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Optimization of hydraulic dampers with the use of Design For Six Sigma methodology

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Analysis and modelling

ABSTRACT

Purpose: The aims of this paper are to identify the root cause of the temporary decrease in the damping force which occurs during the early stage of the stroking cycle's compression phase, the so-called damping lag, to describe measures of the phenomenon and to present methods for optimizing the design towards minimizing this (negative) effect.
Design/methodology/approach: A theoretical background is presented in a constructive and computable manner with emphasis on data-driven modeling. The Design For Six Sigma (DFFS) approach and tools were used to validate the model statistically and, more importantly, to propose a method for data-driven optimization of the design.
Findings: The root cause of the damping lag was confirmed during model validation as being a result of oil aeration. DFFS methodology proved to be useful in achieving design optimality.
Research limitations/implications: The statistical model and conclusions drawn from it are only valid in the interior of the investigated region of the parameter space. Additionally, it might not be possible to find a local minimum of the aeration measure (damping lag) inside the selected region of the parameter space; a/the (depending on the context) global minimum located at the boundary might be the only possible solution.
Practical implications: The optimal value of parameters is not unique and thus additional sub-criteria (cost/durability) can be imposed. Conducting tests in an organized manner and according to the Six Sigma methodology allows the design optimization process to be expedited and unnecessary costs to be eliminated.
Originality/value: Improvements in understanding and measuring aeration effects constitute a clear foundation for further product optimization. Signal post-processing algorithms are essential for the statistical analysis and are the original contribution of this work.
Keywords: Design for Six Sigma; First-principle; Data-driven

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1. Introduction

Six Sigma is a statistically-supported methodology focused on improving processes within different businesses. This methodology is successfully used across automotive [1], aerospace, electrical, mechanical, medical, chemical and other businesses aimed at improving the full range of commonly known processes: research and development, product or process design, testing, manufacturing, finance, logistics and many others. It is not only a quality-oriented methodology [2], it's much broader and is also known as culture change. It provides theoretical and numerical means to define the goal, understand the voice of customers, analyze and improve the situation using statistical evaluation of data and, finally, verify achieved results. There are two main paths in Six Sigma methodology: the classic approach suitable for manufacturing and the more extended approach for engineering. The first approach is concentrated on so-called repair projects run through DMAIC projects, where DMAIC stands for the names of the phases; define, measure, analyze, improve and control. The new product development projects are run through DMADV phases, which are: define, measure, analyze, improve and verify [3,4]. DFSS is extended as it starts with analysis of customer requirements, through design optimization [5,6] and, finally, the start of production. The aim of DFSS is to design a product which meets customer needs and to simultaneously achieve the Six Sigma quality target (3.4 defects per million parts) for the final product. The critical aspect of DFSS is minimization of variation in product characteristics. [7].

The paper presents an application of DFSS methodology for solving the problem of minimizing the damping lag phenomenon in hydraulic shock absorbers [8,9,10]. The described project utilizes DFSS methodology as such and its tools. The project is always initialized with the use of a project charter which defines the scope of the problem, the objective, metrics, and the team assigned to solve the problem [11]. This first step is extremely important for the success of the project and - from a practical point of view - involvement of the necessary resources. Six Sigma, as a statistically-supported methodology, works with data; all steps in the project and conclusions are taken based on data evaluation. Therefore, measurement systems need detailed investigation to provide the sufficient quality of data. The example of Measurement System Analysis (MSA) is mentioned in Section 4. The tool used to optimize design is Design of Experiment (DOE). This is a structured approach to planning and analyzing the model under investigation. It has proved to be extremely useful and practical in the engineering environment [11,12].

Finally, the project needs to be finished according to Six Sigma and the DFSS approach, which means with a control or verification phase. Different statistical tools can be used, such as SPC (Statistical Process Control), a capability study or Gage R&R to verify and control progress in the implementation of improvements. The results of the project for minimizing damping lag were deployed as Standard Test Procedure (STP) in the departments responsible for product tests. As STP is an official and controlled document it can be used across the organization and possible improvement changes can be tracked and communicated.

2. Background

Functionally, an ideal shock absorber (damper) should satisfy the following, sometimes viewed as contradictory, criteria. In order of importance: (i) a car damper has to guarantee good road handling of the car, (ii) it has to be designed for durability, (iii) the radiated noise and emitted vibrations should have as low a level as possible, and (iv) it should ensure passenger comfort. In order to satisfy these design criteria, the data-driven DFSS approach was proposed instead of first-principle one.

2.1. Shock absorber working principles

This sub-section presents the fundamental working principles of a hydraulic shock absorber. The hydraulic double-tube damper presented in Fig. 1 consists of a piston moving within a liquid-filled cylinder. As the piston is forced to move within the cylinder (pressure tube), a pressure differential is built across the piston and the liquid is forced to flow through valves located in the piston and the base-valve assembly. The presence of the piston divides the cylinder space into two chambers: (i) the rebound chamber, that portion of the cylinder above the piston and (ii) the compression chamber, that portion below the piston. The action of the piston transfers liquid to and from the reserve chamber, surrounding the cylinder, through the base-valve assembly located at the bottom of the compression chamber. Two types of valves are used in the shock absorber: (1) intake valves and (2) control valves. The intake valves are basically check valves which provide only slight resistance to flow in one direction and prevent flow in the opposite direction when the pressure differential is reversed. Control valves are preloaded through a valve spring to prevent opening until a specified pressure differential has built up across the valve.

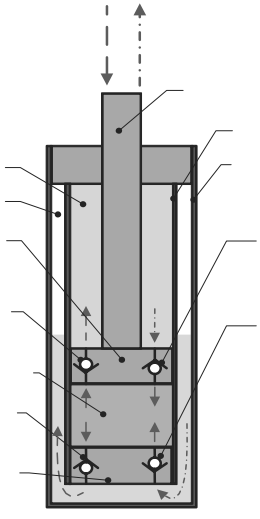

Fig. 1. Shock absorber working principle

The two working phases of a hydraulic shock absorber are distinguished as the compression phase and rebound phase. During the compression phase the rod is tucked into the damper, compression chamber volume decreases and oil flows through the piston compression intake valve (piston intake) and the base compression control valve (base valve) accordingly, to the rebound and reserve chambers. During the rebound phase the rod is ejected from the damper, the compression chamber volume increases and oil flows through the piston rebound control valve (piston intake) and base rebound intake valve (base intake) accordingly, to the rebound and reserve chamber

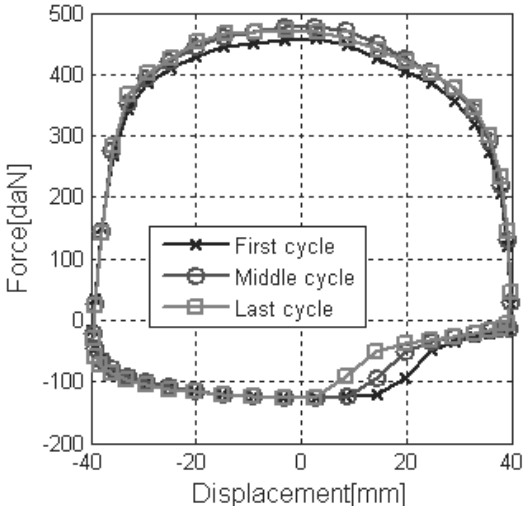

Fig. 2. The force-displacement characteristic of a shock absorber

2.2. The influence of aeration on shock absorber behavior

Aeration is the process by which air/gas is circulated through, mixed with, or dissolved in a liquid. Gas is included in dampers under certain pressure, separately from the oil, to provide compressibility to allow for the rod displacement volume compensation. A liquid that was exposed to a soluble gas (i.e. the liquid came into contact with the atmosphere of a gas that can dissolve in it) can be in one of three forms: liquid-gas solution, liquid-gas bubble emulsion or foam. The liquid-gas solution is prone to bubble formation when the pressure of the liquid-gas solution decreases below the so-called saturation pressure. In this state, the liquid is no longer capable of retaining all the gas in its dissolved form and therefore bubbles occur. The solubility of gas in a liquid is directly proportional to the absolute pressure above the liquid surface (Henry's law), and normally decreases with rising temperature [9]. All of the mentioned liquid-gas mixtures can be considered as liquid with pockets of gas. The dissolved gas has a significant influence on the mixture density and thus on the shock absorber's behavior. The presence of gas bubbles is the cause of the damping force loss in the shock absorber. It is an undesirable and negative effect visible as asymmetry of the force displacement characteristic and should be minimized. Fig. 2 shows the influence of aeration effect on the damper performance based on the force-displacement characteristic. The aeration effect causes a drop in the force visible in the bottom-right corner of the characteristic. The damper was cycled with high velocity of 1.5 m/s, three sequences were plotted to show deterioration of the force-displacement characteristic.

3. First-principle modeling

3.1. Basic terminology

The absolute pressure P, the density $\rho = m/V$ [kg/m^3] and the absolute temperature T of the ideal gas are related by the perfect gas equation

$$PV = mR_G T \tag{1}$$

where R_G is the specific gas constant, which for nitrogen is equal to

$$R_N = 296.80 \tag{2}$$

Clearly, the density of the gas held in temperature T and under pressure P is equal to

$$\rho_G = \frac{P}{RT} \tag{3}$$

Volumetric thermal expansion coefficient α is defined as follows

$$\alpha_L = -\frac{1}{\rho_L}\left(\frac{\partial \rho_L}{\partial T}\right)_{p=\text{const}} \tag{4}$$

Experiments indicate that the dependence of the density in temperature is nearly linear and the formula may be simplified to take the form

$$\alpha_L = -\frac{1}{\rho_L}\left(\frac{\Delta \rho_L}{\Delta T}\right)_{p=\text{const}} \tag{5}$$

which yields that the temperature dependence of the density is a decreasing linear function

$$\rho_L = \rho_L(T) = \rho_{0L}\left[1 - \alpha_L\left(T - T_0\right)\right] \tag{6}$$

where ρ_{0L} is the reference liquid density measured at temperature T_0 and α_L is the volumetric thermal expansion coefficient of the liquid. Equivalently, by renaming ρ_L by ρ_{0L} and T by T_0, one can write that

$$\rho_L = \rho_L(T) = \frac{\rho_{0L}}{1 + \alpha_L\left(T - T_0\right)} \tag{7}$$

For typical damper oil the volumetric thermal expansion coefficient is $\alpha_{oil} \approx 10^{-3}$. Specifically for the purpose of this paper experimental data of density vs. temperature were used. Available data for the oil indicate that

$$\rho_{\text{oil}}(T) = -0.6325 \cdot T + 855.97 \tag{8}$$

The formula was obtained as a linear least squares fit to experimental density data. Solubility of gasses in liquids is directly proportional to the partial pressure of the gas above the liquid surface (Henry's law) and normally decreases with rising temperature [13,14]. Another words, for a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid.

$$p_G = k \cdot c \tag{9}$$

where p_G is the partial pressure of the gas above the liquid-gas mixture, c is the concentration of gas in the oil-gas mixture and k is the Henry's law constant [Pa·m^3/mol]. The quantity of gas that can dissolve in a liquid depends on the particular gas and liquid. If there is any chemical affinity between the two, the amount may be considerable. The extreme case is when the gas is the vapor of the liquid in which case the absorbability is infinite. For non-reacting materials, maximal absorbable mass of gas $m_{GA\max}$ is given by the following bi-linear equation (Henry's law)

$$m_{GA\max} = c_{GA} \cdot V_L \cdot p_G \tag{10}$$

where c_{GA} is the gas absorption coefficient, V_L is the liquid volume and p_G is the partial pressure of the particular gas above the liquid. The absorption coefficient is specific for a particular combination of gas and liquid [13,14].

3.2. Emulsification

Emulsion is a combination of two essentially immiscible liquids, in which one of the liquids is divided into very fine droplets suspended uniformly in the other liquid. The liquids are immiscible in the sense that they do not blend uniformly at the molecular level. The term emulsion is also applied to a finely dispersed gas in the liquid, with the gas in very small bubbles. For the mixture of gas bubbles and the liquid to qualify as the emulsion, yet another condition has to be satisfied i.e. the liquid must not easily absorb the gas content. Hence, the presence of the liquid vapors in the form of bubbles does not constitute the emulsion; their behavior is different because, however great the volume of liquid vapor or however finely divided, the vapor is easily reconverted to liquid by an increase of pressure [14].

A true gas-liquid emulsion is highly stable since the gas from bubbles can be absorbed into the liquid only up to certain, well defined by the pressure, extent. Absorption can be fast only if the liquid has the residual absorption capacity and the gas is in the form of small bubbles with the large total area. Once a fine gas-liquid emulsion is formed, it is difficult to separate out the fine gas bubbles. This is the case of the emulsion formed inside the car damper where the valving causes larger bubbles to be divided into small ones and the emulsion is mixed efficiently thus preventing small bubbles from escaping toward the surface of the oil in the reserve tube [14].

Emulsion formation has a very complicated mechanism and occurs as time scales different from the typical time scales of the damper motion. At the current state of the knowledge and with available damper models, it is not possible to calculate emulsification on-line. The approach used in this research work is based on experimental identification of the emulsion parameters using a damper unit with transparent reserve tube. Analysis of experimental data is presented in the next section; in here, we present a brief, theoretical analysis of the emulsion formation assuming static conditions [13,14].

Depending on the initial gas pressure P_0 [Pa] and liquid volume V_L [m^3] (Henry's law), a certain volume of gas is absorbed into the liquid forming a solution - gas and oil particles are mixed together at the molecular level. If the liquid is left in such a state, the emulsion will not form. Physical properties of the gas solution are very similar to that of the pure liquid. In particular, in most cases, the volume increase is compensated by increased compressibility of the solution. Indeed, the volume of the gas solution V_S is given by [14]

$$V_S = V_L - V_L \frac{p_G}{\beta_L} + C_{GLV} \frac{m_{GA}}{m_L} V_L \tag{11}$$

and it can be assumed that

$$V_L \frac{p_G}{\beta_L} = C_{GLV} \frac{m_{GA}}{m_L} V_L \tag{12}$$

giving $V_S = V_L$. A situation dramatically changes when such a solution is exposed to varying pressure. If the solution does not have a contact surface with the gas, increase of the pressure will have no effect on the gas content. Decrease of the pressure ($P_0 - P > 0$) will however cause some of the dissolved gas to form bubbles since mass of gas that can dissolve in a given oil volume is a linearly increasing function of pressure. The mass of gas present in the liquid in the form of bubbles can be computed from the Henry's law and amounts to

$$m_{G\_bubbles}(P) = m_{GA\max} - m_G(P) = c_{GA} \cdot V_L \cdot (P_0 - P) \tag{13}$$

Summarizing, the mass of gas in bubbles is equal to

$$m_{G\_bubbles} = \begin{cases} c_{GA} \cdot V_L \cdot (P - P_0) & \text{for} \quad P - P_0 > 0, \\ 0 & \text{for} \quad P - P_0 \le 0. \end{cases} \tag{14}$$

It is clear, that presence of bubbles in the oil (emulsification) influences the density of the oil. Since the total volume (emulsion volume V_E) is $V_E = V_L + V_{G\_bubbles}$ and the mass of the emulsion is $m_E = m_L + m_{G\_bubbles} + m_{GA}$, emulsion mean density is

$$\rho_E = \frac{m_E}{V_E} = \frac{m_L + m_{G\_bubbles} + m_{GA}}{V_L + V_{G\_bubbles}} \tag{15}$$

At saturation pressure conditions

$$P_{sat} = \frac{P_{fill} + \alpha_v \cdot V_{oil}/V_{gas} \cdot P_0}{1 + \alpha_v \cdot V_{oil}/V_{gas}} \tag{16}$$

where $\alpha_v = 0.085$ is the Bunsen solubility coefficient, the gas content in the oil can be calculated from Henry's law. Depending on the pressure, the gas will stay dissolved or form bubbles in the oil. It is assumed that if the pressure is higher that the saturation pressure than nothing happens, while when the pressure drops below the saturation pressure then bubbles form instantaneously and there will be a certain mass of gas in the bubbles. The mass of gas in bubbles is the difference between mass of gas dissolved at the saturation pressure and the mass of gas soluble at given, current pressure. It is now possible, using the perfect gas equation, to calculate both, the emulsion density and the mass of gas in bubbles to the mass of the emulsion.

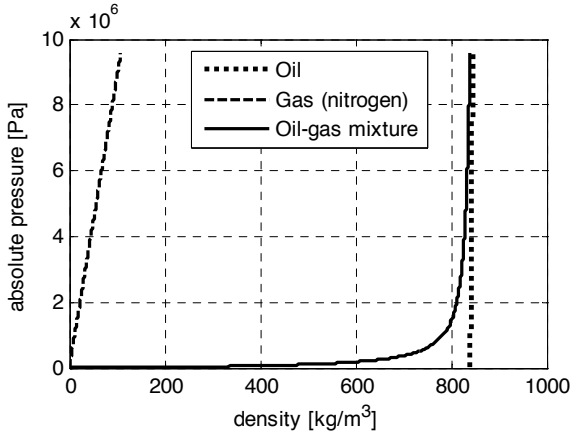

Fig. 3. Density-pressure relation for gas (nitrogen), fluid (oil) and fluid-gas mixture

The following are the assumptions behind the theoretical calculations presented here:

- At model initialization, it is assumed that the damper is filled with oil and gas under pressure.
- Gas dissolves in oil until saturation, i.e. until the pressure drops to (Bunsen coefficient).
- The ratio of mass of gas in bubbles to the total mass of the emulsion is computed using Henry's law.
- For a given pressure and temperature the mass of gas in bubbles is computed with assumption, that bubble formation is an instantaneous process and that all excess gas is in the form of bubbles. It is also assumed that bubbles occur in the entire volume of oil.
- The following are difficulties caused by the assumption made for the theoretical approach:
- Damper dynamics is not taken into account - bubble formation depends on pressure and oil volume, thus, theoretically bubble content should vary between chambers and change during the operation.
- Gas dissolving and bubble formation occur at different time scales (slow) than oil flow (fast). It is therefore impractical to extend the damper models, which typically run for a couple of cycles, to take into account forming the oil-gas bubbles emulsion, which typically takes a couple of hundreds cycles to achieve stable conditions.

4. Data-driven modeling

4.1. Two-phase flow model theory

Solubility of the gas in the fluid can be measured with the χ value described in [13,14]. The χ value is a ratio of the mass of gas to the total mass of fluid and gas. Using a value of χ empirically calculated (based on Henry's law) or obtained by experiment, the density of the homogeneous fluid-gas mixture illustrated in Fig. 3 can be calculated with use of the following formula

$$\rho_{hom} = \left(\frac{\chi}{\rho_{gas}} + \frac{1-\chi}{\rho_L} \right)^{-1}, \qquad \chi = \frac{m_{gas}}{m_L}, \tag{17}$$

$$\chi = \frac{m_{gas}}{m_L} = \frac{p \cdot V_{gas} \cdot M}{R \cdot T \cdot m_L} \tag{18}$$

where: ρ_{hom} is the density of the homogeneous fluid-gas mixture, ρ_L is the fluid density, ρ_{gas} is the gas density, m_L is the fluid mass and m_{gas} is the total mass of the gas dissolved (emulsion) and non-dissolved (bubbles) in the fluid. The densities presented in Fig. 3 were calculated for a constant temperature (isothermal process).

4.2. Analysis of experimental data

This sub-section describes how to process measured data (temperature, pressure and oil height) in order to obtain the value of c at specified moments during the test. From damper geometry, the actual volume of the emulsion is equal to

$$V_E = V_{PT} + h \cdot \pi \cdot (d_{RT}^2 - d_{PT}^2)/4 \tag{19}$$

where d_{PT} is the outer diameter of the pressure tube and d_{RT} is the inner diameter of the reserve tube; h is the height of the oil column; and V_{PT} is the volume of the pressure tube. The volume of dissolved gas and gas entrapped in bubbles is the difference between the total volume of the emulsion and the theoretical volume of oil at a given temperature, $V_{gas} = V_E + V_L(T)$, where the theoretical volume of pure oil in the function of temperature is

$$V_L(T) = \frac{\rho_0 V}{\rho(T)_0} \tag{20}$$

It is assumed that the volume V_0 at a given temperature has the density ρ_0. Typically, the volume V_0 is the volume computed at the beginning of the first test and the density ρ_0 is computed for the temperature measured at the beginning of the first test. The total mass of gas, dissolved and entrapped in bubbles, is therefore readily computed using the formula

$$m_{gas} = \frac{p \cdot V_{gas}}{T} \cdot \frac{M}{R} \tag{21}$$

where: M = 2·14 [g/mol] for nitrogen, R = 8.314 [J/(mol·K)], T is the temperature and p is the absolute pressure.

Before making conclusions from the data, it has to be validated in order of correctness and consistency. For example, a measurement system needs to be evaluated and improved if it is required in the measurement phase of a Six Sigma project. To better understand all the factors influencing the measurement system, the Ishikawa and measurement system process map can be helpful. The Ishikawa example is presented in Fig. 4.

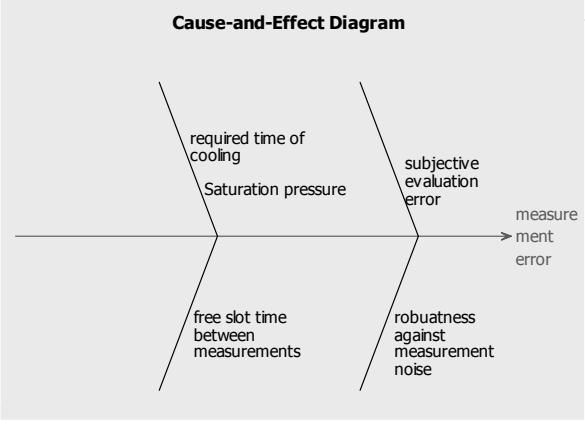

Fig. 4. Ishikawa graph (also called fishbone or cause and effect graph) for incorrect reading of aeration curves

Analyses of the results were performed using Six Sigma tools (DOE analysis). The team decided to start the experiment by varying the 2 most controllable and measurable parameters, i.e. the initial oil volume (V_{oil}) and the initial (before saturation) gas pressure (p_{fill}). The reason for such a choice of parameters comes directly from Henry's law of solubility which relates the mass of dissolved gas to the volume of the liquid and the pressure of the gas. There are several different ways (the so-called aeration measures) to quantitatively describe the degree of aeration and the effects it has on the performance (the so-called damping lag or free stroke). Comparisons have been made on different test and post processing methods. One of the most frequently-used methods, based on customer specification, is to read the curve with the negative effect of damping lag and compare it to the original performance curve. It has been observed by the team that using this method can mean the test results are influenced by the perception of the engineer performing the post processing. To quantify the measurement system's precision, Gage R&R was performed. 40 curves were read twice by 3 engineers, the experiment structure in line with Gage R&R crossed requirements. The results were extremely poor as the total variation of the measurement system was 7 times higher (710%) than the tolerance band, and the maximum allowed percentage is 30%. In some cases the range of measured values was up to 70% of aeration degree. The tolerance percentage is equal to the tolerance band divided by 6 standard deviations of the measurement system. Therefore it is necessary to decrease the variation of the measurement system for a given property with specific tolerance. Fig. 5 shows a graphical representation of Gage R&R results

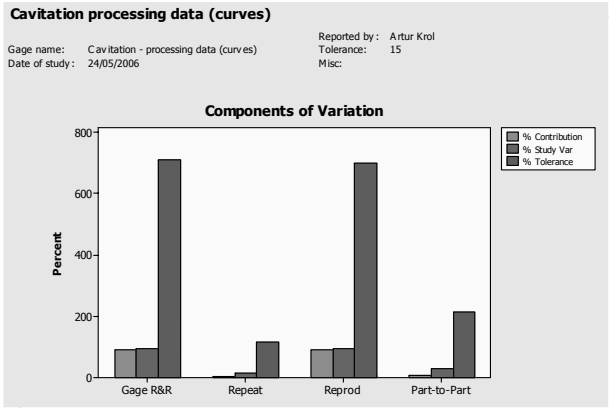

Fig. 5. Component of variation of Gage R&R - situation before improvements

Therefore, for the purpose of this presentation, the free stroke (μ), which is the length of the displacement from the maximal displacement to the point of change for the sign of the force signal's second derivative (the inflection point), was used. This method eliminates the human perception factor in the measurement system.

The major difficulty with this approach is the influence of measurement noise on the inflection point selection method. Iterative use of the Savitzky-Golay filter permits the selection of only the most relevant inflection point. Filter parameters (the degree k of the polynomial and the size n of the frame, for details see [15]) were adjusted iteratively to obtain a single inflection point from which the free stroke was calculated, relative to the length of the test stroke.

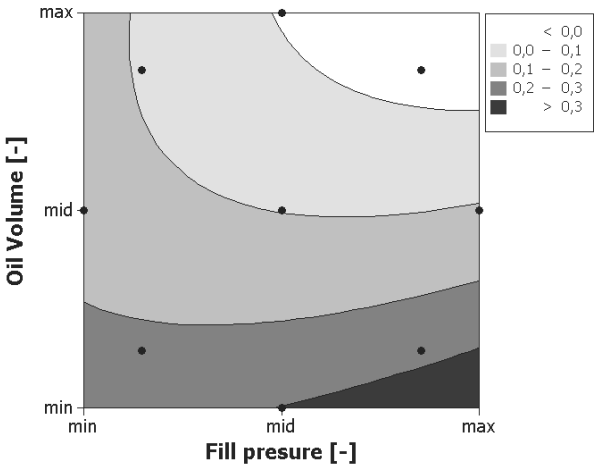

Fig. 6. Contour plot of the response surface of the parameter free stroke μ vs. oil volume V_{oil} and the fill pressure p_{fill} obtained after 500 cycles

The main task and focal point of this paper, namely design optimization by minimizing (negative) aeration effects is achieved by selecting such a combination of parameters, i.e. the gas pressure and the oil volume, for which a chosen aeration measure yields a minimal value. The actual selection process is performed visually based on the contour plot of the best-fit surface, the so-called response surface, created separately for each set of DOE measurements. An example of response surface contour plot for aeration measure is shown in Fig. 6. Such an approach to optimization is feasible thanks to the small number of parameters. In the case of higher-dimensional parameter spaces, other visualization techniques or more automated optimization algorithms may be used. In terms of accuracy, one should note that this optimization approach yields a region of parameter space and permits other criteria (such as cost or durability requirements) to be easily imposed, that is without additional measurements and analysis. In order to validate the new processing method, the so-called controlled Gage R&R was performed (Fig. 7).

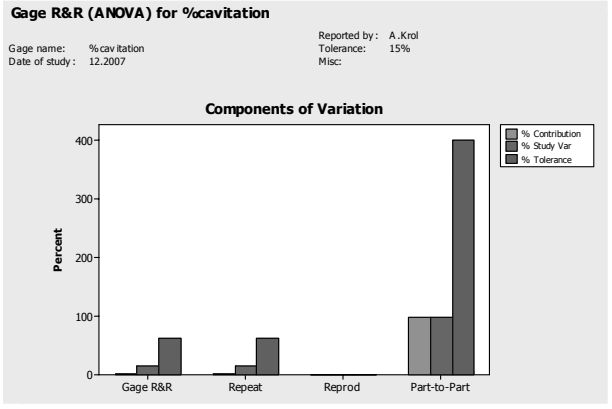

Fig. 7. Chart presents variation of components

The results show a significant improvement, especially for the contribution percentage (from 92% to 2.4%) The other Gage R&R parameter - tolerance, was decreased from 710% to 68%.

5. Conclusions

Modeling the dynamics of bubble formation and transport is a very difficult task for several reasons. The most important ones are the differences between time scales in which aeration processes occur (order of minutes) and the time scales of oil flow through the damper (order of seconds), the existence of uncontrollable parameters on which bubble size depends, the bubble size itself (e.g. oil impurities and sharp edges), and the re-absorption of gas from the bubble surface, etc. At present, the most efficient approach is to use experimental, average characteristics of the oil/gas emulsion (ratio of the mass of gas in bubbles to the mass of the oil-gas bubble emulsion) at model initialization, and predict the force response of the modeled shock absorber. During the work on this paper, the authors began to realize the high level of complication of the aeration phenomenon and decided that more reliable data and data processing algorithms are necessary before any attempt to create a prediction tool can be made. It was decided that, by using Six Sigma methodology and carefully organizing data collection and the analysis process, two goals, namely the continuous improvement of the product and the aeration model identification, can be achieved.

Six Sigma tools (DOE analysis) for the measurement and simulation results indicate that there might be an optimal choice of the controllable parameters (there is a local minimum of the aeration measure in the function of the gas pressure and oil volume), and the exact values of the optimal combination of the parameters depend on the aeration measure. One should, however, notice that in some cases the minimum is only global, i.e. the minimum of the aeration measure is located on the boundary of the region of the parameter space for which the statistical model was fitted. In general, conclusions drawn from the response surface are not valid beyond these boundaries.

Conducting tests in an organized manner and according to Six Sigma methodology allows the design optimization process to be expedited and unnecessary costs to be eliminated. Improvements in understanding and measuring aeration effects constitute a clear foundation for further product optimization. Signal post-processing algorithms are essential for statistical analysis and are the original contribution of this work.

Nomenclature

P	- absolute pressure [Pa]
P_{fill}	- filling pressure [Pa]

P_{sat} - saturation pressure [Pa]
ρ_L - liquid density [kg/m^3]
ρ_{0L} - reference liquid density at 15°C [kg/m^3]
ρ_E - emulsion density [kg/m^3]
T - temperature [K]
T_0 - initial temperature [K]
α_L - volumetric thermal expansion [K^{-1}]
β - compressibility [Pa^{-1}]
p_G - partial pressure of the gas above the oil-gas mixture [Pa]
k - Henry's law constant [Pa·m^3/mol]
c - concentration of gas in the oil-gas mixture [any concentration unit]
α_v - Bunsen coefficient [–]
$m_{GA\max}$ - max. mass of dissolved gas [kg]
m_{GA} - mass of dissolved gas [kg]
$m_{G\_bubbles}$ - mass of gas [kg]
m_E - mass of the emulsion [kg]
c_{GA} - gas absorption coefficient at 15°C [kg/m^{3}MPa]
T_{KG} - absolute gas temperature [K]
c_{GLV} - gas absorption volume coefficient [-]($c_{GLV} \approx 1$)
m_L - liquid mass [kg]
β_L - bulk module [Pa]
V_{GF} - gas volume [m^3]
V_L - liquid volume [m^3]
V_{L0} - initial liquid volume [m^3]
$V_{G\_bubbles}$ - volume of gas in the form of bubbles [m^3]
V_E - volume of oil - gas bubbles emulsion [m^3]
R_G - specific gas constant [–]
R_N - specific gas constant of nitrogen (N_2) [–]
V_{oil} - oil volume [m^3]
p_{fill} - pressure inside the shock absorber [Pa]

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