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Evaluation of Joint Driving Torque and Finite Element Analysis in Articulate Robot through the simulation of Multi-Body Dynamics

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Abstract*: Interest in high-speed articulated robots is increasing for product productivity expansion. High-speed articulated robots operate with rapid acceleration/deceleration moves, requiring dynamic characteristic analysis in the robot designing process. For this dynamic behavior analysis, simulation software is utilized, which supports product design verification and parts optimization. In analyzing the dynamic characteristics using the software, loading conditions can be obtained from experimental data or parts' material characteristics. In a special case where data or experimental data on load conditions are hardly obtainable, multibody dynamics software is utilized. However, it is not easy to define an effective load and boundary conditions for systems with kinetically complicated connections. In order to solve such a problem, this present study investigated how to apply to structural analysis software the dynamic load found using dynamics and structural analysis software. In addition, the dynamic characteristics of high-speed articulated robots and robot link were assumed as a rigid body in implementing the dynamics analysis and structural analysis.

Keywords*: High speed robot, Multi body dynamic analysis, Articulated robot, Robot driving torque, Simulation analysis, Actuator module.

I. INTRODUCTION

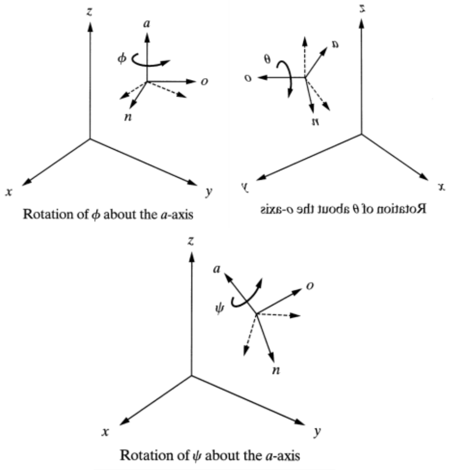
In diverse industrial area, simulation software is employed before prototype making for product design verification and parts optimization with production design. System designing based on simulation is highly useful for product optimization [1]. There are numerous kinds of software for virtual simulation and they are divided into structural, dynamics, thermal/fluid areas. In product designing, structural analysis is an important factor to calculate the stress applied to a product and deformation and determine a product's material and shape. For structural analysis, the load to be applied to a product and boundary condition should be utilized in structural analysis software [2.3]. Usually, it is appropriate to employ the results from experiment. However, in the case of a system with kinetically complicated connections, defining effective load and boundary conditions is not easy.

To solve such a problem, this study described how to apply to structural analysis the dynamic characteristic load found using dynamics and structural analysis software. Recurdyn was employed as dynamics and structural analysis software [7-9]. Recurdyn analyzes system response in the time domain when a force is applied to a rigid body system connected under kinematic constraints. Implicit Integrator, in particular, is applied to this software, which bases on Recursive Formulation on the ground of relative coordinate system [11]. In this study, the parts composition of articulated robot was assumed as rigid body in implementing driving torque and structural analysis. Based on this, an actuator to be applied to robot joints was selected.

II. EVALUATION OF ROBOT JOINT DRIVING TORQUE

A. Coordinate Transformation & Motion Equation

Of the results found from dynamics, the reaction applied to body is force and moment which are vectors having a size and direction. Therefore, it is important that the coordinate to refer to is in which posture. In this study, for coordinate transformation, Euler Angle ZXZ was utilized. Figure 1 shows the expression and coordinate transformation matrix of coordinate systems rotating about the. Z axis, X axis, then, Z axis



$$\mathrm{Euler}(\phi,\theta,\psi)=\mathrm{Rot}(a,\phi)\mathrm{Rot}(o,\theta)\mathrm{Rot}(a,\psi)$$

$$=\begin{bmatrix} C\phi C\theta C\psi - S\phi S\psi & -C\phi C\theta S\psi - S\phi C\psi & C\phi S\theta & 0 \\ S\phi C\theta C\psi + C\phi S\psi & -S\phi C\theta S\psi + C\phi C\psi & S\phi S\theta & 0 \\ -S\theta C\psi & CSC\psi & C\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Fig. 1. Description Euler angle ZXZ and transformation matrix

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Angle is capable of expressing every posture, and with the coordinate transformation, it is possible to transform about a specific coordinate system. Generally, in the case of employing the Global Coordination System, using values without making any specific transformation does not cause a problem. However, since every value reported as a result of the analysis is not based on the Global Coordination System criteria but utilizing the values about a specific time among the analysis results, it is required to consider the posture of center of gravity of body at that time and the posture of markers (coordinate system utilized in Recurdyn to create force or constraints) connected to the body.

Moreover, in order to find a joint component and link motion equation, a dynamic equation is employed, which can calculate component move if force and torque are known. Generally, Newton mechanics is utilized to find a robot component dynamics equation. Applying Newton dynamics in a 3D space having mass distribution, however, is highly complicated; thus, Lagrangian mechanics commonly employed. As Lagrangian mechanics bases solely on the energy term, it is easy to apply in diverse aspects. A Lagrange-based motion equation bases solely on the energy term, inducing a motion equation more easily. Energy equation, particularly, has a squared term, eliminating possible concern over confusion on a sign. The direction of force operation does not have to be considered as well. It is also easily applicable to a multibody system where multiple objects exist

$$\mathrm{K(Lagrangian)} = \mathrm{L(kinematic \cdot Energy)} - \mathrm{P(Potential \cdot Energy)} \cdots\cdots\cdots (1)$$

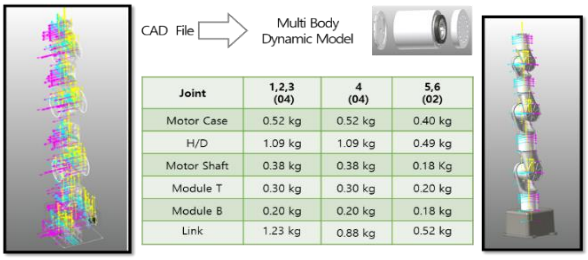
$$F_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{x}_i}\right) - \frac{\partial L}{\partial x_i} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

$$T_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

In the equation, F represents the sum of all external energy forces related to a linear motion; T, sum of all external torques related to a rotational motion; and x, system variable.

B. Model Creation for Model Analysis

In this study, to analysis multibody dynamics of 6-axis articulated robot with 5Kg payload, an STP file is converted to dynamics analysis file provided in the analysis program. then, based on the rigid body analysis affecting motion inertia, the model in figure 2 was established. The two robot models employed a linear-type and elbow-type actuator. The performance of two models' actuator is identical and the appearance of actuator forming a joint is shown in the figure 3. In the event of using a linear-type actuator in joint of each axis of articulated robot, an L-shaped link is utilized to connect the actuator. Figure 3 exhibits the elbow-type joint model with cylindrical link formation.



Joint	1,2,3 (04)	4 (04)	5,6 (02)
Motor Case	0.52 kg	0.52 kg	0.40 kg
H/D	1.09 kg	1.09 kg	0.49 kg
Motor Shaft	0.38 kg	0.38 kg	0.18 Kg
Module T	0.30 kg	0.30 kg	0.20 kg
Module B	0.20 kg	0.20 kg	0.18 kg
Link	1.23 kg	0.88 kg	0.52 kg

Fig. 2. Analysis on rigid body and multi body dynamics.

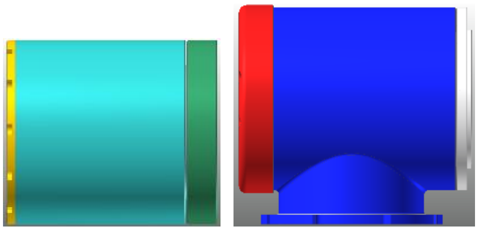


Fig. 3. Actuator module: straight and elbow type

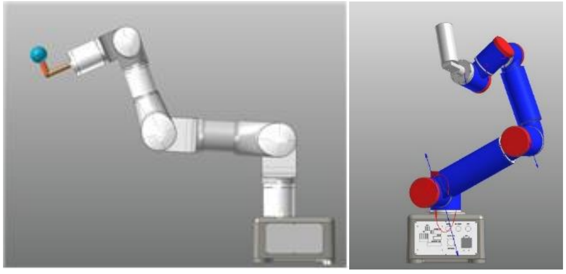


Fig. 4. Articulated robots using straight and elbow type actuator

With respect to the component weight of articulated robot, the weights of actuator and link were estimated based on the property values provided in CAD. As in Table 1, an actuator module consists of motor housing, harmonic drive, motor shaft, top plate, and base plate. The weight was allocated to each part. For parts other than top plate, a module fixed on a base plate using fixed joints was established as a solid model. An actuator module and top plate were designed to have revolute joints and defined as a rotational joint. Top plated and link were formed with fixed joints. Link was also defined as a fixed joint with the base plate of the next axis. That is, top plate, link and base plate are structured using fixed joints and, in the event of robot joint rotation, they are expressed as a solid model. In the dynamics modeling, the weight in the initial design was allocated to modeling parts in establishing the modeling

Table I. Part weight of articulated robot.

	Straight Type Robot		**Elbow Type Robot**	
	Actuator	*Link*	*Actuator*	*Link*
Axis 1	2.5 kg	1.2 kg	2.5 kg	
Axis 2	2.5 kg	3.7 kg	2.5 kg	1.54 kg
Axis 3	2.5 kg	1 kg	2.5 kg	1.3 kg
Axis 4	1.5 kg	0.6 kg	1.5 kg	
Axis 5	1.5 kg	0.6 kg	1.5 kg	
Axis 6	1.5 kg		1.5 kg	
Total	24 kg (Incl. Payload 5 kg)		20 kg (Incl. Payload 5 kg)	

After modeling pre-processing, model analysis was performed in reflection of the geometric characteristics of link and joint. Based on this, structural analysis of robot link was implemented through robot joint torque inspection and structural analysis.

C. Motion Scenario Establishment

In order to estimate the necessary torque for each joint based on the established modeling, the following robot motion scenario was established; each joint operates in the maximum operation range at the max angular velocity and angular acceleration. The acceleration/deceleration was 0.3 second in the initial condition setup. Table 2 shows the operation time and speed of robot. Based on Table 2, velocity profile was estimated at which each joint could move for 5 seconds. Figure 5 exhibits the velocity profile of robot joint axis. In other words, the working range of articulated robot axes 1, 4, and 6 was -180° ~ +180°; acceleration /deceleration time, 0.3sec; joint angular velocity, 120°/sec; and angular acceleration, 600°/sec. Based on these, the profile was estimated as the robot operated in the maximum working range at the max joint velocity for 5 seconds. Figure 5 shows the velocity profile of axes 1, 4 and 6.

Fig. 5.Velocity profile of 1,4,6 Axis

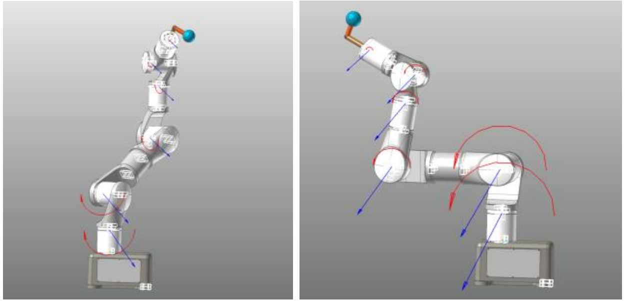


Fig. 6.Example of articulated robot motion

Table II. Specification of articulated robot.

Working Range (Deg.)	*(J1)*	-180° ~ +180° (Module4)
	(J2)	-120° ~ +120° (Module4)
	(J3)	-125° ~ +125° (Module4)
	(J4)	-180° ~ +180° (Module2)
	(J5)	-110° ~ +110° (Module2)
	(J6)	-180° ~ +180° (Module2)
Max. Angular Vel. /Max. Angular Acc (deg/sec) /(deg/sec^2)	*(J1)*	120°/600°
	(J2)	120°/600°
	(J3)	120°/600°
	(J4)	120°/600°
	(J5)	120°/600°
	(J6)	120°/600°

All submitted paper should be cutting edge, result oriented, original paper and under the scope of the journal that should belong to the engineering and technology area. In the paper title, there should not be word 'Overview/brief/ Introduction, Review, Case study/ Study, Survey, Approach, Comparative, Analysis, Comparative Investigation, Investigation'.

D. Torque Estimation through Simulation

After mounting 5Kg payload on a robot, 6 axes of the robot were operated at the max. working range at max. velocity and acceleration. Figure 7 shows the graph of velocity acceleration and torque of the axis 1 in robot operation.

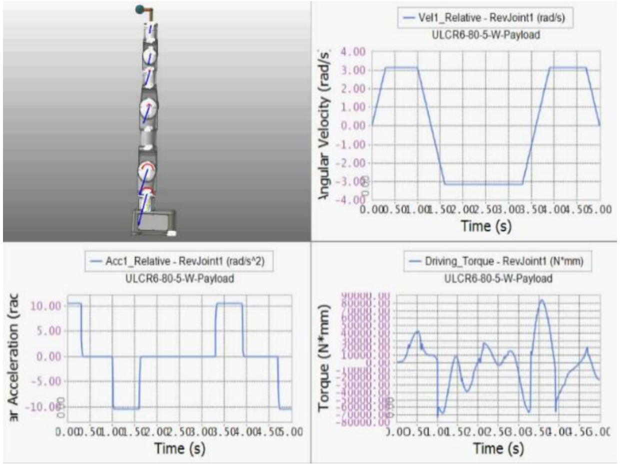


Fig. 7. Simulation result of required driving torque

As a result of the simulation, the axis-2 joint was found to require the max. torque while motion operation. The mean torque was 100.1 N·m; and max. torque, 221.5 N·m. Module 4 had the rated torque of 150.0N·m and max. torque, 235N·m, being set as 66% of the joint-module rated torque, and 94% of joint-module max. torque. Module 2 was found to account for 53% of the rated torque and 73% of max. torque

Table III. simulation result of robot joint torque.

Axis	**Simulation Torque (N·m)**				**Actuator Module (N·m)**	
	Max. Torque	*Min. Torque*	*RMS Torque*	*Max Torque*	*Rated Torque*	*Max Torque*
1	84.3	-73.0	32.1	84.3	150.5 (Module 4)	235 (Module 4)
2	163.0	-211.5	100.5	221.5		
3	88.3	-67.3	39.7	88.3		
4	21.2	-27.8	11.1	27.8	33.2 (Module 2)	67 (Module2)
5	33.3	-36.8	21.8	36.8		
6	4.1	-3,9	1.7	1.1		

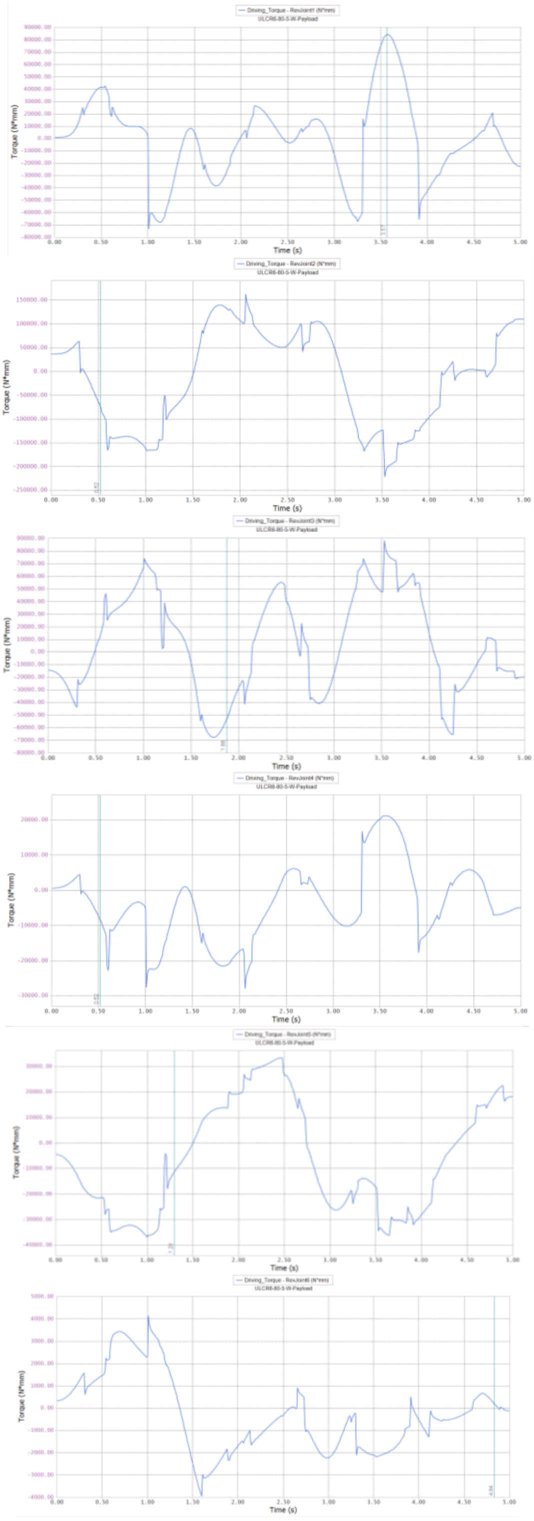


Fig. 8. Simulation result of required driving torque

Figure 8 shows change in torque of each axis in robot operation. As noticed in the torque profile, according to robot postural change, torque working upon robot joints also changed. In terms of robot structure, the axis 2 was expected to require the max. torque, and the simulation results also indicated that the axis 2 needed max. torque during robot operation.

III. EVALUATION OF ROBOT MULTI-FLEXIBILITY BODY DYNAMICS

Multi-Body Dynamics analyzes dynamic behaviors resulted from the force-joint connection status in various rigid bodies. To apply Multi-body Dynamics analysis, the geometric rigid body of the model created in the section above were changed into a flexible body consisting of multiple material points in the mesh pre-processing. A flexible body created in such a mesh process comes to have finite elements in relatively smaller areas. Each flexible body was assigned the property values of parts to be processed in the simulation.

Figure 9 shows the result of mesh creating in the solid link 1 using the mesh type of Solid 4 (Tetra 4). The size of mesh element was set as 2,5% of the diagonal length of bounding box of CAD geometry. After giving 5Kg payload to the robot, 6 robot axes were operated in the max. working range at max. velocity and acceleration for 5 seconds. Table 4 shows the analysis result of stress loaded on to the link after robot operation.

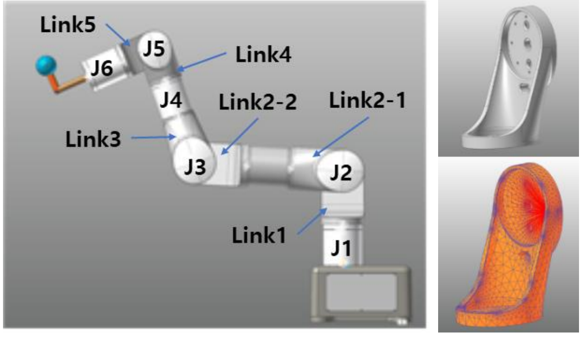


Fig. 9. Generated mesh of articulated robot link

Table IV. Simulation Result of Robot Torque

	Max. Von Mises Stress (M Pa)	
Link 1	745	(Boundary Condition) young's Modulus : 68,9 GPa Shear Elastic Modulus : 26 GPa
Link 2-1	340	
Link 3-2	758	
Link 3	200	
Link 4	325	
Link 5	148	

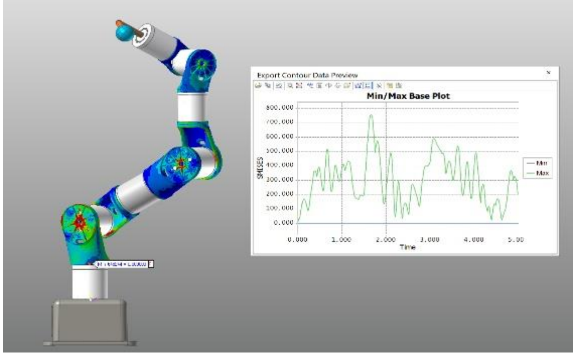


Fig. 10. Simulation of robot structure analysis

As Table 4 shows, the max. robot link strength was found 745MPa, lower than the max. value of the utilized link materials - young's Modulus and Shear Elastic Modulus. In terms of safety rate, each link strength was also found excellent as a result of structural analysis. Based on the structural analysis results, link optimization design progresses.

IV. RESULT AND DISCUSSION

Articulated robots are operated in rapid acceleration /deceleration conditions given the characteristics of motion. For such a rapid motion of robots, it is essential to implement dynamics characteristic analysis in the initial robot design stage; understand robot joint and link velocity, load and stress change characteristics according to robot postures; and reflect them in the initial robot design conditions. For this reason, the study was conducted on the dynamic characteristic analysis of articulated robot's joint and link, and the study results are organized as follows;

(a) Since articulated robots operate with rapid acceleration /deceleration, joint torque must be analyzed in the max. acceleration/deceleration condition. Particularly, as the dynamic characteristics of robot joint vary according to robot postures, given its features, it is important to perform an analysis in the max. acceleration/deceleration status in working range requiring a lot of torque.

(b) Robot joints have great differences according to robot postures. When a robot operates at a low speed, they show almost identical characteristics regardless of robot positions.

(c) In analyzing the dynamic characteristics of 6-axis articulated robot, max. torque is created when multiple axes are operated rather than single axis due to the mutual impact of inertia among the joints.

(d) Robot joints were found to have torque change even in the same postures, depending upon change in robot velocity.

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