VT-1: A Specification Proposal for Realistic Vibrotactile Feedback

Revision Draft 5 | December 2019

1. Introduction

1.1. Scope of the VT-1 specification

The VT-1 specification provides parameters and requirements for creating high-quality, realistic user experiences through vibrotactile (VT) haptic feedback. The specification does not apply to force-feedback/kinaesthetic communication or other modes of sensory feedback, such as thermoreception or nociception.

VT-1 is concerned purely with the quality of the haptic output needed for the user. It does not prescribe any specific API, protocol or other interoperability-related requirements. VT-1 is not an actuator-only specification – it applies to the whole haptic system as a black box. The entire signal chain – from input waveform through any software, firmware, electrical signals and actuators – should be capable of delivering the signal at the output according to the specification parameters.

The scope of the specification stops at the interface between delivery technology and the user. As such, parameters can be measured at this interface, for example, with an accelerometer in a test rig and the quality of the haptic delivery can be evaluated.

The VT-1 specification focuses on high-quality vibrotactile feedback. We refer to simpler vibrotactile feedback that does not meet the VT-1 specification as “basic haptics” in this document.

1.2. Why do we need a specification for realistic vibrotactile haptics?

Consumers are increasingly demanding realistic, immersive experiences for playing games, watching videos, listening to music and more. Whether they are embarking on a gaming adventure, using productivity apps in AR, or adjusting a virtual dial on a car dashboard tablet, they want to feel realistic tactile responses.

In the real world, haptic and audio signals are created from a single, common event, for example, a footstep striking the ground. The haptic and audio signals have different transmission media. The footstep generates both audio and haptic waves. One wave will propagate through the air to your ears, the other through the ground to your feet. The typical characteristics of waveforms (complex shapes and envelopes) are key to describing real-world sensations and conveying realism.

Product manufacturers, haptic technology suppliers and content authors are working to ramp up the development of products and titles that reproduce natural vibrotactile feedback at high fidelity to meet that demand. While these organizations want to highlight the quality of haptic experiences they can generate, there is currently no industry-wide definition for what constitutes “advanced” or “high-definition” (HD) vibrotactile haptics. The lack of standardization complicates communication among industry participants. For example, suppliers have no simple way to convey the quality of capabilities their technologies offer and differentiate their technologies from those of competitors. Meanwhile, manufacturers cannot evaluate competing haptic technologies without extensive testing.

1.2.1. Limitations of previous attempts at standardization

Several product manufacturers have used some version of the term "HD haptics" to claim that their products can deliver a highly realistic experience. But without standardized terminology, these claims serve only as marketing labels.

Meanwhile, some haptic technology vendors have listed some parameters for their own definition of HD haptics, but those specifications have too neatly aligned with the proprietary technologies that these suppliers offer. A true industry-wide specification must be attainable by most industry participants.

1.2.2. Replacing subjectivity with objectivity

Creating a specification is an important first step in replacing dependence on subjective terms and descriptions with objective, quantifiable criteria. Instead of vaguely claiming that a technology or product provides HD haptics, industry participants can use a specification to prove that their products meet a set of well-defined requirements and parameters.

Audio and video industry organizations employ several specifications for creating their content and products – such as specifications for Retina displays, HDTV, CD audio, Dolby Surround, THX, and more. These specifications help ensure content producers deliver material in the right format, and they enable technology suppliers and manufacturers to develop compatible products.

1.3. Benefits of the specification

An industry-wide specification will benefit haptic technology suppliers, product manufacturers and content authors.

1.3.1. Haptic technology suppliers

Suppliers can use the specification to streamline the development of new technologies. They will know which requirements they must meet and what parameter values they must achieve to deliver sufficient levels of functionality and quality. They can also use the specification to objectively communicate that level of quality to the product manufacturers looking to integrate haptic technologies.

1.3.2. Product manufacturers

The specification can help streamline the integration of haptic technologies and reduce risks that those technologies will fall short of expectations. Manufacturers can use the specification to more easily compare and choose from competing haptic technologies that they might want to integrate into their products. They can also mix and match components from suppliers as long as those components all conform to the specification.

1.3.3. Content authors

The specification provides target parameters that can help content authors create detailed audio-haptic assets. Since the specification helps ensure faithful translation of audio content into tactile vibrations, content authors need to meet certain criteria for audio quality. At the same time, the specification can help content authors avoid producing larger, higher-fidelity audio files than necessary.

1.4. How to use the specification

Haptic technology suppliers, product manufacturers and content authors will use the specification in different ways.

1.4.1. Haptic technology suppliers
Suppliers might focus on particular parameters within the specification as they develop their technologies. For example, suppliers building actuators might concentrate on the specification's parameters for dynamic response. Meanwhile, suppliers creating an end-to-end system might additionally use parameters for latency.

1.4.2. Product manufacturers
During the design and manufacturing phases, electrical engineers and mechanical engineers can use the specification to optimize product design. For example, the specification could alert an electronics engineer about the need for an amplifier IC that can handle complex waveforms.

1.4.3. Content authors
The specification does not require content authors to use particular tools or adopt specific workflows. But by defining target parameters for audio output, the specification can help guide authors to tools and workflows that will yield the best audio results for generating vibrotactile feedback.

1.5. How Lofelt arrived at the specification parameter types and values

We created this draft specification by drawing from extensive user testing, existing academic research and real-world product integration experience. We chose requirements and parameters and set parameter values that would allow multiple vendors to meet the specification.

1.5.1. User testing
At Lofelt, we continually employ user testing to gain feedback on our own technologies. We see what works and make tweaks that help deliver better user experiences. By drawing on our user testing in creating the haptics specification, we hope to help streamline the development of new products with realistic vibrotactile haptics. Manufacturers, suppliers and content authors can reduce some of the iterative, trial-and-error work we have already undertaken.

1.5.2. Academic research
As we develop our own technologies, we often refer to the existing academic literature on the physiology of human perception and the use of haptics to activate sensory perception. From that research, we understand, for example, that haptic technologies must operate differently for different parts of the body – a VR controller that provides feedback through fingertips will require a different curve than a chair designed to vibrate a person's entire body. Our proposed specification takes human physiology into account.

1.5.3. Real-world considerations
Lofelt has worked with manufacturers to bring several products to market that integrate our haptic technologies at a reasonable cost. That experience has helped us understand the practical considerations of integrating haptic technologies. In particular, we understand that the specification will only be useful if vendors can actually meet it and create products meeting the VT-1 quality level without excessive costs.

1.5.4. Technology agnosticism

A haptic specification is not useful if it can be met only by a limited number of vendors and technologies. In drafting this specification, we have attempted to be technology agnostic. For example, we do not specify a particular brand or type of actuator – and we have not set parameters than only one brand or type can meet.

Nor did we focus the specification for a particular use case. The VT-1 specification should be relevant and useful whether a company is creating a handheld controller or a VR bodysuit.

1.6. Summary of parameters

The specification includes several key requirements and parameters, which are described more fully in the next section. We also gave careful consideration to which requirements and parameters we would not include. In particular, we did not include requirements or parameters that might vary significantly from one use case to the next.

Included
– Waveform source material
– Independence of amplitude and frequency
– Frequency response
– Frequency resolution
– Dynamic response
– Dynamic resolution
– Distortion
– Latency
– Transient Response

Not Included
– Physical dimensions or mass
– Type of technology (e.g., VCM, Piezo, EAP)
– Axis/axes of vibration
– Resonant frequency/frequencies and Q
– Maximum G
– Operating voltage/current
– Over-driving/braking
– Bit depth
– Sampling frequency
– Number of actuators
– Quietness (mechanical noise)
– Use case/location on the body
– Hardware-only vs. integrated software and hardware haptics solution
– Calibration
– Fatigue/reliability
– Cost

1.7. How to measure parameters

Parameter values are only useful if organizations adopting the specification employ standardized tools for generating those values. In the appendix, we have provided full details of the tools a vendor needs to generate the measurements. Those tools are easy to acquire and use – they should not be a roadblock for adopting the specification.

2. Specification

Important Note:
This document is a work-in-progress proposal. Areas that need further development or use placeholder values are marked in yellow highlight. We welcome all feedback from the haptic technology community regarding this specification. We want the specification to evolve and become a useful, shared baseline for everyone. Contact details are at the end of this document – please let us know your comments.

2.1. Overview

Parameter	Description	Key Value
Waveform source material		Yes
Independence of amplitude and frequency		Yes
Frequency response	Width of frequency response across which the system can deliver the minimum dynamic range. Larger is better.	20 Hz or more
Dynamic Response	Height of dynamic response above the perception threshold which the system can deliver across its frequency response. Larger is better.	12 dB or more
Frequency resolution	Size of steps between frequencies delivered by the system. Smaller is better.	Low (<50 Hz): 0.5 octaves or smaller Medium (>50 Hz & <120 Hz): 1 octave or smaller High (>120 Hz): 2 octaves or smaller
Dynamic Resolution	Size of amplitude steps delivered by the system. Smaller is better.	0.3 G or smaller
Transient Response	Rise time from 0 to 100% of the minimum dynamic response level. Shorter is better.	2.25 cycles or shorter
	Fall time from 100% of minimum dynamic response level to below perception threshold. Shorter is better.	2.25 cycles or shorter
Total Harmonic Distortion	THD of the system. Smaller is better.	30% or smaller
Latency	Time between the arrival of the audio/video/event signal and its corresponding haptic signal. Smaller is better.	Physical event: 20 ms or smaller Audio: 10 ms or smaller Video: 20 ms or smaller

2.2. Waveform source material

Definition: The original input source should be based on a continuous waveform. Requiring a continuous waveform clarifies the relationship between source and haptic output.

Underlying reasoning: Using waveforms allows for the real-world simultaneous mix of sharp transients and longer tones. Of course, waveforms do not need to be audible—they can consist solely of sub-audible frequencies.

Limitations with basic haptics: Haptic technologies that use only amplitude and duration, or that are created by discrete on/off control signals, result in artificial, machine-like buzzing. These basic haptic technologies cannot represent real-world haptic information.

Specification: An author of haptics effects can use an audio waveform as source input for the haptic system. The waveform can be in the form of analog electrical signals or digital signals, such as I2S, PCM values or software arrays of values.

Measurement: none needed

2.3. Independence of amplitude & frequency

Definition: Specifying the independence of amplitude and frequency enables the potential reproduction of complex waveforms. Adding this requirement prohibits the use of simple ERMs.

Underlying reasoning: In the real world, haptic signals have independent amplitude and frequency. (Consider the haptic vibrations created by approaching footsteps.) Controlling amplitude and frequency independently is essential for mimicking real-world haptic information.

Limitation with basic haptics: With a standard ERM, amplitude and frequency are dependent on each other. As a result, reproducing real-world haptic information is impossible.

Specification: Within the given range of operation, it must be possible to vary amplitude and frequency independently. A standard ERM would not pass. However, standard LRAs, voice-coil actuators, piezo and EAP actuators would pass this test. Note that this test does not rule out some novel configuration of ERMs or combinations including ERMs if the criterion is thereby satisfied. Note also that this test is not measuring the frequency response of the system; testing is done within the lower amplitude bounds of the declared frequency range.

Measurement: Use a standard test jig with a 100 g mass. First test amplitude by setting input sine waves at the lower, center and upper frequencies of the declared frequency range. Ramp amplitude from zero up to the upper limit of the minimum dynamic response (12 dB above perception threshold). Using an oscilloscope with frequency measurement, ensure that the frequency does not change more than +/- 5% of the source.

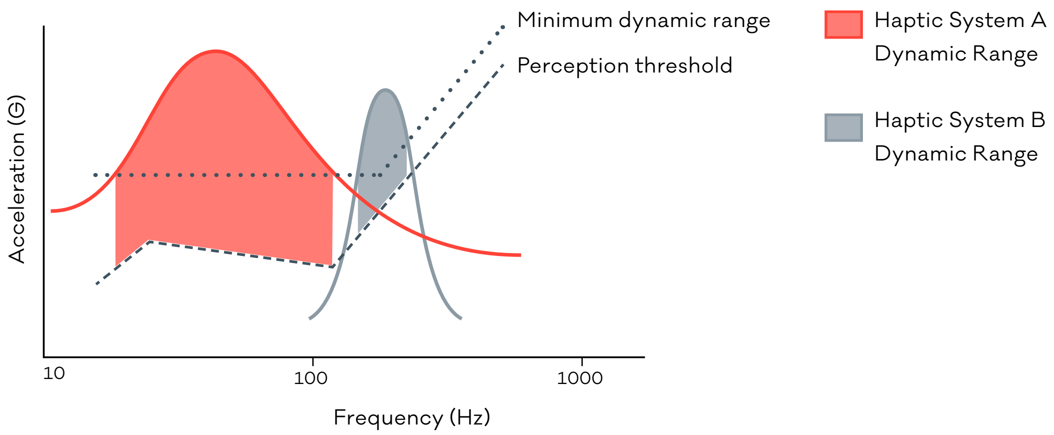
2.4. Frequency response

Definition: The frequency response parameter is the usable frequency spectrum for conveying haptic feedback to the user. The system needs to provide more force than the perceptual threshold plus the minimum dynamic range. As such, frequency response is closely tied to the dynamic response. The frequency response can be discontinuous – in other words, it can include both a low-end range plus a high-end range.

Underlying reasoning: In the real world, haptic signals are complex waveforms containing a range of different frequencies. Even though frequency perception in the haptic range is very coarse compared with auditory frequency sensitivity, reproducing this variety of frequencies is key to realistic feedback.

Notes:
This is the most important – and also the toughest – parameter to specify, as it depends strongly on the use case. The parameter should be a dynamic range above the perception threshold, which depends on frequency. For example, in the low-frequency band, you might need a minimum of 0.5 G above a 0.3 G threshold.

2.5. Dynamic response



Definition: The dynamic response parameter is the usable dynamic range above the perception threshold that enables different strength levels to be perceived.

Underlying reasoning: In the real world, haptic vibrations arrive with continuous changes in intensity. Humans can perceive even very subtle changes of less than 1 dB. A realistic experience is dependent on the system's capability of presenting multiple levels above the perception threshold. However, absolute values are very dependent on the use case, so the specification must be relative to a use-case perception threshold. This parameter is closely related to the dynamic resolution parameter.

Limitation with basic haptics: An amplitude range that is too narrow will not allow any modulation and nuance to be delivered to the user. It will feel like a switched on/off vibration.

Specification: The dynamic range should have at least 12 dB of headroom above the chosen use-case perception threshold.

Measurement: Use a standard test jig with a 100 g mass and an accelerometer connected to an oscilloscope.Input signal sine waves at the upper and lower ends of the declared frequency range and select the baseline perception threshold from a use-case table. Show a minimum of 12 dB amplitude range across the declared frequency range.

2.6. Frequency resolution

Definition: Frequency resolution is the number of discrete steps across the usable bandwidth. A minimum number of steps is needed to create a realistic haptic experience.

Underlying reasoning: In the real world, haptic signals arrive with a continuous, analog frequency range. However, the tactile ability to discriminate between vibration frequencies is quite limited when compared to the auditory system[1]. Frequency sensitivity also changes with absolute frequency – generally, the higher the frequency, the less sensitive we are. This lower sensitivity means that you can optimize the haptic signal chain to deliver only what we can sense. However, you should ensure that this optimization is not done in such a crude way that the steps are easily perceptible by touch.

For many haptic technologies, this parameter will be irrelevant, since those technologies will support a continuous range of frequencies. But it is added here for clarification in case other solutions appear, such as arrays of single-frequency actuators.

Limitation with basic haptics: In real-world haptics, there are many sources that generate smooth frequency sweeps across a frequency range, such as an accelerating car. If the frequency resolution steps are too large, the user will not feel a smooth sweep, but instead an artificial experience with discrete steps.

Specification:

Low frequencies (<50Hz)	Medium (>50Hz & <120Hz)	High (>120Hz)
Min. 1 step per half octave	Min. 1 step per octave	Min. 1 step per two octaves

Measurement: Use a standard test rig with a 100 g mass. Input sine waves with frequency sweeping continuously across the declared frequency response. Measure the frequency steps (if any) in the output acceleration.

[1] See Merchel, S. (2014). Auditory-Tactile Music Perception (ISBN:978-3-8440-3161-4), Shaker Verlag, Germany.

2.7. Dynamic resolution

Definition: The dynamic resolution is the number of discrete steps in force. A realistic haptic experience requires a minimum number of steps.

Underlying reasoning: The tactile dynamic range is considerably smaller than the auditory dynamic range[2]. Like the frequency resolution, this parameter will be irrelevant for many haptic technologies since those technologies will support a continuous range of amplitudes. But it is added here for clarification.

Limitation with basic haptics: Discrete on/off or stepped intensity levels produce a mechanical, artificial feeling.

Specification: Minimum 1 step per 0.3 G.

Measurement: Use a standard test rig with a 100 g mass. Input sine waves with amplitude ramping up continuously from 0 to the maximum. Measure the amplitude steps (if any) in the output acceleration.

Notes:
1. *Although amplitude sensitivity changes with frequency, it is not a significant variation, so we take the worst case.*
2. *This parameter will be irrelevant for haptic technologies that support a continuous range of amplitudes, though it might be interesting if an actuator has a threshold at the start to get moving.*

2.8. Distortion

Definition: The distortion parameter measures total harmonic distortion (THD) – a term used frequently in the audio industry. Lower distortion means the haptic system produces a more accurate reproduction of the original source waveform.

Underlying reasoning: Tactile perception is much less sensitive to changes in waveforms compared with audio perception. However, a degree of fidelity to the original shape is still important. Differences in vibration character – for example, soft, sharp, clean or noisy – can be perceived in this specification. Whereas audio technology THD values should be in the single digits or even less than 1%, our tests have shown that with haptics, THD values can be much higher before differences are perceived.

Limitation with basic haptics: If the THD is too high, the waveform characteristics/timbre are lost or incorrectly translated. For example, the feeling of a smooth signal that turns more noisy will not be perceived correctly. By introducing higher-frequency harmonics, excessive THD may also make the system audible when quiet operation is desired.

Specification: Maximum THD of 30%

Measurement: Measure THD at a number of frequencies across usable bandwidth. Tested at the top of the dynamic range level.

[2] Ibid.

2.9. Latency

Definition: Latency is the time between the arrival of an audio or video signal and the corresponding haptic signal. For the haptic perception, rise time is an additional factor. But we are defining latency independently of rise time (with an idealized perfect rise time).

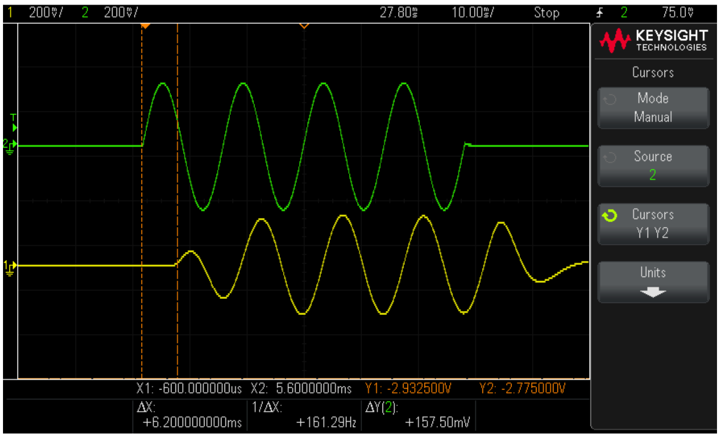
Underlying reasoning: To create a realistic perception of an event, the user must receive the haptic information at the same time as the audio or visual information so the multimodal signals can be correlated into one experience.

Limitation with basic haptics: With basic haptics, the user might perceive (even subconsciously) the haptics as separate from the audio, video or event. The result is an artificial experience.

Specification

Latency between type of event and haptic perception	Maximum latency over given frequency range of operation
Physical event	20 ms
Audio	10 ms
Video	20 ms

Measurement: For audio-to-haptic latency, use an oscilloscope to capture both the audio signal at the loudspeaker and the accelerometer signal attached to the actuator. Measure the time between the same parts of the signals using the oscilloscope cursors. A dynamic source signal is useful for comparison purposes.



2.10. Transient response

2.10.1. Rise time

Definition: Rise time is the time for a sine wave to rise from rest (0) to 90% of perception threshold.

Underlying reasoning: A fast rise time is essential to convey dynamic characteristics of real-world haptic signals, sharpness, "clickiness" and crispness.

Limitation with basic haptics: With a fast rise time, signals can feel more precise. Conversely, the slow rise times of basic haptic technologies render the dynamics mushy or indistinct.

Specification: Max 2.25 cycles (for example, 38 ms at 60 Hz, 14 ms at 160 Hz) over a given frequency range of operation.

Measurement: Use an actuator in a test jig. Drive with sine wave at test frequency. Monitor force with the accelerometer connected to oscilloscope. Test at least at three different frequencies – minimum and maximum frequency range, and f0. Within two and a quarter cycles, the actuator should have risen from 0 to 90% of the maximum given.

Notes:
We don't set the test frequency, as the test should be done across the frequency range and the threshold may change with frequency

2.10.2. Fall time

Definition: Fall time is the time for a sine wave to fall from constant G to below the perception threshold.

Underlying reasoning: Similar to rise time, a fast fall time is essential to convey dynamic characteristics of real-world haptic signals the sharpness, clickiness and crispness.

Limitation with basic haptics: With a fast fall time, signals can feel more precise. Conversely, the slow fall times of basic haptic technologies render the dynamics mushy or indistinct.

Specification: Max. 2.25 cycles over the given frequency range of operation.

Measurement: Use an actuator in the test jig. Drive with sine wave at test frequency. Monitor force with the accelerometer connected to an oscilloscope. Test at least at three different frequencies – minimum and maximum frequency range, and f0. Within two and a quarter cycles, the actuator should have fallen from a constant force to below the perception threshold.

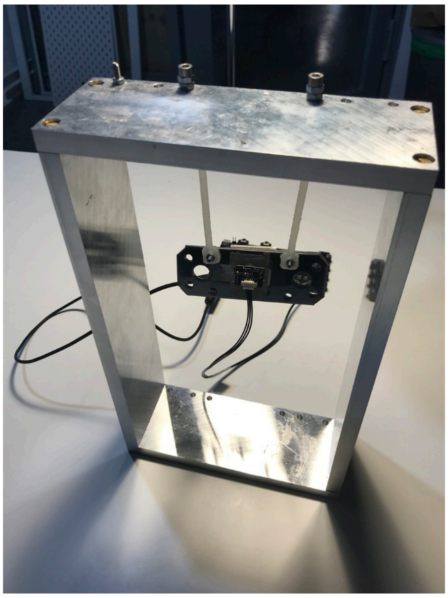
Notes:
We don't set absolute G as the minimum threshold for feeling haptic changes according to frequency and context.

Appendix - Measurement Set-up

A1 Test jig, suspension, mass

The Test Jig
A well-designed test jig holds the device under test (DUT) and sensors in such a way that the energy created by the DUT – and only this energy – is collected by the sensors. It strives to reduce any external influences on the system so that the data collected reflects the real performance of the DUT. It should enable consistent and repeatable measurements.

Lofelt employs the approach of suspending the DUT from a heavy frame such that the DUT is not coupled to any materials other than the desired attached mass as seen in the image below:



The frame is made from four pieces of aluminum metal arranged in a rectangle. This particular frame weighs 1300 g. The goal is to make the frame massive enough that it isolates any possible vibrations from the table reaching the DUT and sensors, and also prevents energy created by the DUT from dissipating into the frame and table.

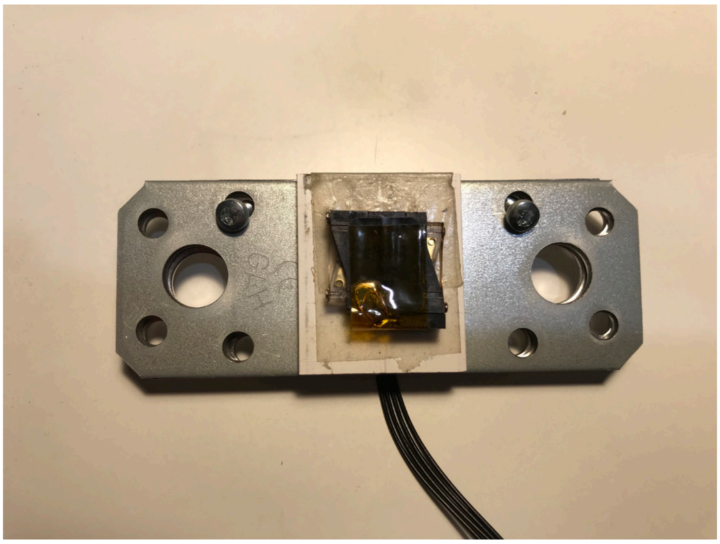
Connected to the top of the frame are elastic bands from which a steel plate is suspended. The elastic bands are made of silicon rubber. They have as little stiffness as possible, so that they allow free side-to-side (left-right) movement of the steel plate to which the DUT and sensors will be attached.

The Attached Mass
The steel plate serves both as a mounting platform for the DUT and sensors, as well as a defined mass that is used during the evaluation of the test results. (The output energy measured of the DUT will change depending on the mass to which it is attached). Each steel plate weighs 50 g. Additional plates can be attached to increase the attached mass used in the test.

An attached mass of 100 g is used for tests. Many in the industry already use 100 g attached mass when testing actuators, so using 100 g here allows the test results to be easily compared against test results of other actuators. Note, VT-1 is not just testing the actuator, but the whole haptic system – nevertheless, the principle applies.

The DUT should be attached to the center of the steel plate in such a way that the vibration direction of the DUT corresponds with the two axes in which the steel plate can move (parallel to the ground). It should not be mounted in a way where the vibration direction is along the up-down axis, as this would cause the elastic bands to absorb some of the energy ultimately affecting the results.

The DUT is attached to the steel plate using 3M double-sided adhesive tape, as shown in the following image:



A2 Measurement sensor

An accelerometer is used for measuring the DUT. Lofelt uses an accelerometer based on an Analog Devices ADXL325. This accelerometer IC was chosen for the following characteristics:
– Measurement range: Up to 6 G (within the ranges of current Lofelt haptic systems)
– Sensitivity: 174 mV/G (allows small, subtle changes in G to be captured)
– Frequency range: 0.5 Hz to 1600 Hz (covers the entire haptic perception range)

The accelerometer is mounted to the opposite side of the steel plates from the DUT. Even if the accelerometer is multi-axis, every effort should be made to orient the accelerometer such that one of its axes corresponds with the vibration direction of the DUT. This makes analysis of the acceleration data easier since the majority of the acceleration will be captured by a single axis.

The accelerometer is fixed to the steel plate with 3M double-sided adhesive tape as shown in the following image:

The accelerometer output is then connected to the measurement system – an oscilloscope for real-time observation or into an analog-digital converter for logging and subsequent analysis.

A3 Test signal generation

The VT-1 specification describes the full haptic system, not just the actuator. Most parameters need an input waveform such as sine wave for testing. The system under test should be capable of either taking the wave as external input or generating the wave itself, for example, by using stored waveform samples. Real-time conversion of input audio is not a requirement.

Test signal waveform input → Haptic System under test → Measured waveform output

Further Information

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Revision history

Draft 5
– Added Table of Contents
– Updated scope and moved to start of doc
– Added parameter overview table and notes on work-in-progress
– Added Further Information page
– Added Appendix

Draft 4
– First public version for Smart Haptics 2019