Approximation methods applied in assessment of valve system fatigue failure

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Abstract. This paper proposes an analytical tool that supports the design process of a disc spring valve system used in hydraulic dampers. The proposed analytical tool obtains a key design characteristic of a valve, which is the flow rate and the corresponding maximum stress level in the stack of plates. The tool is prepared based on the cases produced by a first-principle model using a finite element approach. The finite element model was calibrated based on experimental results to provide accurate results in the entire range of input parameters.

1. Introduction

This paper proposes an analytical tool that supports the design process of a disc spring valve system used in hydraulic dampers [1]. Such a valve is also representative of a broader family of valve systems used in many other industrial applications. The tool accelerates the valve system design process. The paper considers a valve system that combines a number of circular metal plates, referred to further in the paper as a stack of plates. The proposed analytical tool obtains a key design characteristic of a valve, which is the flow rate and the corresponding maximum stress level in the stack of plates, as a function of pressure load. The stress level enables the ranking of valve settings for the durability criterion. The calculation process is based on the response of a nonlinear data-driven model which approximates the a priori simulated cases to cover the complete ranges of input design parameters, namely the number of plates, their thickness and diameter. The cases are produced by a first-principle model using a finite element approach. The model was calibrated based on experimental results to provide accurate results in the entire range of input parameters. The advantage of the analytical tool is the possibility to immediately provide a pressure-stress-flow characteristic of a valve instead of repeating time-consuming calculations for each new setting of input parameters. The objectives of the paper are as follows: to (i) prepare the Artificial Neural Networks (ANNs) to approximate simulation data, (ii) validate the ANNs and (iii) demonstrate an example of the rapid design of a hydraulic damper valve system with the use of the ANNs.

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2. Problem description

A conventional hydraulic damper that contains a specific type of valve system consisting of a number of circular metal plates, referred to further in the paper as a stack of plates (see Figure 1), is taken into consideration. This valve is part of a piston that is kinematically forced to move up and down in a liquid-filled cylinder. During its movement, the piston divides the cylinder space into two chambers – the vacuum chamber and the compression chamber. The flow of the fluid from one cylinder chamber to the other is restricted by the valve – stack of plates. The pressure difference between the two parts of the cylinder creates the resultant force that acts as a pressure on the bottom surface of the lower plate of the valve system. This resultant pressure causes bending of the stack of plates and valve opening. It should be noticed that the height of the opening depends not only on the pressure difference between the vacuum and compression chambers, but on the stiffness of the stack of plates as well. The opening height is then the first major characteristic of the valve system because, by controlling the fluid flow, it indirectly controls the damping force of the hydraulic damper [2]. The second characteristic of the valve is its durability, which denotes the number of ‘open-close’ cycles that can be performed by the valve before its destruction. It was earlier described by [3-4] that the maximum stress level that exists in the plates when the applied load creates deflection of the stack limits the durability of the system. A compression valve that works only in one direction is presented in Figure 1a. The direction of the piston movement inside the cylinder and the direction of the fluid flow are marked by arrows. Interested readers can find a more detailed description of the valve system design in [2].

![Figure 1. A cross section of a valve system](image)

Designing the valve stack of plates is then an optimization process where the criteria are both damping force and valve system durability characterized by maximum stress level in the stack of plates [4]. To facilitate the valve system design process, a model of the system can be created to simulate the behaviour of the stack of plates under applied loads. This model should be capable of reproducing the essential properties of a valve system during operation in a shock absorber, i.e. stack opening and stress level in the plates.

A special non-linear Finite Element Model, further referred to as the FE Model, has been developed by [4]. This proposal uses Finite Element discretization to model the behaviour of a circular plate stack. The model allows users to improve understanding of the contribution of a stack of plates' corresponding components, including the plastic deformation phenomenon and simulation of complex...
cases. As an output of the analysis, the height of the stack opening as well as the maximum value of von Mises stress level in each plate can be obtained. The model was prepared in the Abaqus software environment. The FE Model was correlated with experimental data and its ability to solve the problem presented above was confirmed [4]. The mentioned FE Model, however, has several disadvantages, such as (i) the long time required for model preparation and (ii) for analysis, especially when the analysis is performed in several steps, (iii) the high cost of commercial software required to perform the analysis and (iv) special requirements concerning the workstation on which the software can run. All these features become significant when optimization or identification tasks have to be performed, since the fitness function evaluation requires a large number of plate stack configurations to be solved. The hydraulic valve optimization process can be illustrated by the scheme presented in Figure 2.

![Figure 2. Scheme of the conventional and rapid valve system design process](image)

The main disadvantage of such an approach is that the time needed for simulating the behavior of the valve is very long. A very time consuming optimization process occupies the workstation and commercial software for a long period of time – analysis of 20 different settings of the valve requires more than 30 min. During one optimization run there is a need of analysis of more than 500 different valve designs what extends the optimization process to many hours. Because of what mentioned above, there is a need of speed up of the valve system optimization process and, if possible, decrease the negative impact of disadvantages mentioned above. One way to accelerate the optimization process is to improve the optimization algorithm fitness function evaluation by replacing the FE Model solution of the boundary-value problem by an approximation of the solution as presented in Figure 3.
3. Approximation method

Different types of artificial neural networks (ANNs) are well recognized as an efficient and easy-handling tool for several engineering tasks, like identification of defects, optimization or classification tool, etc. The ANNs, especially Feed Forward Neural Networks (FFNNs), are already identified as very good approximators of different boundary-value problems [5].

The Artificial Neural Networks (ANNs) have been chosen as an approximator because of several advantages:

(i) They are a universal tool that is applicable for a wide range of engineering problems (linear, non-linear).
(ii) They are able to generalize; it is possible to train the ANN in such a way that the interpolation and approximation error are at the same level.
(iii) ANNs are easy to operate and can be used by engineers in industry conditions.
(iv) ANNs are resistant to the poor quality of the data set that participates in their creation (e.g. non-uniform data distribution within the range).
(v) It is possible to re-train existing ANNs in the future and update their parameters according to the newest measurements/calculations of the valve system.

The feed forward neural networks with sigmoid activation functions trained using back propagation algorithms are used in this paper for approximation of the key design characteristics of the valve system. The FFNNs were created and trained using the Matlab Neural Network Toolbox, thus interested readers can find more details concerning the architecture and training method in [6]. The Approximation Tool approximates the stack behaviour in order to obtain a key design characteristic of a valve, in other words, the opening height and the corresponding maximum stress level in the stack of plates as a function of pressure load. The stack of plates already described in previous paragraphs is considered. The model shown in Figure 1b consists of a pyramidal stack of three circular plates. The stack is clamped between the support washer and the bottom internal and external support. The thicknesses of all plates as well as the outer diameter of Plate 1 and Plate 2 are the design variables. The outer diameter of the bottom plate (Plate 3) is constant. These design variables, as well as the value of pressure applied to the bottom surface of Plate 3, are the inputs of the Approximation Tool. The outputs are the opening height of the stack of plates and maximum values of von Mises stress in all three plates. Thus the length of the input vector of the approximation model is $N=6$ and the length
of the output vector is L = 4. The vector x is given to the input of the approximation model and, as a result of the approximation, the output vector y is obtained. Vectors x and y are then described by Eq. (1).

\[\begin{align*}
\mathbf{x} &= \begin{bmatrix} x_1, \ldots, x_N \end{bmatrix}, \\
y &= \begin{bmatrix} y_1, \ldots, y_L \end{bmatrix}
\end{align*}\]

(1)

where \( N \) is the number of input and \( L \) is the number of output variables. The input and output vectors collected together create the pair of vectors. The total number of 4178 pairs is prepared to train the networks. The data obtained with use of a non-linear FE Model, already described in previous paragraphs, is randomly divided into three sets. The size of these sets is presented in Table 1. The range of design variables is presented in Table 2. The input and output vectors collected in the training set, and which are presented to the network during the training process, adjust the network parameters. During the learning process there is a risk of ‘over-learning’ of the network. This means the interpolation error of the training set will decrease but, at the same time, the generalization abilities of the ANN will become worse. To avoid ‘over-learning’ the approximation error of the validation set is observed. The third set of data – the testing set – is prepared to give neutral information about the approximation abilities of the ANN. This data has no effect on the training process.

Table 1. Size of sets used for training and testing of FFNNs

| No of pairs | Training set | Validation set | Testing set | TOTAL |
|-------------|--------------|----------------|-------------|-------|
|             | 2801         | 692            | 685         | 4178  |

Table 2. Design variables for approximation task

| Thickness Plate 1 [mm] | Thickness Plate 2 [mm] | Thickness Plate 3 [mm] | Out. diam. Plate 1 [mm] | Out. diam. Plate 2 [mm] | Press. [bar] |
|------------------------|------------------------|------------------------|-------------------------|-------------------------|-------------|
| min/max 0.15/0.35       | 0.15/0.35              | 0.15/0.35              | 10/22                   | 10/22                   | 2.5/50      |

The multi input – single output (MISO) neural networks are chosen to approximate the given problem. For each design variable of the valve system (opening height, maximum stress level in Plates 1, 2 and 3), a separate approximator is prepared. Although this attempt increases the complexity of the training process, it has several advantages:

- The approximator of each design characteristic is independent from other approximators.
- This allows tuning of the approximator responsible for opening height approximation without influencing other networks.
- This tuning can be performed by additional runs of the training process.

When all outputs are given by one approximator (MIMO), such additional runs, which should improve the response for one output, can lead to ‘over-learning’ of the rest of the network outputs, and improving the error of the response of one output can negatively affect others. The results of approximation of the opening height, max von Mises stress in Plates 1, 2 and 3 are presented in Table 3. The FFNNs were trained by the Levenberg-Marquardt method [5-6]. This method is a combination of the gradient descent method and Newton’s Method. The approximator performance is judged with the help of Mean Square Errors. Three different errors for each approximation problem are measured – training set error (MSEL), validation set error (MSEV) and testing set error (MSET). It should be mentioned that the level of the MSE depends on the range of the values that are compared. Thus for opening height approximation, when the range of output variables is between 0.01 and 1.03mm, the MSE values will be at a very low level. In cases of stress approximation, the MSE value will be at a higher level.

Table 3. The results of approximation of the opening height, max von Mises stress in Plates 1, 2 and 3
4. Case study

The goal is to design a stack of plates of a hydraulic damper valve system to obtain a pressure-opening curve within the range presented in Figure 4.

The pressure-opening curve was transferred from the pressure-flow characteristic according the formula (2)

$$q = Cd \cdot A \cdot \sqrt{\frac{2p}{\rho}}$$

(2)

Where $Cd = 0.6$ is a discharge coefficient, $\rho=960$ kg/m$^3$ is fluid density and $A$ is the flow area given by equation (3)

$$A = 2\pi R \cdot H$$

(3)

Where $R$ is the radius of the piston valve and $H$ is the opening height. The Matlab Optimization Toolbox™ is used in the optimization process. The Genetic Algorithm (GA) is chosen since this optimization solver can handle optimization problems with nonlinear, linear, and bound constraints, and does not require fitness functions to be differentiable or continuous [5]. The optimization solver changes the design variables, which are the diameters of Plate 1 and 2 and thickness of all three plates within the range presented in Table 1. To evaluate the fitness function, the opening height is calculated by the Approximation Tool based on the design of the stack of plates proposed by the optimization solver. The FFNN described in the previous paragraph is used by the Approximation Tool to
approximate the opening height for 20 pressure values from 2.5 bar to 50 bar. The optimization process was performed several times in order to avoid the influence of starting point selection on the optimization results. The time needed to perform one optimization process is up to 1 min. Thus the cost of the optimization task repetition is negligible. Figure 5 shows the pressure-opening curves for different designs found in six optimization processes.

![Figure 5](image)

**Figure 5.** The achieved opening height – pressure drop characteristic of a damper valve system with 20 points used for fitness function evaluation.

It can be noticed that the results of optimization are within the specified range with one exception – the pressure-flow curve of Run 02 is outside the specification for small flows. For all selected designs, the maximum von Mises stress level was calculated in order to find the best design in terms of fatigue durability. Based on the results of the optimization process and stress calculations, the best option – Run 05 – was chosen. Results achieved with the help of the ANNs were then compared with the results obtained by the FE Model. Figure 6a presents the opening height – the pressure drop characteristic of the valve stack design No. 5 approximated by FFNN and calculated by the FE Model.

![Figure 6](image)

**Figure 6.** a) The opening height – pressure drop characteristic calculated by the FE Model and approximated by FFNN; b) Deformation of the valve stack calculated by the FE Model.

Deformation of the valve stack, provided by the FE Model, is presented in Figure 6b. All six designs found by the optimization algorithm, are presented in Table 4.
Table 4. Predicted maximum von Mises stress and failure rate of each design

| Run  | Stress in Plate 1 [MPa] | Stress in Plate 2 [MPa] | Stress in Plate 3 [MPa] | Fatigue (the worst case) [number of cycles] |
|------|------------------------|------------------------|------------------------|-------------------------------------------|
| Run 01 | 2 810                  | 5 430                  | 2 734                  | N/A                                       |
| Run 02 | 992                    | 1 775                  | 2 717                  | N/A                                       |
| Run 03 | 1 392                  | 1 314                  | 2 099                  | 0.2 mln                                   |
| Run 04 | 1 091                  | 3 785                  | 3 287                  | N/A                                       |
| Run 05 | 842                    | 1 534                  | 1 580                  | 1.6 mln                                   |
| Run 06 | 958                    | 1 630                  | 3 191                  | N/A                                       |

Fatigue is the progressive and localized structural damage of a valve disc that occurs when a disc is subjected to cyclic pressure loading. High cycle fatigue strength, above $10^4$ cycles and typically below $10^8$ cycles, is considered in case of valve systems. This type of fatigue is described by stress-based parameters which mainly contribute to crack or disc damage. The maximum stress values should be less than the ultimate tensile stress limit, and may be below the yield stress limit of the material. Fatigue failure appeared in the form of propagating cracks from the middle of the outer ring of the intake valve due to the very high pressures (Figure 7).

A fatigue prediction model neglects microphysical disc properties and disc contact conditions for simplification. Disc fatigue is a complex transient phenomenon influenced by disc shape (solid or perforated material), geometry (thickness), temperature, surface finish (anisotropy after rollover), presence of oxidizing or insert chemicals, thermal and chemical treatment, residual stresses, contact (fretting), dislocations etc. There are linear and nonlinear fatigue hypotheses which are applicable to a constant load cycles. Fatigue life at variable amplitude is predicted by using material properties from constant amplitude laboratory tests obtained with linear or nonlinear damage accumulation hypothesis. Such tests were performed using a servo-hydraulic equipement to load the disc at specific displacement to reproduce the conditions in a hydraulic damper operation. In order to characterize the sensitivity to fatigue, a large number of disc stacks were tested at continuous sinusoidal cycling with a constant amplitude and frequency. The obtained Wöhler diagram (Figure 8) allows to correlate the number of cycles until disc damage and the stress in the plates (Table 4).
Figure 8. Experimental Wöhler curves

Figure 9 shows that the criterion of disc damage is the first drop in the maximum observed force measurement.

Figure 9. Displacement signal of an exemplary end phase of a test
5. Conclusions

The paper describes the proposal, implementation and example of application of the Feed Forward Neural Networks intended to support the design process of a disc spring valve system used in hydraulic dampers. The FFNNs allow users to obtain a key design characteristic of such a valve, in other words, flow rate and the corresponding maximum stress level in the stack of plates as a function of pressure load, plate thickness and diameter. The paper considers a valve system that consists of a combination of washers configured as a stack of circular plates. The number of plates, their diameter and thickness directly affect the damping force of a shock absorber and the stress level in plates. Due to a significant non-linear relationship between the applied load and opening of the stack, the most popular are computational models of the stack which use Finite Element (FE) spatial discretization and assume axial symmetry of the stack of plates. The Finite Element Method (FEM) provides accurate results, however, it has two disadvantages: (i) the time required for computation and model preparation (pre-processing) strongly depends on the complexity of the model geometry. Additionally, (ii) the FE analysis itself is time consuming – analysis of 20 different settings of the valve requires more than 30 min. of analysis (excluding model preparation and result reading). The model requires a commercial license and an efficient workstation to complete simulation in a reasonable amount of time. The license needs to be maintained even if it is not used for simulation purposes. A proposal of the authors is to improve the design process and availability of simulation results by replacing FEM on-line calculations with the use of a data model approximating simulated cases. This allows computationally expensive analyses to be avoided by construction of an approximation model that will be able to replace high-fidelity code during optimization. This paper proposes the final step in fatigue risk assessment of a valve system. The obtained stress is mapped into the fatigue domain, to predict the number of cycles until disc damage conditions. The validation is performed based on the approximation error of the training and validation set, and generalization abilities measured by MSE of the testing set of data. A valve design process depends on fitness function minimization, which was evaluated using the FFNN. The valve stack designs, selected during the optimization process, were then ranked with respect to durability. A final design that fulfils all requirements was indicated.

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