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Analysis of Joint Compliance Effect for a Robot Manipulator

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***Abstract*— High joint stiffness is important if the robot manipulator has to be controlled for high precision of the end effector. But low joint stiffness is important when the manipulator is used where impact forces are applied to the manipulator structure. In this reason, if the mobile manipulator is used in the off-road environment, the design concept of the manipulator has to be different. In this paper, the research results on robot manipulator on the mobile platform for an off-read environment will be introduced.**

***Index Terms*— Off-road environment, Joint stiffness, Compliance, Impact, Robot manipulator.**

I. INTRODUCTION

If the mobile manipulator is used in the off-road environment, the compliance of joint is more important than the stiffness of joint. In other words, the design concept of the manipulator has to be different when it is used in the off-road environment. High joint stiffness is important if the robot manipulator has to be controlled for high precision of the end effector. But low joint stiffness is important when the manipulator is used where impact forces [1][2] are applied to the manipulator structure.

In this paper, the research results on robot manipulator on the mobile platform for an off-read environment will be introduced. In chapter 2, the concept of joint compliance for a mobile manipulator will be introduced. In chapter 3, an example to implement the joint compliance at each joint will be described. In chapter 4, the effect of compliance will be analyzed.

II. JOINT COMPLIANCE

Consider the manipulator which carries or holds the payload on its arm as shown in Figure 1. Here, a red circle means the rotational joint and a blue arrow means the vibrational force induced by the mobile platform which is moving on the paved road or off-road. Payload is carried on the lower arm of the manipulator. The payload makes reaction joint torques at each joint against the gravitational force. When the manipulator's motion is steady in the direction of up-and-down, the reaction torque is equal to the gravitational torque. When the manipulator's motion is dynamic in the direction of up-and-down, the reaction torque is greater than the gravitational torque.

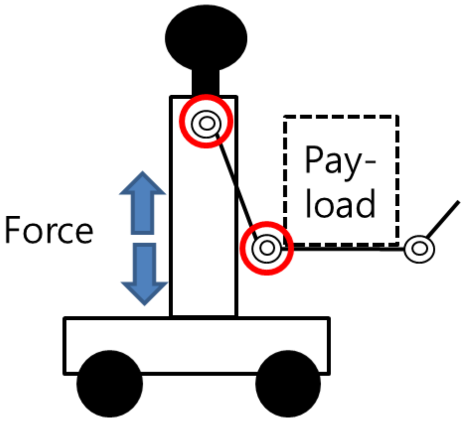

Fig.1 A mobile manipulator which carries or holds the payload on its arm

If the manipulator is moving on the well-paved road as shown in figure 2, the design concept of the manipulator is not different from the usual robot manipulator because the reaction joint torque is equal to the gravitational torque when the manipulator's motion is steady in the direction of up-and-down.

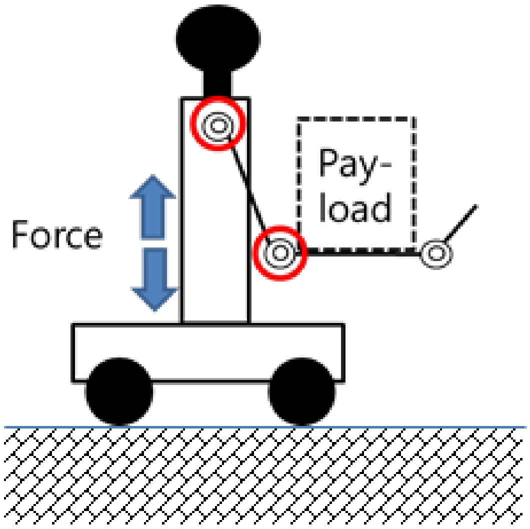

Fig.2 A mobile manipulator which carries or holds the payload on its arm on the well-paved road

In the off-road environment, the vibrational force or impact are induced to the manipulator on the mobile platform as shown in Figure 3. When the manipulator's motion is dynamic in the direction of up-and-down, the reaction torque is greater than the gravitational torque. In this case, high stiffness will make mechanical structure of the reducer (gear box) broken down because the magnitude of the vibrational force induced by the mobile platform are very big. Actually, it

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is a kind of impact force.

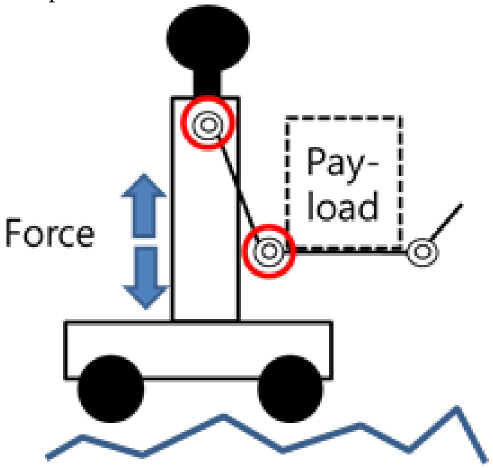

Fig.3 A mobile manipulator which carries or holds the payload on its arm on the off road

This kind of impact force is very harm to the stiffness mechanical system. In this research, a spring mechanism is added to each joint to implement compliance as shown in figure 4.

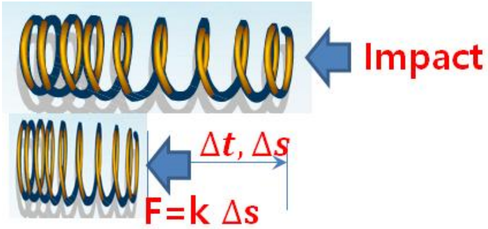

Fig.4 A spring added to each joint to implement compliance

III. IMPLEMENTATION OF JOINT COMPLIANCE

In Section 2, the design concept for the mobile manipulator for off-road environment was introduced. In this chapter, a example design will be introduced. To implement joint compliance, an actuator, a 1st reducer, a 2nd reducer, a compliance mechanism, a 1st encoder, a 2nd encoder and a controller are used in this example. A compliance mechanism can be placed between the 1st reducer and 2nd reducer. The detail description will be explained as bellows;

- Actuator: Usually BLDC motors can be used as an actuator and it has the 1st Encoder system to measure the motor rotation angle. The example in this paper includes a 1st reducer, a 2nd reducer, a compliance mechanism, a 2nd encoder, a controller.
- 1st Reducer: The rotation of a BLDC motor is reduced by the 1st reducer. A harmonic driver is used as the 1st reducer. Usually gear ratio is 50 to 160. A kind of spring, shown in figure 4, has to be used to make compliance. It can be easily place between the 1st reducer and 2nd reducer. The authors suggest a harmonic drive for 1st reducer and worm-wheel-mechanism for 2nd reducer.
- 2nd Reducer: As mentioned above, a worm-wheel-mechanism can be good choice. The 1st reducer is conned to the worm and the worm rotate the wheel. The efficiency of a worm & wheel mechanism is very low. But it has the property of the “self-locking”. Self-locking means the manipulator motion can be locked although unexpected moments are applied to the robot manipulator. This means that the vibrational force induced by mobile platform moving on the off-road cannot make the input rotation (worm rotation), thus the BLDC motor doesn’t have to generate the reaction control torque to get over the vibrational force caused by the off-road. As a result, the total energy consumption is reduced. Reaction torque at each joint has to be absorbed by the structure because it is impact or shock and it can make the 1st and 2nd reducer broken down. The mechanical reducer (worm-wheel) cannot absorb this kind of impact or shock because a wheel of worm-wheel mechanism is made of bronze-steel alloy or aluminum-steel alloy and it has very good property of the low friction but are very weak.
- Compliance mechanism: In this reason, an additional compliance mechanism has to be added to absorb the reaction torque induced by the off-road. So a compliance mechanism is needed. A kind of spring, shown in figure 4, has to be used to make compliance. It can be easily place between the 1st reducer and 2nd reducer. The authors suggest a harmonic drive for 1st reducer and worm-wheel-mechanism for 2nd reducer. The compliance mechanism can be implemented using a spring and damper.
- 2nd Encoder: The compliance mechanism makes the vibrational force absorbed. The compliance mechanism also makes the undesirable deformation. This deformation makes it difficult to control the manipulator because the deformation cannot be measured using the 1st encoder equipped on the 1st actuator. In this reason, the 2nd encoder to measure real rotation of the joint. It can be equipped on the 2nd reducer (worm-wheel mechanism). The motor rotation is measured by the the 1st encoder equipped on the BLDC motor and the output rotation of the worm-wheel gear is measured by the 2nd encoder equipped on the worm-wheel gear mechanism.
- Controller: The measured angles (a motor rotation and a worm-wheel gear rotation) can be used for the 2 different purposes. The first purpose is to measure the rotational deformation of the manipulator and to compensate it. The other purpose is to predict the joint reaction torque. The worm-wheel mechanism is used for “self-locking” to increase the energy efficiency of the total system. But this kind of “self-locking” makes it impossible to guess the actual reaction joint torque with the information of the measured current of the BLDC motor. The torque sensor equipped on the worm-wheel gear mechanism can be alternative. But it is not easy to implement the equipment of a torque

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sensor at each joint. The 2nd encoder is the better way. It is easy to equip the rotational 2nd encoder on the worm-wheel mechanism. Also, it is possible to calculate the reaction torque using the difference of the measured two angles of the 1st encoder rotation and the 2nd encoder rotation if the spring constant of the passive compliance is known.

IV. COMPLIANCE EFFECT

To design the real actuation module, the effect of the compliance has to be analyzed to determine how much compliance is needed for the designed robot manipulator on the mobile platform for off-road travel. For this purpose, a series of simulations are performed. In this chapter, it is supposed that the vibrational motion in up-and-down direction applied to the mobile platform as shown in figure 1.

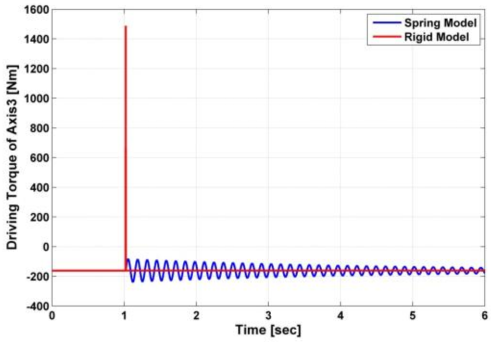

Fig. 5 Reaction torque response: (Red line) the reaction torque in the case of the rigid joint (Blue line) the reaction torque in the case of the compliant joint.

The reaction torque response is simulated. Figure 5 shows the simulation result when a 5G impulse is applied to the torso of the manipulator. In the figure, “Red line” means the reaction torque in the case that the each joint is rigid without any compliant mechanism. “Blue line” means the vibrational reaction torque in the case that the compliance mechanism is equipped on each joint. The dramatic absorb of the impact force is shown when the additional compliance is added to each joint. But absolutely, the additional compliance necessarily generates the static or dynamic deflection and it makes difficult to be controlled.

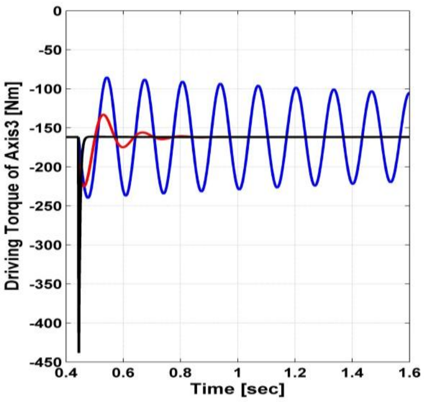

Fig. 6 Reaction torque response: Rotational joint stiffness is K=10000Nm/rad

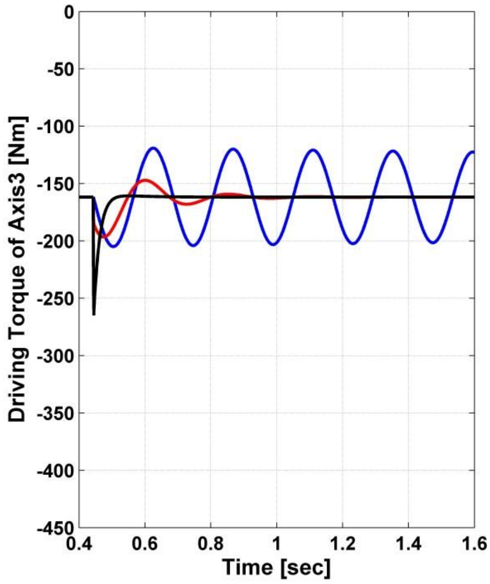

Fig. 7 Reaction torque response: Rotational joint stiffness is K=3000Nm/

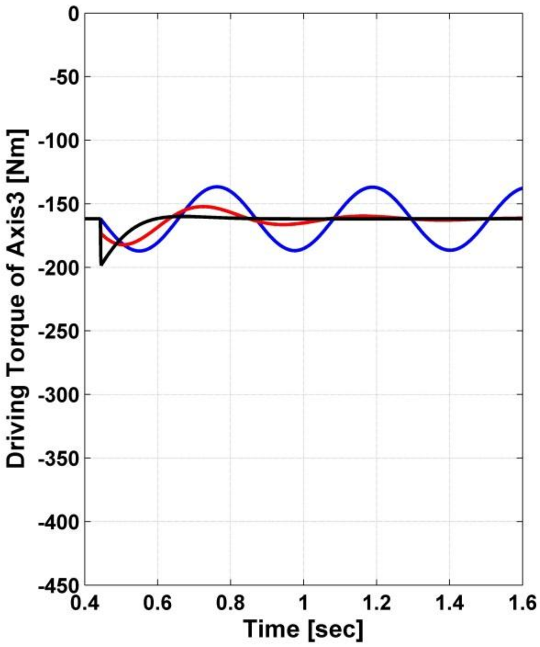

Fig. 8 Reaction torque response: Rotational joint stiffness is K=1000Nm/rad

Figure 6 shows the reaction torque response when the joint rotational stiffness is K=10000Nm/rad. In this case, static deflection is 7mm and natural frequency is 7.5Hz. “Blue line” is the reaction torque when the damping is near zero. In this case, the max reaction torque is 148% of the static torque. “Red line” is the reaction torque when the damping is proper. “Black line” is the reaction torque when the damping is very high.

Figure 7 shows the reaction torque response when the joint rotational stiffness is K=3000Nm/rad. In this case, static deflection is 23mm and natural frequency is 4.1Hz. “Blue

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line" is the reaction torque when the damping is near zero. In this case, the max reaction torque is 126% of the static torque. "Red line" is the reaction torque when the damping is proper. "Black line" is the reaction torque when the damping is too much.

Figure 8 shows the reaction torque response when the joint rotational stiffness is K=1000Nm/rad. In this case, Static deflection is 70mm and natural frequency is 2.3Hz. "Blue line" is the reaction torque when the damping is near zero. In this case, the max reaction torque is 115% of the static torque. "Red line" is the reaction torque when the damping is proper. "Black line" is the reaction torque when the damping is too much.

It is clear that the high stiffness (low compliance) makes small static deflection and the high natural frequency. Also it is clear that the low stiffness (high compliance) makes small big deflection and the low natural frequency. Finally, it is clear that the excessive damping makes the excessive reaction torque.

V. CONCLUSION

For the mobile manipulator used in the off-road environment, the compliance of joint is more important than the stiffness of joint. In this reason, if the mobile manipulator is used in the off-road environment, the design concept of the manipulator has to be different. In this paper, the research results on robot manipulator on the mobile platform for an off-read environment were introduced. In chapter 2, the concept of joint compliance for a mobile manipulator was introduced. In chapter 3, an example to implement the joint compliance at each joint was introduced. In chapter 4, the effect of compliance was shown.

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Doohyeong Kim received Ph.D degree in Mechanical Engineering from KAIST, KOREA. He has been working for Korea Institute of Machinery and Materials (KIMM), Korea, since 1982, where he is currently a principal researcher. His research fields includes design and control of heavy payload manipulators and a wire-driven mechanism for a light weight dual arm robot manipulator for industrial applications

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