Design and structural verification of locomotive bogies using combined analytical and experimental methods

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Abstract. The paper presents a practical methodology for design and structural verification of the locomotive bogie frames using a modern software package for design, structural verification and validation through combined, analytical and experimental methods. In the initial stage, the bogie geometry is imported from a CAD program into a finite element analysis program, such as Ansys. The analytical model validation is done by experimental modal analysis carried out on a finished bogie frame. The bogie frame own frequencies and own modes by both experimental and analytic methods are determined and the correlation analysis of the two types of models is performed. If the results are unsatisfactory, the structural optimization should be performed. If the results are satisfactory, the qualification procedures follow by static and fatigue tests carried out in a laboratory with international accreditation in the field. This paper presents an application made on bogie frames for the LEMA electric locomotive of 6000 kW.

1. Introduction

Bogies are complex equipment with vital role in the operation of railway vehicles, having the role of carrying the vehicle body and ensuring the traction and braking forces. Taking into account the bogie importance in the security of railway vehicles on the long run, the nowadays regulations require that the structural strength of the bogies should be validated at various static and dynamic stress configurations that may appear during the life-cycle of the bogie.

Structural strength validation procedures of the bogies used in the European area are regulated by the EN 13749/2001 and EN 15827/2011 standards according to which the validation program shall be established on the basis of: analysis, laboratory static tests, laboratory fatigue tests, track tests. For a new design of the bogie destined to a new application, all four validation stages shall be used, though the fatigue tests can be replaced by other methods that demonstrate the required fatigue life.

The article dealt with procedures followed by Softronic Craiova for the design and structural assessment of the new bogies designed for the electric locomotive with asynchronous motors LEMA 6000kW. The complete design and validation procedure takes into account the relationship with a program for structural validation by tests in a laboratory with international accreditation.

In order to achieve the LEMA bogies, the Softronic procedure follows the following steps:

- 3D design using a CAD dedicated program, such as ProEngineer;
- Structural analysis using a dedicated finite element analysis (FEM) program, such as Ansys;
- Experimental modal analysis (EMA) using dedicated hardware and software, such as Pulse;
Calibration of FEM model by correlation with EMA model, eventually model optimization;
Analytical assessment of the bogie stress response to the regulated static and dynamic loads, on the bases of the calibrated and optimized FEM model;
Static and dynamic tests in the international accredited laboratories.
On track tests;
The paper presents the theoretical background of FEM end EMA, similarities and differences between the two types of analysis, and the need to validate the FEM model through the data obtained by EMA tests. An application of combined analysis carried out on the new design of the LEMA bogie is presented too.

2. Basic principles of applying the combined analysis

From the point of view of experimental modal analysis-EMA, any mechanical system can be modelled by a discrete system consisting of 'n' lumped points with mass 'm_k' joined by elastic elements of 'k_k' rigidity and damping elements 'c_k'. For this system, under the action of a set of external excitation, \{Q(t)\}, the response is governed by the following system of equations [3]:

\[
[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{Q(t)\}.
\]

The system response to the external excitation, \{Q(t)\}, is presented as a sum of 'n' modal contributions due to each separated degree of freedom:

\[
\{X(\omega)\} = \sum_{k=1}^{N} \left[ \frac{\psi_k^T \cdot \psi_k}{a_k (-\mu_k + i(\omega - \nu_k))} \right] \{Q(\omega)\} + \sum_{k=1}^{N} \left[ \frac{\psi_k^T \cdot \psi_k}{a_k (-\mu_k + i(\omega + \nu_k))} \right] \{Q(\omega)\}.
\]

Where:
- \([M], [C], [K]\) - matrix of mass, damping and rigidity;
- \{\dot{x}(t), \ddot{x}(t), x(t)\} - column vectors of acceleration, velocity and displacement;
- \(\psi_k\) and \(\psi_k^T\) - the 'k' order eigenvector;
- \(\mu_k\) and \(\nu_k\) - the 'k' order of damping ratio and eigenfrequency (natural frequency);
- \(a_k\) and \(\tilde{a}_k\) - the 'k' order norming constants;
- \(\omega\) - external excitation frequency.

The essence of experimental modal analysis is to determine the modal parameters, \(\{\psi_k\}, \mu_k, \nu_k\), \(k=1 \ldots n\), from the experimental measurements made on the equipment brought into controlled vibrating state with simultaneous determination of excitation and response. The controlled vibration state can be achieved by using one of the following low-level energy excitation methods: relaxed step force, sinusoidal excitation, random narrow/wide band excitation or impact force method. The impact force method is very good for modal analysis of bogie frames, and it is widely used, this method being implemented with more advanced modal identification algorithms procedures.

From the point of view of finite element analysis-FEM, the mechanical structure is discretized into finite elements of various types, between which are established mathematical links, equivalent to the physical links between adjacent elements or between them and environment. FEM mathematical model corresponding to physical model is similar to EMA mathematical model, the difference between the two models being that in the finite element analysis it is not taken into account the system damping. FEM mathematical model is governed by the following system:

\[
[M]:\{\dot{x}\} + [K]:\{x\} = \{0\}.
\]
where the matrices $[M]$ and $[K]$ have the same significations as to the EMA analysis.

Resolving the system leads to the analytical determination of mechanical system in terms of eigenfrequencies and eigenmodes, that is to say, the modal parameters which must to be approximately the same as those determined through experimental modal analysis. The both types of analysis, FEM and EMA, characterize the mechanical system through a set of intrinsic modal parameters that define the system eigenmodes independent of interaction with environment. Through EMA analysis the modal parameters are provided by even the mechanical system itself brought in a controlled vibration state.

The FEM analysis works with an approximate mathematical model, which approximations can be more or less grossly resulting from both geometrical modelling and used material characteristics. Although the geometrical model can be perfect, and motion equations in the mathematical model can be perfect, everything will result in approximately analytical model, because it is known that the material characteristics ever used in modelling features do not coincide with the real material characteristics used in the real structure. In addition, it is well known that any manufacturing process is accompanied by the execution errors more or less grossly.

From the above it follows that a good analytical model cannot be achieved except by validation with data from the real system obtained by experimental modal analysis. Through the correlation analysis of the modal forms obtained from the two models, FEM and EMA results the required information to adjust the analytical model, so that the analytical model best approximates the real system response. This is so-called procedure of analytical model "upgrade", or regeneration of the analytical model. A good analytical model, validated through experimental data can be used with confidence to assess the system response to imposed stresses, as long as they are maintained the hypotheses that formed the basis of grounding the analytical.

3. Application of combined analysis to the LEMA bogie frame
Under Ansys 14.5 was achieved the FEM model of LEMA bogie frame. Figure 1 represents the FEM model and in table 1 are given the mechanical characteristics of materials used in the frame.

The mesh has been structured so to make a network with finite elements of tetrahedron type having a size of 20 mm. The number of used elements is 350791 and the number of nodes is 826173, with the bonded type contacts between the elements.

![Figure 1. FEM model of LEMA bogie frame.](image)

**Table 1.** Mechanical characteristics of materials used in the LEMA bogie frame.

| Property                              | Value     |
|---------------------------------------|-----------|
| Young's modulus (elastic modulus)     | 210 GPa   |
| Yield strength for nonwelded elements | 350 MPa   |
| Yield strength for welded elements    | 325 MPa   |
| Tensile strength                      | 510 MPa   |
On the analytical model of the bogie frame was run the Modal Analysis module of Ansys, and they was determined the eigenfrequencies and eigenmodes of bogie frame, that are presented in table 2 and figures 3-6 together with the experimental modal analysis results. The analytical model was exported as a file containing aggregate both geometric model and modal shapes. On the same bogie frame was applied a test of experimental modal analysis, bogie frame being placed on four springs, as in the normal operating position. For excitation and acceleration measuring response were selected a number of 10 points, as shown in the figure 2. It was used the impact excitation method, for excitation being used an impact hammer type 086D20 of 25 kN

The tests execution was performed under PulseLabshop. The modal parameters estimation was performed under PulseReflex-Modal Analysis and was been finished with export of modal shapes and structure geometry. The modal analysis was performed in the frequency range of 0 - 100 Hz, in this domain being determined a number of 7 eigenmodes.

It was carried out the correlation analysis between the EMA model and FEM model using the correlation module PulseReflex-Correlation Analysis, which loads and displays in the same panel the animated modal shapes resulted from EMA and FEM. Correlation analysis provides a way that the analytical models to be verified against test models through graphical comparisons and numerical correlation. Graphical comparisons are performed using:
- Animation: Compare modes using side-by-side, overlaid or difference animations;
- Complexity: Validate mode shape complexity.
Correlation is performed using widely accepted tools to verify the data. These tools include:
- Modal Assurance Criteria (MAC): Evaluate the independence between modes;
- Orthogonality Matrix: Assess the quality of the measured data;
- Cross-orthogonality Matrix: Measure the degree of correlation between two models.

Table 2 presents the result of correlation analysis and in figure 3 to 6 are represented the bogie frame in the first four eigenmodes

| Mode | FEM Model Damped Frequency (Hz) | EMA Model Damped Frequency (Hz) | Damping (%) | Complexity | Error Damped Frequency (%) | MAC Modal Assurance Criterion |
|------|---------------------------------|---------------------------------|-------------|------------|--------------------------|------------------------------|
| 1    | 30.73                           | 30.19                           | 0.28        | 0.0128     | 1.7925                   | 0.975                        |
| 2    | 37.43                           | 37.95                           | 0.32        | 0.2374     | 0.0138                   | 0.910                        | -1.406                      |
| 3    | 48.10                           | 49.08                           | 0.17        | 0.0015     | 0.01992                  | 0.968                        | -2.033                     |
| 4    | 60.64                           | 61.86                           | 0.14        | 0.0014     | 0.01982                  | 0.901                        | -2.023                     |
| 5    | 66.66                           | 65.66                           | 0.13        | 0.0031     | -0.0152                  | 0.970                        | 1.501                       |
Analyzing the data in table 2 and figures 3-6, result the following conclusions:

- Modal shapes corresponding to analytical model are highly correlated with experimental modal shapes, taking MAC correlation factor greater than 0.9;
- Global error for assessing the analytical eigenfrequencies fall within 1.7%, compared with the real eigenfrequencies determined by EMA;
- Taking into account the MAC correlation factors and the global error for assessing the analytical eigenfrequencies it can be concluded that the FEM analytical model is correct and can be used for theoretical analysis of bogie frame response to static and dynamic loads applied in accordance with standards EN 13749/20011 and EN 15827/2011.

4. Analytical assessment of the LEMA bogie frame to the imposed loads

For the preliminary check of the bogie frame capability to withstand to exceptional and normal loads applied according to EN 13749/20011, on the above presented analytical model, validated by experimental data, were applied all configurations of static loads imposed by mentioned standard.

From all the test configurations, in the paper is presented the case involving the highest mechanical stresses on the bogie frame, namely the longitudinal shock loads in which a the bogie frame is subjected to a longitudinal force equal to bogie inertia force under an acceleration of 3 g.

The figure 7 shows the scheme of the loads application and the figure 8 shows the distribution on bogie frame surface of the equivalent von Mises stress.

![](image1)

**Figure 7.** Loads for longitudinal shock with 3g acceleration. Scheme of loads application.

![](image2)

**Figure 8.** Loads for longitudinal shock. Distribution of equivalent Von Mises stress.

In order to assess the bogie frame conformity with the request of loads of longitudinal shock, it is taken into account that the equivalent von Mises stress distribution presents a limited number of areas, reduced in size, the largest tensions having the values of 448.64MPa and 455.15 MPa. These stresses exceed the elastic limit of 350MPa, but are below the tensile strength of 510MPa, given in table 1. Given the exceptional nature of the loads, that solicit the areas beyond the elasticity is very limited, and that the maximum stresses are below the tensile strength of 510MPa, it is concluded that the LEMA bogie frame corresponds to a shock scenario of collision with amplitude acceleration of 3g.

5. Conclusions

A good analytical model developed by FEM, finite element analysis, methods requires validation through experimental data obtained by EMA, experimental modal analysis.

By applying the combined procedures of analytical and experimental analysis, presented in the article, it is concluded that the LEMA bogie frame is correctly designed and sized in terms of withstanding to static and dynamic requirements in accordance with the standards in the field.

Assignation

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References

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