, volume control is shown by a LED 7-segment display, while source selection with a row of LEDs.

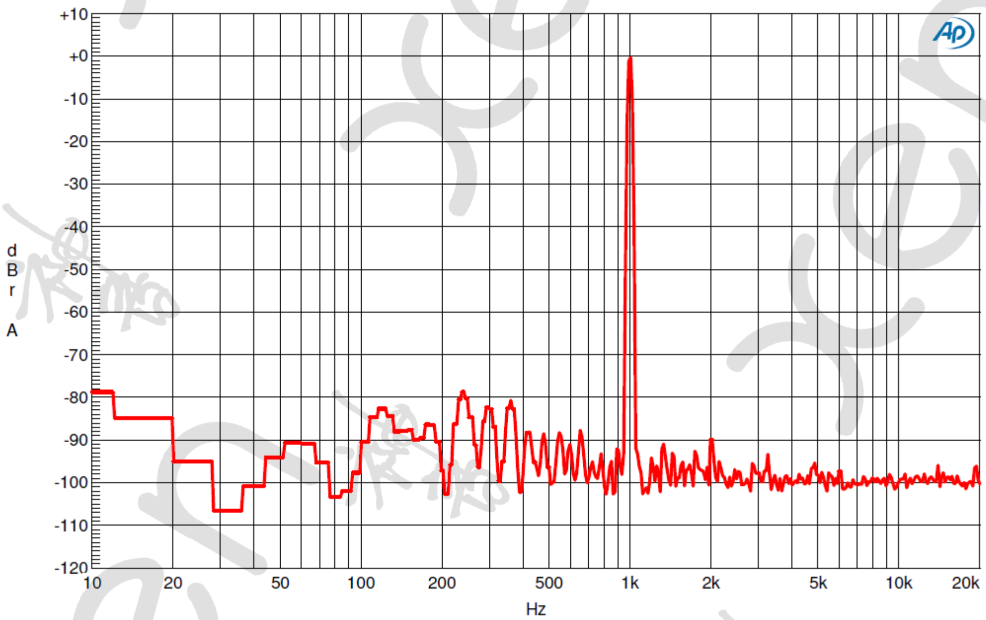
Enclosure

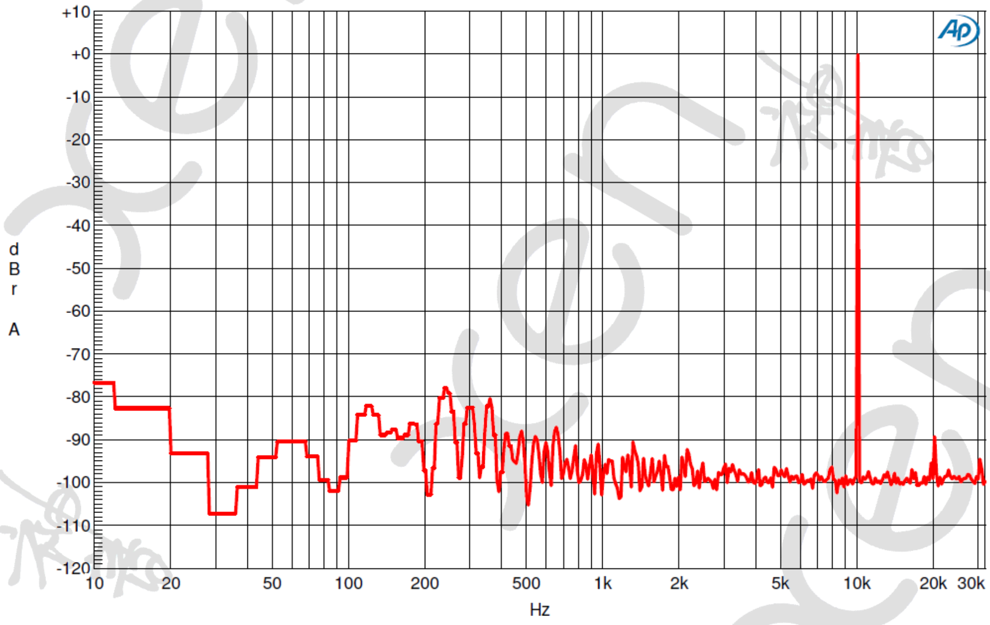
For convenience, the Breeze 3213 heatsink case was chosen as enclosure. The heatsinks are capable of 60W dissipation each with ~30°C above ambient, according to a Natsink simulation, which from experience is rather conservative. There is enough space for the amplifiers, a custom 400VA transformer, 4x dual-rail cap multipliers, as well as all the above-mentioned auxiliaries plus a pair of speaker protection modules. The design can also be used as a common platform for a generic integrated amp. The Mini Dissipante 3U 300mm from Hifi2000 is also of compatible dimensions, but we like the 3213 better..

Measurements

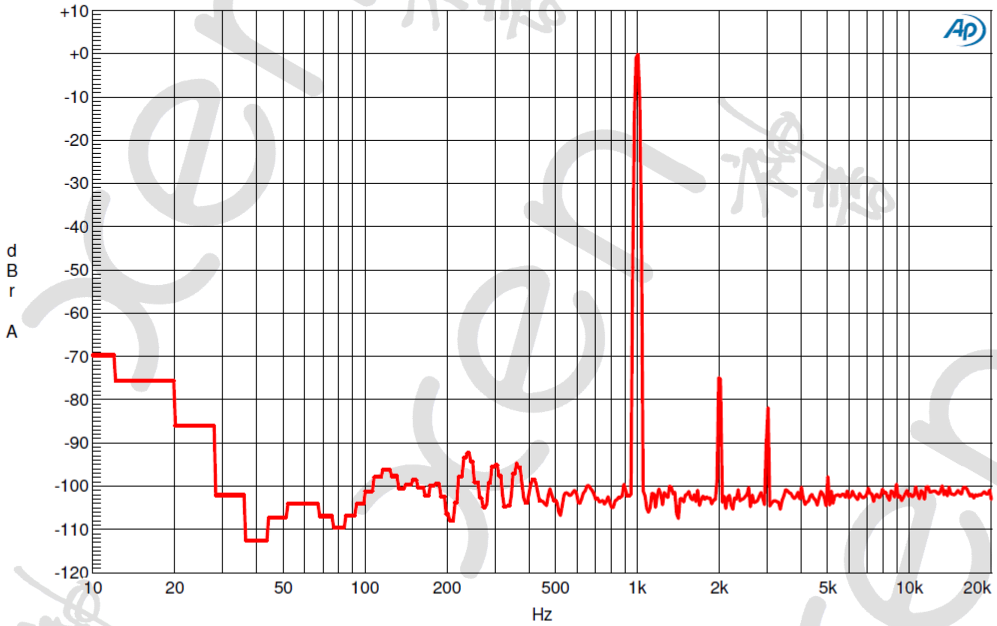
F5P & M2OPS on their own

The F5P frontend was first tested on its own. Distortion was measured at 1kHz and 10 kHz with an Audio Precision SYS2722. Bandwidth was set at ~400kHz with a 470p feedback cap, as there was a small 1dB hump at ~500kHz. When left on its own to drive the 350R feedback network, distortion was about -90dB at 1kHz +/-4V. It was purely H2, with all higher harmonics buried in noise. Distortion at 10kHz is essentially the same as at 1kHz.

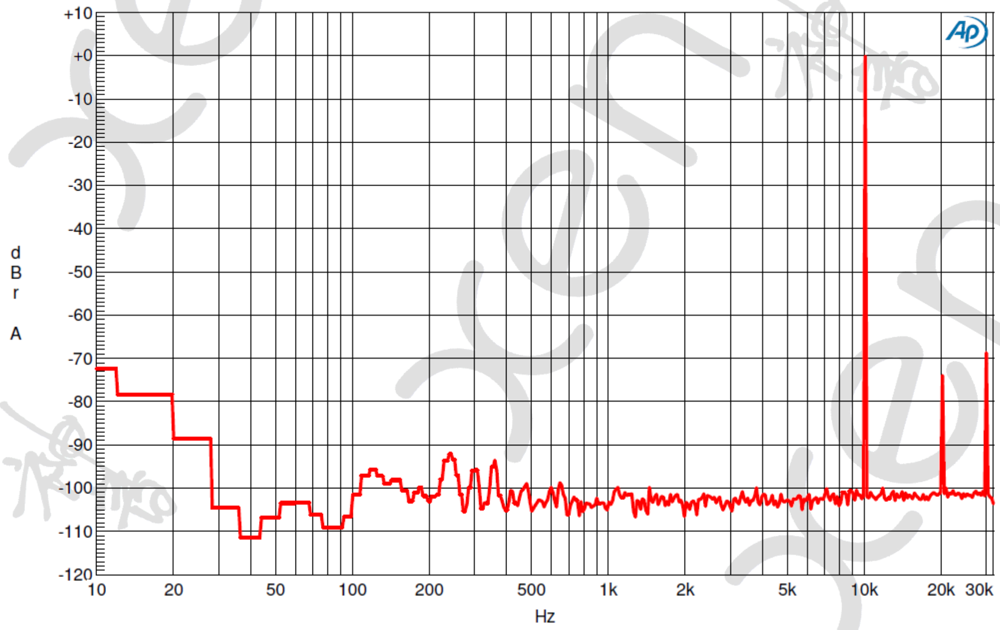




At maximum output of +/-20V, distortion at 1kHz is about -75dB H2 and -83dB H3.



At 10kHz, H2 is same as at 1kHZ, but H3 increases to -69dB.



The M2OPS was also measured on its own. Bias was automatically at 1.25A without any trimming. DC was stable to less than +/-5mV after warm-up. The bandwidth was more than 2Mhz which was the limit of the function generator. That even when loaded with the Stereophile reactive dummy speaker. Distortion figures were already published in Reference [2].

F5Pi with MFB

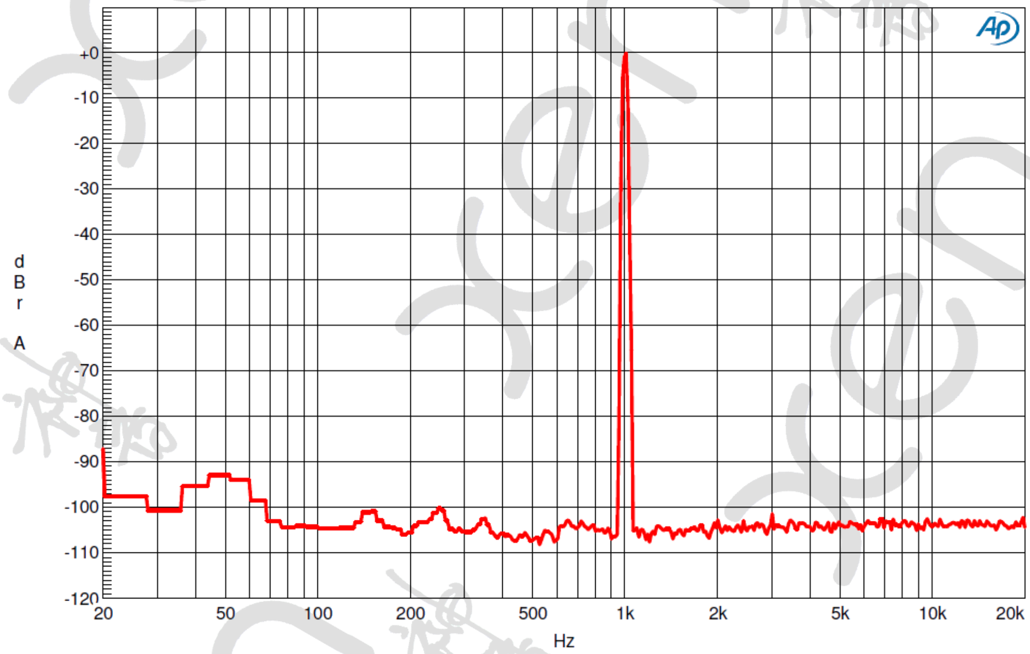
As mentioned earlier, the OLG of F5P frontend, just like that of the F5 power amp, is load dependent. When the F5P is combined with the M2OPS, the feedback resistor network is no longer driven by the 2nd stage MOSFETs, but by the M2OPS. If 20dB of MFB is to be applied, the load impedance seen by the F5P frontend is increased by 10x. This in turn means that the OLG is also increased by 20dB.

50dB NFB is not necessarily a problem in itself, although one might not like the sonic signature of high-NFB amplifiers. The problem is more that it eats into stability margins, especially when driving reactive load. This can be recovered by increasing the resistive load at the output of the frontend. By varying the value of this load resistor, one can also vary the OLG and its bandwidth.

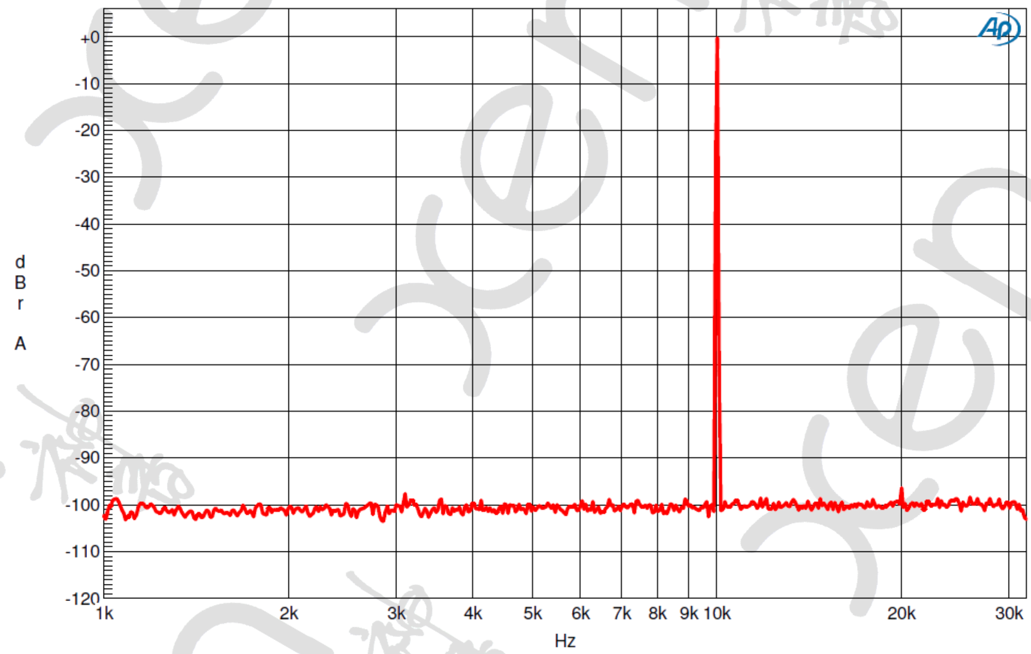
Due to the high bandwidth of the M2OPS, the frequency response of the combined F5Pi was determined by the frontend. Response was a clean 1st-order drop, with or without dummy speaker (reactive load). The amplifier was powered by lab supply followed by simple C-R-C during test.

With the frontend having the same load as if it were on its own, the distortions are essentially the same as before. The M2OPS adds next to nothing to that, and one can get essentially equal performance by excluding the OPS from the feedback loop. The benefit of MFB is largely in reduced output impedance, or increased damping factor.

The performance was also measured by adjusting the frontend load resistor to give 45dB global NFB. As expected, distortion was lower due to the increase in NFB. At 1kHz, distortion was close to noise level, with H2 and H3 below -100dB. At 10kHz, H2 was -97dB; H3 was below -100dB. There was again minimal difference in THD between 1kHz and 10kHz.

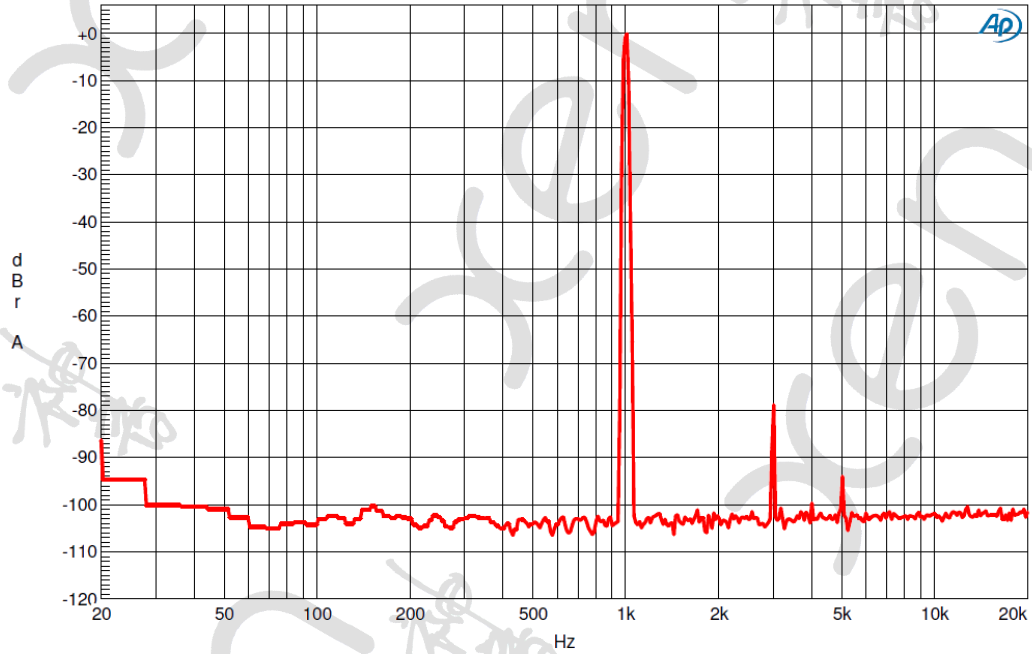


FFT 1kHz 1W into 8R, 45dB NFB

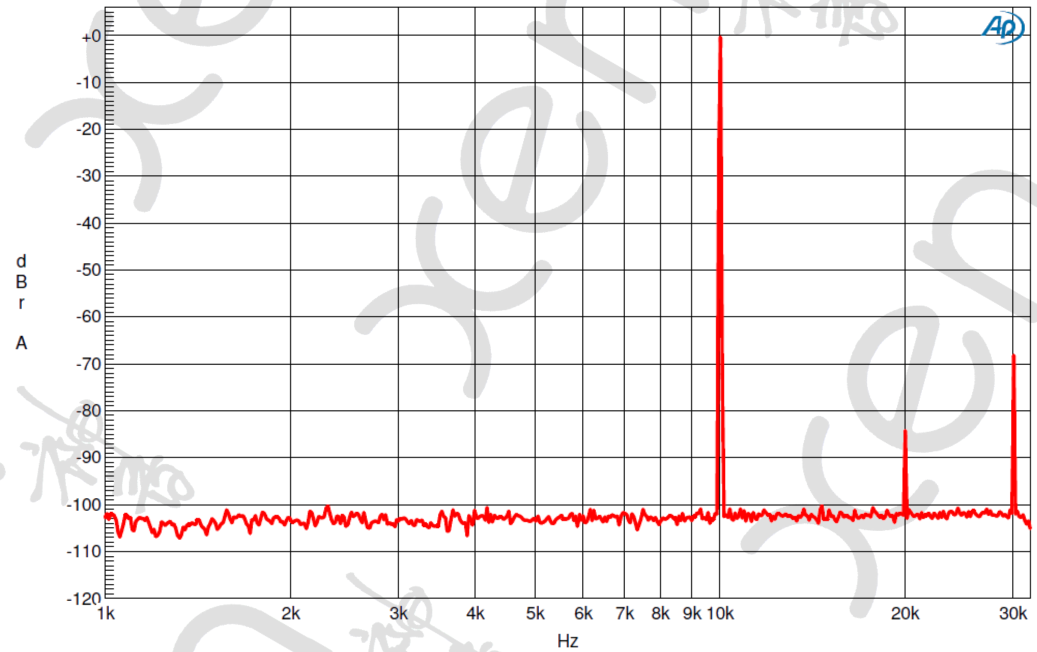


FFT 10kHz 1W into 8R, 45dB NFB

At 1kHz 25W into 8R, the amplifier is close to the verge of leaving Class A, and distortion is higher as expected. H2 is still very decent at -80dB, or 0.01%, with H3 at -95dB. At 10kHz, H3 becomes dominant at ~-70dB. But then your tweeter might not be too happy with 25W ?

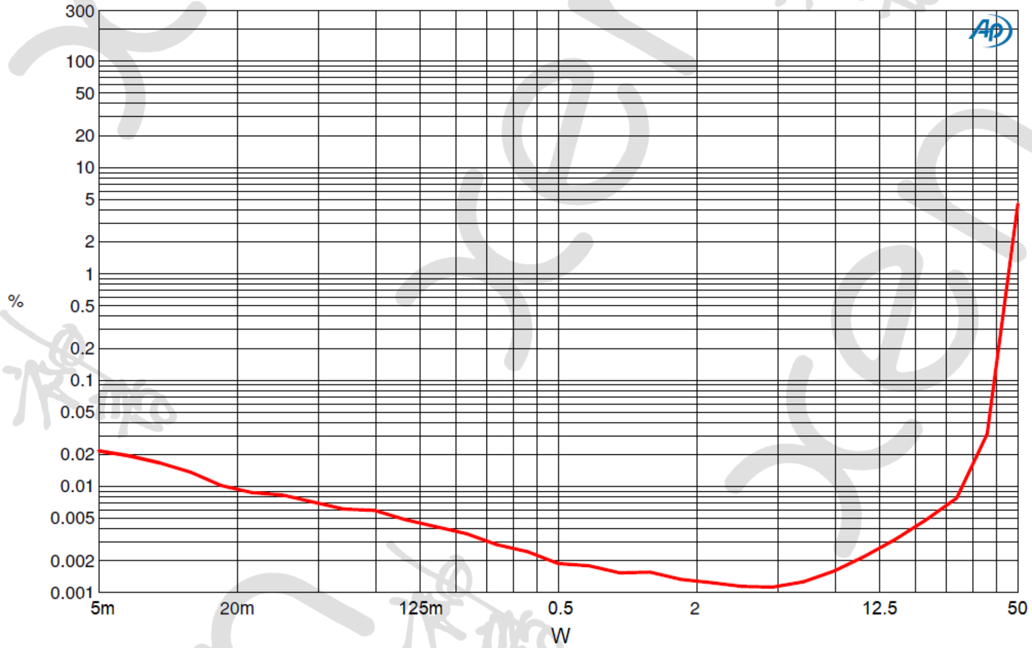


FFT 1kHz 25W into 8R, 45dB NFB



FFT 10kHz 25W into 8R, 45dB NFB

THD vs Power has also been measured. Only a lab supply was used during the test, and we wanted to see the distortion of the amplifier itself, the signal was filtered between 400Hz and 30kHz. As can be seen, distortion is below noise level up to 4.5W, at which THD is 0.001%. It then rises continuously to 0.01% at 25W, and 0.02% at 32W. The latter corresponds to the practical useable power of the amplifier into 8R. The results also show how important a low-noise power supply is to yield the full benefit of this low-distortion amplifier. (Noise level in the measurement corresponds to 40µVrms.)



THD vs rms Power 1kHz into 8R, 45dB NFB

The measurements were only done with 8R load, for which the OPS was optimised. The advantage of DIY is that one can optimise the OPS for a specific load as required. Especially when using separate supplies for the VAS and the OPS, one can easily optimise for 4R load, by reducing OPS rail voltage to 18V but increase bias to 1.75A. This will ensure Class A operation up to 10Vrms (25W rms) while keeping the same dissipation for the output devices. The VAS remains unchanged.

Measurements of the Complete Integrated Amplifier

The final integration was done with the amplifier in MFB as mentioned before, and with 30dB NFB. The complete setup functions without any issues.

Heatsink temperature rises to 25°C above ambient after 1 hour. And DC offset changes by 50mV from cold, but is stable to mV levels after 45 minutes. 50mV is no issue for speakers and well below the trigger level of the speaker protection circuit. But we trim it to 25mV (half way) at steady state, so that it never exceeds 30mV in magnitude from cold to warm.

Bias current per amplifier is 1.3A at 20°C, and rises slightly to 1.35A at 45°C. So in this particular build, there is actually some room for increasing the bias.

Distortion measurements were repeated with the entire integrated amplifier, with the Viktor low-distortion oscillator as signal input, and using the on-board attenuator to set the desired output voltage. The results are essentially the same as those shown above, i.e. -90dB H2 and -105dB H3 at 1W into 8R.

Appendix A Pure Logic Solution for Source Select & Volume Control

A rotary Encoder + CD4013 +74HC2G04 can be converted to simulate an up button + a down button [14]. This is used to drive a 2-digit 7-segment common-cathode LED display via 2x cascaded CD40192 + MC14511B [15].

For driving the switched-relay volume, 2x cascaded CD40193 should be used instead, with logic limiting the count to 6 bits. The volume change can be made to trigger by push button with a single 74HC174.

To set the upper limit for the CD40193, set the inputs to 00111111 (63). Use the 7th bit of the counter output to trigger the load flag. When counting from 63 to 64, it will go 01000000 briefly. But the load flag should then force itself back to 63 within 0,3µs, which is much quicker than the relays could respond.

For the lower limit at zero, use the borrow flag to trigger the reset pins. For the 40192, set the inputs to "6" and "4" in BCD. Then connect the binary load flag from the 40193's to the BCD load flag. The 40192 borrow flag can act on their own for lower limit at 0.

Pure logic. No MCUs, no XOs.

References

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