Robustness in Liquid Transfer Vehicles with Delayed Resonators

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Abstract: - In the present paper, the dynamic model of a liquid transfer vehicle with delayed resonators is modified to take into account simultaneous wear to the front and rear springs. This failure is mathematically formulated as increase to the spring constant with simultaneous decrease to the damping factor. A sloshing suppression control scheme, designed knowing only the nominal values of the resonator parameters while considering their real values to be unknown, is applied to the real system. Then, the sets of resonator parameters where the feedback control law produces satisfactory results are determined, thus verifying robustness of the proposed control scheme.

Key-Words: robustness analysis, liquid transfer, delay resonators, spring wear

1 Introduction

In casting and steel industries, molten metal is usually moved from the furnace to the casting areas using automotive carts that carry tanks filled with the molten metal. A significant problem that has to be solved is the suppression of the liquid's sloshing within the tank. Sloshing is dangerous, since it may cause overflow, as well as deterioration of the product quality due to contamination and excessive cooling of the molten metal [1].

Several studies of sloshing suppression have appeared in the literature (see for example [1]–[12]). Many of these works approximate the liquid's motion using a pendulum-type model ([1]-[5], [8], [10], [11]). Optimal control ([12]), as well as H_∞ control methods ([5], [8]) have been proposed. Active control methods that actuate the rotational motion of the tank have been proposed in [1] and [5]. Both these works considered sloshing suppression during an accelerated translational motion of the vehicle along a straight path, while the proposed controllers used measurements of the water level displacement.

Another approach proposed in [13] uses active vibration absorption for sloshing suppression, using delayed resonators (see f.e. [14]-[16]) for the case of liquid transfer using a tank mounted on a vehicle. In particular, a static feedback law is proposed whose parameters are evaluated using a simulated annealing algorithm.

In the present paper, the dynamic model of the plant presented in [13] is modified to take into account simultaneous wear to the front and rear springs of the resonator. This failure is modeled as increase to the spring constant of the resonators with simultaneous decrease to the damping factor [17]. Then, robustness of the control scheme introduced in [13], is studied under the aforementioned uncertainty in the resonator parameters due to wear. In particular, the controller proposed in [13] is designed considering knowledge only of the nominal values of the resonator parameters. The controller is then applied to the real system whose parameters may vary from the nominal values. The contribution of the present paper consists in determining the sets of resonator parameters where the feedback control law produces satisfactory results.

Another interesting problem concerning robustness issues related to liquid parameter variations in a liquid transfer structure with robotic manipulator has been studied in [18].

2 Liquid Transfer Vehicle Modeling

Consider the liquid transfer application presented in Figure 1 (see [13]). The liquid is contained within a tank, carried by an automotive vehicle. Assuming that the vehicle moves on a straight path, the whole motion of the liquid transferring structure can be faced as a two dimensional problem.

The tank may rotate with respect to the vehicle. The rotation of the tank is appropriately controlled through an actuator that applies a torque $u(t)$ to the tank. The vehicle is assumed to move on a horizontal level. Unevenness on the level of the vehicle's motion is modeled as force disturbances $F_f(t)$ and $F_r(t)$ acting on the front and the rear wheel, respectively, of the vehicle. The vibrations of the vehicle are absorbed by four absorbers, two of which act as active absorbers and the rest two as passive absorbers. The passive absorbers (suspension) are two identical conventional spring-damper structures that connect the platform of the vehicle with the front and the rear wheel, respectively. The active vibration absorbers are two identical mass-spring-damper trios that utilize position feedback with controlled delay (see f.e. [13]-[15]) and are placed on top of the vehicle's platform at the position of the front and the rear wheel, respectively. The function of the active vibration absorbers is based on a technique called Delayed Resonators [14]-[16].

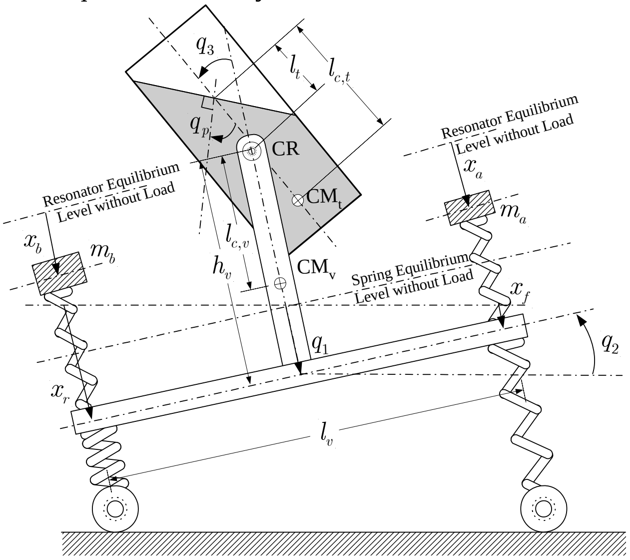

Fig. 1: Liquid transfer application [13]

The equivalent liquid transfer structure, based on the representation of the tank with a rotating joint and the representation of the liquid's motion with a pendulum, is given in Figure 2 (see [13]).

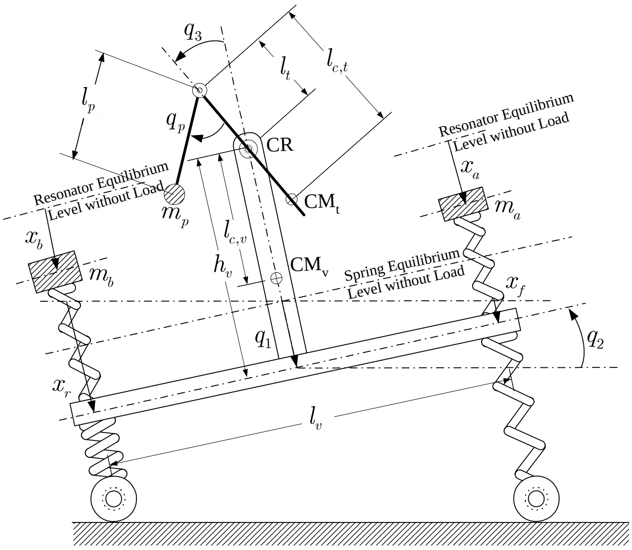

Fig. 2: Representation of liquid's motion with a pendulum [13]

In order to develop the dynamic model of the system, it is assumed that the parameters of the front and rear resonator, as well as the respective control delay are equal. Furthermore, it will be assumed that due to wearing, the spring constants and dumping factors will differ from their nominal values. This difference, although constant and equal to both resonators, will be assumed to be unknown, while only the nominal value of the respective parameter will be known. According to [17], the influence of wear to the springs can be described as increase to the spring constant and decrease to the dumping factor. Let $q = \begin{bmatrix} q_1 & q_2 & q_3 & q_p & x_a & x_b \end{bmatrix}^{\mathrm{T}}$ denote the generalized coordinates of the structure, with q_1 the vertical deviation of the platform from the level corresponding to the natural length of the passive absorbers' spring, q_2 the rotation angle of the vehicle's platform, q_3 the rotation angle of the tank with respect to the vehicle, q_p the rotation of the pendulum with respect to the tank and x_a, x_b the aforementioned deviations of the resonators. Furthermore, let m_p, m_t, m_v and m_{res} be the pendulum, tank, vehicle and resonator masses respectively, h_v and l_v be the vehicle height and length, respectively, $l_{c,v}$ be the distance of the vehicle's center of mass (CM) from the center of revolution (CR), l_t be the distance between CR and the free surface of the liquid, $l_{c,t}$ be the distance of the tank's center of mass (CM) from the free surface of the liquid, l_p be the pendulum length, ψ_r be the resonator spring's free length, k_{res} be the resonator spring constant, k_e be the suspensions spring constant, c_{res} be the resonators dumping factor, c_e be the suspensions dumping factor, c be the liquid coefficient of viscosity, I_t be the tank moment of inertia, I_v be the vehicle moment of inertia, g_{res} be the resonator feedback gain, τ be the resonator feedback delay and g be the gravity acceleration. With respect to resonator spring constant and dumping factor it will be assumed that $k_{res} = \overline{k}_{res} + \delta k_{res}$, $c_{res} = \overline{c}_{res} - \delta c_{res}$ where $\overline{k}_{res}$ and $\overline{c}_{res}$ are the known nominal values of the respective parameters and δk_{res} and δc_{res} are unknown constant disturbances to the respective values due to wear.

According to [13], the nonlinear dynamic model of the above presented plant takes on the form:

$$\begin{bmatrix} D(q(t)) & 0_{2\times 2} \\ 0_{2\times 2} & I_{2\times 2} \end{bmatrix} \ddot{q}(t) + \begin{bmatrix} C(q(t),\dot{q}(t)) \\ C_r(q(t),\dot{q}(t)) \end{bmatrix} \dot{q}(t) +$$

$$\begin{bmatrix} G(q(t),q(t-\tau)) \\ G_r(q(t),q(t-\tau)) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} u(t)$$

$$+ \begin{bmatrix} \cos(q_2(t)) & \frac{l_v}{2} & 0 & 0 & 0 & 0 \\ \cos(q_2(t)) & \frac{-l_v}{2} & 0 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} \tau_d(t) \quad (2.1)$$

The elements of the matrices $D(q) = \left[d_{ij}(q)\right]$ $i,j = 1,\ldots,4$, $C(q(t),\dot{q}(t)) = \left[c_{ij}(q(t),\dot{q}(t))\right]$, $i = 1,\ldots,4$, $j = 1,\ldots,6$, $C_r(q(t),\dot{q}(t)) = \left[c_{r,ij}(q(t),\dot{q}(t))\right]$, $i = 1,2$, $j = 1,\ldots,6$, $G(q(t),q(t-\tau)) = \left[G_i(q(t),q(t-\tau))\right]$, $i = 1,\ldots,4$ and $G_r(q(t),q(t-\tau)) = \left[G_{r,i}(q(t),q(t-\tau))\right]$, $i = 1,2$ are nonlinear functions of the structure's generalized variables and their respective velocities. Note that $D(q)$ is a symmetric positive definite matrix. The elements of these matrices are given by the following equations [13]:

$$d_{11} = m_v + m_t + m_p$$

$$d_{12} = \left[l_{c,v}m_v - h_v\left(m_v + m_t + m_p\right)\right]\sin(q_2) + \left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\sin(q_2 + q_3) + l_pm_p\sin(q_2 + q_3 + q_p)$$

$$d_{13} = \left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\sin(q_2 + q_3) + l_pm_p\sin(q_2 + q_3 + q_p)$$

$$d_{14} = l_pm_p\sin(q_2 + q_3 + q_p)$$

$$d_{22} = I_t + I_v + \left(l_t^2 + l_p^2 + h_v^2\right)m_p + \left[\left(l_{c,t} - l_t\right)^2 + h_v^2\right]m_t + \left(h_v - l_{c,v}\right)^2 m_v + 2h_v\left[-l_{c,t}m_t + l_t(m_t + m_p)\right]\cos(q_3) - 2l_pm_p\left[l_t\cos(q_p) + h_v\cos(q_3 + q_p)\right]$$

$$d_{23} = I_t + \left(l_t^2 + l_p^2\right)m_p + \left(l_{c,t} - l_t\right)^2 m_t + h_v\left[-l_{c,t}m_t + l_t(m_t + m_p)\right]\cos(q_3) - l_pm_p\left[2l_t\cos(q_p) + h_v\cos(q_3 + q_p)\right]$$

$$d_{24} = l_pm_p\left[l_p - l_t\cos(q_p) - h_v\cos(q_3 + q_p)\right]$$

$$d_{33} = I_t + (l_t^2 + l_p^2)m_p + (l_{c,t} - l_t)^2 m_t - 2l_pl_tm_p\cos(q_p)$$

$$d_{34} = l_pm_p\left[l_p - l_t\cos\left(q_p\right)\right],\ d_{44} = l_p^2m_p$$

$$c_{11} = (2c_v + 2c_{res})\cos(q_2(t))$$

$$c_{12} = \left\{\left[l_{c,v}m_v - h_v\left(m_v + m_t + m_p\right)\right]\cos(q_2) + \left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\cos(q_2 + q_3) + l_pm_p\cos(q_2 + q_3 + q_p)\right\}\dot{q}_2 + \left\{\left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\cos(q_2 + q_3) + l_pm_p\cos(q_2 + q_3 + q_p)\right\}\dot{q}_3 + +l_pm_p\cos(q_2 + q_3 + q_p)\dot{q}_p$$

$$c_{13} = \left\{\left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\cos(q_2 + q_3) + l_pm_p\cos(q_2 + q_3 + q_p)\right\}\left(\dot{q}_2 + \dot{q}_3\right) + l_pm_p\cos(q_2 + q_3 + q_p)\dot{q}_p$$

$$c_{14} = l_pm_p\cos(q_2 + q_3 + q_p)\left(\dot{q}_2 + \dot{q}_3 + \dot{q}_p\right)$$

$$c_{15} = c_{16} = -c_{res}\cos(q_2(t)),\ c_{21} = 0$$

$$c_{22} = \left\{\left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\sin(q_3) + l_pm_p\sin(q_3 + q_p)\right\}h_v\dot{q}_3 + l_pm_p\left[l_t\sin(q_p) + h_v\sin(q_3 + q_p)\right]\dot{q}_p + \tfrac{1}{2}(c_v + c_{res})l_v^2 / \cos^2(q_2)$$

$$c_{23} = \left\{\left[l_{c,t}m_t - l_t\left(m_t + m_p\right)\right]\sin(q_3) + l_pm_p\sin(q_3 + q_p)\right\}h_v\left(\dot{q}_2 + \dot{q}_3\right) + l_pm_p\left[l_t\sin(q_p) + h_v\sin(q_3 + q_p)\right]\dot{q}_p$$

$$c_{24} = l_pm_p\left[l_t\sin(q_p) + h_v\sin(q_3 + q_p)\right]\times\left(\dot{q}_2 + \dot{q}_3 + \dot{q}_p\right)$$

$$c_{25} = -c_{26} = -\tfrac{1}{2}l_vc_{res},\ c_{31} = 0$$

$$c_{32} = \left\{\left[-l_{c,t}m_t + l_t\left(m_t + m_p\right)\right]\sin(q_3) - l_pm_p\sin(q_3 + q_p)\right\}h_v\dot{q}_2 + l_pl_tm_p\sin(q_p)\dot{q}_p$$

$$c_{33} = l_pl_tm_p\sin(q_p)\dot{q}_p$$

$$c_{34} = l_pl_tm_p\sin(q_p)\left(\dot{q}_2 + \dot{q}_3 + \dot{q}_p\right)$$

$$c_{35} = c_{36} = c_{41} = 0$$

$$c_{42} = -l_p m_p \left[l_t \sin(q_p) + h_v \sin(q_3 + q_p) \right] \dot{q}_2 + \\ + l_t \sin(q_p) \dot{q}_3$$

$$c_{43} = -l_p l_t m_p \sin(q_p)(\dot{q}_2 + \dot{q}_3)$$

$$c_{44} = c l_p^2 \cos^2(q_2(t) + q_3(t) + q_p(t))$$

$$c_{45} = c_{46} = 0$$

$$c_{r,11} = -c_{r,15} = c_{r,21} = -c_{r,26} = -\frac{c_{res}}{m_{res}}$$

$$c_{r,12} = -c_{r,22} = -\frac{c_{res} l_v}{2 m_{res} \cos^2(q_2)}$$

$$c_{r,13} = c_{r,14} = c_{r,16} = c_{r,23} = c_{r,24} = c_{r,25} = 0$$

$$g_1(q(t), q(t-\tau)) = g(m_v + m_t + m_p) + \\ 2(k_e + k_{res}) q_1(t) \cos(q_2(t)) - \\ k_{res} \left[x_a(t) + x_b(t) \right] \cos(q_2(t)) \\ -g_{res} \left[x_a(t-\tau) + x_b(t-\tau) \right]$$

$$g_2(q(t), q(t-\tau)) = g \left[l_{c,v} m_v - h_v (m_v + m_t + m_p) \right] \\ \sin(q_2(t)) + g \left[l_{ct} m_t - l_t (m_t + m_p) \right] \times \\ \sin(q_2(t) + q_3(t)) + g l_p m_p \sin(q_2(t) + q_3(t) + q_p(t)) \\ \tfrac{1}{2}(k_e + k_{res}) l_v^2 \tan(q_2(t)) - \tfrac{1}{2} k_{res} l_v \left[x_a(t) - x_b(t) \right] \\ g\, m_{res} \left[2\psi_r + x_a(t) + x_b(t) \right] \sin(q_2(t)) - \\ \frac{1}{2} g_{res} l_v \left[x_a\left(t-\tau\right) - x_b\left(t-\tau\right) \right]$$

$$g_3(q(t), q(t-\tau)) = g \left[l_{ct} m_t - l_t (m_t + m_p) \right] \sin(q_2(t) \\ + q_3\left(t\right)\Big) + g l_p m_p \sin\left(q_2\left(t\right) + q_3\left(t\right) + q_p\left(t\right)\right)$$

$$g_4(q(t), q(t-\tau)) = g l_p m_p \sin(q_2(t) + q_3(t) + q_p(t))$$

$$g_{r,1}(q(t), q(t-\tau)) = \frac{g_{res}}{m_{res}} x_a(t-\tau) + g \cos(q_2(t)) + \\ \frac{k_{res}}{m_{res}} \left[-q_1(t) - \tfrac{1}{2} l_v \tan(q_2(t)) + x_a(t) \right]$$

$$g_{r,2}(q(t), q(t-\tau)) = \frac{g_{res}}{m_{res}} x_b(t-\tau) + g \cos(q_2(t)) + \\ \frac{k_{res}}{m_{res}} \left[-q_1(t) + \tfrac{1}{2} l_v \tan(q_2(t)) + x_b(t) \right]$$

The control input of the structure is the torque $u(t)$ that actuates the joint representing the tank's motion, while the disturbance vector $\tau_d(t) = \left[\tau_{d,1}(t) \quad \tau_{d,2}(t) \right]^{\mathrm{T}}$ is given by $\tau_{d,1}(t) = F_f(t)$, $\tau_{d,2}(t) = F_r(t)$, where F_f and F_r disturbance forces that act on the front and the rare wheel, respectively, along the direction of the passive absorbers' springs.

3 Robustness Analysis of the Closed Loop System

In [13], a proportional feedback controller of the form

$$r(t) = \left[f_1 \quad f_2 \quad f_3 \right] \left[q_2(t) \quad q_3(t) \quad \dot{q}_3(t) \right]^{\mathrm{T}} \qquad (3.1)$$

has been proposed in order to succeed sloshing suppression during liquid transfer for the liquid transfer vehicle with delayed resonators, presented in the previous section. The parameters of this controller are chosen via a simulated annealing algorithm based on the linearized model of the plant. It must be noted that parameters of controller (3.1) were determined in [13] considering that $k_{res} = \overline{k}_{res}$ and $c_{res} = \overline{c}_{res}$. In what follows, the robustness of controller (3.1) is studied under uncertainty on the parameters of the resonators. More specifically, it will be examined whether the performance of the closed loop system remains satisfactory for several values of δk_{res} and δc_{res}. Assume that (see also [13])

$$m_p = 2.744\left[\mathrm{kgr}\right],\ m_t = 1.68\left[\mathrm{kgr}\right]$$

$$m_v = 15.20\left[\mathrm{kgr}\right],\ m_{res} = 0.77\left[\mathrm{kgr}\right]$$

$$h_v = 0.30\left[\mathrm{m}\right],\ l_v = 0.50\left[\mathrm{m}\right],\ l_{c,v} = 0.304\left[\mathrm{m}\right]$$

$$l_t = 0.033\left[\mathrm{m}\right],\ l_{c,t} = 0.113\left[\mathrm{m}\right]$$

$$l_p = 0.0442\left[\mathrm{m}\right],\ \psi_r = 0.10\left[\mathrm{m}\right]$$

$$\overline{k}_{res} = 52000\left[\mathrm{N/m}\right],\ k_e = 62000\left[\mathrm{N/m}\right]$$

$$\overline{c}_{res} = 16\left[\mathrm{kgr/sec}\right],\ c_e = 2500\left[\mathrm{kgr/sec}\right]$$

$$c = 1.88\left[\mathrm{N\,sec/m}\right],\ I_t = 7.193 \cdot 10^{-3}\left[\mathrm{kgr\,m^2}\right]$$

$$I_v = 0.329967\left[\mathrm{kgr\,m^2}\right],\ g_{res} = 32976\left[\mathrm{N/m}\right]$$

$$\tau = 0.0195\left[\mathrm{sec}\right],\ g = 9.81\left[\mathrm{m/sec^2}\right]$$

$$F_f(t) = \begin{cases} 1000\left[\mathrm{N}\right] & 0 \le t \le 0.5[\mathrm{sec}] \\ 0\left[\mathrm{N}\right] & t > 0.5[\mathrm{sec}] \end{cases}$$

$$F_r(t) = F_f(t - 0.25)$$

For these parameter values, the controller parameters that achieve satisfactory sloshing suppression have been determined in [13] to be:

$f_1 = -56.801$, $f_2 = -9.5239$, $f_3 = -0.0308$

The robustness of the closed loop system will be examined for the following range of uncertainty: $\delta c_{res} \in \left[13.6, \overline{c}_{res}\right]$ and $\delta k_{res} \in \left[\overline{k}_{res}, 59800\right]$. For the closed loop performance to be considered satisfactory, a condition is necessary to be met concerning the maximum allowable angle of the pendulum. More specifically, the maximum absolute value of the pendulum's angle has to remain smaller than or equal to $51.696°$. This angle limitation does not allow the free surface of the fluid to approach closer than $1\left[\mathrm{cm}\right]$ to the edges of the tank. Assuming that this limitation holds, the robustness of the closed loop system in each case will be examined using the following cost criteria

$$f_1\left(\delta k_{res}, \delta c_{res}\right) = \sqrt{\int_0^\infty q_p\left(t\right)^2 dt} \qquad (3.2a)$$

$$f_2\left(\delta k_{res}, \delta c_{res}\right) = \sqrt{\int_0^\infty q_3\left(t\right)^2 dt} \qquad (3.2b)$$

The integrals in criteria (3.2) are guarantied to converge to some value. This is because the steady state values of $q_p\left(t\right)$ and $q_3\left(t\right)$ are equal to zero.

Using simulation results for several values of the uncertain parameters, we determine an area of the $\left(\delta k_{res}, \delta c_{res}\right)$ plane where the maximum pendulum angle condition is met. This area is presented in Figure 3. From this figure it can be observed that this area covers a significant range in the $\left(\delta k_{res}, \delta c_{res}\right)$ plane. Hence, it is verified that controller (3.1), introduced in [13], is indeed robust. This can also be verified by the cost criteria (3.2). Indeed, using the simulation results, it can be observed that for those values of the uncertain parameters that lie within the area where the maximum pendulum angle condition is met, the corresponding values of the cost criteria, introduced in (3.2), do not significantly change. Finally in Figure 4, the closed loop pendulum angle response is presented for the cases a) $\delta k_{res} = 0$ and $\delta c_{res} = 0$ and b) $\delta k_{res} / \overline{k}_{res} = 9\%$ and $\delta c_{res} / \overline{c}_{res} = 9\%$. Note that the second case is marginally inside the area where the maximum pendulum angle condition is satisfied. It can be observed that the two responses are visually identical. The same observation holds for all $\left(\delta k_{res}, \delta c_{res}\right)$ where the maximum pendulum angle condition is satisfied. This is consistent with the fact that the cost criteria (3.2a) and (3.2b) do not significantly change inside that area.

4 Conclusions

In the present paper, the dynamic model of a liquid transfer vehicle with delayed resonators, presented in [13], has been modified to take into account simultaneous wear to the front and rear springs of the resonators. This failure has been mathematically formulated as increase to the spring constant of the resonators with simultaneous decrease to the damping factor. The robustness of a sloshing suppression control scheme, introduced in [13], has been studied under the aforementioned uncertainty in the resonator parameters. In particular, the controller proposed in [13] is designed considering knowledge only of the nominal values of the resonator parameters. The controller is then applied to the real system whose parameters may vary from their nominal values. The contribution of the present paper consists in determining the sets of resonator parameters where the feedback control law produces satisfactory results. It has been observed that there exists a significant area in the $\left(\delta k_{res}, \delta c_{res}\right)$ plane where the maximum pendulum angle condition is met, while it has been verified that the controller is robust for a wide range of the uncertain parameters.

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References

[1] K. Yano, S. Higashikawa and K. Terashima, "Motion control of liquid container considering an inclined transfer path," *Control Eng. Practice*, vol. 10, pp. 465-472, 2002.

[2] J. Feddema, C. Dohrmann, G. Parker, R. Robinett, V. Romero and D. Schmitt, Robotically controlled slosh-free motion of an open container of liquid, *1996 IEEE Int. Conf. on Robotics and Automation*, Minneapolis, Minnesota, April 1996, pp. 596-602

[3] K. Terashima, M, Hamaguchi and K. Yamaura, Modeling and input shaping control of liquid vibration for an automated pouring system, *35th Conf. on Decision and Control*, Kobe, Japan, 1996, pp. 4844-4850

[4] J. T. Feddema, C. R. Dohrmann, G. G. Parker, R. D. Robinett, V. J. Romero and D. J. Schmitt, Control for slosh-free motion of an open container, *IEEE Control Systems Magazine*, vol. 17, no. 1, pp. 29-36, 1997

[5] K. Yano and K. Terashima, "Robust liquid container transfer control for complete sloshing suppression, *IEEE Trans. Control Systems Techn.*, vol. 9, pp. 483-493, 2001

[6] K. Yano, S. Higashikawa and K. Terashima, Liquid container transfer control on 3D transfer path by hybrid shaped approach, *2001 IEEE Int. Conf. on Control Applications*, 5-7, 2001, Mexico City, Mexico, pp. 1168-1173

[7] K. Yano, T. Toda and K. Terashima, Sloshing suppression control of automatic pouring robot by hybrid shape approach, *40th IEEE Conference on Decision and Control*, Orlando, Florida, USA, December 2001, pp. 1328-1333

[8] K. Terashima and K. Yano, Sloshing analysis and suppression control of tilting-type automatic pouring machine, *Control Eng. Practice*, vol. 9, pp. 607-620, 2001

[9] H. Sira-Ramirez, A flatness based generalized PI control approach to liquid sloshing regulation in a moving container, *American Control Conference*, Anchorage, USA, May 8-10, 2002, pp. 2909-2914

[10] S. Kimura, M. Hamaguchi and T. Taniguchi, Damping control of liquid container by a carrier with dual swing type active vibration reducer, *41st SICE Annual Conference*, 2002, pp. 2385- 2388.

[11] Y. Noda, K. Yano and K. Terashima, Tracking to moving object and sloshing suppression control using time varying filter gain in liquid container transfer, *2003 SICE Annual Conference*, Fukui, Japan, 2003, pp. 2283-2288

[12] M. Hamaguchi, K. Terashima, H. Nomura, Optimal control of liquid container transfer for several performance specifications, *J. Advanced Autom. Techn.*, vol. 6, pp. 353-360, 1994

[13] M.P. Tzamtzi, F.N. Koumboulis, N.D. Kouvakas and G.E. Panagiotakis, A Simulated Annealing Controller for Sloshing Suppression in Liquid Transfer with Delayed Resonators, *14th Mediterranean Conf. on Control and Autom.*, Ancona, Italy, June 2006.

[14] N. Olgac and B. T. Holm-Hansen, A novel active vibration technique: delayed resonator, *Journal of Sound and Vibration*, vol. 176, no. 1, pp. 93-104, 1994

[15] N. Olgac, H. Elmali and S. Vijayan, Introduction to the dual frequency delayed resonator, *Journal of Sound and Vibration*, vol. 189, no. 3, pp. 355-367, 1996

[16] D. Filipovic, N. Olgak, Delayed resonator with speed feedback including dual frequency - theory and experiments, *36th Conf. on Decision and Control*, San Diego, California, USA, Dec. 1997, pp. 2535-2540

[17] O. Buyukozturk and T.-Y. Yu, Structural Health Monitoring and Seismic Impact Assessment, *5th National Conf on Earthquake Engineering*, Istanbul, Turkey, May 2003

[18] M.P. Tzamtzi, F.N. Koumboulis, Robustness of a Robot Control Scheme for Liquid Transfer, *Int. Joint Conf. on Comp., Information, and Systems Sciences, and Eng. (CIS²E 07)*, Dec. 2007.

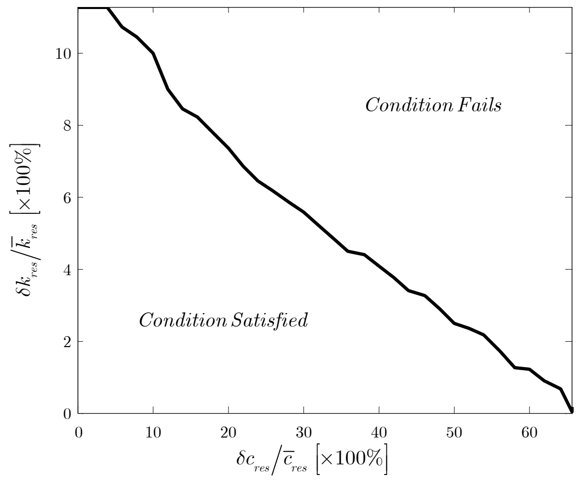

Fig. 3 Robustness analysis for the closed-loop system of the liquid transfer vehicle with uncertain resonator parameters

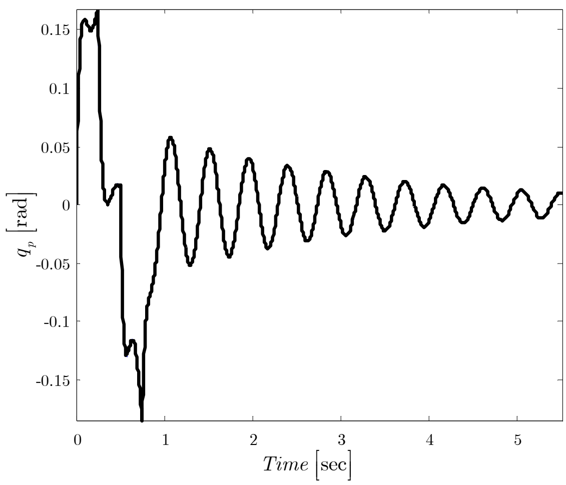

Fig. 4 Closed loop pendulum angle for $\delta k_{res}/\overline{k}_{res} = 0$ and $\delta c_{res}/\overline{c}_{res} = 0$ (continuous) and $\delta k_{res}/\overline{k}_{res} = 9\%$ and $\delta c_{res}/\overline{c}_{res} = 9\%$ (dotted) (visually identical)