To be or not to be . . . this mortall coile . . .[1]
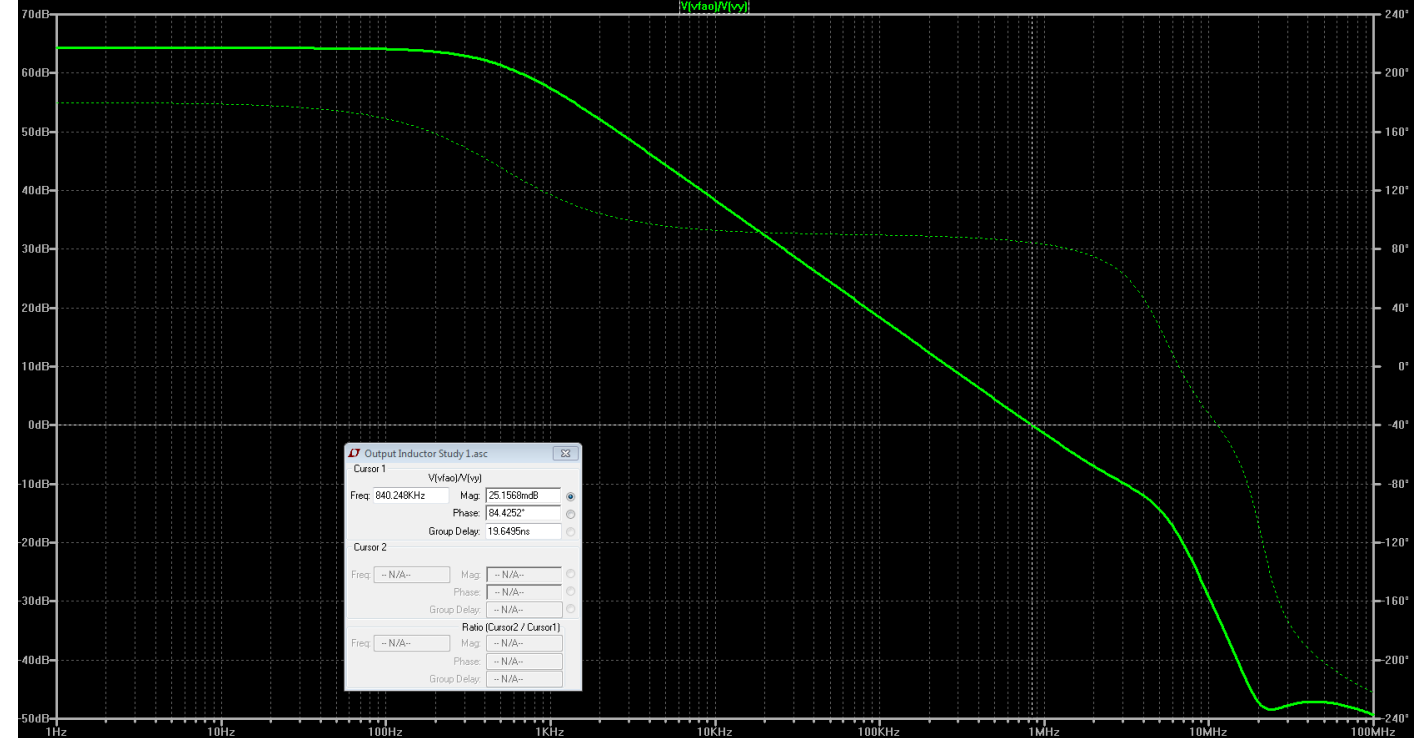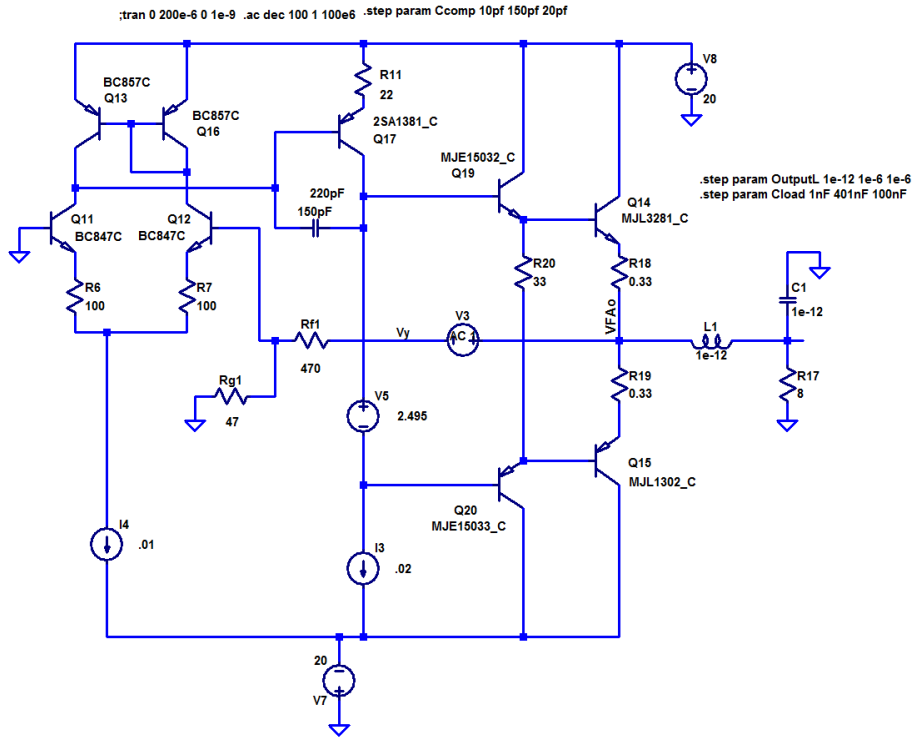
A brief investigation into the use of inductors to couple amplifiers to real world loads.

*Andrew C. Russell*   *www.hifisonix.com*

[1] Literal translation of coile (also spelt 'coyle in old English) is 'fuss' or 'bother'. With acknowledgements to Will S.

Model Amplifier Used for this Investigation. This is the basic amplifier design loop performance driving a standard 8 Ohm load with the capacitive load set to ~0 F and output coupling inductor set to 0

The amplifier gain and phase margin are exemplary, with close to 85 degrees phase margin at the ULGF of c. 840 kHz.
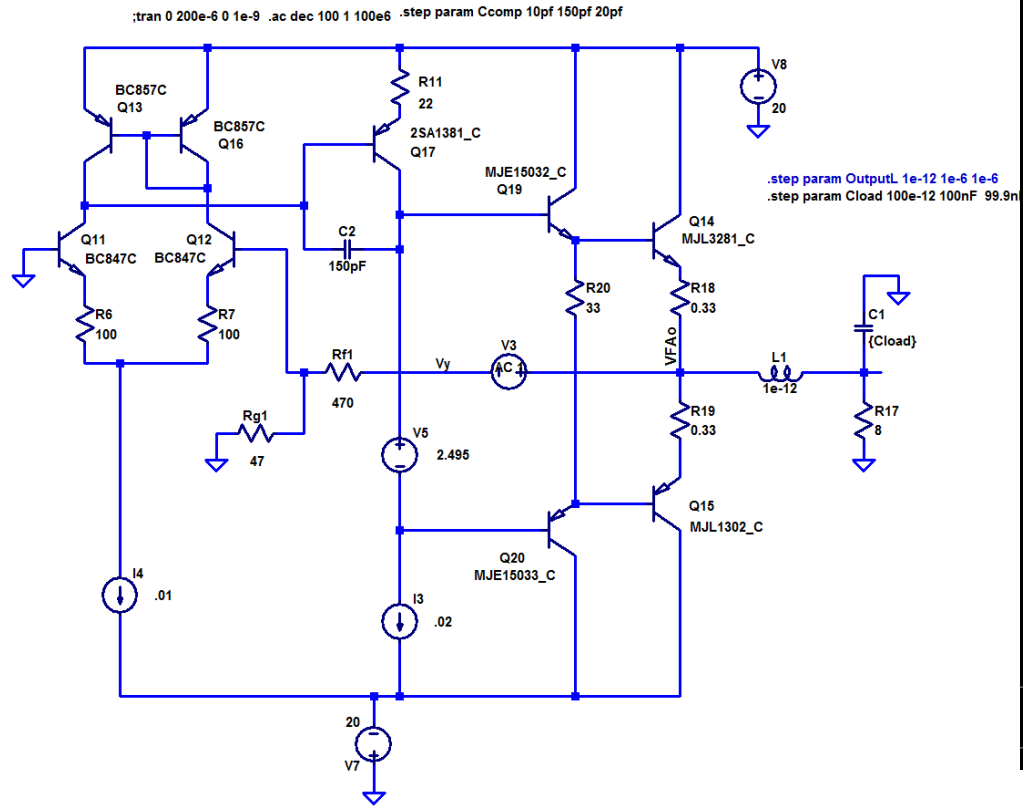
Basic Capacitive Load Test Without Output L. This plot shows what happens when a 100nF capacitor loads the output of an amplifier with moderate OLG (about 85 dB in this case with the loop closed a conservative 840 kHz) with and without an inductor. The green trace is with 100pF load and the red with a 100nF load. Without the inductor, the amplifier phase margin degrades rapidly, while larger values of output capacitor will almost certainly cause oscillation. The capacitor load causes the HF pole to migrate *down* in frequency, and above the 0 dB intercept – i.e. the gain is greater than 1 and the phase shift > 180 degrees and the result in instability.
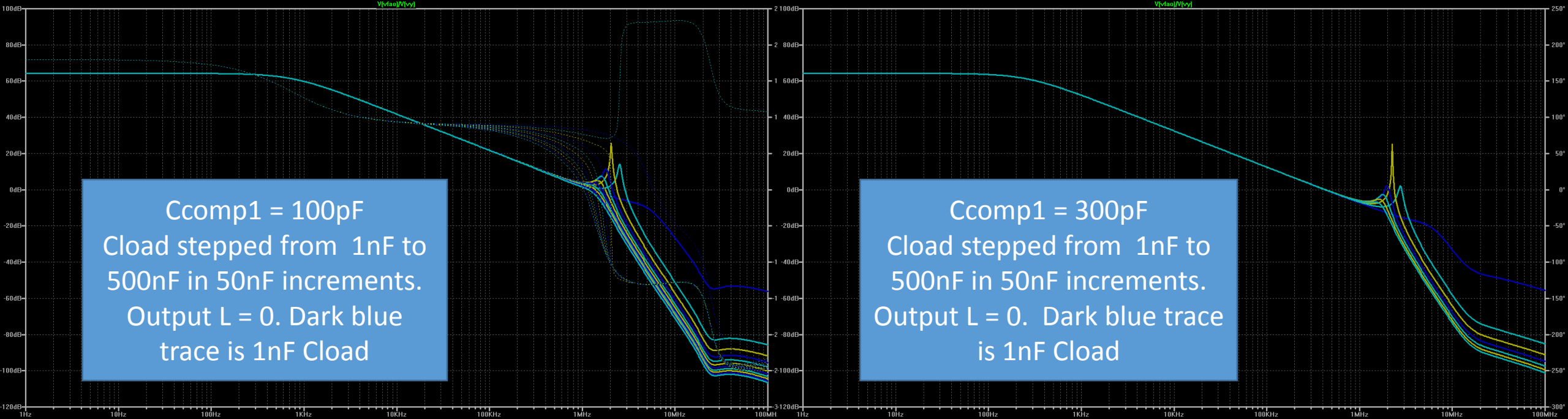
In amplifiers that do not use an output L, you can decrease the ULGF by increasing the emitter degen resistors (R6 and R7) and Ccomp1 in combination or individually. This pushes the HF pole higher in frequency and below the ULGF intercept, giving more leeway for HF pole migration. Note that just increasing Ccomp1 on its own does not always solve the problem – the HF pole kink with a capacitive load still locates at >0 dB, and the gain margin is severely degraded – see next slides.

Some designers rely on the speaker and speaker cable intrinsic inductance to help isolate the amplifier from potentially high load capacitances.
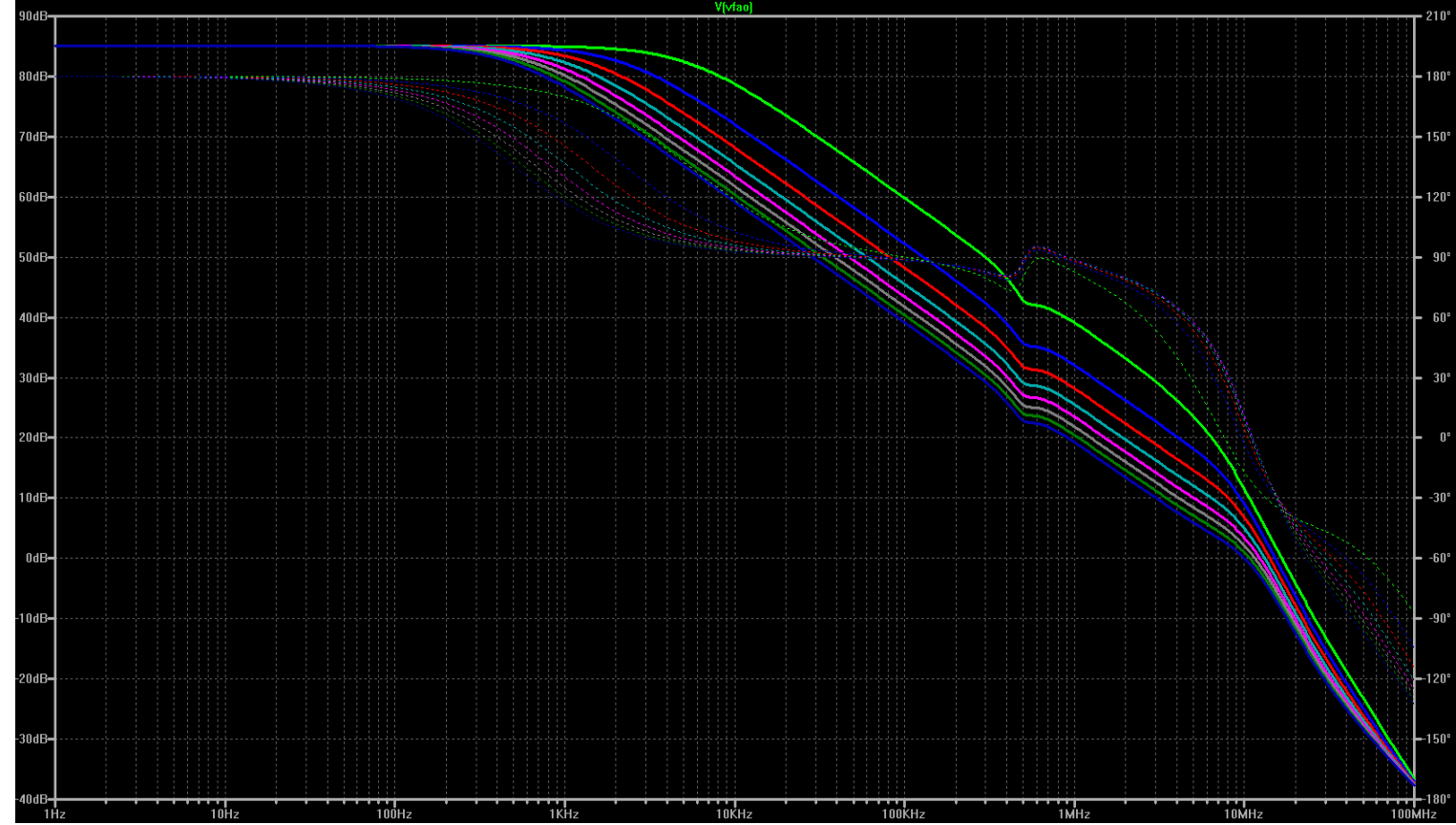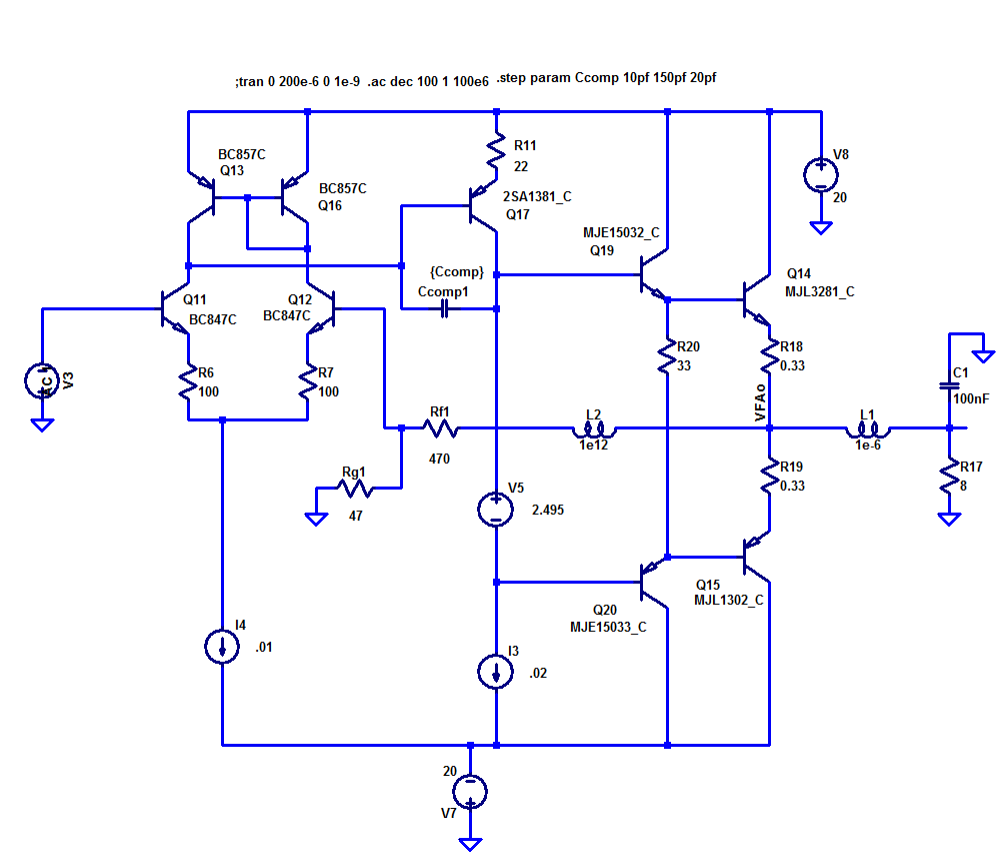
Pole Splitting. This plot shows the effect of Ccomp1 (i.e. Cdom) in the open loop condition. With a value of 10 pF (the green trace), the OPS pole lies *above* the 0 dB OLG intercept, and the phase margin is about -20 deg – i.e. is not stable and would oscillate. As Ccomp1 is increased in value, the LF pole moves down in frequency, while the HF pole moves up in frequency – so called 'pole splitting'. With a 100nF load and Ccomp1 = 150pF, the second pole lies at the ULG intercept, and there is about 20 degrees of PM – the amplifier is stable with a capacitive load.

An inductor of 1uH is used for these simulations. The kink in the transfer response at ~400 kHz is the output inductor resonating with the load capacitor C1 (100nF).

Ccomp1 = 100pF
Cload stepped from 1nF to 500nF in 50nF increments.
Output L = 0. Dark blue trace is 1nF Cload

Ccomp1 = 300pF
Cload stepped from 1nF to 500nF in 50nF increments.
Output L = 0. Dark blue trace is 1nF Cload

The effect of Lowering ULGF to Improve Cload Tolerance. These simulations show how by decreasing the ULGF, the HF pole is pushed further below the ULG and higher in frequency, making the amplifier more tolerant of capacitive loads. The output L ~0H. In the LHS panel, with Ccomp1 = 100pF, on a square wave you will get overshoot and possible instability during part of the output waveform (see the 'Bowes' test). On the RHS panel, Ccomp1 = 300pF and even with a heavy 500nF load, the phase margin is >50 degrees. However, the gain margin in the RHS plot shows that this amplifier would have stability problems with *heavy* capacitive loads. To summarize, lowering the ULGF can improve capacitive load tolerance, but for heavy loads is will still not provide adequate gain margin.

It appears that 1~2nF Cload is about as much as an amplifier can tolerate *without a output coupling inductor* before stability problems manifest.

Cload in this plot is stepped from 100pF to 500nF. Output coupling inductor is 1 uH
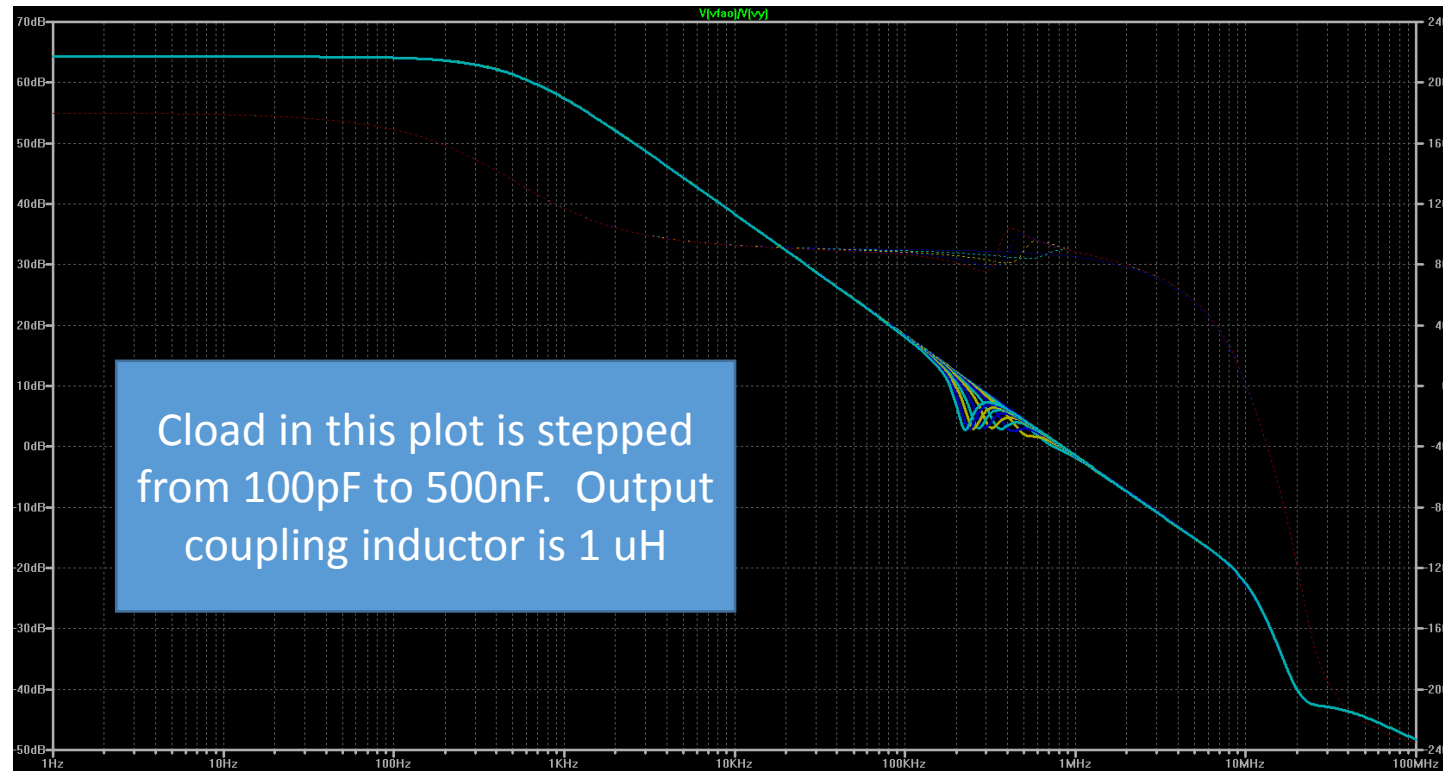
1uH is Enough to Ensure Unconditional Stability. In this plot, Ccomp1 is set to 150pF, setting the ULGF to ~840 kHz. A 1uH inductor is used to couple the amplifier to the output load. The result is the amplifier is unconditionally stable for loads of up to 500nF. The gain and phase margin are hardly affected by the capacitive load.

The kinks in the response from about 200 kHz through to 700 kHz are as a result of the output L resonating with the load capacitance. This is quite normal, and also takes place in amplifiers without an output L – it is instead just the speaker cable and speaker L that resonate with any capacitive load that may be present.
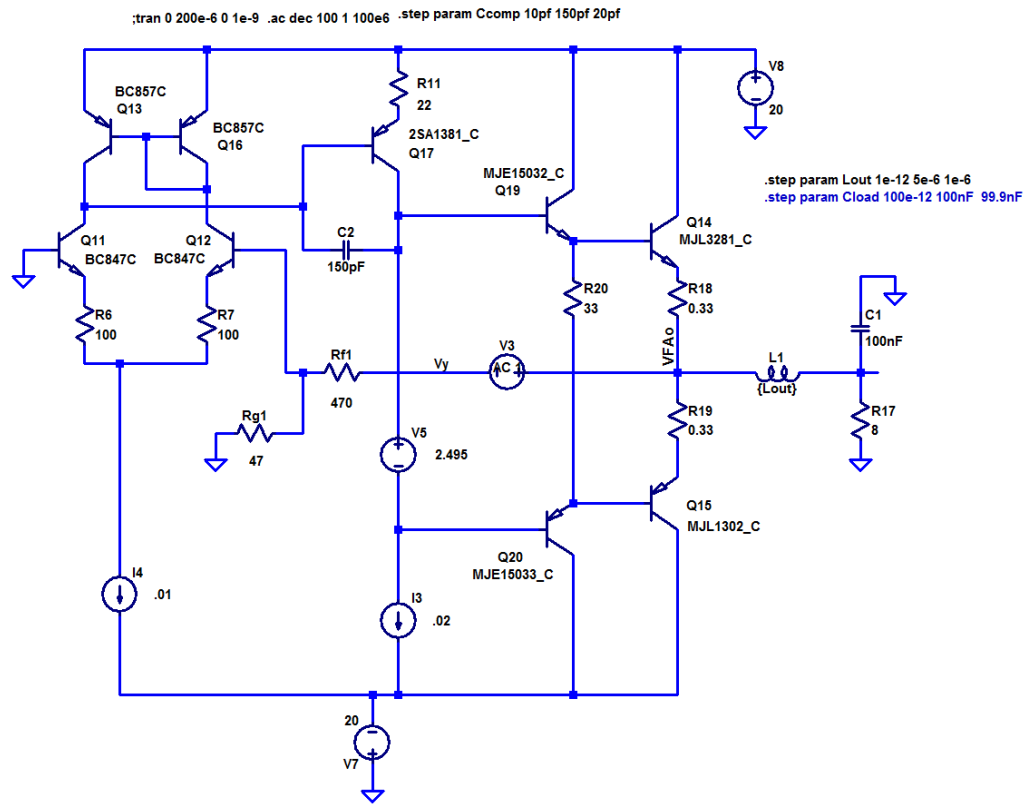
Effect of Output L's from 0uH to 5uH. In this final plot, the amplifier output is loaded with 100nF and the output coil is stepped from 0 to 5uH. As shown in the earlier slides, without the coil, the output HF pole which in this design lies at ~10 MHz and almost 20 dB below the UG intercept, migrates up to about 2 MHz with about 30 dB of peaking and +25dB gain margin – i.e. it is unstable.

With the output coupling inductor, just 1uH is enough to ensure unconditional stability, with values much higher than this bringing marginal if any additional benefit. Note also that it does not seem to matter what type of compensation is used – MC, MIC, TMC etc – the basic requirement to isolate the amplifier output from capacitive loads remains the same.

Output Coupling Inductors: Summary

- A 1uH output coupling inductor can guarantee unconditional stability with any practical capacitive loads where, into a purely resistive load the amplifier phase margin is >60 degrees and the gain margin >10 dB.

- Amplifiers can be designed without output coupling inductors, using instead the cable and speaker inductance to isolate capacitive load. However, in these designs, adequate gain and phase margin must be incorporated to cater for all eventualities – typically this is achieved by lowering the ULGF. However, even with this approach, care must be taken to ensure adequate gain margin is available with higher capacitive loads.

- It could also be argued that there is no speaker system, or speaker cable of any practical length with inductances of less than 1uH as justification for this approach

- There is a case to argue that by incorporating an output inductor, designers can reliably exploit higher ULGF, and hence higher loop gains, to reduce distortion.

- There is as yet no consensus on the audibility of output coupling inductors, although most practitioners agree that at or below 1uH, they are inaudible. Further, a 1uH coupling inductor will generally be lower that the speaker cable inductance.