ESD Force Noise and Range for Various Modes of Operation

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Assumptions – Following T1200479-v2

- Bias channel is low passed, so has negligible noise

- Control channel voltage noise is independent of drive amplitude

- All ESD quadrants have the same force range

3 Possible Modes of Operation

1. Maximum range – Bias voltage at maximum. Use an offset on the control voltage to get symmetric bipolar force range.
2. Reduced bias – same as max range mode, but with a smaller bias to reduce noise.
3. No control voltage offset – the control voltage offset is turned off to reduce noise. Bias is at maximum.

Maximum Range Mode - range

$F = \alpha\left(V_b - V_s\right)^2$ ESD force

if $V_s = -V_b$

$F_{\max} = \alpha\left(V_b + V_b\right)^2$ Max force for a voltage limit of V_b

$F_{\max} = 4\alpha V_b^2$

To get bipolar actuation, we typically set DC force of half the maximum range

$F = F_{dc} + F_{ac}$ Splitting the force into DC an AC parts

$F_{dc} = \frac{1}{2}F_{\max} = 2\alpha V_b^2$ → realized with → $V_{s,dc} = \left(1-\sqrt{2}\right)V_b$

$\left|F_{ac}\right| \le \frac{1}{2}F_{\max} = 2\alpha V_b^2$ AC force range

if $V_b = V_{b,\max}$ → $\boxed{\left|F_{ac}\right| \le \frac{1}{2}F_{\max} = 2\alpha V_{b,\max}^2}$

Maximum Range Mode - noise

recall

$$F = \alpha\left(V_b - V_s\right)^2$$ ESD force

expanding

$$F = \alpha\left[V_b^2 - 2V_bV_s + V_s^2\right]$$

Splitting the signal voltage into a control part and noise part

$$V_s = V_c + v_n$$

Plugging this back in

$$F = \alpha\left[V_b^2 - 2V_b\left(V_c + v_n\right) + \left(V_c^2 + 2V_cv_n + v_n^2\right)\right]$$

And simplifying

$$F = \alpha\left[V_b^2 - 2V_bV_c + V_c^2 - 2V_bv_n + 2V_cv_n + v_n^2\right]$$

assume $v_n^2 \approx 0$

$$F = \alpha\left(V_b^2 - 2V_bV_c + V_c^2\right) + 2\alpha\left(V_c - V_b\right)v_n$$

$$F_n = 2\alpha\left(V_c - V_b\right)v_n$$ This is the general solution for force noise

Maximum Range Mode - noise

Splitting the control voltage into a DC part and AC part

$$V_c = V_{c,dc} + V_{c,ac}$$

$$V_{c,dc} = \left(1 - \sqrt{2}\right) V_b$$ As before, for the half max force offset

recall

$$F_n = 2\alpha\left(V_c - V_b\right) v_n \quad \text{and} \quad V_b = V_{b,\max}$$

The average force noise amplitude is found setting $V_{c,ac} = 0$

$$\boxed{F_{n,ave} = 2\sqrt{2}\alpha V_{b,\max} v_n}$$

Note, this is a factor root 2 greater than in T1200479-v2, due to the inclusion of the V_c term.

This is the expected noise if the AC voltage is much less than the bias

If not, the maximum force noise amplitude is found setting $V_c = -V_{b,\max}$

$$F_{n,\max} = 4\alpha V_{b,\max} v_n$$

Reduced Bias Mode

- Reuse the range equation from the full range mode, but with smaller bias voltage

$$\boxed{|F_{ac}| \leq 2\alpha V_b^2}$$

This assumes we enforce symmetric saturation (control could go to max, even if bias doesn't, but we assume the control stays within the bias).

For example,

$$\text{if } V_b = \frac{1}{\sqrt{2}} V_{b,\max} \quad \text{then}$$

$$|F_{ac}| \leq \alpha V_{b,\max}^2$$

Which is half the range of the full range mode

- Reuse the noise equation from the full range mode, but reduce the bias

$$\boxed{F_{n,ave} = 2\sqrt{2}\alpha V_b v_n}$$

and

$$F_{n,\max} = 4\alpha V_b v_n$$

For example,

$$\text{if } V_b = \frac{1}{\sqrt{2}} V_{b,\max} \quad \text{then}$$

$$F_{n,ave} = 2\alpha V_{b,\max} v_n \quad \text{and} \quad F_{n,\max} = 2\sqrt{2}\alpha V_{b,\max} v_n$$

Which is root 2 less than the full range mode

No Control Voltage Offset Mode

- Range

$V_c = V_{c,dc} + V_{c,ac}$ As before, split the control voltage into a DC part and AC part

Set the DC part to 0

$V_{c,dc} = 0$

$F_{dc} = \alpha V_{b,\max}^2$ The DC force is now half what it was in max range mode, assuming max bias

The AC range is then (since the total force can go from 0 to $4\alpha V_b^2$)

$-\alpha V_{b,\max} \le F_{ac} \le 3\alpha V_{b,\max}^2$ → for symmetric saturation → $\left| F_{ac} \right| \le \alpha V_{b,\max}^2$

The symmetric range is half the max range mode, and the same as dropping the bias by root 2 in reduced bias mode.

- Noise

$F_n = 2\alpha \left(V_c - V_b \right) v_n$ Recall the general solution for force noise

$F_{n,ave} = 2\alpha V_{b,\max} v_n$ This noise is root 2 less than the max range mode, and the same as dropping the bias by root 2 in reduced bias mode.

$F_{n,\max} = 2\sqrt{2}\alpha V_{b,\max} v_n$ For symmetric range, where max force comes from $V_c = \left(1 - \sqrt{2}\right) V_b$

Conclusions

- We can reduce the noise of the ESD by operating it out of the typical full range mode, at the expense of reduced force range.
- The mode where the DC control voltage is set to zero is equivalent to reducing the bias voltage by sqrt(2) in the reduced bias mode.
- According to this modeling, adding extra infrastructure to the ESD simulink diagram to remove the DC control voltage is not needed. Just reduce the bias voltage instead.