Chapter 19
Niceclick: A New Frontier for Haptic Technologies

Elvio Bonisoli, Luca Dimauro, Simone Venturini, Salvatore Paolo Cavallaro, and Flavio Cerruti

Abstract The use of touch screens and displays is quickly increasing in the automotive industry, especially for supercars. Touchscreen commands are affected by the problem of feedback to drivers, i.e. the driver cannot look at the touch display; indeed, he needs to understand if the required command is received from the car. Haptic surfaces represent the solution to this problem; hence, touch screens with embedded actuators are suitable to switch from mechanical vibrations to human feeling. This paper focuses on an innovative electromechanical device called Niceclick. It is a compact and powerful actuator able to modulate the haptic surface vibrations. After an overview of the tactile perception, measurement systems, human sensibility to vibrations, and psychophysical compliance are analysed to define the parameters of an ideal actuator suitable to create some specific signals, the related frequency bandwidth, and the associate energy profile. The tailored tool, appropriate to get these goals, is described, modelled, and experimentally tested coupled to the fundamental co-system where it is applied. A comparison between rigid and deformative coupled structures is considered to define performance and aims.

Keywords Electromechanical device · Haptic feedback · Tactile perception · Human body vibration frequency · Sensibility

19.1 Introduction

The increment in the number and complexity of command and settings on vehicles led the automotive OEMs to find suitable solutions and technologies [1, 2]. Perhaps, the massive use of touch screens in all everyday devices, particularly in the main interface in vehicles cab, represents a critical issue about the driver safety. In fact, the actuation of a virtual switch on a touch screen does not give any feedback to the driver, which must visually check the correctness of the desired command, diverting the attention from the road. Instead, when a driver interacts with an analogical switch, he receives both tactile and audible feedbacks. The differences in the two sensations are not negligible, and the tactile stimulus is the main feedback.

The human machine interfaces (HMIs) were deeply investigated in the last decade to combine a pleasant driver perception and the desired innovative design aspects [3, 4]. The evolution of automotive HMIs is strictly related to the human tactile perception [3, 5], specifically in haptic surfaces [6]. The haptic surface is a complex interface that includes one or more actuators producing a tactile response [7]. In the state of the art, several attempts have been done in finding a reliable and effective technology for this application, from electrostatic to ultrasonic actuation [6], employing varied system dynamics [8].

The driver population is wide and varied; hence, the preferred vehicle interface style is subjective, due to the different sensitivity to tactile stimuli. Therefore, the interfaces are commonly designed by analysing the typical user characteristics and calibrating button pression feedback on statistical information. Nevertheless, user feedbacks are not objectified in the design process. Using simple devices, researchers are trying to deceive the human perception, creating fictitious sensations.

In this scenario, this paper focuses on an innovative haptic device called Niceclick, a compact and powerful actuator able to modulate the haptic surface vibrations. The device is calibrated on objectified parameters to generate some specific

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feedback patterns with the associate energy profile. A tailored tool called tactilometer has been developed to experimentally characterise tactile perception and to orient design choices in Niceclick development.

The paper is organised as follows: in Sect. 19.2, the state of the art on human tactile perception is presented before introducing the innovative Niceclick device in Sect. 19.3, which is proposed with the application of tactilometer. After that, results of experimental test are presented from both static and dynamic point of views in Sect. 19.4 to describe Niceclick dynamic behaviour. Finally, in Sect. 19.5, remarks about the performed activity and considerations on future developments are depicted.

19.2 State of the Art on Tactile Perception

The human tactile perception is allowed by tactile receptors in human fingertips. The tactile receptors are usually modelled as a four degrees of freedom (DoF) system [9] in which each DoF corresponds to a different fibre-type mechano-receptor sensitive to a defined frequency range. These different corpuscles, described in Table 19.1, are subdivided into slowly adapting (SA) and rapidly adapting (RA) receptors.

The differences in frequency sensitivity of the four corpuscles make the human threshold to vibrations perception frequency dependent, as shown in Fig. 19.1. Moreover, the receptor distribution in the skin determines a dependence on the contact area [11]. The contact area has a double effect on the vibration perception due to the spatial distribution of receptors: if the contact area is up to a 0.1 cm^2, the vibration perception is linearly dependent on the contact, because an increasing number of receptors is involved; for larger contact areas, the probability to involve the low-threshold receptors increases and experienced threshold becomes lower [9].

The perception of a vibrational signal can be even masked by the presence of other vibrations. This mechanism has been experienced recording the perception threshold of a test signal on the index fingertip while a masking signal was exerted on the thenar eminence [12]. A relevant masking effect is observed within the RA-II Pacinian corpuscle and only if both the test and the masking signals activate this type of receptors. An enhancement effect is present too. A signal produces an enhancement in the perception of another signal, belonging to the same frequency range and thus activating the same receptors, if they are separated by a time interval up to 500 ms. Any interaction between different receptors type has not been noticed. As the same, adaptation occurs when a conditioning signal is present in the same frequency range of the test signal.

Table 19.1 Human finger tactile receptors [10]

Corpuscle	Channel	Frequency range [Hz]	Peak sensitivity [Hz]
SA-I Merkel receptor	NP III	0.4÷30	20÷30
SA-II Ruffini corpuscle	NP II	20÷500	200÷400
RA-I Meissner corpuscle	NP I	1÷300	30÷50
RA-II Pacinian corpuscle	P	5÷1000	200÷300

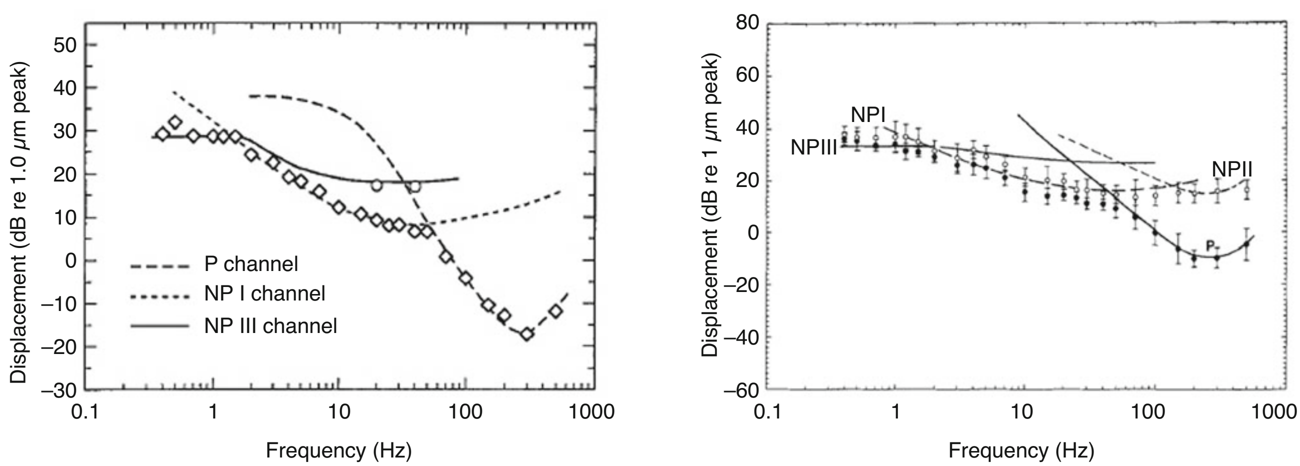

Fig. 19.1 Average threshold, function of stimulus frequency [9, 10]

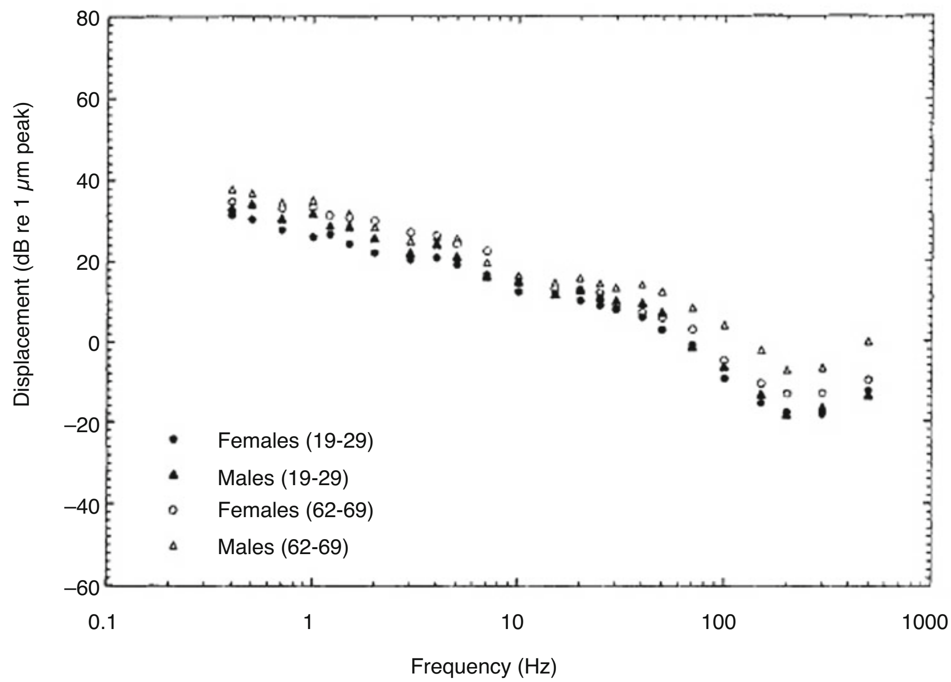

Fig. 19.2 Effect of ageing on sensitivity threshold [10]

Again, the effect is present only within the receptor family [12]. Considering the application of a vibrating haptic surface on a vehicle, the environmental vibration presence must be analysed.

Finally, the tactile perception is affected by subjective characteristics: the age is the most important one, as shown in Fig. 19.2. Experimental tests [10] have shown that the perception thresholds generally increase with the age and even more drastically over 65 years and mostly for RA-II Pacinian channel activating frequencies (above 100 Hz).

Moreover, females have been noticed to generally have a better sensitivity than males. The perception subjectivity enforces the need of a tunable interface. Besides, the same subjectivity brings out the absence of a reliable system for measuring and objectively describing the human tactile perception.

Another tactile aspect that has been investigated is the sense of compliance. This kind of perception is due to SA receptors. Experimental tests demonstrated that the passive perception of objects compliance is referred to the skin deformation sensed by SA-I laying in the sides of the finger pad [13] (in literature, it is referred as "lateral force"). Another important cue is the variation in contact area that clearly identifies a soft surface. Concerning the influence of active pressing, kinaesthetic force does not determine the perception, but can influence it increasing the sense of hardness. This effect is due to the mechanical properties of the fingertip that shows a nonlinear compliance [14]. The perception is function of both finger and object compliances and activated by cutaneous (90%) and kinaesthetic (10%) cues. Analysing the two channels, it came out that in case they are in conflict, an intermediate perception is experienced [15]. This statement opens the possibility to give a displacement illusion of a rigid surface through the stimulation of cutaneous receptors [16] When a surface is deformed by a finger touch, the sensation experienced is due to the friction forces exchanged by skin and surface: this can be effectively reproduced by a vibration that varies with the force exerted, in order to actively feedback a properly tuned reaction simulating hardness or softness. Even if the best and most realistic way to reproduce a sense of compliance is through both kinaesthetic and cutaneous cues [17], haptic devices showed how a tactile stimulus very close to one of real button can be reproduced by a finely tuned vibration.

19.3 Niceclick Device

The Niceclick is a device that recalls an energy harvesting [18–20] in its structure. The Niceclick has been developed by Trama Engineering, in order to get a wide vibrational tuning range, related to the different excitation conditions. It is a linear

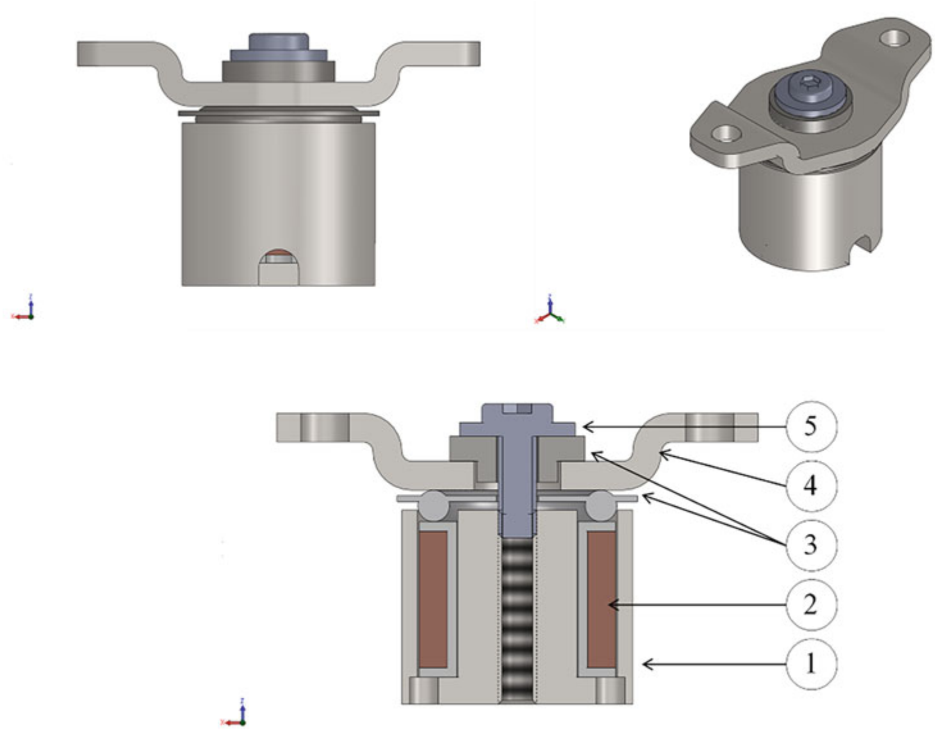

Fig. 19.3 Niceclick in details

actuator, driven by a specific software, that is able to generate a finely tuned vibrating motion as response of an external force input. The three views in Fig. 19.3 show the device in detail; its components are listed below:

1. Metallic body
2. Coil and plastic body
3. Upper and lower elastic elements
4. Omega pad
5. Preload screw

When a current is provided to the coil by a specific driver, the metallic body attracts the omega pad towards itself, compressing the lower elastic element. When no current is applied, the spring pushes upwards the pad: the system, having a single degree of freedom, starts to oscillate at a frequency which is function of the spring elastic coefficient and the mass of the pad. Thanks to the high frequency of current control that the interface allows, the user can generate a completely customised vibration, within a reasonable range of frequency, given by the system dynamics.

As a source, one or more Niceclick can excite a surface, even with a complex geometry, and generate precise and defined sensations on a human finger by working coordinately, although each Niceclick has an independent vibrational behaviour. The different but coordinated Niceclick responses are guaranteed by the innovative device feature that allows to perceive the amount of force acting on the surface and to tune, through the software, their respective vibrational output contributions that together create a properly tuned tactile stimulus, as shown in Fig. 19.4. Furthermore, the control interface allows to set the duration of the semi-period of the push and release phases simulated by vibrational outputs that can be properly tuned by a customisable signal as reported in Fig. 19.5.

As previously mentioned, the two features described above, working together, are fundamental to create a wide range of customisable tactile perceptions, moreover with applications that involve the use of more than just one Niceclick, making this innovative device a new interesting haptic tool.

The next chapter will focus on a higher application of this device, the definition of a standard measurement for vibrational stimuli sensed by a human finger.

Fig. 19.4 Niceclick cooperative functioning

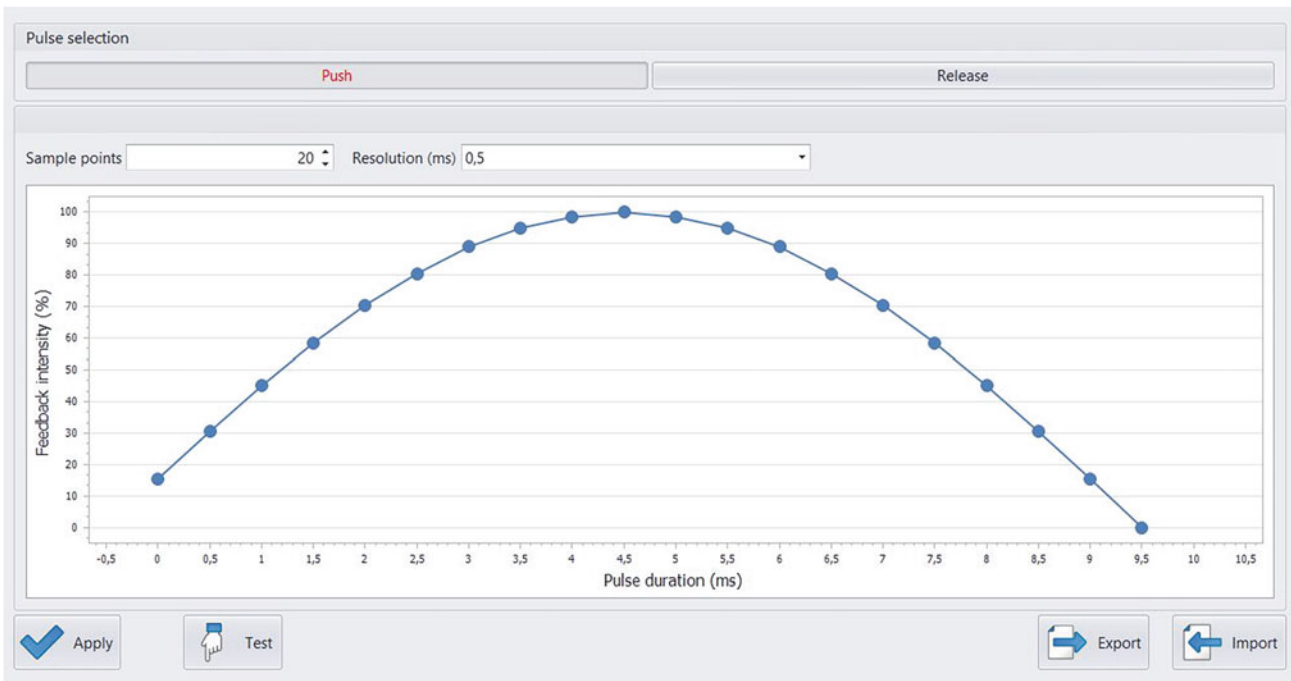

Fig. 19.5 Niceclick signal customisation

19.3.1 *The Tactilometer*

The Tactilometer is a mechanical measuring system, composed by an aluminium supporting structure, a Niceclick, and a pivoting aluminium plate; Fig. 19.6 reports three views of the prototype.

A programmable electronic circuit provides the current to the Niceclick. It is set up to produce two kinds of signal: a continuous vibration and a short actuation, repeated every second. The two are then divided into two level of intensity: the barely sensible and the most pleasant (as suggested by the results of an internal statistical investigation). As can be noticed, on the plate there is a scale, reporting the value of acceleration, expressed in [g], that is sensible in a certain point when the standard signal is sent.

Fig. 19.6 Tactilometer device

19.4 Experimental Tests

The Tactilometer has been used as a test rig for analysing the Niceclick static and dynamic behaviours. Two theoretically identical devices provided by the producer, named "Niceclick 1" and "Niceclick 2", have been tested. For measuring the plate vertical accelerations and displacements, we used a Siemens SCADAS Mobile, three Keyence lasers, and a monoaxial PCB accelerometer. Figure 19.7 reports a setup photograph.

Figure 19.8 displays in detail the three measured points. The accelerometer was placed exactly on the Niceclick projection on the plate upper surface, named "P". The three lasers were used for measuring the displacements of three points: one for the accelerometer upper surface (as the Niceclick vertical motion), one for the barycentre projection on the plate upper surface, "G", and one for a point out of the plane xz, "Q", at the same distance from the hinge as the barycentre.

19.4.1 Static Analysis

The Niceclick static properties have been tested by indirectly measuring the device vertical deformation when a known load was applied in the point "A", shown in Fig. 19.8, positioned in the median point between "G" and "P".

A set of masses, ranging from 10 to 200 gr and shown in Fig. 19.9, was used for the test. The setup allowed to place on point "A" from 10 to 140 gr with fix steps of 10 gr, then 200 gr, as reported by Table 19.2. The load on the Niceclick was composed by the aluminium plate, the omega pad with the two screws connecting it to the plate and the additional load. The elastic element also sustains its weight force. The omega pad mass has been evaluated equal to 2.76 gr, while the two screws can be reasonably assumed to be 1.5 gr together. The m_Ω column includes screws and omega pad. The equivalent load on the Niceclick has been evaluated for every configuration considering the system geometry. Being point "A" in the middle of the distance between "P" and "G", each configuration has the following load distribution on the Niceclick:

$$F_{\text{Niceclick}} = \left(\frac{1}{2} m_{\text{plate}} + \frac{3}{4} m_{\text{load}} + m_\Omega\right) g \tag{19.1}$$

The sum of force constraints balances the mass weight force, corresponding to:

$$F_{\text{hinge}} + F_{\text{Niceclick}} = \left(m_{\text{plate}} + m_\Omega + m_{\text{load}}\right) g \tag{19.2}$$

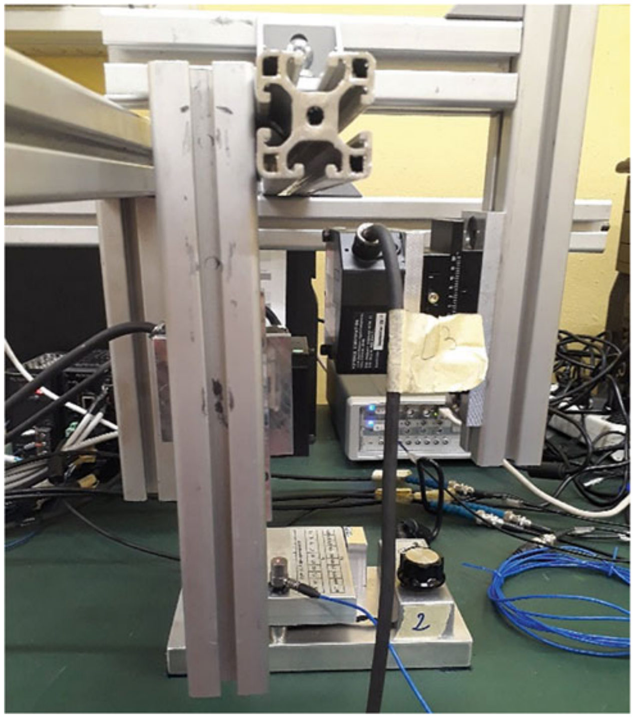

Fig. 19.7 Experimental setup

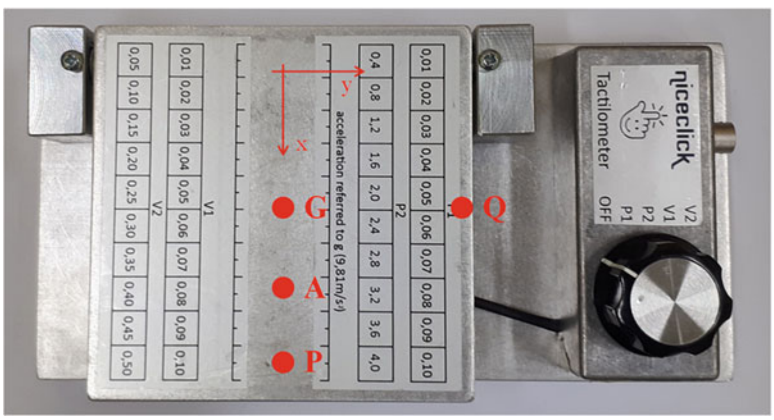

Fig. 19.8 Reference system and measured points

Fig. 19.9 Set of masses for the static loading conditions

Three measures were performed for each configuration, following two up-down cycles. The results for Niceclick 1 are reported only. In Fig. 19.10, the Force-Displacement curves at point "P" are shown.

Table 19.2 Loads evaluation

Configuration	m_{plate} [gr]	m_{Ω} [gr]	m_{load} [gr]	F_{hinge} [N]	$F_{Niceclick}$ [N]
1	550	4.26	10	2.72	2.81
2	550	4.26	20	2.75	2.89
3	550	4.26	30	2.77	2.96
4	550	4.26	40	2.80	3.03
5	550	4.26	50	2.82	3.11
6	550	4.26	60	2.84	3.18
7	550	4.26	70	2.87	3.25
8	550	4.26	80	2.89	3.33
9	550	4.26	90	2.92	3.40
10	550	4.26	100	2.94	3.48
11	550	4.26	110	2.97	3.55
12	550	4.26	120	2.99	3.62
13	550	4.26	130	3.02	3.70
14	550	4.26	140	3.04	3.77
15	550	4.26	200	3.19	4.21

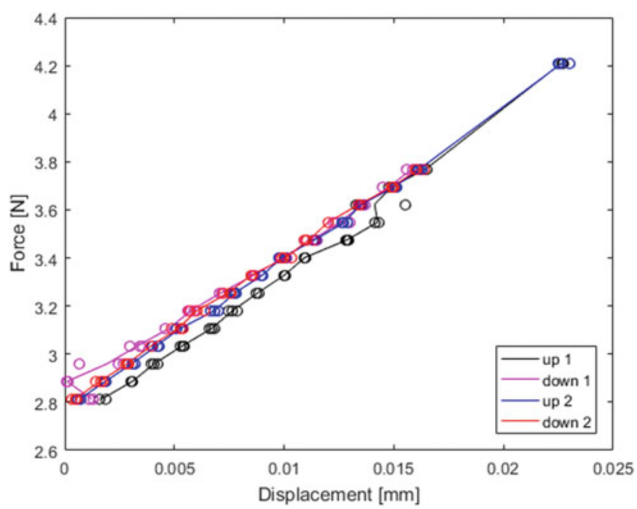

Fig. 19.10 Displacement curves at point "P"

Two interpolation techniques were adopted for trying to describe the elastic properties, a linear and a cubic one, respectively resumed by the following equations:

$$F_{\text{interp}} = k_0 + k_1 x \tag{19.3}$$

$$F_{\text{interp}} = k_0 + k_1 x + k_2 x^2 + k_3 x^3 \tag{19.4}$$

The error was evaluated as well, defined as the mean of the square difference between the experimental and the interpolated values:

$$\text{Eps}^2 = \frac{1}{n} \sum_{j=1}^{n} \left(F_{\exp,j} - F_{\text{interp},j} \right)^2 \tag{19.5}$$

The two function coefficients are reported in Tables 19.3 and 19.4; the plots of interpolated values are shown in Fig. 19.11, for linear (left) and cubic (right) interpolation, respectively.

Considering the results, the elastic element stiffness can be roughly considered linear; however, the more precise description provided by the cubic interpolation highlights a hardening behaviour, visible in the right part of the plots. This characteristic is probably due to the element deformation.

Table 19.3 Linear interpolation coefficients and errors

	k_0 [N]	k_1 [N/m]	Eps^2 [N^2]
Up 2	2.767	62.72 10^3	1.234 10^{-4}
Down 2	2.793	61.36 10^3	1.106 10^{-4}
Up&Down 2	2.778	62.41 10^3	6.662 10^{-5}

Table 19.4 Cubic interpolation coefficients and errors

	k_0 [N]	k_1 [N/m]	k_2 [N/m^2]	k_3 [N/m^3]	Eps^2 [N^2]
Up 2	2.767	65.57 10^3	−4.992 10^8	1.825 10^{13}	7.218 10^{-5}
Down 2	2.775	70.36 10^3	−9.747 10^8	2.914 10^{13}	7.870 10^{-5}
Up&Down 2	2.770	67.83 10^3	−7.133 10^8	2.293 10^{13}	2.408 10^{-5}

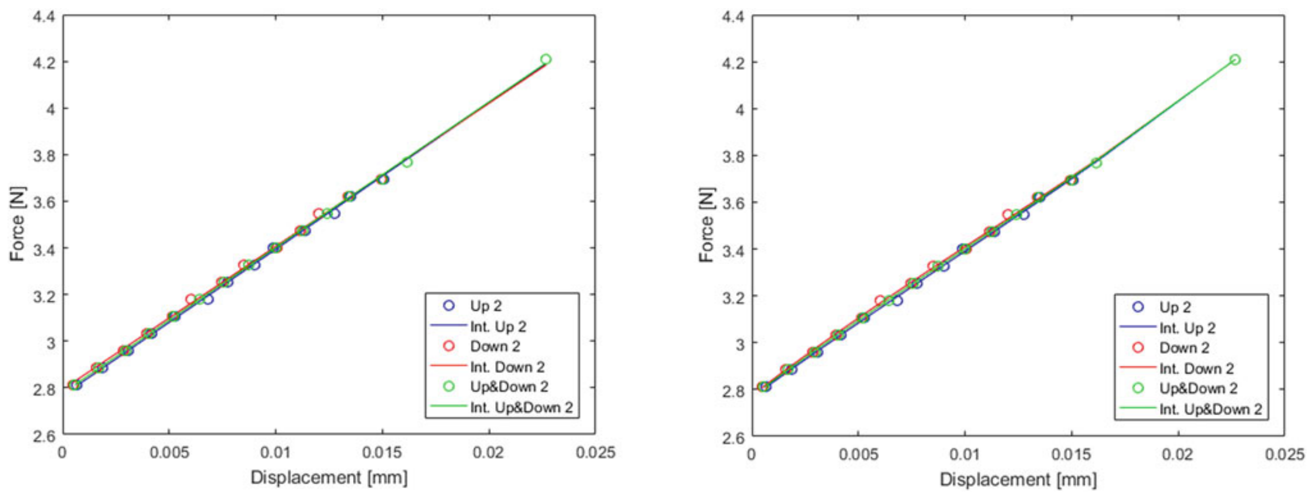

Fig. 19.11 Linear (left) and cubic (right) interpolation

19.4.2 Dynamic Analysis

An impact test was performed for evaluating the system dynamic properties. Because of the complex measuring setup, the only available point on the plate surface was "A"; for reference, see Fig. 19.8. A PCB instrumented hammer was used, together with the three lasers and the monoaxial accelerometer, positioned as described above. Several measurements were performed for each Niceclick, but only the Niceclick 1 results are reported.

Figure 19.12 shows an analytical representation of the system, with the free body diagram of the plate. The dynamic behaviour is expressed by (19.6), where I_O is the plate moment of inertia referred to the hinge, k is the Niceclick stiffness, $l = 80$ mm is the distance between the points "O", and "P" and ϑ is the plate rotational angle (considered very small) around the hinge axis.

The value of I_O was obtained by the following equation:

$$I_O = \frac{1}{12} m L^2 + m \overline{OG}^2 = 1.36 \cdot 10^{-3} \text{ kg} \times \text{m}^2 \tag{19.6}$$

where $L = 100$ mm is the plate length, $m = 550$ gr is the plate mass, and OG = 40 mm is the distance between the barycentre and the rotational axis.

The resonance frequency of the system can be evaluated by the following equation:

$$f = \frac{1}{2\pi} \sqrt{\frac{kl^2}{I_O}} \tag{19.7}$$

Considering as a reliable value of stiffness the Up&Down k_1 coefficient from Table 19.4, the system resonance frequency results:

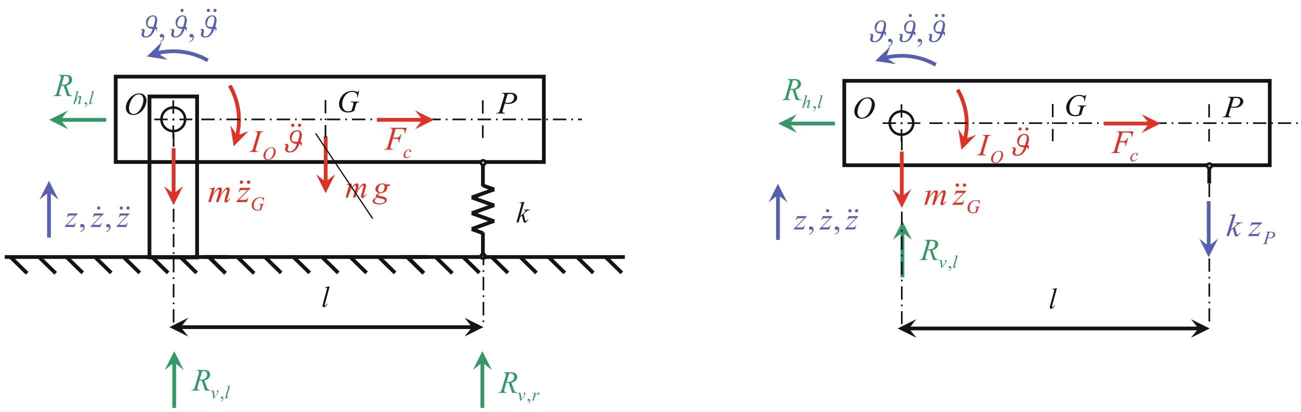

Fig. 19.12 Whole-system representation (left) and plate free body diagram (right)

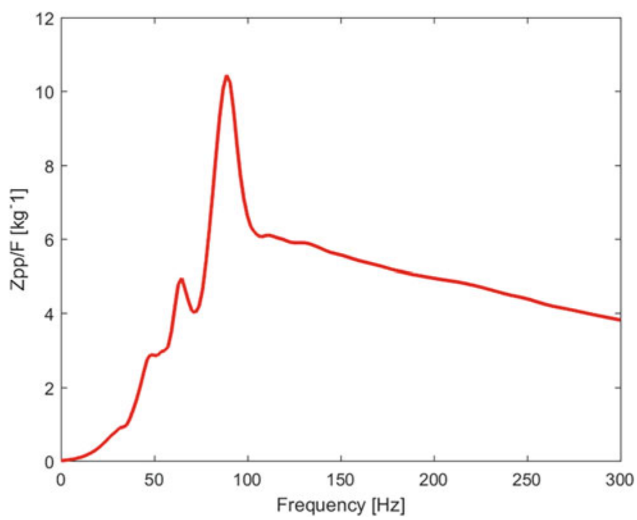

Fig. 19.13 Inertance FRF

$$f = \frac{1}{2\pi}\sqrt{\frac{kl^2}{I_O}} = \frac{1}{2\pi}\sqrt{\frac{67830 \cdot 0.08^2}{1.36 \cdot 10^{-3}}}\ \text{Hz} = 89.96\ \text{Hz} \tag{19.8}$$

The data from the impact test were analysed and the inertance FRF (evaluated in point "P") of Fig. 19.13 was obtained. The system resonance, that is represented in the plot by the highest peak, occurs at a frequency of 88.80 Hz, a value very close to the one in (19.8), calculated from the interpolation coefficient of the static test results.

Finally, the Niceclick dynamic analysis confirmed that the device specifics are perfectly suitable for the haptic applications since his reactiveness and dynamic response cover a very wide accelerometer range that goes beyond the human tactile perception frequency spectrum whose peak is around 250 Hz.

19.5 Niceclick Applications in Haptic Interfaces and Conclusions

The Niceclick is a very powerful haptic device in HMI application. For example, the most used interface on a vehicle is the steering wheel set of buttons, that includes, in certain cases, not only the infotainment system but even lights and screen wipers switches and the gearshift paddles [21]. Therefore, the simple, rectangular shapes are quite an exception. In the paper, the developed tools for developing the feedback patterns are depicted, showing the versatility of the device in different applications. An ad hoc measuring tool is developed to characterise the static and dynamic behaviour of the system.

The characterisation was performed on stiffness of the system showing a linear behaviour for extremely large displacement range, making the Niceclick quite interesting in automotive field. Moreover, it is objectified the state-of-the-art sensation evaluation through calculation of tactilometer natural frequency, which demonstrates the Niceclick suitability for industrial applications.

In the future, it will be studied the effect of the device inside a complex mechanical system, such as a steering wheel haptic interface, to evaluate the prototype performance and to define a methodology for optimal haptic device placement.

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References

1. Akamatsu, M., Green, P., Bengler, P.: Automotive technology and human factors research: past, present and future. Int. J. Veh. Technol. **3**, 1–27 (2013). https://doi.org/10.1155/2013/526180
2. Kern, D., Schmidt, A.: Design space for driver-based automotive user interfaces. In: Proceedings of 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Essen, Germany, pp. 3–10 (2009). https://doi.org/10.1145/1620509.1620511
3. Gaspar, J., Fontul, M., Henriques, E., Silva, A.: Haptics of in-car radio buttons and its relationship with engineering parameters. Int. J. Ind. Ergon. **59**, 29–45 (2017). https://doi.org/10.1016/j.ergon.2017.03.005
4. François, M., Osiurak, F., Fort, A., Crave, P., Navarro, J.: Automotive HMI design and participatory user involvement: review and perspectives. Ergonomics. **60**(4), 541–552 (2017). https://doi.org/10.1080/00140139.2016.1188218
5. Gaspar, J., Fontul, M., Henriques, E., Ribeiro, A., Silva, A., Valverde, N.: Psychoacoustics of in-car switch buttons: from feelings to engineering parameters. Appl. Acoust. **110**, 280–296 (2016). https://doi.org/10.1016/j.apacoust.2016.03.037
6. Altinsoy, M.E., Merchel, S.: Audiotactile feedback design for touch screens. In: 4th International Conference on Haptic and Audio Interaction Design, Dresden, Germany, pp. 136–144 (2009). https://doi.org/10.1007/978-3-642-04076-4_15
7. Basdogan, C., Giraud, F., Levesque, V., Choi, S.: A review of surface haptics: enabling tactile effects on touch surfaces. IEEE Trans. Haptics. **13**(3), 450–470 (2020). https://doi.org/10.1109/toh.2020.2990712
8. Xu, H., Klatzky, R.L., Peshkin, M.A., Colgate, J.E.: Localised rendering of button click sensation via active lateral force feedback. In: 2019 IEEE World Haptics Conference, Tokyo, Japan, pp. 509–514 (2019). https://doi.org/10.1109/WHC.2019.8816158
9. Gescheider, G.A., Bolanowsky, S.J., Pope, J.V., Verrillo, R.T.: A four-channel analysis of the tactile sensitivity of the fingertip: frequency selectivity, spatial summation, and temporal summation. Somatosens. Mot. Res. **19**(2), 114–124 (2002). https://doi.org/10.1080/08990220220131505
10. Gescheider, G.A., Bolanowski, S.J., Hall, K.L., Hoffman, K.E., Verrillo, R.T.: The effects of aging on information-processing channels in the sense of touch: I. Absolute sensitivity. Somatosens. Mot. Res. **11**(4), 345–357 (1994). https://doi.org/10.3109/08990229409028878
11. Verrillo, R.T.: Effect of contactor area on the vibrotactile threshold. J. Acoust. Soc. Am. **35**(12), 1962–1966 (1963). https://doi.org/10.1121/1.1918868
12. Verrillo, R.T.: Psychophysics of vibrotactile stimulation. J. Acoust. Soc. Am. **77**(1), 225–232 (1985). https://doi.org/10.1121/1.392263
13. Bisley, J.W., Goodwin, A.W., Wheat, H.E.: Slowly adapting type I afferents from the sides and end of the finger respond to stimuli on the center of the fingerpad. J. Neurophysiol. **84**(1), 57–64 (2000). https://doi.org/10.1152/jn.2000.84.1.57
14. Srinivasan, M.A., LaMotte, R.H.: Tactual discrimination of softness. J. Neurophysiol. **73**(1), 88–101 (1995). https://doi.org/10.1152/jn.1995.73.1.88
15. Bergmann Tiest, W.M., Kappers, A.M.L.: Cues for haptic perception of compliance. IEEE Trans. Haptics. **2**(4), 189–199 (2009). https://doi.org/10.1109/toh.2009.16
16. Kildal, J.: 3D-press: haptic illusion of compliance when pressing on a rigid surface. ICMI-MLMI. **21**, 1–8 (2010). https://doi.org/10.1145/1891903.1891931
17. Scilingo, E.P., Bianchi, M., Grioli, G., Bicchi, A.: Rendering softness: integration of kinaesthetic and cutaneous information in a haptic device. IEEE Trans. Haptics. **3**(2), 109–118 (2010). https://doi.org/10.1109/TOH.2010.2
18. Tornincasa, S., Repetto, M., Bonisoli, E., Di Monaco, F.: Energy harvester for vehicle tires: nonlinear dynamics and experimental outcomes. J. Intell. Mater. Syst. Struct. **23**(1), 3–13 (2012). https://doi.org/10.1177/1045389X11430739
19. Tornincasa, S., Repetto, M., Bonisoli, E., Di Monaco, F.: Optimization of magneto-mechanical energy scavenger for automotive Tyre. J. Intell. Mater. Syst. Struct. **23**(18), 2055–2064 (2012). https://doi.org/10.1177/1045389X11430741
20. Tornincasa, S., Bonisoli, E., Di Monaco, F., Moos, S., Repetto, M., Freschi, F.: Chapter 30: Nonlinear dynamics of an electro-mechanical energy scavenger. In: Modal Analysis Topics, Vol. 3, Proceedings of the 29th IMAC, A Conference and Exposition on Structural Dynamics Conference Proceedings of the Society for Experimental Mechanics Series 2011., 578 pp., pp. 339–349. Springer (2011). https://doi.org/10.1007/978-1-4419-9299-4_30
21. Galvagno, E., Dimauro, L., Mari, G., Velardocchia, M., Vella, A.D.: Dual Clutch Transmission vibrations during gear shift: a simulation-based approach for clunking noise assessment. In: 2019 SAE Noise and Vibration Conference and Exhibition, June 10–13, 2019, Grand Rapids, Michigan, SAE Technical Paper 2019-01-1553, pp. 1–12 (2019). https://doi.org/10.4271/2019-01-1553