Applying Acceleration Compensation to Minimize Liquid Surface Oscillation

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Abstract

In the present article, an open-loop method on the basis of *Acceleration Compensation* to reduce liquid surface oscillation generated during a high-speed transfer will be described. In order to suppress undesirable liquid vibration effects, a new simple and effective methodology consisting of adapting the gripper orientation is proposed. We assume that as long as there is no relative motion between the liquid and the container, the motion will be slosh-free. To accomplish this objective, the maximum acceleration in every time-instant has to be considered in our computation. This method operates basically in maintaining the normal of the liquid surface opposite to the entire systems acceleration until the completion of the transportation. Experimental results using a manipulator KUKA-KR16 will be demonstrated to validate the effectiveness of our approach.

1 Introduction

During a high-speed transfer, undesirable vibrations may arise on the liquid surface in an open container, and causing possibly degradations in the product quality or even sometimes, producing contaminations in its surrounding environment. This is because of the variation in the container's acceleration, which causes relative motion between the liquid and its container. Hence, it would be beneficial that such motions are accomplished with the utmost delicacy to prevent disturbances originated from undesired oscillations. One typical example is the casting process, where the pouring and the transportation of open containers filled with hot molten steel or glass has to be executed with exact positioning as well as in high-speed to avoid any undesired cooling of the melted material. In this case, the entire process must be performed without spilling-over the content, first, to keep the safety of workers and second, to prevent any contamination in the working area.

The sloshing-effect can cause problems as well to other applications such as the transportation of special chemical liquid products, where the avoidance of any possible agitation would be convenient. For example in the case of launch vehicles with partially filled tanks containing highly flammable fuels [Kim and Choi, 2000]. Here, any inadequate perturbation may induce first of all, instability in the maneuvering control system and second, the possibility of fire or explosion hazards. Another interesting example is [Reyhanoglu, 2003; Fuhrmann, 2003], where the moving liquid within a partially filled tank may affect the control of commercial vehicles carrying liquid cargo and generating possible hazardous rollover effects.

One inefficient solution to solve the problems described above is the reduction of the acceleration during motion, until the liquid can be safely transported to the programmed destination. This leads to a tedious trial-and-error teaching procedure and implies also an enormous increase in the cycle time. Hence, the result is a slowing down of the entire production process.

Diverse techniques using special devices such as baffles and dampers offer other possible solutions as well. These methods attempt to attenuate the intensity of slosh effect with the introduction of passive elements inside the container, such as the insertion of grilles to divide the large interior of the container into smaller compartments. But as a drawback, this adds only unnecessary weight and complexity to the entire system.

On account of this, a further solution addressed to slosh suppression is the implementation of active feedback control. [Ramírez and Fliess, 2002] introduced a Generalized PI controller, where the liquid height and the armature input voltage of the DC motor acting on the container's transportation belt has been measured and used as input and output parameters for the controller.

To attenuate the response of the fluid due to an external disturbance acting on the tank, another interesting approach using two different active feedback control methods has been presented by [Acarman and Özgüner, 2003]. For the control, the first method used surface pressure and the second technique employed a flap actuator mounted on the fluid surface; here the LQG synthesis technique has been applied.

Apart from the inconvenience of high cost and complexity, there are applications where the installation of sensors could be inappropriate due to the physical properties of the transfer materials. Materials such as corrosive liquids or molten metal at high temperature, which could shorten the sensor's lifetime or cause irreversible damaging. In addition, due to the fluid high vibration frequencies, most of common sensors found in the market are not quick enough to measure properly the sloshing and another drawback is the laborious calibration procedure of the sensor elements.

Therefore, another alternative solution is the open loop control via the acceleration reference [Grundelius, 2000]. This work proposes an iterative learning control approach and attempts to find an open loop acceleration reference using the obtained results in the next iteration, and thus, repeating the same procedure until the desired outcome has been accomplished.

Important works proposed by [Yano and Terashima, 2001; Noda *et al*., 2004] adopt strongly the Hybrid Shape Approach to design an advanced control system for automatic pouring processes. The behaviour of sloshing in the liquid container is approximated by the pendulum-type model. In [Yano and Terashima, 2001], a robust controller based on H-Infinity control theory was established to reduce the end-residual vibration in a liquid container transfer and furthermore, an additionally rotational motion control was adopted to permit the sloshing suppression during the transfer acceleration/deceleration phase.

Concerning a similar problem, [Feddema, *et al*., 1996; Feddema, *et al*., 1997] demonstrated that using input shaping techniques can suppress liquid oscillation in an open container, whereas the container was tilted in a way that the normal of the liquid surface stays opposite to the accelerations of the entire system, thus allowing the elimination of the remaining vibrations.

The Active Acceleration Compensation technique was firstly proposed by [Graf and Dillmann, 1997]. To perform and to demonstrate this approach, a Stewart platform (parallel kinematics) was mounted on a mobile robot. It was controlled in a way that any external forces and torques acting on the transferred object can be compensated. A similar work was established by [Decker *et al*., 2001; Dang and Ebert-Uphoff, 2004; Dang, 2002]. The basic principle of this study is based on the emulation of a virtual pendulum to actively compensate disturbances of the acceleration input.

Another approach based on Acceleration Compensation method to reduce shear force was presented by [Chen *et al*., 2006; Zimmermann *et al*., 2006]. It takes additionally into account the maximum acceleration and speed permissible in each actuator of the robot. On the basis of this same principle, the following work shortly described here, provides a feasible solution employing a serial robot kinematics and path planning methods. Undesired sloshing effects in a liquid container produced during a high-speed transfer process can be enormously reduced, too. Furthermore, this new approach neither requires any complex fluid modelling nor the help of an external sophisticated sensing system or vibration feedback information.

In the following sections, a new efficient solution based on the acceleration compensation will be proposed and thoroughly analyzed for a better understanding. Experimental results of a prototypical implementation of our methods will be shortly demonstrated.

2 The "Waiter-Tray" Model

In the preceding sections, the problem of undesirable liquid surface oscillation due to container acceleration was discussed and some approaches have been briefly introduced.

The main idea of this work is to adapt the orientation of the robot's end-effector, which holds a liquid container, in such a manner that undesired sloshing effects can be minimized during and until the end of the programmed motion.

This move mechanism can be observed in humans, carrying fragile objects very fast from one location to another, e.g. a waiter walking in a restaurant holding a tray full of plates and glasses, without throwing them away and without spilling over any liquid. Probably without knowing it, the waiter is trying to incline the tray in such a way that unwanted accelerations and forces acting on the carried objects are avoided.

Our approach is very similar: while the waiter is orienting his hand to tilt the tray in an appropriate manner, the orientation of the robot's end-effector is adapted as well to compensate the undesired acceleration side effects [Figure 1].

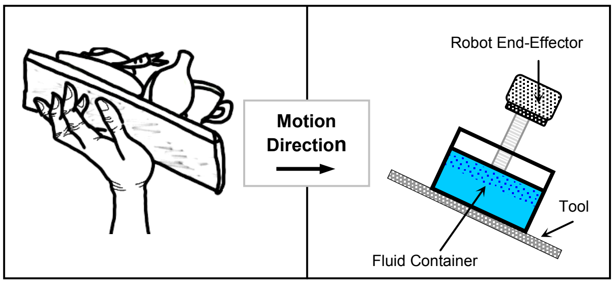


Figure 1. Robot arm simulates a human hand.

2.1 Problem Statement and Assumptions

As described in Section 1, our goal is to suppress undesirable sloshing effects generated inside of the liquid container within a reduced time interval. An important assumption of slosh-free movement is that there is no relative motion between the container and the liquid. To accomplish this objective, the maximum acceleration in every time-instant has to be taken into the computation. In other words, the proposed method operates basically by maintaining the normal of the liquid surface opposite to the acceleration of the entire system until the completion of the transportation.

To simplify the model analysis, several assumptions are considered:

- The fluid is incompressible and inviscid,
- The shear stress is zero,
- The motion is considered to be irrotational,
- Fluid in rigid-body motion is assumed (no deformation),
- External disturbances are negligible.

2.2 Motion Equation

When a mass of fluid undergoes rigid-body motion, then a fluid particle retains permanently its identity which indicates that no deformation of the fluid elements is present. Deriving from Newton's second law of motion, the general equation of motion for a fluid with non-existence of shear stresses can be defined as follows:

$$(\rho \vec{g} - \nabla p) = \rho \vec{a}, \tag{1}$$

with ρ representing the density, $\vec{g}$ the local gravity vector, ∇p the gradient of pressure and $\vec{a}$ the acceleration.

Since the gravity vector points downward (in the negative z-direction, see Figure 2), the component equations in rectangular coordinates are

$$\begin{aligned} -\frac{\partial p}{\partial x} &= \rho a_x && x \text{ direction} \\ -\frac{\partial p}{\partial y} &= \rho a_y && y \text{ direction} \\ \rho g_z - \frac{\partial p}{\partial z} &= \rho a_z && z \text{ direction} \end{aligned} \tag{2}$$

These equations construct the basis for our acceleration compensation approach.

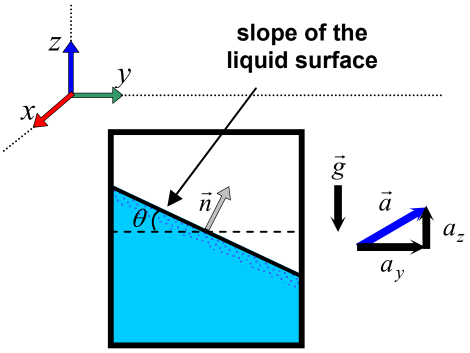
2.3 Liquid in Rigid-Body Motion with Linear Acceleration

First, an open container of liquid is considered. It translates along a straight path with an acceleration $\vec{a}$ as illustrated in Figure 2. Since $a_x = 0$, the pressure gradient in the x-direction from (2) is zero ($\partial p/\partial x = 0$). In the y- and z-directions we get:

$$\begin{aligned} -\frac{\partial p}{\partial y} &= \rho a_y, \\ \frac{\partial p}{\partial z} &= -\rho (g + a_z). \end{aligned} \tag{3}$$

Now the change in pressure between two closely spaced points located at y and z is considered. Thus $y+dy$ and $z+dz$ can be expressed as

$$dp = \frac{\partial p}{\partial y} dy + \frac{\partial p}{\partial z} dz \tag{4}$$



$\vec{n}$ = normal to the liquid surface
θ = tilting angle
$\vec{g}$ = gravity

Figure 2. Free-body diagram.

or in terms of the results from (3):

$$dp = -\rho a_y \, dy - \rho (g + a_z) \, dz. \tag{5}$$

If we consider that the pressure is constant, then $dp = 0$. From (5) it follows that the slope of the liquid surface [Figure 2] is given by the relationship

$$\frac{dz}{dy} = -\frac{a_y}{(g + a_z)}, \tag{6}$$

where dz/dy is equivalent to $\tan(\theta_y)$. Therefore, we obtain

$$\theta_y = \tan^{-1}(a_y / (g + a_z)), \tag{7}$$

where θ_y is the optimal tilting angle of the TCP (Tool Center Point) due to a y-horizontal movement. Additionally, to guaranty that there is no relative motion between the fluid and the container, the accelerations in (7) have to maintain the maximum value at every time-instant. Accordingly, we can compute the value of θ_x as well. Note that the tilting angles are functions of each time-instance t:

$$\begin{aligned} \theta_x(t) &= \tan^{-1}(a_x(t) / (g + a_z(t))), \\ \theta_y(t) &= \tan^{-1}(a_y(t) / (g + a_z(t))). \end{aligned} \tag{8}$$

This is the same result as obtained in [Chen *et al.*, 2006]. Notice that using the same principle, undesired fluid sloshing effects can be suppressed. In the ideal case, if the robot controller adapts the container orientation faithfully according to (8), then the fluid surface is guaranteed to keep its flatness and thus, its slope will remain permanently parallel to the bottom of the corresponding container [Figure 3 and 4].

2.4 Compensation with maximum acceleration

As it can easily be seen from (8), a fast increasing acceleration will lead to fast changes of the tilting angle. Because modern robots are highly dynamic machines, the

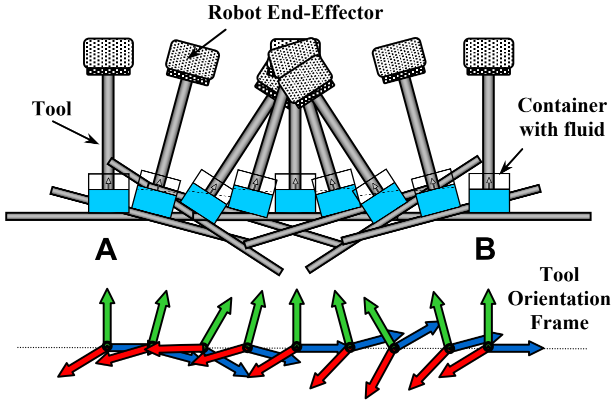


Figure 3. Trajectory of robot TCP with compensated tilting angles.

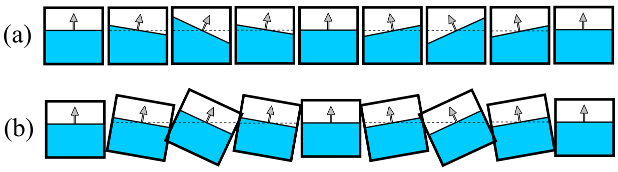


Figure 4. Trajectory of liquid container (a) without and (b) with compensated tilting angles.

acceleration is ramped up very fast to the maximum value (trapezoidal motion profile for the velocity) leading therefore to significant high values of jerk. This fast change of orientation cannot be achieved with a standard robot, because of severe dynamic performance limits, such as maximum motor torque and maximum gear load. One possible solution to overcome this problem is to restrict the maximal jerk and therefore, the ramping up of the acceleration.

However, in such a case the overall cycle time would increase, which is not useful, since the reduction of the cycle time is one of the primary goals of our study.

In the following section, a method for finding a suitable value of the tilting angle without altering the acceleration profile will be discussed in more detail.

3 Optimization Filter

3.1 Average-Filter

In general, different kinds of motion profiles exist, such as triangular, trapezoidal with constant phase, S-curve and S-curve velocity with constant phase profile. For most robotic applications, a trapezoidal velocity profile is utilized by the motion controller to command the motor driver to achieve an optimal high speed movement. This trapezoidal velocity profile has the disadvantage of having “critical switching-zones”, where the acceleration abruptly changes [Figure 5].

Of course, due to computational or mechanical filtering effects these changes appear smoother in reality. Recall that the main idea of the proposed approach is based on using the Cartesian acceleration of the TCP as the principal information to determine the optimal tilting angles. Therefore, it is possible to filter and smooth the computed reference curve of the optimal tilting angles.

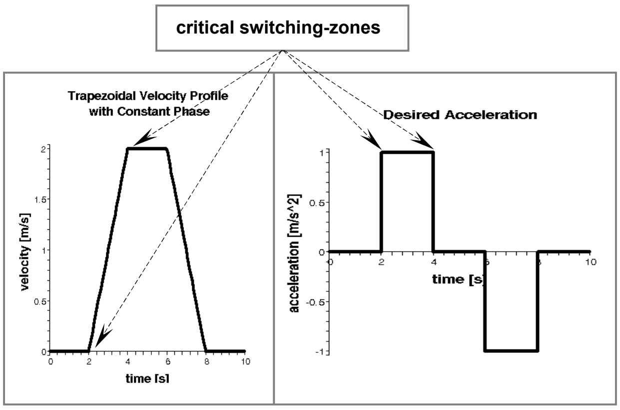


Figure 5. A typical velocity-acceleration profile with some “critical switching-zones”.

Another practical possibility is to filter the reference acceleration. With this filtered acceleration we are able to calculate the corresponding suitable tilting angles. A suitable mechanism of filtering is to average the acceleration data for a specific period of time and replacing the current value by the averaged value. The average filter can be described as follows:

$$y_j = \begin{cases} \left(\sum_{j=0}^{i} x_j \right) / (L+1) & \forall \ i < L+1 \\ \\ \left(\sum_{j=i-L}^{i} x_j \right) / (L+1) & \forall \ L+1 \le i \le n, \end{cases} \tag{9}$$

where x_j represents the current input data point j, y_j the new filtered data-point j, L the filter length and n the total number of data points to be sampled.

This method permits an appropriate “slope adjustment” of the filtered curve through the variable L. L indicates the total number of data points from the neighbourhood of the current selected data point x_j to be involved into the computing algorithm. Please note: Other filters might work as well as long as they have a fixed length, but they have not been investigated so far. It must also be stated that the longer the filter length L is, the smoother is the filtered curve, but as a drawback, it will lengthen the entire motion sequence.

Depending on the magnitude of the constant L, the new filtered values will have diverse lag in time [Figure 6]. This time delay can be computed as follows:

$$t_{delay} = L \cdot I_{ct} , \tag{10}$$

where the notation t_{delay} refers to the time delay introduced after applying the filtering algorithm to the original values and I_{ct} represents the interpolation cycle time of the robot controller.

3.2 Synchronization of Filtered Motion

The robot performs its movements according to the reference acceleration, but the tilting angles for its TCP is computed directly from the filtered acceleration.

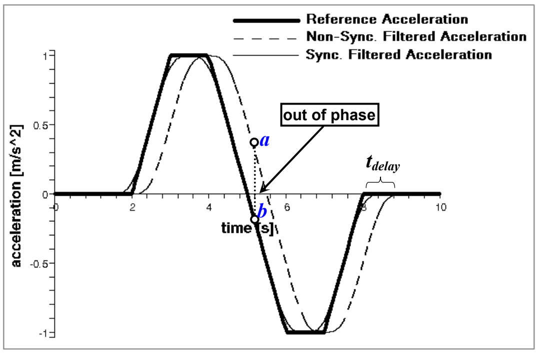


Figure 6. An example of non-synchronized and synchronized acceleration obtained from a S-curve velocity profile.

However, after the filtering, the original reference and filtered curves are "out of phase". This means that in a certain location they do not reach a positive or a negative value at the same time. This phenomenon can be clearly observed in the example shown in [***a-b*** from Figure 6].

At time = 5.2 [s], while the reference acceleration already reaches a negative value, the filtered acceleration still remains positive, producing an abrupt difference between both curves.

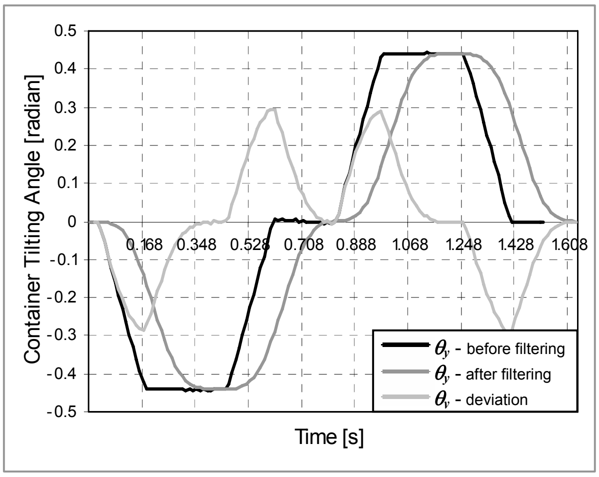


Figure 7. Non-Synchronized Container Tilting Angles - before/after filtering and the corresponding deviations.

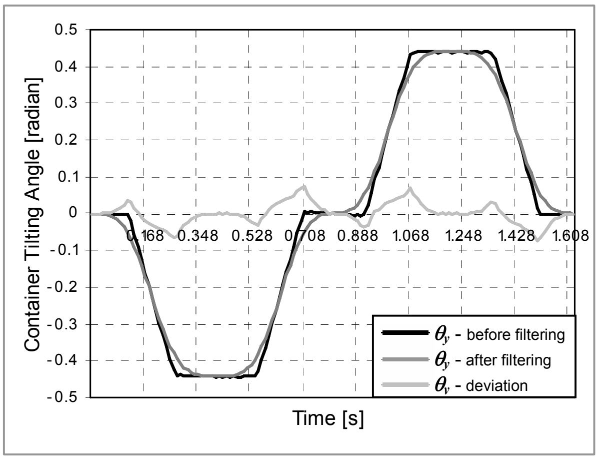


Figure 8. Synchronized Container Tilting Angles - before/after filtering and the corresponding deviations.

This leads consequently to a strong deviation of the computed container tilting angle from the optimal desired value (before filtering) [Figure 7]. A feasible solution to the above problem is the *shifting of the filtered curve*. This implies that the reference curve must move to the right, until the location, where accelerations change their sign, is once again synchronized [Figure 8].

Notice that the smaller the tilting angle deviation is, the lower is the sloshing. It means as well, that the tool needs to change its orientation in a reduced time. But as described before, in most of the cases this is not possible to be performed with a standard robot because of the dynamic limitation. Hence, the real movements have always a deviation from the ideal case. Because of this, even if the undesirable sloshing effect can be considerably diminished, small rest oscillation will exist.

4 Simulation and Experimental Results

4.1 Test-Environment

To verify the efficiency and the feasibility of the new proposed method, experiments with a real robot have been carried out in our laboratory. A testbed consisting of a KUKA KR16 industrial manipulator-6 DOF and a metal tray as carrying tool have been used [Figure 9].

As a test object, a transparent glass-recipient containing water has been utilized. The static liquid level is 40 [mm]. A camera has been adopted as sensor apparatus to observe the liquid behaviour in 2D, and it has been attached directly on the experimental tray, opposing to the glass-recipient. In addition, to distinguish and to facilitate the extraction of the fluid from its background, the water has been intentionally coloured [Figure 10].

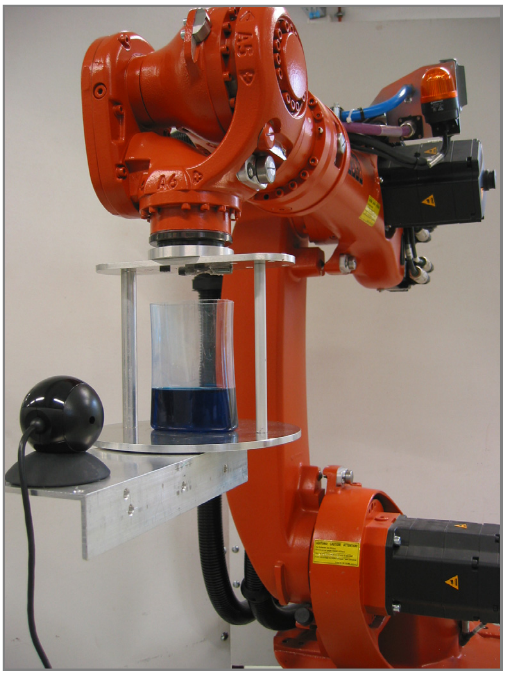


Figure 9. KUKA KR16 industrial manipulator-6 DOF with the carrying tool, the test-recipient with the coloured water and the sensor camera.

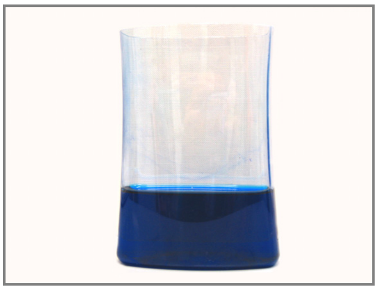


Figure 10. The test glass-recipient with the coloured water.

To simplify the analysis, a simple linear motion along the Y-axis from a start-position A = [930 800 1012] to the end-position B = [930 -800 1012] has been evaluated. Every interpolation cycle time from the robot-controller is 12 [ms].

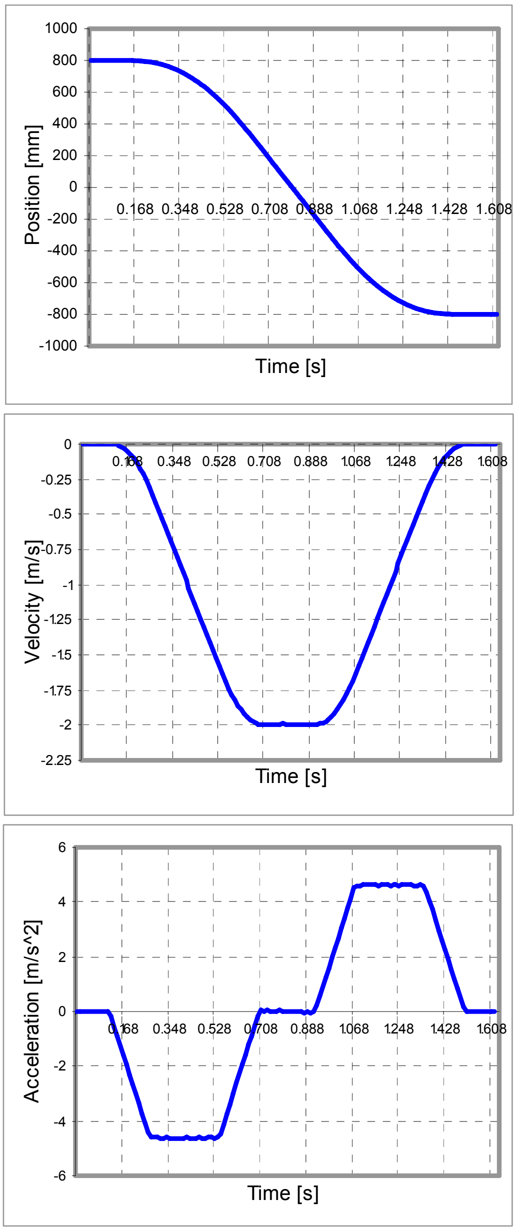


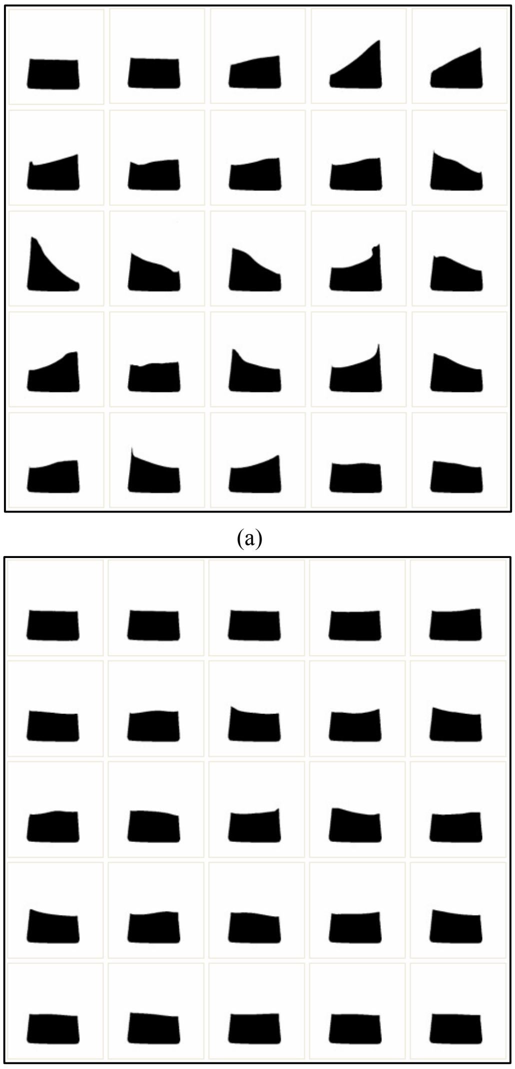
Figure 11. The reference trajectory utilized in our test.

The maximum acceleration for continuous motions has been set to 4.3 [m/s^2]. After the compensation, the translational positions of the original programmed trajectory remains unaltered, only the tool-orientation in each time-instant is modified [Figure 3].

4.2 Experimental Results

Figure 11 shows the reference trajectory employed in this experiment, with its respective position, velocity and acceleration. The entire original trajectory before the compensation has a duration of 1.404 [s].

Measurements of motions *without* and *with* acceleration compensation have been performed. The sequences of filtered images obtained from the experimentation-video verify that the sloshing effect has been diminished significantly [Fig. 12] after applying the new approach. For the compensated movement, the adopted filter length is $L = 9$.



(a)

(b)

Figure 12. Part of image sequences from a linear movement (a) without and (b) with acceleration compensation (the sequence order follows from left to right and from top to bottom).

As described in the previous section, small oscillations will exist at the end of the motion as a consequence of the phase-delay generated after the filtering. In this experimented motion without compensation, the maximum deviation of the peak elevation is approximately 37.5 [mm] respect to the corresponding static level [Figure 13]. Contrary to this, the compensated motion has only a maximum deviation about 5.7 [mm] in its fluid surface.[1] This represents a reduction of approximately 84.7 %.

Notice that in the compensated motion, the liquid surface reestablishes its resting state faster than in the non-compensated case. The maximum amplitude of the oscillations is below 6 [mm], which assures that the liquid can stay safely inside of its container during the entire motion process .

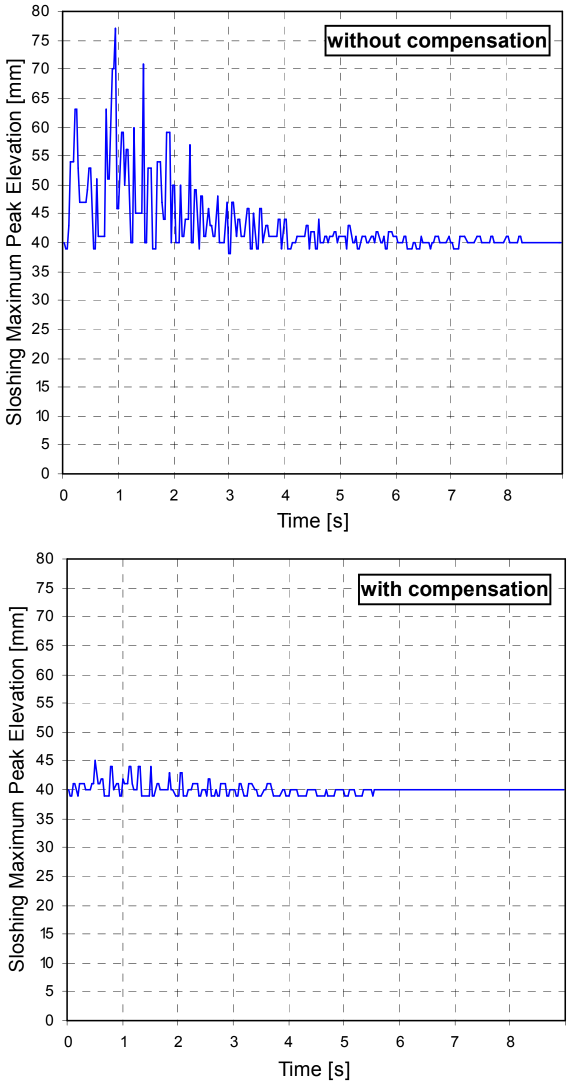


Figure 13. Compensation versus Non-Compensation. Results obtained from the sensor-camera images.

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[1] In both figures 12 and 13, the peak elevations lower than the static level is due to camera low resolution and noises from the acquired images.

5 Summary

To overcome the undesired sloshing problems in a fluid container during high-speed transfer, a new simple, feasible and time optimal approach has been introduced. Comparable to a waiter maneuvering a tray with glasses by adjusting the angle of the tray while quickly moving from one location to the other, this new approach compensates undesired liquid vibration effects by changing the orientation of the robot hand accordingly. No external sensing systems but the information of robot's internal joint encoders are required. An average filter has been employed to approach the acceleration limits of the robot as much as possible and thus still allows fast cycle times. The conceived method has been simulated and experimentally verified. The satisfactory results confirm the effectiveness of the proposed theory.

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