Controlling Impedance at the Man/Machine Interface

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ABSTRACT

This paper presents some recent work on the dynamics of interactions between humans and machines. An experimental apparatus for simulating virtual environments and investigating the man/machine interface is described. Relevant experiments on the mechanical impedance of the human arm are reviewed. Despite active neuro-muscular feedback control, the human arm exhibits the impedance of a passive object. Preliminary results of some new experiments on the adaptability of human arm impedance are presented. These results indicate limitations in the rapidity of parameter-adaptation in humans.

Telerobotic Systems

Despite rapid advances in life-support technology, there remain many important environments (e.g. space, undersea, high-radiation or extreme-temperature environments) which are largely or completely inaccessible to humans, either because of excessive hazard or excessive cost. Conversely, despite advances in robot technology, application of fully-autonomous robot systems in the same environments remains difficult or impractical. Telerobotic systems — human-operated robotic systems with varying degrees of semi-autonomous capability — are a practical way to combine robot technology with human versatility.

From the control systems perspective, teleoperated systems present a new level of challenge for the roboticist. In the most successful robot applications to date (e.g. arc welding, pick and place tasks) dynamic interaction between the robot and its environment is negligible and a model of the robot alone is sufficient for control system design. Contact tasks are considerably more difficult. Dynamic interaction between the robot and its environment — a tool or a workpiece — must be taken into account in the design of the control system. Dynamic interaction can cause severe problems. The by-now-familiar phenomenon of contact instability [16] is a clear example. A force-feedback-controlled robot which is capable of stably executing unconstrained motions is likely to exhibit a severe chattering instability when it contacts a surface. Teleoperated systems are a level more difficult than applying robots to contact tasks because there are at least three distinct systems which interact — the human operator, the robot and its environment. Furthermore, one of the systems — the human operator — is extremely complex and difficult to characterize.

Dynamic interaction between systems may be quantified by their impedances[1]. Recent work [3] has shown that the contact stability problem can be rigorously analyzed *and solved* in terms of impedances. Specifically, it has been shown analytically that the necessary and sufficient condition for an actively-controlled system to remain stable when contacting an arbitrary passive environment is that its driving-point impedance appear to be that of an equivalent passive system. Experimental work [2] has confirmed that controllers which violate this condition exhibit contact instability, while those that satisfy it do not.

One persistent problem in telerobotics has been the implementation of a satisfactory interface between human and machine. The current challenge is to achieve *telepresence* — development of a sensorimotor interface sufficiently initimate to allow the human to feel as though (s)he were in the same environment as the machine. Accurate, high-fidelity control of the machine's motion is generally considered to be essential. Intuitively, it would also seem to be important for the human to sense the force experienced by the machine (or perhaps a suitably scaled representation of it). Bi-lateral or force-reflecting systems are based on this premise but experience to date has failed to show any unequivocal improvement in system performance due to force-reflection. It is widely acknowledged that one of the most important factors is the "feel" of the telerobot. There is less agreement on how to quantify a subjective quality such as "feel" nor how to optimize the "feel" of a teleoperated system. The work reported here is based on the perception that "feel" is a feature of the man/machine interface, therefore, just as dynamic interactions between robot and workpiece may be rigorously quantified by their impedances, the key quantities characterizing "feel" are the impedances of the human and the machine. From this perspective, the telerobot is a multi-port impedance and the relevant aspects of the human operator are characterized by an impedance. Several questions naturally arise: What is the impedance of the human operator? How much does it vary? How rapidly? What is the effect of varying the apparent impedance of the telerobot?

Variable-Impedance Manipulandum[2]

To address these and related questions an experimental facility for investigating human-machine interaction has been developed [5]. It is a computer-controlled manipulandum with programmable mechanical impedance. The mechanical system (see figure 1) is a "direct drive" motorized open-chain planar mechanism. The motors are low-inductance, low-inertia DC servomotors driven by high-bandwidth current-controlled amplifiers. Both motors are mounted on a rigid frame. The first link is mounted directly on the corresponding motor shaft. The second link is mounted on the first link and driven through a parallelogram mechanism. The angular positions and velocities of the mechanism are monitored by encoders and tachometers mounted co-axially on the motor shafts. The mechanism is terminated by a handle which may be grasped by a human. The force which can be produced varies with the position of the handle in the

[1] The term impedance is used here in the sense of a generalized dynamic relation between force and motion.

[2] The machine does not manipulate but is manipulated; hence the term manipuland*um*.

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workspace. When the handle is in the centre of the workspace, the maximum continuous force is at its minimum of 10 N. The peak force (which may be applied for about 1.5 seconds) at the same position is 30 N. In its present configuration, the handle is normal to the plane of motion of the mechanism and the grasping surface is free to rotate on low-friction ball bearings. Thus a human hand grasping the handle is constrained to move in a horzontal plane and the moment about the vertical axis is effectively constrained to be zero. However, the human may exert forces normal to the plane and moments about axes in the plane. To monitor all the exerted forces and moments the handle is mounted to the mechanism through a six-axis force/torque sensor (not shown in figure 1).

Control Architecture

Given the known destabilizing effects of dynamic interactions between systems and the fact that the dynamic behavior of humans is (a) difficult to quantify and (b) highly variable, it was considered imperative to protect both the human subject and the manipulandum against unplanned pathological behavior of the manipulandum. The response to system failure is to disable the power amplifiers and dynamically brake the mechanism by short-circuiting the motor terminals. System shutdown may be triggered independently of any controlling software by (1) momentary loss of power (2) activation of either of two push-button switches, one held by the experimenter, one held by the experimental subject, or (3) by closing any one of a set of multiply redundant limit switches which detect when the mechanism is nearing its limits of travel. System shutdown may also be triggered from the controlling software.

Control algorithms may operate in either of two modes. The first is the conventional digital control mode: all feedback loops are closed through a digital computer and all commands to the motor amplifiers are generated by the digital computer. The second control mode is based on analog feedback loops which bypass the digital computer, connecting the sensor outputs directly to the servo-amplifier inputs. These analog feedback loops are closed through multiplying digital-to-analog converters (MDAC's) which allow the digital computer to set and modify the analog feedback gains. This *digitally-supervised analog feedback control* offers several advantages over conventional digital control. For example, controller stability can be ensured even when the rate at which the digital computer updates its commands drops to zero (e.g. when an algorithm "crashes" the computer).

Control Algorithms

To date a number of control algorithms have been implemented. The most robust is a *simple impedance controller*. This algorithm simulates a two-dimensional spring and viscous damper attached to the end of the mechanism as follows:

$$F = K(X_v - X) - B(V)$$

- F: Force exerted by the manipulandum on the handle
- X_v: Manipulandum handle virtual position[3]
- X: Manipulandum handle actual position
- V: Manipulandum handle velocity
- $K(\,)$: Simulated elastic behavior (may be nonlinear)
- $B(\,)$: Simulated viscous behavior (may be nonlinear)

This target impedance is transformed into actuator and sensor coordinates using the forward kinematic equations relating handle position to motor shaft angle and the forward differential kinematic equations relating handle velocity to shaft angular velocity. The transformed impedance is then treated as a nonlinear feedback control algorithm.

[3] The virtual position is the equilibrium position the handle would reach in the absence of any other forces.

$$X = L(\theta) \qquad V = J(\theta)\omega$$

$$\tau = J^t(\theta)K(X_v - L(\theta)) - J^tB(J(\theta)\omega)$$

- τ: Motor output torque
- θ: Motor shaft angles
- ω: Shaft angular velocity
- $L(\theta)$: Forward kinematic equations
- $J(\theta)$: Forward Jacobian

It has been shown [4,10] that, to the extent that the actuators behave as ideal controlled torque sources and the position and velocity sensors monitor the motion of the motor shafts without intervening parasitic dynamics, this algorithm can provide an extremely robust stability to the manipulandum. In this implementation the servo-amplifiers are current-controlled with a nominal bandwidth of 1 KHz and the position and velocity sensors are mounted on the same shaft as the motor armatures, so these idealizations are in fact accurate characterizations of the hardware for frequencies well above the normal frequency range of human motor behavior. Given these assumptions, if the function B( ) defining the target viscous behavior is positive-definite and the function K( ) defining the target elastic behavior is positive-definite and non-decreasing, then the manipulandum will be stable. Unlike most other robot controllers, dynamic interaction with passive environments of arbitrary complexity or nonlinearity cannot jeopardize that stability. Furthermore, this stability property is insensitive to large errors in the assumed kinematic equations of the manipulator. In particular, if the manipulandum is contacted at any point other than the handle, the stability will not be jeopardized. It is also insensitive to the presence of elasticity (or other passive non-ideal behavior) in the joints or links. Other control algorithms which have been implemented include a computed-torque implementation of an impedance controller [9,15] which (over a limited bandwidth) uses force feedback to impose a target inertial behavior in addition to a target viscous and elastic behavior. More sophisticated implementations of impedance control have been developed by Colgate [2].

Mechanical Impedance of the Human Arm

Understanding the performance of a human interacting with this experimental manuipulandum (or, indeed, any machine) requires a characterization of human impedance. Most measurements of the impedance of human limbs have been confined to single degrees of freedom. The mechanical impedance about the human elbow has been investigated by several researchers. Measurements confirm the common observation that arm impedance can be increased by "tensing" the arm muscles — simultaneously activating opposing muscles about the joints. Lanman [11] reported an incremental stiffness ranging from a minimum below 2 N-m/rad to a maximum as high as 400 N-m/rad. Hayes and Hatze [6] reported a minimum stiffness between 1 and 1.4 N-m/rad. Cannon and Zahalak [1] reported a maximum stiffness greater than 350 N-m/rad. These measurements show that the incremental stiffness about the elbow can vary over a range of at least two orders of magnitude.

Measurements of the incremental damping factor [11] show that it also varied, though over a smaller range. While it is tempting to conclude that the damping factor varies more slowly than the stiffness so as to preserve an invariantdamping ratio, Cannon and Zahalak's measurements indicate that both the limb's natural frequency and damping ratio vary with muscle activation [1]. Characterizing human elbow impedance as a linear, second-order system is, of course, an approximation. The mechanical impedance of the the elbow is a strong function of elbow angle as well as muscle activation (due, for example, to the nonlinear geometry of the attachment of the muscles to the skeleton). Recent experimental work by Murray [13] measured elbow impedance over the full physiological range of elbow angles and muscle activation levels. Theoretical analysis showed that a second-order model with parameters varying with muscle activation and elbow angle was unable to reproduce the experimental observations. The least complex competent characterization required a fourth-order model.

Multi-joint Arm Stiffness

Measurements of the mechanical impedance of the entire arm and hand are considerably more challenging. Even aside from non-trivial experimental difficulties, the number of parameters to be determined grows rapidly with the number of degrees of freedom. However, some interesting measurements have been made. In previously reported work using an earlier version of the apparatus described above, Mussa-Ivaldi et al. [14] measured the incremental stiffness at the hand. While normal human subjects held the handle of the manipulandum at a stable position in the workspace, small perturbations were applied. Measurements of the human's restoring force were made after the system had returned to steady state following the perturbation but before the onset of voluntary intervention by the subjects. Multivariate regression of measured forces onto the applied displacements yielded an estimate of the stiffness in the plane of the apparatus.

One interesting result of these experiments relates to the influence of feedback on the apparent mechanical behavior of a system. Normal human muscles are richly endowed with sensors which monitor the force, length and velocity of shortening of the muscle (and possibly other variables). That sensory information is brought to the spinal cord, where it is fed back to the motor neurons innervating the muscles, as well as passed on to higher levels in the central nervous system. The precise role of this neural feedback is still a topic of debate (see Loeb [12] for a recent comprehensive review) but it clearly influences the response of the limbs to mechanical perturbations — the impedance. Because it may arise, in part, from the behavior of active feedback circuits, the apparent stiffness of the hand need not be that of a passive system; it may contain active components. Active and passive components may be separated as follows [7,8]. The total apparent stiffness, K, may be decomposed into the sum of a symmetric component, K_{sym}, and an anti-symmetric component, K_{anti}.

$$K = K_{sym} + K_{anti}$$

$$K_{sym} = (K + K^t)/2 \qquad K_{anti} = (K - K^t)/2$$

The anti-symmetric commponent is active because the static force field it gives rise to has non-zero curl, which would imply that power could be extracted from the hand continuously and indefinitely by moving it along an appropriate closed path. Conversely, the symmetric component gives rise to a static force field with zero curl. It may therefore be associated with a potential function representing the apparent potential energy stored by displacing the hand from equilibrium. If K_{sym} is positive-definite, it represents an apparently passive behavior.

Because feedback pathways connect the muscles of one joint to the motions of another, there is no *a priori* restriction on the parameters of the apparent stiffness tensor. Given this, it is a remarkable fact (see figure 2) that the measured anti-symmetric component of the apparent stiffness is zero (to within the resolution of the experiments) and the measured symmetric component is positive-definite. Thus, despite the fact that the limb is actively controlled by neuro-muscular feedback, its apparent stiffness is equivalent to that of a completely passive system. In the light of Colgate's recent proof [3] that an apparently passive impedance is the necessary and sufficient condition for a stable actively-controlled system to remain stable on contact with an arbitrary passive environment, this experimental result strongly suggests that neural feedback in the human arm is carefully tuned to preserve stability under the widest possible set of conditions.

Changing Multi-joint Impedance

One of the more important facts confirmed by Mussa-Ivaldi et al.'s experimental measurements [14] is that the human operator's mechanical impedance can be modified voluntarily over a wide range. To investigate this effect, a preliminary experiment has been performed using the facility described above [5]. Human subjects were instructed to hold the handle of the manipulandum stationary at a location in its workspace. Then, using the simple impedance controller, the manipulandum was intentionally destabilized by simulating a negative viscous damper and a positive stiffness attached to the handle. Negative damping and positive stiffness result in unstable oscillations of the handle (and the arm holding it) about an equilibrium position.

To facilitate experimental measurements, the value of the negative damping was chosen so that the combined system — human plus manipulandum — was only slightly unstable. That is, if the human subject did not intervene, the exponential growth rate of the oscillation amplitude was slow relative to the period of the oscillations. Several values of the positive manipulandum stiffness were used to vary the period of the unstable oscillations. To initiate oscillations, the subject was instructed to move the handle a small distance. No further instructions were given. Responses of one subject for several values of manipulandum stiffness are shown in figure 3. In general, the responses consist of an oscillation which grows for a period of a second or more, and then stops growing or declines.

To analyze these experiments, consider oscillations in one direction only and assume that the oscillation amplitudes are small enough that a linear dynamic analysis is sufficiently accurate. Figure 4 shows a log-linear plot of the peak amplitude of each cycle vs. time from the onset of the response of one subject. Plots for oscillations in the X and Y directions and for two values of the manipulandum stiffness (200 N/m and 800 N/m) are shown. Note that up to about 1.2 to 1.5 seconds the logarithm of the peak amplitude grows approximately linearly with time. Up to this time, a reasonably accurate characterization of the data is to assume that the human's impedance parameters remained constant. Those parameters may be estimated as follows. The squared natural frequency of the complete system, w_n^2, is given by:

$$w_n^2 = (K_h + K_m)/(M_h + M_m)$$

where subscripts h and m refer to the human and the manipulandum respectively, and K and M are the effective stiffness and mass, respectively, in the direction considered. In this experiment there is no way the effective mass of the human and the manipulandum may change. If the effective stiffness of the human remained constant across experimental trials, squared natural frequency would be a linear function of manipulandum stiffness with a slope determined by the total effective mass of human and manipulandum.

Figure 5 shows a plot of squared natural frequency vs. manipulandum stiffness. The squared natural frequency was estimated by measuring the period of each oscillation cycle and computing the mean and standard deviaton[4]. Points corresponding to the three largest manipulandum stiffnesses are remarkably linearly related (correlation coefficient from a linear regression was 0.9999). The point corresponding to the lowest stiffness departs significantly from this regression line but also has the

[4] This method neglects the difference between damped and undamped natural frequency. The low damping justifies this approximation.

largest standard deviation. From the slope of the regression line the total mass was estimated to be 1.62 Kg. Subtracting the known manipulandum mass, the effective mass of the human subject was estimated to be 0.8 Kg — a plausible value. The human's natural frequency was estimated from the y intercept of the regression line to be 3 Hz — also a plausible value. The subject's stiffness was estimated from the x intercept of the regression line to be 568 N/m. This value is at the high end of the range of stiffnesses previously measured by Mussa-Ivaldi et al. [14].

The damping ratio of the complete system was determined from the log-linear plots of peak amplitude vs. time (figure 4). It was found to be similar under all conditions and had a value of -0.1. Given the total effective stiffness and total effective mass, the total effective viscosity of human and manipulandum was estimated and, subtracting the negative manipulandum viscosity, the human's effective viscosity was estimated to be 5.5 N-s/m. This yields an effective damping ratio for the human of 0.13. To the extent that this estimate is reliable, it indicates that the human arm is rather lightly damped.

Referring to figures 3 and 4, for a manipulandum stiffness of 200N/m, after about 1.2 to 1.5 seconds the amplitude of the oscillations clearly stops growing and/or declines. Similar patterns are seen for stiffnesses of 400 and 600 N/m, though the data for a stiffness of 800 N/m is inconclusive. This indicates that the subject is responding to the instability, probably by increasing the impedance of the arm. One interesting point is the length of time the subject takes to respond. Normal human sensorimotor response times are typically 250 ms. or less[5]. In contrast, the subject's impedance parameters appear not to change until more than 1200 ms. have elapsed. Extreme caution must be exercised when interpreting limited data from a preliminary experiment such as reported here; the variability of the observations within and across subjects has not been established. Nevertheless, with this caveat, it appears that parameter-adaptation in humans may require a relatively long time to initiate and the rate of change of parameters may be limited.

Concluding Remarks

In teleoperation, the interaction between humans and machines is more than merely an exchange of information — energetic interactions are at least as important. The key quantities characterizing energetic interactions between systems are the impedances at the points of interaction. A thorough quantitative investigation of human arm impedance has only just begun, but as the experiments reviewed above illustrate, already some surprising facts are emerging. The muscular actuators and neural feedback driving the arm would surely constitute an active system, yet experiments to date indicate that the impedance at the hand appears indistinguishable from that of a passive object. The impedance of the human arm is highly adaptable; as task conditions change, the human arm impedance changes. The experiments described above induced a clearly measurable change of impedance parameters. However, despite the human operator's manifestly formidable adaptive capabilities, the results suggest that the rapidity of human adaptation may be limited. Much further work is needed in this area.

Because impedance is the key to characterizing energetic interactions between systems, a means of varying impedance at the interface between human and machine is indispensible for investigating human/machine interactions. The experimental manipulandum described above was designed for that purpose. With no controller active the manipulandum has an extremely low intrinsic impedance — it is highly "backdrivable" — and the system has been used to quantify the kinematics of unrestricted planar hand movements. The manipulandum can exert a known, controlled force on the handle and the system has been used to investigate planar hand movements against a load, and to quantify the "disturbance response" — the mechanical impedance — of the arm and hand. It may also be programmed to oppose the motion of the handle with controlled, variable impedance. Varying the impedance of the manipulandum as a function of the position of the handle simulates programmable "virtual objects" in the workspace. This capability provides a powerful tool for investigating the interplay of human sensory and motor systems in object perception and manipulation.

[5] Visuo-motor response time is typically 250 ms. Audio-motor response time is typically 150 ms.

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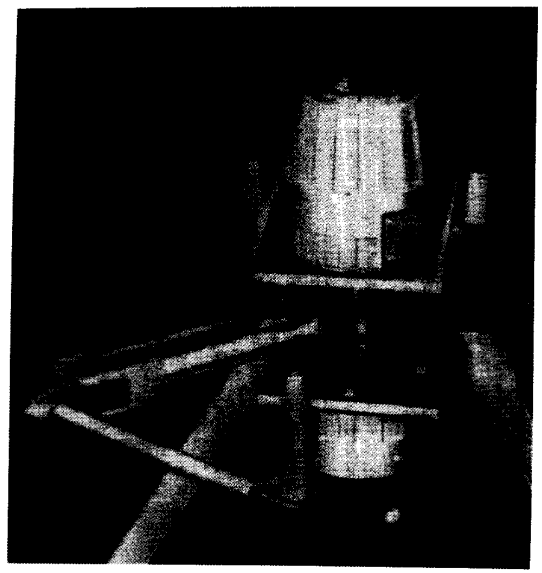

Figure 1. Experimental two-link manipulandum.

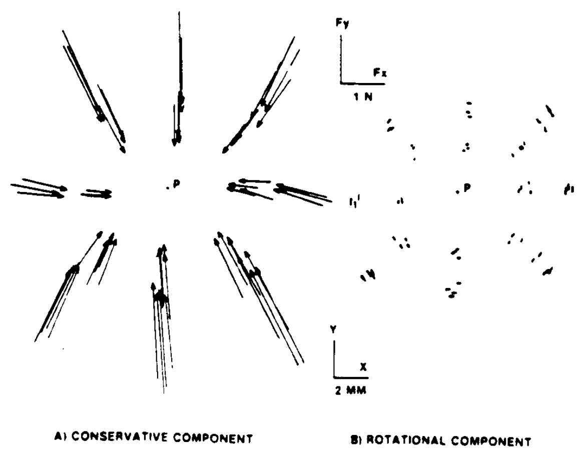

Figure 2. Components of the postural stiffness of the human arm

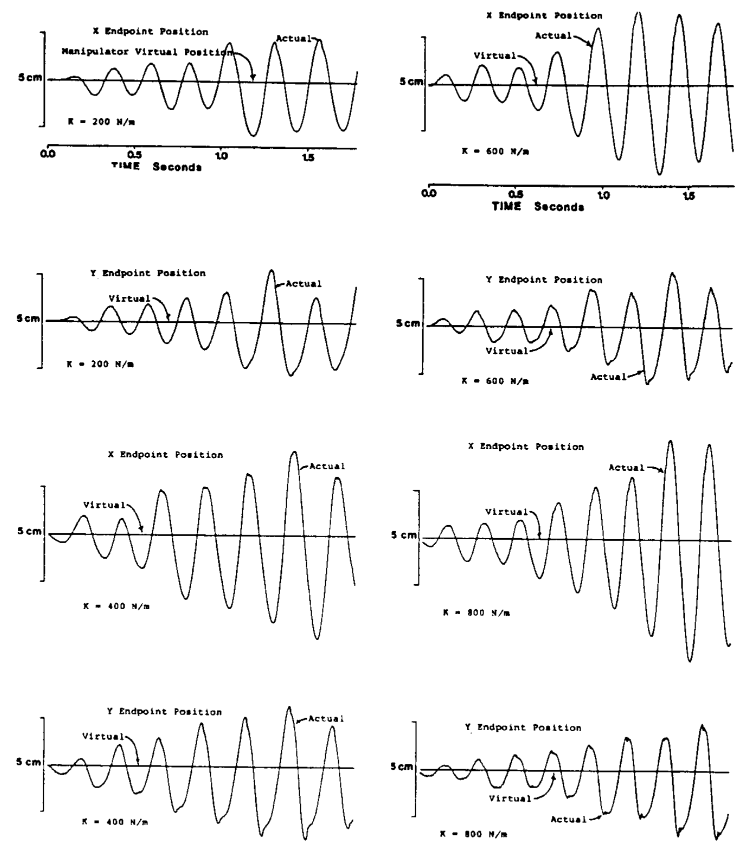

Figure 3. Time response of a human subject to an unstable manipulandum.

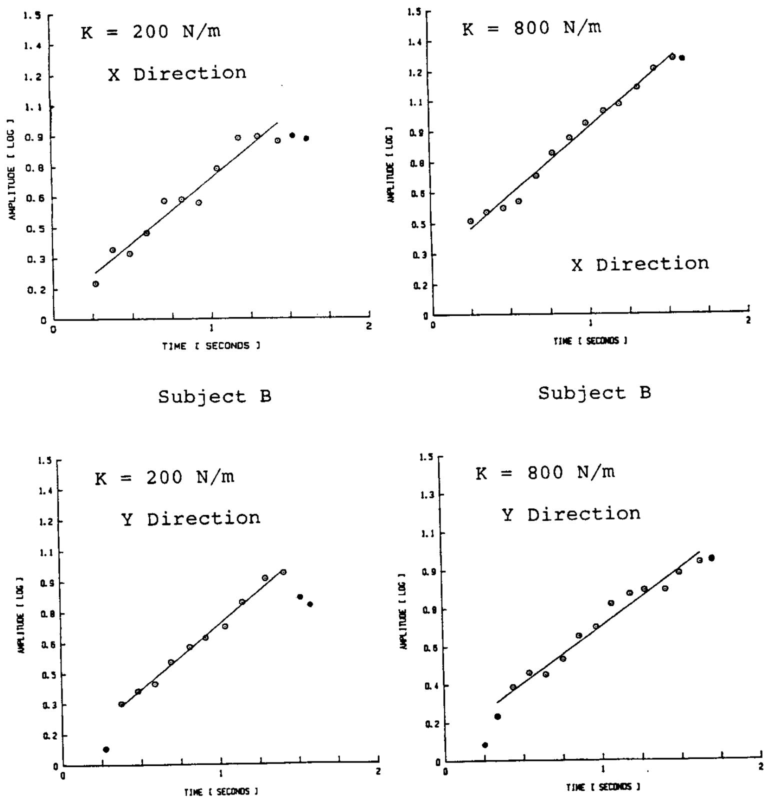

Figure 4. Log-linear plots of peak amplitude vs. time.

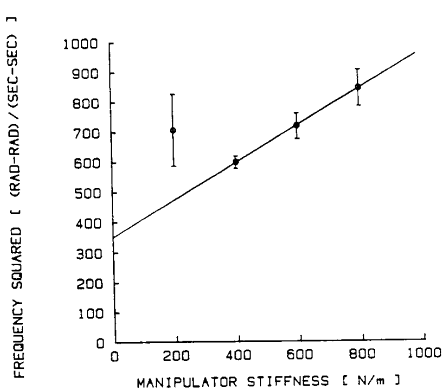

Figure 5. Squared natural frequencies vs. manipulandum stiffness.