Yamaha Professional / HiFi Audio Products

Servicing guide for discrete component power amplifiers

1. Introduction

The use of discrete-component power amplifier stages in audio equipment is so common that most technicians will call upon their own previous experience to diagnose and repair a faulty amplifier. In some cases however, these repairs are attempted without a complete understanding of the internal principles of power amplifier circuit operation.

When faced with an obscure fault symptom in a discrete component power amplifier, many technicians elect to simply replace all of the circuit's semiconductors. Admittedly, less time may be spent replacing a dozen or so cheap transistors than spent analysing the circuit, but while this approach may restore correct operation, it does not guarantee results.

The subject matter presented here describes the circuit analysis and operation of the most common power amplifier configuration used today – the differential input, single ended complementary output configuration. While there have been many innovative circuit techniques and components introduced over the years, contemporary designs have settled on the aforementioned configuration, and this is testament to just how good and universally applicable it is.

2. The Overall Circuit

Figure 1 shows the overall circuit diagram of the complete power amplifier stage. While it is not the simplest possible amplifier configuration, it represents that used in the majority of consumer and professional audio amplifiers. No component values are shown, as these will differ between amplifier designs.

Positive and negative power supply voltages are used and this allows a direct output coupling to the loudspeakers and in some designs, a direct input coupling from the signal source. Transistors Q1 and Q2 form the **Input Differential Pair**. The input signal is applied to Q1 and the negative feedback from the output is applied to Q2. The **Current Source** Q5 supplies this pair with their necessary operating current. The **Current Mirror** formed by Q3 and Q4 converts the output from the differential pair to a single ended signal, which is then applied to the **Voltage Amplifier** Q8 and then to the **Cascode Follower** Q7. Q6 is another current source that provides Q7 with its collector load.

The **Thermal Compensation Transistor** Q9 is used to provide a stable value of "bias", or quiescent output stage current. Q10 and Q11 form the initial section of the **Complementary Output Stage** and act as the driver transistors. The output transistors Q12 and Q13 provide the signal current needed to drive the loudspeaker load.

The amplifier's operation relies totally on the use of negative feedback, and a lack of understanding of this principle can affect the efficient diagnosis of some fault symptoms. Each of the terms shown above in bold print is now explained in detail.

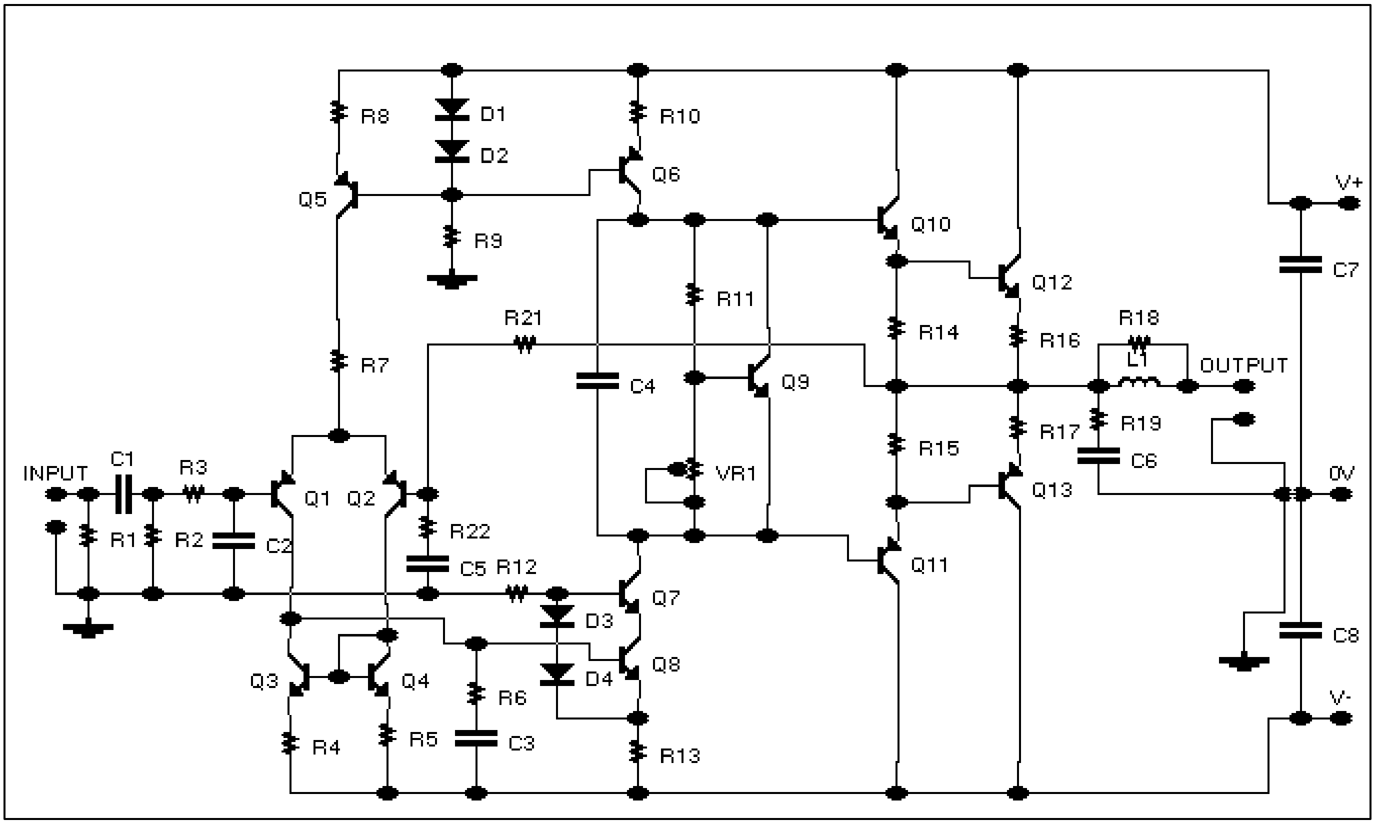

Figure 1. **Overall circuit diagram of the discrete component power amplifier described in the text**

3. The Input Differential Pair

The input signal is applied to the junction of resistor R1 and capacitor C1. R1 allows C1 to remain charged at all times and prevents audible “clicks" from occurring when an input signal is first applied from an external source. When internal preamplifier circuitry precedes the power amplifier stage, the DC coupled preamplifier’s output (normally an IC op-amp) provides this charging path and eliminates the need for R1. Resistor R2 provides a path to ground for Q1’s DC base current and largely determines the impedance presented to the input signal. R2 is also the *sole means by which a working amplifier is able to maintain a DC output voltage of zero*. Q2’s DC base current flows through R21 to the amplifier’s output line. R3 and C2 form a low pass filter that reduces the amplifier’s sensitivity to radio frequency (RF) input signals.

Q1 and Q2 form the differential pair. Their emitters are connected together and both are biased on with a constant current supplied by Q5 (Q5 will be described later). The proportion of this current that Q1 and Q2 each pass depends on the voltage *difference* between their two bases, and through feedback, the pair will always attempt to maintain this difference at zero volts. It is important to understand that in a working amplifier operating linearly (not overdriven or “clipping”), whatever voltage (AC or DC) is present at Q1’s base will *always* be present at Q2’s base. The pair actually compares the input signal with the signal fed back from the output stage by R21, R22 and C5. The comparison results in a difference in the collector currents of the two transistors. In other words, as one transistor passes or “sources” more current, the other sources less. This difference is the “error” signal, and it is in fact this signal - not the input signal - that is ultimately amplified by subsequent stages to produce the amplifier’s output signal.

One could be forgiven for thinking that the signal at Q1's collector (the error signal) should have an amplitude greater than that at Q1's base (the input signal) and that this error signal could be observed with an oscilloscope to determine if Q1 and Q2 are "amplifying". This is not the case however, because as we will see later, an extremely high voltage gain is attainable through the rest of the amplifier. An error signal amplitude of only a few millivolts is sometimes sufficient to swing the output stage to its limits.

The feedback components R21, R22 and C5 were mentioned previously and their contribution to the amplifier's operation must be thoroughly understood. At signal frequencies, C5 (typically a large electrolytic) can be considered a short circuit and so it can be seen that R21 and R22 divide the amplifier's output signal by some factor before it is applied to the base of Q2. At all times, Q1 and Q2 drive the amplifier's output to maintain a zero difference between their bases and this only happens when the amplifier's output is equal to (1 + R21/R22) times the input signal. So with values of say, 47 Kilohms and 470 Ohms for R21 and R22 respectively, the overall gain of the amplifier is 101 (or approximately 40dB).

At lower signal frequencies, the reactance of C5 increases, effectively reducing the overall gain of the amplifier. At DC (no signal), C5's reactance is of course infinite, and so the amplifier's entire output voltage is available at Q2's base (Q2's base current is negligible and so causes no significant voltage drop across R21). Since Q1's base is tied to ground (0 volts) by R2, the comparison action of the differential pair ensures the amplifier's output is also maintained at ground potential. In many Yamaha Hi-Fi amplifiers, the feedback loop incorporates the tone control or equaliser network, and many components - both resistive and capacitive - may be involved. No matter how complex this network is in terms of its effect on the amplifier's frequency response, it must provide a DC path from the amplifier's output back to the differential pair.

4. <u>The Constant Current Source</u>

The constant value of current necessary for the correct operation of the differential pair is supplied by Q5. In simpler designs, a single resistor is used instead but this approach has several disadvantages. These include susceptibility to hum and instability from signal and ripple voltage variations on the power supply rails.

Referring again to the overall circuit diagram in Figure 1, a fixed voltage of about 1.3 volts is developed across diodes D1 and D2 due to current flow through both these and R9. The voltage between the positive supply rail and the emitter of Q5 is about 0.65 volts less than that across D1 and D2 due to the loss across Q5's base-emitter junction. The current flowing through R8 as a result of the voltage drop across it flows out of Q5's collector, through R7 and down to the differential pair. R7 serves two purposes. Firstly, it reduces Q5's thermal dissipation and secondly, it affords some protection to the whole amplifier if Q5 were to fail and go short circuit. The ratio of the voltage drops across R8 and R7 is equal to the ratio of their resistances, because the same current flows through them. When this is not the case, Q5 or its surrounding components are suspect. The importance of Q5's contribution to the amplifier's operation should not be underestimated. Such parameters as frequency response, device dissipation and gain are all directly affected by variations in the design value of the current available from Q5.

In Figure 2a, D1 and D2 are replaced by an LED, which normally drops around 1.6 – 2.2 volts depending on the LED colour used. The circuit's operation is otherwise identical.

To reduce the effects on the value of Q5's collector current by its own self-heating, the circuits shown in Figures 2b and 2c may be used. In Figure 2b, it is Qa that determines the value of current in R8 by maintaining a constant 0.65 volts across it. Q5 simply *delivers* this current as described earlier and has no other effect on it. Qa operates with only 1.3 volts between its collector and emitter terminals, ensuring low thermal dissipation and consequently, the stability of both its base to emitter voltage and the current through R8.

In Figure 2c, Qb acts as a cascode follower stage that allows Q5 to operate with a collector-emitter voltage of about 1.4 volts, again ensuring thermal stability of the constant current value.

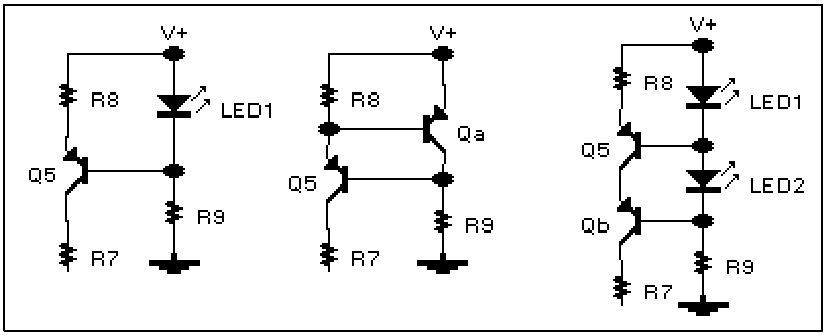

Figure 2a **Figure 2b** **Figure 2c**

Constant current source circuit variations

5. The Current Mirror

The comparison of the input and feedback signals performed by Q1 and Q2 results in a *differential current* flow from each of their collectors towards the negative supply rail. These currents must in some way be converted to a *single ended voltage* that can then be amplified in the subsequent stages. In simpler designs, this voltage is produced across a resistor connected between the collector of Q1 and the negative rail - Q2's collector would in this case, also be connected directly to the negative rail. This method however provides a reduced gain from the differential pair transistors and does not take advantage of the differential current available from them.

Transistors Q3 and Q4 form the actual current mirror. Q3 is forced to "sink" the same value of current that Q2 "sources". In combination, Q1 and Q3 provide a "push pull" action that results in a signal voltage at their collectors. It works as follows -

The current from Q2 (which normally equals that from Q1) flows through Q4 and R5. Q4 acts as a diode because its base and collector are shorted together and thus has a 0.65 volts drop across it, which adds to the voltage drop across R5. Q3 acts as an emitter follower, ensuring identical voltage drops across R4 and R5. With equal values for these resistors, Q1, Q2 and Q3 each pass identical collector currents, the balance of which is affected by signal variations. A negative going signal for example, applied to Q1's base, turns Q1 on harder relative to Q2. Q2's collector current decreases, reducing the voltage drop across R5 and R4 and the current through Q3. This creates a positive going signal output at Q3's collector, which is fed to the next stage, the Voltage Amplifier.

6. The Voltage Amplifier

Transistor Q8 provides almost all of the signal voltage amplification that the amplifier needs in order to function as a negative feedback amplifier. It is connected as a conventional, common-emitter transistor stage with the input signal applied to its base and the output signal taken from its collector. This stage could be viewed as the "half way" point in the amplifier, as it resides between the input stage whose function as we have already seen, is primarily one of signal comparison, and the output stage, which acts as a unity gain buffer.

The voltage gain available from a common emitter stage is roughly determined by the ratio of the values of its collector and emitter resistors. Resistor R13 - Q8's emitter resistor - usually has a value of several tens of ohms. The high gain required in this stage results from the constant current source Q6 appearing as a very high value resistor in Q8's collector current path. Under no-signal conditions, Q6 sources the same value of current that Q8 sinks. In fact it is the same *current*, and this results in close to zero volts being presented to the output stage. It is important to understand that the only means by which the output stage can provide positive going signals is through the current sourcing ability of Q6. Conversely, negative going signals from the output stage can only occur if the current path through Q8 (via Q7) is intact.

In operation, the error signal fed to Q8 effectively *modulates* the value of current that Q8 sinks. If Q8 sinks more current than Q6 sources, a negative output signal results and vice versa.

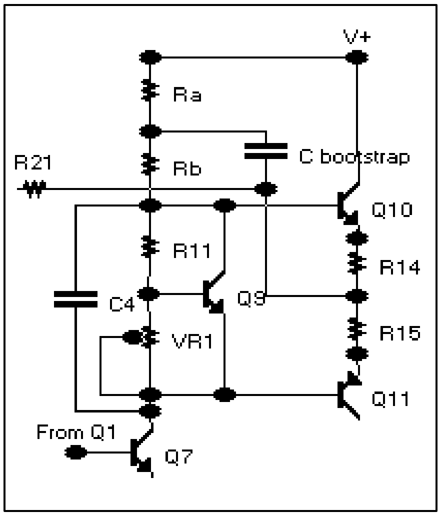

Figure 3 "Bootstrap" capacitor as constant current source

Instead of the constant current source transistor Q6, some amplifier designs use a "bootstrap" capacitor to provide the high impedance collector load for the voltage amplifier (see Figure 3). Under no-signal conditions, the bootstrap capacitor has a DC voltage across it equal to about one half of the positive supply voltage (when resistors Ra and Rb are the same value). Since the voltage across a capacitor cannot change instantaneously, this DC voltage "rides" on top of any signal at the amplifier's output. Rb therefore, has a constant DC component across it but no AC component. In other words, Rb acts as a constant DC current source and an infinite AC resistance. At high signal amplitudes, the voltage at the Ra / Rb junction actually exceeds the positive supply voltage. Without the bootstrap capacitor, the reduced current that flows through Ra and Rb as the output signal swings more positive, severely limits the output stage's ability to deliver current to a load.

7. The Cascode Follower

In some designs, the collector of Q8 is connected directly to the output stage to provide the first point in the amplifier where high signal amplitude is present. However, a common emitter stage operated in this way has two major limitations. Firstly, the gain linearity of a transistor is partly dependent on its collector-emitter voltage and will vary as the signal swings. Secondly, the inherent capacitance within a transistor's base-collector junction results in the so-called "Miller effect" when amplified by large signal voltages at its collector. This effect severely limits the high frequency response of the stage. Both these limitations are overcome by maintaining Q8's collector-emitter voltage at a constant value through the use of Q7.

The voltage at Q7's emitter is held at one diode drop above Q8's emitter through the use of diodes D3, D4 and resistor R12. Q7 passes the same current as Q8 and "sees" a large signal amplitude at its collector but isolates this signal from Q8. Q7 operates as a "common base" transistor stage, where the input signal – Q8's collector current - is applied to its emitter, not its base. Ultimately, Q7 "sinks" a signal *current*, which in conjunction with the current sourced by Q6, results in a large amplitude signal voltage at their collectors. This signal now only needs "buffering" by the high current gain of the output stage before being fed to the loudspeaker load.

If Q7 were to go open-circuit, the amplifier's DC output would swing completely to the positive rail because there would be no way for the input stage to control the output via Q8. However, if Q7 were to go short-circuit, the amplifier could continue to work normally, but Q8 – a small signal, low power device - would suffer from excessive dissipation and most likely fail, causing similar fault symptoms.

If the current sources Q5 and Q6 were both unable to deliver current – as would be the case if R9 was open circuit – the entire output stage would be left “floating”, and would not pass signal. Only the (negligible) leakage currents in Q6 and Q7 would determine the amplifier’s DC output voltage. The low resistance of a speaker connected to the amplifier would most likely tie the output line to zero volts. If checked in this state, it could be wrongly concluded that the amplifier’s DC operation was OK.

8. The Thermal Compensation Transistor

To eliminate the “crossover” distortion inherent in a Class B audio output stage, a quiescent or idling current must flow through the output devices – in this circuit, Q12 and Q13. To achieve this, transistor Q9 is used to maintain a constant voltage between the bases of the driver transistors Q10 and Q11. These in turn allow output stage idling current to flow.

A zener diode is a familiar device that exhibits a constant voltage between its terminals when a current flows through it. Here, Q9 acts as a “variable” zener diode in that the voltage between its collector and emitter terminals (its “VCE”) is adjustable to any desired value. More importantly, by being mounted on the same heatsink as the output transistors, its VCE changes with heatsink temperature to compensate for their characteristics. At any given heatsink temperature, Q9’s VCE in dependant only on the ratio of the resistor values connected to its base terminal. In this circuit, potentiometer VR1 is in parallel with Q9’s base-emitter junction and so has about 0.6 volts across it. If we disregard Q9’s base current, we can see that the current that flows through VR1 also flows through resistor R11, and so the total voltage across VR1 and R11 is –

Q9 VCE = 0.6 (VR1 + R11) / VR1

Let’s say that we require Q9’s VCE to be 2.4 volts. With a VR1 value of say 1Kohm, R11’s value would need to be 3Kohm. Adjusting VR1 alters its ratio to R11, resulting in a change to Q9’s VCE. If Q9 itself were to go short circuit, the output stage would not pass any idling current, but would otherwise continue to work normally. An open circuit Q9, or a failure of any surrounding component that prevents Q9 from conducting, will result in destruction of the amplifier due to the large current flowing through the output devices.

Capacitor C4 ensures that Q10 and Q11 each “see” the same AC signal swing. Theoretically, it would not be needed if Q9’s action were “perfect”. In practice, the signal amplitude at Q11’s base is very slightly higher than that at Q10’s base because of the attenuating effect of Q9. If C4 were to go short circuit, its effect on the amplifier would be the same as in Q9’s case – no bias current. An open circuit C4 however, would have virtually no effect on the amplifier’s operation.

Note that, as drawn in this circuit, a failure of the wiper of VR1 to make contact with its resistive track would simply turn Q9 on harder and reduce output stage idling current. In some designs however, VR1 and R11 are transposed. In that case, a similar failure in VR1 would have the opposite effect and, while an outright failure of the output stage is unlikely, a higher than normal idling current would flow and the amplifier would run much hotter. Since preset potentiometers spend most of their life set to one position, a film can develop on their resistive track through oxidation effects, dust, etc. When adjusting output stage bias current after repairing an amplifier, a wise precaution is to rotate the potentiometer’s wiper several times over the entire track - with the power turned off – before the actual adjustment procedure is performed.

9. The Output Stage

We have already seen that the signal amplitude at the collector of the Cascode Follower Q7 (or that at the collector of Q8, if Q7 is not used) is large enough to drive a loudspeaker load. But since it has only a limited current capability, it cannot be used to drive the load directly. The Complementary Darlington Emitter Follower Class AB Output Stage – to give it its full name - provides the signal current that is needed to drive the load at high power.

The term "Complementary" refers to the use of opposite polarity devices, the most commonly used being NPN and PNP bipolar transistors, and P-channel and N-channel MOSFETs. In this circuit, NPN transistors Q10 and Q12 handle the positive half cycle of the output signal while PNP transistors Q11 and Q13 handle the negative half cycle. During the time that one half is conducting, the other half is "cut off". When operating in this way, an output stage is said to be in "Class B". By running a "bias" or idling current simultaneously though both halves, "Class AB" operation results. The use of both positive and negative supply rails, together with the fact that one side of the load is connected to ground, means that a complementary output stage configuration is the most suitable.

A transistor operated as an emitter follower has a large current gain but a voltage gain of less than unity. Two cascaded emitter follower stages – Q10 and Q12 for example – are referred to as being connected in a "Darlington" configuration, which provides an extremely high overall current gain. The output transistors Q12 and Q13 each has its own emitter resistor, R16 or R17 respectively. The circuit of Figure 1 shows a single output transistor for each half of the output stage, but many designs use multiple devices connected in parallel, each with its own emitter resistor. This allows a higher power capability and/or the ability to drive lower impedance loads. R14 and R15 are the emitter resistors for the driver transistors Q10 and Q11 respectively. Figure 4 shows a variation where R14 and R15 are replaced by a single resistor connected between the emitters of Q10 and Q11, with no connection from either transistor to the output line.

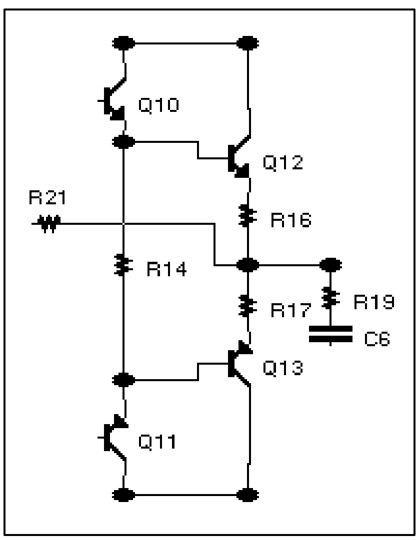

Figure 4 Drive transistor single emitter resistor configuration

Emitter resistors promote current sharing amongst multiple paralleled devices. They also compensate for the tendency of transistors to pass more current as they heat up. If the forward bias on a transistor is not controlled, it will go into "thermal runaway" and destroy itself. The increased voltage drop across its emitter resistor due to the increase in emitter current flow reduces the forward bias on the transistor. This action should not be confused with that provided by the Thermal Compensation Transistor Q9. *Its* purpose is to compensate for the temperature dependence of the output transistors' base-emitter voltages.

An open circuit in either R16 or R17 will prevent the output transistor connected to that resistor from driving the load. If this happens, a signal observed at the amplifier's output may appear symmetrical when the amplifier is not connected to a load, but asymmetrical when the amplifier is loaded. This indicates a lack of drive from one of the output transistors.

When tracing the cause of an offset voltage at the amplifier's output, it may sometimes be desirable to disconnect the output transistors from the rest of the circuitry if any doubt exists about the bias circuitry's ability to control idling current. As long as the feedback loop remains intact, this technique is quite permissible. In figure 1, it can be seen that even if Q12 and Q13 were not fitted, the feedback loop remains intact because R14 and R15 connect Q10 and Q11 to the output line. Whilst obviously not capable of driving a load in this state, the amplifier can otherwise still be checked for AC signal flow and DC conditions. However, to maintain the integrity of the overall feedback loop when using this technique in the circuit of Figure 4, it would be necessary to temporarily connect resistors from the emitters of Q10 and Q11 to the output line.

10. Amplifier stability

So far, the analysis of the amplifier circuit of Figure 1 has concentrated on the DC operation of each stage, which should help with the diagnosis and repair of most faults. However, some amplifiers exhibit high frequency oscillation or wrong signal gain. These problems require an understanding of those components in the amplifier that determine its AC performance and stability.

We accept that if a signal is applied to an amplifying stage, an output signal from that stage will result. Whether or not the input and output signals resemble each other is not important here. What *is* important is that the output signal is *delayed* with respect to the input signal due to capacitive effects within transistors. To humans, this delay is imperceptibly short – but there, nonetheless. Each cascaded stage adds to the overall delay. For any given delay, there will exist a signal frequency whose half cycle period equals that delay. This can also be viewed as phase inversion at that frequency. Now what has all this to do with stability?

The amplifier circuit in Figure 1 is just such a series of cascaded stages. The differencing stage (transistors Q1 and Q2) expects the input and feedback signals to be in-phase. But the phase of the feedback at that previously described critical frequency stage is inverted. This *positive* feedback makes the amplifier unstable and it oscillates at that frequency. To prevent this, the amplifier's forward gain - the gain available from the base of Q1 through to the output - is rolled off at high frequencies by the combination of resistor R6 and capacitor C3. These components ensure that at the critical frequency, the amplifier's gain is so low that no feedback signal is available – and no oscillation can exist. Any open circuit in these components will result in high frequency oscillation.

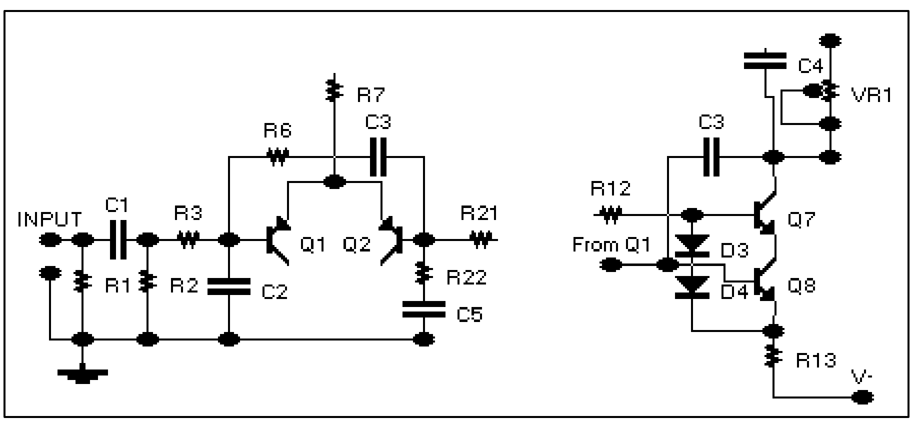

Figure 5a **Figure 5b**

Alternative Frequency Compensation methods

Figures 5a and 5b show alternative locations for the frequency compensation components R6 and C3. In Figure 5a (as in Figure 1), very little or no AC or DC voltage appears across C3. In Figure 5b however, C3 is subjected to large voltages and care should be taken that the replacement component has an adequate voltage rating.

Just as the amplifier's forward gain can affect its stability, so too can the gain (or more correctly, the attenuation) of the feedback network – resistors R21, R22 and capacitor C5. You will recall that the overall (or "closed loop") gain of the amplifier is set by the equation, (1 + R21/R22) and the gain at DC is unity due to the presence of C5. Open circuits anywhere in the series path through R22 and C5 to ground reduce the AC gain to unity by allowing full negative feedback. However, at the critical frequency described earlier, the feedback is *positive* and the amplifier may oscillate. A short circuit in C5 has no effect on the amplifier's AC (signal) gain or stability, but may cause a DC offset of up to several volts to appear at the amplifier's output. This is because any difference between the base-emitter voltages of the differential pair transistors Q1 and Q2 is considered to be a valid signal (albeit a DC one) and is amplified by the closed loop gain. When tracing the cause of a small DC offset at the amplifier's output (up to around 5 volts or so), first check that Q1's base is at ground potential - if it is, replace C5.

Moving now to the amplifier's output, the series network of R19 and C6 provides a high frequency path to ground that is independent of the loudspeaker load. High frequency, large amplitude output signals such as those that occur under "clipping" conditions, may cause R19 to get hot and if it (or C6) was to go open circuit, the amplifier may oscillate. In my experience, these components are the first to be suspected when diagnosing an unstable amplifier.

The output choke L1 and resistor R18 isolate the feedback loop from the loudspeaker load. The combination provides a rising series impedance with frequency, limited only by the value of R18. Without these components, any capacitance at the amplifier's output, such as that exhibited by lengthy speaker cables, can delay the phase of the feedback and may cause instability. Failure of either component is unlikely, but broken connections or shorts across components can all cause problems.

When repairing any amplifier, care should be taken when replacing transistors with substitute devices. Most technicians will be well aware of the need to consider the DC characteristics of a substitute transistor – its voltage, current and power ratings. Equally as important in a feedback amplifier however, is the transistor's transition frequency (Ft) specification. Its value can range from several hundred Kilohertz (KHz) for some power devices to several thousand Megahertz (MHz) for small signal devices. The values of the frequency compensation components C3 and R6 take into account the Ft ratings of all the devices in an amplifier. If a substitute device is fitted that has a lower Ft rating than that of the original part – and this is more likely to occur with large power output devices - the amplifier will more than likely oscillate. As an example, many older Yamaha amplifiers use TO3-case power transistors in their output stages. These devices have an Ft rating of around 10MHz. The familiar 2N3055 power transistor would appear to be a suitable substitute but its Ft rating of 500KHz would almost guarantee amplifier instability if it were used.

Some output stage devices, particularly MOSFETs, are very sensitive to the inductive effects of some types of wirewound emitter (or source) resistors. Some circuits use several paralleled carbon or metal film 1 watt resistors per device instead of a single 5 watt wirewound resistor. If the replacement resistors are not the correct types, amplifier instability may result.

Finally, mention needs to be made about grounding and its effect on an amplifier's AC and DC stability. You will notice in the circuit diagram of Figure 1 that separate ground returns back to the power supply exist for the amplifier's front end and loudspeaker. The reason for this is to prevent large output signal currents from affecting the integrity of the input signal earths. The negative speaker terminals on most amplifiers are connected back to the power supply by heavy gauge wires or circuit board tracks. The power supply is in turn connected into the amplifier's chassis. The power amplifier's input ground – the one that the differential pair uses – is usually grounded either directly into the chassis, or indirectly through a preamplifier, and then into the chassis.

If the differential pair loses its ground reference, the DC voltage at the amplifier's output will "float" between the power supply rails because the differential pair has no way of "knowing" what ground is. If you have removed a circuit board or rear panel in order to obtain easier access when tracing this fault symptom, be careful that you have not inadvertently removed a ground return as well!

11. Conclusion

When diagnosing a power amplifier problem, the fault symptom gives a clue as to which part of the circuit is most suspect. A "blown up" amplifier – one that has destroyed its output stage – is unlikely to have been caused by any problem in its front end. Once the (obviously) damaged components are replaced, the amplifier should be fully functional. However, an amplifier whose output line exhibits a voltage offset – but which hasn't "blown up" – may have a problem in its front stages, or feedback loop, or even its grounding. There would be little point in initially suspecting output stage components or bias circuitry. Oscillation, as we have seen, is most likely due to failure of one or more of the frequency compensation components within the circuit.

Joseph Pantalleresco
Technical Support Coordinator
Professional and Music Products
Yamaha Music Australia

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