Comparison of Current Feedback Op Amp SPICE Models (HA5013)

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Introduction

Op amp SPICE models are widely used to simulate circuit performance, but there is always the question of how well does the SPICE simulation fit the real world. Bottom line this boils down to another question, "can you bet your design career on it"? The answer is an emphatic no! SPICE is an important tool, and it should be used wherever appropriate, but don't begin to trust it unless you have tested it's answers. First, SPICE is a computer program, thus it is subject to all the vagaries of a machine/software package. Second, the SPICE model is an approximation, and you can't trust approximations until you understand them and their limitations. Before a SPICE model can be trusted it must be tested in a known circuit, and it must yield results comparable to the op amp data sheet. This paper tests four SPICE models from four different major current feedback amplifier manufacturers, and presents the results for your perusal. If you are not going to use one of the tested op amps the actual test results will not be as important as the test procedure, programs, and philosophy.

Model Test Procedure

The model testing was completed using a standard set of PSPICE programs which are contained in Intersil Corporation Application Note AN9523 titled "Evaluation Programs For SPICE Op Amp Models", AnswerFAX Doc. # 99523. The inverting gain, non-inverting gain, and transient response programs were selected for the model testing because they yield data adequate for a model/data sheet comparison. The application note contains six programs which cover most op amp parameters. Almost any program can be used for the evaluation, but it must use the op amp in the same configuration as the data sheet.

The program must enable the selection of the pertinent component values, such as the feedback resistor, so that the evaluation can be done at the data sheet conditions. This is required for the comparison to be valid because the op amp must be evaluated at the exact data sheet operating conditions so the SPICE generated data and curves can match the data sheet data and curves. The component values that need to be considered are the feedback resistor, input and/or output terminating resistor, load resistor, load capacitor, gain setting resistor, and power supply voltage.

During the evaluation you must keep in mind that the idea is to determine how closely the model matches the op amp as it is characterized in the manufacturer's data sheet. Remember, you are not trying to characterize the op amp. You may find a better method to characterize the op amp, and this is good information for future use, but it is not germane for evaluating the model. Application note AN9523 is a handy tool to use for model evaluations because it allows for and encourages the incorporation of the data sheet operating conditions. In addition it runs three parallel circuits and automatically normalizes the data for three different gains, inverting or non-inverting, in one pass of the program. The programs are the closest thing to an industry standard, and they are available in the application note or on the Intersil SPICE model disk.

Comparison Criteria

The comparison criteria results from the distillation of a series of conversations with design engineers. Some might call it an arbitrary or even punitive standard, but it is the only one in existence, so it will be used. When the peaking is within 2dB, this is considered to be good correlation, while peaking in excess of 2dB is designated as marginal. Although the best case is where the data sheet matches the model results, data sheet peaking less than the model peaking is preferable because it is less likely to lead the designer to optimistic conclusions. Peaking causes the emphasis of the high frequencies contained in the signal so it usually leads to distortion.

Bandwidth correlation of the model to the data sheet within 20 percent is acceptable. Data sheet bandwidth greater than the model bandwidth is preferable because it leads to conservative design.

The transient response correlation should be within 20 percent, but this parameter is secondary to the peaking and bandwidth. It is extremely difficult to get good transient response from a model, so many model designers sacrifice this parameter in favor of the frequency response plots.

The data sheet curves are obtained from measurements made on a "typical" IC, and considering the difficulties encountered when measuring CFAs, these curves are only repeatable to a few percent. The model approximates the IC performance, so it should be expected that there will be some differences between the curves produced by the model and the data sheet curves. The tolerances set out above are meant to account for these differences.

Op Amps Compared In The Evaluation

The following op amps were selected for evaluation: the Intersil HA5013 [1], the Analog Devices.

TABLE 1. RESULTS OF THE NON-INVERTING GAIN EVALUATION

OP AMP	GAIN	DATA SHEET PEAK/DIP	MODEL PEAK/DIP	DATA SHEET -3dB BW	MODEL -3dB BW
HA5013	1	3.2dB	2.5dB	125MHz	120MHz
	2	3.1dB	1.9dB	110MHz	98MHz
	10	0dB	0dB	70MHz	58MHz
AD811	1	0dB	2.3dB	119MHz	110MHz
	2	0dB	0.3dB	115MHz	115MHz
	10	0dB	0dB	100MHz	105MHz
CLC414	2	0dB	2dB	70MHz	210MHz
	6	0dB	0dB	96MHz	125MHz
	10	0dB	0dB	60MHz	68MHz
LT1229	2	0.2dB Peak	0.8dB Dip	102MHz	120MHz
	10	0dB	0dB	60MHz	70MHz
	100	0dB	0dB	13MHz	7MHz

AD811 [2], the Comlinear CLC414 [3], and the Linear Technology LT1229 [4]. These op amps were selected on the following criteria: availability, current feedback architecture, available SPICE models, the bandwidths are similar, and the remaining parameters are similar. No attempt was made to review the model to determine if one model appeared to be superior to another; the only criteria for selection is given above. There are some other companies that might have been included in the comparison, but their models were not on hand when the comparison was done.

Test Results For Non-Inverting Op Amps

The conditions for each test are exactly the same as those given on the vendor's data sheet. At first glance this may seem unfair because one vendor tests with a 10pF load and another does not specify a load capacitor (how do they get probes and loads that don't have capacitance?), but because we are evaluating each model against its data sheet, it is a fair comparison. The load conditions for each op amp comparison are given in Table 2. A separate simulation with a small capacitive load was run for each op amp model to check for instability. The results of the non-inverting gain evaluation are summarized in Table 1.

The HA5013 data is shown in Figure 1. The HA5013 model indicates 0.7dB less peaking than the data sheet, and it indicates 5MHz less bandwidth than the data sheet. Both of these numbers are well within the comparison criteria so it is safe to assume that the model represents the IC very well for the non-inverting gain configuration.

The AD811 data is shown in Figure 2. The AD811 model has 2.3dB peaking while the data sheet shows 0dB peaking. The model bandwidth is 9MHz less than the data sheet bandwidth. This is marginal performance for the model, but if it is used to evaluate a circuit the results will be pessimistic so the designer should be safe.

This model, see Figure 3, shows a spike in the frequency response at 900MHz when a 4pF load capacitor is added to the circuit. If the spike is just an artifact produced by the model it may have no effect on the actual circuit performance, but if it shows up in the IC transfer function it could cause high frequency oscillation problems. Clearly, the spike needs to be investigated further before the designer can be comfortable with the IC and the model. The data sheet shows quite a bit of difference between the frequency response curves at ±15V and ±5V power supply operation. The SPICE model analysis shows no difference between these curves, so unless further information comes to light, it must be assumed that the model does not include effects due to power supply variations.

The CLC414 data is shown in Figure 4. The CLC414 model has 2dB of peaking versus the data sheet peaking of 0dB, and the model bandwidth is 210MHz versus the data sheet bandwidth of 70MHz. The difference in the peaking numbers is within our criteria with the high number being in the model so it is acceptable. The bandwidth difference is so large that the model might be not be usable because it will predict overly optimistic results. Also, the model may need some help; sometimes these models need the addition of external components to aid convergence or measurements. It would be in the designer‘s best interest to contact the manufacturer‘s applications department prior to proceeding with a design based on this model.

Figure 5 shows the effect of adding a 4pF load capacitance. Notice that the peaking increases about 1dB, and the -3dB bandwidth increases about 7 percent when the load capacitor is added to the circuit. This is normal operation for a CFA, and it can be countered by increasing the feedback resistor a few percent [5].

The LT1229 data is shown in Figure 6. The LT1229 model has a 0.8dB dip, while the data sheet shows a 0.2dB peak. The numbers are small, but they go in opposite directions, so overall it adds up to a 1dB error which is acceptable. The model bandwidth is 120MHz, and the data sheet bandwidth is 102MHz, so this does not meet the evaluation criteria. Furthermore, the model will predict a much better high frequency performance than the IC can deliver, so the designers must factor this into their calculations.

TABLE 2. LOAD CONDITION FOR EACH NON-INVERTING GAIN EVALUATION

OP AMP	POWER SUPPLY	LOAD RESISTOR	LOAD CAPACITOR	GAIN	FEEDBACK RESISTOR
HA5013	±15V	400Ω	10pF	1	1000Ω
				2	681Ω
				10	383Ω
AD811	±15V	150Ω	0pF	1	750Ω
				2	649Ω
				10	511Ω
CLC414	±5V	100Ω	0pF	2	500Ω
				6	500Ω
				10	500Ω
LT1229	±15V	100Ω	0pF	2	750Ω
				10	750Ω
				100	750Ω

Figure 7 shows the effect of adding a 4pF load capacitance to the LT1229. The dip decreases about 0.4dB, while the -3dB bandwidth increases about 12 percent. Again, this is normal operation for a CFA, and it can be countered by increasing the feedback resistor a few percent.

Figure 8 shows the non-inverting frequency response at ±5V power supplies. The data sheet predicts a bandwidth change from 102MHz to 60MHz when the power supplies are changed from ±15V to ±5V. The model shows a change from 120MHz to 60MHz when the supply voltage is changed. This is an example of why the model needs to be examined before doing any design is with it. At 15V supplies the designer has to worry about getting optimistic results, while at 5V supplies the design results should be right on target. This is also a good example of a SPICE model which includes a good supply voltage dependency function.

Test Results For The Inverting Op Amps

The conditions for each test are exactly the same as those given on the vendor‘s data sheet. The load conditions for each op amp comparison are given in Table 4. The results of the inverting gain evaluation are summarized in Table 3. The LT1229 data sheet did not include any inverting gain curves, so it was not included in this evaluation.

The HA5013 data is shown in Figure 9. The HA5013 model indicates 1dB less peaking than the data sheet, and it indicates 15MHz less bandwidth than the data sheet. Both of these numbers are well within the comparison criteria, so it is safe to assume that the model represents the IC very well for non-inverting gain. The model bandwidth for the gain of 10 configuration is 70MHz compared to a data sheet bandwidth of 22MHz, thus this model will yield overly optimistic answers at high inverting gains. If the model designer has to make a compromise, it will usually happen at high inverting gains. The compromises are made at high inverting gains because this is where CFAs are used the least.

The AD811 data is shown in Figure 10. The AD811 model indicates 0.8dB of peaking, and when this is compared to the data sheet which has no peaking it all looks fine. The model does have 2.3dB peaking when it is in a gain of -10 configuration, thus, depending on what gain the designer is working at, allowances may have to be made for this error. Again, the compromise has been made at high inverting gains. The model bandwidth matches the data sheet bandwidth very well.

The CLC414 data is shown in Figure 11. The CLC14 model indicates 0.3dB of peaking, and when this is compared to the 0.8dB peaking shown on the data sheet it is well within the comparison criteria. The model bandwidth is 180MHz compared to the data sheet bandwidth of 97MHz, so the model will predict overly optimistic frequency performance. The -10dB performance of this model is excellent, which proves that not all model designers push the poorer performance into the high inverting gain configurations.

Time Domain Testing

Each op amp was evaluated with a ±100mV square wave input signal to determine the small signal time domain response. If a photograph of this response is in the data sheet, then a comparison can be made to find out how well the PSPICE simulation mirrors the time domain response. If the photograph is not contained in the data sheet, this data still has value because it can be compared to the theoretical time domain response as calculated from the second order transfer function equation n [6].

TABLE 3. RESULTS OF THE INVERTING GAIN EVALUATION

OP AMP	GAIN	DATA SHT. PEAK/DIP	MODEL PEAK/DIP	DATA SHT. -3dB BW	MODEL -3dB BW
HA5013	-1	1.5dB	0.5dB	100MHz	85MHz
	-2	0.4dBDip	0.6DipdB	80MHz	80MHz
	-10	0dB	0dB	22MHz	70MHz
AD811	-1	0dB	0.8dB	115MHZ	110MHZ
	-10	0dB	2.3dB	95MHz	105MHz
CLC414	-1	0.8dB	0.3dB	97MHz	180MHz
	-5	0.6dB	0dB	88MHz	98MHz
	-10	0dB	0dB	70MHz	55MHz

TABLE 4. LOAD CONDITION FOR EACH INVERTING GAIN EVALUATION

OP AMP	POWER SUPPLY	LOAD RESISTOR	LOAD CAPACITOR	GAIN	FEEDBACK RESISTOR
HA5013	±15V	400Ω	10pF	-1	750Ω
				-2	750Ω
				-10	750Ω
AD811	±15V	150Ω	0pF	-1	590Ω
				-10	511Ω
CLC414	±5V	100Ω	0pF	-1	500Ω
				-5	500Ω
				-10	500Ω

The HA5013 small signal pulse response (equivalent to the time domain response) is shown in Figure 12. The model and the data sheet both show a few percent of overshoot which is very good correlation.

The AD811 small signal pulse response is shown in Figure 13. The PSPICE program was not able to complete the analysis because the time domain response never settled down. The program chooses the time step size according to the activity of the response, and the AD811's very active response dictated a small time step, which resulted in too many calculations. The time domain response overshoots the final value by 160mV for a 200mV step. This is almost a complete reflection of the input step, and it is very unusual. This phenomena may be related to the spike in the non-inverting frequency response curve, but wherever it comes from, it must be investigated and resolved before the model is usable for time domain analysis.

The CLC414 small signal pulse response is shown in Figure 14. The model overshoot is 100mV, and it settles out in 30ms. There is no photograph of the small signal pulse response in the data sheet, so the model cannot be compared to the data sheet. How much can the model's transient response be trusted? The only way to determine this is to test the op amp, and then compare the test results to the model results. Considering the large amount of overshoot, and the bandwidth results, this may be a wasted effort.

The LT1229 small signal pulse response is shown in Figure 15. The model overshoot is 85mV, and it does not settle out for 43ns. The small signal rise time is shown in the data sheet, and the photograph has very little overshoot. The model overshoot is much more than one would expect from an op amp which has very little peaking in its frequency transfer function, thus it seems safe to assume that the model adds overshoot to the time domain response. The model is usable for transient analysis, but picking the model artifacts out of the plots will be laborious and possibly misleading.

Summary

No model meets the evaluation criteria in every case, and this is because the models are approximations of reality. Also, the data sheets, which in this analysis have been considered to be the standard, contain some degree of error. This lack of correlation between the data sheet and the models will always exist; and the proof is that the op amp design engineers always complain that the process models are not accurate enough. The paradox is that when the process models evolve enough to become really accurate the process has usually aged and is becoming obsolete.

The HA5013 model is the most accurate by any standard. It meets all the evaluation criteria except at one point. This is because the model performance standards were set first, and then the model was constructed to meet the performance standards. Designing the model involves a trade-off between complexity, run time, convergence capability and accuracy. The HA5013 model was able to optimize these parameters through the use of some special techniques.

The LT1229 model is acceptable except for its transient performance. The other models will be hard to use with good accuracy.

The model should be first evaluated against the data sheet. If excellent correlation is obtained, such as the HA5013 gave, then the model results can be trusted. If any doubt exists about the model, then electronic circuit theory, a good calculator and the lab must be employed to settle the questions.

When the model performance matches the data sheet performance, and both match the lab performance the results are trustworthy. This model can be used to predict the performance of any linear circuit configuration which converges.

References

[1] Data sheet for HA5013, Intersil Corporation, 1994. AnswerFAX Document No. 3654

[2] Data sheet for AD811, Analog Devices, 1994

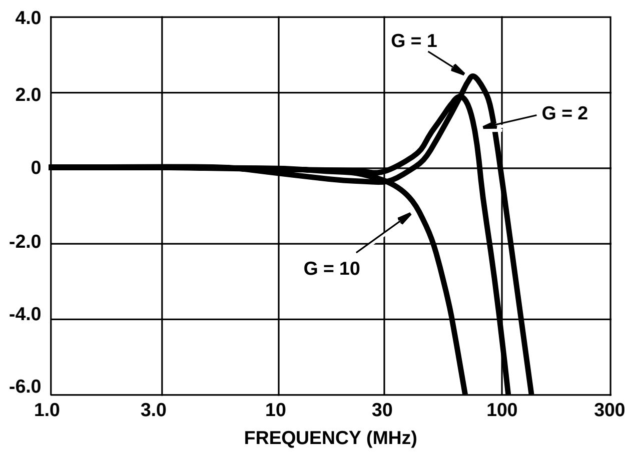

FIGURE 1. NON-INVERTING FREQUENCY RESPONSE OF THE HA5013

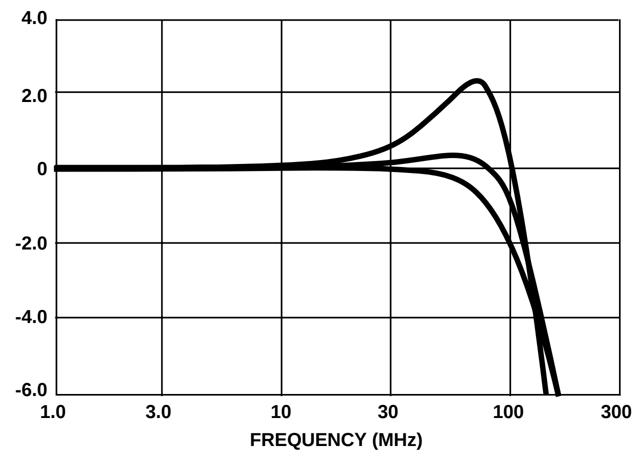

FIGURE 2. NON-INVERTING FREQUENCY RESPONSE OF THE AD811

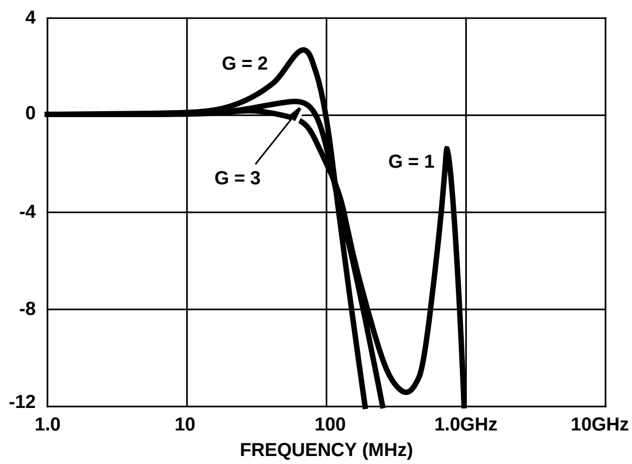

FIGURE 3. UNEXPECTED NON-INVERTING FREQUENCY PLOT FOR THE AD811

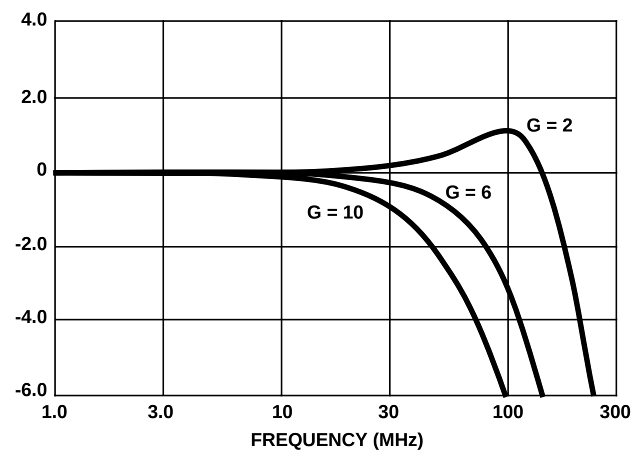

FIGURE 4. NON-INVERTING FREQUENCY RESPONSE OF THE CLC414

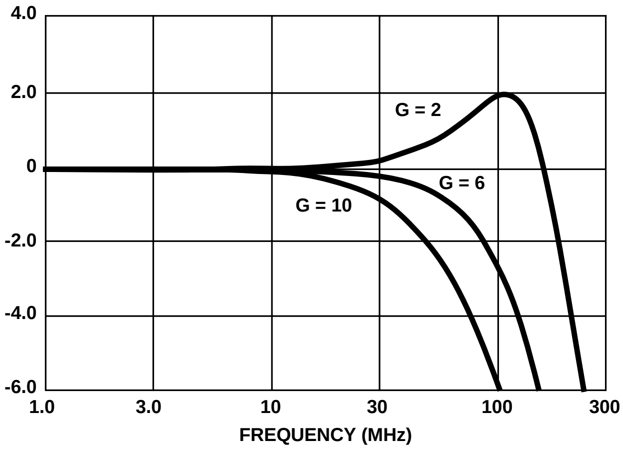

FIGURE 5. EFFECT OF 4pF LOAD ON THE CLC414

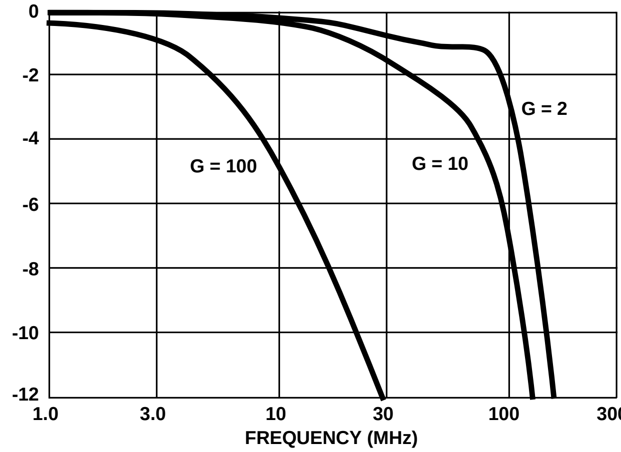

FIGURE 6. NON-INVERTING FREQUENCY RESPONSE OF THE LT1229

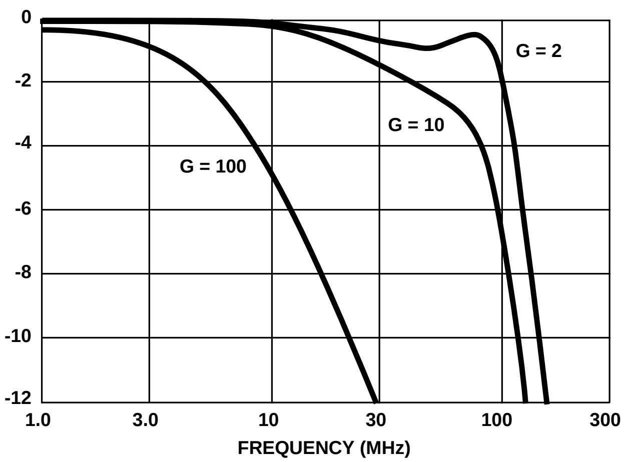

FIGURE 7. EFFECT OF THE 4pF LOAD ON THE LT1229

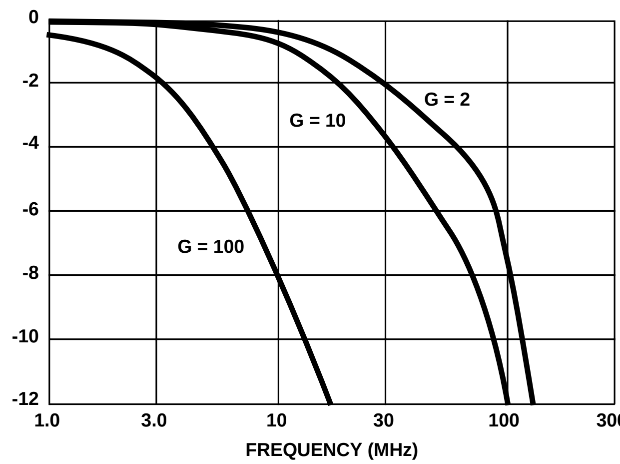

FIGURE 8. NON-INVERTING FREQUENCY RESPONSE OF THE LT1229 AT ±5V

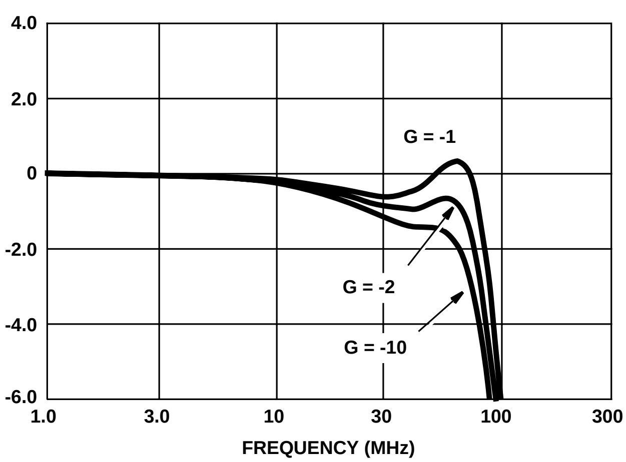

FIGURE 9. INVERTING FREQUENCY RESPONSE OF THE HA5013

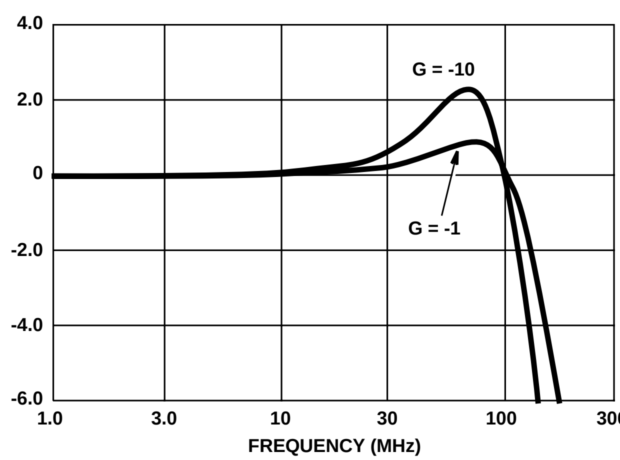

FIGURE 10. INVERTING FREQUENCY RESPONSE OF THE AD811

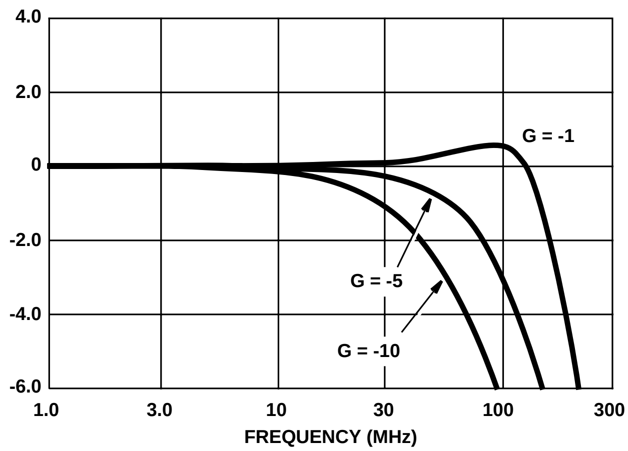

FIGURE 11. INVERTING FREQUENCY RESPONSE OF THE CLC414

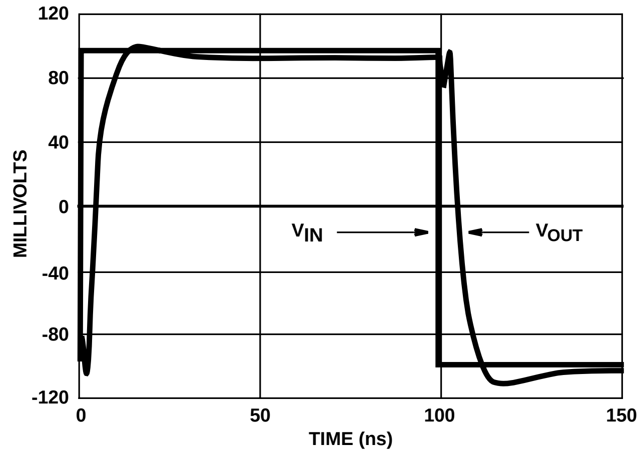

FIGURE 12. HA5013 SMALL SIGNAL PULSE RESPONSE

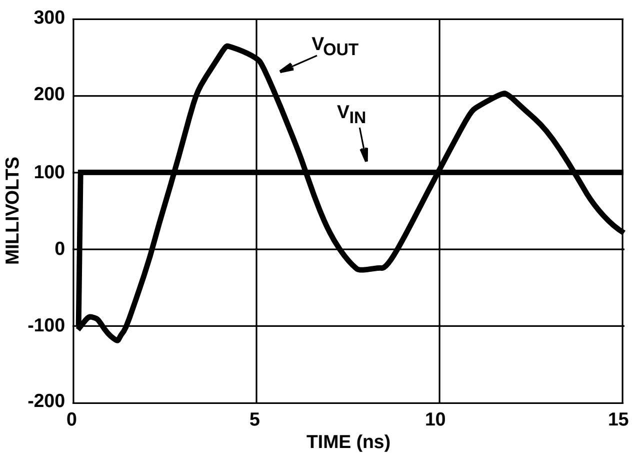

FIGURE 13. AD811 SMALL SIGNAL PULSE RESPONSE

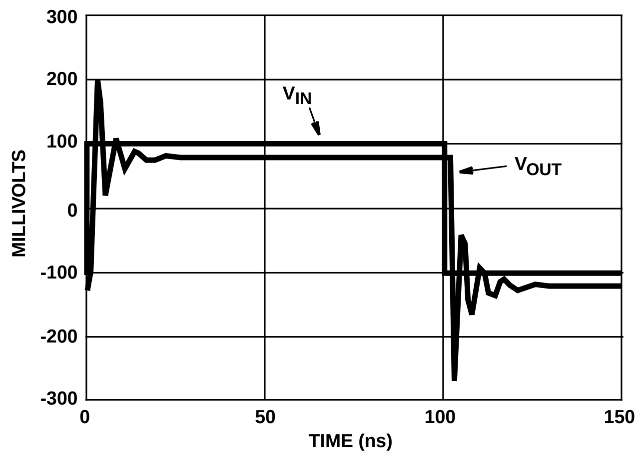

FIGURE 14. CLC414 SMALL SIGNAL RESPONSE

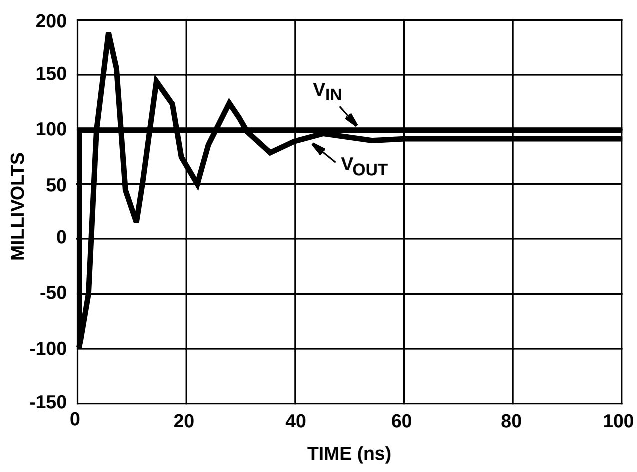

FIGURE 15. LT1229 SMALL SIGNAL PULSE RESPONSE