MODAL ANALYSIS AND OPTIMIZATION OF VEHICLE BODY STRUCTURES BY USING STOCHASTIC ALGORITHM

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In today's design, the complexity of systems and increasing demand for safer, more efficient and less costly has created new challenges in science and engineering. Locomotives is produced that is designed according to customer order and technical needs of most customers, targets of companies based designer and manufacturer of locomotives always be on the path of progress, and seeks to offer products with higher technology than other competitors. Modal analysis has evolved into a standard tool for structural dynamics problem analysis and design optimization. In each engineering and design problem, optimization can be applied. The objective of the optimization is to choose the best plan among acceptable plans. Body structures quality based primarily on indicators such as natural frequency, displacement, fatigue life and the maximum stress occurring in the body takes place. Natural frequency of the various components of the system and adapt them to each other in order to avoid the phenomenon of resonance is important. In this study, body structures of ER24 locomotive has been studied that manufactured by MAPNA Industries. A combination of stochastic optimization algorithm and artificial neural networks is proposed to find the optimal weight of structures, optimum weight obtained by the optimization algorithm is acceptable if the natural frequencies had been satisfied. Optimization of locomotive's structure has been done with an emphasis on maintaining locomotive abilities in Static and dynamic field. The results indicate that the use of optimization techniques in the design process is powerful and effective tool for identifying and improving the main dynamic characteristics of structures and also Performance Optimization in stress, noise & vibration field.

1. Introduction

Since cities are growing and people are becoming more busy, transport systems have to improve. Vehicle manufacturers are investing to raise the travelling speed, to increase the passenger capacity of the vehicles, as well as to provide better passenger comfort [1]. With the use of advanced lightweight structures for the vehicle design, structural dynamics in connection with vehicle running dynamics is increasingly important.

In the field of vehicle development, objectives that are driven by the competition, like to shorten the time to market, to create innovative designs, and to lower the vehicle costs, are forcing the vehicle engineers to use new development methods. Virtual prototyping computer tools have made considerable progress in recent years. They are widely used for modelling and simulating the
dynamic motion of complex vehicle systems [2]. Working with virtual prototyping technology has shown potential to improve the product development process.

Unwanted vibrations are detrimental to the performance of dynamical systems. In addition to causing trouble for the proper functioning of the system, reducing the life of the structure is at fault. Vibrations in vehicles with internal combustion engines have great importance, including the locomotives must also be considered. Also, this issue is very important, because the standards and criteria specified used in the product design and product is used in different working conditions.

In the past design occurred through experience and expensive laboratory tests. Analytical methods were impossible or very difficult. However, demand for new designs with considering aspects such as: weight loss, decrease fuel consumption, safety and economic aspects, recyclability and availability of parts not reduced. Therefore, various studies have been conducted in this context. The most important research on locomotives modal analysis and methods for its optimizing can be mentioned the following.

Kymasy and partovi[3] studied Static and dynamic analysis on the G16 locomotive chassis to optimize it. Also finding locomotive chassis important connections and make changes on them in order to increase the structural stiffness and offered several suggestions have been made to improve the natural frequency.

Subik & hey[4] aided modelling and simulation trying to improve the stability, accident and rolling resistance of the vehicle structure and modal analysis techniques used for this purpose. The results of simulation and modal testing indicate correspondence between the two methods. After verification of the results, in order to optimize the cross-section has been changed. The results show an increase in the natural frequency and Improvement in dynamic properties.

The work described has been done using the computer tools and software such as Hyper mesh, MD Nastran and Matlab. The numerical results have been compared to the results of experimental modal analyses (MAPNA results).

2. **Modal analysis**

The vibration and acoustical behavior of a mechanical structure is determined by its dynamic characteristics. This dynamic behavior is typically described with a linear system model. The inputs to the system are forces (loads), and the outputs are the resulting displacements or accelerations. System poles usually occur in complex conjugate pairs, corresponding to structural vibration ‘modes.’ The pole’s imaginary part relates to the resonance frequency and the real part to the damping. Structural damping is typically very low (a few percent of critical damping). The system’s eigenvectors, expressed on the basis of the structural coordinates, correspond to characteristic vibration patterns or “mode shapes.” System identification from input-output measurements yields the modal model parameters. This approach is now a standard part of the mechanical product engineering process.

The free motion of a mechanical structure is governed by a partial differential equation. By applying discretization techniques, such as the finite-element method, a linear finite dimensional model results:

\[
\begin{bmatrix} M \end{bmatrix} \dot{\{x\}} + \begin{bmatrix} C \end{bmatrix} \{x\} + \begin{bmatrix} K \end{bmatrix} \{x\} = 0.
\]  

(1)

where \{x\} ∈ R is a vector of generalized displacements, and M, C and K are the mass, damping and stiffness matrices respectively. The linear mechanical systems considered here are such that M is symmetric and positive definite while K is symmetric and positive-semidefinite. The solution of these equations leads to an Eigenvalue problem that is solved in terms of the modal parameters[5].

Specific to the mechanical problem is the straightforward physical interpretation that can be given to the system's Eigenvalues and Eigenvectors. System poles in structural dynamics usually
occur in complex conjugate pairs, each pair corresponding to a structural "mode". The pole's imaginary part relates to the resonance frequency and the real part to the damping. Structural damping is typically very low (a few % of the critical damping), hence this damping is usually expressed as a ratio with respect to the critical damping.

The modal representation of a mechanical structure can be determined analytically if a lumped mass-spring system is concerned. In the general case of a continuous structure, a numerical approximation by means of a Finite Element Model (FEM) is made, discretizing the structure in a finite number of physical coordinates.

The advanced finite element model used in order to body structures modal analysis, significant increase in analysis time. The mass normalization method is used to obtain the eigenvalues and natural frequencies. A model locomotive in advanced finite element model consists only of plates with different thicknesses. The body structure is modelled much detail as possible. The model is more applicable to real structures.

0 to 30 Hz frequency has been studied in modal analysis. Up to a frequency of 30 Hz three different elastic (Structural) mode shapes exist. The mode shape with the lowest frequency shows a torsion of the car body structure. At higher frequencies lateral, vertical bending and local mode shapes of the car body exist. The locomotive is shown in Figure 1 and Finite element model of Body structure with sheet thickness is shown in Figure 2.

![Figure 1. ER 24 locomotives.](image)

![Figure 2. Sheet thickness (a) and body structure finite element model (b).](image)

Boundary conditions are free – free and Depending on the boundary condition. The first six natural frequencies equal to zero. And the first non-zero natural frequency is seventh mode. The natural frequencies and mode shapes can be used to measure compliance [6]. Natural frequencies and mode shapes obtained from finite element analysis and modal testing is shown in table 1.
### Table 1. Natural frequency and mode shape.

<table>
<thead>
<tr>
<th>mode</th>
<th>Mode shape</th>
<th>$\omega_p$ (Hz)</th>
<th>$\omega_f$ (Hz)</th>
<th>$%\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#7</td>
<td>1st torsion</td>
<td>7.8</td>
<td>7.87</td>
<td>0.89</td>
</tr>
<tr>
<td>#8</td>
<td>1st lateral</td>
<td>19.2</td>
<td>19.43</td>
<td>1.10</td>
</tr>
<tr>
<td>#9</td>
<td>1st bending</td>
<td>24.9</td>
<td>25.53</td>
<td>2.53</td>
</tr>
</tbody>
</table>

$\omega_f$ = Natural frequency finite element model  
$\omega_p$ = modal testing (experimental modal analyses)  

$\%\Delta = \frac{|\omega_p - \omega_f|}{\omega_p} \times 100$

![Figure 3](image.png)

**Figure 3.** first torsional (a) lateral (b) and bending (c) mode.

Acceptable error between the results of the finite element model modal analysis and modal testing is three percent. Optimization algorithm in each step reviewed response improvement rate and move into the specific plan or method. In order to optimize the objective function, optimization algorithm acquires values in each stage of the algorithm. Since the call objective function value and the constraints by the finite element model lead us to waste the time and In order to speed up data retrieval, the artificial neural network is used as an alternative to finite element model.

### 3. Artificial neural network

The current interest in artificial neural networks is largely a result of their ability to mimic natural intelligence [7]. Artificial neural networks are composed of a set of artificial neurons, a simple model of a biological neuron, which is arranged on a set of layers. One of the most important characteristics of neural networks is learning. Artificial neural networks have two operation modes, training mode and normal mode. In training mode, adjustable parameters of networks are modified. In normal mode, the trained networks are applied for simulating of outputs [8].

The locomotive body structure is composed of 13 different thicknesses. 8 Thickness of the thickness used in body structure has been considered as design variables. Artificial neural network have been designed with eight neurons in the input layer (thickness of each sheet) and 4 neurons in output layer (3 first non-zero natural frequency and body structures mass). Using finite element software, 145 data is generated that data is including Sheet thickness, natural frequency and Body structures mass.

80 % of data is considered for network training and the remaining data is used to test the trained network. It is observed that trained neural network, estimates natural frequency and mass of the body structure with acceptable error. Average error of neural networks is 2.23% and neural net-
works estimates mass and natural frequency with a precision of about 97%. The output of the trained neural network and finite element model for test data is shown in the figure 4.

Figure 4. The output of the artificial neural network (ANN) and finite element model for data test.

Mass of body structure as a objective function has been considered To minimizing. The natural frequency can be used as equality constraints. The optimization problem to minimize the mass of the body structure has been done by changing the sheet thickness of the body structure with preserving the natural frequencies. Neural network predicts the natural frequencies and mass. By knowing of the neural network weights and activation function neurons, the output of the neural network can be expressed based on its input by an explicit mathematical relationship. The activation function of network’s neurons is sigmoid (logsig), therefore, output of trained neural network can be defined as follows.

\[
Output = \frac{1}{1 + e^{-\left(\sum_{i=1}^{\text{layers}} [\text{bias}] + \sum_{j=1}^{\text{output}} \left[\text{bias}2]\right)]}}
\]

There are several ways to convert the constrained optimization problem into unconstrained optimization problem. The most common method is penalty function method. A constrained optimization problem that can be defined in order to minimize is expressed as follows. \(h(x)\) is equality constraint and \(g(x)\) is inequality constraint[9].

\[
\begin{align*}
\min f(x_i) \\
g_j(x_i) &\leq 0 \\
h_k(x_i) &= 0
\end{align*}
\]

Objective function of optimization problems is a criterion for comparing different designs and selects the best plan. Minimizing the objective function should not be adversely affect on the behavior and performance of the optimization problem. To convert the constrained optimization problem into unconstrained optimization problem. The external penalty function is used like the following:

\[
P(\{x_i\}) = \sum_{i=1}^{n} \left\{ \max \left[0, g_i(\{x_i\})\right]^p \right\} + \sum_{j=1}^{m} \left\{ h_j(\{x_i\})^p \right\} \\
\min \Phi(x,r) : f(\{x_i\}) + r[P(\{x_i\})]
\]
Φ(x,r) is secondary objective function or artificial objective function, f(x) is the main objective function, r is penalty function coefficient, penalty function coefficient is usually constant and large value. Using a constant and large value for the penalty function coefficient makes optimizer algorithm easier to search in the search space.

4. Optimization

Optimum design of structures is to select design variables such that the cost or weight of the structure is minimized, while all the design constraints are satisfied. Determination of optimum design is performed by considering and minimizing the cost or weight function of structures as the objective function. By choosing the design variables from a set of available values various numerical optimization methods can be selected to evaluate the optimal solution of optimization problems. In the present paper, particle swarm algorithm (PSO) is used to solve the optimization problem.

PSO is originally attributed to Kennedy, Eberhart and Shi[10 &11] and was first intended for simulating social behavior as a stylized representation of the movement of organisms in a bird flock or fish school. Each particle is a possible answer in the search space. The stages of the algorithm is shown in the figure5.

![Figure 5. Flow diagram of particle swarm optimization algorithm.](image)

The optimization problem can be easily described as to find an argument x whose relevant cost f(x) is optimum, and it has been extensively used in many different situations such as industrial planning, resource allocation, scheduling, pattern recognition.

5. PSO optimization results and discussion

Optimization process begins with 100 particles which are distributed randomly in the search space. The maximum number of iterations is 50 iterations and If the distance between two iteration, Improvement in the objective function is lower of a certain value (0.01) Optimization process is abandoned. In addition of this stop condition, If after 5 iterations no improvement does not happen in the objective function, Optimization process is abandoned. Optimizing the objective function per number of iteration is shown in figure 6.
Figure 6. The best answers in each iteration of PSO.

Optimization process is performed by the algorithm in 33 iterations and after this iteration are not achieved better results. After the end of optimization process, optimal sheets thickness offered by the algorithm are applied on finite element model. Weight of body structures in original state is 14,600 kg and in optimized state weight of body structure is 13,920.4 kg, indicating a decrease 4.65% of the body structure weight. Frequency Response function Graph (FRF)[5] for the basic model and the optimized model is shown in figure 7.

Table 2. Natural frequency and mode shape of original and optimized model.

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>1st torsion</th>
<th>1st lateral</th>
<th>1st bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>14600 kg</td>
<td>7.87</td>
<td>19.43</td>
<td>25.53</td>
</tr>
<tr>
<td>Optimized</td>
<td>13,920.4 kg</td>
<td>7.87</td>
<td>19.44</td>
<td>25.54</td>
</tr>
</tbody>
</table>

Figure 7. FRF of the original model and optimized model offered by the PSO.

6. Conclusions

The purpose of this research is finding economical and effective ways to improve the efficiency. Through reducing body structure weight and maintaining body structure natural frequency in order to optimize used Optimization algorithms. That have been modelled from nature or natural events are better than others. The particle swarm algorithm is a new method, which has great abilities to cope with different types of optimization problems. However, it is still in its infancy and in-
tensive studies are needed to improve its performance. Results presented by this algorithm show that the algorithm has been successful in achieving the targets and algorithms is effective and applicable for solving various problems.

REFERENCES

4. A. Subic, J. He, "Improving bus rollover design through modal analysis", International Journal of Crashworthiness, (1997), 22, 139 -152.