## Abstract

Active haptics is a new promising technology intended to add to standard touch devices (like touch buttons, touch pads, touch screens) a vibration effect that gives a feedback to the user's finger. The feedback general use is to confirm that a specific action has been done (a touch button has been pushed, a gesture has been recognized) avoiding other feedback solutions (an example is a status LED that require the user to look at it).

Active haptics can generate nearly unlimited different haptic effects as it is driven by the software, but it is not so clear how to define the level of perception by users as generally any evaluation depends on subjective judgements.

This article will show a method to transform 'subjective judgement' of haptic perception in 'objective measure' of haptic perception. To pursue this goal, two instruments called respectively Tactilometer and Clickmeter are described in addition to a mathematical strategy to evaluate and show measured results.

## Acronyms

| | |
|---|---|
| $P_{p0}$ | Haptic Pulse Minimum Perception level |
| $P_{pp}$ | Haptic Pulse Preferred Perception level |
| $P_{v0}$ | Haptic Vibration Minimum Perception level |
| $P_{vp}$ | Haptic Vibration Preferred Perception level |
| $P_R$ | Haptic Relative Perception Level |
| $T_p$ | Haptic Perception Time Interval |
| HHPF | Human Haptic Perception Filter |
| PSD | Power Spectral Density |

## Subjective perception of haptics

If a person is asked to feel with his finger a vibration on a surface, he will describe it in several ways:

- I like it/I don’t like it
- It is too low/It is too high
- I perceive it well/It is hard to perceive
- I like this effect/I don’t like this effect
- It is too long/It is too short (in time)

and much more.

If another person is asked to describe the same vibration, sometime he will agree with the previous person, some time he will describe it in a totally different way.

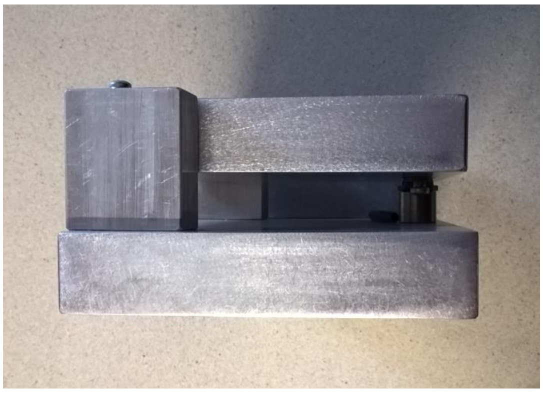
Moreover, there are questions that nobody is able to answer. An example is the following experiment: Two different vibrations of different intensity are created on two different surfaces. Some people are asked to answer to the following question: “if the level of perception of the first vibration is ‘*one’*, what is the level of perception of the second vibration?” Most of the people will just say ‘I have no idea’, who decides to answer with a number will give a subjective evaluation that cannot be used nor in a statistic, neither for mathematical evaluations as for somebody ‘*two*’ is a big increase, for others ‘*one hundred*’ is the big increase.

As the only way to transform ‘subjective judgement’ in ‘objective measurement’ is statistics, a method to get reliable answers from people has to be defined.

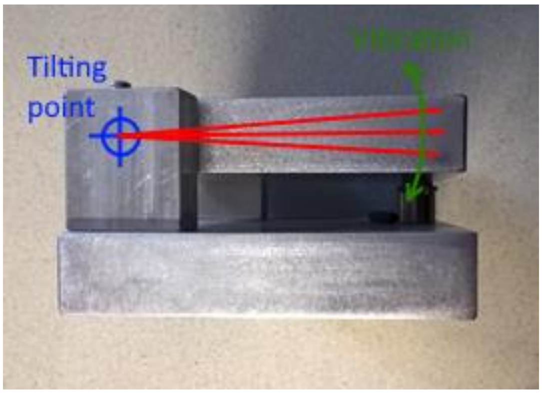
## The tactilometer

The tactilometer is an instrument able to generate a controlled vibration on a tilting surface. The vibration level around the tilting point is zero, the vibration on the opposite side is a predefined level. As the tilting surface is a very rigid one, if a user touches the surface with a finger going from the tilting point to the opposite side, a linear increase of intensity from zero to a maximum level of vibration will be perceived. The following images show what has just been described.


Tactilometer, top view



Tactilometer, side view




Tactilometer, how it works

The basic functionality of the tactilometer is the ability to create two different types of controlled vibrations:

- Short pulses, needed to evaluate haptic perception similar to 'clicks' in standard switches
- Continuous vibrations, needed to evaluate haptic perception of long haptic effects

The reference controlled vibrations are calibrated with an accelerometer measuring g (1g=9,81m/s$^2$).

- The short pulse is defined as one cycle of sinusoidal wave of 100Hz (duration of 10mS)
- The continuous vibration is the sinusoidal wave at 100Hz

The intensity of vibration, after some tests with several people, has been chosen to cover the complete range of haptic perception going from zero (no perception at all) to a maximum level that is generally judged as 'too much'. As human perception is quite high if referred to continuous vibrations while is quite low if referred to short pulses, the tactilometer offers the possibility to choose 4 different ranges of vibrations with the following meaning:

1. Measure of minimum level of perception of short pulses
2. Measure of preferred level of perception of short pulses
3. Measure of minimum perception of continuous vibrations
4. Measure of preferred level of perception of continuous vibrations

To extend investigations in human perception, the tactilometer offers enhanced functionalities, i.e. it is able to generate pulses and vibrations in the range of 50Hz to 1KHz with pulse duration from one sinusoid cycle to continuous sinusoid generation. Moreover, the haptic vibrations intensity can be controlled in order to be constant in all the range of generated frequencies. This functionality will be described and used to demonstrate some features of the human perception needed to properly define the 'human haptic perception filter' HHPF described in further on in this document.

## From subjective to objective measure of haptic perception

As described above in this document, it is quite easy to get from people subjective judgement of a haptic vibration but subjective judgements cannot be used in engineering activities to design haptic devices. That means that an objective strategy to measure haptic perception has to be defined.

As the tactilometer instrument has been defined to pursue this goal, we show here the adopted strategy.

There are two questions that can be asked to a person during a haptic measure that will be answered in a quite precise way:

1. Please touch the tactilometer surface and tell me the point where you start to feel the haptic sensation
2. Please touch the tactilometer surface and tell me the point where you feel your preferred level of haptic sensation (a pleasant level, so not too high and not too low)

As the tactilometer has two working modes, the short pulse mode and the continuous vibration mode, every person will indicate 4 different numbers that we define in the following way:

- Haptic Pulse Minimum Perception level
- Haptic Pulse Preferred Perception level
- Haptic Vibration Minimum Perception level
- Haptic Vibration Preferred Perception level

The unit of measurement of the four numbers is acceleration expressed in [g], multiples of gravitational acceleration. The numbers are the amplitude of the sinusoid.

Jury tests made among a big number of people ([1]) give the possibility to collect the four numbers and evaluate them with standard statistic procedures. What has been discovered is that numbers will go in a standard Gaussian distribution where is it possible to calculate an average value and a variance. A very good result of this investigation is that the variance is quite small, meaning that the haptic perception is not so different from person to person.

It is possible to use the average statistic values to define real objective numbers that can be used for engineering calculations:

- $P_{p0}$ – Haptic Pulse Minimum Perception level, statistic average value
- $P_{pp}$ – Haptic Pulse Preferred Perception level, statistic average value
- $P_{v0}$ – Haptic Vibration Minimum Perception level, statistic average value
- $P_{vp}$ – Haptic Vibration Preferred Perception level, statistic average value

These four numbers are the basis to go from subjective to objective haptic perception evaluation and to define the haptic measure method described in the following parts of this document.

([1]) Today the evaluation of these numbers has been realized by a private company, so today is not possible to show the database with precise numeric results. As the method to produce this result has been defined by TRAMA ENGINEERING, we are searching for research entities like universities in order to validate and officially publish it – If somebody is interested, please contact: f.cerruti@trama-engineering.com.

## Extending objective measure to the perception frequency range

From an engineering point of view, it is very important to define a general procedure to measure haptic perception in an objective mode. The main problem we want to solve in this chapter is the following: thanks to the tactilometer instrument and some statistics calculations, a method to measure haptic feedback has been defined but it refers only to sinusoidal vibrations at a specific frequency and specific durations. Is it possible to generalize this method in order to be able to measure all the possible haptic effects covering all the range of frequencies perceived by a person?

There are two possibilities:

1. The first is to configure the tactilometer to work at several different frequencies and to repeat the same procedure used to identify the perception reference values like $P_{pp}$ and $P_{vp}$
2. The second is to compare the perception at different frequencies with the $P_{pp}$ and $P_{vp}$ levels measured with the standard tactilometer

The first possibility is not really applicable because, as the sensitivity to haptic vibration is decreasing when frequency is increased, to reach preferred perception values at high frequency requires so high level of vibrations that are not really linked with the concept of haptics.

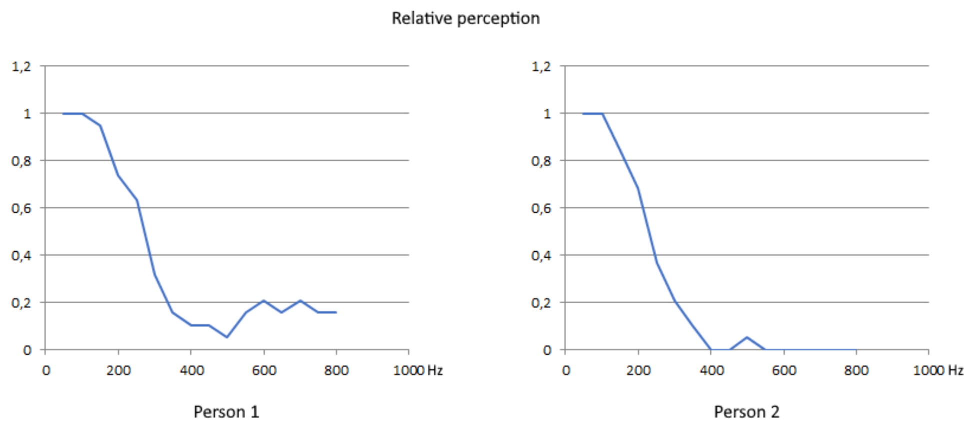
The second possibility is easy to implement using two tactilometers. The experiment is shown in the following picture:

The result of this experiment is called ‘human haptic perception filter’ (HHPF) that is a mathematical model to describe the contribution to the haptic perception of the complete range of sensed frequencies.

## The human haptic perception filter definition (HHPF)

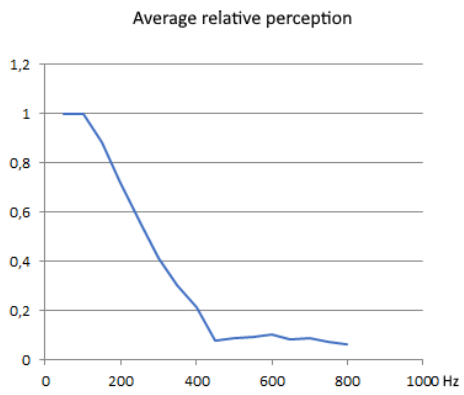
A person is asked to put the same finger of their two hands on two different tactilometers. Both the tactilometers are configured in the continuous vibration mode. The first tactilometer will generate the standard frequency, the second tactilometer is configured to generate the same acceleration level at different frequencies. The person is asked to keep the finger on the second tactilometer in a specific position: the position is always the same for all the test frequencies. The person is then asked to move the finger of the first tactilometer in order to get the same level of haptic perception of the second tactilometer. The position on the first tactilometer is recorded for each frequency. As the distance from the tilting point is related to the acceleration level, the ratio of the two positions on two tactilometers corresponds to the relative perception of the specific frequency.

Jury tests made on a big number of people ([1]) give the possibility to collect the data and create a diagram representing the result of this experiment for each single person. Two of these results are shown in the following pictures.



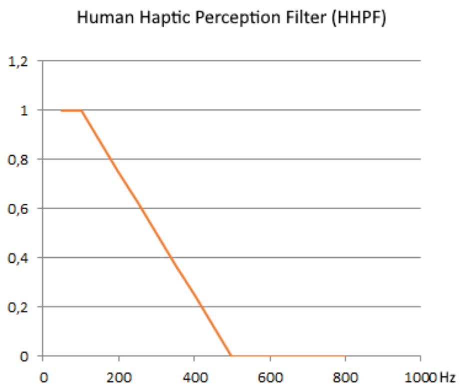

It is important to underline that the starting frequency of this measure is 50Hz. The reason of this choice is the following: humans perceive two following haptic pulses as two separate pulses if the time distance between them is more than 20mS while perceive just one 'big' pulse if the time distance is less than 20mS. That means that frequency below 50Hz are perceived as a sequence of independent pulses instead of a vibration so cannot be part of the perception filter definition.

Averaging the results of all the collected data of all the people and interpolating it with a simplified mathematical formula, it is possible to define a function that describes the human perception to haptic vibrations when different frequencies are applied. The result of this experiment, called human haptic perception filter (HHPF) is represented in the following chart:




Assuming that over 500Hz the measured perception is just noise, a simplified mathematical function that interpolates the HHPF filter with enough precision ([1]) is the following:

- From 0Hz to 50Hz, f=0
- From 50Hz to 100Hz, f = 1
- From 100Hz to 500Hz, f = -0,0025 x + 1,25
- Above 500Hz, f = 0

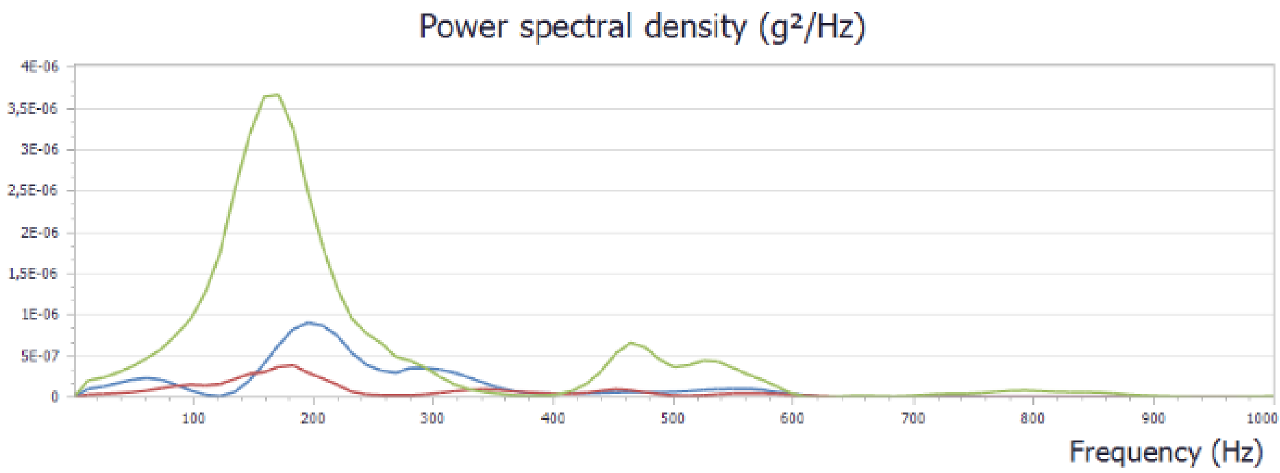



The HHPF is the base for calculating the haptic perception of a haptic vibration which frequency spectrum is composed by the contribution of several frequencies.

## Broadband random vibrations analysis with PSD

Before describing the proposed method to measure the haptic perception, some more information and some more assumption have to be specified.

Vibration experts, typically mechanical engineers, are used to analyzings the effects of vibrations using a diagram called PSD: Power Spectral Density. A PSD is the measure of signal's power (2) content versus frequency. A PSD is typically used to characterize broadband random signals. The amplitude of the PSD is normalized by the spectral resolution employed to digitize the signal. For vibration data, a PSD has amplitude units of [$g^2$/Hz]. An example of PSD of 3 different vibrations is in the following picture:

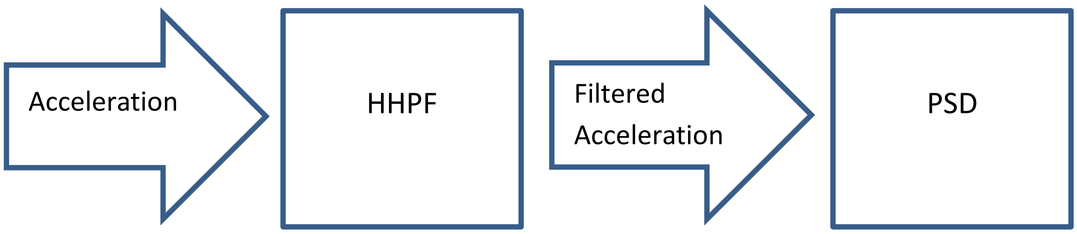



Our assumption is that when a haptic vibration is composed by the contribute of several frequencies (broadband random vibrations) the perceived level of the haptic feedback is related to the energy delivered by the vibration to the finger (2). This assumption is justified by several jury tests (1).

(2) It is important to note that the Power represented in the PSD in not a Power in physical sense, as $g^2$/Hz is a measure of a squared acceleration multiplied by a time that corresponds to [$m^2/s^3$]. The PSD calculation is based on 'Signal theory mathematics' that considers $|x(t)|^2$ the instantaneous power of a signal and the integral of that function in the period T, the Energy of that signal. In this kind of analysis the physical dimensions of the signal have no meaning.

## Broadband random vibrations analysis applied to haptics

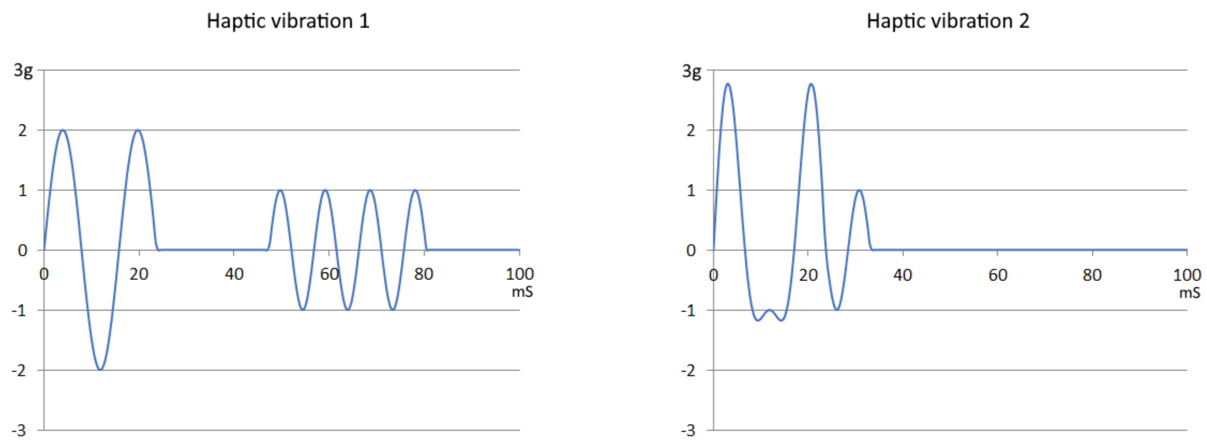
If the PSD is a very good instrument to evaluate vibrations in mechanical systems, its application to haptic systems need some more steps. The main point is that the human perception of vibrations has frequency limitations described by the HHPF (Human Haptic Perception Filter). In order to properly evaluate the haptic perception, the correct algorithm is shown in the following diagram:




The result of this calculation will show a diagram that clearly identifies the haptic perception of a haptic vibration by a human being.

## The haptic energy diagram

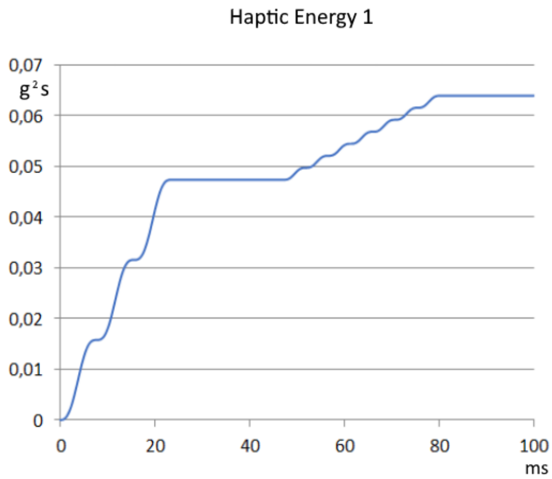
The PSD diagram applied to a HHPF filtered acceleration gives a lot of information about the haptic perception of a vibration, nevertheless it is not identifying completely a haptic sensation. The reason why PSD is not sufficient is because it is an analysis limited to the frequency domain while to univocally identify a haptic vibration some analysis in time domain is needed. To better understand this phenomenon, we can compare two  cases of vibrations represented in the following diagrams:

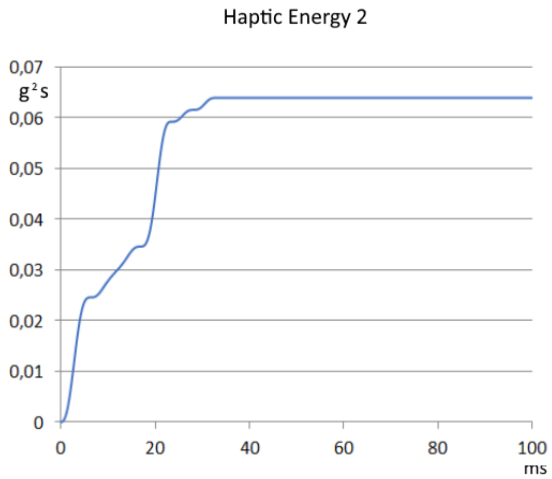



The two haptic vibration profiles have the same PSD, as they are the sum of the same two sinusoids, the only difference is the phase of the high frequency sinusoid. From the haptic perception point of view, the first profile will be perceived as a two subsequent pulses effect while the second profile will be perceived as just one intense pulse.

A solution to univocally describe a haptic vibration is to add to the PSD diagram a new diagram that shows how the Energy (²) of the pulse is increasing in time.

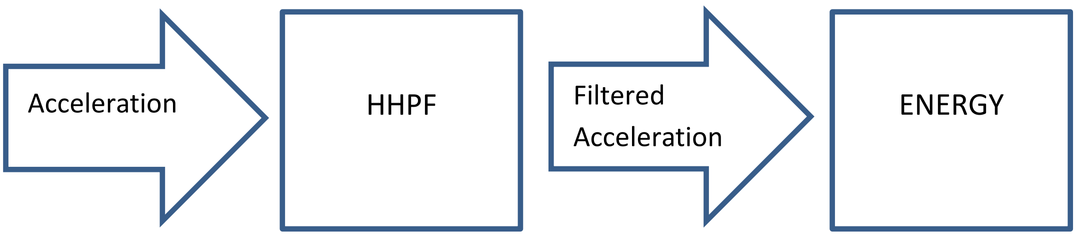
The Energy (²) diagrams corresponding to the two previous haptic vibrations are the following:




With this diagram it is clear that the two vibrations are not the same as the Energy (²) is delivered in different timings.

It is important to remember that the human perception depends on frequencies, that means that the Energy (²) diagram has to be calculated after applying to the acceleration signal the HHPF filter:




As the PSD diagram plus the Energy (²) diagram represents univocally a haptic vibration, they can be used both for haptic analysis and for haptic vibration synthesis.

## The haptic perception relative level

Before describing the complete proposed method to measure the haptic perception, we want to investigate one more functionality that engineers require during their job.

During the development of an active haptic system, often it is needed to evaluate the 'overall level of haptic perception'. The reason why this request is very important is because, especially for automotive applications, vibrations are present in the car everywhere and haptic perception of HMI devices can be 'cancelled' by the interference of other vibrations. In such situation, engineers are requesting for a quick method to increase or decrease active haptic perception: looking at the PSD diagram or to the energy diagram is not so easy.

The goal is to define a simple number that describes the haptic perception in order to be able to answer to requests like: "please increase the level of perception by 2, please decrease the level of perception by 0,8".

The starting point to define this number is to remember that, thanks to jury tests and statistic calculation, we have defined for the tactilometer two precise level of perception:

- $P_{pp}$ – Haptic Pulse Preferred Perception level
- $P_{vp}$ – Haptic Vibration Preferred Perception level

Using the rules described in the previous chapter, it is possible to generate the diagram of the haptic energy of the $P_{pp}$ and $P_{vp}$ haptic effects. The $P_{pp}$ pulse will have a finite energy while the energy of the $P_{vp}$ will increase in time forever. We can find the time when the energy of the $P_{vp}$ vibration reaches the energy of the $P_{pp}$ pulse and define this time as 'time interval for the relative level calculation'. We will indicate this time interval as $T_p$ (haptic perception time interval) and from experimental numbers ([1]) it has been evaluated in 80ms.

Thanks to the $T_p$ definition, now we can define a reference method to measure the level of the haptic perception that will work properly both for pulses and for vibrations.

We can define the Haptic Perception Level as the Energy ([2]) delivered to the finger by the vibrating surface in a period of $T_p$.

As this calculation will give as a result a number that is not easy to use by engineers, it is better to define a Haptic Relative Perception Level ($P_R$) that refers to the measured perception level of the two well known preferred levels $P_{pp}$ and $P_{vp}$, that now, thanks to the measure method just defined, have the same value.

To help us in this definition, we can use the logarithmic Weber-Fechner law, the law that describes the level of perception of a stimulus in the human body:

$$P=K \ln (S/S_0)$$

where:

- P is the perception level
- K is a constant related to the sense involved in the perception
- S is the intensity of the stimulus
- $S_0$ is the minimum intensity of a stimulus that can be perceived by a person

It is possible to define:

- $P_{ref}$ as the perception level (Haptic Energy) of the $P_{pp}$ ([1]) pulse
- $P_0$ as the perception level (Haptic Energy) of the $P_{p0}$ ([1]) pulse
- $P_m$ as the perception level (Haptic Energy) of the measured pulse

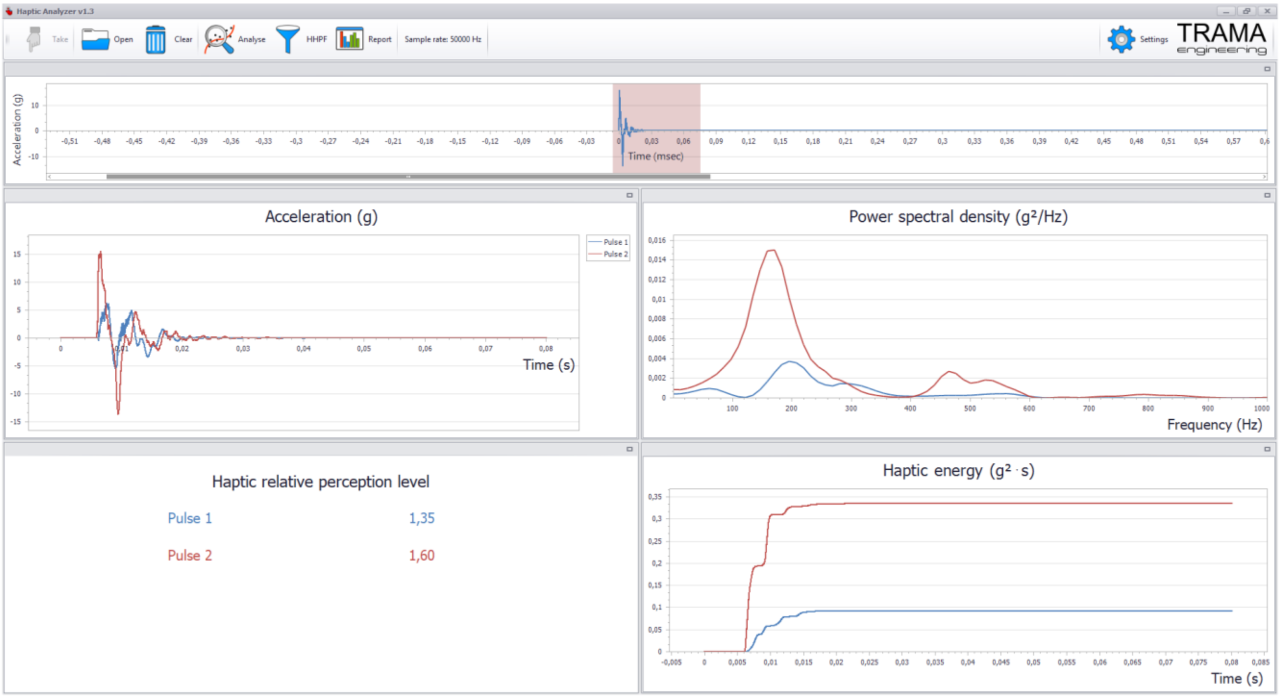
Finally the $P_R$ can be calculated with the following formula:

$$P_R = \ln(P_m / P_0) / \ln(P_{ref} / P_0)$$

## Objective method to measure and evaluate the human haptic perception

The proposed method to measure the haptic perception of a haptic vibration is to create four different diagrams: the acceleration in time, the PSD filtered with the HHPF, the Energy filtered with the HHPF, the $P_R$ calculation. These four diagrams can be shown together to completely describe the human haptic perception of a vibration.

A software suitable to perform this task, called Haptics Analyzer, has been developed. An image of a measure session is shown in the following picture.




The Haptics Analyzer software integrates the HHPF calculation so the diagrams could be shown both in the standard acquisition mode than in the filtered mode: this feature is very important when the goal is to optimize the energy delivered to the haptic surface by a haptic actuator.

## The clickmeter

An instrument capable of measuring and analyze haptic pulse in real time has been developed. It is composed by an acquisition system able to get data from an accelerometer. The software Haptics Analyzer can be connected with the acquisition system in order to get acceleration data in real time and show results. This instrument has been called 'clickmeter' as it is intended to analyze haptic effects that generally are related to real switches or active haptic emulation of switches.