3D Environmental Force:Position Impedance Variation for Different Motion Parameters

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***Abstract*—The skill preservation of an expert has been a serious problem for countries with aging population because decrease of the number of successors. The concepts of haptic database and force sensor recorder which have been developed recently suggests solutions of using third multimedia type of haptic communication. Haptic information is a bilateral information of the law of action and reaction. The reaction from real world includes not only position and force information but also environmental impedance. In this paper, the behavior of environmental impedance has been studied with the changes of the different motion parameters like applied force, velocity, position and depth on the object 3D space. This idea is exemplified using a rubber balloon and a rubber sponge which is often modeled using simple linear equations. The experimental results show the importance of considering motion parameters when abstracting haptic information for a haptic database. Nonlinear impedance variations against the motion parameters suggest the necessity of adopting complex haptic abstraction techniques.**

***Keywords*—haptic data base; force sensor recorder; Disturbance Observer (DOB); hysteresis; motion parameters; environmental impedance**

I. Introduction

Limitations of information recording facilities of characters and/or pictures which were used in ancient time were expanded to auditory information with the invention of the radio in 18th century. Furthermore in mid-19th century, the invention of video tape recorder facilitated static and dynamic visual information storage. With the rapid development of communication technologies, internet enables transmission of text documents, sounds, and visual information worldwide. That information is captured by human auditory and visual organs of ears and eyes. Although the human body has haptic organs, the information acquired using conventional methods and visual information does not contain haptic information like force [1].

In recent years the concept of haptic information storage and reproduction has been proposed [2]. Preservation of human haptic information in a haptic database provides facility to reproduce it at any time at anyplace. Expert skills of motion reproduction capability decline with the aging of people and decrease the number of successors especially in artistic machining, artistic pottery, etc. By using haptic information robots are expected to work in production lines as well as in open environments. Further haptic database can preserve once skills on to the next generation. This is called as motion copying system. The motion copying system includes human haptic information in terms of position and force information which are recorded during motion saving mode. Recording haptic information is done by bilateral control of action and reaction [1] using motion saving system. The bilateral control system consists of two main parts named as master and slave. The master is the operator who issues the commands and the slave which is in contact with the environment follows the commands of the master. Position and force information is transmitted bilaterally between the slave side and the master side [3].

Bilateral controller with disturbance observer (DOB) [4] gives the vivid force sensation from the real environment. Therefore real environment force and position information also should be recorded successfully for preservation and reproduction. The Force Sensation Recorder (FSR) in [5] proposes the preservation and reproduction of force sensation from the real environment. The FSR abstracts position and force information including the environmental information like environment impedance from the real environment based on the acceleration control architecture. This information is extracted during the abstraction mode of the FSR. The motion copying system stores the haptic information of human and FSR stores the information of the environment. Therefore at the motion loading stage of the motion copying system has virtual master and slave follows the haptic data recorded in the database where as FSR has virtual environment and master feels the environmental model as he moves the manipulator. Fig. 1 shows the concept of motion copying system and Fig. 2 shows the concept of FSR.

The sensation of real environment via a database requires advanced environment modeling. The studies in [2], [6] and [7] have used a rigid object with high stiffness as an example for building the haptic database. Above studies have not considered low environmental impedance objects. The behavior of environmental impedance has not been studied during above studies since those have not considered environmental model variation with different motion parameters like applied force, applied velocity and deformed depth on a selected point of the environment. Previous studies have not considered property change of environmental model as actuator moves along the 3D space on environmental surface. In studies of [5] and [8] have been used sponge as an environment and modeled it as a function of stiffness and viscosity for considerable force range and they have not considered the environmental impedance behavior for different velocities and deformed depth and surface position on the 3D environment. This paper proposes an impedance model as a function of its motion parameters and highlights the importance of considering the different motion parameters of actuator on environmental impedance changes for construction of real environmental model for haptic databases.

This paper is organized as follows. The environmental model and its parameter estimation for different motion parameters are considered in section II. In section III, experimental results are presented in order to verify the environment impedance variation with different motion parameters of the actuator. Finally, this paper is summarized and concluded in section IV.

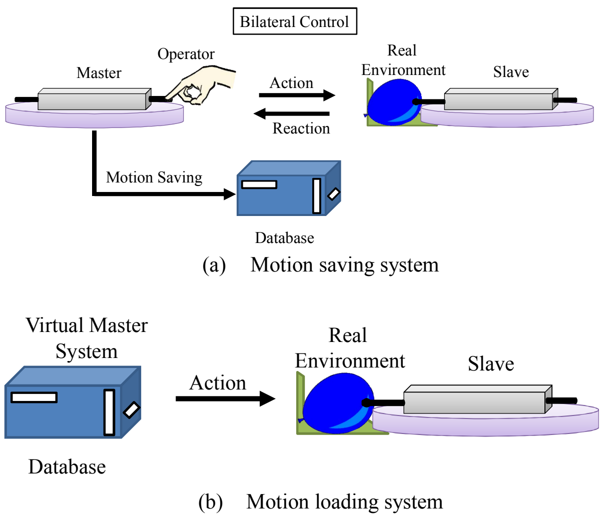


Fig. 1. Motion copying system.

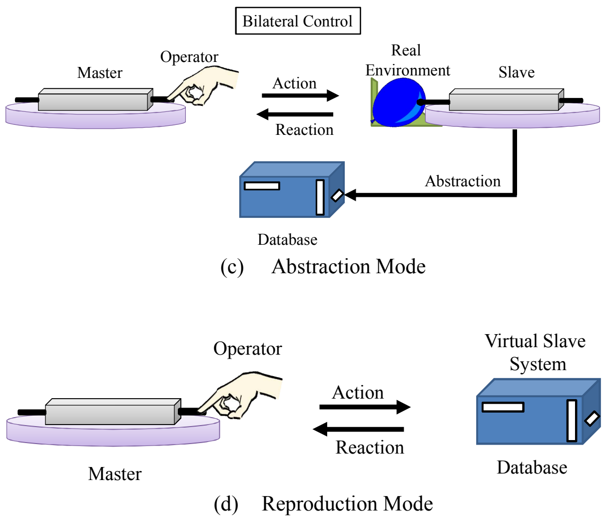


Fig. 2. Force sensation recorder

II. Modeling

A. Model of the Environment

The environment which is the object interested in the study is modeled as a simple linear mass, damper and spring model and environment reaction for operator force can be represented as (1) and (2) denotes its Laplace representation. The relationship between environment reaction and position denotes the environmental impedance as (3). These parameters are expected to be calculated using the 3D data during the experiment.

$$F_e = m_e\ddot{x} + b_e\dot{x} + k_e x = F_m + F_b + F_k = F_{op} \quad (1)$$

$$F_e = (m_{(e)}s^2 + b_{(e)}s + k_{(e)}).x \quad (2)$$

$$F_e = Z_e.x \quad (3)$$

Where, F_e : Environment reaction force
m_e : Environmental mass
b_e : Environmental damping coefficient
k_e : Environmental spring coefficient
F_m : Force from the mass
F_b : Force from the damper
F_k : Force from the spring
F_{op} : Operator force
x : Position change of the environment
Z_e : Environmental impedance
s : Laplace operator

The notations $\dot{x}, \ddot{x}$ denote corresponding velocity and acceleration. The environment model in (1) assumes constant $m_{(e)}$,$b_{(e)}$, and $k_{(e)}$. This paper proposes an impedance model as a function of its motion parameters as (4).

$$F_e = m_{(\ddot{x})}\ddot{x} + b_{(\dot{x})}\dot{x} + k_{(x)}x \quad (4)$$

It is proposed that m_e, b_e and k_e are function of $x, \dot{x}$ and $\ddot{x}$ as $m_{(\ddot{x})}, b_{(\dot{x})}$ and $k_{(x)}$.Therefore it is possible to identify and estimate variable environmental impedance through this modeling. Fig. 3(a) shows the model of proposed variable impedance model. To study the variation of environmental impedance along the environment surface h, a setup shown in Fig. 3(b) is used.

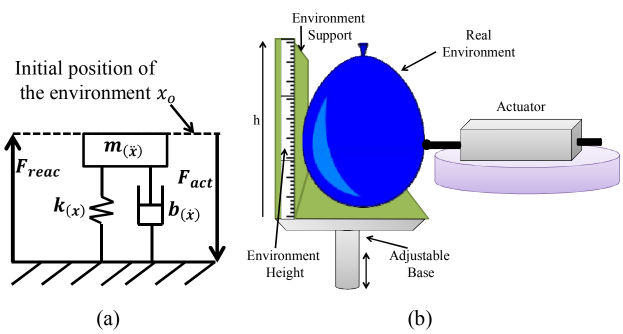


Fig. 3. (a) Environmental model of mass, spring, damper. (b) Setup for identification of *k, b, m* variation along the surface of environment.

B. Estimation of Environmental Impedance

The estimation of $k_{(x)}, b_{(\dot{x})}$ and $m_{(\ddot{x})}$ is done as follows.The spring coefficient $k_{(x)}$ variation with compression depth x is estimated using a position controller. A series of position commands similar to Fig. 4(a) is applied on environment surface and data is acquired when actuator maintains a stationary position. Because x is stable $\dot{x}, \ddot{x}$ is approximated to be zero and reaction force from the environment obeys (5).

$$F_e = k_{(x)}x = F_k \tag{5}$$

Once the variation of k with x is obtain actuator is operated with series of different constant velocity commands similar to Fig. 4(b). Since $\dot{x}$ is constant $\ddot{x}$ is approximated to be zero and reaction force from the environment obeys (6).

$$F_e = b_{(\dot{x})}\dot{x} + k_{(x)}x = F_b + F_k \tag{6}$$

Since variation of $k_{(x)}$ with x is obtained in previous step and $\dot{x}, F_e$ are known, the behaviour of b with $\dot{x}$ can be estimated using (6). Next, ramp velocity commands similar to Fig. 4(c) are applied on the environment and reaction force from the environment obeys (4). Since variation of $k_{(x)}$ with x and variation of $b_{(\dot{x})}$ with $\dot{x}$ for corresponding x values are known using (4) the behaviour of m with $\ddot{x}$ can be estimated. Reaction force estimation for above steps are possible by Reaction Force Observer (RFOB). These environmental impedences are calculates as a discrete time modelling. The reaction force from the environment with compression depth x, can be represented by a relationship as (7).

$$[F_{reac,x}] = \left[diag\left([m_{(\ddot{x})} \quad b_{(\dot{x})} \quad k_{(x)}] \begin{bmatrix} \ddot{x} \\ \dot{x} \\ x \end{bmatrix} \right) \right]^T \tag{7}$$

Where,

$$[F_{reac,x}] = \begin{bmatrix} F_{reac,x_1} \\ F_{reac,x_2} \\ \vdots \\ F_{reac,x_n} \end{bmatrix}, m_{(\ddot{x})} = \begin{bmatrix} m_{(\ddot{x}_1)} \\ m_{(\ddot{x}_2)} \\ \vdots \\ m_{(\ddot{x}_n)} \end{bmatrix}, b_{(\dot{x})} = \begin{bmatrix} b_{(\dot{x}_1)} \\ b_{(\dot{x}_2)} \\ \vdots \\ b_{(\dot{x}_n)} \end{bmatrix},$$

$$k_{(x)} = \begin{bmatrix} k_{(x_1)} \\ k_{(x_2)} \\ \vdots \\ k_{(x_n)} \end{bmatrix}, \ddot{x} = [\ddot{x}_1 \quad \ddot{x}_2 \quad \dots \quad \ddot{x}_n],$$

$$\dot{x} = [\dot{x}_1 \quad \dot{x}_2 \quad \dots \quad \dot{x}_n], \qquad x = [x_1 \quad x_2 \quad \dots \quad x_n]$$

Here, 1, 2, …,n denote the number of compression depths considered in the study.

C. Disturbance Observer and Reaction Force Observer

The disturbance observer gives the vivid force sensation from the real environment without using force sensors [9]. The dynamic equation of a linear motor can be represented as in (8) and generated force from it can be written as (9).

$$M\ddot{x} = F_g - F_l \tag{8}$$
$$F_g = K_f I_{ref} \tag{9}$$

Where, M : Motor mass
$\ddot{x}$: Linear acceleration
F_g : Generated force
F_l : load force
I_{ref} : Reference current to the motor
K_f : Motor force constant

Load force F_l can be represented as (10).

$$F_l = F_{int} + F_{ext} + (F_f + B\dot{x}) \tag{10}$$

F_{int}, F_{ext}, F_f and $B\dot{x}$ denote interactive force, reaction force of the mechanical load, static friction and viscous friction. Equation (10) can be re-written by substituting from (8) and (9).

$$M\ddot{x} = K_f I_{ref} - \left(F_{int} + F_{ext} + (F_f + B\dot{x})\right) \tag{11}$$

Parameters M, K_f are subjected to variations and estimation errors. Therefore these can be re-written in terms of nominal values and variations.

$$M = M_n + \Delta M \tag{12}$$
$$K_f = K_{fn} + \Delta K_f \tag{13}$$

M_n, K_{fn} denotes nominal mass and nominal force constant

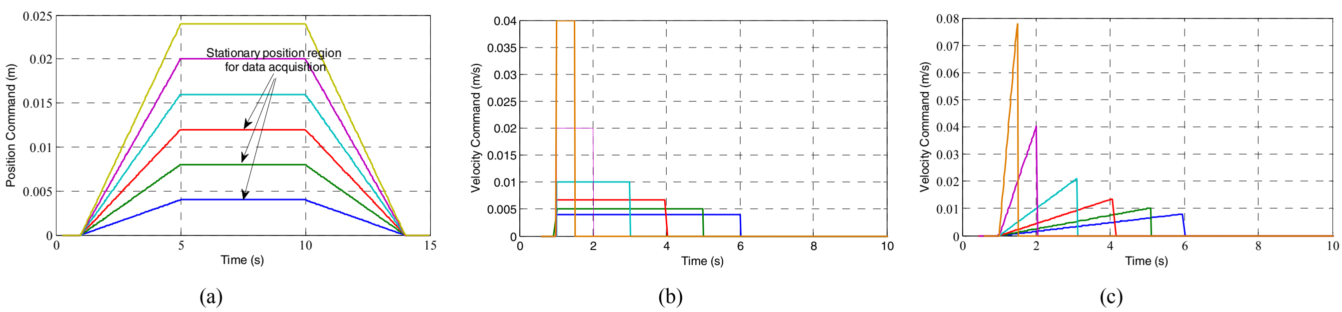


Fig. 4. (a) Position command profiles on the environment. (b) Constant velocity command profiles on the environment. (c) Ramp velocity command profiles on the environment.

of the motor. By substituting (12) and (13) to (11) and rearranging, (14) can be derived.

$$M_n\ddot{x} = K_{fn}I_{ref} - \left(TF_{int} + F_{ext} + \left(F_f + B\dot{x}\right) + \Delta M\ddot{x} - \Delta K_f I_{ref}\right) \quad (14)$$

The term within the parenthesis in (14) is called as total disturbance to the system F_{dis}.

$$\begin{aligned} F_{dis} &= F_l + \Delta M\ddot{x} - \Delta K_f I_{ref} \\ &= F_{int} + F_{ext} + \left(F_f + B\dot{x}\right) + \\ &(M - M_n)\ddot{x} + \left(K_{fn} - K_f\right)I_{ref} \end{aligned} \quad (15)$$

By rearranging,

$$M_n\ddot{x} = K_{fn}I_{ref} - F_{dis} \quad (16)$$

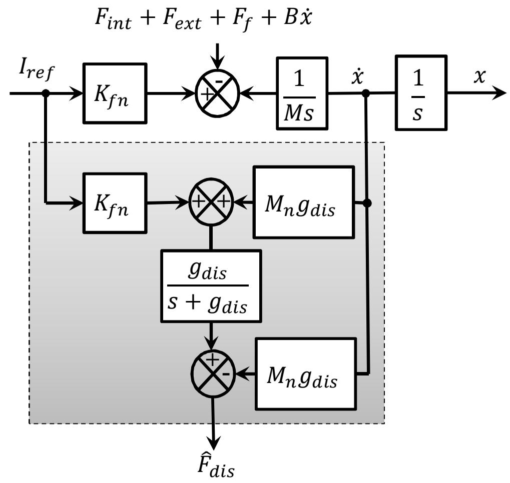
Thus, F_{dis} can be calculated as follows.

$$F_{dis} = K_{fn}I_{ref} - M_n\ddot{x} \quad (17)$$

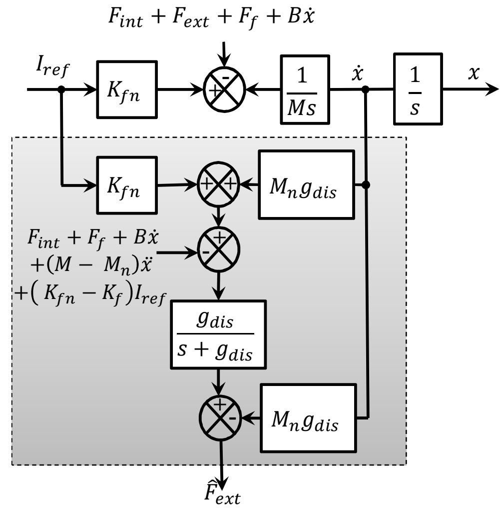
Fig. 5(a) shows the block diagram of the disturbance observer. Disturbance is calculated using I_{ref} and $\dot{x}$. Estimated disturbance $\hat{F}_{dis}$ in (18) is derived from the disturbance, passing through the low pass filter. Cutoff frequency of the low pass filter is denoted by g_{dis}.

$$\hat{F}_{dis} = \frac{g_{dis}}{s + g_{dis}} F_{dis} \quad (18)$$

The estimated disturbance force is used to compensate the low frequency components of the disturbance. The DOB has been modified for reaction force estimation by subtracting the internal disturbance together with the frictional components of the system. Fig. 5(b) shows the block diagram of the reaction force observer.



(a)



(b)

Fig. 5. Block diagrams (a) Disturbance Observer. (b) Reaction Force Observer.

III. EXPERIMENT

A. Experimental Setup

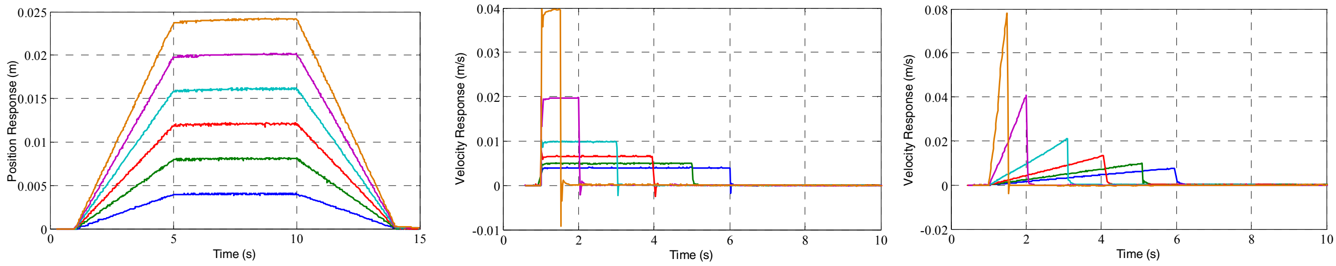
The proposed method is applied to the experimental setup. A linear motor is implemented as an actuator. The experiment is carried out using a balloon and a rubber sponge as the environment. The control software for this system is written using C language on mbed LPC1768. The experimental parameters are listed in Table I. In the experiment, the initial position of the actuator is set on the surface of the environment.

TABLE I. EXPERIMENTAL PARAMETERS

Parameter	Description	Value
K_{pp}	Proportional gain of position controller	650.0
K_{pd}	Derivative gain of position controller	250.0
K_{pi}	Integral gain of position controller	80.0
K_{vp}	Proportional gain of velocity controller	150.0
K_{vd}	Derivative gain of velocity controller	200.0
K_{vi}	Integral gain of velocity controller	80.0
K_{fn}	Motor force constant	3.35 N/A
M_n	Motor mass constant	0.4 kg
g_{dis}	Cut-off frequency of disturbance observer	200 rad/s
dt	Sampling time	150 µs

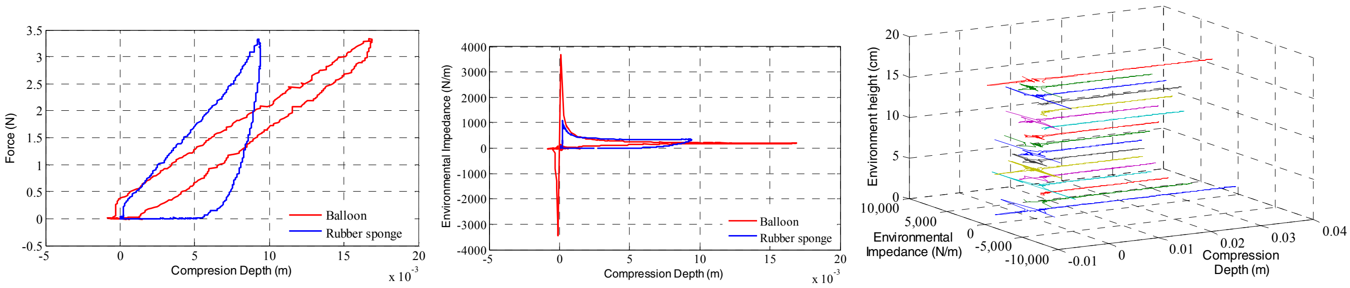
B. Experimental Results

The actuator responses for position, step velocity and ramp velocity are shown in Fig. 6(a), (b), (c) and it verifies that actuator follows the controller. First, a constant force command is applied on the balloon/rubber sponge and recorded its force position variation is as shown in Fig 7(a). The gradient of the graph shows its impedance as Fig. 7(b). Since plotted area for the rubber sponge is larger than for the balloon it indicates that the rubber sponge has more hysteresis loss. The area enclosed by the graph represents the energy absorbed by the object which was tested. A constant force command is applied along the surface of the balloon and environmental impedance



(a) (b) (c)

Fig. 6. (a) Position response of the actuator for environmental spring coefficient estimation. (b) Step velocity response of the actuator for environmental damping coefficient estimation. (c) Ramp velocity response of the actuator for environmental mass coefficient estimation.



(a) (b) (c)

Fig. 7. Environmental impedance variation for constant force command. (a) Force-position variation comparison of balloon and rubber sponge. (b) Impedance variation of balloon and rubber sponge. (c) Balloon environmental impedance variation with its height.

variation is shown in Fig. 7(c). It shows that the impedance of the middle area is high and it reduces towards the edges of the balloon. A middle point is on the environment (balloon) for further study.

The balloon is compressed using the position commands in Fig. 4(a) up to 0.024m in the steps of 0.004m and RFOB response is recorded during the stationary position region and calculated variation of spring constant is shown in Fig. 8(a). Set of step velocities depicted as in Fig. 4(b) are applied on the balloon which results in 0.020 m compression depth in each velocity command. The variation of damping coefficient based on the recorded RFOB response for the balloon is shown in Fig. 8(c). Ramp velocity command is applied on the balloon and variation of calculated mass with acceleration is derived using estimated spring coefficients and damping coefficients and response is shown in Fig. 8 (e). The above procedure is repeated for the rubber sponge and results of calculated spring constant, damping coefficient, and mass are shown in Fig. 8 (b), (d) and (f) respectively. When comparing two environments, results show that rubber sponge has high environmental impedance. The negative values of damping coefficient of balloon indicate the bounce back effect. The calculated mass of both balloon and rubber sponge varies in a considerable range and reach a constant value as the compression acceleration increased.

IV. CONCLUTION

This paper proposed a variable impedance model for environmental object representation. The Environment object impedance varies along the surface. The results of spring coefficient as a function of compression depth, damping coefficient as a function of compression depth and compression velocity, mass as a function of compression depth and compression acceleration show environmental impedance variation with different motion parameters. For a balloon damping coefficient gives negative values which is not practicable as a result of the bounce back effect. As damping coefficient is negative calculated mass is negative for the balloon for the given region. Calculated mass value does not represent a practical value. Therefore when constructing haptic database for the purpose of haptic communication, environment object reconstruction mode should consider complex haptic abstraction techniques as the non linear behaviour of the responses. Conventionally used simple environmental impedance model is valid only for spring damper applications. If a real world object is expected to be used for the skill preservation the proposed impedance model as a function of its motion parameters should be used.

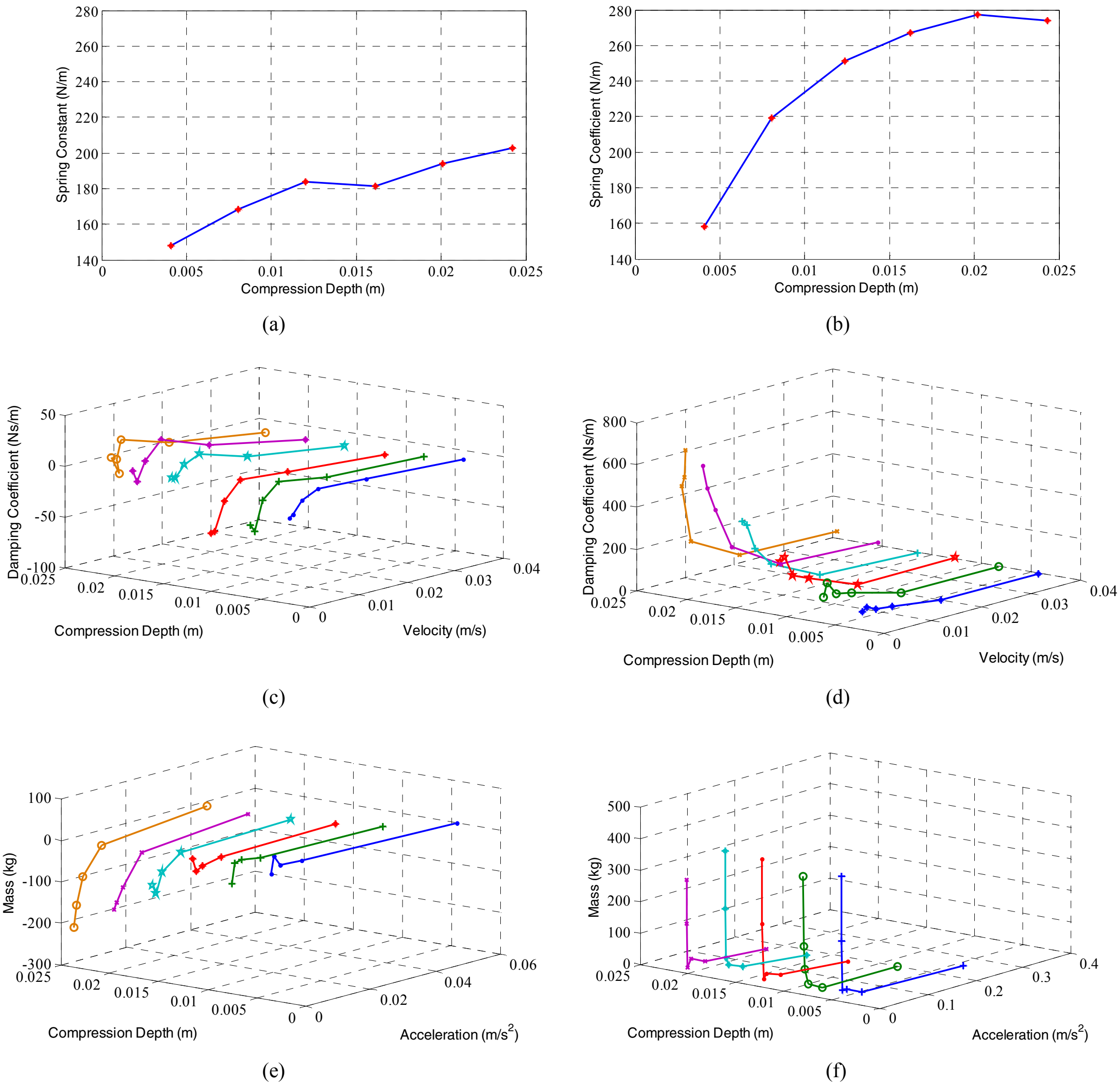


Fig. 8. Environmental impedance variation with motion parameters. (a) Spring coefficient variation of balloon with compression depth. (b) Spring coefficient variation of rubber sponge with compression depth. (c) Damping coefficient variation of balloon with velocity and compression depth. (d) Damping coefficient variation of rubber sponge with velocity and compression depth. (e) Calculated mass variation of balloon with acceleration and compression depth. (f) Calculated mass variation of rubber sponge with acceleration and compression depth.

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