HAPTICS
INDUSTRY FORUM

Measuring Haptics in Touch-Sensitive Automotive User Interfaces

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1 Authors

The authors of this document are members of the Automotive Working Group subcommittee in the Haptics Industry Forum.

Elisa Santella	GREWUS
Markus Obermayr	TDK
Jockum Lönnberg	TDK
Erin Ramsay	Innovobot
Bing Xie	AAC

2 Overview

In [1], we provided an overview of use cases in which haptics is known to provide meaningful added value to automotive interfaces. In this document, we drill down to the next level of detail - how to measure haptics in touch sensitive automotive user interfaces. We describe the basics of good haptic feedback, present a methodology to extract relevant information that better captures the tactile information to be displayed with a haptic system, distinguish between passive and active haptics, specify the parameters of interest and their target values, list the measuring equipment that can be used, and provide a sampling of measurement results that can be expected.

Note that this document deals with the measurement of vibrating surfaces, and in general those vibrating surfaces will be referred to as haptic (user) interfaces that provide haptic feedback.

3 Who should read this document

The target audience for this document is project managers, system designers, user experience designers, and engineers working in the automotive industry at OEMs, Tier1, Tier2, and Tier3 suppliers who are tasked with adding haptic functionality to automobiles. This document assumes technical familiarity with measuring equipment and the ability to read and interpret measurement graphs.

4 Basics of good haptic feedback

Touch-sensitive surfaces (e.g., touchpads or touchscreens) are relatively new input devices that are replacing the traditional mechanical buttons and switches found in old automotive interfaces. One of the major drawbacks of these surfaces, when first introduced, was the lack of tactile confirmation that is provided by all mechanical parts. In order to create that tactile confirmation, and potentially other haptic experiences, it is important to understand how haptics, or the tactile information, is produced by those mechanical interfaces. In this document, we will differentiate the tactile information produced by mechanical buttons and switches from that produced by haptic interfaces. We will call passive haptics, the tactile information generated by mechanical interfaces as the **tactile experience** produced by those interfaces is not programmable and remains the same over its entire life cycle[1].

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[1] Kalpesh R. Vaghela, Amaury Trockels, Marco Carobene,
Active vs passive haptic feedback technology in virtual reality arthroscopy simulation: Which is most realistic?,
Journal of Clinical Orthopaedics and Trauma,
Volume 16,
2021,
Pages 249-256,
ISSN 0976-5662,
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(https://www.sciencedirect.com/science/article/pii/S0976566221001351)

Another reason why we call this **passive haptics** is because all the measurements and specification of those haptic interfaces are performed, traditionally, using static methods (Force vs. Displacement curves, see section 4.1). However, it is well known that tactile information is dynamic in nature and for this reason a different set of performance metrics are necessary to describe and measure the performance of a haptic user interface. These metrics will be discussed in detail in section 4.2, we will discuss what they are, and how to measure them to ensure consistency from system to system, whether it is a couple of prototypes, or the end of the production line for thousands of devices. We will call this measurement “active haptics measurement” to differentiate them from the “passive haptics measurements”. The term ”active haptics” is used because the haptic effect can be programmable and it is dynamic in nature; as opposed to passive haptics that is not programmable and has been characterized using static measurements.

The parameters for the quantification of active haptics are

- Haptic feedback design / type of haptic effect (e.g. impulse or vibration pattern)
- Human perception (haptic & sound) as a basis so that respective parameters can be measured in sufficient resolution
- Physical parameters, e.g., acceleration, frequency, displacement, etc.

To understand the specifications of tactile systems, and therefore the actuators used to produce those sensations, and how they relate to haptics, it is first necessary to understand the psychophysics of the human mechanoreceptor system.

In haptics, we think broadly about the four classes of mechanoreceptors: Merkel, Ruffini, Pacinian, and Meissner [2]. These four receptors broadly sense vibration, surface texture, deformation, and pressure. They work together to provide nerve pulses to the brain that enable the tactile sensation of the world. The signals from these nerves are merged in the brain to create a tactile perception of the world. The goal of a haptic actuator, and thus a haptic system, is to stimulate one or more of these mechanoreceptor systems to create a touch experience.

For a haptic system, it is useful to think about actuators from the perspective of the type of haptic experience stimulation they provide. The various types are broadly summarized in Table 1 [2]. When talking about creating haptic experiences like vibration or texture, we can see immediately that our perception of those effects is dynamic in nature as those receptors respond to dynamic excitation and not to static forces or displacements. We will see in section 4.2 that the traditional way of specifying performance for passive haptics does not apply to active haptics but there is a way to extract the appropriate information from those systems to specify dynamic haptic systems.

The key elements of haptic system performance to ensure a consistent haptic experience are:

- Acceleration
- Frequency
- Latency /response time and stop time
- Actuator characteristics

Table 1: Actuation Types

Haptic Experience	**Actuation Type**	**Relevant Mechanoreceptors**
Vibration	Electromagnetic	Pacinian + Meissner
Vibration + Texture	Piezoelectric	Pacinian + Meissner + Merkel
Friction	Electrostatic, ultrasonic	Meissner + Pacinian
Kinesthetic	Electromagnetic, Electroactive Polymers, Pneumatic, Hydraulic	Golgi tendon organs, Muscle spindles
Stretch + Deformation	Electromagnetic, Electroactive Polymers	Ruffini, Meissner, Merkel

4.1 Passive Haptics - Force based (Traditional Process)

The standard way to define passive haptic in standard tactile switches is the definition of a force-displacement diagram called ‘S curve’, see Figure 1. Here we explain how “haptics” has been quantified until now: S-Curve (a “good” mechanical switch):

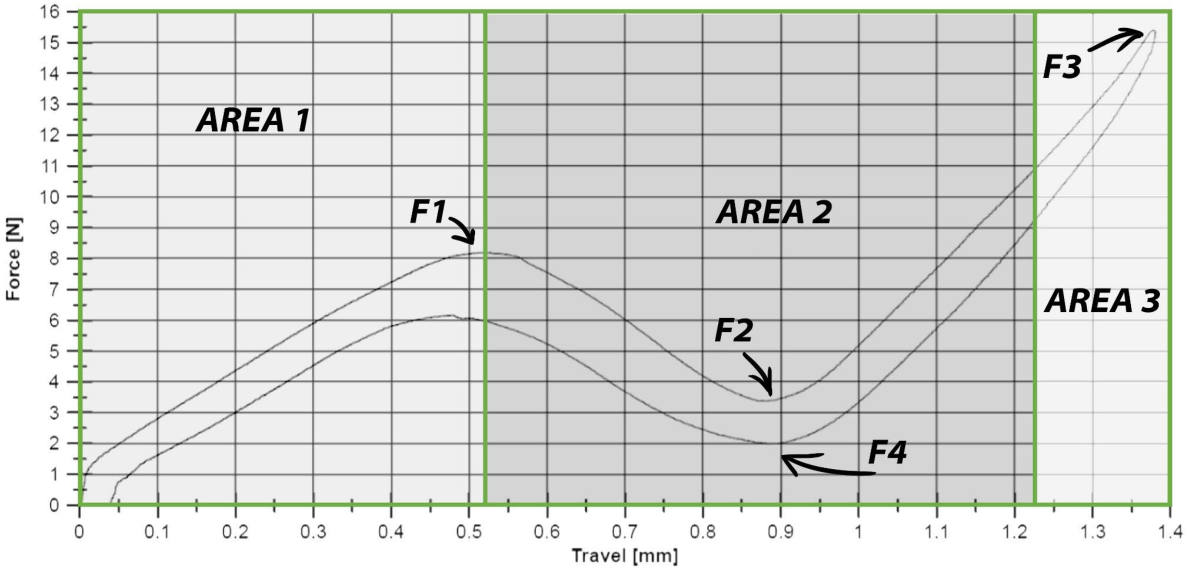


Figure 1: Force-Displacement curve of mechanical switches

The S-curve shows how the position of the switch pusher and the force applied to it are correlated during a user action from "Off" to "On" to "Off" states of the switch. The curve is always double: the upper S-curve defines the push action thanks to the values F1, F2, and F3, and the lower S-curve describes the release action thanks to F4. The area within the two curves is called the switch hysteresis.
This curve defines the elastic behavior of the switch. In physics, the force-displacement curve represents the elastic constant of a spring and this information has nothing to do with the human perception of vibrations and sound.

The force vs. Travel graph in Figure 1 can be sectioned in three distinct areas as follows.

- Area 1: This part of the S-curve can be called the "pressure zone" because the finger is pressed against the contact area of the switch. The human finger perceives the force increasing from 0 to the maximum value F1.
- Area 2: This part of the S-curve can be called the "flying zone". In this area, the spring inside the switch collapses causing the finger to accelerate toward the bottom of the switch. In this area, the finger perceives the lack of force because the force F1 suddenly decreases. Also, in this case, the finger does not perceive the travel, however, it is in this zone that the user perceives the so-called “click” of the switch.
- Area 3: This part of the S-curve could be called the "crash zone". After accelerating in the "flight zone", the finger crashes against the bottom of the switch. The strong deceleration produces a force peak that the user perceives well.

In Automotive, OEMs and Tier1s, are familiar with the specification of mechanical switches (S-Curve, force-displacement diagram). But active haptics requires different parameters and characteristics. As mentioned above, Area 2 is where the tactile information is conveyed to the user but it is not captured with the measurements described above.

4.2 Haptics - Time based (new approach)

Measuring a system with active haptic feedback requires a new approach. The time based approach allows for the consistent measurement of systems regardless of whether they are “active” or “passive”, including systems with little deflection of the surface but with a high acceleration.

4.2.1 Time-based measurement of passive haptic elements

Using a time-based measure to obtain information from a mechanical switch allows us to get a different perspective of the press event, which from the haptics perspective is the most important characteristic to capture information from. Figure 2 shows the force (magenta line), and the acceleration signal over time obtained when a user interacts with a mechanical switch. In that figure, the switch is pressed with a slow speed resembling the force signal discussed in Figure 1. In Figure 3, the force and acceleration data were captured using a faster interaction speed (pressing faster than in Figure 2). Figure 3 also depicts the different zones used to classify passive haptics as in Figure 1. We can see that in Area 1 and Area 3, the user feels the change in pressure and possibly deflection of the button but he does not really feel the acceleration. Area 2, happens very quickly and is here where the user feels the detent, the feeling that the button has been pressed or released. The oscillations in the acceleration signal in Area1 and Area 3 are artifacts created when the mechanics of the switch collide or impact internally creating some oscillations.

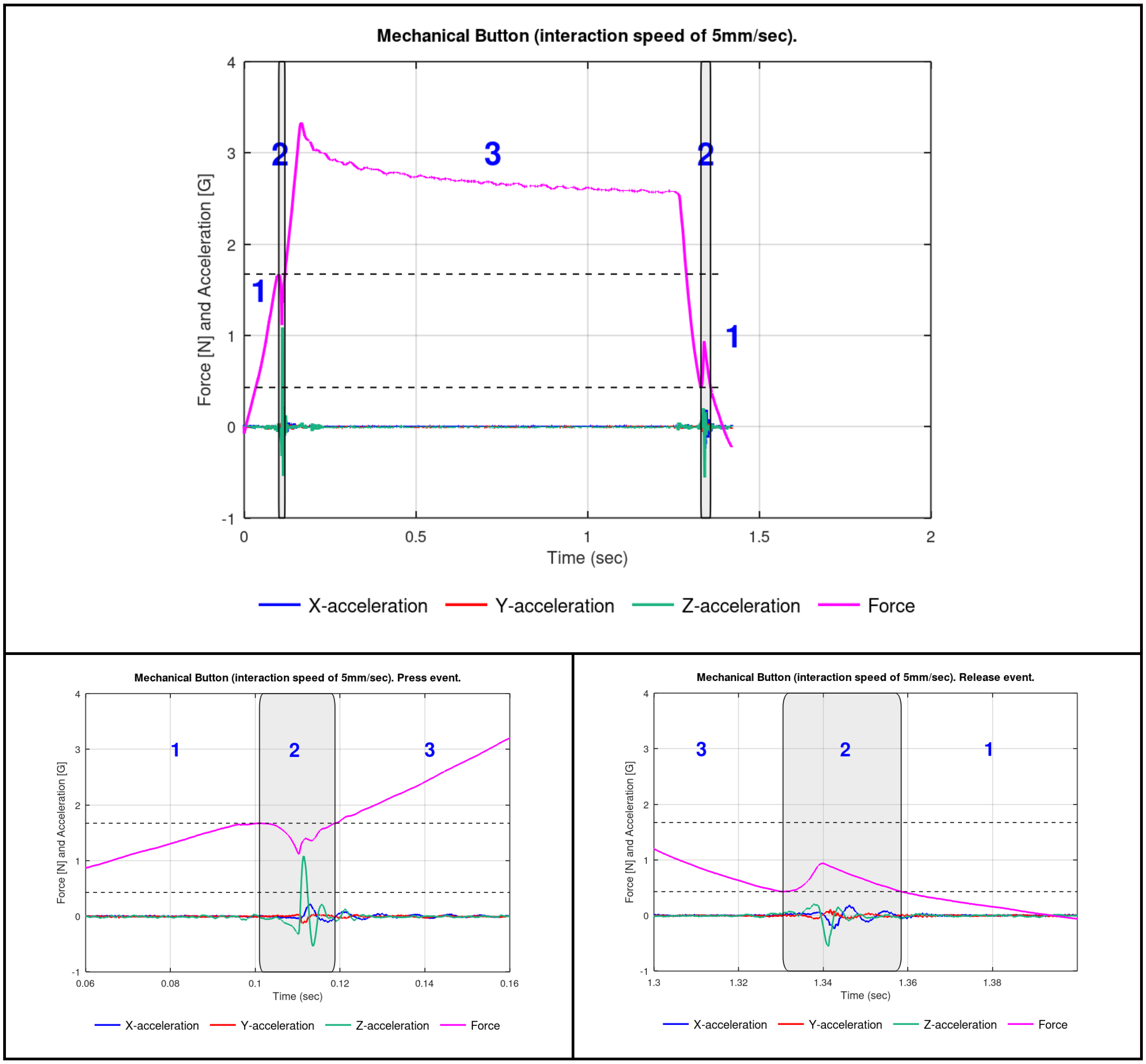


Figure 2: Force and acceleration vs. time of a mechanical switch (slow speed measurement). Top graph shows the entire press and release interaction. Bottom-left graph shows the details of Area 2 where the dynamic, tactile behavior of the switch happens when the user presses the switch. Bottom-right graph shows the release with the corresponding tactile behavior.when the user moves away from the switch.

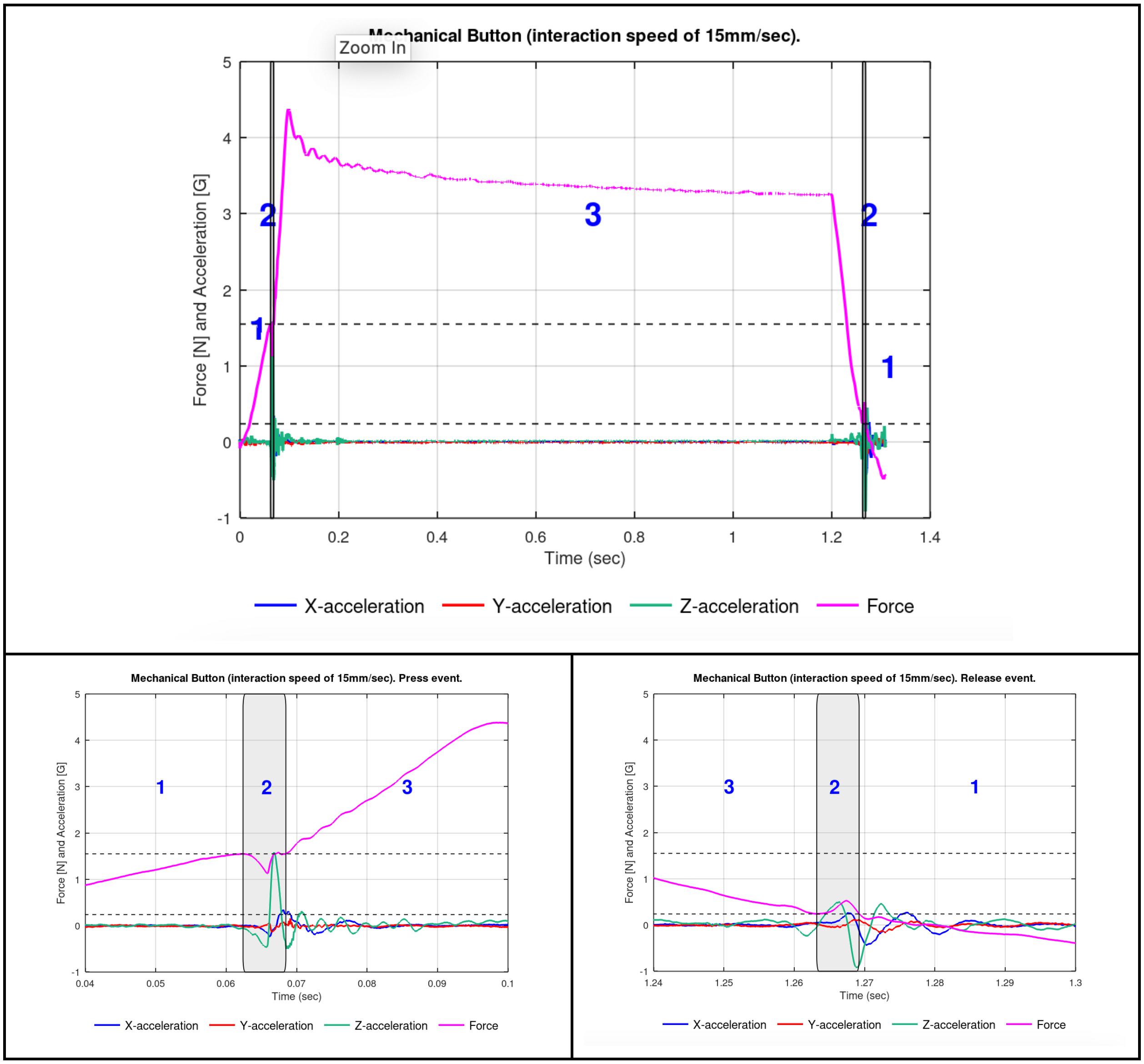


Figure 3: Force and acceleration vs. time with different areas (fast measurement speed). Top graph shows the entire press and release interaction. Bottom-left graph shows the details of Area 2 (blue number) where the dynamic, tactile behavior of the switch happens when the user presses the switch. Bottom-right graph shows the release with the corresponding tactile behavior.when the user moves away from the switch.

We can see in Figure 2 that the finger contacts the button at the left of Area 1 and a more downward force is applied until F1 is reached. The user then feels the detent as the button physically collapses in a dynamic event taking less than 50 ms in Area 2; this area where the tactile mechanical “click” feeling is perceived by the user. The User then moves into Area 3 reaching the end of travel of the button and begins to reduce force. When F4 is reached another dynamic event happens when the button regains its structure again, taking less than 50 ms, just before lifting their finger off the surface.

Pressing the same button at a different speed as depicted in Figure 3 gives a different result. Note that F1, F2 and F4 remain the same but the acceleration (only normal shown) changes significantly. This can be seen in Figure 2 and Figure 3. In Figure 2 the force increases at a lower rate as it takes ~100 msec to reach F1 compared to ~60 msec that takes to reach F1 in Figure 3.

Other mechanical buttons have higher force levels, and less travel, meaning that the time spent in area 2 gets even smaller and more dynamic, with higher accelerations. In Figure 2, about 20 msec is spent in Area 2 and to reach this Area 2 a force of 1.8N is needed. Figure 4 depicts a stronger switch for which ~40 msec is spent in Area 2 and a force more than 6N is needed to reach F1. Note also that the acceleration measured is different for each of the mechanical switches.

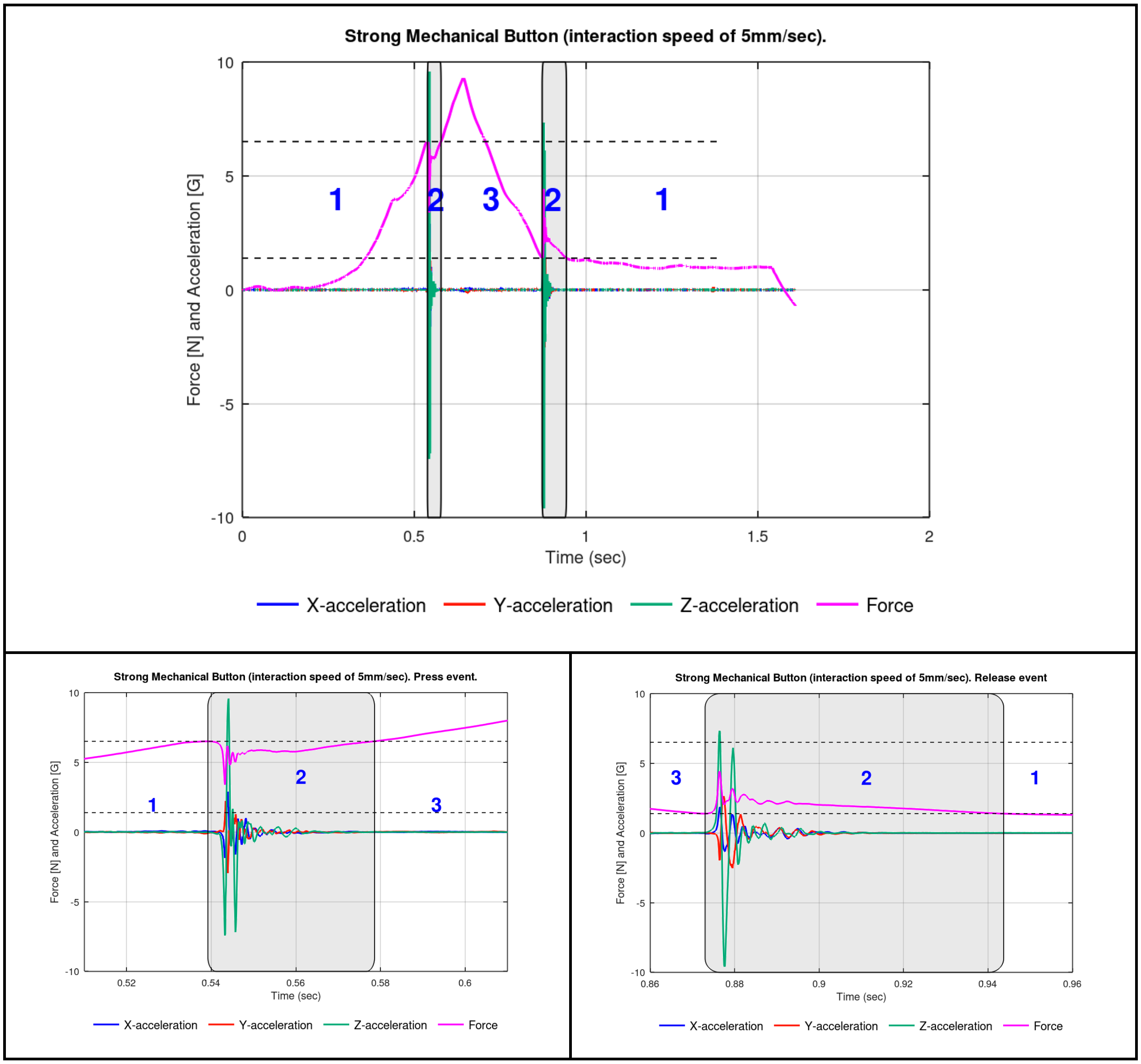


Figure 4: Force and acceleration vs. time with different areas for a stronger switch.. Top graph shows the entire press and release interaction. Bottom-left graph shows the details of Area 2 (blue number) where the dynamic, tactile behavior of the switch happens when the user presses the switch. Bottom-right graph shows the release with the corresponding tactile behavior.when the user moves away from the switch.

With passive haptics defined by the time-based domain we can now consider the dynamic behavior of the user interaction with mechanical buttons and switches. We have defined the interaction in such a way to compareway this will allow us to effectively compare the experience with an active haptic system.

4.2.2 Time-based measurement of active haptic elements

This same approach can be used on active haptic surfaces as seen in Figure 5. In this case no drop in force is seen during the detent, (no F1 visible). The force curve remains smooth through both the press and release haptic events (Area 2). There is no physical switch in the device, the surface has almost no vertical displacement, but instead a force sensor is monitored and when a force threshold is reached, an active haptic response is triggered. The measurement below is taken from a commercial touchpad device with active haptic feedback. In this use case, the user feels a consistent click in all locations on the touchpad, allowing a larger, thinner, more enjoyable touch surface experience. When well executed, many users will not understand that there is no physical button in the device.

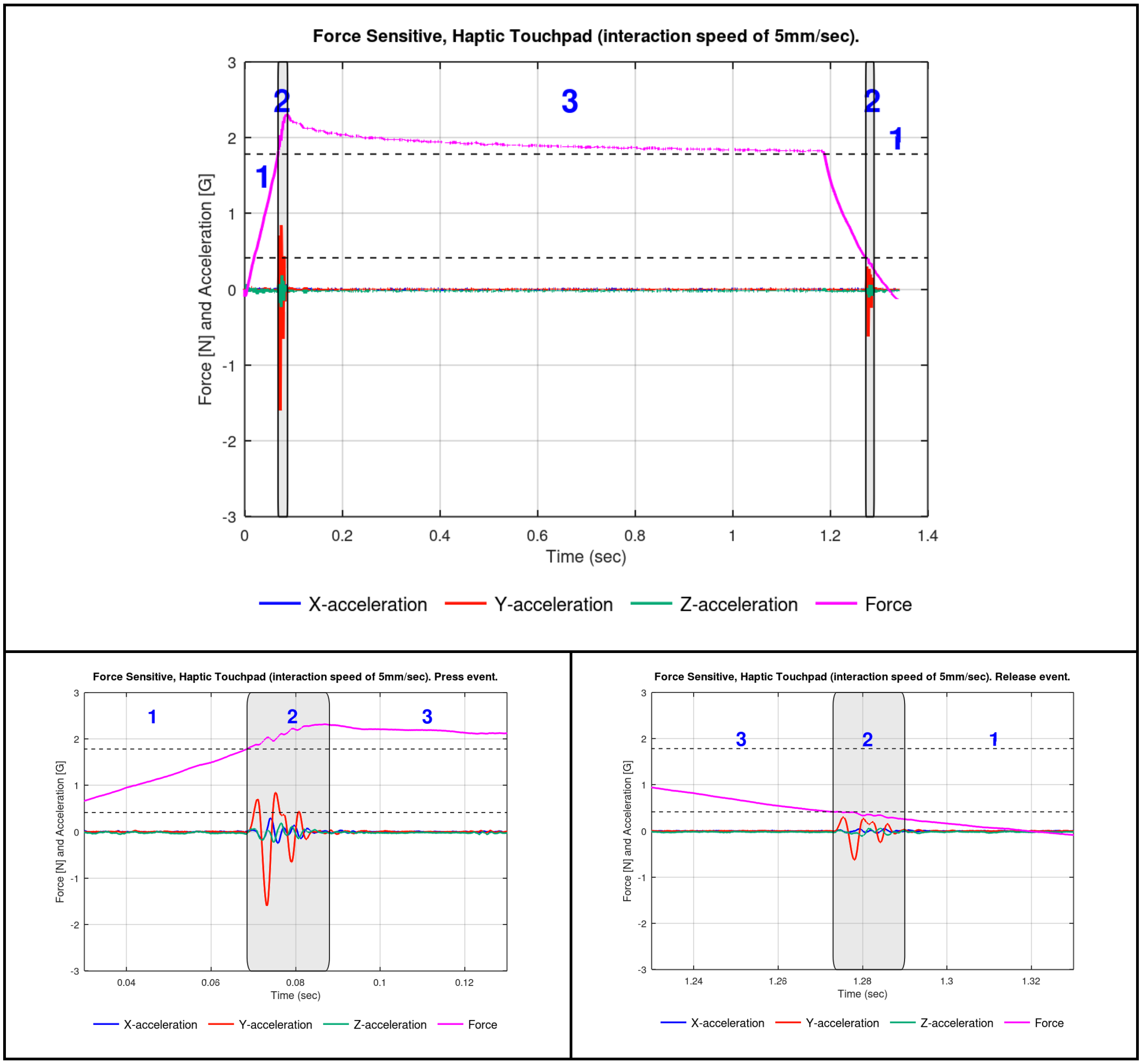


Figure 5: Acceleration and Force over time for a Haptic Touchpad.

The above measurements are force and acceleration based, it is also possible to measure displacement, but that displacement will be extremely small and serve no purpose for the characterization of the haptic touchpad.

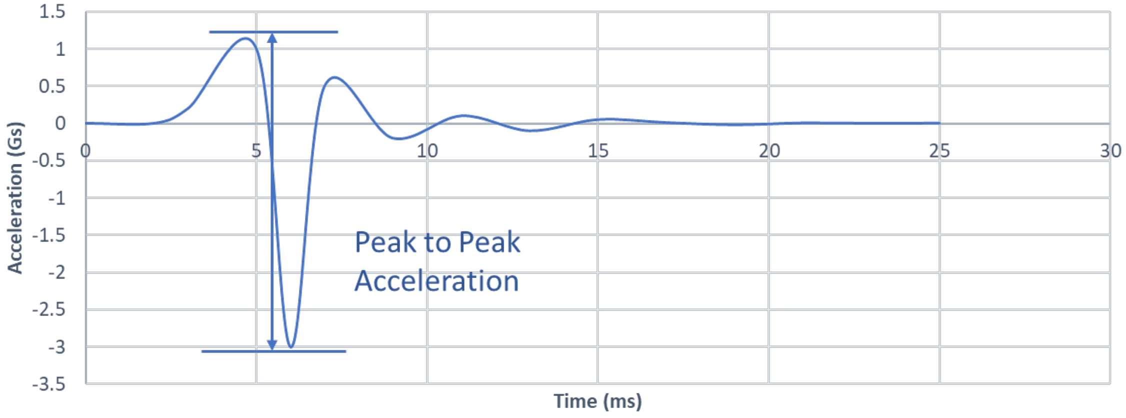
4.3 Time-based measurement parameters

Several different tools can be used to measure these time-based dynamics. These include accelerometers, load cells, vibrometers and microphones. The following section shows how each measurement device can be used to define values that are relevant to the measurement of haptics.

4.3.1 Accelerometer-based measurements

4.3.2 Acceleration

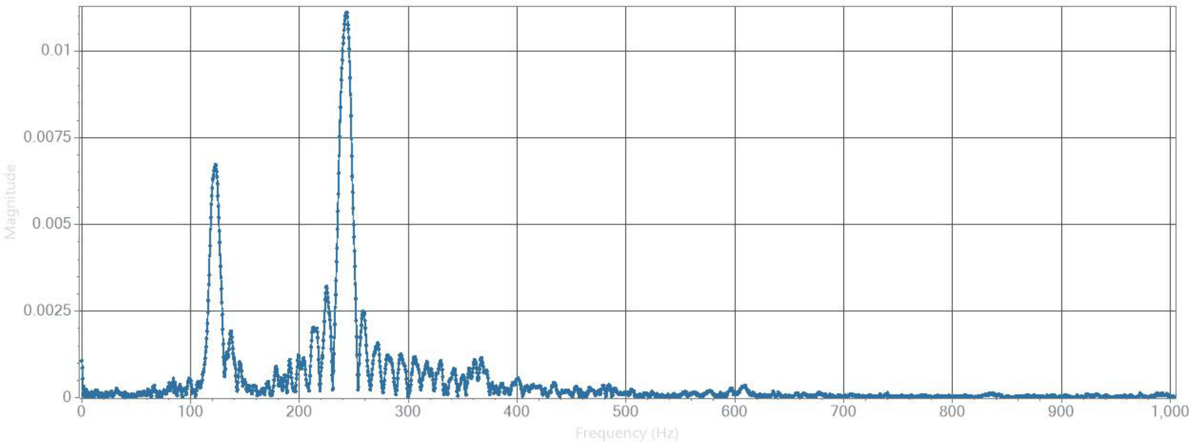
When measuring reaction properties, the acceleration is measured by taking the time acceleration value of the largest positive peak and the largest negative peak.



figurePicture 7: Acceleration vs. time: Peak to Peak acceleration

4.3.3 Frequency

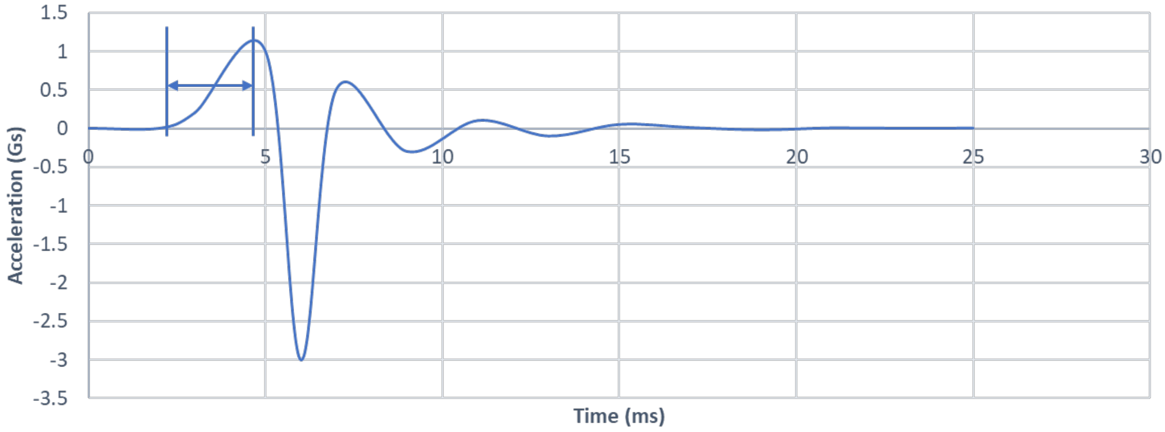
When measuring the acceleration of a haptic feedback, the dominant frequencies can be obtained with the FFT.



figurePicture 8: Acceleration Magnitude vs. frequency: In this example a double click effect shows the dominant frequencies 130Hz and 250Hz in the frequency domain

4.3.4 Rise time / Fall time

The rise time is measured by taking the time when acceleration starts to deviate from zero to 90% of the maximum acceleration (could be positive or negative acceleration). The fall time is accordingly 90% to 0%.



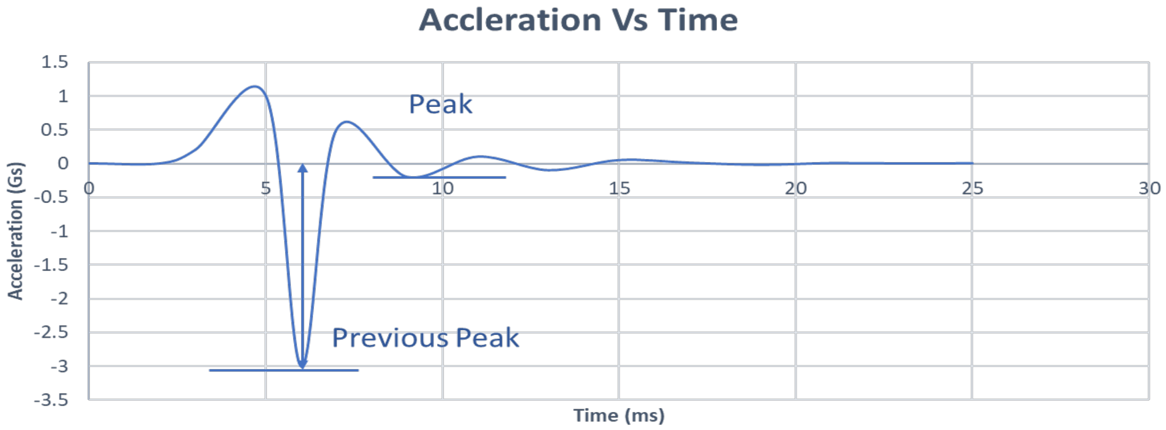
figurePicture 9: Acceleration vs time: Rise time

4.3.5 Decay ratio

The decay ratio indicates how quickly the system returns to a base state.

Decay Ratio = Peak2 Acceleration / Peak 1 Acceleration

Defined as the ratio of the magnitude of an acceleration peak of a naturally decaying oscillating system to the previous peak of the same system. It is a unitless number between 0 and 1. In the case of normal mechanical buttons, this number is usually very low, but not always in active haptic systems.



figurePicture 10: Acceleration vs. time: Delayratio

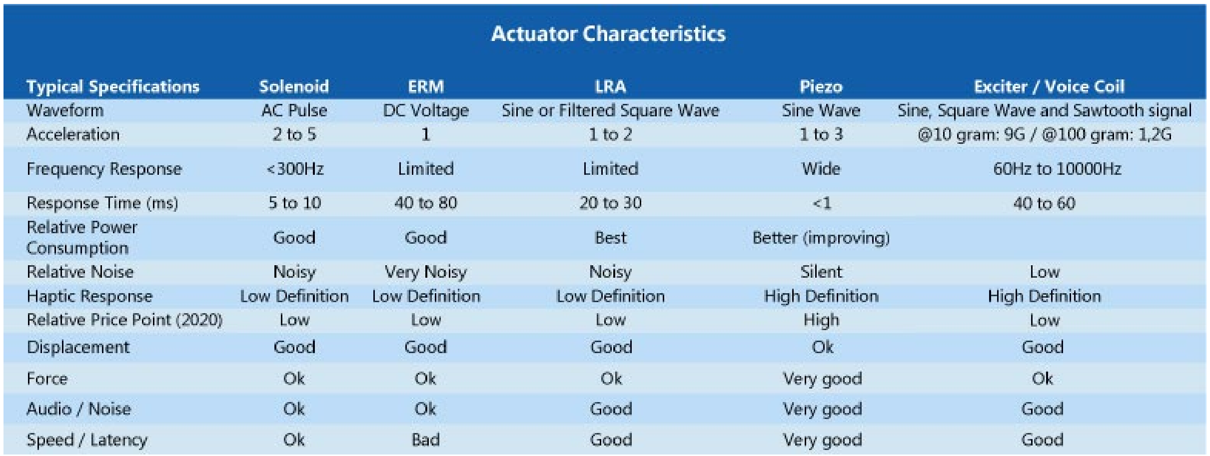
4.4 Audio

Audible noise is always a factor in systems that have moving parts. While this specification document does not detail acceptable audible noise, we strongly suggest to the reader to consider the impact of unintended audible noise on the end user experience and consider this during their design and subsequent measurement activities. Consideration should also be given to designing acoustics rather than just preventing them. This could even improve the user experience in some cases, see section 5.1.5.5

4.5 Active Haptics

Currently, the most commonly used actuators for active haptics are vibrotactile actuators. These generate haptics by moving a surface, usually in the form of a vibration or impulse. The typical passive haptics button is also vibrotactile haptics, but due to its nature an active haptics actuator can allow for much more flexibility in the haptics response compared to a button.

There are many forms of vibrotactile actuators, but the most common ones are as follows:
- **ERM (Eccentric Rotating Mass):** These are the simplest and cheapest haptic actuators. By rotating an off-center mass, they can provide basic buzzes, and are/were commonly found in pagers, older mobile phones and gamepads
- **Solenoid:** Solenoids are also a rather simple and straightforward solution to provide haptics. In these electromagnets , a coil is moving a mass to a mechanical stop, and then reset by a spring.
- **Voice Coil:** Voice Coils are basically audio speakers, but without the membrane. They allow for a good frequency bandwidth, and are for example used in the Sony Playstation 5 Gamepad buttons.
- **LRA:** Linear Resonant Actuators are similar to voice-coils, but they generate haptic feedback by vibrating a mass at a specific frequency. Most modern smartphones are using an LRA as the haptics actuator, with the iPhone Taptic Engine being the most famous example
- **Piezo:** Piezo Actuators are using the piezoelectric effect to provide the force to vibrate a surface. These allow for excellent acceleration & force resulting in high definition haptic responses. Traditionally piezo actuators were more expensive than other solutions, but recent developments have brought down the cost resulting in new commercial releases e.g. in laptop trackpads.



Actuator Characteristics

Typical Specifications	Solenoid	ERM	LRA	Piezo	Exciter / Voice Coil
Waveform	AC Pulse	DC Voltage	Sine or Filtered Square Wave	Sine Wave	Sine, Square Wave and Sawtooth signal
Acceleration	2 to 5	1	1 to 2	1 to 3	@10 gram: 9G / @100 gram: 1,2G
Frequency Response	<300Hz	Limited	Limited	Wide	60Hz to 10000Hz
Response Time (ms)	5 to 10	40 to 80	20 to 30	<1	40 to 60
Relative Power Consumption	Good	Good	Best	Better (improving)	
Relative Noise	Noisy	Very Noisy	Noisy	Silent	Low
Haptic Response	Low Definition	Low Definition	Low Definition	High Definition	High Definition
Relative Price Point (2020)	Low	Low	Low	High	Low
Displacement	Good	Good	Good	Ok	Good
Force	Ok	Ok	Ok	Very good	Ok
Audio / Noise	Ok	Ok	Good	Very good	Good
Speed / Latency	Ok	Bad	Good	Very good	Good

figurePicture 11: Actuator Characteristics - Source SAR Insight & Consulting

Due to the inherent differences of these actuators, some actuators are better in situations than others. For example, the piezos are suited best for providing localized haptics like a button, but if you want to vibrate a whole device like a smartphone or wearable, they might struggle and an ERM or LRA might be a better choice. If the haptic feedback should include clicks, an ERM will not be a good choice. If a wide frequency response is needed, voice coil and piezo will be best. It is always important to look at the individual strengths and weaknesses of the actuators to determine which one is best for one's application.

In order to compare the actual strength of the haptic feedback between actuators, most commonly acceleration is used. In reality other factors like displacement, force and frequency have a strong influence on how strong the haptic feedback is received. Acceleration & displacement will of course still be the main influence on the strength of the feedback, but the right frequency is also important. The receptors in the human skin for vibration feedback react best with certain frequencies, for example for the fingertips a frequency of around 180Hz will be felt as strongest.

In addition, factors like latency, speed, noise etc. will make a big difference if a haptic signal is received as good, even if it is strong. These depend not always on the actuator itself, as for example bad latency is often caused by the driver and software than the actuator. In addition, for all actuators the mechanical integration is key for a good haptic feedback, bad integration can lead to low force, unwanted noise, resonances etc. Even the best actuator will not be able to compensate for bad mechanical integration!

4.6 Active Haptics - other

Surface haptic devices modulate the friction between the surface and the fingertip, and can thus be used to create a tactile perception of surface features or textures. To measure surface friction, a specially designed test system is necessary. In this document we only cover the measurements of vibro-tactile feedback (from an electrical impulse to a mechanical force that moves the touch surface).

We do not want to leave Kinesthetic Haptics Technologies unmentioned in this document. However, we will not talk about measurement here. The requirements are very different from the vibrotactile.

Rotary haptic systems also play an important part of the user experience, with new technologies becoming available for automotive use.

5 Measuring haptics

Haptics systems can be measured in a number of different ways. As discussed in the previous section above we have introduced the ability to measure haptics feedback (both active and mechanical) in the time based domain using acceleration. This is made possible by newer tools and a focus on broadening the parameters of a touch interaction.

We can measure haptic systems using an accelerometer, rigidly affixed to the surface, through the use of precision laser vibrometers, or as HIF members are learning, through an accelerometer mounted to a compliant capacitive tip attached to a probe that is capable of simultaneously loading the haptic surface while capturing time domain based accelerometer data. In all cases, these measurements will have common phases and parameters.

5.1 Phases of a touch and Parameters

We should consider several factors when measuring the interaction between a surface and user. These include but are not limited to;

5.1.1 Loaded versus unloaded surface

A surface is considered “loaded” when someone is interacting with it. The act of touching a surface, or pressing on it, will change the mechanical response. There is value in measuring the performance of a haptic system with no interaction (remote triggering) but the best measure of the user experience will be simulation of the added interaction of finger(s) with the surface during playback.

5.1.2 The touch interaction

When a user touches a screen or surface, there are several stages or events that can be captured, with different systems having different options. This should be considered when taking measurements. When a finger approaches a surface, there can be a proximity sensor that detects the finger a distance from the surface, then there can be a contact sensor that detects surface contact. The finger then continues to engage with the surface in increasing pressure, typically until there is some system response which leads the user to stop the interaction, first decreasing pressure and then ending contact with the surface.

The timing and quality of active haptic feedback is a key component in shaping this user experience as the types of sensors, lag time between sensors and haptic output, mechanical response time all have an effect. The ability of the system to detect pressure (or a pressure approximation such as increased finger surface area) and the timing of the playback have a significant effect on the type and duration of a user touch.

5.1.3 Where data is captured

Data is best captured whenever the finger is in contact with the surface and there is active haptic feedback. Measurement tools can capture this data, simultaneously acting as a finger and capturing the data.

5.1.4. Key performance metrics

Haptics performance can be captured with a range of measurements. This document proposes a base, from where individuals can expand on

5.1.4.1 Delay

This captures the time from when a touch interaction is registered by the touch or force control to when electrical signal is sent to the actuator circuit. Usually measured in milliseconds. Ideally this time is as short as possible. The limitations are the frequency of touch input sensing, OS handling of the interrupt and sending output to the haptic controller.

5.1.4.2 Rise Time

This captures the time from when electrical signal is sent to the haptic actuator from the amplifier to when the first acceleration peak is reached. Often measured in milliseconds. The limitations here are the mechanical time constant of response of the actuator. Where traditional spinning mass motors may take tens of milliseconds to reach peak, piezo or solenoid actuators will have a rise time in milliseconds. Resonant actuators and voice coils will often be somewhere in between, depending on design.

5.1.4.3 Haptic peak

This captures the point of maximum acceleration of the haptic playback, measurements are taken in [g] and are measured from lowest peak to highest peak.

5.1.4.4 Fall time

This captures the time required to return to rest from the haptic peak. This is directly correlated to the Decay Ratio discussed above. Damping of the system, either active or passive will greatly reduce fall time.

5.1.5. Factors that influence haptic feedback

The factors that can influence haptic feedback are many. It is best to consider as many factors as reasonable and ensure the desired experience is achieved. Some of the classes of factors and examples are but not limited to:

5.1.5.1 Mechanical

This includes the type of, and friction of the interaction surface, the moving mass, the displacement of the system, whole body or surface only motion, suspension design, system stiffness, actuator location, normal or lateral movements, lateral x or y or xy movement, consistency across the surface, and more.

Quality and consideration of some of these design elements will affect performance in testing, while others will be apparent only in the context of certain use cases. For example a quality suspension design with consistent haptic performance across the surface with a cover material of appropriate friction qualities will result in strong performance. Similarly in a suspended surface with lateral actuation, slider interactions that are parallel to the direction of actuation may not feel as expected to the user.

5.1.5.2 Sensing

High quality haptic systems have a dependency on the quality of the sensing technology. Sensors that are poorly tuned and trigger without contact or have false readings will result in a terrible user experience, even if the haptic test results meet a specification. For the best haptic experience, additional to classic capacitive touch sensing, force sensing is recommended. This opens the possibility for more haptic effects, i.e. touch and release haptic patterns and adjusting exact trigger thresholds.

5.1.5.3 Actuator selection

Actuators create motion in haptic systems, which create the user experiences in haptic interfaces. Different actuators have different qualities, benefits, and limitations. System designed can select from single or multilayer piezo, Linear Resonant Actuators, Eccentric Rotating Mass motors, voice-coils, solenoids, braking systems and so much more. Selections will be driven by cost, packaging requirements, system mass, available power, cost and complexity of integrated circuit requirements. All of these factors can influence the resulting user experience of the haptic interface.

5.1.5.4 Haptic Control Signals (Driving)

The control signals for haptics must be aligned with the selection of actuator and mechanical design. Rotating mass systems can take advantage of short periods of overdriving voltage to overcome slow actuator response times and negative voltage to rapidly stop an actuator. Piezo electric actuators require smooth curve drive signals to avoid creating audible clicks and pops while resonance systems (linear resonant actuators) are highly resonant require precise driving frequencies for optimal performance and often closed loop control to create snappy, high decay ratio sensations. Voice coil actuators/exciters can be driven in a wide frequency range and are not so dependent on the resonance frequency (can be used for playing additional sound as well).

5.1.5.5 Acoustic

It is important to consider that automotive user interfaces are multi-modal. They are visual, tactical, and auditory. Automotive brands have corporate design and this includes audio concerns. When designing haptic user interfaces it is critical to limit the amount of unplanned for audible noise, directly from the mechanical system as well as in the resulting integrated component. Touch interface systems that have an inconsistent audio experience, risk breaking the haptic illusion of a button click and can result in negative user affinity.

Acoustic output, either created as a by-product of the haptic system, or created to play in concert with haptic feedback, can enhance the overall experience as long as the audible portion matches the experience created by the haptic user interface.

5.1.5.6 Physical Environment

The physical environment for the system should be considered in the design and measurement process. Are we interacting with an exterior surface exposed directly to the elements, or an interior surface? What are the performance requirements across a range of temperatures and is this relevant in the context of human perception at these temperatures?

5.1.6 Harmonizing with traditional measurement

As described in the introduction to section 5 there are many different ways to measure haptic performance. The advantage of emerge measurement tools where “an accelerometer mounted to a compliant capacitive tip attached to a probe that is capable of simultaneously loading the haptic surface while capturing time domain based accelerometer data”, are such that they allow for the 1:1 mapping from the time domain to the traditional measurements of force/displacement curves.

This is illustrated in the graphs below:

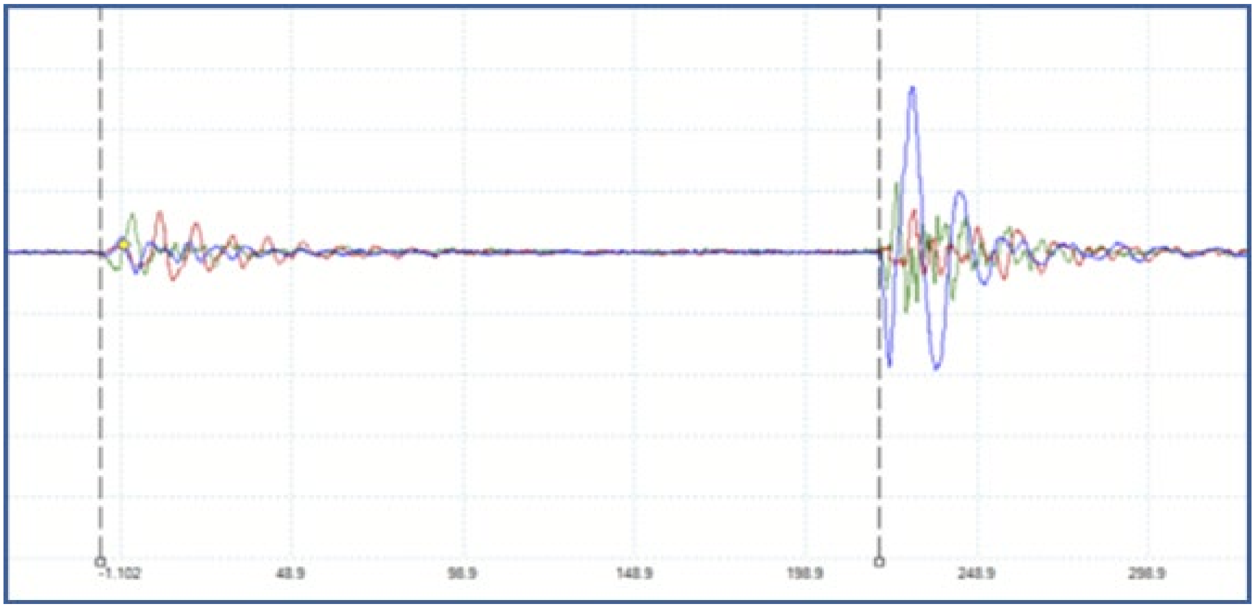
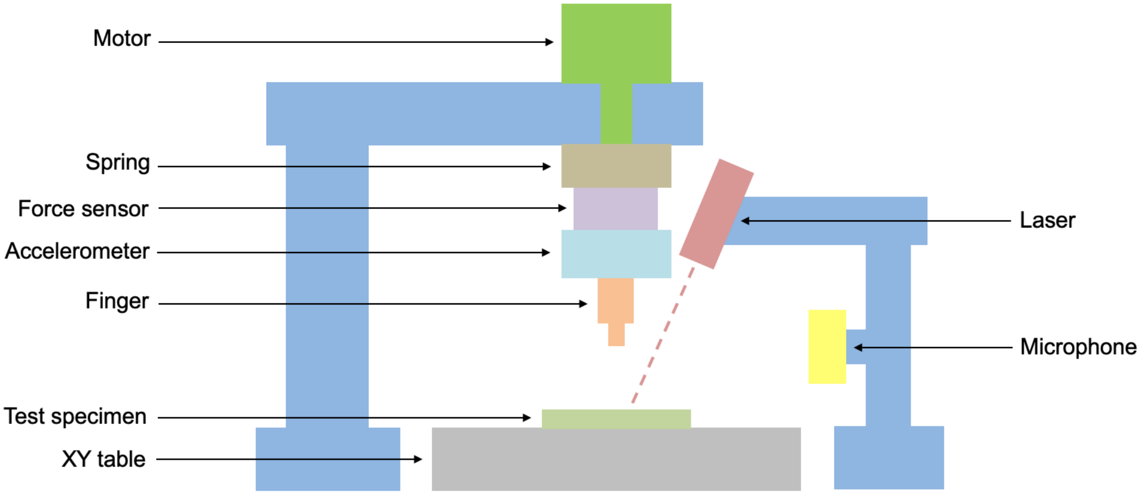


Figure 12: S-Curve graph, overlaid with Snap Ratio K/Curve

5.2 Measuring equipment

To quantify the specified parameters an appropriate measurement system is required. Suitable measurement systems begin with simple accelerometers (purchasable for circa 100 USD) and evolve into customized haptic measurement devices able to assess everything we feel and hear, i.e. our (user) experience.

A conceptual example of a highly developed haptic measurement device is shown in figure 13 below. For further explanation regarding each functional element please see table below.



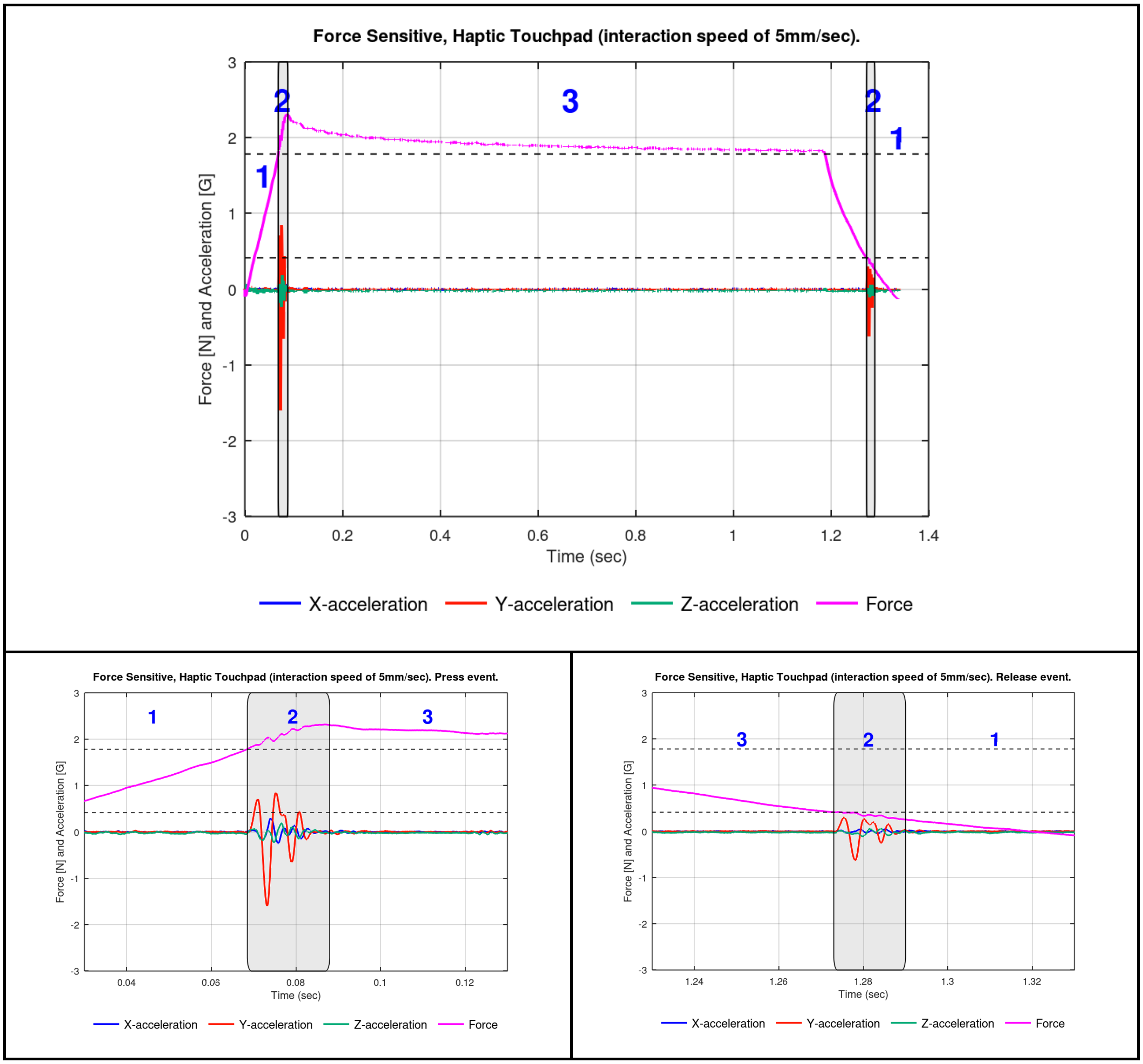
FigurePicture 13: Haptic measurement device

Table 2: Description of components of an ideal measurement system

Motor	Moves the finger up and down with high precision, each step should be <1 um
Spring	Compensates for the haptic movement. The active haptic displacement may be upwards, downwards or sidewards. The (adjustable) spring compensates for such movement.
Force sensor	Measures the force of the finger towards the test specimen
Accelerometer	Measures the haptic acceleration of the finger
Finger	The touch point between the test device and the test specimen. The material of the finger should have the same stiffness as a human finger, e.g. to ensure a contact to the test specimen during haptic actuation.
Test specimen	The haptic device
XY table	Able to move the haptic device
Laser	Measures both the passive deflection (from the pressure of the finger) and active haptic deflection (from the haptic actuator) of the touch surface. Furthermore, the laser can also be used to measure vibrations outside the actual touch surface/area in order to quantify ‘leakage’.
Microphone	Measures the sound (or noise) created by the haptic movement

The system is too complex for end-of-line tests and also it was not designed to be suitable for that.
The proposed measurement system is designed to support the development of a haptic application.

The trigger threshold is dependent on the application. The force that is applied by the measurement system is adjustable and can be chosen depending on the application under test. In general, a value between 3 and 5 N is typical.

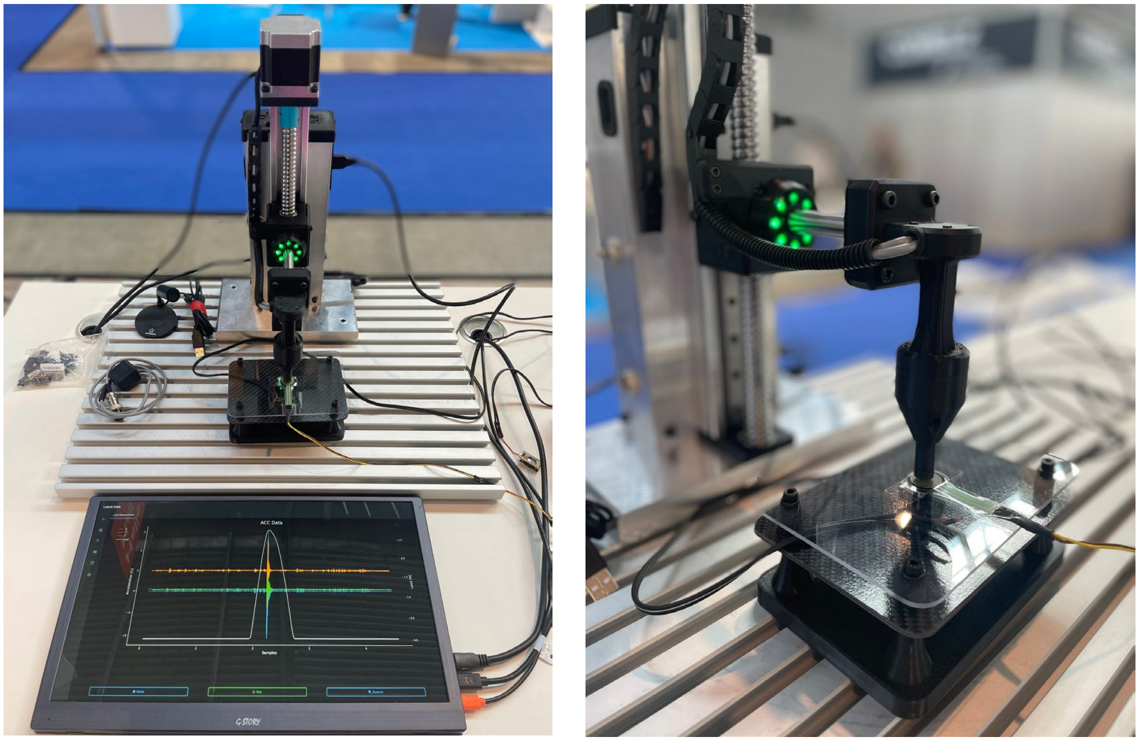


FigurePicture 14: Acceleration and Force over time for a Haptic Touchpad.

5.3 Measured results

Example of a few devices which were measured, and why they performed in such way

- pictures of measurement systems



FigurePicture 15 (right) and & 16 (left): ArFi - Artificial Finger measurement system

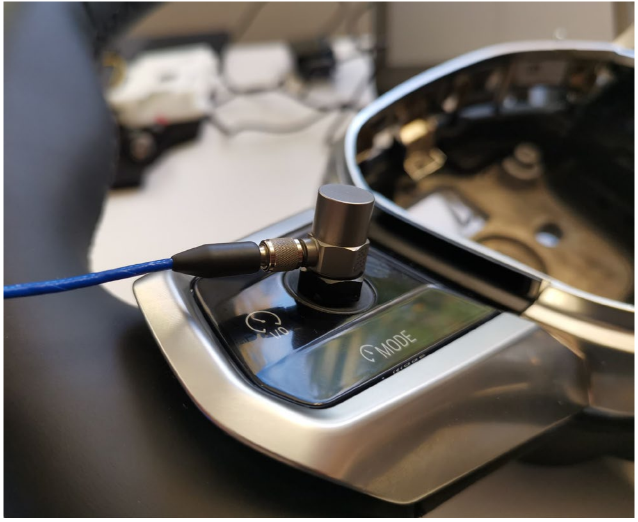


Figure FigurePicture 17: Acceleration sensor

5.3.1 Sample measurements

Sample touchpad

Figure 18: Sample touchpad and location of measurements

Below the touchpad, the exciter / voice coil actuator technology is used for haptic and acoustic feedback.
At the marked points on the surface the acceleration was measured. The measurements were done using the measurement system described under 5.2 with an applied force of 3N on the touchpad. The highest acceleration was reached for signals with 145Hz.

6 Discussion & conclusion

- **Consider the complete application** (Not the haptic determination in an ideal system)
  This includes measurements of the complete application (not only the actuator). It allows the haptic feedback to be optimally adapted to an application, for example in terms of frequency and acoustic optimization.

- For the best user experience, the **interplay between sensing and haptics** should be harmonized. This enables precise alignment of trigger points and timing. Therefore it is important to measure force trigger thresholds and delays as well.

- **Quantify the physical parameters** (Book of requirements)
  Define test setup and procedure to capture credible measurement data including general raw data processing such as filtering requirements
  Consider the mechanical conditions during a measurement (e.g. no load applied vs. 3N load) as they have a strong influence on the results