

Manipulating Deformable Linear Objects: Manipulation Skill for Active Damping of Oscillations

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Abstract

While handling deformable linear objects (DLOs), such as hoses, wires or leaf springs, with an industrial robot at high speed, unintended and undesired oscillations that delay further operations may occur. This paper analyzes oscillations based on a simple model with one degree of freedom (DOF) and presents a method for active open-loop damping. Different ways to interpret an oscillating DLO as a system with 1 DOF lead to translational and rotational adjustment motions. Both were implemented as a manipulation skill with a separate program that can be executed immediately after any robot motion. We showed how these manipulation skills can generate the needed adjustment motions automatically based on the readings of a wrist-mounted force/torque sensor. Experiments demonstrated the effectiveness under various conditions.

1. Introduction

Manipulating deformable linear objects (DLOs), such as hoses, wires, or leaf springs with an industrial robot system involves coping with many uncertainties. At the start of each manipulation operation, it is hard to determine the exact shape of a DLO. In many situations, the DLO is even oscillating. Both shape and oscillation depend on the object's manipulation history and may vary for each individual DLO. In addition, they are influenced by the inevitable action of gravity, inertia, and contact forces. Unfortunately, these variations are typically very difficult to predict with sufficient precision. Thus, purely model-based approaches are likely to fail in real world situations. In order to compensate for these uncertainties, an obvious approach is based on the use of sensors.

Many researchers investigated manipulation tasks involving deformable objects. Kraus and McCarragher

used a wrist-mounted force/torque sensor to insert a bending beam into a narrow slit [6], Nakagaki et al. used a force/torque sensor and a vision system to insert a wire into a hole under friction [7]. Inspired by Hasegawa [3], Henrich et al. [1], [4], [8] and Schlechter [9] developed a complete set of force-based manipulation skills for changing a single contact state between a DLO and its polyhedral environment.

Although the dynamic effects of deformable objects cannot be neglected, especially when the objects are moved at high speeds by a robot arm, the effects of oscillations were not taken into account in the work described above. As shown in Figure 1, the uncertainty resulting from oscillation may cause failure during the insert-into-hole operation. If these oscillations caused by inertia can be depressed during all motions or eliminated as soon as possible after each motion by a separate manipulation skill, previous work can be reused as it is.

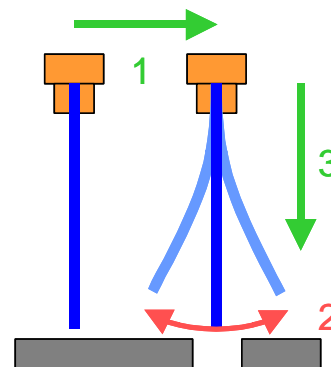


Figure 1: A quick operation (1) causes vibration (2), resulting in uncertainty and failure, e.g., when inserting a DLO into a hole (3)

Oscillation reduction of flexible structures has been a research topic for many researchers: Chen et al. have

reviewed previous work and presented a passive, open-loop approach for vibration-free handling of deformable beams [2]. Similar ideas dealing with rigid bodies can be found in [5] and [10]. However, application of the method presented in [2] is limited to relatively simple trajectories and assumes a stable workpiece at the start of each motion. Considering the complex manipulations involved in practical situations, such as avoiding obstacles, picking-up, insert-into-hole, etc., the stable start condition cannot be satisfied easily.

With respect to manipulation, only oscillations that may cause failure of the next operation need to be eliminated. Yue discussed a purely model-based method to reduce the vibration of DLOs using adjustment motions [11]. Since the effectiveness depends on how well the model matches the real DLOs and how well the simulated robot operation matches the real operation, it is possible to design a nearly perfect adjustment motion for one given situation, which is most likely to fail in all other situations.

Therefore, resuming the work of Yue and Henrich [12], force/torque sensor-based manipulation skills to actively damp DLO oscillations were developed. These manipulation skills can be executed right after any robot motion. They perform an open-loop adjustment motion, which is generated automatically inside the manipulation skill by analyzing data from a force/torque sensor mounted on the robot's wrist. In order to reduce the undesired oscillations to an acceptable level in lots of different situations, a simple, quite general model of an oscillating 1-dimensional mass/spring system supported by sensor data is used.

The rest of the paper is organized as follows: In Section 2, the theoretical adjustment motion needed for an oscillating mass spring system with only one degree of freedom is analyzed. Section 3 describes how the parameters for the adjustment motion can be obtained from sensor data. In Section 4, two possible ways of adopting the calculations to an oscillating DLO are introduced. Finally, some experimental results are presented in Section 5.

2. Active Damping of a 1 DOF Mass/Spring System

First, a system with only one degree of freedom (1 DOF) is considered. It consists of a mass m fixed to the end of a linear spring with stiffness k and damping coefficient c . The spring is held by the robot. The gripper

position is given as a function of time $x_G(t)$; the position of the mass is $x_M(t)$ (Figure 2).

In a first phase, the gripper position remains unchanged. Considering the balance of forces, the position $x_{M,i}(t)$ of the mass is the solution to the following differential equation:

$$m \cdot \ddot{x}_{M,i} + c \cdot \dot{x}_{M,i} + k \cdot x_{M,i} = k \cdot (x_G(0) + d)$$

(d is the distance between the gripper and the mass at rest).

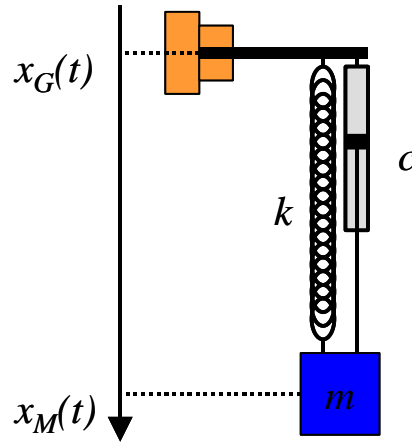


Figure 2: Mass/spring system with one degree of freedom. A mass m is suspended to a spring with stiffness k and damping c

If the mass is released at time 0 at a distance x_0 from its position at rest, the initial conditions for the solution are given as:

$$\begin{aligned} x_{0,1}(0) &= x_G(0) + d + x_0 \\ \dot{x}_{0,1}(0) &= 0 \end{aligned}$$

Assuming low damping, the desired solution is:

$$\begin{aligned} x_{M,i}(t) &= x_G(0) + d \\ &+ x_0 \cdot e^{-a \cdot t} \left(\cos(\mathbf{w} \cdot t) + \frac{\mathbf{a}}{\mathbf{w}} \sin(\mathbf{w} \cdot t) \right) \\ \mathbf{a} &= \frac{c}{2m} \quad \mathbf{w} = \sqrt{\frac{k}{m} - \frac{c^2}{4m^2}} \in R \end{aligned}$$

In a second phase, the oscillations from the first phase are damped actively. Therefore, the gripper is moved between some points in time t_0 and t_1 . It is at rest before t_0 and after t_1 . The motion is a (co)sine function with the same period \mathbf{w} as the workpiece oscillation, with the

amplitude x_{\max} and the phase \mathbf{j} , representing the point in time t_0 :

$$x_G(t) = x_{\max} \cdot \cos(\mathbf{w} \cdot t - \mathbf{j})$$

$$t_0 = \frac{\mathbf{j}}{\mathbf{w}} \text{ and } t_1 = t_0 + n \cdot \frac{\mathbf{p}}{\mathbf{w}} \text{ with } n \in \mathbb{N}$$

This implies that $x_G(t) = x_{\max}$ for all $t \leq t_0$ and $t \geq t_1$.

Of course, the gripper motion disturbs the balance of forces and the motion of the suspended mass reacts to the gripper motion. Similar to the undisturbed case, the mass's resulting position $x_{M,2}(t)$ is the solution to the following differential equation:

$$m \cdot \ddot{x}_{M,2} + c \cdot (\dot{x}_{M,2} - \dot{x}_G) + k \cdot (x_{M,2} - x_G - d) = 0$$

Replacing x_G by the above chosen motion type, this leads to:

$$m \cdot \ddot{x}_{M,2} + c \cdot \dot{x}_{M,2} + k \cdot x_{M,2}$$

$$= -c \cdot x_{\max} \cdot \mathbf{w} \cdot \sin(\mathbf{w} \cdot t - \mathbf{j})$$

$$+ k \cdot (x_{\max} \cdot \cos(\mathbf{w} \cdot t - \mathbf{j}) + d)$$

Of course, the mass's motion and speed are continuous at t_0 .

$$x_{M,1}(t_0) = x_{M,2}(t_0)$$

$$\dot{x}_{M,1}(t_0) = \dot{x}_{M,2}(t_0)$$

From those initial conditions, the following solution is obtained:

$$x_{M,2}(t) = e^{-a \cdot t}$$

$$(x_{\max} \cdot \cos(\mathbf{w} \cdot t) \cdot (A_1 \cdot \sin(\mathbf{j})) + A_2 \cdot \cos(\mathbf{j}))$$

$$- x_{\max} \cdot \sin(\mathbf{w} \cdot t) \cdot (A_1 \cdot \cos(\mathbf{j})) + A_2 \cdot \sin(\mathbf{j}))$$

$$+ x_0 \frac{a + \mathbf{w}}{\mathbf{w}}$$

$$+$$

$$(x_{\max} \cdot \cos(\mathbf{w} \cdot t) \cdot (B_1 \cdot \cos(\mathbf{j})) - B_2 \cdot \sin(\mathbf{j}))$$

$$+ x_{\max} \cdot \sin(\mathbf{w} \cdot t) \cdot (B_1 \cdot \sin(\mathbf{j})) + B_2 \cdot \cos(\mathbf{j}))$$

$$+ d)$$

$$A_1 = \frac{\mathbf{w} \cdot (\mathbf{a}^2 + 2 \cdot \mathbf{w}^2)}{\mathbf{a} \cdot (\mathbf{a}^2 + 4 \cdot \mathbf{w}^2)}; A_2 = \frac{\mathbf{w}^2}{(\mathbf{a}^2 + 4 \cdot \mathbf{w}^2)}$$

$$B_1 = \frac{\mathbf{a}^2 + 5 \cdot \mathbf{w}^2}{\mathbf{a}^2 + 4 \cdot \mathbf{w}^2}; B_2 = \frac{2\mathbf{w}^3}{\mathbf{a} \cdot (\mathbf{a}^2 + 4 \cdot \mathbf{w}^2)}$$

The point in time t_0 (\mathbf{j}) is chosen in a way that the mass no longer oscillates at t_1 :

$$\dot{x}_{M,2}(t_1) = 0$$

$$\ddot{x}_{M,2}(t_1) = 0$$

This system of equations is solved with respect to \mathbf{j} and x_{\max} :

$$\mathbf{j} = \mathbf{p} - \arctan\left(\frac{2 \cdot \mathbf{w}^3}{\mathbf{a} \cdot (\mathbf{a}^2 + 3 \cdot \mathbf{w}^2)}\right)$$

$$x_{\max} = x_0 \cdot \frac{e^{-\frac{a}{\mathbf{w}} \mathbf{j}} \cdot |\mathbf{a}| \cdot \sqrt{\mathbf{a}^2 + 4 \cdot \mathbf{w}^2}}{e^{\frac{n \cdot \mathbf{a}}{\mathbf{w}} \mathbf{p}} - 1} \cdot \mathbf{w}^2}$$

With decreasing damping c , the phase \mathbf{j} and the amplitude x_{\max} converge:

$$\lim_{c \rightarrow 0} \mathbf{j} = \lim_{a \rightarrow 0} \mathbf{j} = \frac{\mathbf{p}}{2}$$

$$\lim_{c \rightarrow 0} x_{\max} = \lim_{a \rightarrow 0} x_{\max} = \frac{2 \cdot x_0}{n \cdot \mathbf{p}}$$

The free oscillation, the gripper motion and the resulting damped motion of the mass are illustrated in Figure 3.

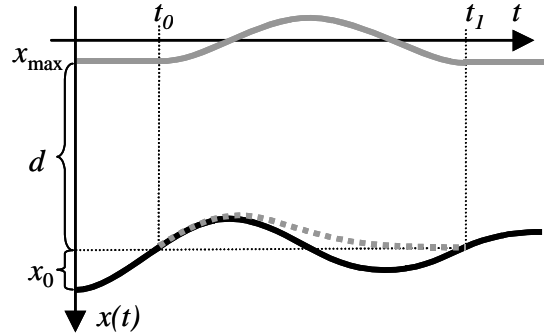


Figure 3: The free oscillation from phase 1 (black), the gripper motion (gray) and the resulting damped motion of the mass (gray, dashed)

3. Parameter Determination from Sensor Data

Using the theory about the adjustment motion necessary to actively damp the oscillation, the needed parameters are determined using a wrist-mounted force/torque sensor. The force measured by a non-calibrated sensor is given by:

$$F(t) = k \cdot (x_{M,1}(t) - x_G(0) - d) + F_{offset}$$

F_{offset} is a constant offset. If the sensor is calibrated and if the motion direction of the mass is parallel to the gravity vector, this offset is equal to the weight of the mass.

The phase of the movement is equal to the phase of the force and can be determined by the first extremum in the force signal. Let us call this extremum $F(0)$. Thus, the following two extrema are $F(T/2)$ and $F(T)$ with T the period of the motion. Using these, ω can be calculated as $2\pi/T$. The force-offset F_{offset} and the damping coefficient a can be found from the difference between two consecutive extrema as follows:

$$\begin{aligned} F(0) - F(T) &= k \cdot ((x_{M,1}(0) - x_G(0) - d) \\ &\quad - (x_{M,1}(T) - x_G(0) - d)) \\ &= k \cdot x_0 \cdot (1 - e^{-aT}) \\ &= (F(0) - F_{offset}) \cdot (1 - e^{-aT}) \end{aligned}$$

Thus,

$$\begin{aligned} \frac{F(0) - F_{offset}}{F(T) - F_{offset}} &= e^{aT} \\ \Leftrightarrow a &= \frac{1}{T} \cdot [\ln(F(0) - F_{offset}) - \ln(F(T) - F_{offset})] \end{aligned}$$

Analogously, for $F(0) - F(T/2)$,

$$a = \frac{2}{T} \cdot \left[\ln(F(0) - F_{offset}) - \ln\left(F_{offset} - F\left(\frac{T}{2}\right)\right) \right]$$

thus:

$$F_{offset} = \frac{F(0)F(T) - F\left(\frac{T}{2}\right)^2}{F(0) + F(T) - 2F\left(\frac{T}{2}\right)}$$

Now, as the robot motion is started right after the occurrence of the third extremum, the displacement x_0 at this point in time is still needed in order to calculate the adjustment motion. Obviously x_0 can be obtained from

$$x_0 = \frac{F(T) - F_{offset}}{k}$$

The stiffness k of the spring can be found from $k = m(\alpha^2 + \omega^2)$ if the mass m is known. Of all parameters,

the mass m can be determined most easily, in some situations even online ($F_{offset} = mg$).

4. Active Damping of an Oscillating DLO

In this section, a real oscillating DLO is considered. For simplification, a homogenous leaf spring of length L and mass m is assumed. Only the dominant mode of oscillation is regarded. The vibration is supposed to be free within a plane perpendicular to gravity. Under this last assumption, gravity force can be omitted. Using a calibrated sensor, the mass of the spring as well as the location of the center of gravity, which may lead to the spring length, can be determined via gravity force and moment. In this situation, all parameters for the active damping can be obtained on-line from sensor data!

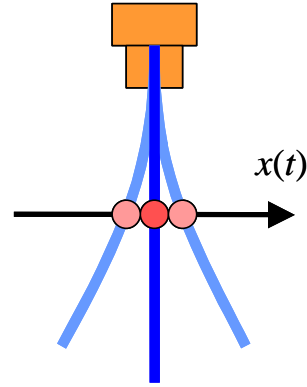


Figure 4: Leaf spring oscillation approximated by 1 DOF translational oscillation of its center of mass

For small oscillation amplitudes, the spring may be regarded as a translational 1 DOF mass/spring system with its complete mass concentrated at the center of mass (Figure 4). The adjustment motion is parallel to the spring's orientation at rest. This type of adjustment motion is called *translational*. All calculations can be adopted from Sections 2 and 3 ($d = 0$). As the moment can more easily be measured accurately, the force can be determined by the spring length L :

$$F(t) = \frac{M(t)}{L/2}$$

On the other hand, the spring may be regarded as an undeformable beam of mass m fixed to a torsion spring (moment linearly dependent on deflection angle) with stiffness k' ($[k'] = \text{Nm/rad}$) and damping c' ($[c'] = \text{Nm/(rad/s)}$) held in the gripper. Thus, the rotational center lies at the end of the gripper. The gripper

orientation angle is given as a function of time $\mathbf{q}_G(t)$ and the orientation angle of the beam is $\mathbf{q}_M(t)$ (Figure 5).

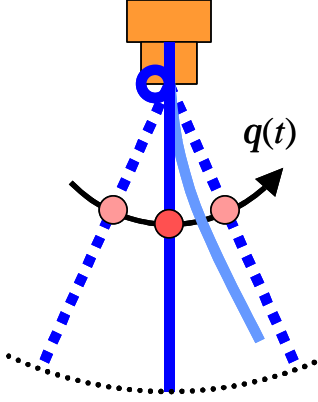


Figure 5: Leaf spring oscillation approximated by 1 DOF rotational oscillation $\mathbf{q}(t)$ of an undeformable beam fixed to a torsion spring held by the gripper

A beam of mass m and length L can be modeled as N equidistant (distance= L/N) small masses (mass= m/N). Thus, with N approaching infinity, the inertial moment of the beam can be found as follows:

$$\begin{aligned} M_{inertia} &= \lim_{N \rightarrow \infty} \sum_{i=1}^N \frac{m}{N} \left(\frac{L}{N} i \right)^2 \ddot{\mathbf{q}}_M \\ &= \lim_{N \rightarrow \infty} \frac{mL^2 \ddot{\mathbf{q}}_M}{N^3} \frac{N(N+1)(2N+1)}{6} \\ &= \frac{mL^2}{3} \ddot{\mathbf{q}}_M =: m' \ddot{\mathbf{q}}_M \end{aligned}$$

Substituting this into the equilibrium of moments, the orientation $\mathbf{q}_M(t)$ of the beam can be found as the solution to the following differential equation:

$$m' \ddot{\mathbf{q}}_M + c' (\dot{\mathbf{q}}_M - \dot{\mathbf{q}}_G) + k' (\mathbf{q}_M - \mathbf{q}_G) = 0$$

All calculations from Sections 2 and 3 can be adopted by simply changing x into \mathbf{q} , F into M , adding primes ($'$) to the coefficients m , c and k , and finally substituting $m' = mL^2/3$. The adjustment motion based on these assumptions is called *rotational*.

5. Experimental Results

The manipulation skills based on both the translational and the rotational adjustment motion were implemented using Adept's V+ robot language on a Stäubli RX 130 equipped with a wrist-mounted force/torque sensor 90M31A from JR3. The adjustment motions were lim-

ited to one period of the workpiece oscillation ($n = 2$). This is the fastest possible adjustment if the DLO is to be stabilized at the originally intended position. Sensor data is processed using an appropriate onboard low-pass filter with a cutoff frequency of 7.8 Hz and a delay of around 130 ms in order to locate the extrema with a simple, ordinary procedure. In the experiments a steel leaf spring of length $L = 53$ cm with $18 \text{ mm} \times 0.5 \text{ mm}$ cross section and mass $m = 35$ g, an aluminum beam of length $L = 100$ cm with $15 \text{ mm} \times 2 \text{ mm}$ cross section and mass $m = 80$ g, and a brass beam of length $L = 73$ cm with $10 \text{ mm} \times 2 \text{ mm}$ cross section and mass $m = 118$ g were used as workpieces. The first 3 cm of all DLOs were used to hold them with the robot gripper. Let l be the perpendicular DLO endpoint deflection from its position at rest. Figure 6 shows that the average residual relative amplitude of the endpoint deflection (l/L [%]) over ten experiments depended on the beginning amplitude for both kinds of adjustment motions and the different sample workpieces.

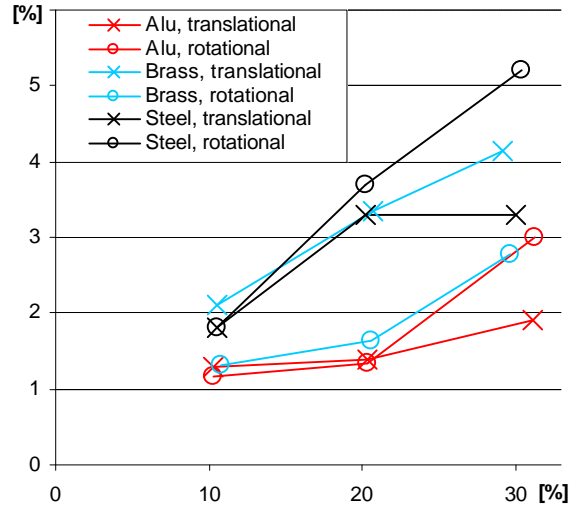


Figure 6: Average residual relative amplitude [%] of the endpoint deflection over ten experiments depended on the beginning amplitude for both kinds of adjustment motions and the different workpieces

The duration of an adjustment motion depended on the period of the oscillation plus a constant delay (0.5 s) to assure that there were no remaining inertial effects from robot deceleration other than a proper DLO oscillation. Thus, for the aluminum beam, an active damping manipulation skill took 2.4 seconds, for the brass beam it required 2.3 seconds and for the steel ruler 2.7 seconds. On the other hand, the decay time for a decrease of oscillation amplitude from around 10% down to about

2% without adjustment motion was around 30 seconds for all three sample objects; decay time to less than 1% deflection was longer than 50 seconds.

In the current implementation, the sensor is not calibrated and thus the manipulation skills require the length L and mass m of the workpiece as parameters. Since the presented model does not exactly fit reality, it is possible (and may be useful) to fine-tune the adjustment motions for special situations (expected range of amplitudes, materials, ...) using a correction factor or non-complex term for the amplitude x_{\max} of the adjustment motion.

6. Summary and Future Work

In this paper, workpiece oscillations were analyzed based on the simple model of a mass/spring system with one degree of freedom. Furthermore, a strategy for active damping of these oscillations was presented. It was shown how the parameters for the active damping can be obtained from sensor data. As a result of different methods to approximate the behavior of a DLO using this 1 DOF model, two types of adjustment motions, translational and rotational, were found. Both were implemented as manipulation skills. In experiments, the effectiveness of these easily and transparently attachable adjustment motions was shown. In the near future we will try to integrate the influence of gravity, thus allowing for other planes of oscillation. The possibilities of determining all parameters (such as: plane of oscillation, direction for the translational adjustment motion, ...) on-line will be investigated, perhaps implementing a calibrated sensor.

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