Loader Crane Modal Analysis Using Simplified Hydraulic Actuator Model

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Abstract. Paper presents results of numerical and experimental analyses on dynamic properties of hydraulic loader crane. Both analyses were carried out in two loader cranes configurations first with telescopic boom sections partially extended and second fully retracted. Numerical analysis based on finite element method was conducted. There were used simplifications on hydraulic actuator models, that resulted in reduction of model order. Hydraulic actuators were modeled by rod elements with equivalent stiffness based on full hydraulic system built in Matlab. Developed model included parameters of valves, hydraulic pump and actuators itself. The main goal of the research was to develop a simplified model of hydraulic loader crane for dynamic analyses. The use of simplified models, the results of which are in line with the results obtained in experimental studies, allows to shorten the computational time. The findings of the presented studies show that, in spite of used simplifications, the results of numerical analyses and experimental studies are consistent.

Keywords: Loader crane · Modal analysis · Dynamics · Vibrations · Finite element modelling

1 Introduction

Hydraulic loader cranes are mechanisms which consist of chain of flexible links connected with each other by translational and rotational joints. Cranes offer possibility of moving, lifting and lowering various heavy objects, impossible to be transferred by a man. Moreover great advantage of these machines is their mobility, they can work in various directions and in wide ranges, thanks to this it is possible to avoid problems with transport. Objects can be placed in the indicated place without the need to transport and install any additional lifting device. Loader cranes usually contain several hydraulic cylinders which control the movement of individual crane components. In many industries, the use of these cranes turned out to be a revolutionary phenomenon, which greatly facilitated the performance of activities necessary to implement various plans and investments.

The great advantage of loader cranes is their versatility, which is the reason why requirements for them are still increasing. They are expected to work quickly and accurately. Moreover their lifting capacity increases and the structures are smaller and smaller, therefore their design is more complex. As a result, increasingly complex

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models are required at the design stage. Therefore, it is valuable to use reasonable simplifications in models.

During operation, the cranes are exposed to very high loads, which are also accompanied with dynamic forces. Of particular importance is the ability to model such extortion in the design process, where it is possible to predict the behaviour of the structure for dynamic forces. The most common method used in modelling of such structures is finite element method, which was used in presented paper. A novelty in the presented work is the use of a simplified hydraulic cylinder model, the stiffness of which is determined depending on the level of extension of the piston. The actuator stiffness model was developed in Matlab, and then the obtained stiffness characteristic was linearized in order to use this model in modal analysis.

2 Research Problem

The issue of loader cranes analyses is very often undertaken in scientific papers. The construction is analyzed in terms of static loads, structural stability, analysis of kinematics, fatigue analysis or vibrations. Whereas dynamic analysis of structure is one of the most valuable in terms of loader cranes there are papers which consider analytical modelling of dynamic properties such as eigenvalues or mode shapes.

There are many papers which present results obtained with experimental analysis of vibrations of loader cranes [1, 2]. Furthermore there are papers which present analytical, experimental and numerical methods of dynamic analysis of loader cranes. Author in [3] built sophisticated mathematical model for statics and dynamics. He used the formalism of Lagrange equations and rigid body method. He considered flexibility of support system, crane's links and drives. He concluded that flexibility of loader boom is significant in terms of obtained results in frequency analysis. In paper [4] authors besides building analytical model using Hamilton principle, applied finite element method. They compared the results obtained with both methods and achieved good agreement between changes in the frequencies. They considered changes in length of the boom and angle of its inclination. But as they mentioned, results should be verified by experimental research on a real object [5]. In paper [6] authors presented theoretical model of a loader crane where the telescopic booms were substituted by Euler-Bernoulli beams and connections between them were modeled by springs. They considered elastic connection to the ground and verified obtained results with experimental ones.

One of very useful tools in dynamic area of research of loader cranes is finite element method that was used by many authors in their investigations. In [7] author presented results for numerical and experimental vibration analysis of loader crane. He compared results obtained for ten variants of selection of components flexibility. He came to conclusions that model could be simplified by nonflexible components found out through thorough investigations.

There are many other researches in this area of investigations. Authors of paper [8] presents results of research on residual vibrations of loader crane for different stopping positions. They conducted their analyses for simplified single-link flexible planar and curved manipulators, but their FEM results were comparable with experimental results. They used verified model for further investigations.

Authors in paper [9] carried out analyses of telescopic platform, they conducted analytical and finite element method and verified results with experimental research. Concluding, there is a great number of papers describing investigations on loader cranes, but most of experimental investigations were conducted on simplified object and numerical analyses on full FEM model.

This paper presents results of the dynamic analysis (carried out for two configurations, differing in the level of extension of the hydraulic actuator pistons) of HIAB XS 111 loader crane finite element model simplified with rod elements that substituted hydraulic actuators. Stiffness of these elements was obtained using structure model build in Matlab. Such structure has been built on the basis of method presented in paper [10]. Mentioned model included parameters of valves, hydraulic pump and actuators itself. In order to verify obtained results, experimental analyses on real full scale object were conducted.

3 Modelling the Mechanic and Hydraulic System

Predicting loader crane dynamics is very important issue from the control point of view [11, 12], due to vibration occurring during operation [13]. However, due to the complicated structure of these devices and the interaction between the mechanical system and the hydraulic system it is a rather difficult task. Both the description of the dynamics mechanical system and the modeling of hydraulic fluid flows are quite complex. Most computing packages allow modelling of separate mechanical, hydraulic or pneumatic systems. However there are few that allow the synthesis of two types of systems, in analyzed case: modelling a mechanical and a hydraulic system including interactions between the systems.

The mechanical and the hydraulic systems interaction of HIAB XS 111 DUO loading crane were modelled in MATLAB/Simulink SimScape package. Developed model allows to study the interactions between mechanical and hydraulic systems. Both domains of the model are interacting on each other, for example, the increase in the pressure in the chamber of a given actuator affects the value of the force that this actuator manages. However, when the force is applied to the actuator, this will change the pressure in its chambers. Figure 1 shows a part of the model.

The stiffness of the hydraulic actuator consists of the stiffness of the mechanical components of the cylinder and the compressibility of the hydraulic oil. Because the hydraulic oil is characterized by high compressibility, its impact on the stiffness of the hydraulic cylinder as a whole is significant enough that in some cases the stiffness of the metal components of the system can be neglected and only the stiffness resulting from compressibility of the oil can be examined.

In addition, the change in piston extension level affects the amount of oil in the cylinder chamber, and this has a huge impact on the rigidity of the system. Therefore, an attempt was made to determine the stiffness of hydraulic cylinders of a loading crane in various configurations.

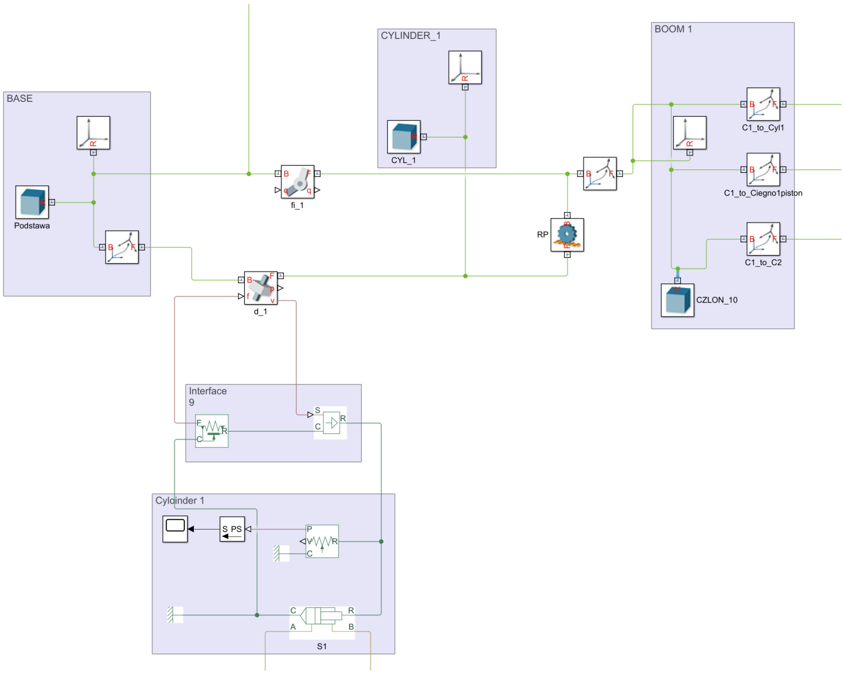

Fig. 1. Part of the model in Matlab of the mechanical system and the hydraulic loading crane HIAB XS 111 DUO.

To determine the stiffness of the actuators, a linearly increasing force was applied to the end of the working tip of the crane (Fig. 2). The applied load was perpendicular oriented to the ground plane, thus representing the force from the carried load. This resulted in changes of forces acting on the components of the whole model, also on the increase of the compression force of the No. 2 and 3 actuators (Fig. 2). Next, the forces acting on the actuators and their displacement in the direction along the piston rod were measured using the functions available in the SimScape package. Obtained data allowed to determine the equivalent stiffness of the actuators.

Stiffness diagrams are shown in Fig. 3. Because in each configuration in initial conditions, the forces acting in the crane's drives and joints are not zero, it was not possible to determine the substitute stiffness of the actuators for forces lower than the initial forces F_i acting on the actuators (initial equilibrium conditions). This is particularly noticeable for the "max" configuration,

3.1 Numerical Results

Numerical analysis was conducted in Midas NFX. Previously prepared CAD geometry of the structure was used. Geometry was discretized into hexahedral element mesh presented in Fig. 4. To improve the FEM efficiency structured mesh was used. In discretization process 1st order elements were used and in total there were 1 192 565

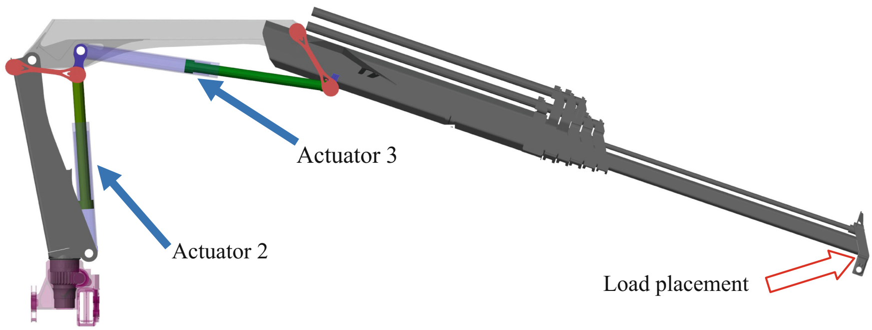

Fig. 2. Load placement in stiffness determining procedure.

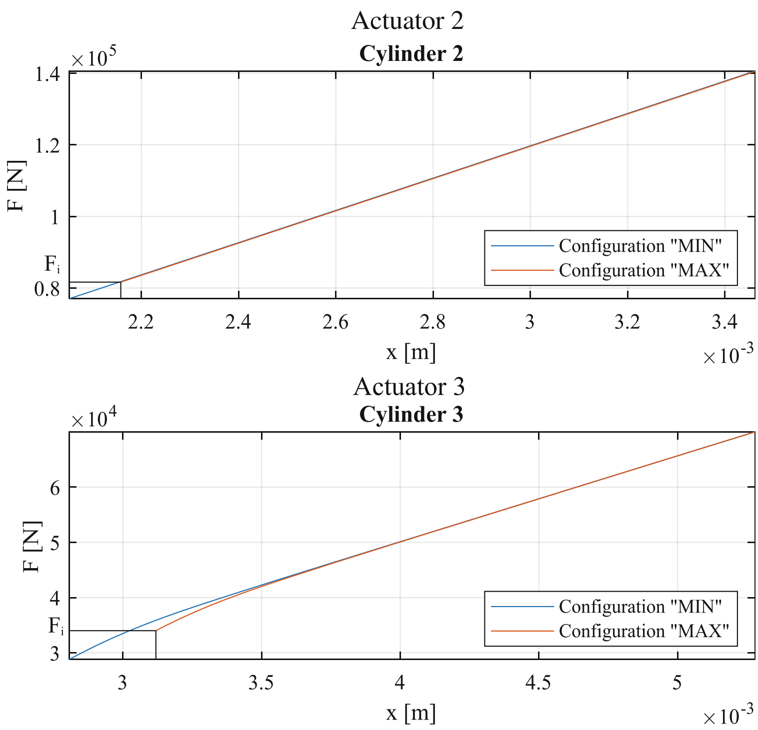

Fig. 3. Stiffness characteristics for actuator 2 and 3 in different configurations.

nodes and 748 087 elements. There were used fixed constraints in chosen areas, modelling connection to the supporting trail, using bolts. Paper presents selected mode shapes obtained from modal analysis.

The analyses have been conducted for two crane configurations. The first with telescopic boom sections partially extended was called “max” and second fully retracted was called “min”. In both configurations all of the hydraulic actuators, were

Fig. 4. Mesh of hydraulic loader cranes with actuators substituted by rod elements.

modeled by simplified elements with stiffness obtained on the basis of model developed in Matlab.

Model simplifications consisted of replacing full actuator model with rigid and rod elements (with linear stiffness characteristic) that replaced hydraulic actuators (Fig. 5). Those simplifications were based on preliminary test results which checked whether the system meets Maxwell's reciprocal theorem. Verification was made by comparing the measured FRF for a force input at the end of telescopic boom and response at a crane column with measured FRF where input force location and response location was swapped. Measured FRF correspond directly, this gave grounds for such simplification procedure.

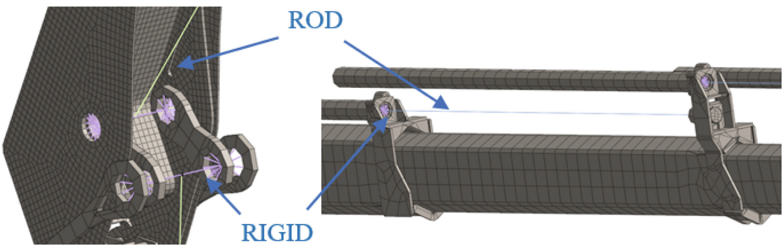

Fig. 5. The way of modelling actuators using rigid and rod elements.

Owing to applied simplifications model became smaller and as a result calculations were faster. Furthermore, the use of such simplifications makes reconfigurations much easier. Basing on the characteristics designated from full crane model built in Matlab, subsequent actuators parameters were obtained and equivalent (linearized) stiffness was calculated and assigned to ROD elements. Contact between translational booms was modelled as sliding contact.

On the basis of preliminary experimental investigations it was concluded that supporting system in both configurations appears to be very solid, resulting very low values of vibration amplitudes. Although the supporting trail was omitted in the modeling process, the method of fixing the crane to the support was modeled by applying appropriate constraints.

Selected results obtained on the basis of numerical modal analysis are presented in Fig. 6.

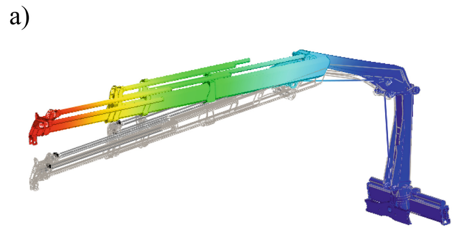

Fig. 6. Results obtained from FEM analysis for (a) max configuration (f = 1.061 Hz) and (b) min configuration (f = 1.848 Hz).

3.2 Experimental Results

In order to validate developed FEM model an experimental modal analysis was conducted. The tests were carried out for a crane placed on a trailer with concrete counterweights to ensure stability, i.e. in conditions in which loader cranes are used.

The structure was excited at the end of the telescopic boom, where the structure is usually excited during normal operation. In order to determine the spatial mode shapes excitation was realized in three orthogonal directions using modal hammer with 1,5 kg head mass. Use of such modal hammer results with 26 kN force impact. It allowed to obtain appropriate excitation conditions and respectively good coherence function, despite distance between sensors and excitation point of approximately 10 m (in “max” configuration). Experimental setup is presented schematically in the Fig. 7.

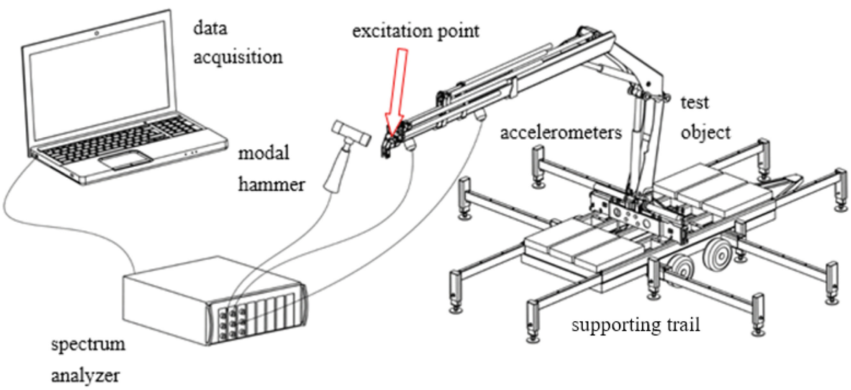

Fig. 7. Experimental setup

After the preliminary activities, including i.e. sensor connections, temperature stabilization of measuring equipment, setting a signal acquisition and processing parameters, experiment itself was conducted. The rowing accelerometer variant of impact test was realized. To ensure high quality of measured results excitation was done with instant monitoring of: response signal level, power spectral density of exciting signal and coherence function. Moreover, transfer function, determined after each impact, and after linear averaging was observed.

On the basis of FRF's (frequency response functions), modal model was build using Polymax method for estimating a set of natural frequencies and modal shapes, with default values of tolerance on frequency – 1% and mode shapes vector – 5%. Obtained values of natural frequencies are presented and compared with FEM model results in Table 1.

Table 1. The frequencies of Hiab XS 111 HI DUO in two configurations for experimental and numerical analyses.

Mode number	"Max" variant		"Min" variant	
	Experiment	FEM analysis	Experiment	FEM analysis
1	0.915 Hz	1.061 Hz	1.929 Hz	1.848 Hz
2	4.272 Hz	6.070 Hz	3.093 Hz	1.972 Hz
3	4.869 Hz	6.102 Hz	7.109 Hz	7.972 Hz
4	7.823 Hz	8.634 Hz	9.069 Hz	9.255 Hz
5	8.387 Hz	10.475 Hz	9.579 Hz	10.088 Hz

Next step of analysis was to calculate modal vectors, which are needed for animation of mode shapes. In-depth analysis of those animations allows to interpret relations between each boom of loader crane [14], estimate flexibility of certain booms in each configuration and validate in detail the established FEM model. Figures 8 and 9

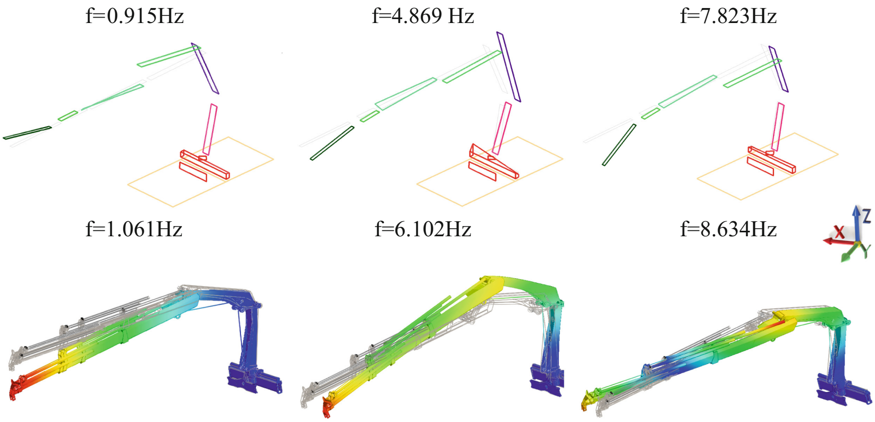

Fig. 8. Frames of mode shape animation at selected frequencies for "Max configuration".

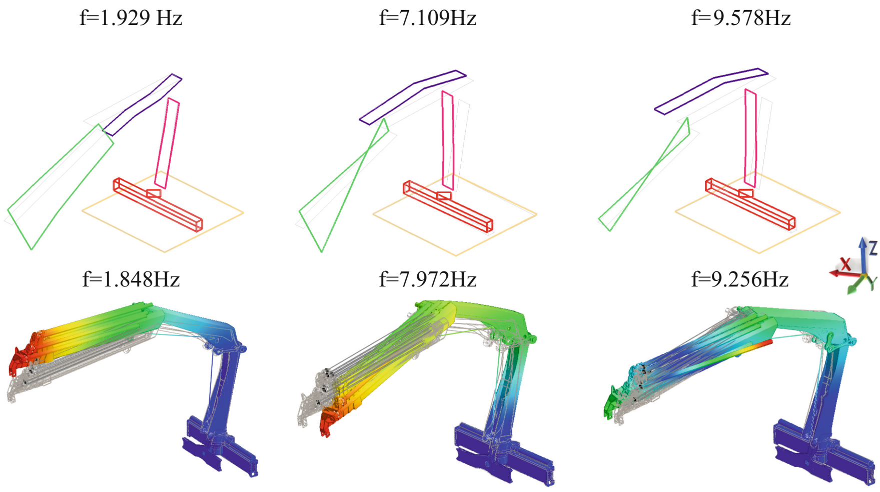

Fig. 9. Frames of mode shape animation at selected frequencies for “Min configuration”.

presents comparison of mode shapes obtained on the basis of experiment and FEM model for “max” and “min” configurations.

Analysis of determined mode shapes leads to a conclusion that in “max configurations” booms can be treated as rigid. Differences between mode shapes results from phase relations of certain booms movement. Significant drop of crane tip in Z direction can be observed for each of those mode shapes.

Interpretation of mode shapes, estimated for “min configuration” of loader crane shows different nature of vibrations (Fig. 9). Flexibility of booms can be observed affecting bending modes and torsional modes.

4 Discussion

To sum up the analysis, two investigations were conducted in two different configurations of loader crane both numerical and experimental. Thanks for proposed simplifications it was possible to save time and build model of smaller order. Hence, solving eigenproblem for established FEM model for different configurations becomes less problematic and less time-consuming. Furthermore, results obtained for both methods were comparable.

On the basis of the conducted analyses, one can also draw conclusions about the dynamics of the loader crane itself. Loader crane in each configuration had different dynamic properties. In “max configuration”, crane mode shapes with stiff booms only, can be observed. It means, that relative displacement (rotation) of booms dominates over flexibility of them. It’s related to significant dimensions of booms and its moments of inertia. Interaction between mechanical part of this structure and hydraulic system can be observed, resulting in this kind of motion.

In "min configuration", flexibility of booms can be observed. Such a flexible behavior should be expected for extended configuration rather than retracted. This proves that examined loader crane dynamic characteristic is changing significantly due to spatial configuration of booms.

5 Conclusions

Summing up, the proposed simplified hydraulic cylinder model allows you to determine the form of the crane's natural frequencies for various configurations. The results obtained on the basis of the model show acceptable agreement with experimental results, both in terms of natural frequencies and mode shapes. The developed model can provide support at an early stage of the design process.

The analysis presented in the article may be treated as a preliminary stage for further dynamic research of the considered construction. In the next stage, it is planned to carry out analyses aimed at determining the frequency response functions and time responses of the system.

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