Study on Automatic Spray of Distribution Boom System of Truck-Mounted Concrete Pump

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Abstract: Truck-mounted concrete pumps have been adopted in many construction projects. However, the investigations about the automatization or robotization of distribution boom system of the truck-mounted concrete pump are very scattered. In this study, a scheme of automatic concrete spray of the distribution boom system of the truck-mounted concrete pump has been presented and discussed. The concrete spray process and the kinematics of the boom sections were analyzed including its inverse kinematics problem. Transient dynamic analysis was performed to validate the effect of the new control system on the boom system base on the flexible body co-simulation among ANSYS software, ADAMS software and Matlab/Simulink software. A three-dimensional simulation was programmed to imitate the process of automatic spray and verify the control algorithm. The simulation result shows that the system can pour concrete on a long narrow area automatically thereby satisfying, and the trajectory movement of boom mechanism.

Keywords: Concrete pump, boom system, automatic spray, co-simulation.

INTRODUCTION

The pumping of concrete is universally accepted as one of the main methods of concrete distribution and placement in the field of construction. As a favorable placing option, it provides advantages over other methods such as crane and skip, hoists and conveyors for building constructions. Therefore, the use of concrete pumps is increasing throughout the world, along with the pumping technologies, that are also becoming more reliable. In order to improve working efficiency of concrete pumping, much attention has been given to the automatization or robotization of the distribution boom system of Truck-mounted concrete pumps [1-7].

In many cases, pumping concrete automatically instead of manual operation will lessen the operator's labor intensity and dramatically increase the productivity (Fig. **1**). However, for a satisfactory implementation of automatic concrete distribution there are many problems needed to be solved. For example, although a robotization to the distribution boom system of concrete pump is not difficult in principle, it is not easy to eliminate the vibration problem during automatic concrete distribution in practice [8, 9]. To solve this problem, it needs to systemically consider the trajectory planning of prescribed assignments, multi-body dynamics,

Fig. (1). Pumping concrete for residential projects.

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vibration of the boom system, dynamic control of kinematics and kinetics, etc. during the process of automatic concrete distribution.

Therefore, in this study, an automatic spray system of pumping concrete was schemed. We used finite element method, dynamics method, control method as well as their co-simulations by ANSYS software, ADAMS software and Matlab software to validate the effect of the whole system on the automatic spraying of the distribution boom pump. The results might provide useful references for design and development of the distribution boom system of Truck-mounted Concrete Pump.

ANALYSES ON THE AUTOMATIC SPRAY SYSTEM

Normally, the pump operator controls the entire machine *via* a radio remote control unit. This includes not only the movements of all sections (boom arms) of the multi-section boom, but also to the volume of concrete to be poured. Moreover, the control of operation sequence is submitted to guarantee that the movement of every section of boom and the location of distributed concrete are as smooth as possible [7].

Traditionally, the boom control is accomplished by using a single joystick. In this case, a pump operator controls each individual boom hydraulic cylinder and the slewing gear, preferably directly proportional, in order to secure a precise positioning of the end hose, on the construction site [7]. This means the operator has to shift at least five joysticks in turn.

However, to control the boom-end hose move along a long narrow field under the operator manipulation is not an easy task. It is almost impossible for an operator to control accurately and smoothly the hose end through a long linear narrow field. Therefore, a strong man is needed to arrange and regulate the end hose position, since the end hose is made of synthetic rubber that can be bent.

The automatic spray system was developed to simplify the spray operation in this study. The spray operation process is that in which the operator moves the end hose from one end of a wall (a prescribed trajectory) to another end, i.e. from Point 1 to Point 2 (shown in Fig. (**2**)), and lets the control system record the boom sections' postures (relative rotational angles of every boom section). Based on the two ends of the wall, the control systems draw out a straight-line equation, i.e. the trajectory of the end hose. Then the straight-line is divided into a number of sections and correspondingly, the posture of the boom is solved using Jacobian pseudoinverse algorithm. Finally, the boom mechanism, driven by a hydraulic system, can pour the wall automatically according to the solved postures one by one from the 2nd point to the 1st point. During spraying operation of the concrete, the operator has to adjust the boom movement step and concrete flow velocity if necessary.

About redundant robotic manipulators, different techniques and criteria have been used to resolve the redundancy, while optimizing certain objectives. Methods used to resolve the redundancy of the manipulators include Jacobian pseudoinverse algorithm [10, 11], singular value decomposition [12, 13], damped least-squares method [14, 15], joint torque optimization [16], minimal base reaction [17], neural network [18, 19], and genetic algorithm [20], *et al*. The singular value decomposition has played an important part in solving inverse kinematic problem of redundant robot manipulators [12, 13]. The damped least-squares method, which is based on the singular value decomposition, is an efficient method for eliminating numerical problems at the singularities [14, 15]. In this paper, we assume that the motion posture planning of the boom mechanism during concrete pouring process is defined within singularity avoidance, therefore, the conventional method, Jacobian pseudoinverse algorithm, is used to resolve the redundancy of the boom mechanism, since it is simple and effective.

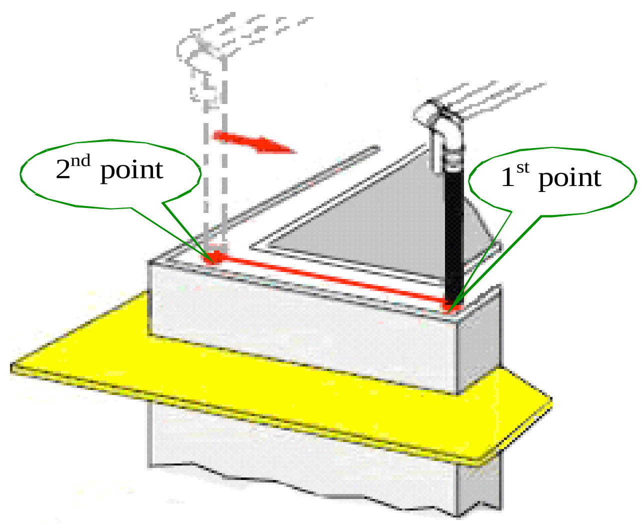

Fig. (2). Route of the end hose.

KINEMATIC RESOLUTION OF THE REDUN-DANT BOOM SYSTEM

A manipulator is said to be redundant when the dimension of the task space *m* is less than the dimension of the joint space *n*. In case of a redundant manipulator, $r = n\text{-}m$ ($r \geq 1$) is the degree of redundancy [9, 10].

The concrete boom system can be considered as a redundant manipulator, as shown in Fig. (**3**). It includes four sections, four hydraulic cylinders and one turntable. All the sections are considered as rigid bodies. In practice, there are small flexural displacements in all the sections, during spraying process of concrete. These displacements can be compensated by the control system.

For the multiple-arm boom system of a truck-mounted concrete pump, the end hose position is a function of joint variables of boom sections. The kinematic function is defined as:

$$X = f(\theta) \tag{1}$$

where X is the $m \times 1 (m = 3)$ position vector of the end hose, and θ is the $n \times 1 (n = 5)$ joint angle vector. $n > m$, in the case of redundant manipulator.

The differential kinematic function is given by

$$\dot{X} = J\dot{\theta} \tag{2}$$

where $\dot{X}$ is the 3×1 velocity vector of the end hose, $\dot{\theta}$ is the 5×1 joint velocity vector, and J is the 5×3 Jacobian matrix.

Now, the desired trajectory in workspace is given as $X(t)$ and we need to find the joint angle trajectory $\theta(t)$, corresponding to $X(t)$. We can obtain $\theta(t)$ by solving the following inverse kinematics equation:

$$\dot{\theta} = J^{+}\dot{X} + (I - J^{+}J)\phi \tag{3}$$

where J^{+} is a pseudoinverse matrix, and ϕ is a vector of arbitrary joint velocities projected in the null space of J. We can resolve the redundancy by specifying ϕ, so as to satisfy an additional constraint.

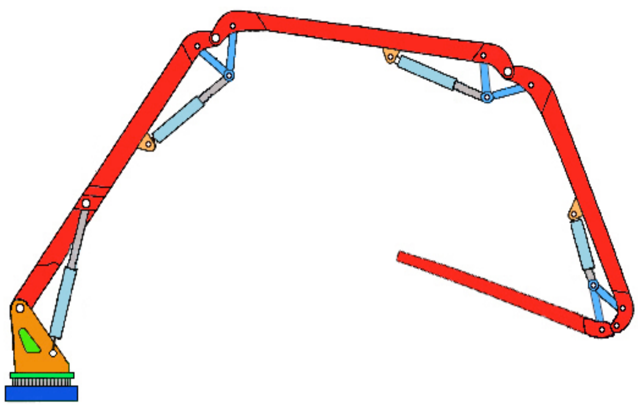

Fig. (3). A four-section boom system.

For a line trajectory to be poured, the end hose positions are definite beforehand. That is to say, a series of trajectory coordinate X is known, the trajectory coordinate X been corresponding to the joint angle θ, and the joint angle θ can be solved by Equation (3). We utilize MATLAB software to calculate the joint angle θ and the boom trajectory, is shown in Fig. (**4**). In this study, the motion posture planning of the boom mechanism during concrete pouring process is defined, within singularity avoidance.

We saved five joint angles (θ) with respect to every step (X) a data file, which will be used in the next phase. In ADAMS, these joint angles are imported and create five Splines (The Spline is a command of ADAMS and a two-order Spline is used in this study). These Splines are applied to five revolution MOTIONs to control the boom movement. As shown in Fig. (**5**), the end hose can move along the desired line.

We also produced five Splines by using Measure function on the joints (one rotational joint on the turn-table and four translational joints on the hydraulic cylinders). These Splines were exported into two columns data files and will be imported into Matlab for co-simulation.

DYNAMIC ANALYSIS USING ADAMS

In order to verify the influence of new automatic spray system on the boom, we performed a dynamic analysis using ADAMS and Simulink.

The co-simulation method used here is implemented by using ADAMS/Controls software for simulation of the mechanical system and MATLAB/Simulink for simulation of the hydraulics system. Generally, MATLAB/Simulink is also used to model the control concepts, which can drive the dynamic characteristics of a system based on sensor feedback, while ADAMS is used to model mechanical parts of the system, that are influenced by their geometric structure as well as external loads and forces imposed on them.

The mechanical parts of concrete boom system are shown in Fig. (**5**) and the hydraulic control system is shown in Fig. (**6**) [21-24].

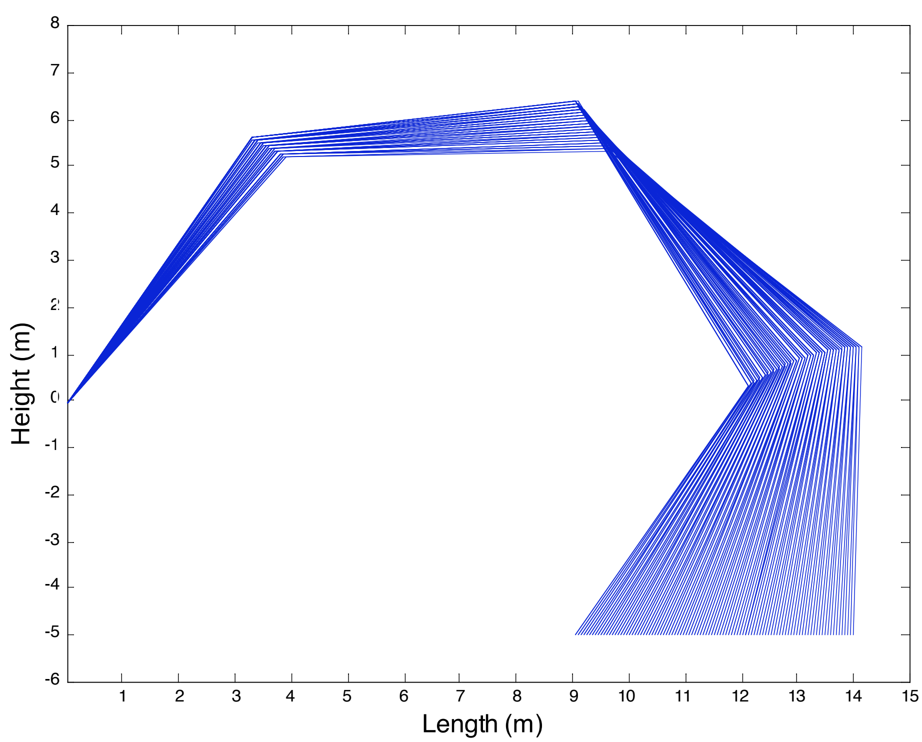

Fig. (4). The movement postures of the boom system for a straight-line trajectory.

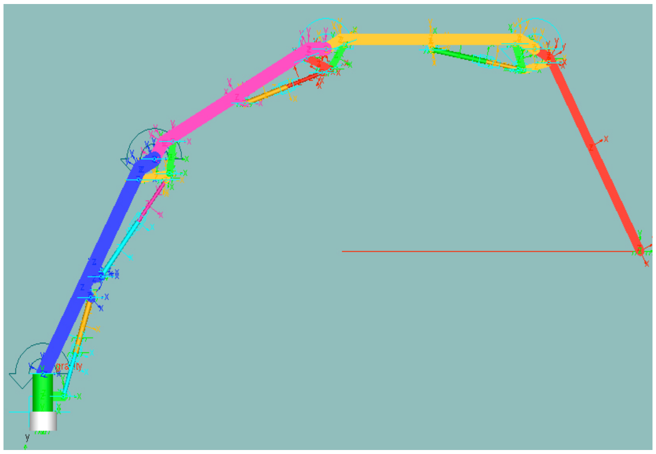

Fig. (5). Kinematics simulation in ADAMS.

In Fig. (**6**) there are four PistonRods and one Rotor. They were controlled by the five Spline data files.

One drawback of the ADAMS program is that all components are assumed to be rigid. In the ADAMS program, tools to model component flexibility, exist only for geometrically simple structures. To account for the flexibility of a geometrically complex component, ADAMS relies on the data transferred from finite-element programs such as ANSYS. The ANSYS-ADAMS Interface is a tool provided by ANSYS by which the data can be transferred from the ANSYS program to the ADAMS program [25-29].

To analyze the boom strength, we need to build flexible arms of the boom mechanism in ADAMS. Obviously, the boom arms do not belong to geometrically simple structures in a sense. It will produce wrong results if we use a box part to take the place of the boom arm. So, we have to create a flexible boom arm using ANSYS.

In ADAMS, flexible bodies are defined by importing the modal data, calculated by an external finite elements program. A special data file (MNF file) is used to transfer frequency and amplitude data for a selected number of vibration modes, from a finite element code to ADAMS program. Craig Bampton modes, which are required for defining constraint connections to flexible bodies, are transferred from the finite element code by defining master nodes. For each master node, constraint mode information is stored in the MNF file.

CREATING FLEXIBLE BODY

Since the first arm of the boom system is subjected to the biggest load, we created a flexible arm in ANSYS to substitute the first rigid arm for co-simulation in ADMAS. Because a flexible body analysis requires a high performance on the PC, we only used one flexible arm, the first arm, i.e. in this study.

Element Type

The element type will affect on the computation time and result accuracy. For the boom system, the structure is not very complicated so, we select two solid types, SOLID45 and SOLID92 in ANSYS program, for different regions of the first arm of the boom system.

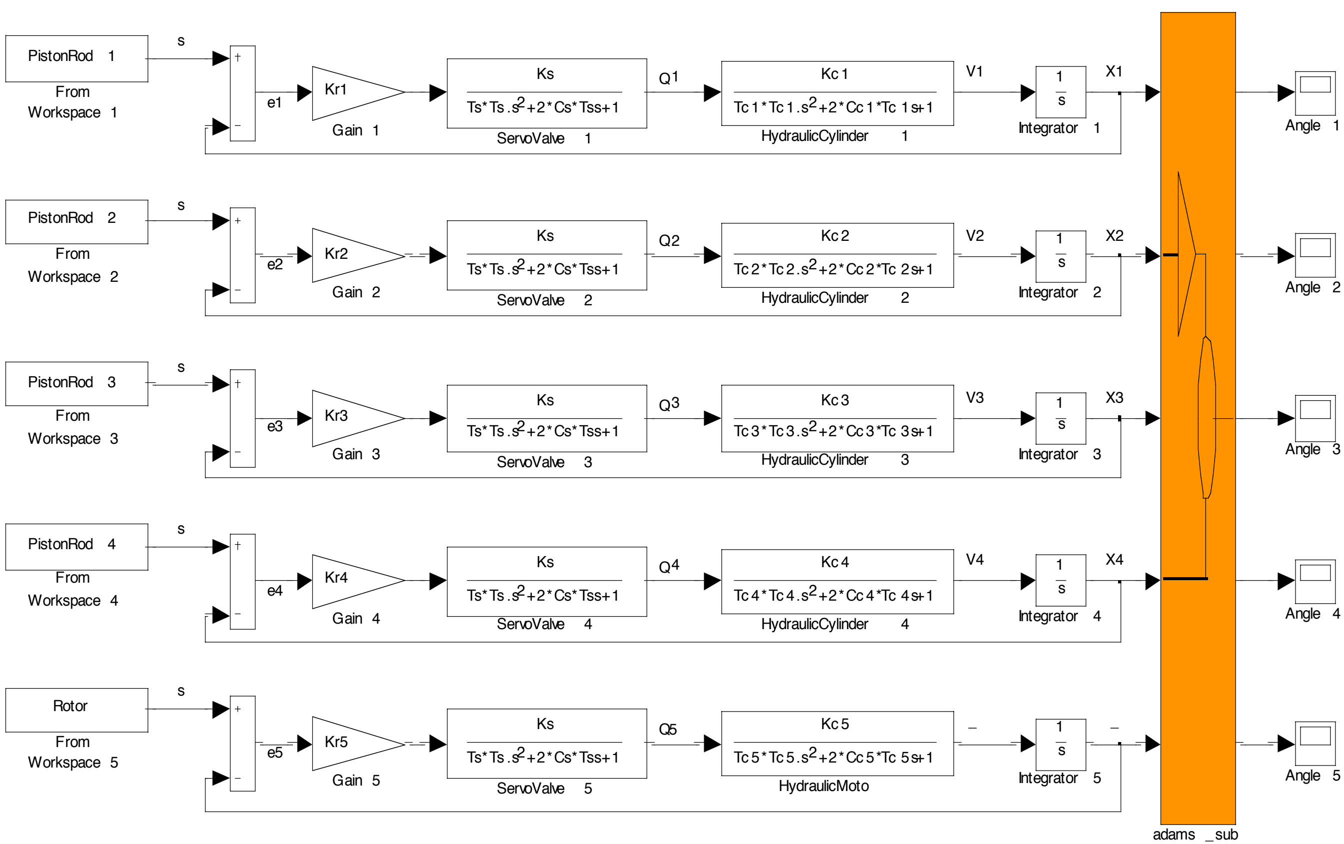

Fig. (6). The control scheme of Co-simulations in ADAMS and Matlab/Simulink.

Material Property

The boom of truck-mounted concrete pump is made of fine grained structural steel, which is a kind of high strength steel. Its material property is as follows, elastic modulus 2.1×10^{11}Pa, Poisson ratio 0.3, density 7.8×10^{3}kg/m^{3} and tensile strength 800MPa.

Master Node

The master node is the joint between the boom and other parts, such as hydraulic cylinders and the turntable. According to the constraints, loads and driving forces on the first arm, five master nodes are defined. These master nodes use MASS21 element with a tiny real constant and a huge elastic modulus.

Meshing

The first arm is divided into nine parts with workplane. The regular parts are meshed with SOLID45 element, while the others are meshed with SOLID92 element. This method reduces element number dramatically and certainly saves computation time. The meshed model of the first arm is shown in Fig. (**7**). The five pink areas are rigid coupled areas.

Finally, using ANSYS interface for ADAMS program, the first arm model is exported into a MNF file.

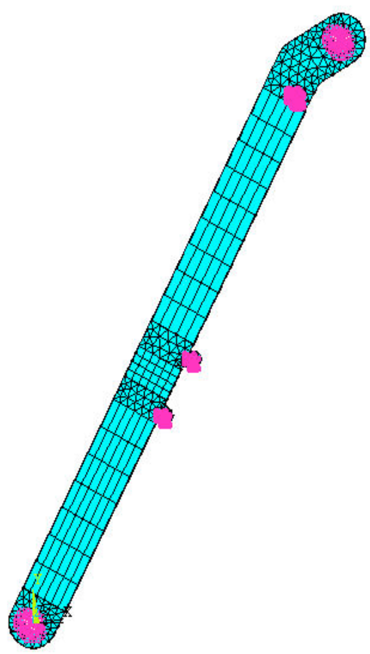

Fig. (7). Finite element model of the first arm of the boom system.

FLEXIBLE BODY SIMULATION

The flexible arm is created in ADAMS by the neutral file imported from ANSYS, to replace the first rigid arm. The boom movement is simulated again under the previous control SPLINE on the revolution MOTION, shown in Fig. (**8**). There is a slight fluctuation on the end hose trajectory since the first arm is replaced with a flexible body and it has an inevitable vibration.

In order to analyze accurately stress and strain on the first arm during automatically spraying concrete, a load step file (including the load applied on five master nodes in every time step) is exported from ADAMS. Then the data file will be imported into ANSYS, to perform a transient dynamic analysis to check the stress and strain on the first arm and will afford information to modify or optimize the structure of the boom arm.

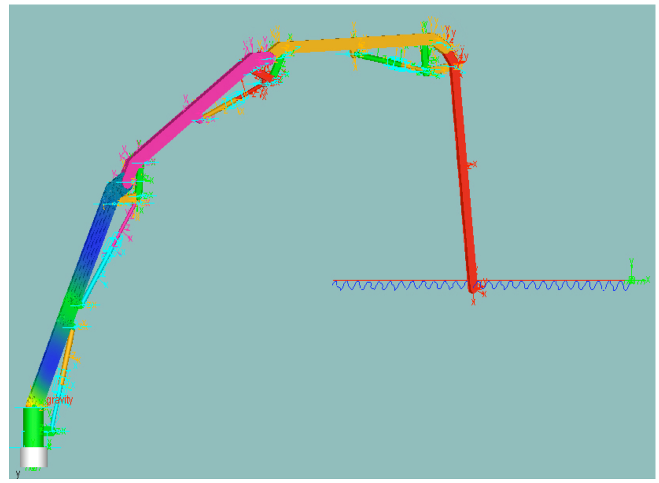

Fig. (8). Kinematics simulation of the boom system with the flexible arm (the first arm) in ADAMS.

TRANSIENT DYNAMIC ANALYSIS IN ANSYS

There are two methods to use the load file in ANSYS. One is to select the load on the arm in the most dangerous situation and then to perform a static analysis and obtain the stress and strain. Another is to carry on a transient dynamic analysis with the load changed in steps, and then to predict the time history of stress and strain. The former method is impractical because in a sense it is difficult to select the most dangerous situation. So in this paper, the latter method is applied to process the load step. In order to reduce the calculation, only the first fifty load steps are imported into ANSYS and the loads on five master nodes are applied to five rotational joints, respectively. After the transient dynamic analysis, we can view the results in ANSYS postprocessor. The relationship between stress and time-history is shown in Fig. (**9**) and equivalent stress on the second load step is shown in Fig. (**10**).

In the postprocessor of ANSYS, we find that the stress in the joint area is higher than that of other regions with respect to every load step. We select a node in the high stress area and track the stress time-history. The result is shown in Fig. (**9**). It shows that in the beginning, the stress increases rapidly and reaches the maximum at the second step, about 640MPa, and then gradually falls down and at the twentieth step the stress tends to be steady, about 350MPa. The first-order vibration frequency of the arm is 4.9Hz. The previous experiment studies [8, 30] reported that the vibration frequency is 4.69Hz.

According to the stress time-history, we load the equivalent stress on the first arm at the second step, one of the most dangerous situations, as shown in Fig. (**10**). From Fig. (**10**) we can find that the stress in most areas varies from 200MPa to 250MPa, except the joint area. The reference [30] also reported the similar stress value by experimental measurement. Considering that the arm model has no fillet,

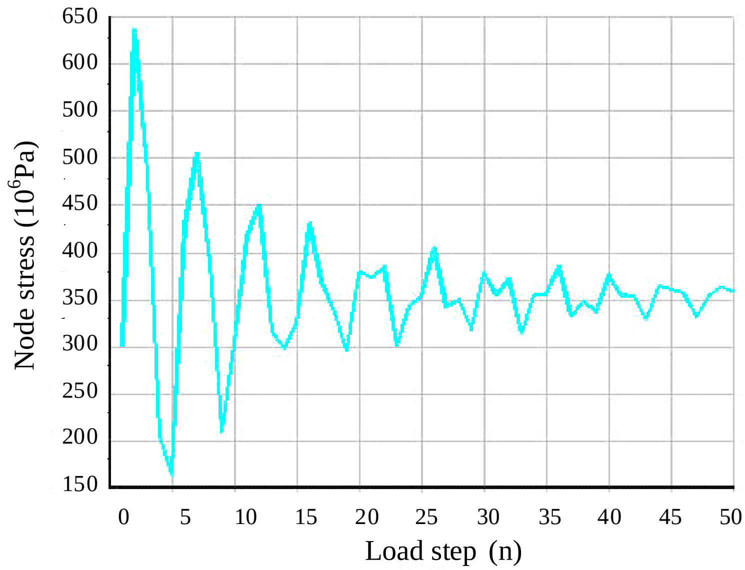

Fig. (9). The time-history curve of stress for a node on the flexible arm.

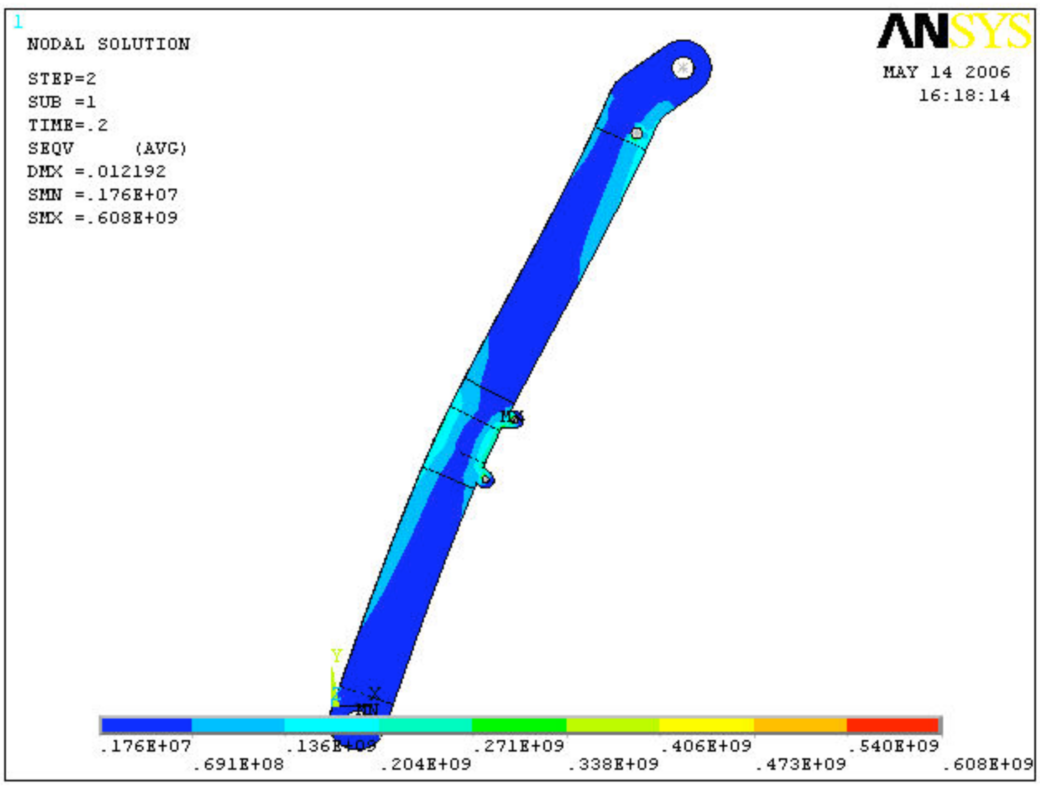

Fig. (10). The equivalent stress distribution of the first arm in ANSYS.

the number of simulation steps is less and in the beginning of loading, the arm motion acceleration is also high, so, the maximum stress at the joint region should be lower in the real arm. Therefore, the strength of the first boom arm is within a permissible range.

AUTOMATIC SPRAY SIMULATION

Virtual reality is a technology, which allows a user to interact with a model in a computer-simulated environment [31-36]. It is the result of the combination of human imagination and electronic technologies. It provides people a useful tool to study and examine a model or system before it is actually manufactured [37-39]. In order to verify the automatic spray system, we utilized virtual reality technology to simulate it in a three-dimensional environment. The simulation program was developed with Visual C++ and OpenGL. The model of a truck-mounted concrete pump and its distribution boom system was designed in 3DSMAX, and then was imported into the program [40-42]. The final model of the truck-mounted concrete pump and its boom system are shown in Fig. (**11**).

The object of this simulation is to imitate the work process of the concrete boom system. The default setting of this system is a linear spray. In the first step, we can move the end hose to a specified position through five scroll bars in the left control panel in Fig. (**12**) and press down the 'Record' button. Secondly, we can move the end hose to another end of the wall and record it. Now the control module has recorded two key points of the trajectory line. After we pressed the 'Pour' button, the whole system begins to pour concrete automatically along the trajectory line.

In Fig. (**12**), the red thin line is the predefined trajectory and the blue thick line is the actual trajectory. This

Fig. (11). Truck-mounted concrete pump and its boom system in virtual reality environment.

Fig. (12). Automatic spray system simulation in virtual reality environment.

simulation system can verify whether any interference occurs between boom sections and whether the boom movement is smooth. The simulation result shows that the system can pour concrete on a long narrow field automatically, and the boom movement is smooth.

CONCLUSIONS

The automatic spray system of the distribution boom system of the truck-mounted concrete pump has been studied and the kinematic redundancy is solved. A co-simulation method was used to check the dynamic response of concrete pouring process of the automatic spray system. Virtual reality technology was used to simulate the automatic spray process. Based on the dynamic loads obtained from above-mentioned analyses, the finite element method was used to analyze the structural strength of the boom system. These systemic numerical simulation methods will provide a strong assistance for the development of new concrete boom systems.

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