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Using Acceleration Compensation to Reduce Liquid Surface Oscillation During a High Speed Transfer

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***Abstract*—An open-loop method on the basis of *Acceleration Compensation* to reduce liquid surface oscillation generated during a high-speed transfer will be presented in this paper. In order to suppress the undesirable liquid vibration effects, so called 'sloshing', a new simple and effective methodology consisting of adapting the gripper orientation is proposed. The assumption of slosh-free movement will be valid so long as 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 considered in the computation. This represents that our 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.**

I. INTRODUCTION

DURING a high-speed transfer application with open container containing liquid, undesirable vibrations in the current liquid may arise. Due to changes in the container's acceleration, a relative motion between the container and the liquid may be produced. It may cause undesirable oscillations and generating quality degradations of the product or even contaminating its surrounding. Hence, it would be beneficial that such motions are accomplished with the utmost delicacy to prevent disturbances originated from those undesired oscillations. One typical example is the casting process, where the pouring and transportation of open container filled with hot molten steel or glass has to be executed with exact positioning and as well as in high-speed to avoid any undesired cooling of melted material. In this case, the entire process must be performed without spilling-over the content, to conserve the product quality and most important, to keep the safety of workers and to prevent any contamination in the working area.

As well, the sloshing-effect causes problems frequently in other areas such as the transportation of special chemical liquid products, where the avoidance of any possible agitation would be convenient. E.g., the case of launch vehicles carrying partially filled tanks containing highly flammable fuels [1]. Here, any inadequate perturbation may induce instabilities in the maneuvering control system and yield possibilities of fire or explosion hazards. Another two interesting examples to be mentioned are in [2][3], where the moving liquid within a partially filled tank may affect the control of commercial vehicles with liquid cargo and generating possible hazardous rollover effects.

One inefficient solution to solve the above described problem 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 as well, an enormous increase in the cycle time. 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, introducing these 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. [4] 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 have 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 [5]. 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, because of the physical properties of the transfer material. Material such as molten metal at high temperature or corrosive liquids, which could shorten the sensor's lifetime or cause irreversible damaging. Additionally, due to fluid high vibration frequencies, most of common sensors found in the market are not quick enough to measure properly the sloshing. As another drawback, is the laborious calibration procedure of the sensor elements.

Therefore, another alternative solution is the open loop control. Important works proposed by [6][7] 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 [6], a robust controller based on H-Infinity control theory was established to reduce the residual vibration in a liquid container transfer and

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furthermore, an additional rotational motion control was adopted to permit the sloshing suppression during the transfer acceleration/deceleration phase. Concerning a similar problem, [8][9] 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 resulting accelerations of the entire system, thus allowing for further elimination of the remaining vibrations.

The Active Acceleration Compensation technique was firstly proposed by [10]. To perform and to demonstrate this approach, a Stewart platform was mounted on a mobile robot. It was controlled in a way that any forces and torques acting on the transferred objects could be compensated actively during the motion. A similar work was established by [11]. 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 in [12][13]. 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. Undesired sloshing effects in a liquid container produced during a high-speed transfer process can be also enormously reduced. Furthermore, this new approach neither requires any complex fluid modeling and neither 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 basic fluid motion equations will be briefly introduced and thoroughly analyzed for a better understanding of our approach. Experimental results of a prototypical implementation of our methods will be shortly demonstrated.

II. THE "WAITER-TRAY" MODEL

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 are minimized during and until the end of the programmed motion. This efficient and robust approach 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 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 [Fig. 1].

III. PROBLEM STATEMENT AND ASSUMPTIONS

As described in Section I, our goal is to suppress within a reduced time interval, undesirable sloshing effects generated inside of the liquid container during the motion process.

The assumption of a slosh-free movement will be valid, so long 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 consideration in our computation algorithm. 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 accomplish the objectives above described, important considerations must be stated to simplify our analysis:

- the fluid is incompressible,
- the shear stress is zero,
- the motion is considered irrotational,
- fluid in rigid-body motion is assumed (no deformation),
- external disturbances are negligible.

Considering the above conditions, the following section will introduce the motion equation of fluid, which is important to be used later to compute the optimal tilting angles.

IV. 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. Therefore, Newton's second law of motion may be applied to evaluate the forces acting on the particle. Generally, two types of forces are exerted on a fluid particle: body forces and surface forces [14]. They can be expressed as follows:

$$d\vec{F}_{body} = dm\,\vec{g} = \rho\, dV\,\vec{g} = \rho\,\vec{g}\,dx\,dy\,dz, \tag{1}$$

where $dm = \rho\, dV$ the differential fluid element of mass, $\vec{g}$ the local gravity vector, ρ the density, and $dV{=}dxdydz$ the volume of the particle in Cartesian coordinates. Considering that in a static fluid, no shear forces can be present, thus the only surface force in consideration is the pressure force,

$$d\vec{F}_{surface} = -\nabla p\; dx\,dy\,dz, \tag{2}$$

with ∇p representing the gradient of pressure. Then the resultant forces acting on the fluid particle can be defined as

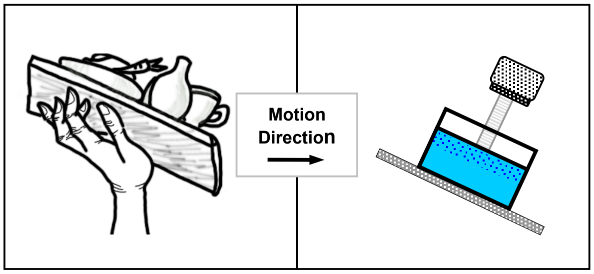


Fig. 1. Robot arm simulates a human hand.

$$d\vec{F} = d\vec{F}_{body} + d\vec{F}_{surface} = (\rho\,\vec{g} - \nabla p)\, dV. \tag{3}$$

For a fluid particle, Newton's second law gives

$$d\vec{F} = dm\,\vec{a} = \vec{a}\,\rho\, dV \tag{4}$$

so,

$$(\rho\,\vec{g} - \nabla p) = \rho\,\vec{a}, \tag{5}$$

is the general equation of motion for a fluid with non-existence of shear stresses. Since the gravity vector points downward (in the negative z-direction, see Fig. 2), the component equations in rectangular coordinates are

$$\begin{aligned} -\frac{\partial p}{\partial x} &= \rho\, a_x && x \text{ direction} \\ -\frac{\partial p}{\partial y} &= \rho\, a_y && y \text{ direction} \\ \rho\, g_z - \frac{\partial p}{\partial z} &= \rho\, a_z && z \text{ direction} \end{aligned} \tag{6}$$

These equations construct the fundamental basis for our acceleration compensation approach.

A. Model Formulation. 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 Fig. 2. Since $a_x = 0$, the pressure gradient in x-direction from (6) is zero ($\partial p/\partial x = 0$).

In y- and z-directions, we obtain:

$$\begin{aligned} -\frac{\partial p}{\partial y} &= \rho\, a_y, \\ \frac{\partial p}{\partial z} &= -\rho\,(g + a_z). \end{aligned} \tag{7}$$

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

$$dp = \frac{\partial p}{\partial y} dy + \frac{\partial p}{\partial z} dz \tag{8}$$

or in terms of the results from (7):

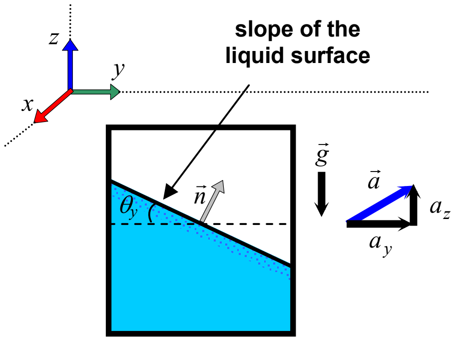
$$dp = -\rho\, a_y\, dy - \rho\,(g + a_z)\, dz. \tag{9}$$

If we consider that the pressure is constant, then $dp = 0$. From (9), it follows that the slope of the liquid surface [Fig. 2] is given by the relationship

$$\frac{dz}{dy} = -\frac{a_y}{(g + a_z)}, \tag{10}$$

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

$$\theta_y = \tan^{-1}(a_y/(g + a_z)), \tag{11}$$



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

Fig. 2. Free-body diagram.

θ_y is the optimal tilting angle of the TCP (Tool Center Point) due to a y-horizontal movement. In an ideal case, to guaranty that there is no relative motion between the fluid and the container, the acceleration in (11) at every time-instant has to maintain its maximum value. With the same analogy, we can compute the values of θ_x. Note that the tilting angles are functions of each time-instance t:

$$\boxed{\begin{aligned} \theta_x(t) &= \tan^{-1}(a_x(t)/(g + a_z(t))), \\ \theta_y(t) &= \tan^{-1}(a_y(t)/(g + a_z(t))). \end{aligned}} \tag{12}$$

This is the same result as obtained in [12]. Notice that using the same principle, undesired fluid sloshing effects can be suppressed. In the ideal case, during a high-speed motion, if the robot controller adapts the container orientation faithfully according to (12), then the fluid surface is guaranteed to be kept its flatness and thus, its slope will remain permanently parallel to the bottom of the corresponding container [Fig. 3 and 4].

B. Compensation with Maximum Acceleration

As it can easily be seen from (12), a fast increasing of acceleration will lead to fast changes of the tilting angle. Because modern robots are highly dynamic machines, the acceleration is ramped up very fast to the maximum (trapezoidal motion profile for the velocity) leading to high

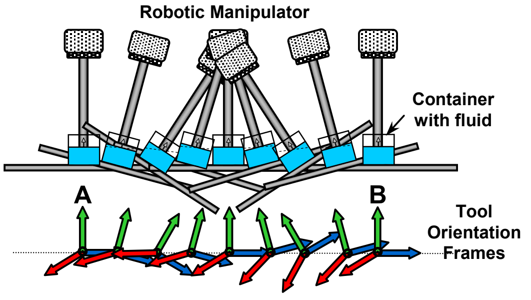


Fig. 3. Trajectory of robot TCP with compensated tilting angles.

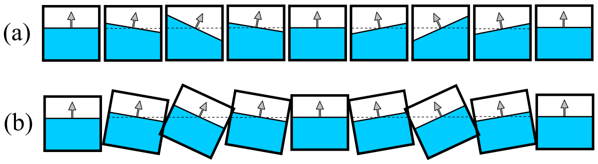


Fig. 4. Trajectory of liquid container without (a) and with (b) compensated tilting angles.

values of jerk. To achieve the optimal tilting angles during the high-speed motions, the angles have to change very fast. This fast change of orientation can not 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, to reduce 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 our primary goals.

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.

V. OPTIMIZATION FILTER

A. *Average-Filter*

For most robotic applications, a trapezoidal velocity profile is utilized by the motion controllers 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 [12]. 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 basis to determine the optimal tilting angles, therefore, it is possible to filter and smooth the computed optimal tilting angles.

Another practical possibility is to filter the reference acceleration. With this filtered acceleration, we are able to calculate the corresponding suitable tilting angles. An appropriate mechanism of filtering for the acceleration data is to average them for a specific period of time and replace the current value by the average value.

The average filter can be described as follows:

$$y_j = \begin{cases} \left(\sum_{j=0}^{i} x_j \right) / (L+1) & \forall \ i < L+1 \\ \left(\sum_{j=i-L}^{i} x_j \right) / (L+1) & \forall \ L+1 \le i \le n, \end{cases} \tag{16}$$

where x_j denotes the current input data value j, y_j the new filtered data value j, L the filter length and n, the total number of data values to be sampled. As before described, x_j represents in our case, the acceleration in each Cartesian position obtained from the original reference path and y_j is the new "filtered acceleration" that will be used subsequently to compute the corresponding "smoothed" tilting angle.

This method permits an appropriate "slope adjustment" of the filtered curve through the variable L. L indicates the total number of data values from the neighbourhood of the current selected data value x_j to be involved into the computing algorithm. Please note: 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.

This time-delay can be computed as:

$$t_{delay} = L \cdot I_{ct}\,, \tag{17}$$

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.

B. *Synchronization of Filtered Motion*

The robot will perform its movements according to the reference acceleration, but the tilting angles for its TCP will be computed in this case, from the filtered acceleration.

However, after the filtering, the original reference and the 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 area shown in [***a-b*** from Fig. 5]. Here we can contemplate, while the reference acceleration already reaches a negative value, the filtered acceleration still remains positive, producing an abrupt difference between both curves. This leads consequently to a strong deviation of the computed container tilting angles from the optimal desired tilting values (before filtering). A feasible solution for this problem is the *shifting of the filtered values*. This implies that the reference curve must be moved to the right side until the location, where the accelerations change their signs, is once again synchronized [12].

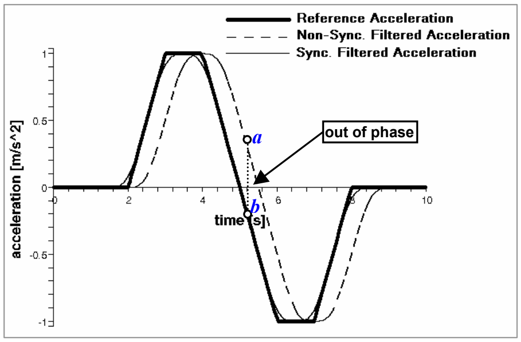


Fig. 5. An example of non-synchronized and synchronized acceleration obtained from a S-curve velocity profile.

Observe that the smaller the tilting angle deviation is, the lower is the sloshing, and therefore, it also implies a fast change of tool orientation in a reduced time.

But in most of the cases, this is not possible to be performed with a standard robot because of its dynamic limitation. Hence, the executed movements will always have a deviation from the ideal case, at least the ideal tilting angles can be faithfully performed. Because of this reason, even if the undesirable sloshing effects can be considerably diminished, small oscillations will still exist at the end of motion.

VI. SIMULATION AND EXPERIMENTAL RESULTS

A. Test-Environment

To verify the efficiency and the feasibility of the approach, experiments with a real robot have been carried out in our laboratory. A testbed consisting of a KUKA KR16 industrial manipulator (6 degrees of freedom) has been used. A metal tray as liquid container carrying-tool has been mounted directly at the flange of the robot.

To show that the approach is independent of container physical characteristics, tests realized with different kinds of container forms and sizes have been performed. In this article, we will show experimentations using a transparent spherical glass-recipient (radius=40 [mm]) and to simplify the image extraction, the liquid has been intentionally coloured.

Additionally, we employed a camera as sensor apparatus to observe the liquid behaviour in 2D, and it has been attached directly on the experimental tray beside the glass container.

B. Simulation Results

To simplify the analysis, a simple linear motion along the Y-axis from the start-position A = [930 800 1012] to end-position B = [930 -800 1012] has been evaluated. Every interpolation cycle time from the robot-controller is 12 [ms] and the maximum acceleration has been set to 7 [m/s^2]. The entire original trajectory before the compensation has a duration of 1.404 [s].

The synchronization effects explained in section V will be analyzed here with the help of software simulation. In Fig. 6, we observe clearly that the deviated tilting angles between the ideal (before filtering) and the filtered values differ enormously in the non-synchronized case.

This means that we are moving further away from the ideal compensation, and this implies consequently that instead of minimizing the sloshing, the oscillations will increase in contrary, largely. For the same particular example, after the synchronization [Fig. 7], the filtered tilting angles still have a deviation of approximately 8.12% and therefore, rest liquid surface oscillations will still slightly exist at the end of the motion.

C. Experimental Results

With the same path used in the software simulation, two motions have been carried out and evaluated: motions *without* and *with* acceleration compensation.

The sequences of filtered images obtained from the experimentation-videos verified that the sloshing has been diminished significantly [Fig. 8] after applying the new approach. For the compensation, the filter length adopted here was $L = 8$.

As described in the previous section, small oscillations will exist at the end of motion as a consequence of the phase-delay and deviation generated after the filtering. Here, in the case of motion without compensation, the maximum deviation of the peak elevation, from the fluid surface in motion respect to its static level, is approximately 35.36 [mm] [Fig. 9]. In contrast to the non-compensated case, the compensated motion has only a maximum deviation about 2.857 [mm]. This represents a reduction of approximately 91.92 %.

Notice that in the compensated motion, the liquid surface reaches again its resting state faster than the non-compensated case and all generated oscillations have been

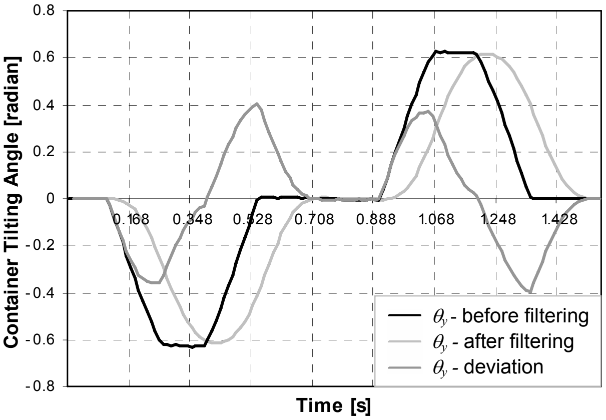


Fig. 6. Non-Synchronized container tilting angles before and after filtering and the corresponding deviations.

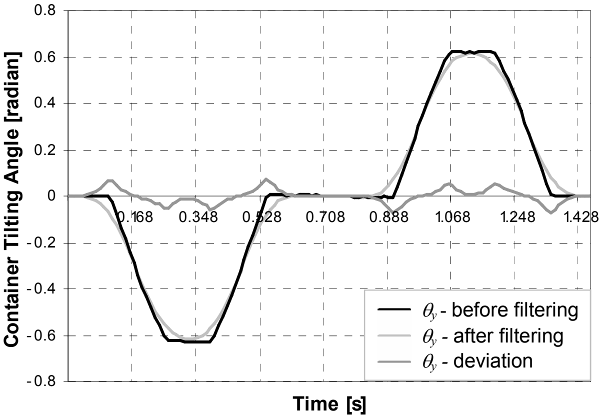
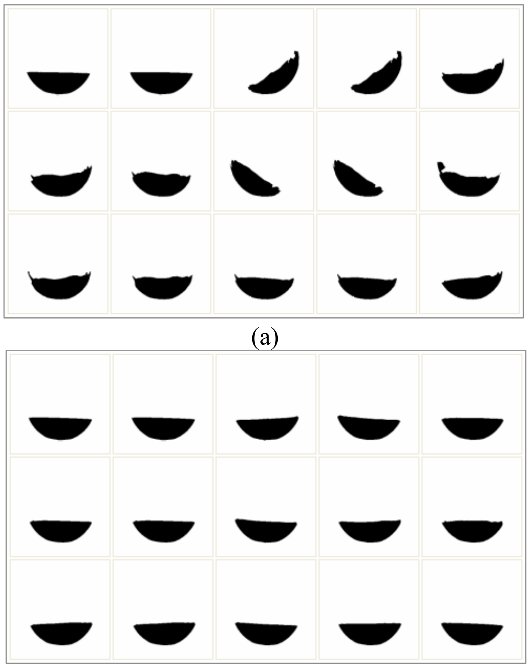


Fig. 7. Synchronized container tilting angles before and after filtering and the corresponding deviations.



(a)

(b)

Fig. 8. Part of image sequences from a linear movement realized without (a) and with (b) acceleration compensation. The sequence order follows from left to right and from top to bottom.

keeping an amplitude no larger than 3 [mm] and therefore, it guarantees that the fluid stayed safely inside of its container until the end of the motion.

VII. CONCLUSION

To overcome the problem of vibrations produced in a high-speed transfer with fluid container, a new simple 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 starting-position to the end-position, our approach compensates undesired liquid vibration effects during the motion by changing the orientation of the robot hand accordingly. No external sensing systems but the robot internal joint encoders information are required. An average filter has been employed to approach the acceleration limits of the robot as much as possible and thus still allowing fast cycle times. The conceived method has been simulated and experimentally verified. The satisfactory results confirm the effectiveness of our proposed theory.

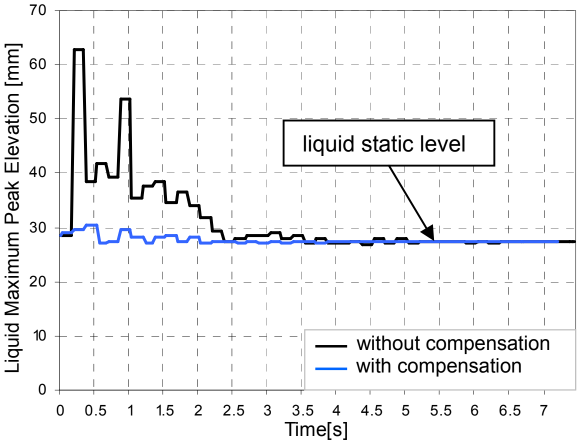


Fig. 9. Compensated motion vs. non-compensated motion. Results obtained from the sensor-camera images.

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