Application Report

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Haptic Implementation Considerations for Mobile and Wearable Devices

Mandy Barsilai — *Haptic Products*

ABSTRACT

This document presents a comparative view of typical ways for implementing vibration and haptics in wearable devices.

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1 Introduction

Haptics and vibration effects are relatively new features being implemented in a growing number of mobile and wearable devices. Given the unique needs of mobile and wearables devices in terms of power consumption, form factor and haptic/vibration performance, selection of the optimum haptic solution may differ from other consumer products. Among the alternatives, there are mainly three types of actuators available: LRA, ERM, and BLDC actuators. Each of the actuator types offer different trade-offs in terms of power consumption, vibration strength, and form factor. The following sections expand on the trade-off among different actuators and circuit implementation.

2 Actuator Description

2.1 Eccentric Rotating-Mass (ERM) Actuators

Eccentric rotating-mass motors (ERMs) are typically DC-controlled motors of the bar or coin type. ERMs can be driven in the clockwise direction or counter-clockwise direction depending on the polarity of voltage across the two pins. Bidirectional drive can be made possible in a single-supply system by differential outputs that are capable of sourcing and sinking current. By switching driving directions, it is possible to "brake" the actuator, which helps eliminate long vibration tails which are undesirable in haptic feedback systems.

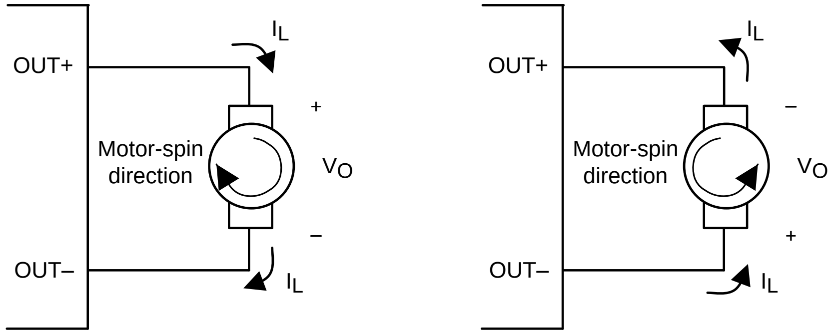

Figure 1. Motor Spin Direction in ERM Motors

ERM's are brushed DC motors; the commutation happens mechanically through the brushes, making the electronics relatively easy to design and implement; a simple DC voltage or PWM signal can be used. In the case of a PWM, the duty-cycle will be proportional to the vibration strength. However, the presence of brushes requires additional power consumption for a given vibration strength, and tend to wear out with use, impacting reliability.

ERM actuators also show a relationship between vibration strength and the angular frequency. This characteristic implies that the only way to achieve a particular acceleration is by having a particular angular frequency. A typical acceleration versus frequency profile is shown in Figure 2. This property is one that gives the ERM's its distinctive feel.

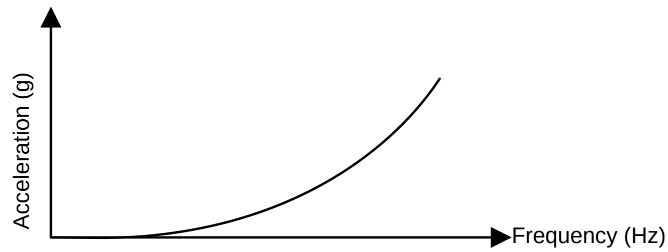

Figure 2. ERM Acceleration Versus Frequency Response

Given the mechanical properties of ERM actuators, they are intrinsically slow, so transitions between a rest state and a moving state (and vice versa) may take a noticeable amount of time. To overcome the inertia of the mass of the actuator, these actuators are often *overdriven* for a short amount of time before going to the rated voltage of the motor to sustain the rotation of the motor. Overdrive is also used to stop (or brake) a motor quickly. Refer to the data sheet of the actuator for safe and reliable overdrive voltage and duration.

2.2 Brush-Less Direct Current (BLDC) Actuator Module

BLDC actuators tend to be of the coin type, and operate in a similar way as an ERM. BLDC actuators differ from ERM in that instead of having mechanical commutation, the commutation happens electrically, which eliminates the need for brushes. All else being equal, the BLDC actuator is more reliable and power efficient than an ERM. However, the BLDC electronic requirements are more involved than in the case of an ERM. For this reason, BLDC modules are available, which integrate the BLDC driver inside the actuator's enclosure, making the BLDC "look" like an ERM, by requiring only a positive voltage and GND to be driven. A picture of a BLDC module is shown in Figure 3.

Figure 3. BLDC Module Picture

Existing BLDC modules make electrical braking impossible, since it is not possible to reverse the direction of the driving signal. Keep in mind that the voltage applied to the module goes first to power the driver, which implies that PWM signals cannot be used. It is also important to note that the driver inside consumes power, and has a response time that will impact the overall performance of the module.

Existing BLDC modules have additional restrictions in terms of the voltage requirements; since the voltage applied to the wires is supplying an IC, the actuator will not move for voltages below the power-up voltage of such an IC, which tends to be around 2.9 V. This implies that very soft vibrations, and ramp effects are unattainable.

2.3 Linear Resonance Actuators (LRA)

Linear resonant actuators (LRAs) are resonant systems that will produce vibration when exercised at or near its resonance frequency. LRAs vibrate optimally at the resonant frequency and tend to have a high-Q frequency response which translates into a rapid drop in vibration performance at small offsets from the resonant frequency (typically of 3 to 5 Hz). A typical acceleration versus frequency profile is shown in Figure 4. Many factors also cause a shift or drift in the resonant frequency of the actuator such as temperature, aging, the mass of the product to which the LRA is mounted, and in the case of a portable product, the manner in which the product is held. Furthermore, as the actuator is driven to the maximum allowed voltage, many LRAs will shift several hertz in frequency because of mechanical compression. All of these factors make a real-time tracking auto-resonant algorithm critical when driving LRA to achieve consistent, optimized performance.

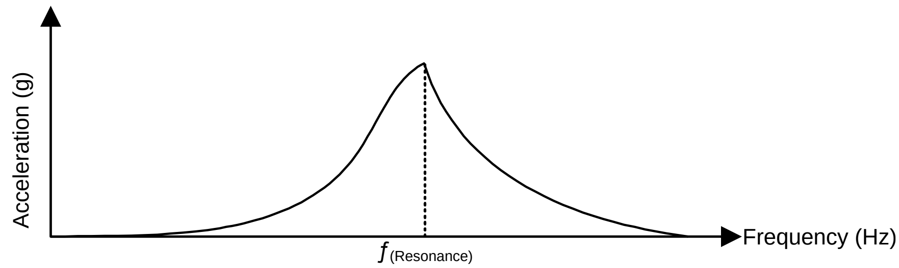

Figure 4. LRA Acceleration Versus Frequency Response

Braking is possible with LRA actuators, and its achieved by driving the LRA with 180° of phase shift. LRAs can also be overdriven for a short amount of time to decrease the "start-time" and "brake-time". Refer to the data sheet of the actuator for safe and reliable overdrive voltage and duration.

LRAs tend to be of the coin type, but there are other form factors available. Technological innovation has made possible the shrinkage of LRA actuators to heights of 2.5 mm, and diameters of 8 mm, making LRA actuators one of the best choices for mobile and wearable devices.

Given that LRAs lack the brushes present in ERMs, they tend to consume less power for a given amount of vibration strength when operated at resonance frequency. For more information on energy consumption for haptics, refer to (SLOA194).

LRAs tend to have a faster response time than ERM and BLDC actuators, which together with optimum overdrive and braking makes possible very quick, sharp effects, such as the "pulsing" effect shown in Figure 5.

Figure 5. LRA Pulsing Waveform

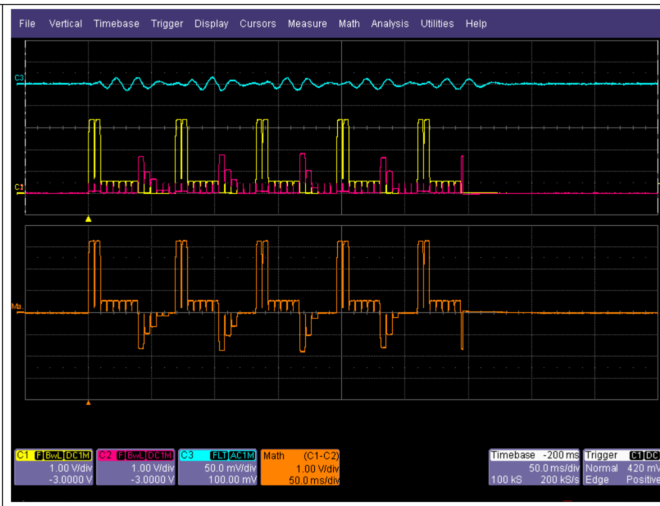

Figure 6. ERM Pulsing Waveform

3 Design Considerations

3.1 Braking

Braking is one of the most important actions required for sharp, crisp haptic effects. Without it, the actuator will continue to vibrate until its own mechanical damping puts it to rest, which is actuator specific and can last hundreds of milliseconds.

The ability to brake an actuator resides on accurately driving it in the opposite direction with the optimum strength and for the optimum time. Such a result can be attained by careful manual tuning, however, since the properties of the actuator change constantly due to temperature, aging, mechanical compression, and so forth, is not possible for an open-loop manually tuned system to operate optimally all the time. The alternative method is by using a closed-loop system, such as the one provided in TI's DRV2603, DRV2605, and DRV2605L, that monitors the status of the actuator and reacts with the appropriate strength and for the appropriate time, dynamically adjusting to any change and, therefore, optimizing the braking performance. Figure 7 shows a typical performance of a click with and without braking in a closed-loop system.

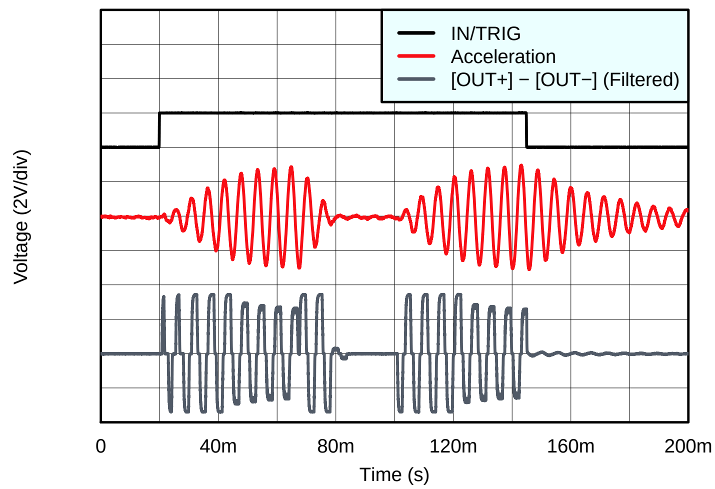

Figure 7. LRA Click With and Without Braking

For the case of ERM actuators, the ability to brake requires voltage to be applied in the opposite direction. For this reason, braking is not possible if using the typical FET implementation, since it can only provide voltage in one direction. Braking is possible, however, if an H-bridge or other differential output solution is used (such as TI's DRV8601, DRV2603, DRV2605, and DRV2605L devices).

BLDC modules have a similar limitation to the ERM FET implementation, since it is not possible to reverse the direction of the BLDC actuator. A typical BLDC module alert effect is shown in Figure 8. Figure 9 is shown for comparison.

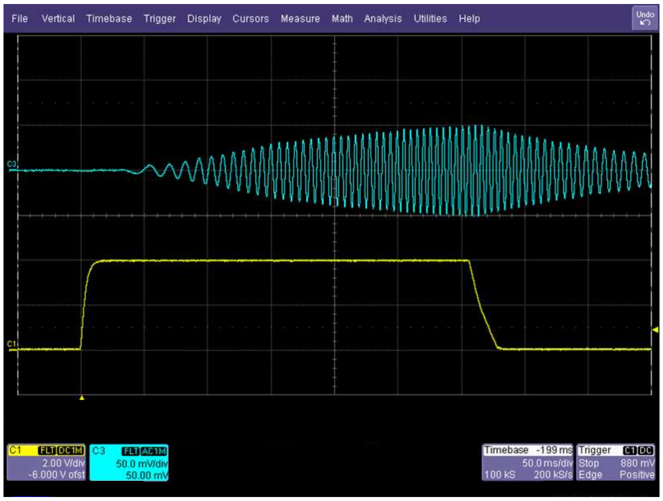

Figure 8. Typical BLDC Module Alert Effect

Figure 9. Typical ERM Alert Effect With TI's Closed-Loop Driver

3.2 Overdrive

Overdriving consists of applying a voltage that is higher than the steady state voltage for a short period of time to reduce the time that an actuator takes to transition from the rest state to the desired steady state (start-time) and from the steady state to the rest state (braking).

Overdriving can be achieved by careful manual tuning, but this process faces the same limitations as manual tuning for braking, and therefore is not the optimal solution. A closed-loop system can automatically overdrive and dynamically adjust to the actuator's changes to optimize the overdrive performance.

An alert effect with an LRA in a closed-loop with automatic overdrive and braking is show in Figure 10. The reduced start-time and brake-time when compared with performances such as the one shown in Figure 8, translate into a crisper and sharper haptic feel.

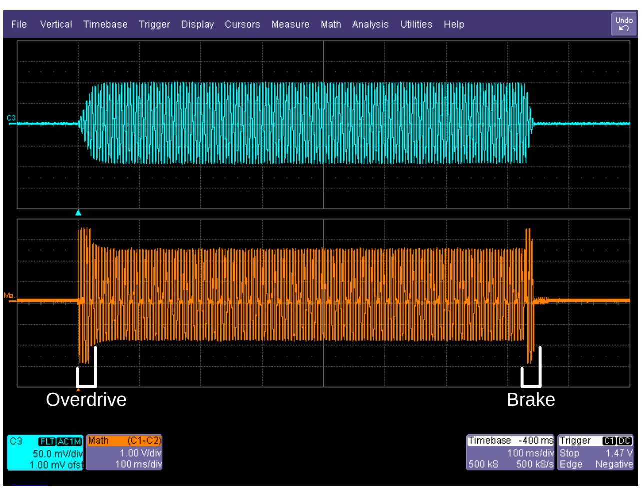

Figure 10. Typical Alert Effect With LRA in Closed-Loop

3.3 Headroom

The actuator's vibration strength is proportional to the driving signal. Therefore, the supply voltage sets a limit for maximum vibrations on a particular system. For LRA actuators in particular, a differential output is recommended in order to maximize the vibration strength. If using a typical Li-Ion battery, a single ended solution (such as that obtained by a single FET implementation) will be limited to the voltage of the battery, which will make waveforms such as the one shown in Figure 7 not possible to obtain.

3.4 Resonance Tracking for LRA

As described in Section 2.3, driving an LRA at resonance is extremely important. This can be achieved by manually characterizing the actuator and then generating a signal with fixed frequency in an open-loop configuration. However, since the resonance frequency can shift and also due to part-to-part variations, a closed-loop system that tracks the resonance of the LRA (such as DRV2603, DRV2605 and DRV2605L) is the preferred solution for LRA implementations.

3.5 Power Consumption

Power consumption is a critical design consideration in mobile and wearable devices, since the battery is usually very small (for example 110 mAh) and the device is expected to last long times without a charge. All else equal, LRAs and BLDCs tend to be more efficient than ERM actuators. However, keep in mind that the BLDC driver inside the BLDC module may take away some of the advantages that the BLDC provides. Section 4 shows comparative data, among other metrics, in power consumption.

4 Actuator Comparison

Measurements between ERMs, LRAs and BLDCs were taken for comparison. ERM and LRA actuators were driven with the DRV2605 driver from TI. The BLDC module was powered by a simple FET circuit, as shown in Figure 11.

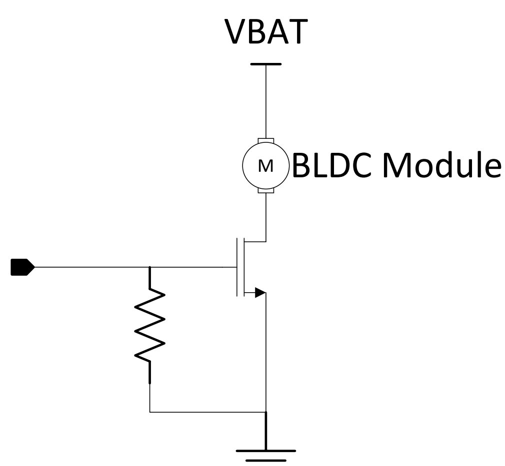

Figure 11. Circuit for Driving the BLDC

Alert waveforms comparing 4 different actuators are shown in Figure 12, Figure 13, Figure 14, and Figure 15.

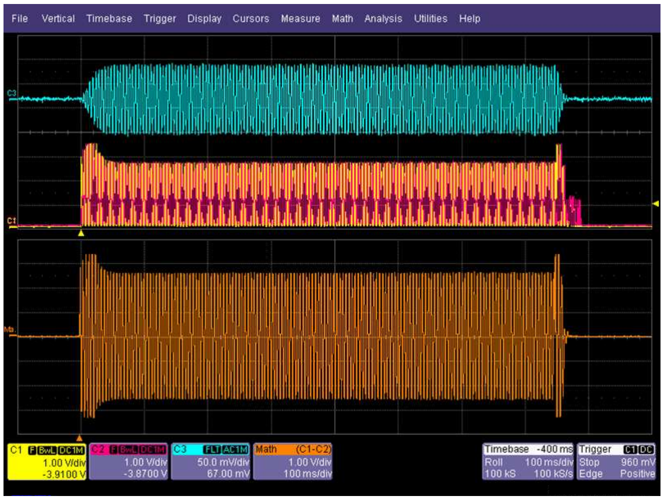

Figure 12. LRA Alert Waveform - AAC1030

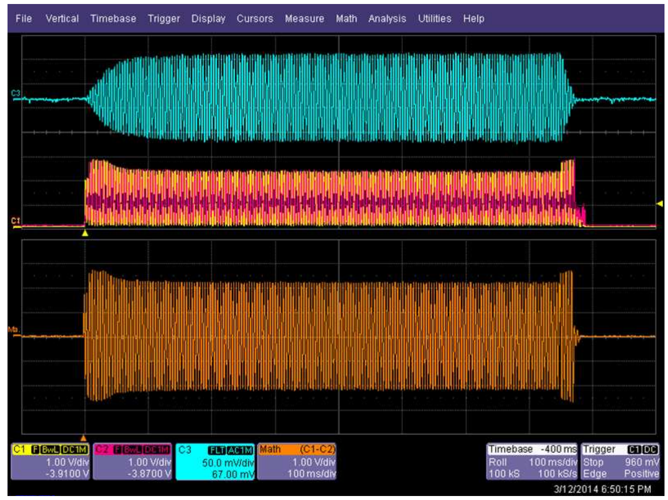

Figure 13. LRA Alert Waveform - SEMCO0832

Figure 14. ERM Alert Waveform - NRS2574i

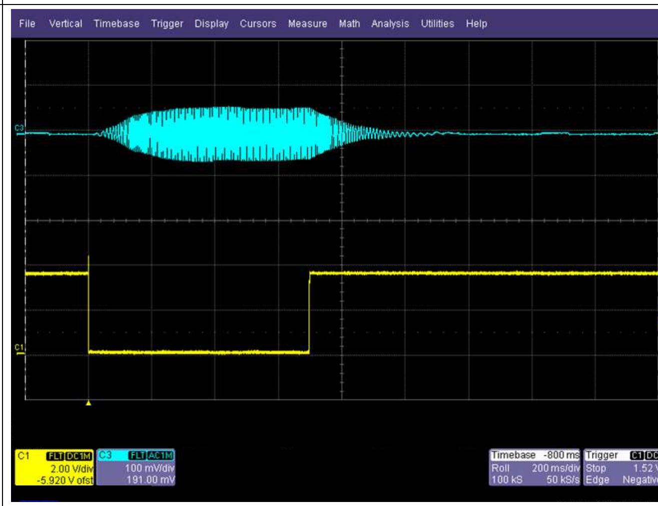

Figure 15. BLDC Alert Waveform

Triple click waveforms comparing 3 different actuators are shown in Figure 16, Figure 17, and ERM Triple Click Waveform - NRS2574i (BLDC modules cannot do clicks).

Figure 16. LRA Triple Click Waveform - AAC1030

Figure 17. LRA Triple Click Waveform - SEMCO0832

ERM Triple Click Waveform - NRS2574i

Current consumption versus battery voltage, and acceleration versus battery voltage are shown in Figure 18, Figure 19, Figure 20, and Figure 21 (measurements related to ERM and LRA were taken using the DRV2605 driver from TI). Since in some instances the acceleration used as comparison is not attainable due to actuator or system limitations, the acceleration plots are also provided.

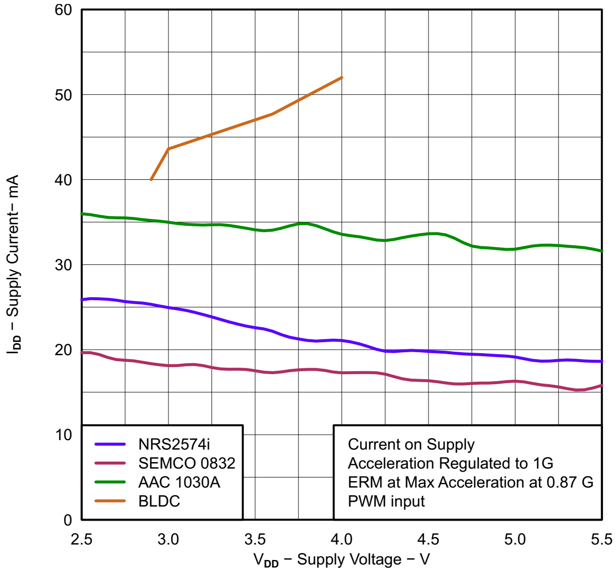

Figure 18. Current Consumption Comparison With 1 G of Acceleration

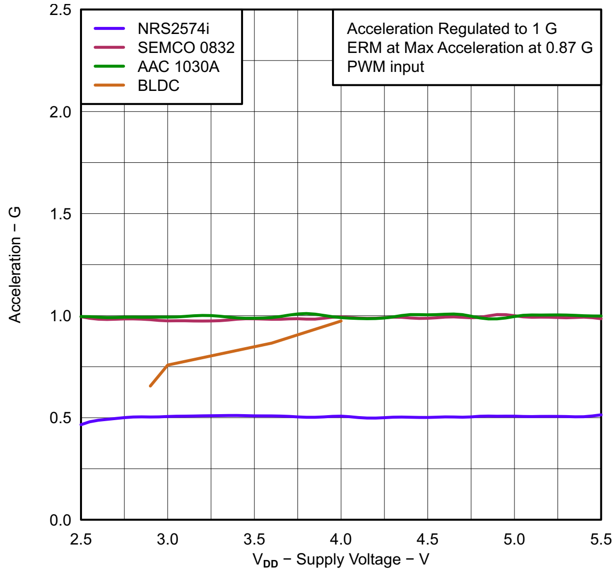

Figure 19. Acceleration Comparison With 1 G of Acceleration

ERM Triple Click Waveform - NRS2574i (continued)

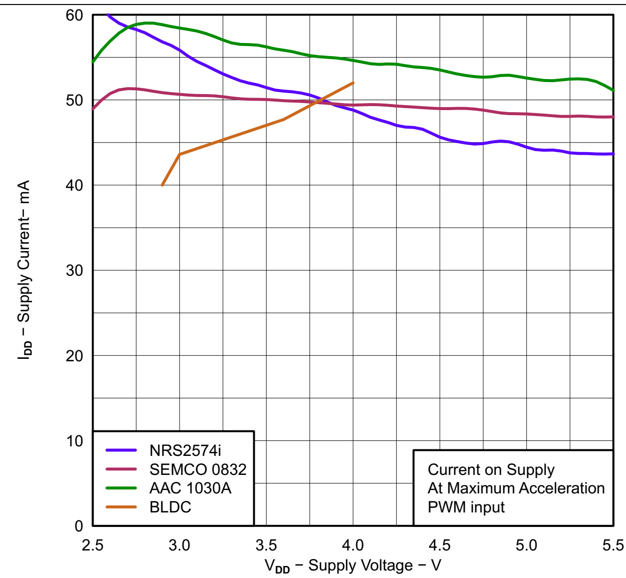

Figure 20. Current Consumption Comparison With Maximum Acceleration

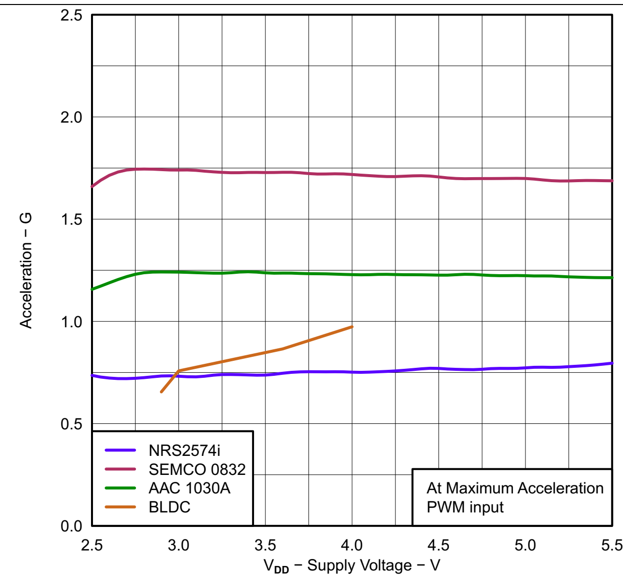

Figure 21. Acceleration Comparison With Maximum Acceleration

A table comparing start-time, brake-time and acceleration performance is shown in Table 1. Note that when it comes to start-time and brake-time, smaller is better.

Table 1. Actuator Comparison Table With VBAT = 3.6 V

ACTUATOR/DRIVER	BLDC/FET	NRS2571i/DRV2605	AAC1030/DRV2605	SEMCO0832/DRV2605
Start-Time [ms]	400	47	43	93
Brake-Time [ms]	350	37	17	24
Maximum Acceleration [g]	0.95	0.75	1.25	1.75
Efficiency [g/W]	4.85	3.95	6.25	9.71