Analysis and Design of Heavy Duty Handling Robot

Gwang-Jo Chung
Principal Research engineer in Robotics & Control Group
Korea Institute of Machinery & Materials
Daejon, Korea
gjchung@kimm.re.kr

Doo-Hyung Kim, Chan-Hoon Park
Principal Research engineer in Robotics & Control Group
Korea Institute of Machinery & Materials
Daejon, Korea
kdh649@kimm.re.kr , chpark@kimm.re.kr

Abstract- **In automation of manufacturing process, especially in mechanical industry, robot system now became a most general solution. Currently, one of the expanded applications of robot system is a heavy duty handling of huge and heavy parts. Actually some models with the payload over 600Kg or more are already developed and commercialized. In this paper, we introduce the design process of heavy duty industrial robot especially on the analysis technology that we adopted to build the native model of KIMM. In design process of articulated robot, with the payload over 300Kg or more, it requires static and dynamic analysis for manipulator that enables the selection of core components such as motor and decelerator. Although there are several commercialized software programs for analysis of kinematics and dynamics, we used the self developed S/W 'RODAN' that is specialized for inverse dynamics analysis. In his paper, we also introduce this S/W and it's applications for the analysis of heavy duty industrial robot design.**

Keywords— **Heavy duty robot. Robot design, Inverse dynamic, Kinematics, Components selection.**

I. INTRODUCTION

In general, it requires several steps in analysis and design process on the development of industrial manipulator including 1) Analysis of task and work environment 2) Determination of physical specifications 3) Kinematics and Dynamic analysis 4) Software simulation of work range and payload 5) Balancing weight design and analysis 6) Selection of proper parts and components 7) Repeat the process 3)~6) until it reaches to desired characteristics of statistics and dynamics. After the above design process, it follows manufacturing process that requires system redesign and calibration according to the mass property of materials that used for balancing and dynamics structure. Moreover, through the test of the mechanical resonant frequency, we should let this parameter to be higher to reduce the settling time in positioning and to increase the mechanical durability.

Finally, with the completed assembly drawings, we may prepare some detailed drawings for each parts, components and total systems. In this paper, we introduce this procedure applied to the heavy duty robot manipulator with the payload of 600Kg or less. In chapter 2, we present the determining procedure of structural specification of manipulator. Following chapter 3 describes the balancing unit design and chapter 4 explains the dynamics analysis procedure of the manipulator.

II. TASK AND SPEC'S OF HEAVY DUTY HANDLING ROBOT

A. *Task application of heavy duty handling robot*

Since the year 2002, several advanced countries in robotics developed heavy duty handling robot with the payload of 500Kgf or more, currently at least 4 companies in Japan and 3 countries in Europe presented the commercialized model. These models are mainly developed for machine tending for huge machine tools to serve machining process of large engine parts or heavy molding components.

Distinctively from the handling robots with the payload 400Kgf or less, these models over 500Kgf payload are enabling to handle the full assembly of car body to serve the welding robots to access in any direction of working. In other case, handling ability over 500Kgf, allows the relocation of target parts without removing from the jig fixture or work table to reduce the jig fixing procedure in mechanical process. Figure1 and 2 shows these application examples in automobile industry.

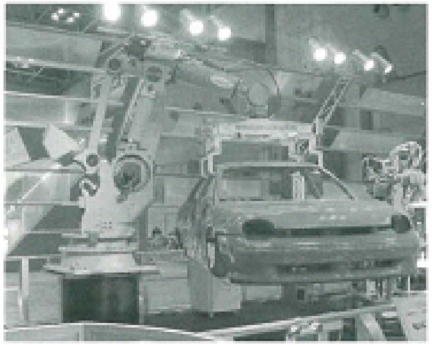

Figure 1. Car body transport (Nachi)

Figure 2. Motorcycle transport (Kawasaki)

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B. *Determination of robot specifications*

Currently commercialized model of heavy duty handling robot has a payload up to 600Kgf or less. The limitation of the payload should justly depend upon the task necessities in industrial fields. But in developer's aspect, it should be determined according to the affordable parts such as motors and transmissions.

Through the survey of market and application field, we also determined the payload to be 600Kgf that enables the handling of whole automobile car body. And we also consider 1) the weight of load and gripper, 2) the dimension of the car body, 3) task process of manufacturing including process condition and tact time etc,.

Table 1 shows the specification of heavy duty robot from FANUC INC., as the bench mark of the design.

Table 1. Robot Specification (Fanuc)

payload (Kgf)		**600**
Pepeatability (mm)		**± 0.4**
Horizontal Reach (mm)		**2800**
Axes motion speed (deg/sec)	**1~3**	**80**
	4,5	**100**
	6	**160**
Wrist moment (Kgf-m)	**4,5**	**340**
	6	**170**

Besides, we also designed the work range (that depends upon horizontal reach), affordable inertial moment, environmental conditions (temperature, humidity, vibration and noise, IP grade etc.). After the determination of the specifications above, we could fix the arm length that enables the kinematics simulation of work range and boundaries.

In general, commercialized S/W allows this procedure easily. As an example of the work range simulation, figure 3 shows that of FANUC robot model.

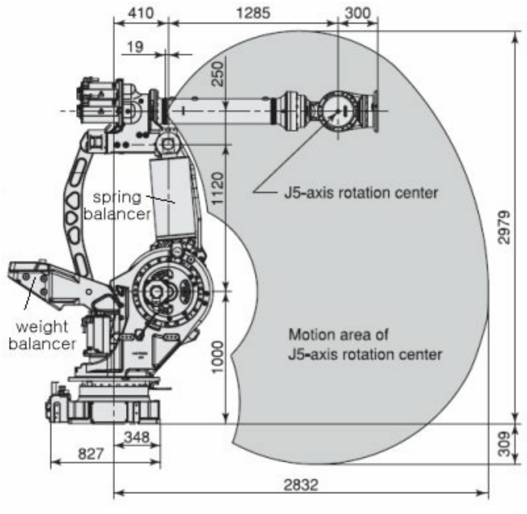


Figure 3. Robot Dimension (Fanuc)

III. BALANCING UNITS

In heavy duty handling with the industrial manipulator, balancing unit is essential for reducing the biased load, caused by gravity, delivered to the joint driving motor

There might be two trends of count balancing techniques; one is the passive balancing that utilizes passive components such as metal weight or springs, mostly adopted in Japanese companies. The other is active balancing with the hydraulic force and control techniques, mostly preferred in European companies.

In this study, we selected the passive counter balancing with the spring for 2nd axis and with the metal weight for3rd axis.

A. *Weight Balancing*

One of the popular physical solutions to reduce the biased load in robot manipulator is so called weight balancing. This method is very effective to required manipulator joint, but on the contrary, balancing weight itself may act as an undesirable load to the other joint axes. So, it must be designed properly and carefully for proper physical effect of balancing.

Key point of the design must consider followings.

1) Weight of balancer needed at the most frequently applied payload.

2) Balancer that works at the cross of driving torque between 1st and 3rd axes.

3) Proper shape and dimension of balancer that does not interfere with the normal task operation.

The following figure 4 shows the example of determining the weight balancer for reduce the motor load.

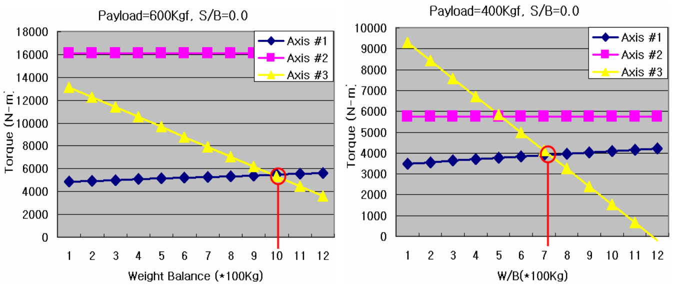


Figure 4. Analysis of Balancing weight

B. *Spring Balancing*

To reduce the motor load of 2nd axis, we adopt a spring balancing unit. First, a location of the installation of spring unit must be determined and next, the required spring constant should be calculated.

Because there is no theoretic and logical method to determine the location of the spring, we usually determine it depend upon the intuition of the designer. There may exists many location for proper installation, the designer select 2 or 3 model points of location in advance, then through the simulation, optimal location may be selected.

Following figure 5 shows two kinds of balancing method that mostly used in real design.

Through the simulation, we consider the balancing effect and mechanical interference to fix the proper case.

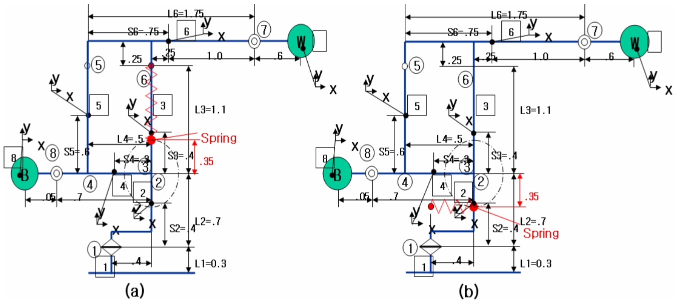


Figure 5. Arrangement of spring balancer

Hereafter, we must determine the spring constant also through the simulation. Normally we determine the spring constant to be the minimum value to reduce the effect of load torque. Therefore, it may be less than rated torque. If the spring constant is too high, it may act as a reaction force in high speed motion, causing undesirable internal force of the structure that may induce the vibration. So, in general case, control technology of the counter balancing effect also developed in application.

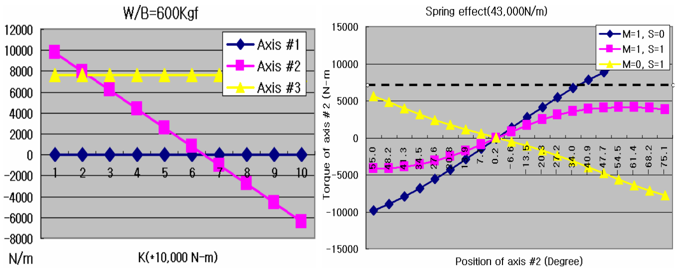


Figure 6. Effect of spring constant

IV. DYNAMIC ANALYSIS

This stage is the most important procedure to decide the specification of the motor and reducer.

Dynamic analysis in heavy duty robot is a problem of inverse dynamics that derive the capability of the motor and reducer from the given condition of robot joint motion including position, speed and acceleration of the manipulator.

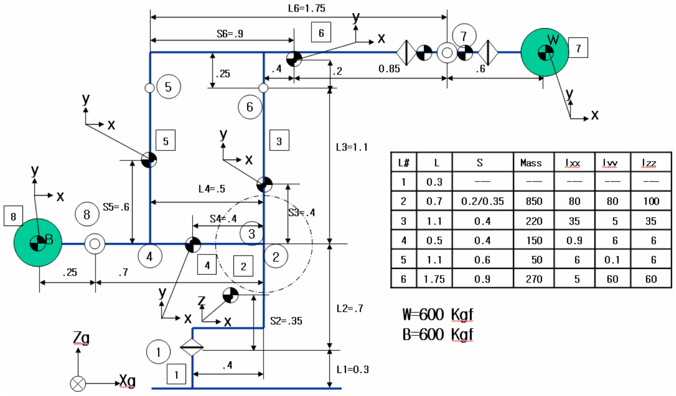
There are several commercialized programs such as DADS, ADAMS, SAMCEF, and so on, that allows the very easy solution of direct dynamics. But, inverse dynamics problem may be solved with the obtained value of direct dynamics and it must go several times iteratively.

In this research we developed specialized program for inverse dynamics, named as "RODAN (Robot Dynamic Analysis)

After this we introduce analysis procedure using this software.

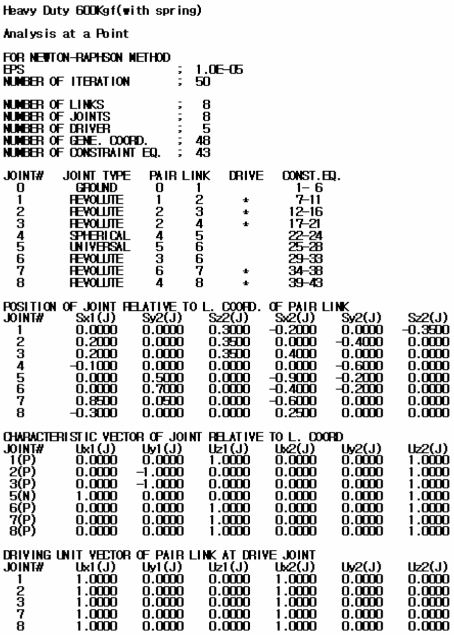
A. *Robot Modelling and IinputData*

We presents figure 7 as a model of the inverse dynamic analysis of the 6 axes articulated manipulator



L#	L	S	Mass	Ixx	Iyy	Izz
1	0.3	---	---	---	---	---
2	0.7	0.2/0.35	850	80	80	100
3	1.1	0.4	220	35	5	35
4	0.5	0.4	150	0.9	6	6
5	1.1	0.6	50	6	0.1	6
6	1.75	0.9	270	5	60	60

Figure 7. Robot modeling for dynamic analysis



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Heavy Duty 600Kgf(with spring)

Analysis at a Point

FOR NEWTON-RAPHSON METHOD
EPS                          ;  1.0E-05
NUMBER OF ITERATION          ;  50

NUMBER OF LINKS              ;   8
NUMBER OF JOINTS             ;   8
NUMBER OF DRIVER             ;   5
NUMBER OF GENE. COORD.       ;  48
NUMBER OF CONSTRAINT EQ.     ;  43

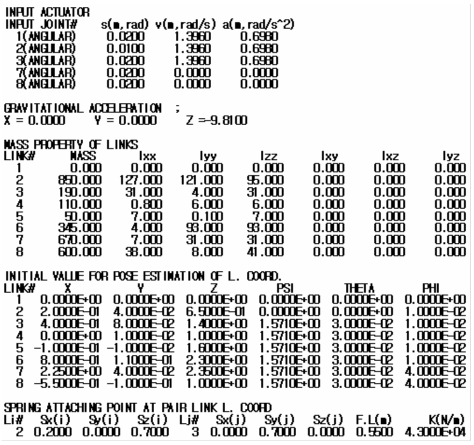
JOINT#   JOINT TYPE   PAIR LINK   DRIVE   CONST.EQ.
  0        GROUND      0     1              1- 6
  1       REVOLUTE     1     2      *       7-11
  2       REVOLUTE     2     3      *      12-16
  3       REVOLUTE     2     4      *      17-21
  4       SPHERICAL    4     5             22-24
  5       UNIVERSAL    5     6             25-28
  6       REVOLUTE     3     6             29-33
  7       REVOLUTE     6     7      *      34-38
  8       REVOLUTE     4     8      *      39-43

POSITION OF JOINT RELATIVE TO L. COORD. OF PAIR LINK
JOINT#     Sx1(J)    Sy2(J)    Sz2(J)    Sx2(J)    Sy2(J)    Sz2(J)
  1        0.0000    0.0000    0.3000   -0.2000    0.0000   -0.3500
  2        0.2000    0.0000    0.3500    0.0000   -0.4000    0.0000
  3        0.2000    0.0000    0.3500    0.4000    0.0000    0.0000
  4       -0.1000    0.0000    0.0000    0.0000   -0.6000    0.0000
  5        0.0000    0.5000    0.0000   -0.9000   -0.2000    0.0000
  6        0.0000    0.7000    0.0000   -0.4000   -0.2000    0.0000
  7        0.8500    0.0500    0.0000   -0.6000    0.0000    0.0000
  8       -0.3000    0.0000    0.0000    0.2500    0.0000    0.0000

CHARACTERISTIC VECTOR OF JOINT RELATIVE TO L. COORD
JOINT#     Ux1(J)    Uy1(J)    Uz1(J)    Ux2(J)    Uy2(J)    Uz2(J)
 1(P)      0.0000    0.0000    1.0000    0.0000    0.0000    1.0000
 2(P)      0.0000   -1.0000    0.0000    0.0000    0.0000    1.0000
 3(P)      0.0000   -1.0000    0.0000    0.0000    0.0000    1.0000
 5(N)      1.0000    0.0000    0.0000    0.0000    0.0000    1.0000
 6(P)      0.0000    0.0000    1.0000    0.0000    0.0000    1.0000
 7(P)      0.0000    0.0000    1.0000    0.0000    0.0000    1.0000
 8(P)      0.0000    0.0000    1.0000    0.0000    0.0000    1.0000

DRIVING UNIT VECTOR OF PAIR LINK AT DRIVE JOINT
JOINT#     Ux1(J)    Uy1(J)    Uz1(J)    Ux2(J)    Uy2(J)    Uz2(J)
  1        1.0000    0.0000    0.0000    1.0000    0.0000    0.0000
  2        1.0000    0.0000    0.0000    1.0000    0.0000    0.0000
  3        1.0000    0.0000    0.0000    1.0000    0.0000    0.0000
  7        1.0000    0.0000    0.0000    1.0000    0.0000    0.0000
  8        1.0000    0.0000    0.0000    1.0000    0.0000    0.0000
```

a) Structural parameter



```
INPUT ACTUATOR
INPUT JOINT#     s(m,rad) v(m,rad/s) a(m,rad/s^2)
  1(ANGULAR)      0.0200    1.3960    0.6980
  2(ANGULAR)      0.0100    1.3960    0.6980
  3(ANGULAR)      0.0200    1.3960    0.6980
  7(ANGULAR)      0.0200    0.0000    0.0000
  8(ANGULAR)      0.0200    0.0000    0.0000

GRAVITATIONAL ACCELERATION   ;
X = 0.0000      Y = 0.0000      Z =-9.8100

MASS PROPERTY OF LINKS
LINK#      MASS       Ixx       Iyy       Izz       Ixy       Ixz       Iyz
  1        0.000     0.000     0.000     0.000     0.000     0.000     0.000
  2      850.000   127.000   121.000    95.000     0.000     0.000     0.000
  3      190.000    31.000     4.000    31.000     0.000     0.000     0.000
  4      110.000     0.800     6.000     6.000     0.000     0.000     0.000
  5       50.000     7.000     0.100     7.000     0.000     0.000     0.000
  6      345.000     4.000    93.000    93.000     0.000     0.000     0.000
  7      670.000     7.000    31.000    31.000     0.000     0.000     0.000
  8      600.000    38.000     8.000    41.000     0.000     0.000     0.000

INITIAL VALUE FOR POSE ESTIMATION OF L. COORD.
LINK#     X           Y           Z          PSI         THETA        PHI
  1   0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  2   2.0000E-01  4.0000E-02  6.5000E-01  0.0000E+00  0.0000E+00  1.0000E-02
  3   4.0000E-01  8.0000E-02  1.4000E+00  1.5710E+00  3.0000E-02  1.0000E-02
  4   0.0000E+00  1.0000E-02  1.0000E+00  1.5710E+00  3.0000E-02  1.0000E-02
  5  -1.0000E-01 -1.0000E-02  1.6000E+00  1.5710E+00  3.0000E-02  1.0000E-02
  6   8.0000E-01  1.1000E-01  2.3000E+00  1.5710E+00  3.0000E-02  1.0000E-02
  7   2.2500E+00  4.0000E-02  2.3500E+00  1.5710E+00  3.0000E-02  4.0000E-02
  8  -5.5000E-01 -1.0000E-01  1.0000E+00  1.5710E+00  3.0000E-02  4.0000E-02

SPRING ATTACHING POINT AT PAIR LINK L. COORD
Li#   Sx(i)   Sy(i)   Sz(i)  Lj#   Sx(j)   Sy(j)   Sz(j)   F.L(m)      K(N/m)
  2  0.2000  0.0000  0.7000    3  0.0000  0.7000  0.0000  0.5500  4.3000E+04
```

b) Motion parameter

Figure 8. Input data for inverse dynamic analysis

The input data of "RODAN" software prepared with data above for inverse dynamic analysis shown as figure 8 above.

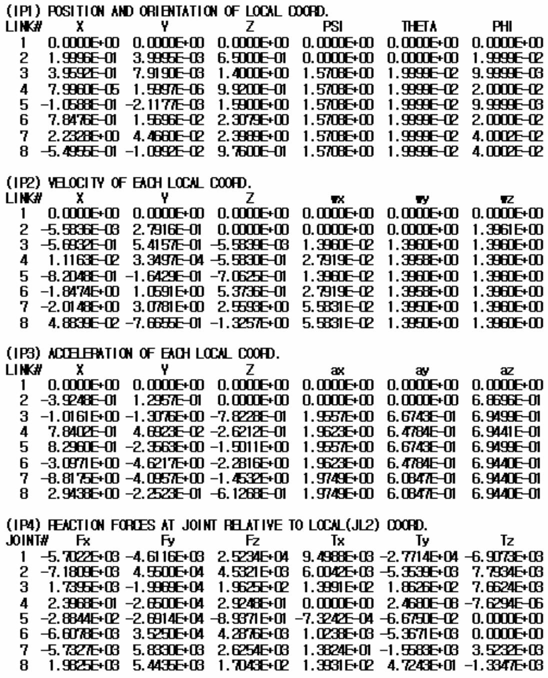
8-a) show the characteristics value of robot mechanism, and 8-b) is for dynamic characteristics

B. *Result of Analysis and Component Selection Procedure*

Figure 9 shows the result of inverse dynamics analysis.

In figure, among the reaction forces appeared at (IP4), the value of driving vector of each joint motor means a joint driving torque by which we may determine the capacity of the motor and reducer.

The other values except this means a reaction force applied to the joint that allows obtaining the boundary condition for simulation of stress and displacement of the manipulator.



```
(IP1) POSITION AND ORIENTATION OF LOCAL COORD.
LINK#     X           Y           Z          PSI        THETA        PHI
  1   0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  2   1.9996E-01  3.9995E-03  6.5000E-01  0.0000E+00  0.0000E+00  1.9999E-02
  3   3.9592E-01  7.9190E-03  1.4000E+00  1.5708E+00  1.9999E-02  9.9999E-03
  4   7.9960E-05  1.5997E-06  9.9200E-01  1.5708E+00  1.9999E-02  2.0000E-02
  5  -1.0588E-01 -2.1177E-03  1.5900E+00  1.5708E+00  1.9999E-02  9.9999E-03
  6   7.8476E-01  1.5696E-02  2.3079E+00  1.5708E+00  1.9999E-02  2.0000E-02
  7   2.2328E+00  4.4660E-02  2.3989E+00  1.5708E+00  1.9999E-02  4.0002E-02
  8  -5.4955E-01 -1.0992E-02  9.7600E-01  1.5708E+00  1.9999E-02  4.0002E-02

(IP2) VELOCITY OF EACH LOCAL COORD.
LINK#     X           Y           Z           wx          wy          wz
  1   0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  2  -5.5836E-03  2.7916E-01  0.0000E+00  0.0000E+00  0.0000E+00  1.3961E+00
  3  -5.6932E-01  5.4157E-01 -5.5839E-03  1.3960E-02  1.3960E+00  1.3960E+00
  4   1.1163E-02  3.3497E-04 -5.5830E-01  2.7919E-02  1.3958E+00  1.3960E+00
  5  -8.2048E-01 -1.6429E-01 -7.0625E-01  1.3960E-02  1.3960E+00  1.3960E+00
  6  -1.8474E+00  1.0591E+00  5.3736E-01  2.7919E-02  1.3958E+00  1.3960E+00
  7  -2.0148E+00  3.0781E+00  2.5593E+00  5.5831E-02  1.3950E+00  1.3960E+00
  8   4.8839E-02 -7.6655E-01 -1.3257E+00  5.5831E-02  1.3950E+00  1.3960E+00

(IP3) ACCELERATION OF EACH LOCAL COORD.
LINK#     X           Y           Z           ax          ay          az
  1   0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
  2  -3.9248E-01  1.2957E-01  0.0000E+00  0.0000E+00  0.0000E+00  6.8696E-01
  3  -1.0161E+00 -1.3076E+00 -7.8228E-01  1.9557E+00  6.6743E-01  6.9499E-01
  4   7.8402E-01  4.6923E-02 -2.6212E-01  1.9623E+00  6.4784E-01  6.9441E-01
  5   8.2960E-01 -2.3563E+00 -1.5011E+00  1.9557E+00  6.6743E-01  6.9499E-01
  6  -3.0971E+00 -4.6217E+00 -2.2816E+00  1.9623E+00  6.4784E-01  6.9440E-01
  7  -8.8175E+00 -4.0957E+00 -1.4532E+00  1.9749E+00  6.0847E-01  6.9440E-01
  8   2.9438E+00 -2.2523E-01 -6.1268E-01  1.9749E+00  6.0847E-01  6.9440E-01

(IP4) REACTION FORCES AT JOINT RELATIVE TO LOCAL(JL2) COORD.
JOINT#    Fx          Fy          Fz          Tx          Ty          Tz
  1  -5.7022E+03 -4.6116E+03  2.5234E+04  9.4988E+03 -2.7714E+04 -6.9073E+03
  2  -7.1809E+03  4.5500E+04  4.5321E+03  6.0042E+03 -5.3539E+03  7.7934E+03
  3   1.7395E+03 -1.9969E+04  1.9625E+02  1.3991E+02  1.8626E+02  7.6624E+03
  4   2.3968E+01 -2.6500E+04  2.9248E+01  0.0000E+00  2.4680E-08 -7.6294E-06
  5  -2.8844E+02 -2.6914E+04 -8.9371E+01 -7.3242E-04 -6.6750E-02  0.0000E+00
  6  -6.6078E+03  3.5250E+04  4.2876E+03  1.0238E+03 -5.3671E+03  0.0000E+00
  7  -5.7327E+03  5.8330E+03  2.6254E+03  1.3824E+01 -1.5583E+03  3.5232E+03
  8   1.9825E+03  5.4435E+03  1.7043E+02  1.3931E+02  4.7243E+01 -1.3347E+03
```

Figure 9. Result of dynamic analysis

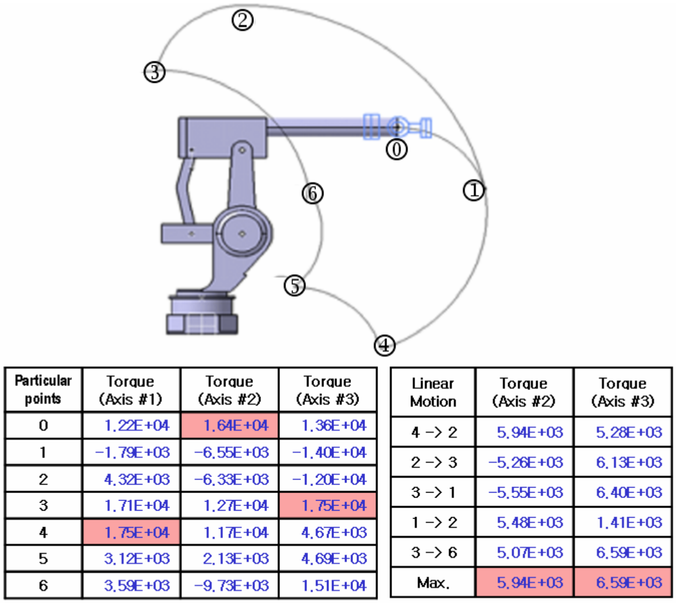
It requires both the maximum and rated capacity of the actuators to determine.

In case that robot repeats the fixed cycle, we could easily calculate the duty ratio that is one of the major factors to determine the motor capacity,

But in general case, because the duty cycle may not be fixed in some case, the maximum and rated capacity must be considered to determine as follows.

In figure 10, if we define an origin point and several particular boundary points as references, we may consider the rated torque to be the maximum torque occurred during the linear motion between arbitrary two points within these references.

Figure 11 show the changes of torques during the linear motion from the particular point 4 to point 2.



Particular points	Torque (Axis #1)	Torque (Axis #2)	Torque (Axis #3)
0	1.22E+04	1.64E+04	1.36E+04
1	-1.79E+03	-6.55E+03	-1.40E+04
2	4.32E+03	-6.33E+03	-1.20E+04
3	1.71E+04	1.27E+04	1.75E+04
4	1.75E+04	1.17E+04	4.67E+03
5	3.12E+03	2.13E+03	4.69E+03
6	3.59E+03	-9.73E+03	1.51E+04

<Max. Torque>

Linear Motion	Torque (Axis #2)	Torque (Axis #3)
4 -> 2	5.94E+03	5.28E+03
2 -> 3	-5.26E+03	6.13E+03
3 -> 1	-5.55E+03	6.40E+03
1 -> 2	5.48E+03	1.41E+03
3 -> 6	5.07E+03	6.59E+03
Max.	5.94E+03	6.59E+03

<Rated Torque>

Figure 10. Max. and rated torque at particular points

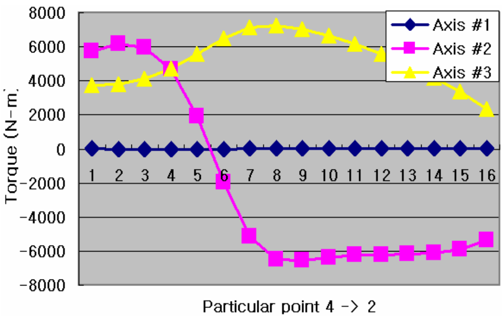


Figure 11. Torque for linear motion

C. *The result of component selection*

According to the dynamic analysis ad torque simulation, we must select the actual model of motors and reducers.

Generally, to save the cost for system construction, the applicable specification of the parts must be selected from the commercialized components.

And in other aspects, in case of motors, it must be selected according to the prepared rated and maximum value of the torque and speed (r.p.m.).

Also in case of reducers, reducing ratio and torque (maximum and rated)that were prepared in manufacturer, must be considered.

Since the motors and reducers should be work in accord, it will be better to consult the recommendations of manufacturer.

Here, selected motor and reducers of the designing manipulators shown in table 2.

In case of axis 4~ 6, axes for wrist, the motors and reducers may also be selected properly from the moment data given in table 1.

Table 2. Selected reducers and motors

	Axes No.	1st. Axis	2nd. Axis	3rd. Axis
Load	Max. Starting Torque	1.749E+04	1.640E+04	1.750E+04
	Linear Motion Torque	-	5.94E+03	6.59E+03
Reducer	Reducer Ratio	214	200	←
	Accel/Deccel Torque	2.205E+04	1.715E+04	←
	Rated Torque	8.820E+03	6.850E+03	←
Motor	Demand Max. Torque	81.65	81.88	87.37
	Demand Rated Torque	-	29.66	32.90
	Kw,(Max./Rated)	7(100/33.4)	←	←
	Speed(Max./Rated)	2000/2000	2000/2000	2000/2000

V. MISCELLANEOUS CONSIDERING POINT

Besides the selection of the core components and parts, there may exists several miscellaneous considering point as follows,

1) Study on the internal stress and displacement applied to the manipulator arm. - In general, through the FEM analysis, the thickness of the arm materials musu be adjusted, but it needs a proper compromise with the problems of the reducing weight, the stiffness of system, and absolute position error (accuracy) etc.

2) Study on the vibration problem. - Because it is mostly generated by the weak stiffness of the reducer rather than the arm material, there are no remedies in designing process. Only if that the vibration generated is less than minimum required frequency (5~10Hz approx.), it would be better to select the higher stiffness of reducer although it is sufficient in torque aspect.

3) Consider on easy assembly and disassembly - Reduce the number and sorts of small components and tools for install and maintenance. - Perfect lubrication and sealing related to the durability and IP grade. - Optimal cabling and durability - Accessibility

4) The others - Considering on the environmental condition including operating, maintenance and repairing.

VI. CONCLUSION

In this paper, we introduce the design process of heavy duty industrial robot especially on the analysis technology that we adopted to build the native model of KIMM.

Heavy duty handling robot, now on developing in KIMM, has the payload of 600Kgf. In case of 300Kgf or more in payload, the static and dynamic analysis is very essential to design the manipulator arm and to select the core components such as motors and reducers.

Although there are several commercialized software programs for analysis of kinematics and dynamics, we used the self developed software program 'RODAN' that is specialized for inverse dynamics analysis.

In his paper we introduce this program and it's applications for the analysis of heavy duty industrial robot design.

Especially, the design of the weight balancer and component selection procedure are successfully applied for the real manipulator arm of KIMM.

Mostly, we presented and explained the result of the analysis rather than theoretical background and mathematical formula.

This study is executed as a part of national project of Korean government, in cooperation with the industrial company (EMK Corp.), the full procedure of developing the robot manipulator in now on process.

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