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To cite this version:

Damien Couroussé. Mechanical impedance. Enaction and enactive interfaces : a handbook of terms, Enactive Systems Books, pp.194-196, 2007. <hal-00978979>

HAL Id: hal-00978979
https://hal.archives-ouvertes.fr/hal-00978979

Submitted on 15 Apr 2014

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Mechanical impedance is a transposition to mechanics of the term impedance that is used and defined in circuit theory. The theory of circuit (theory of Kirchhoff networks) is basically applicable to electric networks but can be considered more generally as a unifying simplified theory of physics available in several domains like mechanics, electromagnetism, aero-acoustics and fluids mechanics.

Similarly to Maxwell or Newton physics, the theory of Kirchhoff networks involves local properties and dual variables (current & voltage, magnetic & electric field, force & motion, flow & pressure, etc.), and furthermore constitutes a discrete and modular description of physical systems. Within this formalism, physical systems are described as networks made of inter-connected dipolar entities whose constitutive property is to present two poles constituting input and output of a circulating flow. These abstract dipoles are not necessarily elementary physical elements; they may be sub-networks or a pair of poles belonging to a multi-pole element [Boite and Neirynck, 1983].

The electric impedance is defined as the voltage to current ratio that is related to a dipole. This definition is meaningful if this ratio represents an invariant property of the dipole (i.e. independent on the current and voltages temporal variations) and then appears as a characteristic property of a physical object or system. More generally, the concept of impedance could be extended to an abstract operator that would link the physical dual variable and would stand for the invariant property of a system at its dipolar link point.

In the domain of mechanics, the concept of impedance is mainly used in vibro-acoustics, aero-acoustics and fluid mechanics where small or non-geometrical motions are considered. Indeed like Kirchhoff theory the concept of impedance is only limited to non-geometrical dynamical systems (i.e. a system in which no distance related properties are considered in its motion space).

In the field of haptics, some works present the mechanical impedance as a static representation ($F=ZxV$) [Colgate and Brown, 1994]. A more general approach considers that the mechanical impedance of a given mechanical system also depends on the frequency of the mechanical perturbation [Lawrence and Chapel, 1994], [Lawrence et al., 1996].

Hence, the mechanical impedance (Z) can be defined as an operator providing a force (F) given a displacement (V):

$$F = Z(V)$$

When one wants to evaluate a haptic device in situ, one of the most basic tests used is the model of the virtual wall. It allows testing two very important properties of a haptic device:

- The quality of hard contacts. By colliding the simulated wall, it is possible to evaluate how powerful are the actuators, how fast and how stable is the control loop, how precise are the sensors, etc.
- The quality of motion at free movement. Inherent friction, proper mass of the moving parts, and other physical characteristics limit performances of haptic devices at free movement. If they become perceptible from the user's point of view, the presence of the haptic device becomes perceptible between the user and what is simulated.

This means that a perfect haptic device should be able to simulate

- very hard contacts, like when hitting a strong wall or a big plate made of metal;

- pure free movement, that is, movement that wouldn't make the user lose more energy that the energy he/she would loose if he/she wasn't grasping the haptic device.

From the mechanical engineer's point of view, an infinitively hard contact corresponds to infinite mechanical impedance, whereas a purely free movement corresponds to mechanical impedance that is null.

When designing a haptic device, the difficulty is to achieve at the same time these two properties (quality of free movement and quality of hard contact). It is not possible to obtain such a haptic device, because the two requirements of free movement and hard contacts require opposite technological design solutions. This maximum range of mechanical impedance is defined as the Z-Width of a haptic device in [Colgate and Brown, 1994], which is in this paper assumed to be comparably as broader as the dynamic range of the device.

A very rough example can illustrate this problem: when one wants to increase the hardness of contacts, one may want to increase the power of the actuators. However, due to the fact that actuators provide a ratio of power over mass that is limited by the technology chosen, increasing the power of the actuators will lead to increase their mass. This will lead to increase the whole inertia of the kinematic chain, thus decreasing the quality of free movement.

In the domain of haptics and teleoperation robotics, the concept of impedance has mainly been used because it allowed dealing with system composition and system separation. In these disciplines basic compositions between three types of systems have to be considered: device-object, device-human, human-object where the device is an artificial haptic device or a robot. In these conditions it may be helpful to characterize intrinsic properties of each of these three entities at their coupling points where there are linked with the others. This leads to apply the usage of the impedance concept to physical objects, to robots at the point of their end effectors, to haptic device at their manipulating point, and to the human hand.

Several classical haptic issues are defined and treated with the help of impedance concept, including: transparency of a teleoperation system; specification of a haptic simulators human behaviour characterization; compliance of a robot device.

Finally, various specialized usages of impedance term are also available in haptics device domain and haptic simulation, such as: impedance matching; impedance range (Z-Width); characteristic impedance; critical impedance; gyration impedance.

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