Vibration damping performance of the electrohydraulic self-leveling unit of the tracked platform of robotic bricklaying combine

R. Dindorf 1*, P. Wos 1

1Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

*E-mail: dindorf@tu.kielce.pl

Abstract. The study proposes the use of a semi-active hydro-pneumatic spring damper unit for damping pressure pulsations in the servohydraulic leveling system of an electrohydraulic self-leveling unit of a tracked platform of a robotic bricklaying combine (RBC). The semi-active hydro-pneumatic spring damper unit consisted of a gas spring in the hydro-pneumatic accumulator and a controlled hydraulic damping valve. A model of a hydro-pneumatic accumulator with a connection tube was presented, using lumped hydraulic elements in the form of resistance, inductance, and capacitance (RLC). This model was transformed into a form of frequency impedance, from which the amplitude and phase characteristics were determined. The complex impedance of the throttle valve was determined, in which the real part is resistance and the imaginary part is reactance. Finally, the damping performance characteristics of a semi-active hydro-pneumatic spring damper unit were analyzed.

Keywords: vibration, vehicle, automotive safety

1. Introduction

The implementation of advanced technology in construction using robots significantly accelerates and leads to an improvement in the quality of the bricklaying and plastering work. Recently, productivity improvement has not been a major problem in the construction sector, but there is a lack of a sufficient supply of skilled construction workers. Currently, the construction sector is approaching a decisive period of rapid automation and robotization of traditional and innovative technological processes. Robotics is considered a potential solution to improve the efficiency of the construction industry. There have been many reports in literature on the implementation of masonry robots. One study [1] presented research on the possibility of automating masonry. A masonry robot capable of autonomously building walls using cinder blocks is designed. Pritschow et al. demonstrated an automated masonry construction process on a building site using a mobile robot [2]. Madsen analyzed the benefits and weaknesses of SAM100 (Semi Automated Mason) cooperating with a mason worker, which smooths out excess mortar [3]. SAM100 is more effective for large box-shaped structures, such as warehouses. These structures were primarily composed of bricks and other masonry materials. An alternative method is panelization or prefabrication of brick panels in a plant environment [4]. In [5], the author presented a comprehensive methodological process for implementing automation and robotics in housing construction. In previous studies, the authors presented a hydraulic control system for the self-leveling system of a tracked platform for a robotic bricklaying combine (RBC) [6–7]. In cooperation with the industrial
partner Strabag Poland, an innovative research project aimed at designing, manufacturing, and implementing the first mobile RBS in Poland. Strabag is a large international company that focuses on building, construction, civil engineering, and transportation infrastructures. The RBC project was designed for masonry technology classified as a "mobile masonry robot". The main applications of mobile RBS are the facades and partition walls of offices and residential buildings, as well as industrial halls. The mobile RBC enables bricklaying of walls with dimensions limited to the working space of the robot. RBS optimizes the time, cost, and efficiency of masonry work and reduces the amount of waste. The mobile RBC is characterized by a new and innovative design solution, the task of which is to robotize the time-consuming and heavy bricklaying work traditionally performed by hand by masons.

Figure 1 shows a 3D model of an RBC. This RBC is built with a bricklaying robot, a tracked platform (built-up tracked undercarriage with hydraulic unit), the hydraulic self-leveling unit, the brick warehouse, the brick feeder, a control cabinet, and the control panel. Due to the large mass of the bricklaying robot, the brick warehouse with feeders, and the control cabinet, a stable, robust and vibration-resistant leveling system is required. Four hydraulically extendable legs were used to stabilize the position of the tracked platform during automatic bricklaying. The main task of this hydraulic self-leveling unit is to raise the tracked platform to the desired height and precisely level it. The use of an electrohydraulic self-leveling unit is justified in the following cases: level control is needed; level control needs to work frequently; level control needs to react quickly; robust components are required; hydraulic supply is available. The operating conditions of the heavy bricklaying robot with variable load mass cause mechanical vibrations of the structural connections and hydraulic elements of the hydraulic leveling unit. Excess mechanical vibration affects the accuracy of RBC operation. These vibrations excite pressure pulsations in the hydraulic actuators of the self-leveling units. A semi-active hydro-pneumatic spring damper unit was used to reduce the pulsation loads in hydraulic actuators. It is desirable to use a semi-active hydro-pneumatic spring damper unit in which the damping of pressure pulsations is controlled in response to constantly changing excitations of the hydraulic actuator. The semi-active hydro-pneumatic spring damper unit consists of a gas spring in the hydro-pneumatic accumulator and a controlled hydraulic damping valve. The air spring absorbs the excited pressure pulsations, and the hydraulic damper absorber dissipates vibration energy.

![Figure 1. 3D model of an RBC: 1 – bricklaying robot, 2 – tracked platform, 3 – hydraulic self-leveling unit, 4 – brick warehouse and brick feeder, 5 – control cabinet, 6 – control panel.](image-url)
Two electrohydraulic self-leveling units were used to lift and level the tracked platform of an RBC, in which four support legs mounted on a cross-layout are hydraulically extended. The electrohydraulic self-leveling unit is shown in Figure 2.

**Figure 2.** Electrohydraulic self-leveling unit of an RBC: a) view of the extendable one support leg, b) cross-layout of the hydraulically extended support legs: 1 – hydraulic actuator, 2 – support leg.

Figure 3 shows the servohydraulic leveling system with a semi-active hydro-pneumatic spring damper unit used in further analytical considerations.

**Figure 3.** Schematic diagram of the servohydraulic leveling system with a semi-active hydro-pneumatic spring damper unit: 1 – proportional directional control valve, 2 – hydraulic leveling actuator, 3 – proportional throttle valve, 4 – connecting tube, 5 – hydro-pneumatic accumulator.
The leveling of an RBC occurs in two stages: maximum extension of the supporting legs and then lifting and leveling of the tracked platform. In the first stage, the cylinders extend the supporting legs without external load until they come into contact with the ground. In the second stage, the actuators pressed the supporting legs until the tracked platform was raised to the required height. This is followed by leveling in which the servohydraulic leveling systems are controlled to the horizontal position of the track platform. After leveling, the tracked platform is locked mechanically. During robotic bricklaying, the tracked platform was dynamically loaded. These loads generate vibrations transmitted to the bricklaying robot and the servohydraulic leveling system. Therefore, a semi-active hydro-pneumatic spring damper was introduced to maintain the stable position on the track platform exposed to vibration during robotic bricklaying. A semi-active hydro-pneumatic spring damper unit was introduced to maintain a stable position of the dynamically loaded tracked platform during robotic bricklaying. An electrohydraulic self-leveling unit comprises two support legs and two servohydraulic leveling systems with a semi-active hydro-pneumatic spring damper unit. The servohydraulic leveling system consists of a hydraulic leveling actuator, a 4/3 proportional directional control valve, directly operated with electrical position feedback, and integrated control electronics (ICE). The semi-active hydro-pneumatic spring damper unit consists of a 2/2 proportional throttle valve, a connecting tube, and a hydro-pneumatic accumulator. When a controlled throttle valve is placed between the hydraulic actuator and the accumulator, adjustable damping is achieved, which occurs in semi-active shock absorbers. The throttle valve continuously controls the flow resistance (throttling) using the voltage of the proportional solenoid coil. As the coil voltage increases/decreases, the valve spool shifts to increase/decrease flow resistance.

2. Transfer function of the hydro-pneumatic accumulator including the connecting tube

The hydro-pneumatic accumulator with the connecting tube can be modelled by lumped circuit elements in the form of resistance, inductance, and capacitance (RLC),

\[
L_h \frac{dq_c}{dt} + R_h q_c = p_c - p_a ,
\]

\[
q_c = C_a \frac{dp_a}{dt} \Rightarrow \frac{dp_a}{dt} = \frac{1}{C_a} q_c ,
\]

where \(q_c\) is the flow rate in the connecting tube, \(p_a\) is the pressure of the gas (nitrogen) in the accumulator, \(p_c\) is the pressure in the connecting tube, \(L_h\) is the hydraulic inductance of the connecting tube,

\[
L_h = \frac{\rho a}{\pi r^2} ,
\]

where \(r\) is the inner diameter of the connecting tube, \(\rho\) is the density of the oil, \(a\) is the velocity of the sound

\[
a = \frac{K}{\sqrt{\rho}} ,
\]

where \(K\) is the bulk modulus of oil, \(R_h\) is the hydraulic resistance of the connecting tube from the Hagen–Poiseuille equation,

\[
R_h = \frac{8 l \eta}{\pi r^4} ,
\]

where \(l\) is the length of the connecting pipe, \(\eta\) is the dynamic viscosity of oil,
Cₐ is the gas capacitance of the hydraulic accumulator [4],

\[ C_a = \frac{dV}{dp} = \frac{V_0}{n p_0} \left( 1 - \frac{\Delta V}{V_0} \right)^{n+1} \approx \frac{V_0}{n p_0}, \]  

where \( p_0, V_0 \) is the pressure and volume of the gas in the initial state and \( n \) is the polytropic index of change in the gas state.

After differentiation of Eq. (1) and substituting Eq. (2), it is obtained:

\[ C_a L_h \frac{d^2 q_c}{dt^2} + C_a R_h \frac{dq_c}{dt} + q_c = C_a \frac{dp_c}{dt}. \]  

After the Laplace conversion, Eq. (7) was transformed into a transfer function,

\[ G_a(s) = \frac{q_c(s)}{p_c(s)} = \frac{C_a s}{C_a L_h s^2 + C_a R_h s + 1} = \frac{C_a s}{1/2 \omega_n^2 + 2 \zeta \omega_n s + 1}, \]  

where \( \omega_n \) is the natural frequency,

\[ \omega_n = \frac{1}{\sqrt{C_a L_h}}, \]  

\( \zeta \) is the damping coefficient,

\[ \zeta = \frac{1}{2} C_a R_h \omega_n. \]  

The transfer function \( G_a(j\omega) \) in the frequency domain of the accumulator, including the connecting tube, has the form:

\[ G_a(j\omega) = \frac{q_c(j\omega)}{p_c(j\omega)} = \frac{C_a j \omega}{1 - \frac{\omega^2}{\omega_n^2} + 2 \zeta j \omega} = \frac{1}{\alpha + j \beta}, \]  

where \( \alpha \) and \( \beta \) are the constant coefficients,

\[ \alpha = \frac{1}{C_a \omega_n}, \]  

\[ \beta = 2 \zeta, \]  

3. Impedance of the hydro-pneumatic accumulator with the connecting tube

Fluctuations of a pressure and flow rate in the hydro-pneumatic accumulator including the connecting tube can be modelled in the frequency domain using the impedance \( Z(j\omega) \), which, analogously to the electrical impedance in an AC circuit (ratio voltage to current), is determined by the ratio of pressure \( \Delta p \) and flow rate \( q_c \):
\[ Z(j\omega) = \frac{\Delta p(j\omega)}{q_s(j\omega)} \text{ in } \frac{Pa}{m^5}. \] (14)

The impedance \( Z_a(j\omega) \) of the hydro-pneumatic accumulator with the connecting tube is reciprocal to (11);

\[ Z_a(j\omega) = \frac{p_a(j\omega)}{q_s(j\omega)} = \alpha \left[ \beta + j \left( \frac{\omega}{\omega_n} - \frac{\omega_n}{\omega} \right) \right]. \] (15)

From Eq.(15) results the impedance modulus;

\[ |Z_a(j\omega)| = \alpha \sqrt{\beta^2 + \left( \frac{\omega}{\omega_n} - \frac{\omega_n}{\omega} \right)^2}, \] (16)

and the impedance argument;

\[ \arg[Z_a(j\omega)] = \arctan \left( \frac{\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}}{\beta} \right). \] (17)

Eq.(16) was presented in a dimensionless form;

\[ |Z_A(j\omega)| = \frac{|Z_a(j\omega)|}{\alpha} = \sqrt{\beta^2 + \left( \frac{\omega}{\omega_n} - \frac{\omega_n}{\omega} \right)^2}. \] (18)

The characteristics of the impedance amplitude and impedance phase of the hydro-pneumatic accumulator for the basic parameters introduced: \( l = 0.01 \) m, \( r = 0.0025 \) m, \( p_0 = 1 \) MPa, \( V_0 = 0.001 \) m\(^3\) are shown in Figures 4 and 5.

Figure 4. Characteristics of the impedance amplitude.
Figure 5. Characteristics of the impedance phase.

4. Damping performance of a semi-active hydro-pneumatic spring damper unit

The best mathematical way to write the impedance of the valve is a complex form, the real part is the ‘resistance’ $R$ and the imaginary part is the ‘reactance’ of an inductive element $Z_L = j \omega L$;

$$Z(j\omega) = R + Z_L = R + j\omega L,$$

or of a capacitance element $Z_C = 1/j\omega C$;

$$Z(j\omega) = R + Z_C = R + \frac{1}{j\omega C},$$

where $\omega$ is the angular frequency, $R$ is the resistance, $L$ is the inductance, and $C$ is the capacitance.

The phenomenon of flow through the valve describes not only the resistance $R$, but also the inductive effect $L$ observed as a result of the high flow velocity. The capacitive effect can be explained by the volume of fluid contained in the valve chamber between the connection port and the orifice, the flow rate through the throttle control valve;

$$q_v(z) = \frac{C_d A(z)}{\sqrt{\rho}} \sqrt{\Delta p},$$

where $C_d$ is the discharge coefficient, $A$ is the area of throttle valve, $\Delta p$ is the pressure drop, $z$ is the shift of a spool valve;

$$z = \frac{z_{\text{max}}}{u_{\text{max}}} u = K_z u,$$

where $K_z$ is the gain factor and $z_{\text{max}}$ is the maximum deflection of the spool from the center position, $z_{\text{max}} = \max(|z_{\text{min}}|, |z_{\text{max}}|)$, $z_{\text{min}}$ is the minimum spool stroke, $z_{\text{max}}$ is the maximum spool stroke, the spool path is limited to $z_{\text{min}} \leq z \leq z_{\text{max}}$.

Eq.(18) linearization for small perturbations around the operating $n$-point;

$$q_v(z_n) = \frac{\sqrt{2}}{2} \frac{C_d A(z_n)}{\sqrt{\rho}} \Delta p = \frac{1}{R(z_n)} \Delta p,$$

where $R$ is the flow resistance through the throttle control valve;
\[ R(z_n) = \frac{2}{\sqrt{2}} \frac{\sqrt{\rho}}{C d A(z_n)} \sqrt{\Delta p_n}. \]

The dynamic valve model is presented as the first-order differential equation given by

\[ q_v = \frac{1}{R} \Delta p + C \frac{d\Delta p}{dt}, \quad \Rightarrow \quad q_v(s) = \frac{1}{R} \Delta p(s) + C s \Delta p(s), \]

where \( q_v \) is the flow rate in the control valve, \( \Delta p \) is the pressure drop, \( C \) is the capacitance of the valve, and \( R \) is the flow resistance.

The impedance of the throttle valve is characterized by a PT1 transfer function;

\[ Z_v(s) = \frac{\Delta p(s)}{q_v(s)} = \frac{R}{1 + R C s} = \frac{R}{1 + T s}, \]

where \( T \) is the constant time \( T = RC \);

\[ Z_v(j\omega) = \frac{\Delta p(j\omega)}{q_v(j\omega)} = \frac{R}{1 + j\omega T}. \]

It is possible to remove the effects of the impedance of the capacitive component of the valve impedance by shifting the point at which the impedance is measured inside the valve so that the effective volume is zero. The impedance measured in this way is closer to the simple resistance model, and then (27) has the form \( Z_v = R \).

The impedance function results from the flow continuity equation in a semi-active hydro-pneumatic spring damper unit,

\[ q_c = \frac{1}{Z_a} p_c = q_v = \frac{1}{Z_v} \Delta p = \frac{1}{Z_v} (p_A - p_c) \]

\[ p_A = \left( \frac{Z_v}{Z_a} + 1 \right) p_c \quad \Rightarrow \quad Z_p = \frac{P_A}{P_c} = 1 + \frac{Z_v}{Z_a} \]

where \( p_0 \) is the upstream pressure set by the control valve and \( p_c \) is the downstream pressure.

The impedance function was calculated from (29);

\[ Z_p(j\omega) = 1 + \frac{R}{\alpha \beta + \alpha j \left( \frac{\omega}{\omega_n} - \frac{\omega_n}{\omega} \right)} \]

The impedance modulus was determined as follows;

\[ |Z_p(j\omega)| = \sqrt{1 + \frac{R^2}{\alpha^2 \beta^2 + \alpha^2 \left( \frac{\omega}{\omega_n} - \frac{\omega_n}{\omega} \right) \beta^2}} \]

The semi-active hydropneumatic spring damper unit can be evaluated by the damping performance defined as follows;

\[ D = 20 \log |Z_p(j\omega)| \quad dB \]

Based on (32), the characteristics of the damping performance of the semi-active hydro-pneumatic spring damper unit were determined. Figure 6 shows the characteristics of the damping performance for
different input voltages $u$ of the controlled throttle valve at the upstream pressure $p_A = 1$ MPa. Figure 7 shows the characteristics of the damping performance for different upstream pressures $p_A$ at the input voltage $u = 5$ V of the throttle valve.

![Figure 6](image1.png)

**Figure 6.** Characteristics of damping performance for different input voltages $u$ of the controlled throttle valve at upstream pressure $p_A = 1$ MPa.

![Figure 7](image2.png)

**Figure 7.** Characteristics of damping performance for different upstream pressures $p_A$ at input voltage $u = 5$ V of the throttle valve.

The effectiveness of the damping system was evaluated using the peak pressure overshoot ratio defined as follows:

$$
\delta_p = \frac{\Delta p}{p_{pp}} = \frac{p_{pp} - p_{sp}}{p_{pp}}
$$

(33)

where $\Delta p$ is the overshoot of the peak pressure, $p_{pp}$ is the peak pressure, and $p_{sp}$ is the set pressure.

Figure 8 compares the simulation and the experimental shock pressure ratio for different shock forces.
Figure 8. Comparison of the peak pressure overshoot ratio for various shock forces.

5. Conclusions
This study focuses on the frequency analysis of the damping performance of a semi-active hydro-pneumatic spring damper unit in the servo-hydraulic leveling control of a semi-active electrohydraulic leveling unit of a tracked platform of an RBC. Based on the impedance characteristics, the parameters of the hydro-pneumatic accumulator and connected tube were selected to minimize pressure pulsation for a given flow rate. By controlling the flow resistance of the throttle valve, the damping performance characteristics of the semi-active hydro-pneumatic spring damper unit were selected for the vibrations of the servo-hydraulic leveling system excited by external loads of the robotic bricklaying combine. Moreover, this work requires further research on the control system of a semi-active hydro-pneumatic spring damper unit.

Acknowledgments
This study, part of a research project POIR.04.01.02-00-0045/18-00 ‘Development and demonstration of a robotic bricklaying and plastering system for use in the construction industry’, was financially supported by the National Centre for Research and Development in Poland within the framework of the Smart Growth Operational Programme 2014-2020.

References
[1] Dakhli Z and Lafhaj Z. 2017 Robotic mechanical design for bricklaying automation. Cogent Engineering vol.4 pp.1-22.
[2] Pritschow G, Dalacker M and Kurz J. 1995 Gaenssle, M. Technological aspects in the development of a mobile bricklaying robot. In Proc. 12the ISARC. I. Sym. on Auto. and Rob. in Const. Warsaw, Poland, 30.05-01.06.1995 pp.1–8.
[3] Madsen A J. 2019 The SAM100: Analyzing labor productivity. Construction Management Department, California Polytechnic State University, San Luis Obispo USA.
[4] Rihani R A and Bernold L E. 1996 Methods of control for robotic brick masonry. Automation in Construction 4 pp.281-292.
[5] Pan W. Methodological development for exploring the potential to implement on-site robotics and automation in the context of public housing construction in Hong Kong. Ph.D. Thes. Lehrstuhl für Baurealisierung und Baurobotik, Technische Universität München, München 2020, Germany.
[6] Wos P, Dindorf R and Takosoglu J. 2020 The electro-hydraulic lifting and leveling system for the bricklaying robot. In Book: Lecture Notes in Mechanical Engineering Springer no 13 pp 215-227.
[7] Wos P, Dindorf R and Takosoglu J. 2021 Bricklaying robot lifting and leveling system. Communications - Scientific Letters of the University of Žilina vol 23 no 4 pp B257-B264.