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ADVANCED THEORETICAL-EXPERIMENTAL METHOD FOR OPTIMIZATION OF DYNAMIC BEHAVIOUR OF FIREFIGHTING VEHICLE MODULAR SUPERSTRUCTURES

Mr Saša R. Mitić *
Faculty of Mechanical Engineering, University of Belgrade
Dr Branislav B. Rakićević
Faculty of Mechanical Engineering, University of Belgrade
Dragan D. Stamenković
Faculty of Mechanical Engineering, University of Belgrade
Dr Vladimir M. Popović
Faculty of Mechanical Engineering, University of Belgrade

This paper shows elaborated theoretical-experimental method used to optimize dynamic behaviour of modular superstructures of firefighting vehicles. Harsh exploitation conditions under which firefighting vehicles operates and special requirements for this type of vehicles require dedicated approach to optimization of superstructures in terms of stress, deformation, fatigue, noise, comfort and effectiveness. Optimization implies selection of optimal shapes, materials, dimensions, mountings, suspension, damping and insulation of modules to attain optimal dynamic behaviour of superstructure. Method described in this paper can be divided into two interconnected parts – theoretical and experimental. Theoretical part consists of numerical modelling of superstructure variants and calculation of their responses to dynamic excitations using FEM, whose results are later validated through experiments. Experimental part of this method is based on excitation of superstructure physical models with, for this purpose specially developed, mechanical exciter, monitoring of superstructure response and changing of the input parameters in the design of superstructure to create the superstructure with best possible dynamic characteristics. Natural frequencies of structures, important in terms of resonant zones, are obtained using bump tests and FFT analysis. This method has proved suitable for optimization of dynamic behaviour of modular superstructures such as those of firefighting vehicles. Complete testing installation used in this method is illustratively shown in this paper. Also, there are guidelines for further development and improvement of this method.

Key Words: Special-purpose vehicles, Modular superstructure, Optimization, Dynamic behaviour, Mechanical exciter, FEM, FFT analysis, Bump test

INTRODUCTION

Identification of dynamic behavior of vehicle superstructures is very important in process of creating the superstructure with optimized dynamic characteristics. It is very demanding and complex activity, especially when it comes to superstructures of special-purpose vehicles. Harsh conditions in which these vehicles operate and wide spectrum of special requirements they have to meet lead to rise of complexity of such optimizitaion [3]. Another fact that adds to complexity of this type of research is lack of adequate recommendations from the chassis producers for builders of this type of superstructures. That creates the necessity for establishing effective method for their optimization [11].

Modular structures present actual conceptual orientation of leading world producers of firefighting vehicles. Modular concept includes several independent and separated units, with different characteristics and different influence to vehicle

** Faculty of Mechanical Engineering, Kraljice Marije 16, 11000 Beograd; smitic@mas.bg.ac.rs*

chassis and separately suspended to a chassis [1]. This modules also interact with each other by transferring the loads and damping excited vibrations [2].

In the case of firefighting vehicles, dynamic excitation of superstructures comes from road surface and installed devices in operation. These excitations could cause fatigue, exceeding of permissible stresses and noise levels, unwanted movements, lower the level of comfort and reduce the efectiveness of vehicle, which is, in case of firefighting vehicles, of great importance [4].

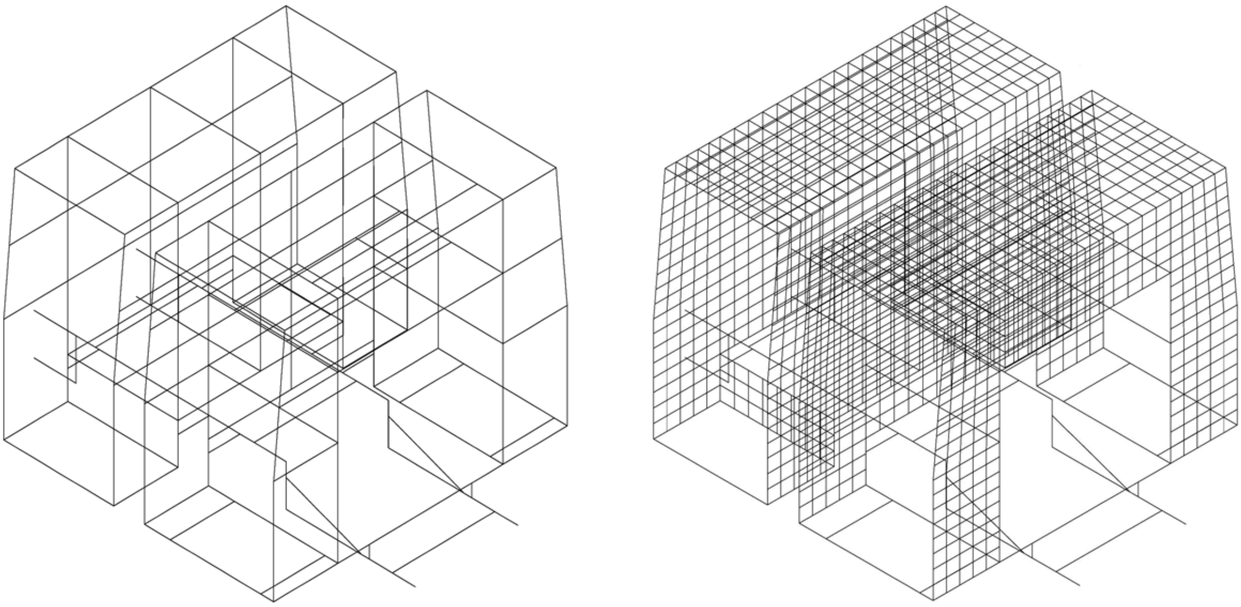


Figure 1. FEM model of one superstructure variant (beam and plate finite elements)

Therefore, it is essential to determine the integral dynamic behaviour of complete superstructure to enable its optimization.

Complexity of development and optimization process reflects in necessity of incorporation of modern numerical and experimental methods [8]. Different variants of superstructure modules and their joints were numerically modelled and their dynamic behaviour was simulated using numerical prototyping. Experiments have been conducted to validate the results acquired by numerical prototyping and to identify parameters that can not be obtained by analysis of numerical model.

NUMERICAL SUPERSTRUCTURE MODELLING

Finite Element Method (FEM) has been used for making numerical models and dynamic behavior simulations of superstructure modules and superstructure in general. FEM analysis has been done using "KOMIPS" software package [5]. During this process, variable inputs are material, dimensions, shapes, damping and suspension. Several different variants of superstructure have been made by varying these inputs [6]. Outputs from this analysis are rigidity of modules and joints, stresses, deformations and accelerations of superstructure points. Results obtained through this analysis are later validated by experimental testing of physical models of superstructure variants. FEM models of one variant of superstructure are shown on Figure 1.

TESTING INSTALLATION

Testing installation shown on Figure 2 consists of frequency converter, mechanical exciter with built-in force transducer, accelerometers (whose number depends on acceleration measurement points of superstructure), digital acquisition system and computer with installed all software needed for recording and post-processing of data [9].

The role of mechanical vibration exciter is to apply harmonic force of desired amplitude and frequency, in desired direction and on desired position of the analyzed superstructure, which allows us to monitor its dynamic behaviour under the effect of such force. Harmonic force is applied as an inertia force generated by rotation of exchangeable weights acting as unbalanced masses. By choosing the mass of weights and their angular velocity we can attain the amplitude and frequency of force we need. Rotating motion is transferred from electro-motor to flywheels by belt drive. Exchangeable weights are attached to flywheels with bolts. Force generated by rotation of unbalanced masses is transmitted to the structure through the two spherical joints and force transducer, as shown on Figure 3.

Dynamic response of tested superstructure is measured by accelerometers placed on desired measurement points of superstructure in desired directions. Recorded data are postprocessed by spectral analysis software to determine the amplitudes and frequencies of measured accelerations. Spectral analysis is done by FFT (Fast Fourier Transform), a computer algorithm for computing the DFT (Discrete Fourier Transform) using the "Sigview 1.99.0" software [12].

Presented installation is also used for bump tests to determine the natural frequencies of superstructures. This is done by measuring the dynamic response of superstructures after a transient impact on desired point of superstructure and in desired direction. Determination of superstructure natural frequencies is important from the aspect of identification of resonant zones in which the excited superstructure may get during testing or exploitation. Resonance is a very dangerous phenomenon which causes increase of stresses, deformations and noise level, decrease of comfort and could lead to failure of whole system. Because of that, it is necessary to optimize the structure in such way that it doesn't get into resonant zones in everyday operation. One of the diagram obtained by bump test is shown on Figure 4.

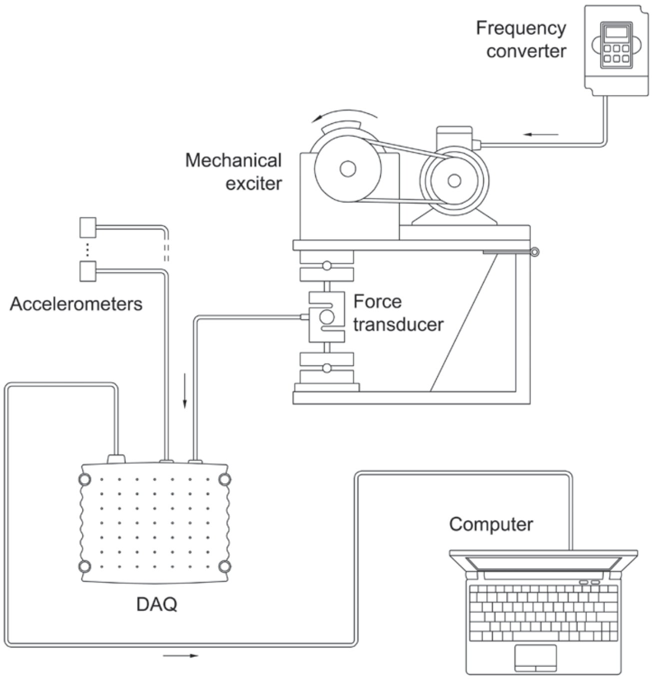


Figure 2. Testing installation

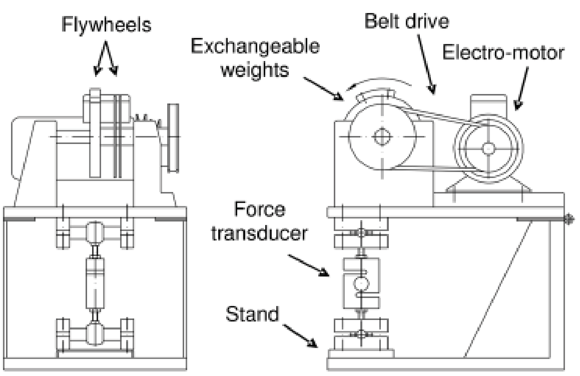


Figure 3. Mechanical vibration exciter

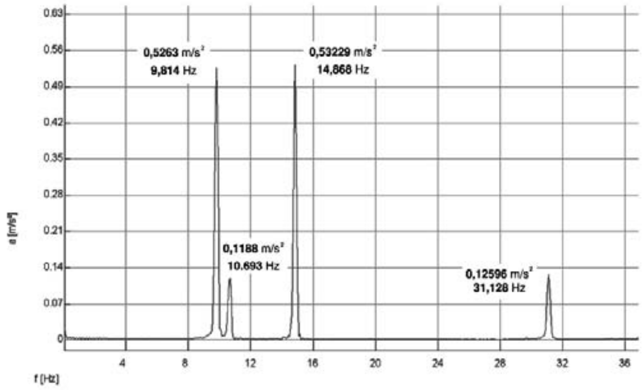


Figure 4. Natural frequencies of one of the superstructure variants

OPTIMIZATION METHOD

As mentioned before, optimization method is consisted of theoretical and experimental part. Since the optimization of dynamic behaviour of firefighting vehicles superstructures present a complex task, this two parts must be interconnected to ensure its maximum effectiveness. Making of physical models and carrying out the experiments takes time and money. Use of numerical modelling cuts down the number of experiments needed, and thus decreases the cost and duration of research. Experiments are conducted to validate the data acquired from numerical analysis and to determine parameters that cannot be analyzed by numerical methods used, such as noise level. Whole optimization process is shown on Figure 5.

Process inputs are maximum permissible values of stress, deformation and noise, desirable comfort and dynamic superstructure behaviour in terms of resonant zones avoiding. Process begins with making of numerical models using FME. Several models are made with different dimensions, shapes and materials used, and with different mountings, joints and metal sheeting. Same software package used for creation of numerical models is used for analysis of stresses and deformations under dynamic load. After numerical analysis, physical models of superstructures are made based on numerical models.

First experiment carried on these physical models is comprised of transient impact and analysis of response of superstructure to such excitation. This experiment is called “bump test” and is used for determination of natural frequencies of structures. Next step is testing of physical models using mechanical vibration exciter in order to observe dynamic behaviour of structure under such excitation. When, using numerical modelling and experiments, most optimal variant of superstructure is found, we can proceed to the design of superstructure.

After design and construction of superstructure is done and vehicle with this superstructure is put into operation, it is necessary to track its dynamic behaviour in real exploitation conditions, to prove that the output superstructure has optimal dynamic characteristics, and to collect data needed for further improvements of superstructure.

RESULTS AND DISCUSSION

For the purpose of obtaining adequate test results, mechanical vibration exciter was attached to several structures. Structures used in this experiment are:

- foundation
- beam girder
- post – two heights of mounting
- fire-fighting vehicle superstructure fixed to foundation – two positions of mounting [7]
- fire-fighting vehicle superstructure on wheels (free) – three positions of mounting

These structures are shown on Figure 6(a-h).

Figure 7(a-i) shows the results of experiments that have been performed. On these diagrams FR represents the theoretical values of force, while FS represents the actual, real values. This values are represented depending on mass of weights and frequency of rotation of these weights, for previously mentioned analyzed structures [10]. Also, the natural frequencies of structures are shown for consideration of the effect of resonance on deviation of actual values of force from theoretical values.

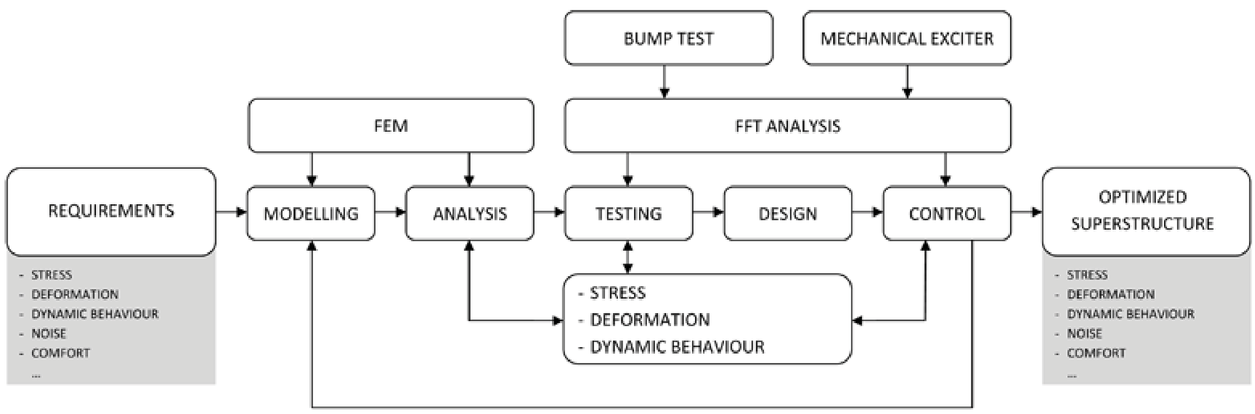


Figure 5. Optimization method scheme

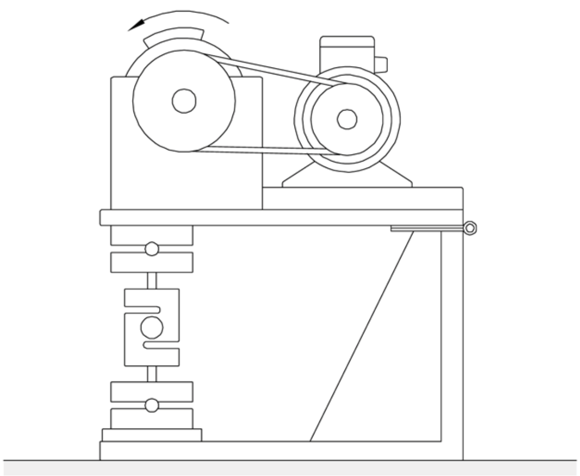


Figure 6a) exciter attached to foundation

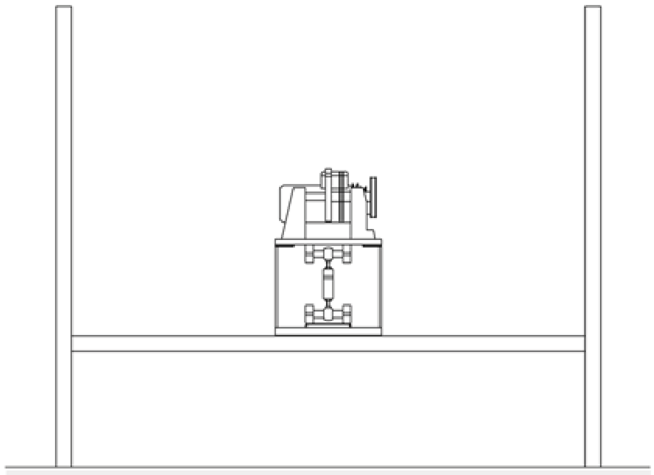


Figure 6b) exciter attached to beam girder

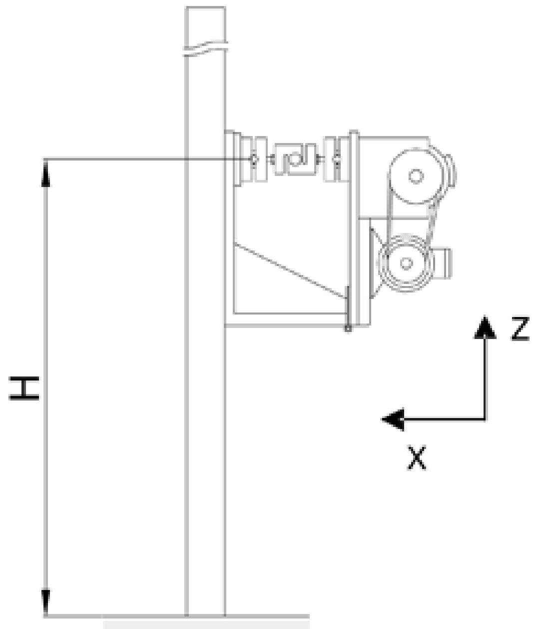


Figure 6c) exciter attached to post

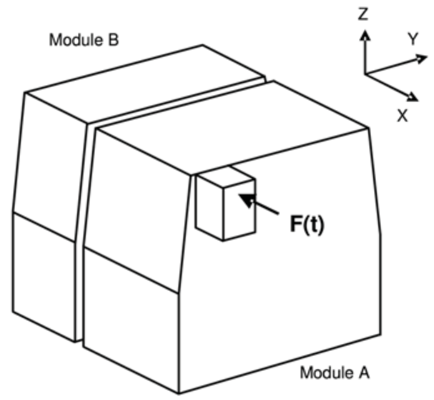


Figure 6d) exciter attached to fixed superstructure in X direction

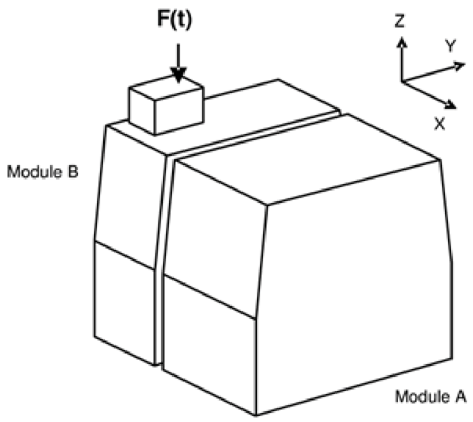


Figure 6e) exciter attached to fixed superstructure in Z direction

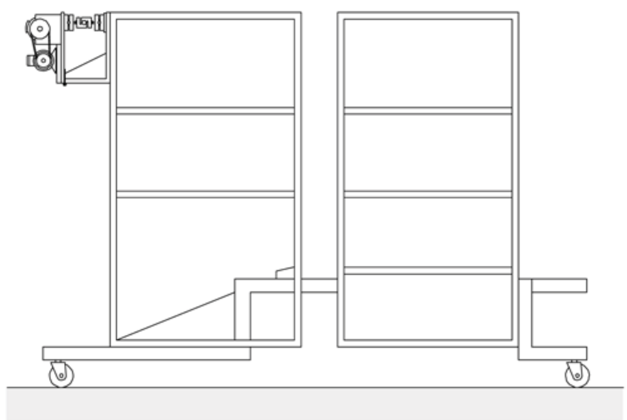


Figure 6f) exciter attached to free superstructure in X direction

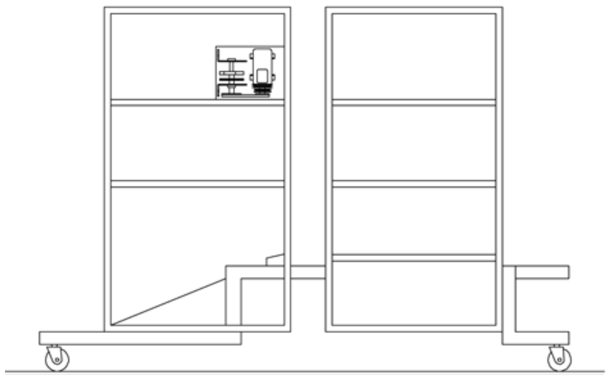


Figure 6g) exciter attached to free superstructure in Y direction

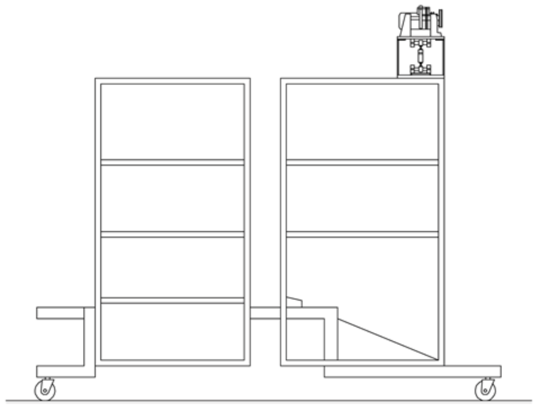


Figure 6h) exciter attached to free superstructure in Z direction

Figure 6. Analyzed structures

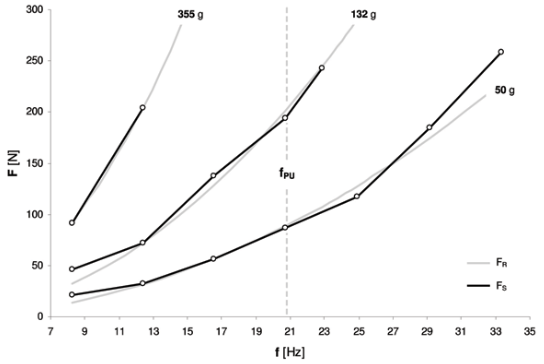


Figure 7a) exciter attached to foundation

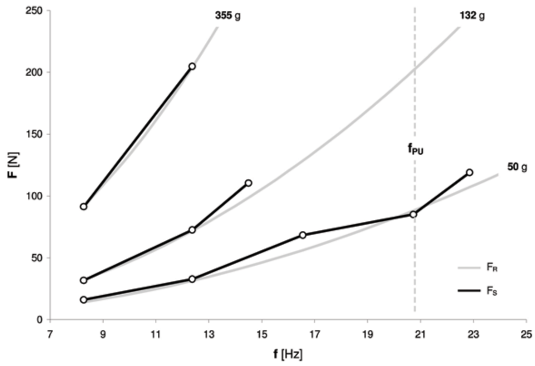


Figure 7b) exciter attached to beam girder

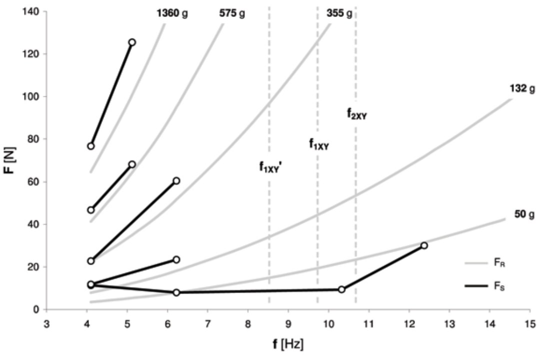


Figure 7c) exciter attached to post at the height of 1290 mm

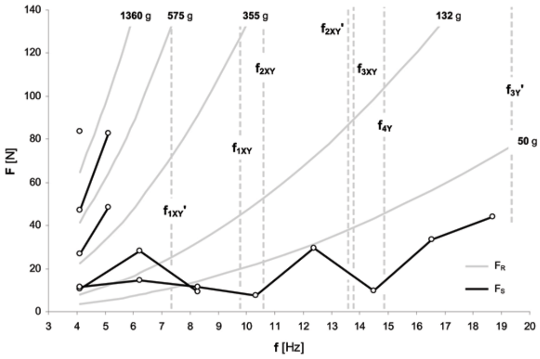


Figure 7d) exciter attached to post at the height of 1675 mm

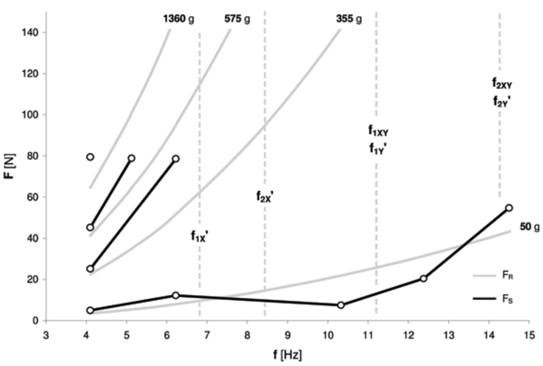


Figure 7e) exciter attached to fixed superstructure in X direction

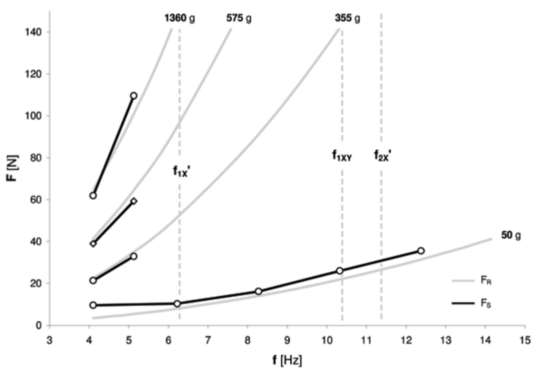


Figure 7f) exciter attached to fixed superstructure in Z direction

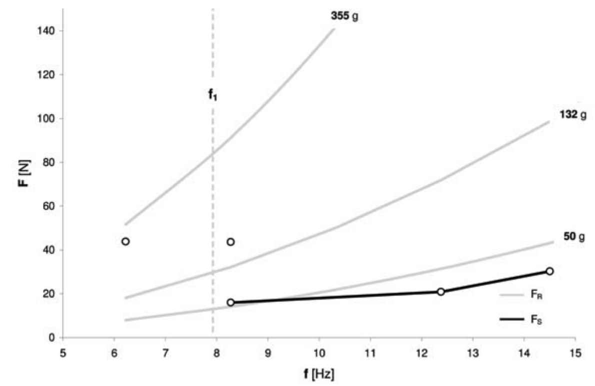


Figure 7g) exciter attached to free superstructure in X direction

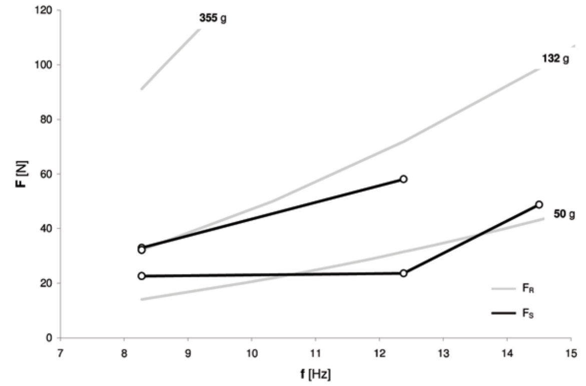


Figure 7h) exciter attached to free superstructure in Y direction

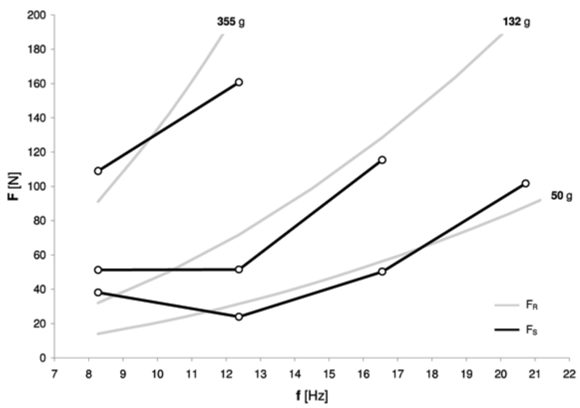


Figure 7i) exciter attached to free superstructure in Z direction

Figure 7. Actual and theoretical values of force

Relation between actual force and acceleration measured at the point and in direction of application of force in case when exciter is attached to post is shown on Figure 8.

Figure 9 shows the ratios of actual and theoretical values of force for various frequencies and various masses of weights for specified stiffness of structures. Horizontal axis represents the reciprocal value of stiffness of structures which are shown in Table 1.

Points marked with X represent ratios of actual and theoretical force in resonant zones, while points marked with empty circle represent ratios of actual and theoretical force for values of force not high enough to attain wanted signal-to-wanted ratio. That is the reason why some of these points lays out of acceptable zone, marked with 5%, 10% and 15% area.

Table 1. Stiffness of structures

Structure	Stiffness c [N/mm]
Foundation	∞
Beam girder	6250
Fixed superstructure (Z direction)	2941.17
Post (1290 mm)	741.17
Post (1675 mm)	336
Fixed superstructure (X direction)	94.78

Ratios with values lower than 0.8 are not shown on Figure 9 and are all results of resonance. Also, ratios with values higher than 1.8, which are result of unfavourable signal-to-noise ratio, are not shown.

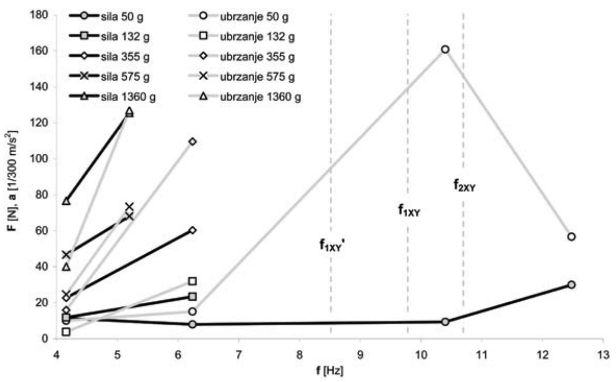
CONCLUSIONS

Identification of dynamic behaviour is important activity in modelling, analysis, testing and control of firefighting vehicle superstructures. It is desirable to implement identification of dynamic behaviour into all this processes. Method shown in this paper make this possible by incorporating theoretical and experimental activities to optimize the superstructure dynamic characteristics.

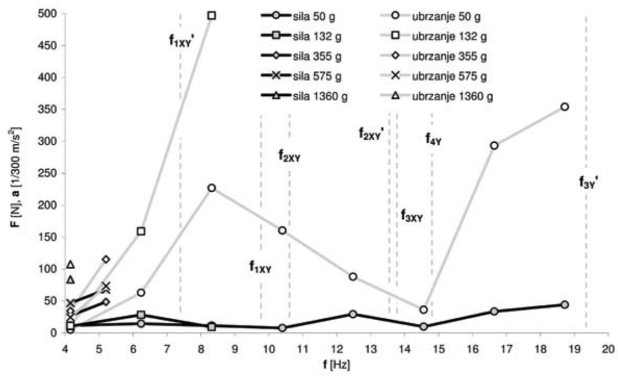
All tests have been made with empty, unloaded structures. Increasing of mass of vehicle should bring to more acceptable results, so the resonant zones should be moved higher and the complete vehicle structure should have much better behaviour applying higher forces.

It can be noticed that deviations grow with decrease of stiffness of structures. For the values of stiffness inherent in vehicle structures these deviations are in satisfactory limits. The mechanical vibration exciter is entirely applicable outside resonant zones for values of force higher than 10 N and for values of stiffness characteristical for vehicle structures.

Method showed good results in reducing of superstructure stresses, deformations and noise levels generated by dynamic load in firefighting vehicle exploitation. It also led to creation of superstructure capable of performing all required tasks without getting into resonant zones and threatening the vehicle functionality.



8a) exciter attached to post at the height of 1290 mm



8b) exciter attached to post at the height of 1675 mm

Figure 8. Actual force and acceleration

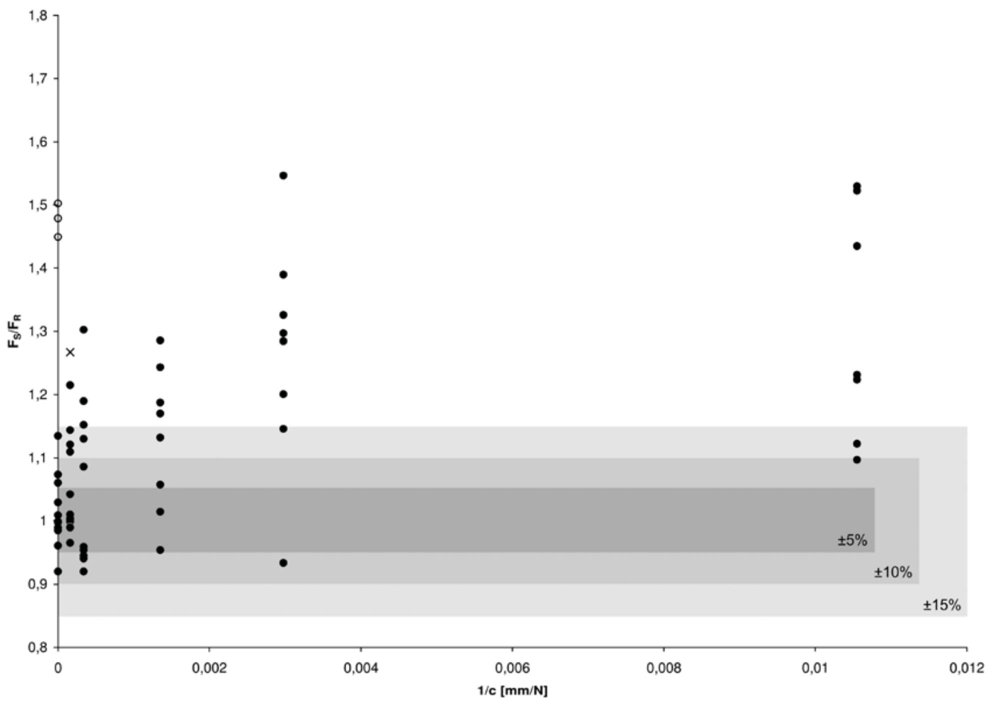


Figure 9. Ratios of actual and theoretical values of force depending on stiffness of structure

As a future activities, it is necessary to analyze the influence of interconnection of separate modules, as well as the influence of module supports. These analysis, together with previous achievements, should bring us to defining of knowledge base, which should provide real and reliable state identification of modular structures in early phases of design and product development process.

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