Automatic Gain Control (AGC) Hardware Implementation

David Finch
Power Systems Application Lab
STMicroelectronics, Inc.

OVERVIEW

This document describes the implementation and considerations of a low-cost, highly reliable AGC solution. It is intended to be used as a reference document for employees of Quartet Technology, Inc. and STMicroelectronics, Inc.

The task of maintaining a regulated peak-to-peak amplitude of a sinusoidal signal can be realized with a number of solutions, yet the task itself is nontrivial. The prototype circuit described in this document was designed to drive the ADC in a Voice Recognition system. The chief design objectives are as follows:

- Maintain a constant signal amplitude of approximately 1.5 V_{PP}
- Accurate spectral reproduction of user's voice
- Consistent, reliable audio processing
- Low cost (sub $5 US)

The advantages to using an AGC loop prior to A/D conversion include:

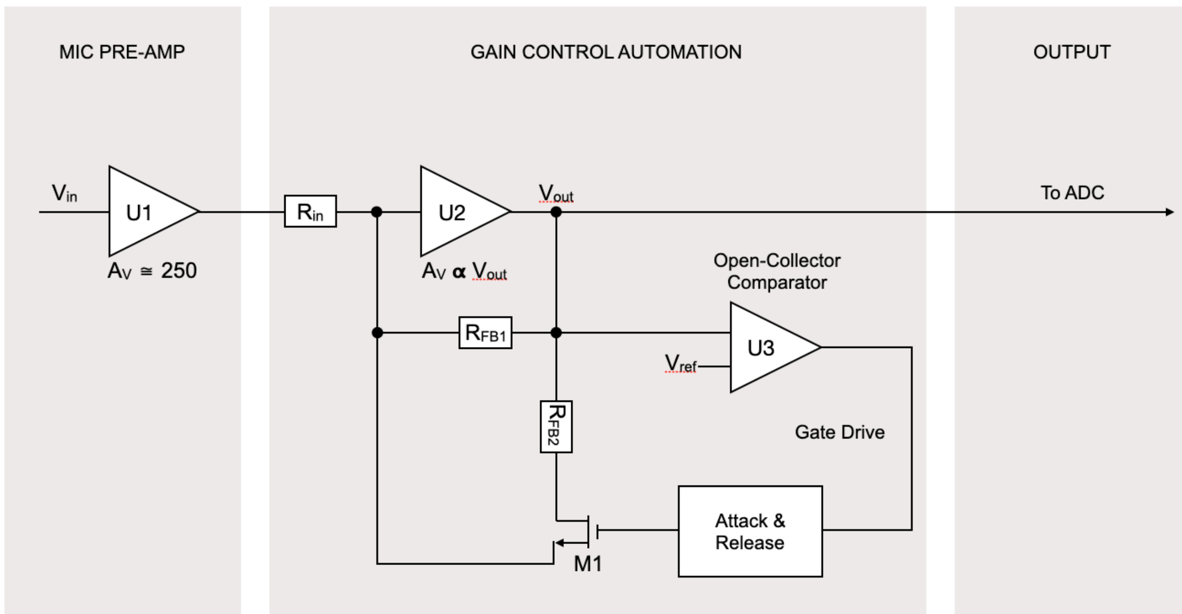
- More comfortable, "natural" command vocalization for the user
- Improved system performance for individuals with physical or neurological impairments which would limit or inhibit the motor skills required to manually adjust a gain potentiometer or to maintain suitable on-axis positioning with an input transducer
- Potential increase in DSP word recognition rate for any user
- Support for low-cost, low-output-amplitude transducers, such as generic electret microphones

The following sections describe the AGC circuit, providing a theory of operation, design objectives and challenges, layout considerations, component selection, and testing methodology.

THEORY OF OPERATION

This AGC solution employs a feedback architecture. In contrast with a feed-forward design, the feedback architecture significantly reduces the number of components required; operating on the low-amplitude transducer signal in a feed-forward environment requires additional gain staging and, in this case, presents no significant advantage.

A simplified block diagram is provided here (please refer to figure A-1 for the complete practical schematic):



Simplified block diagram illustrating AGC mechanism.

Op amp U2 is the central audio amplifier in the loop; the gain of this device is controlled by the feedback circuitry. It is important to note that U2 has an *inverting* configuration, which allows the input signal amplitude to be amplified or cut (in this circuit, over a total range of 26 dB). The output of U2 is buffered and low-pass filtered, and ultimately drives the A/D converter. For microphones that output signals on the order of hundreds of microvolts or less, it will be necessary to drive the AGC loop with a separate, fixed-gain preamplifier. Care must be taken to ensure the stability of each stage.

The feedback network around U2 realizes automated gain control and comprises $\mathbf{R_{in}}$, $\mathbf{R_{FB1}}$, $\mathbf{R_{FB2}}$, **U4** (open-collector comparator, specified as such for two reasons), and MOSFET **M1**. The output signal, $\mathbf{V_{out}}$, is compared to a fixed DC reference voltage $\mathbf{V_{ref}}$ at U4 (not shown).

While $\mathbf{V_{ref} \propto V_{out.pk}}$, the MOSFET remains off. Therefore, during positive gain corrections with the MOSFET completely off, the gain of amplifier U2 is given by:

$$A_V = (R_{FB1}) / (R_{in})$$

When $\mathbf{V_{out.pk}}$ exceeds $\mathbf{V_{ref}}$, the output of U4 turns the MOSFET on, proportional to the amount by which $\mathbf{V_{out.pk}}$ exceeds $\mathbf{V_{ref}}$. This action modifies the gain of U2 by altering the total equivalent feedback resistance. Therefore, during negative gain corrections with the MOSFET in saturation, the gain of amplifier U2 is given by:

$$\mathbf{Av = (R_{FB1} || R_{FB2}) / (R_{in})}$$

Thus a suitable gain range has been determined, which at its limits is characterized by

$$\mathbf{A_{V,HIGH} = (R_{FB1}) / (R_{in})}$$
$$\mathbf{A_{V,LOW} = (R_{FB1} || R_{FB2}) / (R_{in})}$$

The associated gain factor of inverting amplifier U2 can be assigned a non-zero fractional value (greater or less than unity), thus affording an opportunity to amplify or attenuate the audio signal as needed. Typically, the signal coming from a microphone or from a mic preamp stage will require amplification rather than attenuation since the A/D converter with which the AGC circuit is interfaced specifies 750mV peak amplitude.

In the practical circuit shown in figure A-1, the values of the feedback path components have been selected such that:

$$V_{out,min} = 0.75 * V_{in} \quad \text{and}$$
$$V_{out,max} = 10 * V_{in}$$

Which, in decibels, equates to up to 2.5 dB attenuation and up to 20 dB amplification, respectively, yielding a total asymmetrical gain range of 22.5 dB. The loop gain has been designed to be somewhat narrow, specifically for this application. As the preamplifier provides approximately 48 dB gain — amplifying the microphone signal to an order of magnitude suitable for the codec — the AGC loop is designed for subtle gain corrections after the preamp stage.

Another important consideration is the gain correction attack/release time. If the circuit is designed to respond slowly to amplitude peaks, then it would be possible to drive the A/D converter with a signal amplitude in excess of the operating range for some length of time. At either extreme (clipping or low signal level), the signal distortion could be so severe as to fail the recognition engine. Conversely, a very fast, over-zealous response time will result in equally undesirable signal distortion resulting from the rapid fluctuations in signal level.

PRACTICAL DESIGN CONSIDERATIONS

This section presents practical information for the AGC loop and microphone preamplifier design. Measurement results are also provided.

Preamplifier

The preamplifier (preamp) stage is designed to support an ordinary electret microphone with an output on the order of hundreds of microvolts. Due to this low signal level, and for the sake of design simplicity, a very low-noise op amp is used. The LM833 dual low-noise op amp from STMicroelectronics specifies a noise figure of 4.5 nV/√Hz.

Two op amps are used in the preamplifier, each serving as a first-order low-pass filter (LPF) to minimize noise throughput. The critical initial stage provides a gain of 5:1. The subsequent stage provides 50:1 gain, for a total input gain of 250V/V (approximately 48 dB); the filter cutoff for each stage is roughly 4 kHz. Generally, any practical opportunity for noise filtering should be exploited.

The preponderance of gain activity in the preamp stage allows for subtle corrections in the AGC loop. Limiting the gain range of the AGC loop helps to eliminate signal distortion.

The microphone input is AC-coupled; further AC-coupling is recommended between the preamp and the AGC loop. In both cases, a 1.0 μF capacitor is sufficient.

AGC Loop

As mentioned above, the loop is responsible only for subtle gain corrections, due to the high gain of the input stage. The maximum amplification is $10*V_{in}$, and the maximum attenuation is $0.75*V_{in}$. The signal rarely needs attenuation under normal operating conditions, so the loop provides amplification until the peak signal voltage exceeds the designated reference voltage.

The loop evaluates peak voltages of the audio signal and compares this value to a fixed DC reference voltage. For best operation with the audio codec, a reference voltage of 750 mV to 850 mV is recommended; the circuit in figure A-1 provides an 850 mV reference.

TL431 Regulator

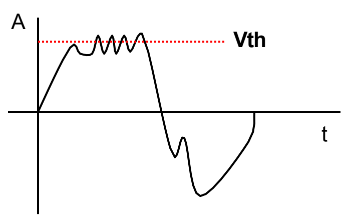
The TL431 regulator provides a 2.5-volt DC reference voltage. The device requires at least 1 mA at its cathode, and will operate up to 100 mA. Taking these two points into consideration, the TL431 reference voltage is divided to supply the AGC reference voltage, as shown in figure A-1.

The AGC reference voltage is applied directly to the inverting terminal of the LM393 open-collector comparator. Although the current draw on this terminal is relatively low, the TL431 circuit must provide some current to prevent overloading. Specifically, this regulation circuit should provide at least 10 mA to maintain a sufficient DC reference. Any further variations in the reference voltage can be compensated by a 1.0 μF capacitor across the TL431. Since the AGC reference voltage is particularly critical, resistors of 1% tolerance are recommended.

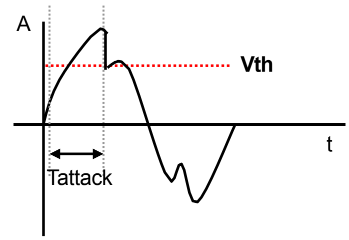
LM393 Open-Collector Comparator and Response Time

The LM393 comparator compares the peak signal level to a fixed DC reference, V_{ref}, supplied by the TL431 circuitry. While the peak signal amplitude exceeds Vref, the output swings high via pull-up resistance on the output pin. When the output swings high, the external MOSFET turns on, thus reducing the gain of U2 to a fractional value. This action can cause severe distortion if the overall gain of U2 is not kept relatively low.

Severe audio distortion can result from very high-frequency MOSFET switching, either by directly reshaping the amplitude with respect to time, or by way of radiated noise. The former can also occur for very slow attack times. The figures below illustrate the potential distortion associated with attack and release times:

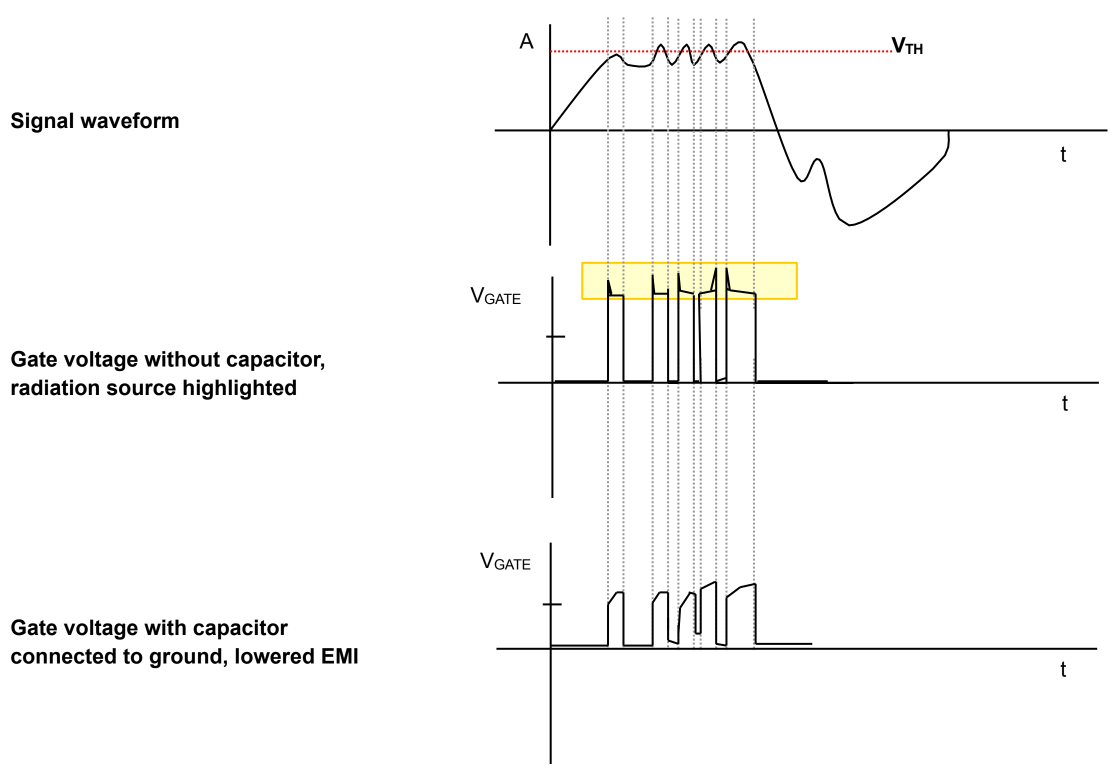


A. Very fast attack/release time



B. Slow attack/release time

To accommodate this delicate MOSFET gate timing issue, a simple mechanism is implemented with a 0.47 μF capacitor from gate to ground and an external gate resistance of 100 Ω. When the LM393 output swings high, there is some delay while the capacitor charges, but not so much as to let the signal amplitude exceed much higher than V_{ref}. Once the LM393 output returns to ground, the gate capacitor discharges. To extend the release time, a resistor can be added to the LM393 output pin. However, in this circuit, a quick release time is acceptable. The figures below illustrate how adding an external capacitance to the gate of the MOSFET eliminates potentially influential noise radiation:



LAYOUT CONSIDERATIONS

Because any preamplifier circuit will be prone to noise problems, it is necessary to follow some guidelines to insure reliable operation.

The three primary sources of layout-related noise in this circuit will be the switching action of the MOSFET, improper supply bypassing and signal filtering, and improper grounding.

To eliminate problems caused by the MOSFET gate action, the audio circuitry and control circuitry (namely, the LM393 and STS25NH3LL MOSFET) should be spaced at a reasonable distance from one another – at least 10 cm, ideally, with a generous amount of copper between circuits. Additionally, although each amplification stage is low-pass filtered, it is recommended to separate the final AGC signal stage from the input preamp signal network. This will ensure minimal high-frequency noise coupling in the preamp stage, since the control circuitry is part of the AGC stage.

Any high-frequency filter capacitors (such as C3, C4, C7, and C8) should be placed as close to the IC pins as possible, ideally no more than 1.5 cm from the pin, and should exhibit very low ESR characteristics. Supply bypassing is recommended for the Vcc rails; a 1.0 μF electrolytic in parallel with a 0.1 μF tantalum provides sufficient filtering.

Grounding is an important consideration. To avoid a problematic line hum, care must be taken to separate the power and signal grounds such that no ground loops are present in either path, with only **one** common ground node to connect the various ground paths.

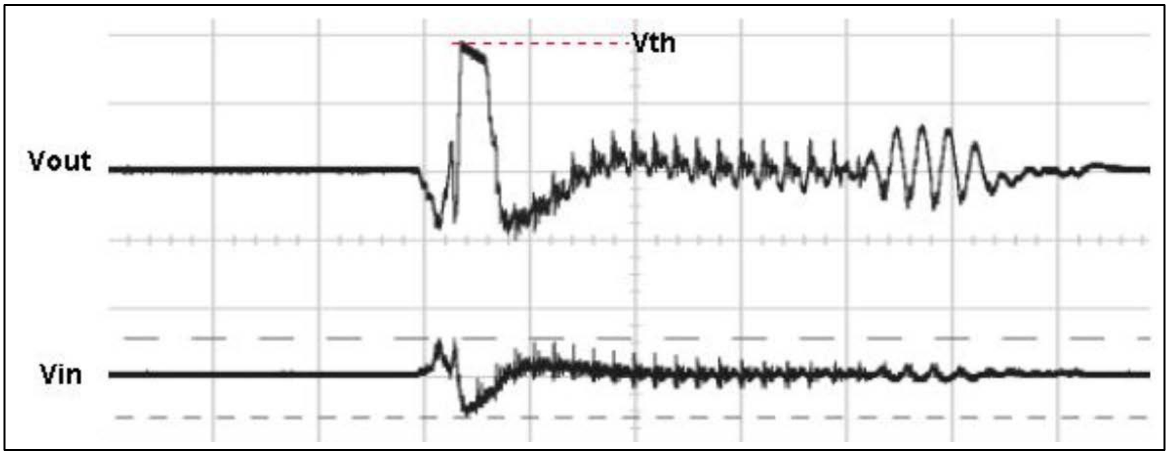
MEASUREMENT PROCEDURES AND RESULTS

The measurement process involved the use of a digitized speech sample for consistent replication during circuit analysis, and actual user vocalization to determine the approximate recognition rate in the field.

Design Verification

In order to verify the circuit operation under controlled, repeatable conditions, a voice command was digitized and stored, with a microphone boost of 20 dB to preserve signal integrity. The voice command sample was then converted to analog domain using the Audio Precision System II D/A generator, and attenuated by 20 dB to compensate the initial microphone boost. This signal was delivered to the microphone input of the AGC preamplifier.

Figure M-1: V_{out} vs. V_{in}, with time. V_{in} measured at output of preamplifier. NOTE: $V_{out,pk}$ does not exceed V_{ref} (V_{th}).



X: **10 ms/div**
Y: **500 mV/div**
Ch. 1: **$V_{out,p-p}$**
Ch. 2: **$V_{in,p-p}$**
V_{ref}: **850 mV**

Microphone: Omnidirectional electret
Voice Command: “Phone”

Figure M-2: (Top) V_{out} vs. V_{GATE}. (Bottom) V_{out} vs. V_{GATE} expanded to show detail.

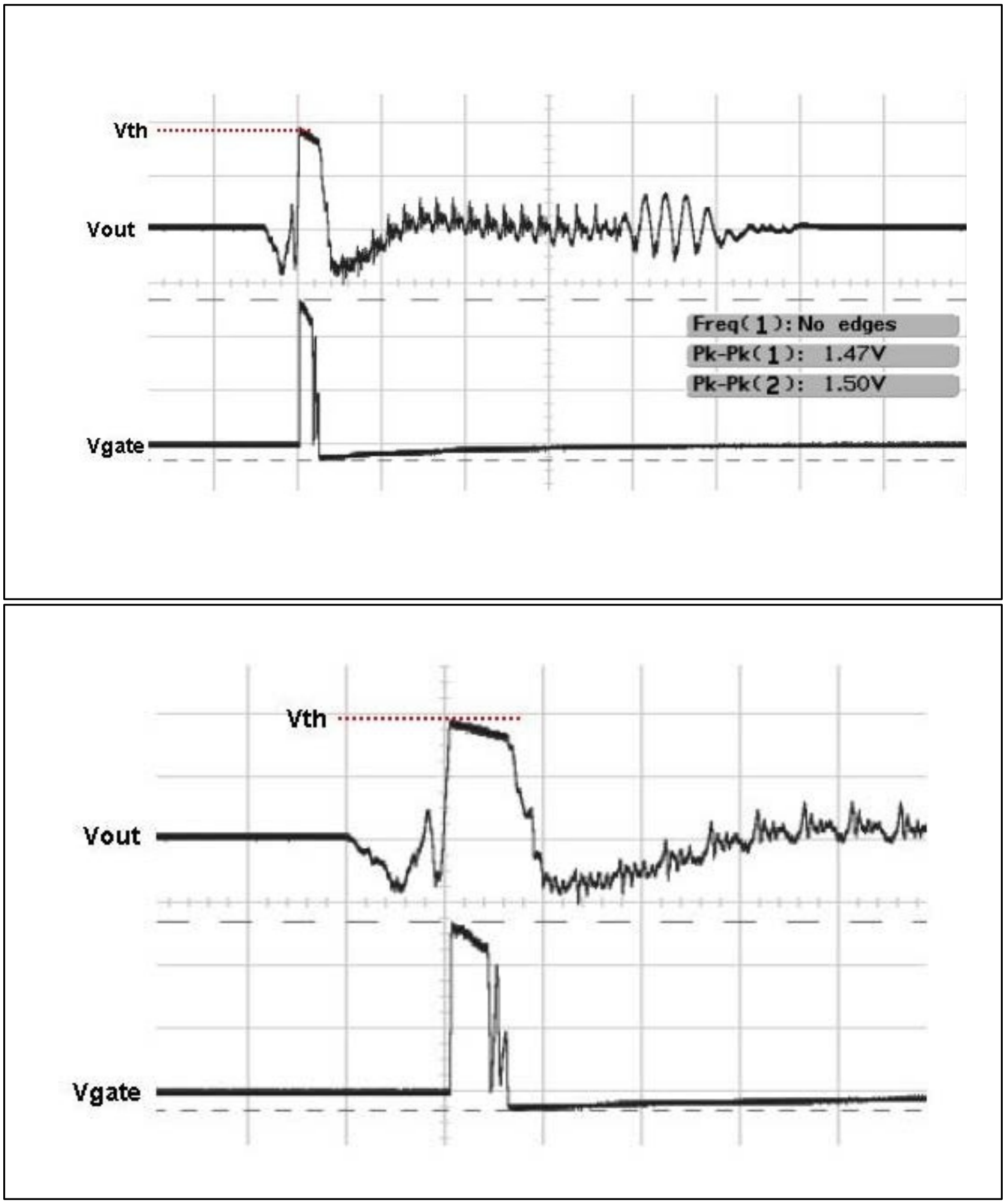
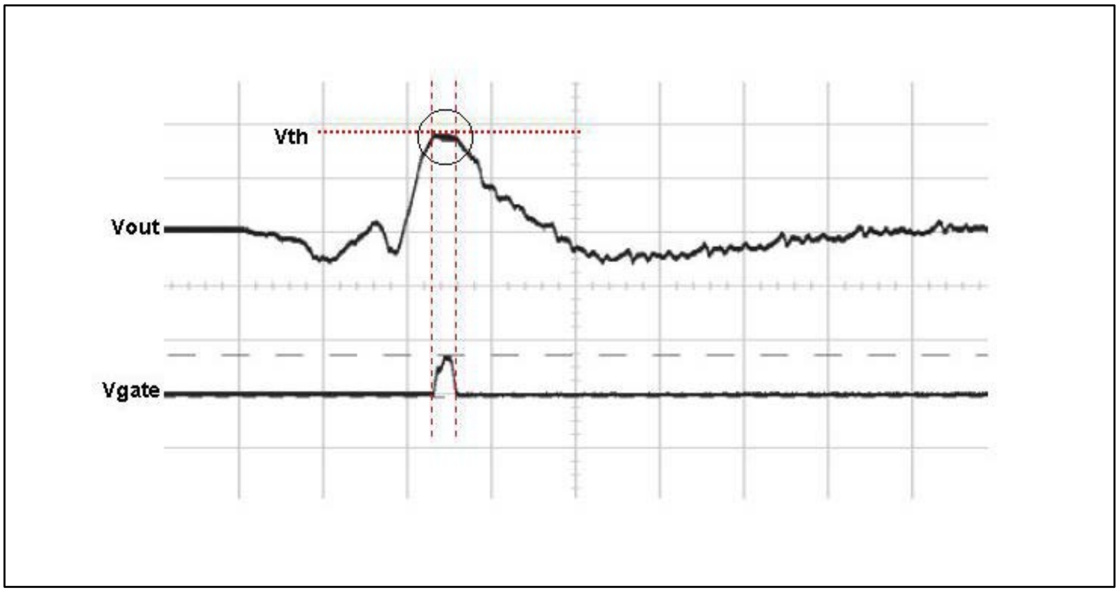


Figure M-3 shows the gate pulse in response to a signal of lesser amplitude. Both the duration and the amplitude of the pulse have decreased proportionally to the amount by which $V_{in,pk}$ exceeds V_{ref}.

Figure M-3: V_{out} vs. V_{GATE}. Note that $V_{out,pk}$ causes the LM393 output to swing high. Due to the attack & release time, the MOSFET threshold voltage is not reached.



PREDICTIONS FOR FIELD OPERATION

The objective for this series of measurements was to test the circuit in a practical user environment under realistic, yet controlled and repeatable conditions, in order to collect data which would help to predict the circuit behavior in the field.

The same electret microphone used in the previous analyses was mounted to a fixed location on the lab bench, and connected directly to the circuit. The electret remained on at all times during the test. The ambient sound pressure level at the microphone capsule during the test was measured to be 63 dB SPL.

Voice commands were uttered at ranges of 3, 6, 9, and 12 feet. User positioning with respect to the microphone capsule ranged from 0º (on-axis) to ±90º about all three axes. Clearly, the terms *loud*, *normal*, and *soft* are subjective, and don't make for good, reliable data. Therefore, a range was assigned which defined how strongly the user might project their voice. Any system response to vocal projections exceeding this limit were not included in the test results. To define this range, an SPL meter was fixed 6 inches from the user's mouth, and the user supplied three utterances of the word, "test", in increasing projection intensity. The results are shown below:

Projection Intensity / *Perceived*	**Deviation from Ambient (dB SPL)**
Low / *Quiet speech*	+12
Average / *Normal speech*	+16
High / *Moderately loud speech*	+20

The output of the AGC circuit was connected directly to the microphone input of the Euterpe Hands-Free Car Kit demonstration system. Native echo and noise cancellation software was disabled for the duration of each test.

Each range test consisted of a set of 16 user-independent words from ST's standard recognition library. Each 16-word set was attempted ten times, for a total of 160 words per test (three tests per distance metric, totaling 12 tests). The resulting recognition rate for each range is given by:

$$R = T/A$$

where :
R = *recognition rate*
T = *total number of words per test*
A = *actual number of utterances per test*

The data collected from this test suggest the approximate recognition rate one can expect to see in the field for systems placed in rooms or areas with similar ambient sound pressure levels. Test results are provided in the tables below using the following parameters:

- Distance: Distance from user to microphone capsule
- Polarity: User positioning referenced to 0º on-axis
- Ambient: Ambient sound pressure level at microphone capsule
- G1: Gain of preamp stage 1 (V/V)
- G2: Gain of preamp stage 2 (V/V)
- G3,fix: Gain of AGC stage with MOSFET off
- T: Total number of words per test
- A: Number of user attempts per test

Table 1.

Distance	Polarity	Ambient @ Mic	G1	G2	G3,fix	**T**	**A**	**Recognition Rate**
3'	0-90, X-Y-Z	63 dB SPL	5	51	10	160	178	**89.89%**

Attempt	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	AVG
Start	1	1	1	1	1	1	1	1	1	1	1
Dial	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	2	2	1	1	2	1	2	2	1.5
3	1	1	1	1	1	1	1	1	1	1	1
4	2	1	1	1	1	1	2	1	2	1	1.3
5	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	2	2	3	1	2	1	1	1.5
7	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1
Zero	1	1	1	2	2	1	1	1	2	1	1.3
Oh	1	1	1	1	1	1	1	1	1	1	1
Previous	1	1	1	1	1	1	1	1	1	1	1
Dial	1	1	1	1	1	1	1	1	1	1	1
Yes	2	2	1	1	1	1	1	1	1	1	1.2
Total per Test	**18**	**17**	**17**	**19**	**18**	**18**	**18**	**17**	**19**	**17**	

Table 2.

Distance	Polarity	Ambient @ Mic	G1	G2	G3,fix	**T**	**A**	**Recognition Rate**
6’	0-90, X-Y-Z	63 dB SPL	5	51	10	160	182	**87.91%**

Attempt	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	AVG
Start	1	1	1	1	1	1	1	1	1	1	1
Dial	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1
2	1	2	2	1	1	1	2	1	1	1	1.3
3	1	1	1	1	1	1	1	1	1	1	1
4	2	3	1	1	2	1	2	1	2	1	1.6
5	1	1	1	1	1	1	1	1	1	1	1
6	1	1	3	1	1	2	1	2	1	1	1.4
7	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1
Zero	1	2	1	2	2	1	1	1	2	2	1.5
Oh	1	1	1	1	1	1	1	1	1	1	1
Previous	1	1	1	1	1	3	1	1	1	1	1.2
Dial	1	1	1	1	1	1	1	1	1	1	1
Yes	1	1	1	2	1	2	1	1	1	1	1.2
Total per Test	**17**	**20**	**19**	**18**	**18**	**20**	**18**	**17**	**18**	**17**	

Figure A-1. Test circuit.

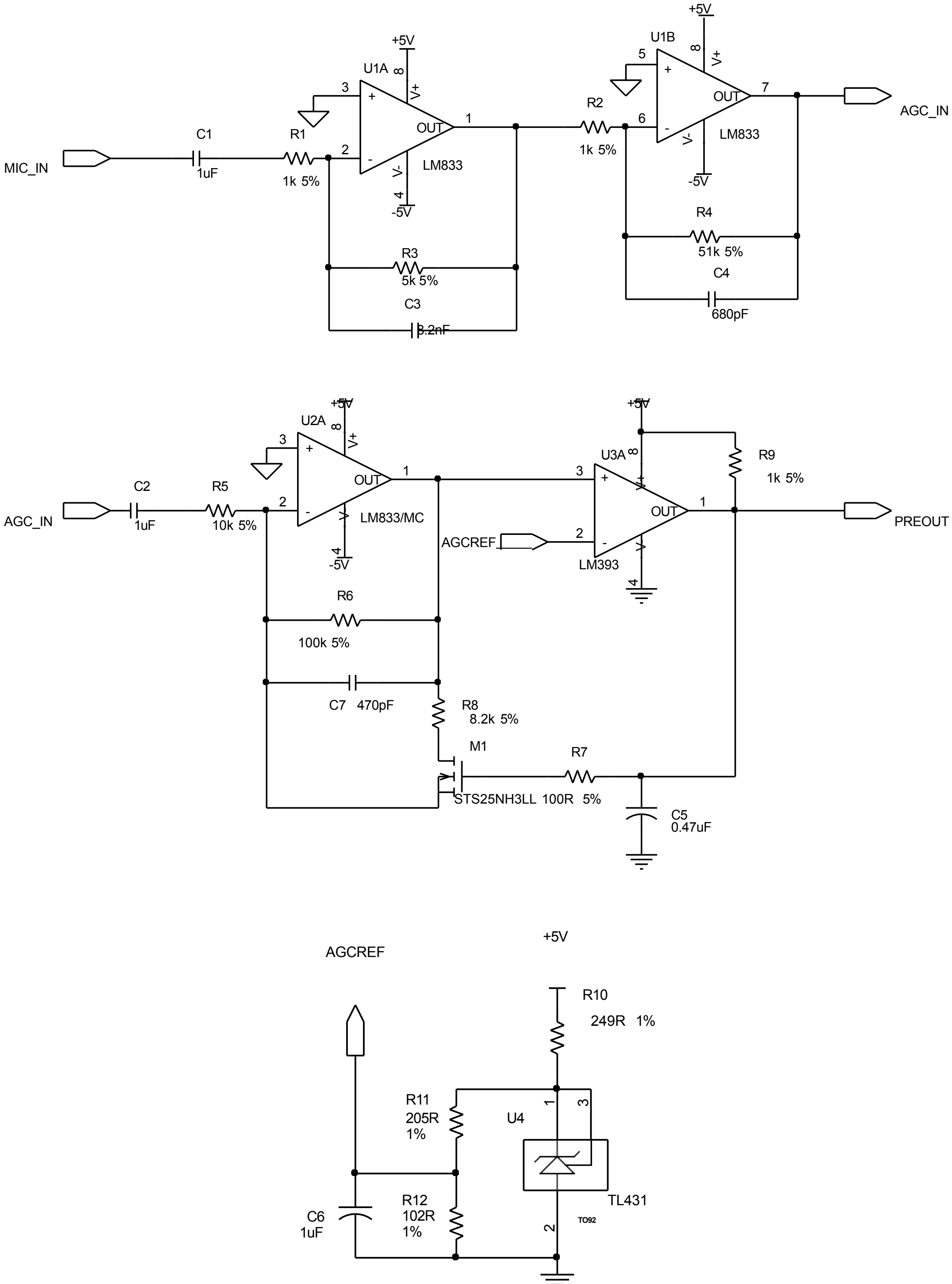


Figure A-2. Model of user test area. Microphone capsule located at origin, facing in the positive X-direction.