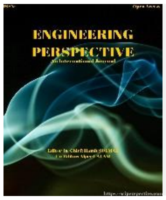

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Research Paper

Study on the Flexible Dynamic Analysis of the Wheel Loader Under Working Conditions and Comparison with Static FEA Results

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ABSTRACT

The boom is the main body part of the mechanism for wheel loader earth-moving machines. It is critical that the boom is able to both meet the kinematic requirements and withstand the stresses that come from the breakout and lifting of the material during operation. Theoretical forces can be extracted from the mechanism after the completion of the kinematic modeling. The boom, which can be examined under static conditions with reference to these forces, can be evaluated within the framework of basic requirements. However, within the scope of this approach, it is not possible to determine the problems that may occur in the dynamic working conditions of the wheel loader. This may cause unexpected failure. For this reason, the boom design, which has met the requirements in terms of static strength, should also be reviewed dynamically. In this study, the kinematically designed boom part was first analyzed in the MSC Mentat package program in the most statically critical position. In order to be evaluated dynamically, the structure was modeled as flexible dynamics in the MSC Adams package program. In this way, stress-time distributions of the boom were obtained from data on working conditions. According to these results, the structure was also examined dynamically in terms of strength.

Keywords: Earth Moving Machinery; Finite Element Method; Flexible Dynamic Analysis; Wheel Loader

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1. Introduction

Construction machinery has become indispensable in the understanding of modern industry, as it contains the conveniences that human labor cannot provide (in many areas such as job security and economics, especially in sustainability). Both the incomparable increase in the amount of work done per unit of time and the decrease in the need for raw materials to be spent during this period constitute a critical basis for the construction machinery to be an irreplaceable part of most sectors. The workload that construction machines are expected to handle is also increasing significantly. In this context, the increase in the variety of machines developed specifically for the task performed is a natural output of the process. Excavators, motor graders, compactors, wheel loaders, and backhoe loaders are the form of the basis of generally accepted construction machinery.

Wheel loader construction equipment can be used in many different sectors such as mine sites, construction sites, demolition sites, garbage separation, and waste areas. Each field has different usage requirements compared to each other. Although the usage areas vary, the basic working conditions undertaken by the wheel loaders are breakout, loading, and lifting operations. In general, these use cases also occur as a successive cycle. For this reason, generalizing the use over a single cycle will not be the wrong approach for wheel loaders. However, since wheel loaders can perform the loading cycle in many different work areas, it is necessary to consider these difficult conditions. In some places, it is expected to lift a single and large marble mass, while in some places it is expected to work with fine and/or coarse-grained sand, gravel, or soil materials. What is expected from wheel loaders is to meet all these requirements. Studies on force calculations and optimization of the loader mechanism have been published by Pavlovic J [1].

The operation also called the usage cycle, which involves breakout, loading, lifting and then dumping respectively, constitutes a work sequence for the wheel loader. Alleyne A. G. carried out studies on the movement conditions of the mechanism in the creation of loading models for the powertrains in construction machines [2]. It can perform this process with a mechanism that works connected to its main body and is driven by a hydraulic system. The loader mechanism generally consists of 5 basic parts. These are the boom that forms the main body of the mechanism, the z-bar that provides the diagonal transmission of the bucket movement, the linkage that acts as the transmitter, the bucket that provides the transport and loading of the material, and the cylinders that drive the whole system. The kinematic and dynamic simulation studies for the loader construction equipment z-bar part were carried out by Janosevic D [3].

The boom accommodates all other working parts due to the setup of the mechanism. For this reason, it is the basic element that meets all the loads that the construction machine is exposed to due to field conditions and transmits it to the main body. It is critical to meet the structural strength criteria in the design of the boom, as it acts as the main carrier and transmitter in the wheel loader usage cycle. Worley M. D.'s simplified dynamic model design study for boom design has been published [4]. Studies on the optimum design of the loader boom mechanism were carried out by Yu Y., Shen L., and Li M. [5]. Zhang Z. and He B. carried out studies on the optimum and adaptive design of wheel loader construction machines [6].

In this study, the boundary conditions to which the boom design is exposed were determined and input was created for both static and flexible dynamic analysis. The strength performance of the design was reviewed within the framework of the determined boundary conditions.

2. Material and Methods

The stages of determining the boundary conditions covering the working conditions of the boom model, whose kinematic and 3D design has been completed, are shared under the title of materials and methods. The diagram showing the workflow within the scope of materials and methods is shared below. The steps for the study were carried out over the shared flow (Figure 1).

Figure 1. Material and method workflow

2.1 Calculation of Theoretical Force Values

Calculation of wheel loader boom mechanism force values constitute the basic inputs for both static and flexible dynamic analysis processes. For this reason, it is critical to calculate the force capacities by the free-body diagram of the design. A free-body diagram of the mechanism is shared below (Figure 2).

In the creation of the free body diagram, the distances of all connection points as well as the freedom of movement and rotation should be considered. In addition, the 5 basic components that create the skeleton of the mechanism should be considered as rigid. The free-body diagram of the mechanism fixed to the main body from A, B, and C points is shared in Figure 2. Research on mechanism calculations in loaders is also mentioned in the study of spatial kinematic modeling and simulation of wheel loaders. Li Y. performed and analyzed matrix analyses of the mechanism using MSC Adams in kinematic analysis [7]. In the mechanism design, the power source is a hydraulic drive. Since the power comes from hydraulics, mechanism optimization also affects the fuel consumption of the construction equipment. To ensure minimum power consumption, the analysis and calculations of the kinematic design were carried out by Shin K. in the mechanism optimization study [8]. The kinematic setup is the main factor in the calculation of the load values. The force ranges that the cylinders can apply are used to determine the theoretical capacity of the system. In the loader boom optimization study, the force calculations for a wheel loader mechanism are mentioned. In this study published by Kolte S, the mechanism capacities were revealed over the cylinder values [9].

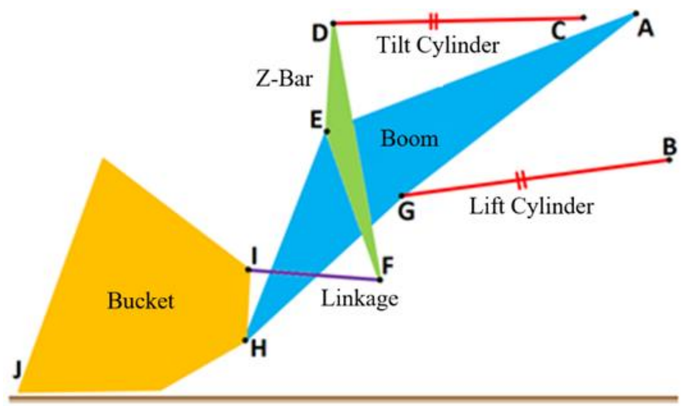

Figure 2. Free body diagram

Wheel loaders have critical positions determined by standards. Breakout position which is focused on the maximum hydraulic force capacity for material and critical tipping load which is the determination of wheel loader stability are the most important of these. The position known as the material force is called the breakout force in literature. Technical information for this force is determined by the ISO 14397-2 standard [10].

The part numbering highlighted in the relevant standard is named the lift cylinder, safety chain, axle support center, force measuring device, pulley, and ground plane respectively. The breakout force value, which must be calculated by the standard, is also important for boom strength evaluation. Theoretically, the highest force on the structure is determined by this value. The basic approach is based on the fact that the total moment and force values are 0 due to the static balance [11]. Static calculation formulas used for force values are shared below.

$$\sum_{i=1}^{n} M = F_1 * D_1 + F_2 * D_2 + \ldots F_n * D_n = 0 \quad (1)$$

$$\sum_{i=1}^{n} F_{x,i} = 0 \quad (2)$$

$$\sum_{i=1}^{n} F_{y,i} = 0 \quad (3)$$

In addition to the breakout force, the machine tipping load value is also critical. In this position, the force value is calculated at the furthest load center reach, considering the balance condition of the machine. With this calculation, the safe load value that the building can carry after breaking the material is determined. The ISO 14397-1 standard is binding for wheel loaders' balance position lifting capacity. Static calculations were carried out by taking into account the overturning criteria in the mechanism kinematic diagram, which was brought to the appropriate position according to the standard requirements. Detailed descriptions of the calculation steps are taken from the relevant standard [12].

2.2 Static Analysis with Finite Element Method

The first step in evaluating the boom design in terms of strength is to perform static analysis using the finite element method under critical load boundary conditions according to referenced standards. With the calculation of the theoretical force data, the boundary conditions that form the basis of the static analysis inputs are also completed. The finite element method is based on dividing a 3D design into small mathematical equations and solving it with matrix definitions. The smallest structure that is divided and converted into the mathematical matrix is called an element. This process is called meshing the 3D data and is performed in the MSC Apex package program. Mesh quality affects the effectiveness of the finite element analysis directly. On the one hand, the use of the mesh with poor element quality negatively affects the accuracy of the solution results, on the other hand, obtaining extremely good element quality unnecessarily prolongs the solution time. Considering this situation, the most appropriate element size and quality determination was performed for the relevant design. In the mesh step, the HEX8 element type was used because it has better performance in getting consistent results and contributes to obtaining the optimum solution time. In addition, since only boom strength values will be examined in this study, linear bar elements were preferred instead of cubic mesh elements in z-bar, link, bucket, and cylinder elements. In this way, both the kinematic structure of the mechanism was preserved, and the use of elements was concentrated on the boom. The model, the mesh step of which was completed, was transferred to the Marc package program to perform analyses with the finite element method. Defining the kinematic degrees of freedom correctly in the finite element model is one of the most important issues in the analysis. The loader mechanism is designed to have only freedom for rotation at all connection points known as a revolute joint. Rigid mathematical equations named RBE'2 is preferred in FEA works so that the freedoms can be defined accurately.

RBE'2 approach is based on combining selected connection nodes with rigid mathematical equations at a central node. In this way, the motion kinematics in the relevant axis is provided. The schematic image for the related definitions is shared below (Figure 3).

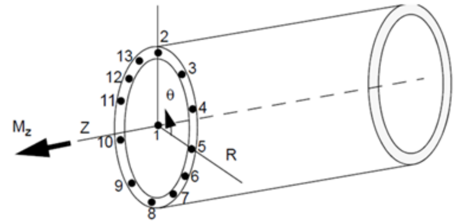

Figure 3. RBE'2 connection schematics

Construction machines are exposed to high stresses from place to place throughout their lifetime. This raises certain requirements in both the kinematic and structural design phases. The mechanism that meets the requirements in terms of kinematics must have sufficient strength to withstand the forces structurally. To meet high stress values with elastic material behavior, S355J2C-N steel is generally used in the construction machinery industry. S355J2C-N steel was taken as a reference in this study, which was carried out to examine the boom design. The mechanical properties of the relevant structural steel are shared in detail in the table below (Table 1). The data of the TS-EN 10025-2 standard is taken as a reference in the mechanical properties of steel.

Table 1. Material properties of S355J2C-N [13]

Young's modulus (GPa)	210
Poisson's ratio	0.3
Yield Strength (MPa)	355
Elongation (%)	22

The analysis model, whose boundary conditions, material data, and kinematic freedoms were defined, was analyzed statically by using the finite element method by both the ISO 14391-1 standard and the ISO 14391-2 standard.

2.3 Flexible Dynamic Analysis

When the field working conditions of wheel loaders are reviewed, it is seen that the general structure is heavily influenced by dynamic conditions. Dynamic conditions arise from both the operation of the boom mechanism and the machine traveling. In this study, the effects of the boom mechanism were evaluated. It is not possible to obtain time-dependent stress maps for operating conditions in the design, whose analyses are performed for only static FEA under critical positions. With the flexible dynamic analysis performed in the MSC Adams package program, both the boom time-stress map and the dynamic effects caused by the mass inertia were examined. In this way, it is aimed to determine the stress distributions that may be overlooked in static boom stresses. The steps to be followed to perform the flexible dynamic analysis are shared below (Figure 4). While applying these steps, definitions were made by making use of the field data of the wheel loader.

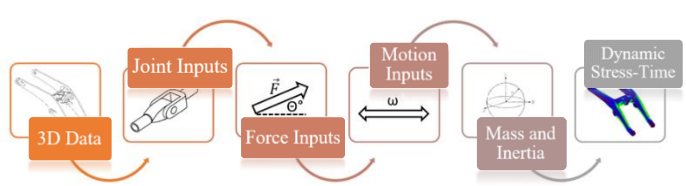

Figure 4. Flexible dynamic analysis stages

One of the most important issues to be considered during the verification phase of a design is to determine the conditions of use by the field data. In this way, the analysis boundary conditions can be defined by the field conditions and according to the results, if needed, design changes will be made with a correct progression. The working loop cycle of the wheel loader front arm mechanism can be evaluated through 4 main movements. These movements are breakout, loading, lifting, and dumping. For these stages, it was also taken as a reference in the study of examining the front mechanism kinematics of loader construction machines in the combined mechanism methodology [14]. In addition, in the study examining the structural improvement methods of loader construction equipment with static and dynamic measurements, the mentioned cycle stages were taken into consideration [15]. The detailed schematic image of the mechanism is shared below (Figure 5). The numbers on the image represent the breakout, loading, lifting, and dumping positions, respectively.

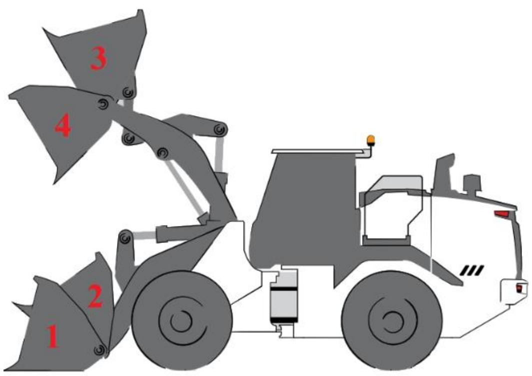

Figure 5. Mechanism movement stages

Solid models, whose mechanism design was completed, were transferred to the MSC Adams program. Since the flexible dynamic analysis is performed on the boom, simplifications have been made without changing the kinematic design. In the boom design, on the other hand, the main design was adhered to accurately determine the stress concentrations.

All the joints are designed to have only rotational freedom in the kinematic model. The correct definition of these joints in the Adams model is critical for force and moment transfer. For this reason, joints are defined by adhering to the free body diagram. Afterwards, the force values, which were calculated by ISO 14397-1 and ISO 14397-2 standards, were integrated into the 4-stage loading cycle. Drive inputs are provided to both the lifting and tilting cylinders for loading movements. It aims to accurately describe the dynamic effects of the mechanism by using machine field data in the categorization of cylinder movements. At this stage, considering the motion setup, the cylinder drives, and force inputs are formulated based on time. In the formulation approach, the Step5 function embedded in the MSC Adams program was used. This approach provides a quintuple polynomial approximation to the Heaviside step function. There are continuous first and second derivatives. Its third derivative is discontinuous at x=x0 and x=x1. The visual of the formulation input parameters is shared below (Table 2). The equation input data is entered in the format STEP5(x, x0, h0, x1, h1). Since the soft dynamic analysis is performed in the time domain, x data is defined as time.

Table 2. Step5 formulation input parameters

X	Independent variable
X0	X-axis start variable
X1	X-axis ending variable
H0	H axis start variable
H1	H-axis ending variable

When STEP5(time, 1, 0, 2, 1) is defined as the reference input, an output in the format shared below is received (Figure 6).

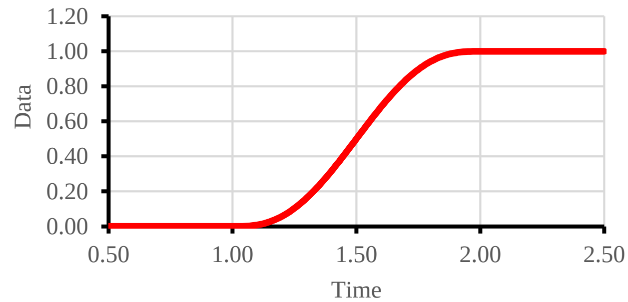

Figure 6. STEP5 formulation output graph

Both cylinder motion and force data are defined in the MSC Adams program using the STEP5 function. Images of the relevant entries are shared below in order (Figures 7 & 8).

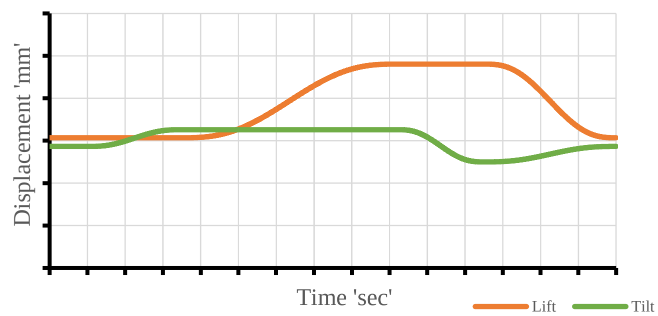

Figure 7. Motion input data for cylinders

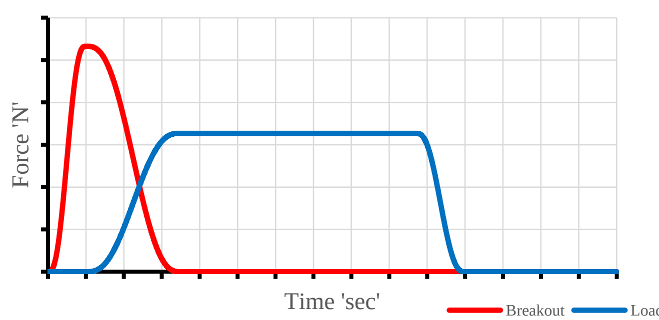

Figure 8. Force input data for condition steps

After defining the force and motion inputs, the mass and inertia information obtained from the 3D design program were transferred to the MSC Adams program. Then, the flexible dynamic analysis was solved in the MSC Adams package program.

3. Comparison of the Analysis Results

The evaluation of the stresses obtained with the static analysis outputs alone is not sufficient for the systems that are to be examined dynamically in the operating condition. While stress distributions can be obtained only for a selected moment with static conditions, stress maps can be obtained depending on the time in flexible dynamic analyses. In this way, the results can be examined over a determined cycle, and design changes can be made if needed. Wheel loaders work in dynamic conditions in the field. For this reason, examining the mechanism parts only under static conditions is not sufficient in terms of strength evaluations. The most important reason for this difference is that while the strength results of a stationary model under certain boundary conditions are obtained in static conditions, mass inertia is also involved in dynamic analysis. This difference was also obtained in the wheel loader boom examination. Stress distributions for static and dynamic analysis results are shared below with Von Mises theorem (Figures 9 & 10). Effects of the dynamic loading on the boom are clearly seen compared to static FEA results.

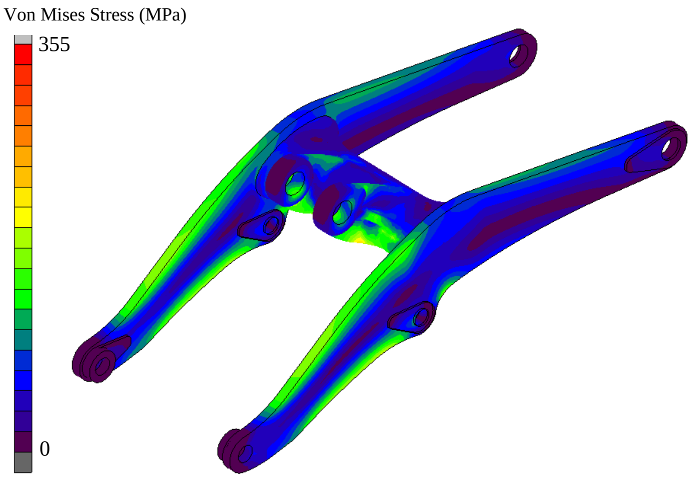

Figure 9. Static analysis stress distribution for breakout condition

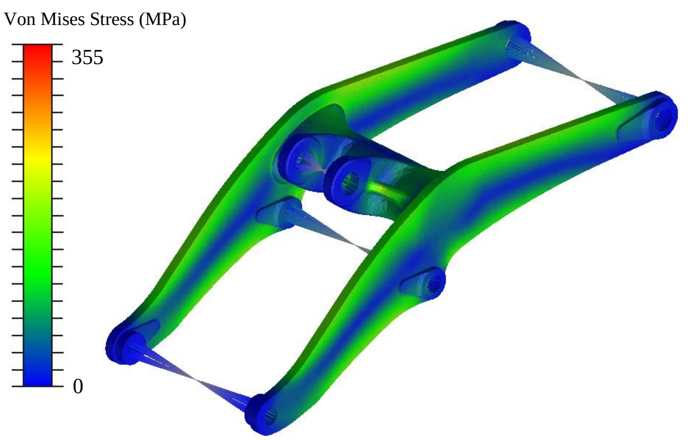

Figure 10. Dynamic analysis stress distribution for breakout condition

Flexible dynamic analyses performed by the working conditions to obtain time-dependent stress distributions play an important role in determining the possible critical stress distributions and concentration that may occur on the parts within the cycle time. The stress distributions obtained for each loading cycle stage of the boom design, which is analyzed as flexible dynamic according to the working cycle, are shared with the Von Mises stress theorem. Images are listed for breaking (I), loading (II), lifting (III), and dumping (IV) steps, respectively (Figure 11).

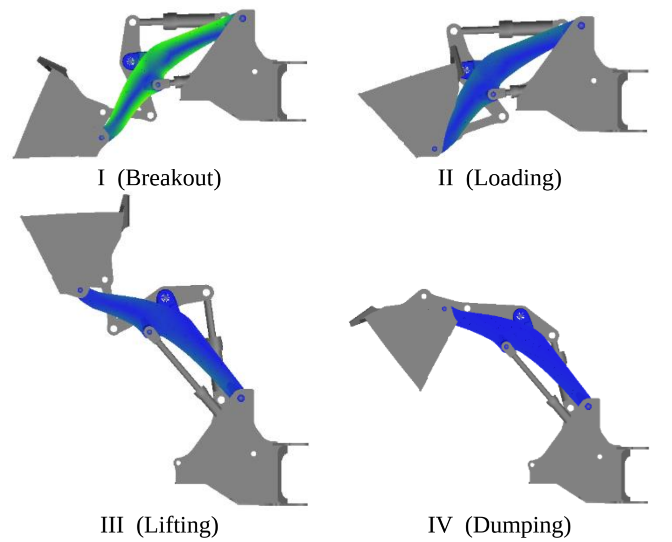

Figure 11. Flexible dynamic stress distribution according to steps

4. Conclusions

In wheel loader earth-moving machinery, the boom mechanism is the main part that is exposed to dynamic loads due to field working conditions. In this study, the force values of the boom mechanism, which is kinematic and 3D design has been completed, were calculated according to ISO 14397-1 and ISO 14397-2 standards. Then, static analyses were carried out with the finite element method in the MSC Marc program by the standard positions of the design. To determine the effects of the dynamic effects on the structure on the stresses, the dynamic analysis model was prepared in the MSC Adams program by utilizing the field data. The boom 3D design data has been added to the analysis as a flexible dynamic due to the evaluation of the strength. First, the static and dynamic analysis stress distributions were compared to each other for the positions specified by the standard. Then the flexible dynamic analysis outputs are examined for a specified cycle for the wheel loader.

When the data obtained as a result of the studies carried out are evaluated;

- For the earth-moving machines that are heavily exposed to dynamic loading, stress results obtained from static FEA provide an initial idea about the strength of the design.
- Determining the inputs for dynamic data as a result of field working conditions and performing dynamic analyses accordingly is a more accurate method for interpreting dynamic conditions.

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Nomenclature

FEA	Finite element analysis
Fx	X-axis component of the referenced force (N)
Fy	Y-axis component of the referenced force (N)
M	Total moment of the system (N.mm)
$RBE'2$	Multi-Point constraints element used in FEA

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Gökberk Biçer: Conceptualization, Methodology, Supervision, Software, Writing – original draft

Mehmet Can Katmer: Conceptualization, Supervision, Writing – original draft

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