

Rehabilitating Cathode Followers

Are cathode followers poorly suited to driving capacitive loads in comparison to common cathode amplifiers?

The answer may surprise you.

By Christopher Paul

I was flipping through some old audio magazines and was surprised to discover that it has been over 20 years since I presented the then as-yet-to-be-named “Mu Follower” circuit in the pages of *The Audio Amateur*¹. A quick Google search of the phrase revealed ongoing interest in the circuit, from audiophiles presenting and discussing what they’ve built to advertisements for commercial products that feature it. People have made many modifications including using different triodes for the top and bottom tubes and even replacing the top tube with a pentode!

Like any circuit, however, it has its limitations and has attracted its share

of criticisms. Probably the predominant criticism relates to the fact that its output is essentially a cathode follower (CF). And we all know how poorly those circuits drive capacitive loads, right? I mean, the CF tube actually disconnects from the load on the negative stroke, doesn’t it?

This belief in the unsuitability of the CF for driving capacitive loads is widespread. Even a well-regarded web-published reference on tube design actually shows a schematic with a CF output line stage that sports a graphic of a bomb with a lit fuse!

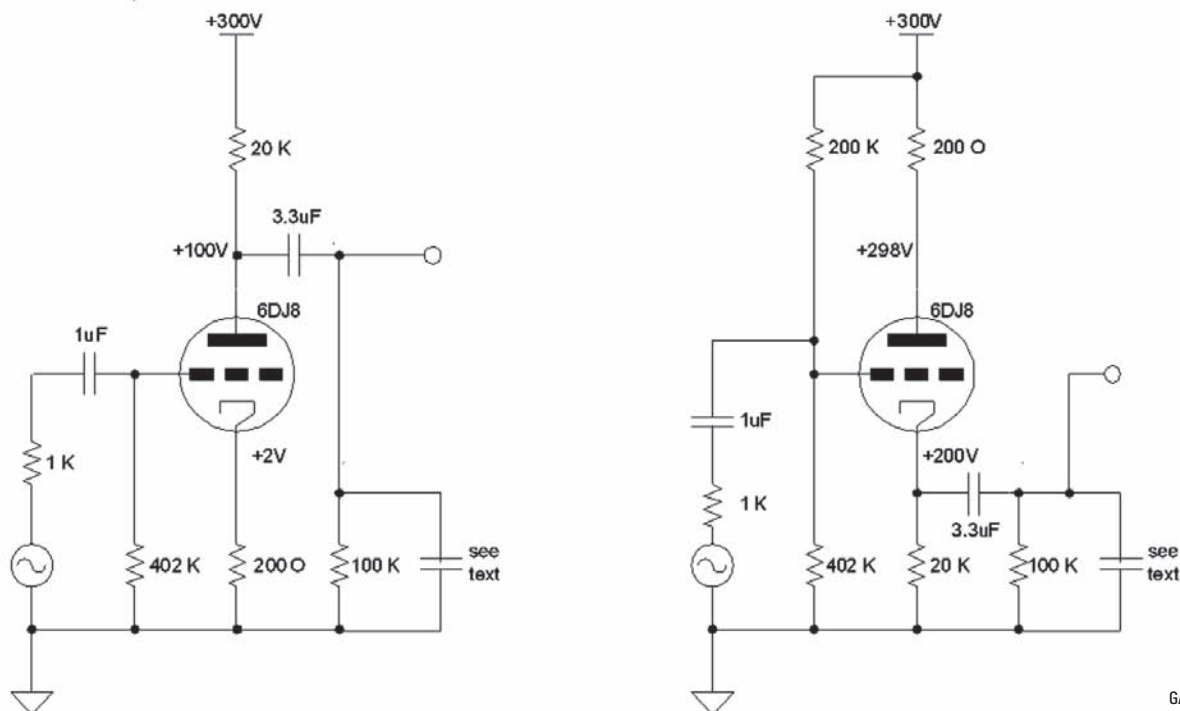
But how bad is it in actuality? I’ve never encountered an attempt to quan-

tify this problem, yet I’ve always wondered about it myself. So I thought I’d take a stab at it.

THE CF INDICTMENT

As I understand it, the basic concern is as follows. A line stage output swings over the range of several volts. If it’s a cathode follower, its grid swings over approximately the same range as its cathode (actually, a little more). If the cathode is coupled to ground through a capacitor and if the grid drops far enough quickly enough, the cathode may fail to keep up with the grid and the tube might completely stop conducting current. Then the only thing that can pull the output down

FIGURE 1: The common-cathode amplifier on the left is the “equivalent counterpart” of the cathode follower on the right.



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is the cathode bias resistor, a weak passive device that is not up to the task of preventing distortion because it can't change the capacitor voltage quickly enough.

This is thought not to be the case with the common-cathode amplifier (CCA). With the load capacitor connecting the plate to ground instead of the cathode, the grid can swing as quickly as it likes and the cathode will tend to follow it; there is no capacitor to prevent the cathode from doing so. Even if there is a cathode decoupling capacitor, the signal on the grid is usually much smaller than that at the output because of the gain of the amplifier. The grid simply doesn't travel far enough to bias the tube off, or so goes the argument.

To determine the validity of this point of view, you must take a quantitative instead of a qualitative tack. You need to propose and run a test in which you can subject a CF and its equivalent CCA counterpart (whatever that means) to the same challenging loads and compare their performances.

DESIGNING THE TEST

First, consider the question of what "equivalent counterpart" CCAs and CFs would look like. I would argue that circuits using the same triode type biased to identical plate voltages and currents and having identical static and dynamic load lines would fit the bill. A suitable pair might employ 6DJ8s set for 100V and 10mA. The CCA would have its grid biased to 0V DC, a cathode resistor of 200 Ω , and a 20K plate resistor connected to a 300V DC supply.

The CF would be constructed by swapping the CCA plate and cathode resistances, maintaining the 300V plate supply and biasing the CF grid to about 200V DC. 6.3V DC heater supplies would be tied to each cathode. A large coupling capacitor would connect the outputs to a ground-referenced capacitive load. I chose a 3.3 μ F capacitor I had handy for output coupling.

You need to define a capacitive load. For a long time, 1nF was considered to be a standard for a severe load provided by a line stage cable. You could argue this choice, but it seems a reasonable first selection; I'll get to more severe loads later on.

In parallel with 1nF, place a 100k Ω

resistor that represents what might appear at the input of a tube power amp. **Figure 1** shows the completed CF and CCA circuits.

Now you need to choose a load signal. Audio signals are band-limited, so it is unreasonable to employ, say, a square wave at the stage inputs. A sine wave should do. You'll need a high audio frequency and level to get a large slew rate and to allow the capacitor to present the biggest drive challenge. I think 2V RMS is a reasonable choice for an output at line levels; any higher and just about any power amplifier is going to experience more problems than the line stage driving it. (Of course, to establish identical output load levels, the AC signals at the grids of these two circuits will differ to compensate for differing circuit gains.)

For a frequency, let's get silly and choose 20kHz. I hope no one really expects to be dealing with a signal like this and that if they do, they will at least concede that signal levels fall off at more than 6dB per octave above this frequency. That means the load will still demand the highest peak current at 20kHz.

With circuit details, load, frequency, and signal level defined, you should check the dynamic load line on the plate curves for any problems before you actually perform the test. From **Figure 2**, (which shows this load line), note first that the circuits are not making any significant deviations from the zero signal operating point—the signal varies by only a few volts and less than .5mA out of the available 10. So don't expect any gross distortion, "disconnection from the load," or "failure to follow" the signal applied to the grid.

Second—and here's what's really interesting—did anybody notice that I didn't mention circuit topology? This dynamic load line should apply to both the CF and the CCA, suggesting that you should expect similar performances from the two circuits.

TEST MEASUREMENTS

Sure enough, when you build and test the circuits, your expectations are borne out. Neither circuit exhibits any visible misbehavior, as you can see in **Figs. 3** and **4**. It looks as though you'll need to

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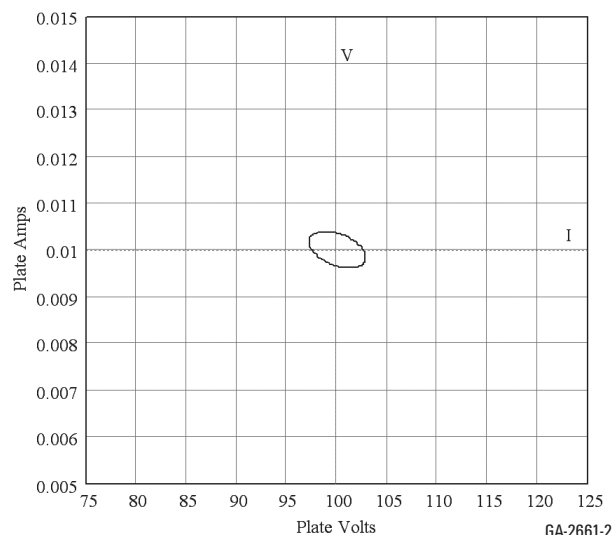
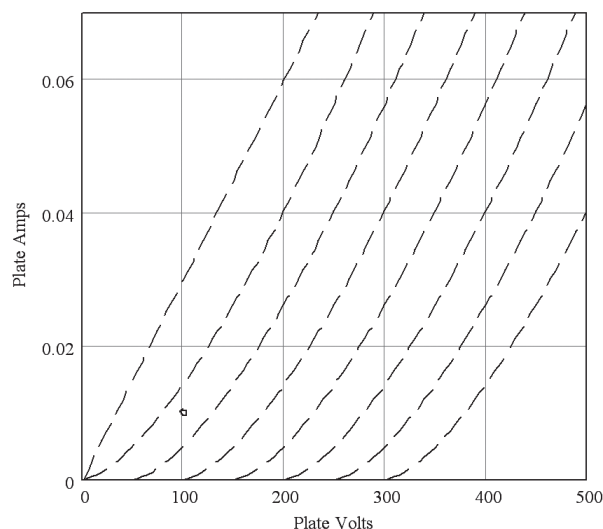
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FIGURE 2: Load line (full scale and zoom) of CF and CCA with 1nF load capacitances (plate and curves shown are approximations only).



work harder to get the CF at least to grossly distort.

Back to the load line examination then. Increase the value of load capacitance to 22nF. **Figure 5** shows that although there is much more variation in plate current, in neither circuit should

the tube shut off.

I'm sure that distortion has risen significantly, because the tubes are now operating within the compressed portion of the plate curves, but neither tube should yet be disconnecting from the load. The test results of **Figs. 6** and **7** bear this out. At

22nF, the CF still refuses to disconnect or to behave any worse than the CCA.

I needed to increase the load capacitor to 47nF before the load line in **Fig. 8** would predict a problem. Under these conditions, the tube was being called on to pass a negative plate current, some-

FIGURE 3: CCA output with a load capacitance of 1nF.

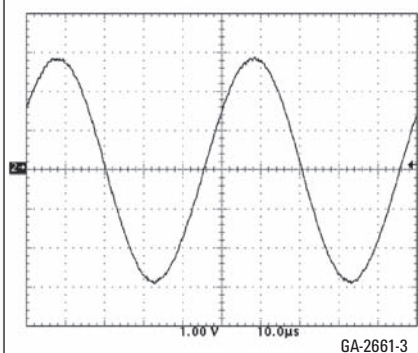


FIGURE 5: Load line of CF and CCA with 22nF load capacitances (plate curves shown are approximations only).

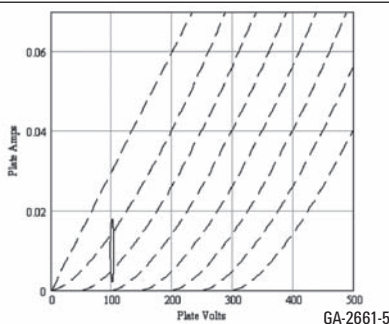


FIGURE 7: CF output with a load capacitance of 22nF.

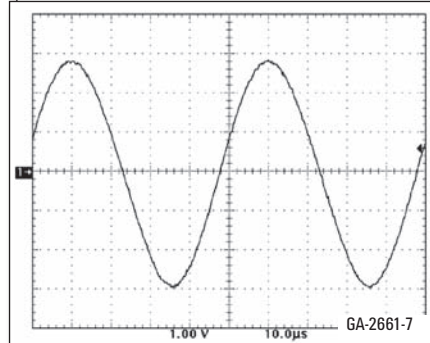


FIGURE 4: CF output with a load capacitance of 1nF.

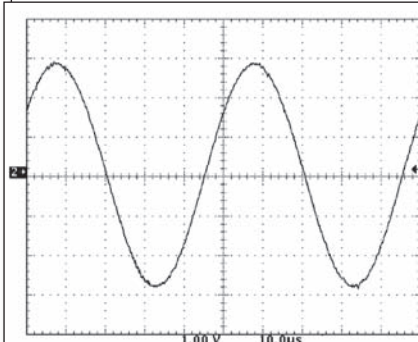


FIGURE 6: CCA output with a load capacitance of 22nF.

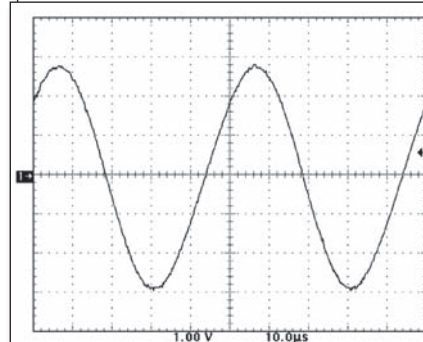
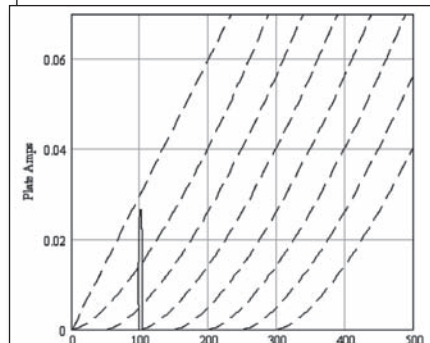


FIGURE 8: Load line of CF and CCA with 7nF load capacitances (plate curves shown are approximations only).



Well, yes. That is, if you're looking only at distortion. But what about frequency response? Here the CF actually has an edge over the CCA.

The output impedance of this CF is around 100Ω, giving a 0.1dB breakpoint of 80kHz into a 1nF load. But the CCA's output impedance of about 20K || ($\mu = 30$) * (200 + 100) Ω = 6200Ω gives a 0.1dB breakpoint of 1300Hz. Even if you completely bypass its 200Ω cathode resistor with a capacitor to get a plate impedance of 2600Ω, the 0.1dB breakpoint rises to only 3100Hz. Certainly not audio-grade performance!

To flatten out the response and form an acceptable line driver, the CCA must be placed within a feedback loop to lower its effective output impedance. The CF has no such limitation. You have a choice of whether or not to use a CF within a feedback loop.

A COMPOUND DRIVER (CD)

Although it would seem that the CF and CCA are up to the tasks of driving any load seen within or by a preamp or line stage, other applications such as driving a headphone directly might make you wish for a driver that excels in both sourcing and sinking current. The obvious next step is to combine the advantages of both circuits by stacking a CF on top of a CCA as shown in **Fig. 12**. This is nothing new and has been done extensively in the past.

I have chosen to retain the previous operating points, although the opportunity exists in this stage to reduce bias currents and improve efficiency. Operation at reduced bias might have come at the cost of increased low-level distortion due to descent into the more compressed portions of the plate curves.

One of the goals of this circuit is to apply drive signals that are identical in

magnitude, but opposed in phase, between the grid and cathode of each of the two triodes. Matching the magnitudes ensures a proper balance in the two sections, and of course the phase inversion is necessary for the proper operation of the driver.

All this is accomplished with the transistor phase splitter. Purists may gasp in dismay at the intrusion of transistors into hallowed thermionic ground, but this component is there because it forms a simple circuit that is visibly (on the scope, at least) linear over the full range of operation until it cuts off, from delivering the maximum drive to the CCA to doing so for the CF. I chose this in favor of a triode; I did not want the nonlinear plate curves of a triode phase splitter near its point of cutoff to cloud the operation of the driver.

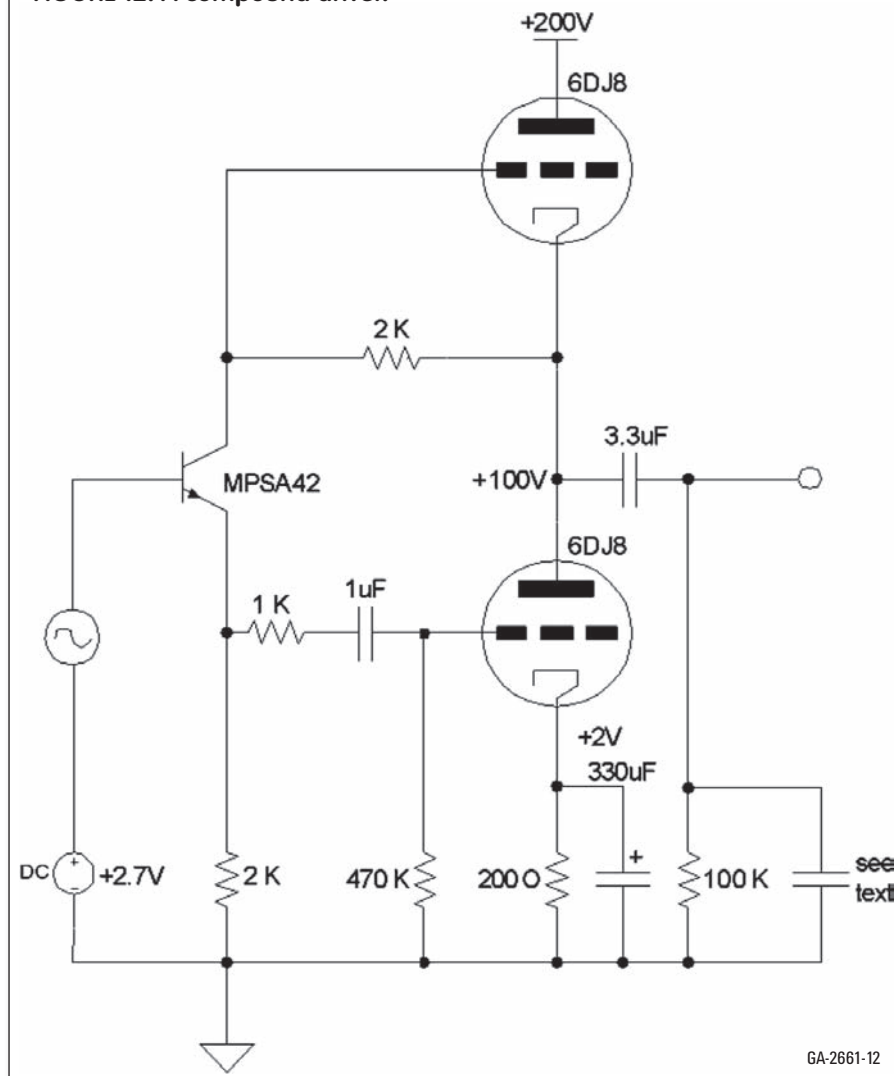
Another point should be made about the CD as well as the CF and CCA: none of the triodes in these circuits can be driven to pull grid current during the application of steady-state sine waves. The three capacitively coupled grids prohibit this; if they were to draw a current on positive peaks, a DC voltage would be established across the capacitors which would re-bias the grids to a point just below that required for grid current to flow.

As for the CF triode in the CD, you can see that the current flowing through the resistor between its cathode and grid into Q2 can flow only in a direction that prevents its grid from being more positive than its cathode, thereby precluding grid current. This establishes a convenient maximum current, common reference point for the purposes of comparing all stages.

So how does the CD drive a 47nF capacitor? Very well, as you can see in **Fig. 13**. **Figure 14** shows that it also does well with a 100nF capacitor (although there is a little compression of the signal at the peaks and troughs). This is a good thing; it needs to do better than twice as well as two CFs or CCAs, or else you would just parallel a pair of those two circuits and avoid the complexities of the CD's phase splitter!

The explanation for this superior drive capability is evident from a glance at the 6DJ8 plate curves. For a peak current drive of $E_c = 0V$ and $E_p = 100V$, 40mA of plate current can be had! Of course, you wouldn't want to bias a triode anywhere

FIGURE 12: A compound driver.



near that point, or else you'd exceed the power ratings for the tube and burn it out.

One other point should be noted. Because of the positive feedback from the CD's CF's cathode to its grid through the 2K resistor, the CD's output impedance is much higher than that of a CF. In fact, it is closer to that of a CCA. You could easily see this by finding what value of resistive load placed at the CD's output would cut the output signal level in half. So like the CCA, the CD would need to be enclosed in a feedback loop to have a low enough impedance to drive a 1nF capacitive load over the full audio bandwidth.

PRACTICAL CONSIDERATIONS

For all three of these circuits—and, in fact, for just about any topology—it is always wise to insert a resistor whose value is commensurate with the required frequency response between the stage output and a capacitive load. Such a resistor can help to prevent oscillation (especially when inter-stage feedback is involved) and provides some limit on the current being called for in the case of unexpected

high frequencies such as RF interference. This can have the salutary effect of reducing distortion within the system as a whole. This wasn't done in the circuits presented here because I wanted to let the load capacitors do their worst.

BACK TO THE MU FOLLOWER

Please excuse me for returning to this subject, but it's my involvement with this circuit that got me to do the research for this article in the first place. I hope I've addressed the concerns of those of you who mistrusted both CFs in general and the use of one in this circuit in particular.

I would like to ask the audio community for a favor. I very much doubt that I was the first to discover the combination of low distortion/high gain ($\sim \mu_{\text{bottom}}$), low output impedance ($\sim 1/gm_{\text{top}}$), and high power supply rejection ($\sim \mu_{\text{top}}$) that this relatively simple circuit has to offer^{1,2}. Does anyone have an earlier reference to a discussion of the characteristics of this topology? Please, no SRPPs! This circuit may have its own charms, but none of them are among those cited above for MFs. The "SRPP" dates from

US patent 2,310,342 issued in 1943, which, by the way, mentioned neither the acronym SRPP nor any term that gave rise to it. (Anyone know where *that* came from?)

CONCLUSION

I've shown both by experiment and by explanation that a cathode follower can drive a capacitive load just as well as an identically biased common-cathode amplifier. The CF, in fact, has an edge over the CCA in that its lower output impedance can drive a 1nF cable with a flat frequency response over the audio range without recourse to enclosure within a feedback loop.

I trust that I identified and addressed the concerns that people had about CFs driving capacitive loads. If you think I've missed something or just flat out disagree with what I've written here, let's hear about it in the *Letters* pages of *audioXpress*! *ax*

REFERENCES

1. Christopher Paul, Letters to the Editor, *TAA* 2/85, p. 51.
2. Christopher Paul, Letters to the Editor, *TAA* 3/91, p. 43.

FIGURE 13: CD output with a load capacitance of 47nF.

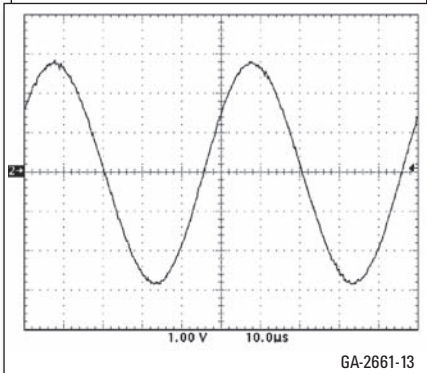
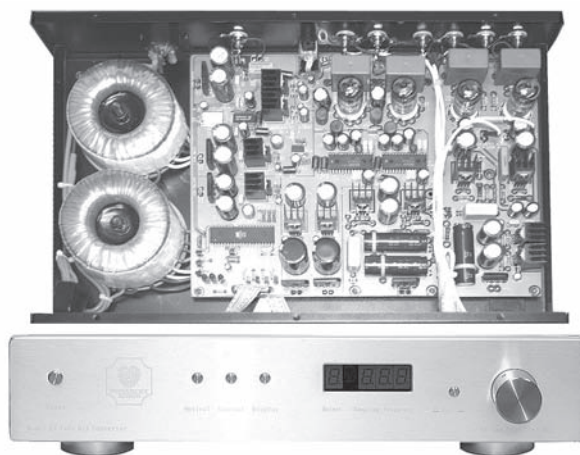
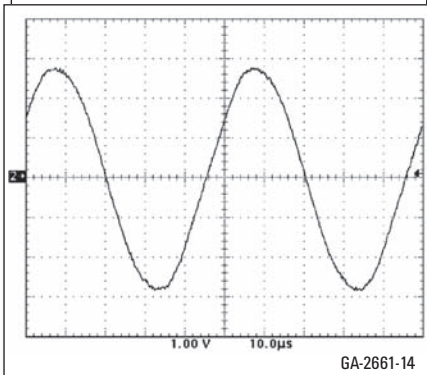


FIGURE 14: CD output with a load capacitance of 100nF.



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