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Static, Modal and Kinematic Analysis of Hydraulic Excavator

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***Abstract*— Hydraulic Excavators are heavy duty earth mover consisting of a boom, arm, bucket and cab on a rotating platform. It works on the principle of hydraulic fluid, with hydraulic cylinders and hydraulic motors. Excavator is subjected to resistive forces which are depends upon the terrain condition. These forces are unpredictable and dynamic in nature which damages the excavator component. Hence it is essential for designer to provide equipment with maximum strength, minimum weight and cost while maintaining maximum reliability and critical factor of safety. Along with this, the geometry of motion, irrespective of causes of motion also important for excavator. For obtaining optimum design, finite element analysis of excavator parts are essential. Also, for obtaining optimum motion of parts with respect to frame of reference, kinematic analysis of excavator is necessary. This paper depicts importing and meshing of CAD model of bucket and lower arm of excavator and its finite element analysis for strength and deformation evaluation. Also this this paper covers the kinematic analysis of whole assembly for understanding the behavior of the various joints which are used for connecting the parts of excavator.**

Keywords— ***Excavator, Hyperwork, Radioss, Bucket, Lower arm, Stress, Mode, Kinematic.***

I. INTRODUCTION

A Hydraulic excavator is heavy duty earth mover which consist of three mechanisms namely boom mechanism, bucket mechanisms and bucket rod mechanism (lower arm mechanism). Boom mechanism consist of boom and oil cylinder of boom. Similarly, bucket mechanism and bucket rod mechanisms consist of bucket and bucket's oil cylinder, bucket rod and bucket rod's oil cylinder respectively. These three mechanisms are interconnected by means of pin hinged [1] .Today hydraulic Excavators are used in excavation, mining, construction, and forestry applications [2]. Because of globalization and fierce competition, excavator use has been increased considerably for mining and other excavation applications which leads to giving more emphasis to design of earth moving component [3].

Digging task is repetitive in nature which imposes the dynamic loads on the teeth of bucket. High rates of damages of parts of excavator leads to increase in maintenance time and reduces machine availability time. Poor strength of the parts leads to reduction in life of parts [4]. Also the excavator is subjected to unpredictable forces (soil-tool interaction forces) which are depends upon terrain condition, as well as soil condition and soil parameters [5]. Therefore, excavator must be strong enough to take the all resistive forces without failure. The force to weight ratio of excavator should be maximum. Structure should be such that the it resist applied forces (stress constraint) and should not deform beyond certain limit (strain constraint). Hence design engineer should provide robust design. Generally boom and bucket rod mechanism subjected to complex stresses such as compressive, tensile, torsional and shocking [5]. Hence finite element analysis (static and modal) and kinematic analysis of bucket and bucket rod become essential.

This paper deals with finite element analysis of bucket and lower arm as well as kinematic analysis of whole assembly for optimum design of excavator.

II. OBJECTIVE

The main objective of this work is to carry out static modal analysis of bucket and lower arm as well as kinematic analysis of whole assembly.

- Finding out forces
- Selection of material
- Importing and meshing of CAD model
- Static structural analysis of bucket and lower arm
- Modal analysis of bucket and lower arm
- Kinematic analysis of whole assembly of excavator

III. METHODOLOGY

In order to proceed with this study, the basic mechanism and component of excavator were understood and then static force analysis for digging operation according to SAE J1179 was carried out but other calculations are not a part of this paper, it is taken from reference [6]. Ductile material that is

HARDOX400 was selected for bucket and bucket rod [5]. Then CAD model was imported and then discretization of model were carried out for refinement of solution in hypermesh. Von mises stress and strain were obtained from Static and modal analysis which were carried out using Radioss solver. Along with this kinematic analysis was also done in hyperworks.

A. Static analysis of bucket and lower arm

In this part, the CAD model of bucket and lower arm are discretized in Hypermesh software. The meshed model of bucket essentially consists of 38195 nodal points and 21927 elements. Out of these elements 20459 are HEXA elements and 1468 are PENTA elements with total 112140 degree of freedoms.

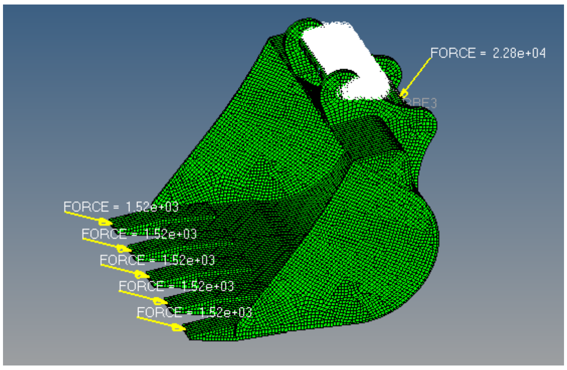

Fig. 1. Forces On Bucket

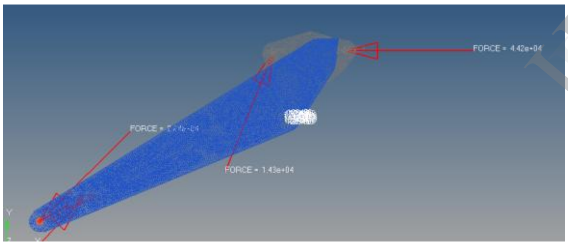

Fig.2 forces On Lower Arm

Now the forces acting on bucket part whiling digging operation are applied at the joints and teeth of bucket as shown figure 1. Similar to the bucket, CAD model of lower arm is also imported into Hypermesh and discretized. Meshed model of lower arm essential consist of 36382 nodal points and 20128 elements. Out of these elements, 18838 are HEXA elements and 1290 are PENTA elements with total 108357 degrees of freedom. The entire body of lower arm is made up of SAILMA 450HI material having yield strength equal to 450 Mpa while mounting lugs of the cylinder are made up of HARDOX 400 [6]. Loading conditions and meshed model of the lower arm is as shown in the figure 2. Finally, models of bucket and lower arm are submitted for static analysis.

B. Modal analysis of bucket and lower arm

Boundary conditions for modal analysis was applied on meshed model of both bucket and lower arm. Modal analysis of both bucket and lower arm were carried out in Altair Radioss solver. Radioss uses EIGRL method for finding out the fundamental frequencies of the model.

C. Kinematic analysis of excavator

Instead of individual parts entire assembly of excavator is taken to carry out kinematic analysis. It involves various steps as follow:

- Initially individual parts were meshed in hyper mesh same way as for static analysis
- Then each part was imported in Hypermesh one by one and various kinematic joints are defined in between them.
- Values of motion acceleration and time for simulation was given in analysis
- Then entire assembly was submitted to Altair Motion solve for solving kinematic problem of the model.

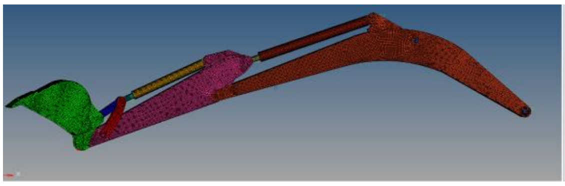

Fig. 3. Assembly Of Exacavator

Figure 3 shows final assembly of excavator with kinematic joints. Various joints added in between various parts are as below:

- Rotational Joints: Upper arm- Upper control cylinder, Upper Arm- Lower arm, Lower arm- Bucket, Bucket- Control Bucket Coupler, Lower arm- arm control coupler, Bucket control coupler – Lower control Piston etc.
- Translational joints: Lower control Piston- Cylinder, upper control Piston- Cylinder

IV. RESULTS AND DISCUSSION

The stress constraint, strain constraints and motion constraints were studied from the analysis of excavator.

A. Static analysis of bucket and lower arm

From figure 4, it is observed that maximum von mises stress is 120.1Mpa which is acting in the region where it is connected to lower control bucket coupler. This maximum stress is lower than yield strength of bucket. Hence design is safe for static load. From the figure 5, it is observed that the maximum displacement (2.229mm) occurs at tip of teeth which is less than the thickness of teeth. Also maximum displacement is within the acceptance limit. Hence design is safe. For safe working of bucket, it should not be deform beyond the limit of acceptance. From figure 6, it depicts that the maximum von mises stress is 97.35Mpa which is acting at the joint which connects the lower arm and boom. This stress is lower than the yield strength of lower arm. Hence design is safe. From figure 7, it is observed that the maximum deformation is 1.48mm which is at free end of the lower arm excavator. This maximum deformation is less than thickness of the lower arm. Hence design is safe for static condition.

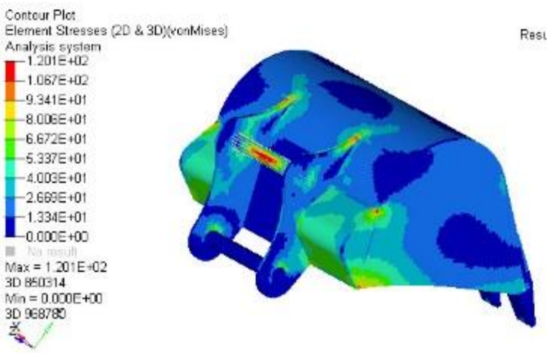

Fig. 4. Von Mises Stress Distribution On Bucket

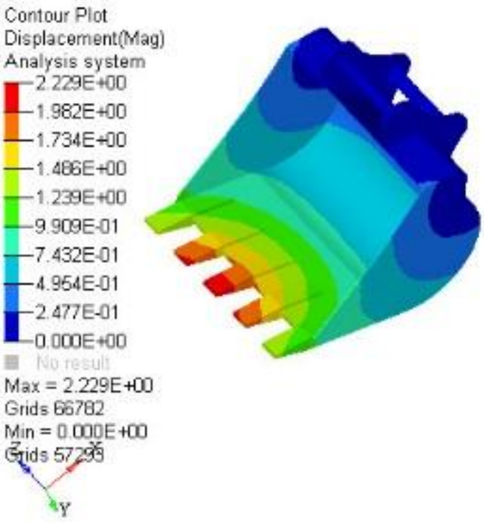

Fig. 5. Displacement On Bucket

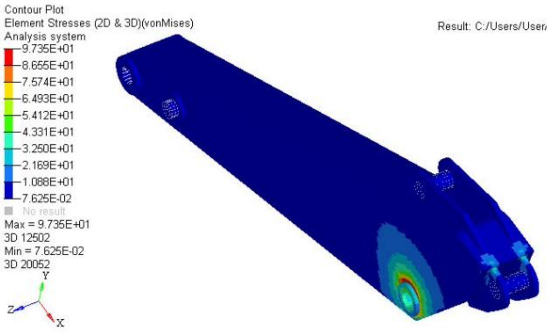

Fig. 6. Von Mises Stress Distribution On Lower Arm

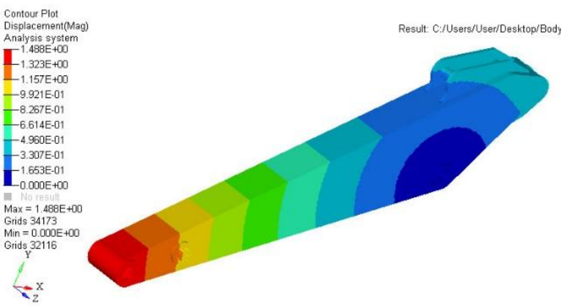

Fig. 7. Displacement On Lower Arm

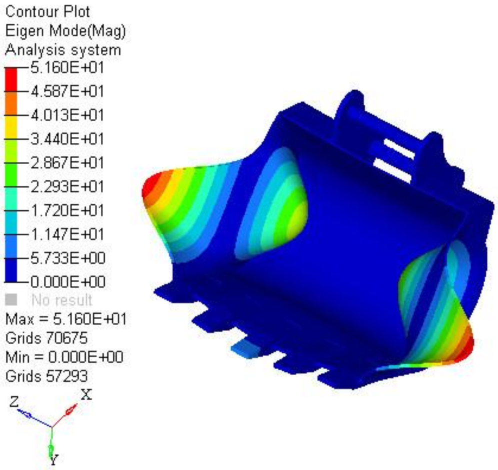

Fig. 8. Modal Analysis Of Bucket

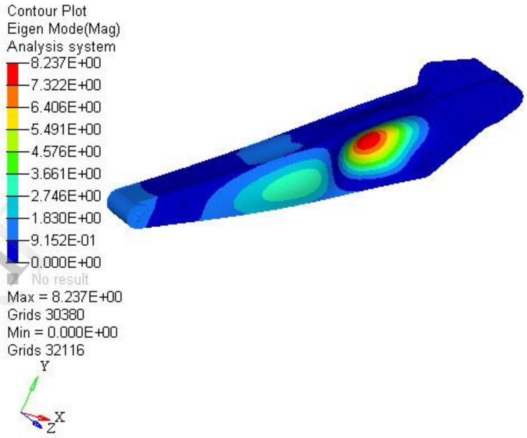

Fig. 9. Modal Analysis Of Lower Arm

TABLE I. MODAL ANALYSIS OF BUCKET AND LOWER ARM

No. Of Modes	Frequency Of Bucket (Hz)	Displacement Of Bucket (mm)	Frequency Of Lower Arm (Hz)	Displacement Of Lower Arm (mm)
1	52.18	12.07	36.93	3.38
2	82.86	14.36	48.16	3.55
3	128.95	12.33	90.49	3.32
4	180.12	35.59	215.24	8.1
5	191.16	48.42	220	3.84
6	204.23	35.58	248.8	2.93
7	350.78	26.38	249.6	4.02
8	367.84	18.3	277.29	7.56
9	407.23	51.6	278.02	8.237
10	420.24	21.55	327.64	7.68

B. Modal analysis of bucket and lower arm

Figure 8 and 9 shows that mode shapes of bucket and lower arm. From the table I, it is observed that the for first 10 modes of vibration, frequency varies from 52.18Hz to 420.24Hz and 36.93Hz to 327.64Hz for bucket and lower arm respectively. Maximum displacement of the bucket and lower arm due to vibration are 51.6mm and 8.237mm respectively. Hence it clearly depicts that number of modes increases with natural frequency. Also modes (or resonance) are purely depends properties of material. Resonance determined from stiffness, mass, damping ratio and boundary condition.

C. kinematic analysis of excavator

Any mechanical system can be considered to be made up of set of mechanical entities that interact with each other by exchanging energy or set of information in proper ways. Motion solve consists of physics based, mathematical models of entities and provide platform to assemble these entities in realistic models of complex mechanical systems. In motion solve, simulation of these models is possible to gain insight into their behavior. The assembled model of components is submitted for simulation in motion solve, the displacement of

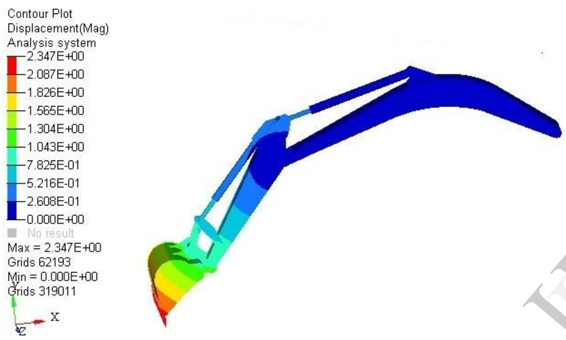

Fig. 10. Total Displacement Of Excavator

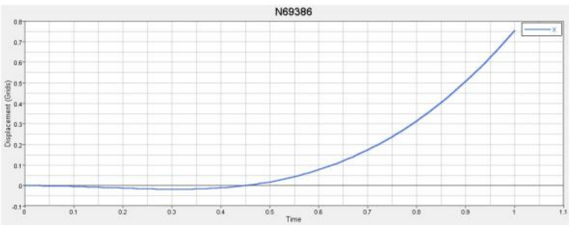

Fig. 11. Displacement Vs Time Plot In X-Direction

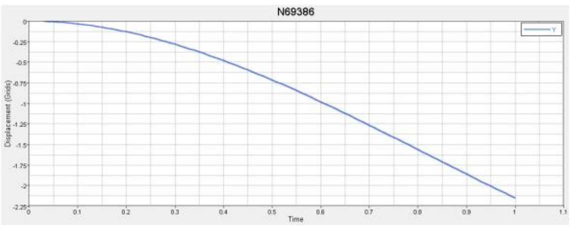

Fig. 12. Displacement Vs Time Plot In Y-Direction

model . Figure 10, shows the total displacement of excavator assembly during digging process. This displacement is corresponding to node number 63386 which is on the teeth of bucket. Figure 11, 12 and 13 shows displacement vs time plot for node number 69386 along X, Y, Z direction. From figure 11 and 12, it is observed that the there is displacement along X and Y direction according to motion constraints. From figure 13, it is observed that because of constraints, there is almost no displacement along Z direction.

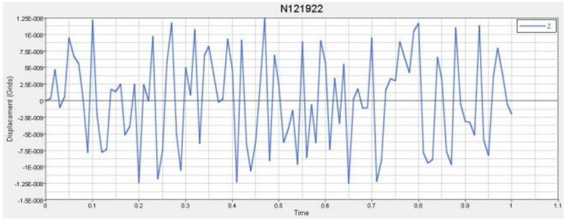

Fig. 13. Displacement Vs Time Plot In Z-Direction

TABLE II. ANALYZED RESULTS

Sr. No.	Bucket(Mpa)	Lower arm(Mpa)
Maximum Von Mises stress(Mpa)	120.1	97.35
Maximum Displacement (mm)	2.229	1.48
Yield strength(Mpa)	1000	450
Factor of safety	8	4

From table II, it is observed that the factor of safety of bucket and lower arm is more than critical factor of safety. Hence design is safe but that will increase the weight and cost. In order to reduce the weight and cost, it is necessary to optimize the design or to change the material without compromising on reliability and durability.

V. CONCLUSION

In this project, importing and meshing of CAD model has been done in hyperwork. Static, modal and kinematic analysis of bucket and lower arm of hydraulic excavator has been carried out using hyperwork. Based on results obtained from analysis, it is concluded that

- Maximum stress and maximum displacement is lower than the limit of acceptance. Hence it resist the applied forces while maintaining the strain lower than certain limit. Ultimately, design of bucket and lower arm is robust.
- Change in material properties lead to change in modes and mode shapes and hence the resonance condition.
- Optimum motion of the part with respect to frame of reference is depend upon kinematic joints. There is scope to find out velocity and acceleration plots from displacement vs. time plot to see the dynamic nature of excavator
- The factor of safety of bucket and lower arm is more than the critical factor of safety. Hence there is scope to carry out optimization of component. Optimization reduces the weight and initial cost.

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