Deriving patterns for the vibration-based damage detection in side frames of bogies

C I Barbinta¹, G R Gillich¹, D Nedelcu¹, and T Manescu²

¹“Eftimie Murgu” University of Resita, Resita, Romania
²“Aurel Vlaicu” University of Arad, Arad, Romania

E-mail: gr.gillich@uem.ro

Abstract. Detecting damage in the incipient state is of crucial importance in monitoring the health of engineering structures. Approaching damage detection as an inverse problem is a common method when vibration-based techniques are used. It implies a precise a priori estimation of the modal parameters. We present in this paper a model to predict the frequency changes due to cracks in the side frames of bogies used to detect the welding defects in T-joints. To this aim, we model the structure and perform simulations using the SolidWorks software. The frequencies for the first thirteen modes are derived for the intact structure and the structure with different damage lengths and positions. By these tests, we first desire to find the optimal fixing of the side frame to reduce the number of vibration modes that are not of interest to the damage detection process. After finding the ideal fixing system, we derive patterns, for different defects, in the form of relative frequency shifts. Finally, we conclude about the damages that can be identified using the derived patterns, the conclusions being traced based on the measurability of the frequency changes.

1. Introduction
The signal representing the vibration response to an excitation contains valuable information about the analyzed structure [1]. Numerous non-destructive techniques were developed in the last decades to observe the appearance of damage in real-time and evaluate its position and severity [2-5]. The core of these methods is the relation between the crack position and dimension, respectively the change in the modal parameters [6-8]. Often, artificial intelligence is used to perform classification and make the correlation between the crack and the modal parameter changes [9, 10]. In all cases, finding the crack in an early state and precise assessment of its position and severity implies using accurate models of the structure [11] and precise evaluation of the modal changes [12-14]. Most of the methods are developed for prismatic beams or plates and consider the damage as a transverse crack [3], but there are also techniques that can be applied to find cracks in pipes [15], frames [16] or other kinds of structures.

In prior research, we found behavioral patterns for simple beam-like structures with open cross-section subjected to large cracks [17]. The best found boundary condition for the analyzed structure with an I-shape cross-section was fixing it at the mid of the web. This ensured obtaining a minimum of vibration modes that cannot be used for damage detection because they present a low sensitivity to cracks. In this paper, we present a study designed to find the best way to fix a complex structure as the lateral frame of a bogie and test the sensitivity of this structure to cracks.
2. Materials and methods
In this research, we concentrate on finding the effect of a crack in the weld joints realized between the web and the flange of the side frame of a bogie, i.e. a longitudinal crack, on its eigenfrequencies. Therefore, we modeled the part of interest of the side frame as a steel beam with an I-shaped cross-section. The bogie of Y25 type is presented in figure 1, while the side frame and the zoom on the cross-section of interest are depicted in figure 2.

![Figure 1. The Y25 Bogie.](image)

The relevant physical-mechanical properties extracted from the SolidWorks library for a structural Stainless Steel are: mass density 7800 kg/m³, Young modulus 2·10¹¹ N/m², Poisson ratio 0.28, tensile strength 513.6 MPa, yield strength 172.3 MPa.

As mentioned, in prior research we fixed an I-beam at the bottom of the inferior flange respectively at the mid of the web. Using the last boundary condition we eliminated some vibration modes that are not relevant for damage detection. Now, because we have a quite similar structure but with a significantly smaller web, we fix it near the upper flange, as shown in figure 2(b).

![Figure 2. The side frame of the Y25 bogie: (a) general view; (b) upper flange with a crack.](image)

The simulated cracks are located in the tee joint realized by welding between the upper flange and the web, as shown in figure 2(b). All cracks have the length \( l = 500 \) mm, the crack depth is \( a = 3 \) mm and the width of the crack is \( d = 0.1 \) mm. We consider here 31 scenarios for the crack position: in the first case the left crack end is positioned at \( x_1 = 25 \) mm from the beam end, afterwards it is removed with a step \( s = 25 \) mm along the frame until it achieves the position \( x_{30} = 750 \) mm. We also consider the position \( x_{31} = 755 \) mm at which the crack is located symmetrically in the frame.
The dynamic behavior of the side frame part is studied by means of the SolidWorks software. For the intact beam, we apply a mesh using elements of 9.4 mm size. It results in a model with 49438 elements and 86027 nodes. For the damaged beam we apply a mesh using elements of 9.4 mm size and a finer mesh using elements of 4.7 mm size. It results in a model with 50285 elements and 87441 nodes.

We perform first a modal study to obtain the first thirteen eigenfrequencies $f_i^u$ of the healthy structure. Afterward, we simulate the cracks corresponding to the 31 damage scenarios and perform again modal studies. The evolution of the frequency $f_i^u$ of the damaged frame with the crack position is analyzed and the relative frequency shifts (RFS) are calculated. The results are presented, along with their interpretation, in the next section.

3. Results and discussions

As a result of the simulation, we obtained a sequence of eigemfrequencies for the healthy beam and for each crack position. Examples of the achieved results are presented in Table 1. One can observe the frequency of the first vibration mode decrease dramatically due to the generated crack, while for the other modes we remark either a medium or a small decrease.

| Mode no. | Healthy beam | Crack position (mm) |
|----------|--------------|---------------------|
|          | x=25 | x=150 | x=275 | x=400 | x=525 | x=650 | x=750 |
| 1        | 621.76 | 563.95 | 573.53 | 576.62 | 578.33 | 578.02 | 578.40 | 578.62 |
| 2        | 627.3 | 622.18 | 622.37 | 622.47 | 622.92 | 623.21 | 622.85 | 623.39 |
| 3        | 644.73 | 634.52 | 634.74 | 634.95 | 633.43 | 632.88 | 631.12 | 630.76 |
| 4        | 675.5 | 660.16 | 661.12 | 661.12 | 661.50 | 661.35 | 660.91 | 661.45 |
| 5        | 720.66 | 703.44 | 706.78 | 706.96 | 703.55 | 703.02 | 705.29 | 707.96 |
| 6        | 779.63 | 764.49 | 766.93 | 761.22 | 762.52 | 767.23 | 763.25 | 760.32 |
| 7        | 850.75 | 838.06 | 835.16 | 834.04 | 838.64 | 833.83 | 834.71 | 838.72 |
| 8        | 879.19 | 871.09 | 872.38 | 873.66 | 873.96 | 873.94 | 874.29 | 874.83 |
| 9        | 883.73 | 880.21 | 880.60 | 881.07 | 881.32 | 881.80 | 881.97 | 882.43 |
| 10       | 898.61 | 895.43 | 895.87 | 896.90 | 895.42 | 893.97 | 893.14 | 892.92 |
| 11       | 923.7 | 919.61 | 915.35 | 917.76 | 917.32 | 918.41 | 917.42 | 915.81 |
| 12       | 933.55 | 920.95 | 922.58 | 922.13 | 919.75 | 919.60 | 922.23 | 923.15 |
| 13       | 959.19 | 954.55 | 954.73 | 955.27 | 955.01 | 954.85 | 954.57 | 955.51 |

From table 1 we can observe that the first mode can indicate the crack extension. For a long crack, we expect obtaining a big difference between the frequency of the healthy and the cracked frame. This difference decreases if the crack is shorter, but still remains significant and easily observable. Therefore, the first mode can be used to recognize the occurrence of cracks. The evolution of the first mode’s eigenfrequency with the crack position is presented in figure 3(a).

The difference between the frequency of the healthy and the cracked frame for any other vibration mode is significantly smaller, so we decide to use these apart from the fundamental frequency and use these for establishing the crack position. After careful analysis, we concluded that we can associate the
medium frequency decrease with the bending vibration modes and the small frequency decreases with the torsional modes.

A typical evolution of the frequency with the crack position for bending modes is represented in figure 3(b), while the evolution for a torsional mode is illustrated in figure 3(c). We notice here that the frequencies associated with the bending modes have a quasi-sinusoidal evolution with the position, while the torsional modes have a slight increase until the crack reaches the center of the frame. It is a question if the torsional modes cannot be used in conjunction with the fundamental mode to estimate the crack length.

From Table 1 and figure 3 we notice the frequency changes due to damage for this type of crack can be easily measured if advanced signal processing methods as that presented in [12] are involved. This remark is also valid for the frequency changes if damaged states of the frame are compared.

![Figure 3](image)

Figure 3. Frequency evolution with the crack position for: (a) mode 1; (b) mode 7 and (c) mode 4.

The Relative Frequency Shift (RFS) carries important information that can be used when applying vibration-based damage detection methods. The RFS, calculated with relation 1, is different for a crack specific position $x$. Figures 4 and 5 present the RFSs for several crack locations.
\[
\text{RFS}_i(x) = \frac{f_i^U(x) - f_i^D(x)}{f_i^U(x)} \times 100 \%
\]  

Figures 4 and 5 show that the RFSs are patterns that are able to characterize a specific crack location. It can be also observed here that the RFS values have the same order of magnitude for a crack with a particular length.

---

**Figure 4.** Relative Frequency Shifts calculated for different crack positions.
Figure 5. Relative Frequency Shifts calculated for the crack positioned at the frame mid-span.

In order to achieve accurate frequency estimation, the accelerometers should be located at positions where the flange attains maximum displacement. Obviously, for the analyzed flange the position is at the ends but some other locations are also available. The results permit concluding that cracks arisen in the weld joint linking the web and the flange of a side frame of a bogie can be detected when vibration-based damage detection methods are involved.

4. Conclusions
We present in this paper a study performed to find out if cracks in the weld joint that link the web and the flange of a side frame of a bogie can be detected using vibration-based damage detection methods. Based on previous and the actual research, we suggest fixing the frame rigidly near the analyzed joint, i.e. fixing the web close to the flange. A distance of 5-15 mm should be taken between the fixing system and the flange. For this fixing condition, detecting the occurrence of the crack estimating its length can be made by involving just the fundamental frequency. To find the position of the crack, the bending modes are the most suitable, as shown in figures 4 and 5 in this study.

Our next approach will concern the use of the fundamental frequency in correlation with the torsional frequencies to make a more effective estimation of the crack extend. Also, in our future studies we will concentrate on internal cracks.

5. References
[1] Vlase S Marin M and Öchsner A 2019 Considerations of the transverse vibration of a mechanical system with two identical bars, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications 233(7) pp 1318-1323
[2] Abdel Wahab M M and De Roeck G. 1999 Damage detection in bridges using modal curvatures: application to a real damage scenario Journal of Sound and Vibration 226 pp 217–235
[3] Farrar C R and Worden K 2007 An introduction to structural health monitoring Philosophical Transactions of the Royal Society A 365 303305
[4] Gillich G R, Wahab M A, Praisach Z I and Ntakpe J L 2014 The influence of transversal crack geometry on the frequency changes of beams Proceedings of International Conference on Noise and Vibration Engineering (ISMA2014) and International Conference on Uncertainty in Structural Dynamics (USD2014) pp 485-498
[5] Ravi J T, Nidhan S, Muthu N and Matii S K 2018 Analytical and experimental studies on detection of longitudinal, L and inverted T cracks in isotropic and bi-material beams based on changes in natural frequencies Mechanical Systems and Signal Processing 101(15) pp 67-96
[6] Gillich G R, Minda P F, Praisach Z I and Minda A A 2012 Natural frequencies of damaged beams - a new approach Romanian Journal of Acoustics & Vibration 9(2) pp 101-108

[7] Praisach Z I, Minda P F, Gillich G R and Minda A A 2011 Relative frequency shift curves fitting using FEM modal analyses Proceedings of the 4th WSEAS International Conference on Finite Differences - Finite Elements - Finite Volumes - Boundary Elements pp 82-87

[8] Gillich G R, Praisach Z I, Onchis D M and Gillich N 2011 How to correlate vibration measurements with FEM results to locate damages in beams Proceedings of the 4th WSEAS International Conference on Finite Differences - Finite Elements - Finite Volumes - Boundary Elements pp 76-81

[9] Khatir S, Dekemele K, Loccufler M, Khatir T and Wahab M A 2018 Crack identification method in beam-like structures using changes in experimentally measured frequencies and Particle Swarm Optimization Comptes Rendus Mécanique 346(2) pp 110-120

[10] Shu J, Zhang Z, Gonzalez I and Karoumi R 2013 The application of a damage detection method using Artificial Neural Network and train-induced vibrations on a simplified railway bridge model Engineering Structures 52 pp 408-421

[11] Seon Park H, Kim J and Oh B 2019 Model updating method for damage detection of building structures under ambient excitation using modal participation ratio Measurement 133 pp 251-261

[12] Gillich G R, Mituletu I C, Negru I, Tufoi M, Iancu V and Muntean F 2015 A method to enhance frequency readability for early damage detection Journal of Vibration Engineering and Technologies 3(5) pp 637-652

[13] Onchis D M, Gillich G R and Frunza R 2012 Gradually improving the readability of the time-frequency spectra for natural frequency identification in cantilever beams Proceedings of the 20th European Signal Processing Conference (EUSIPCO) pp 809-813

[14] Gillich G R, Mituletu I C, Praisach Z I, Negru I and Tufoi M 2017 Method to enhance the frequency readability for detecting incipient structural damage Iranian Journal of Science and Technology, Transactions of Mechanical Engineering 41 pp 233–242

[15] Naniwadekar M R, Naik S S and Maiti S K 2008 On prediction of crack in different orientations in pipe using frequency based approach Mechanical Systems and Signal Processing 22(3) pp 693-708

[16] Fassois S and Sakellariou J 2007 Time series methods for fault detection and identification in vibrating structures The Royal Society - Philosophical Transactions: Mathematical, Physical and Engineering Sciences 365 pp 411–448

[17] Barbinta C I, Tufisi C, Hamat C O, Nedelcu D and Gillich G R 2019 Sensitivity analysis for frequency-based prediction of cracks in open cross-section beams Vibroengineering Procedia 27 pp 7-12