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# Study of Driving Torque through Dynamic Analysis of Robot

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***Abstract:** these days, the interests on the low-cost handling robots are increasing because it is important to get down the unit cost of production to get the price competitiveness. The robot joint with simple mechanism is more suitable to implement the low-cost robot system as well known. The moving parts of robot have to be designed for simple and robust. But the dynamic characteristics analysis is induced by the robot links because they drive in high acceleration and deceleration. In this reason, the dynamic characteristics analysis of the high-speed robot is very important in the design process. In this paper, the study on robot driving torque analysis of an articulated robot has been done and the re-search results will be introduced.*

***Index Terms:** Composite; High Speed Robot; Dynamic Analysis; Robot Driving Torque; Simulation Analysis; Actuator Module,*

## I. INTRODUCTION

The industrial robots is divided into SCARA (Selective Compliance Assembly Robot Arm) and Cartesian robot appropriate for assembly, a simple repeated work process, and articulated robot utilized in complicated and wide-ranging-area work process [1]. The articulated robots have in common the serial link structure with series connection [2,3].

Articulated robots have the advantage of having a relatively larger workable space whereas the disadvantage of having a relatively smaller payload. Structurally, the upper-part link weight is loaded on to the lower-link joint in proportionate to distance. In other words, since the robot's driving part locates inside of the rotating joint, the driving part is required to bear the weight of the robot driving part as well, in addition to that of an object to actually handle [4,5]. In particular, under the influence of gravity, articulated robots receive large torque load on its joint driving machine part. Therefore, they should have a high capacity of motor and reducer and, accordingly, their volume and weight have to be large. In the robot structure, the motor and reducer attached to the upper-part joint link become the load on the motor driving the lower-part joint link. The higher the capacity of upper-part joint driving motor, the larger the load on the lower-part joint. This is a structural disadvantage [6]. To help improve the robot joint torque, reducers with a high gear ratio such as harmonic drive or RV reducer have been utilized. However, it is much limited to improve their torque performance beyond a certain ratio level. In order to solve such a problem, Stewart Platform was suggested, which is in a parallel structure to highly increase the rigidity.7 Moreover, though parallel-type robots have a very high rigidity, their machine mechanism interpretation is much complicated and their workable space is small, causing difficulties in actual system application for the most part. For these reasons, it is increasingly demanded to improve the articulated robot torque by lightening their weight. In addition, product miniaturization, productivity and competitive production cost are growing more significant in the production field. The demand for related robots is surging and light-weight robot development is increasing rapidly.

This paper implemented a joint dynamic characteristic analysis necessary for the development of industrial light-weight articulated robot and, by doing so, conducted an analysis research on robot joint driving torque. In particular, robot weight and payload were determined first, then, the weight was assigned to joint and link to calculate the driving torque required for the joint through dynamic analysis and reflect the result in design

### 1. Geometric Model Generation for Analysis

For this research, maximum torque required for each axis was analysed by utilizing the concept designs of a 7-axis articulated robot with 5 kg payload.

To create a geometric model, a 20 kg articulated robot with 5 kg payload was assigned to each joint and link and the necessary torque for joint was calculated through dynamic analysis program. The assigned weight on the articulated robot is as below; in the articulated robot of table 1, weights for the Actuator Module and link were separately indicated

**Table 1. Weight and Speed of 7 Axes Articulated Robot**

| oint | Speed (deg./sec) | Actuator Module | Link |
|---|---|---|---|
| 1 | 120 | 2.5 kg | 1.0 kg |
| 2 | 120 | 2.5 kg | 1.0 kg |
| 3 | 120 | 2.3 kg | 1.0 kg |
| 4 | 180 | 2.3 kg | 0.9 kg |
| 5 | 180 | 3 kg | 0.65 kg |
| 6 | 180 | 1.5 kg | 0.65 kg |
| 7 | 240 | 5.9 kg (Incl. Payload) | - |
| Weight | | | 20 kg |



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In the articulated robot, the weight of actuator was estimated as the total weight of motor, reducer, sensor and some machining parts as in the Table 1. The weight of main joint axes 1 and 2 was estimated as 2.5 kg and 3, 2.3 kg. The weight of link to which a joint is connected including robot base was estimated as 1 kg identically at the axes 1, 2 and 3.

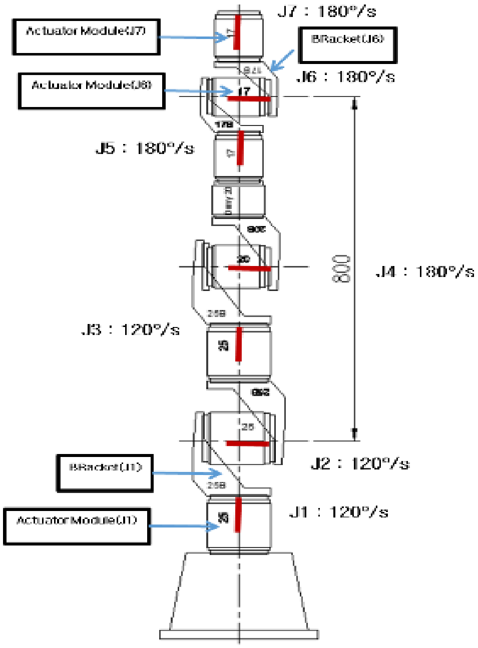


**Figure1. Specification of 7 axes articulated robot.**

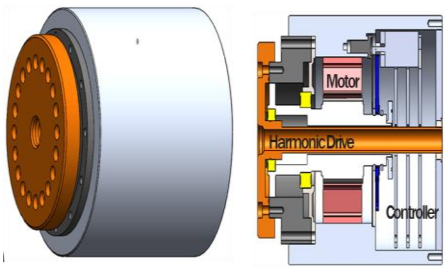


**Figure 2. Structure of actuator module.**

The actuator module consists of motor, harmonic driver, sensor and controller. Figure 2 shows the design of actuator module. To minimize the actuator module, harmonic drive and motor housing integrated design and the wave generator of harmonic driver and motor rotor was connected directly. Also, actuator housing is design optimized through CAE analysis as shown figure 3.

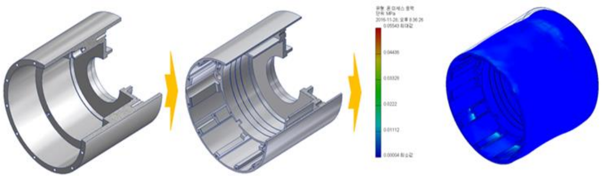

**Figure 3. Optimized design of motor housing.**

Four types of actuator modules were designed through modular concept as shown table 2. Four types of motors were used in Actuator Module and a robot joint was formed by combination of modules. Depending on the load of the robot joint, the motor can be used from 400W to 50W. Module 4 is applied to the main axes 1, 2 and 3 of the robot. The wrist axis of the robot has been applied to the module 2.

**Table 2. Specifications of Actuator Module**

| | | nit | odule 4 | odule 3 | odule 2 | odule 1 |
|---|---|---|---|---|---|---|
| Motor | R ated ower | Patt | 50 | 00 | 00 | 0 |
| | R ated | PM | ,000 | ,000 | ,000 | ,000 |
| | | eg/sec | 2,000 | 2,000 | 2,000 | 2,000 |
| | | ad/sec | 09.4 | 09.4 | 09.4 | 09.4 |
| | R ated orque | T.m | .15 | .95 | .48 | .25 |
| Harmonic Driver | R eduction Ratio | | 00 | 00 | 00 | 00 |
| | E fficiency | | 00 | 00 | 00 | 00 |
| | R ated orque | T.m | 50.5 | 6.5 | 3.6 | 7.5 |
| | M oment | .m | 01 | 34 | 7 | 3 |
| C ontrol | P ower | Signal Cable : Ethercat 4wire | | | | |
| | | Drive Control Power (DC 24V) | | | | |
| | | Drive Motor Power (DC 24V) | | | | |
| | E raek | Solenoid & Friction Ring Type | | | | |

The wrist axis was assumed to have a smaller load and torque compared with the main joint axis. Its actuator and module weights were set around 1.5 kg. The dummy link weight to enhance the working range of 7-axis articulated robot was also included in the actuator. In consideration of its geometric form and size, the link that connects motor to motor or motor to dummy link was set as 1 kg for the main axes of 1, 2 and 3; 0.9 kg for wrist axis 4; and 0.65 kg for axes 5 and 6. The joint angular speed of axes 1, 2 and 3 suggested in the initial concept design was 120 deg./sec; and wrist axes 4, 5 and 6 was 180 deg./sec in this study interpretation.

To determine the motor capacity of articulated robots, joint driving torque design parameter were identified. Rotation inertia conditions and speed characteristics were applied to the geometric model then, the moment and acceleration at robot end and each joint were evaluated through motion response.

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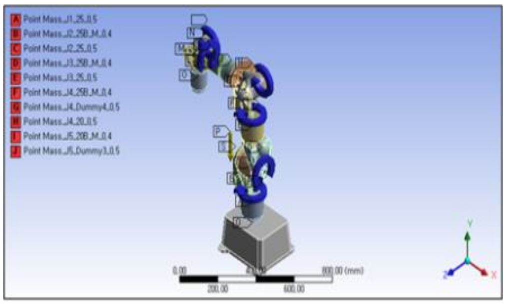

**Figure 4. Simulation model of 7 axes articulated robot.**

Rotation range at which each joint of articulated robot is operable was set at 360° for axis J1, the base axis; 180° for axes J2~J6; and 360° for J7. Motion case was constructed by reflecting motion scenario that considers the practically anticipated operation in driving and motion directions. To ensure the mobility and reliability, the constructed model's mass organization was adjusted and the analytical model was made in rigid-body to measure the joint capability for motor selection. Figure 4 shows the constructed geometric model.

### 2.1 Analysis applied Assy. /Part composition

| Task | Step | | Entry Values (unit : ) | Notes |
|---|---|---|---|---|
| Model Preparation | Scara Top Assy | | 3.9 | |
| | Base-Assy | supp: 67 | | |
| | J1 BASE-5(IP67) | | 01 Fixed_1 | |
| | J2 RV-27C-Body | | 02 Revolute_1 | |
| | ARM01-Assy | | | |
| | J1 007 600W MOTOR COVER-7 | | 01 Fixed_2 | |
| | J3 BEARING COVER-OUT2 | | (03 Revolute_1) | |
| | J4 BEARING COVER 1ARM | | (04 Revolute_1) | |
| | ARM02-U-Assy | supp: 1 | | 1.9 |
| | J3 BEARING COVER-IN | | (03 Revolute_2) | |
| | CABLE BRACKET-IP | | | |
| | J5 JOINT HOUSING-170413 | | 05 Fixed_1 | |
| | ARM02-L-Assy | supp: 1 | | 3.8 |
| | J2 006.FRONT COVER | | 02 Revolute_2 | |
| | J5 010.1ST ARM-V10-1 | | 06 Fixed_2 | |
| | motor mount11 | | | |
| | J4 BEARING COVER-1ST ARM I | | (04 Revolute_2) | |
| | J6 _SHF_SHG 25 xxx 2UH Part2 | | 06 Revolute_1 | |
| | | 6.2 | 0.5 | 5.7 |
| | ARM03-Assy | supp: 2 | | 5.2 |
| | J6 _SHF_SHG-25-xxx-2UH-Part1 | | 06 Revolute_2 | |
| | 013. 2ND ARM-V10-1 | | | |
| | J7 BALL NUT | | (07 Translate_1) | |
| | S-SHAFT_Assy | | | 0.2 |
| | J7 SPLINE SHAFT | | | |
| | 015.TOOL | | (07 Translate_2) | |
| | | 8.8 | 3.4 | 5.4 |

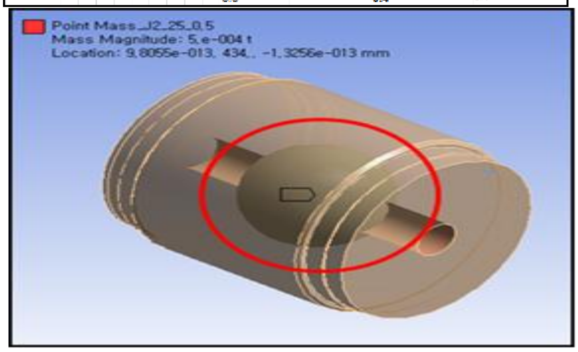


**Figure 5. Construction of robot assembly and part.**

In the analysis model constructed based on a concept design, the part corresponding to robot joint was made with actuator module and the link, brackets. The analysis model part was also organized in a simplified form of rigid body giving inertia to motion. Figure 5 shows the conditions of each part of adjust mass and analysis model in the articulated robot

The analysis model was designed to have 7 joint connections. For the analysis convenience, the robot's base axis was constructed in ground fixed and the other axes, in revolute joint. Figures 6 shows the constructed articulated robot models and their joint axis characteristics.

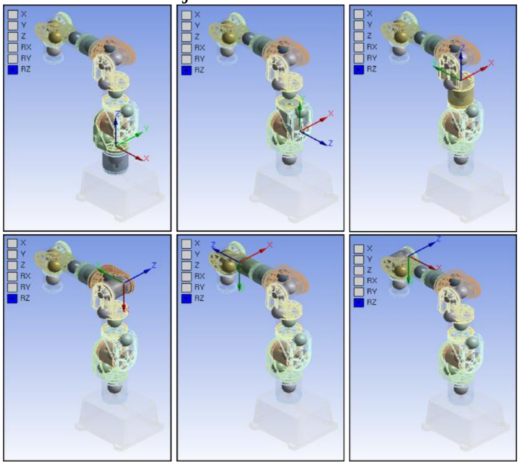

**Figure 6: Characteristic of robot joint.**

### 2.2 Motion Scenario

To calculate the torque required for a joint in the initial robot concept designing, dynamic analysis was implemented then, based on the results on each axis' required torque, motor and reducer capacity was determined. Detailed design is conducted on this basis. As the first phase, to verify mobility performance, each motor speed was ignored and joint angular speed was entered as a motion source. Each axis step was organized with 20 sub-steps and sub-steps were set at 0.05 second to implement analysis. For the 3 second the 7 axes articulated robot implements the motion scenario, the torque required for joint was designed to be calculated. Motion Scenario 1 is about the simultaneous operation of 7 axes in the articulated robot. Scenarios 2 ~11 are to operate one axis with 6 other axes being fixed. Figure 7 shows motions organized for dynamic analysis.

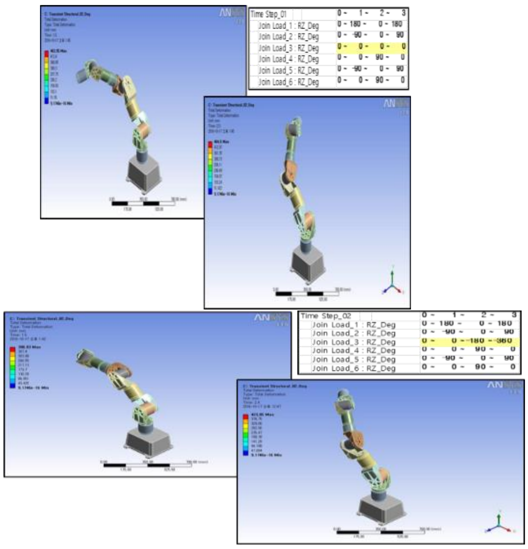

**Figure 7. Motion Scenario 1 of 7 axes articulated robot.**



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### 2.3 Initial & constraint conditions

Motion Case 1 of articulated robot has the scenario of simultaneous operation of all of the robot joints at the maximum motion range. Motion Cases 2~11 have axis-specific conditions for maximum torque generation so that each single robot joint axis operates at the maximum motion range. Table Ⅲ shows the constriction and motion conditions for Multi Body Dynamic analysis.

**Table 3: Motion Case of 7 Axes Articulated Robot**

| | riving Axis | Fixed Axes | Range(Deg.) |
|---|---|---|---|
| Motion Case 1 | LL | 0 | Full Range |
| Motion Case 2 | 01 | J2,3,4,5,6,7 = 0deg | +120 ~ -120 |
| Motion Case 3 | 02 | J1,3,4,5,6,7 = 0deg | +120 ~ -120 |
| Motion Case 4 | 03 | J1,2,4,5,6,7 = 0deg | +180 ~ -180 |
| Motion Case 5 | 04 | J1,2,3,5,6,7 = 0deg | +180 ~ -180 |
| Motion Case 6 | 05 | J1,2,3,4,6,7 = 0deg | +180 ~ -180 |
| Motion Case 7 | 06 | J1,2,3,4,5,7 = 0deg, | +180 ~ -180 |
| Motion Case 9 | 03 | J1,4,5,6,7 = 0deg, J2=90deg | +180 ~ -180 |
| Motion Case 10 | 05 | J1,2,3,7 = 0deg, J4=90deg, J6=90deg | +180 ~ -180 |
| Motion Case 11 | 05 | J1,2,3,6,7 = 0deg, J4=90deg | +180 ~ -180 |
| 1. Speed of Joint: J01~J03: 120°/sec, J04~J06: 180°/sec<br>2. Acceleration of gravity : 9.81m/s$^2$<br>3. Time Step: 1sec/step, No. of Sub Step: 60 Step | | | |

### 2. Robot Multi-Body Dynamics Analyses

In order to analyze the joint driving torque in robot operating environment based on dynamic characteristics, a motion case was established by reflecting a motion scenario considering severe conditions (maximum range, maximum payload and maximum speed) expected in the actual operational situation and the dynamic characteristic structural analysis of motion mass inertia was performed. Figures 8 shows the geometric model generation and analysis processes for driving torque analysis.

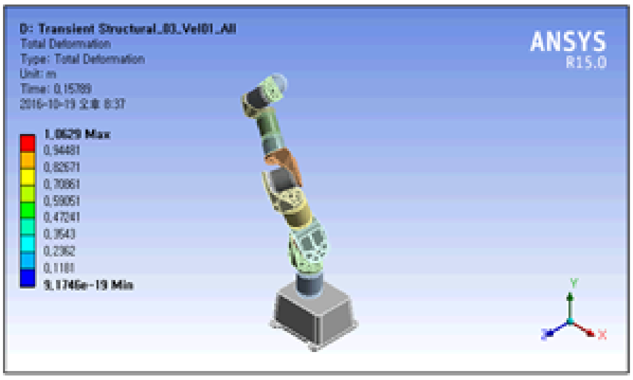


**Figure 8. Simulation of 7 axes articulated robot.**

The robot joint actuator module does rotational motion supported by inertia moment centering on joint rotation axis under force from the robot geometric form's weight to the tangential direction. In other words, the rotation axis moment works as torque. The robot joint torque determination was analyzed with total moment in consideration of all of gravitational acceleration, weight and angular speed. To obtain the maximum driving torque, simulation was implemented to operate the entire robot joint rotation axis then, the maximum torque of each joint was found. In addition, each joint rotation axis was operated at the full range in individual motion cases to make the maximum load for the analysis.

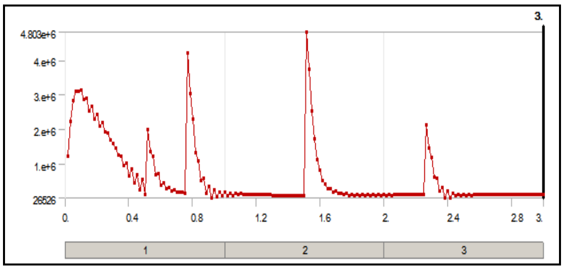

**Figure 9. Total Moment of J1 of articulated robot.**

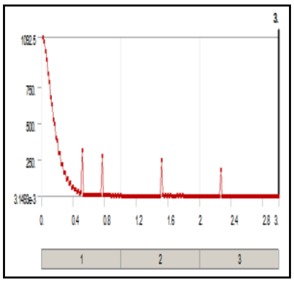

**Figure 10: Angular acceleration of J7 of articulated robot.**

Table 4 shows the results of axis-specific maximum torques through articulated robot dynamic analysis. It was found that the maximum torque was required by the base axis of articulated robot and the farther away from the base axis, the lower the maximum torque was. Moreover, the wrist axis had a smaller driving torque compared with that of the main axis. Of the wrist axes, the axis J5 was found to need the largest torque. Motion Cases 10 ~ 11 showed small torque due to the identical direction of the axis J5 to gravity.


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**Table 4. Result of Robot Joint Driving Torque**

| OINT | Driving Torque(N·mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | *C1* | *C2* | *C3* | *C4* | *C5* | *C6* | *C7* |
| 1 | .80×$10^{6}$ | .77×$10^{8}$ | | | | | |
| 2 | .23×$10^{6}$ | | .60×$10^{8}$ | | | | |
| 3 | .13×$10^{6}$ | | | ,34×$10^{7}$ | | | |
| 4 | .66×$10^{6}$ | | | | .60×$10^{7}$ | | |
| 5 | .34×$10^{6}$ | | | | | .31×$10^{7}$ | |
| 6 | .12×$10^{6}$ | | | | | | .66×$10^{7}$ |

| OINT | Driving Torque(N·mm) | | |
|---|---|---|---|
| | *MC6* | *MC7* | *MC9* |
| 5 | 2.46×1 0$^{7}$ | 1.25×1 0$^{7}$ | 1.34×1 0$^{7}$ |

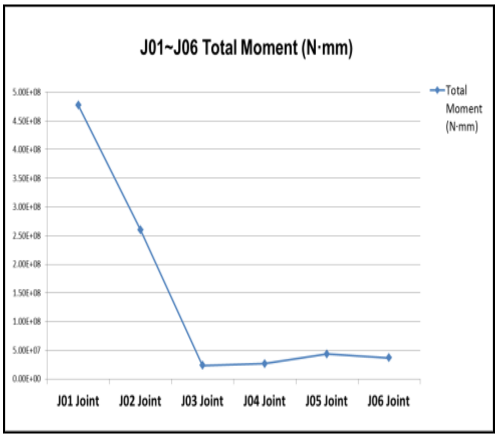


**Figure 11. Total moment of articulated robot join.**

## II. CONCLUSION

Since articulated robots operate under rapid acceleration/deceleration conditions, it is highly important to understand the speed, load and stress characteristics in the initial robot designing phase based on dynamic characteristic analysis. For this reason, dynamic characteristic study on articulated robot was implemented. The study findings are summarized as follows;

(a) Joint dynamic characteristics must be analyzed in the maximum acceleration/deceleration conditions because the robots are operated in the operational condition of severe acceleration and deceleration. In particular, since robot joint dynamic characteristics vary depending upon a robot posture, it is important to analyze at the edge of working space, or, that is, at the end part of robot under the maximum acceleration/deceleration condition.

(b) Robot joint torque shows huge differences according to robot postures. In the case of a low-speed robot operation, almost the same characteristics are found regardless of robot posture.

(c) In the implementation of dynamic characteristic analysis for the 7 axes articulated robot, maximum torque is generated when operating multiple axes rather than single axis due to the mutual inertia influence among joints.

## ACKNOWLEDGEMENT

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