Stable Control of Robotic Manipulator with Collision Phenomena*

(Positioning of Multi-Degrees-of-Freedom Linear Manipulator)

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In this paper, a methodology using the Lyapunov direct method is proposed for analyzing the stability of an n -D.O.F. linear manipulator system, which is positioned on a flexible wall, using the collision phenomena. A methodology for determining the control law which guarantees the stability of the manipulator is also discussed. As collision is a phenomenon involving energy dissipation, it is used in industry for such purposes as suppressing vibrations. On the other hand, in the field of robotics, this phenomenon is considered ought to be avoided, because the controllability of the system becomes poorer at contact. However, in the case where the demand for rapid manipulation in the environment increases, collision becomes an essential problem which must be addressed. In our previous reports, some approaches using the Lyapunov method were discussed. In this report we expanded the manipulator complexity to n -D.O.F. and proved the stability of the system even in the case of collision. Some numerical simulations were also executed to demonstrate the transient behavior of the system and to allow comparison with the results of the theoretical analysis.

Key Words: Stability, Stable Control, Multi-Degrees-of-Freedom, Manipulator, Collision, Lyapunov Method, Simulation

1. Introduction

The current development of robotics is remarkable. In particular, this is true in the research field of sensor-based robots or advanced controlled robots and also in the field of industrial robots working in automated factories^{(1),(2)}. In general, these robots work on environment, when they perform any tasks. For example, manipulators grasp or handle objects. In such operations, contact and/or other interaction occur between manipulators⁽³⁾⁻⁽⁵⁾. Typically, the robots or manipulators are controlled using different control laws in the state before, during and after contact, or are controlled slowly as in a so-called

“guarded motion” in tele-operation to avoid rapid contact or collision⁽⁶⁾, and to avoid quick changes in control laws.

On the other hand, demands are increasing for robots capable of faster movement in the attempt to improve efficiency for the total working system. As the speed of free movement of robots increases, the total time for the manipulator's task will be dominated mainly by the time at the phase of contact. This implies that collision is potentially a major problem to be solved, since contact between a robot and the environment becomes a collision if the motion is fast enough upon contact.

From the physical viewpoint, collision is a phenomenon which makes the system more stable due to the existence of energy dissipation. This phenomenon is used to effectively suppress vibrations in industry. In contrast, in the field of robot control, collision has been treated as a disturbance to the system and avoided in most cases, because it reduces controllability. However, the number of cases in which we cannot avoid the phenomenon has been steadily increasing, as the payload becomes larger in comparison with the stiffness of robots.

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Based on this increasing demand, we have reported some solutions to the collision problems. These studies focus mainly on stability for tasks such as positioning of 1-D.O.F. manipulators with collision phenomena⁽⁷⁾, grasping by a pair of 1-D.O.F. manipulators⁽⁸⁾ or positioning of multi-link manipulators⁽⁹⁾.

In this paper, a methodology using the Lyapunov direct method is proposed for analyzing the stability of a multi-D.O.F. linear manipulator system, which is positioned on a flexible wall, with collision phenomena. In this area of research, some studies which deal with contact problems are available^{(10),(11)}. The linear system in this paper represents not only the linear connection of a mass-spring-damper model manipulator but also a system which is described by linear equations of motion. Examples of this type are a grinder which is forced to a work or an inverted pendulum. With these problems, a methodology for determining the control law of the manipulator which guarantees the system stability is also discussed. Some numerical simulations are also executed to show the transient behavior of the system and to verify the results of the theoretical analysis. As a result, it is shown that a linear manipulator which becomes a nonlinear system due to the collision phenomena can be stably controlled and also that the collision can be utilized to stabilize the nonlinear manipulator-object system.

2. System Stability

In this paper, a mathematical model of the linear multi-degrees-of-freedom manipulator is established as shown in Fig.1 and is described as a linear matrix equation. The problem is to position this manipulator on a flexible wall. The object (wall) is assumed to be expressed as a mass-spring-damper-actuator system and has one D.O.F. in the direction normal to the wall surface. The impact/contact force is assumed to occur due to the local deformations of the manipulator end point and the wall, and it is modeled by the widely used Hertzian force with a nonlinear energy dissipation term. The impact/contact force is always

Fig. 1 General model of linear systems with object

non-negative and the bouncing direction is assumed to be its positive direction.

2.1 Mathematical model and equations of motion

The system is formulated using the following linear system equation.

$$\dot{x} = A^*x + Fx + df_w \quad (1)$$

where x is the state vector, A^* is the system matrix, F is the feedback gain matrix, f_w is the impact/contact force, and d is the constant coefficient vector. As shown in the equation, it is obvious that the control law is linear feedback. When Eq. (2) is satisfied,

$$A = A^* + F \quad (2)$$

Equation (1) can be rewritten as the following equation.

$$\dot{x} = Ax + df_w \quad (3)$$

Here, each term of Eqs. (1) and (3) is described as follows:

$$x = \{x_b \quad x_1 \cdots x_n \quad \dot{x}_b \quad \dot{x}_1 \cdots \dot{x}_n\}^T \quad (4)$$

$$A^* = \begin{bmatrix} 0 & I \\ A_{21} & A_{22} \end{bmatrix} \quad (5)$$

$$F = \begin{bmatrix} 0 & 0 \\ F_{21} & F_{22} \end{bmatrix} \quad (6)$$

$$f_w = \begin{cases} (1 + p\dot{u})Hu^{3/2} & (u \geq 0, \dot{u} \geq -1/p) \\ 0 & (\text{otherwise}) \end{cases} \quad (7)$$

where,

$$u = x_1 - x_b \quad (8)$$

$$d = \left\{ 0 \ 0 \cdots 0 \quad \frac{1}{m_b} - \frac{1}{m_1} \ 0 \cdots 0 \right\}^T \quad (9)$$

From Eq. (2), the following matrix is obtained.

$$A = \begin{bmatrix} 0 & I \\ A_{21} + F_{21} & A_{22} + F_{22} \end{bmatrix} \quad (10)$$

Eq. (7) is a collision model proposed by Fujita⁽¹²⁾, and in the equation, p is a non-negative energy dissipation parameter. Thus, $p=0$ means perfect elastic collision, and when $p>0$, the collision results in energy loss. In the same equation, H is the coefficient of Hertzian force, and is theoretically positive with a high value. In this paper, because the collision is assumed to be of finite duration, Eq. (7) is employed, since it is considered to be most suitable for this purpose. From the conditions of the equation, the system in the conditions of $u \geq 0$ and $du/dt \geq -1/p$ is assumed to be in a contact state; otherwise, a non-contact state is assumed.

2.2 System stability analysis

The stability of the system which accommodates collision is discussed using the Lyapunov method. In order to apply the method, the following scalar function in quadratic form is developed as a candidate for the Lyapunov function.

$$V = x^T P x \quad (11)$$

where,

$$P = P_{nc} + P_c = P^T > 0 \quad (12)$$

P_{nc} is a constant matrix which does not include any collision terms, and P_c is a time-varying matrix which consists only of collision terms. These two matrices are expressed in the following forms.

$$P_{nc} = \begin{bmatrix} P_{nc1} & P_{nc2}^T \\ P_{nc2} & P_{nc3} \end{bmatrix} = P_{nc}^T > 0 \quad (13)$$

$$P_c = \begin{bmatrix} \Delta k & -\Delta k & 0 & \cdots & 0 \\ -\Delta k & \Delta k & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} = P_c^T \geq 0 \quad (14)$$

where,

$$\Delta k = \begin{cases} aHu^{1/2} & (u \geq 0, \dot{u} \geq -1/p) \\ 0 & (\text{otherwise}) \end{cases} \quad (15)$$

Here, a is an appropriate positive constant coefficient, which shows the system stability, if it is determined by a certain manner. In this sense, it is not a control value. If we consider all the above equations, the following equation is obviously satisfied.

$$\dot{V} = \mathbf{x}^T P \dot{\mathbf{x}} \geq 0 \quad (16)$$

We define the partial matrices P_{nci} ($i=1, 2, 3$) of Eq. (13) as Eq. (17).

$$P_{nci} = \begin{bmatrix} p_{nci-bb} & p_{nci-b1} & \cdots & p_{nci-bn} \\ p_{nci-1b} & p_{nci-11} & \cdots & p_{nci-1n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{nci-nb} & p_{nci-n1} & \cdots & p_{nci-nn} \end{bmatrix} \quad (17)$$

($i=1, 2, 3$)

In order to analyze the system stability by the Lyapunov method, the scalar function is differentiated, and the following derivative is obtained.

$$\begin{aligned} \dot{V} &= \dot{\mathbf{x}}^T P \mathbf{x} + \mathbf{x}^T \dot{P} \mathbf{x} + \mathbf{x}^T P \dot{\mathbf{x}} \\ &= \mathbf{x}^T (A^T P_{nc} + P_{nc} A) \mathbf{x} + 2f_w \mathbf{d}^T P_{nc} \mathbf{x} \\ &\quad + \mathbf{x}^T \dot{P}_{nc} \mathbf{x} + \mathbf{x}^T (A^T P_c + P_c A) \mathbf{x} \\ &\quad + 2f_w \mathbf{d}^T P_c \mathbf{x} + \mathbf{x}^T \dot{P}_c \mathbf{x} \end{aligned} \quad (18)$$

The six terms on the right-hand side of Eq. (18) are discussed individually below.

First Term. Because this term is the same as the well-known judgment of manipulator stability in the absence of collision, it is sufficient that the following equations are satisfied.

$$A^T P_{nc} + P_{nc} A = -Q \quad (19)$$

$$Q > 0 \quad (20)$$

Second Term. The coefficient of the impact/contact force f_w is written as in the following equation.

$$\begin{aligned} \mathbf{d}^T P_{nc} \mathbf{x} &= \frac{1}{m_b} \left\{ P_{nc2-bb} x_b + P_{nc3-bb} \dot{x}_b \right. \\ &\quad \left. + \sum_{j=1}^n P_{nc2-bj} x_j + \sum_{j=1}^n P_{nc3-bj} \dot{x}_j \right\} \\ &\quad - \frac{1}{m_1} \left\{ P_{nc2-1b} x_b + P_{nc3-1b} \dot{x}_b \right. \\ &\quad \left. + \sum_{j=1}^n P_{nc2-1j} x_j + \sum_{j=1}^n P_{nc3-1j} \dot{x}_j \right\} \end{aligned} \quad (21)$$

Third Term. As P_{nc} is a constant matrix, the follow-

ing form is satisfied.

$$\mathbf{x}^T \dot{P}_{nc} \mathbf{x} = 0 \quad (22)$$

Fourth Term. When matrices are substituted with appropriate equations and then arranged, the following equation is obtained.

$$\begin{aligned} \mathbf{x}^T (A^T P_c + P_c A) \mathbf{x} &= 2\Delta k (x_1 - x_b)(\dot{x}_1 - \dot{x}_b) \\ &= 2\Delta k u \dot{u} \end{aligned} \quad (23)$$

It is obvious that this term is not related to the matrix A .

Fifth Term. After substitution and calculation, the fifth term satisfies the following equation.

$$2f_w \cdot \mathbf{d}^T P_c \mathbf{x} = 0 \quad (24)$$

Sixth Term. This term is calculated as follows:

$$\mathbf{x}^T \dot{P}_c \mathbf{x} = (\dot{\Delta k})(x_1 - x_b)^2 = (\dot{\Delta k})u^2 \quad (25)$$

This term is also understood not to be related to matrix A .

Here, the second to the sixth term describe the collision effect. If the sum of all these terms is nonpositive and Eqs. (19) and (20) are satisfied, $dv/dt \leq 0$ is shown.

The above conditions in the state of contact and noncontact are considered separately hereafter.

Noncontact State. In the case of the noncontact state, the sum of 5 terms expressed in the Eqs. (21) through (25) is zero. This indicates that Eqs. (19) and (20) provide the sufficient conditions for the system stability.

Contact State. For the contact state, the sum is discussed in greater detail below.

First, the sum of the third term through the sixth term is written as the following equation.

$$\begin{aligned} 2\Delta k u \dot{u} + (\dot{\Delta k})u^2 &= 2aHu^{3/2}\dot{u} + \frac{1}{2}aHu^{-1/2}\dot{u}u^2 \\ &= \frac{5}{2}aHu^{3/2}\dot{u} \end{aligned} \quad (26)$$

If the following relation is satisfied for the second term,

$$\mathbf{d}^T P \mathbf{x} = -b\dot{u} \quad (b = \text{const.}, b > 0) \quad (27)$$

the sum of the second term through the sixth term becomes as follows:

$$\begin{aligned} -2f_w \cdot b\dot{u} + \frac{5}{2}aHu^{3/2}\dot{u} \\ = -2bpHu^{3/2}\dot{u} - \left(2b - \frac{5}{2}a\right)Hu^{3/2}\dot{u} \end{aligned} \quad (28)$$

In Eq. (28), if a satisfies Eq. (29), $\dot{V} \leq 0$ is true.

$$a = \frac{4}{5}b \quad (29)$$

In the above derivation, the key assumption is Eq. (27). Because all terms other than dx_1/dt and dx_b/dt must be zero to satisfy Eq. (27), the following 4 equations are derived.

$$\frac{p_{nc2-bb}}{m_b} - \frac{p_{nc2-1b}}{m_1} = 0 \quad (30)$$

$$\frac{p_{nc2-bj}}{m_b} - \frac{p_{nc2-1j}}{m_1} = 0 \quad (j=1, 2, \dots, n) \quad (31)$$

$$\frac{\dot{p}_{nc3-bj}}{m_b} - \frac{\dot{p}_{nc3-1j}}{m_1} = 0 \quad (j=2, 3, \dots, n) \quad (32)$$

$$\frac{\dot{p}_{nc3-b1}}{m_b} - \frac{\dot{p}_{nc3-11}}{m_1} = -\left(\frac{\dot{p}_{nc3-bb}}{m_b} - \frac{\dot{p}_{nc3-1b}}{m_1}\right) < 0 \quad (33)$$

Stable Condition. From the discussion above, the condition for the system stability are considered to satisfy Eqs. (13), (14), (19), (20) and (30) through (33).

We determine the matrices P , F_{21} and F_{22} which satisfy the stable conditions, checking the 8 equations for stability one by one.

(a) Eq. (14) is always satisfied.

(b) From Eqs. (30) and (31), we assume Eq. (34) to simplify the problem.

$$P_{nc2} = 0 \quad (34)$$

In this case, Eq. (13) is rewritten in the following form.

$$P_{nc} = \begin{bmatrix} P_{nc1} & 0 \\ 0 & P_{nc3} \end{bmatrix} > 0$$

From this equation Eqs. (35) and (36) must be satisfied.

$$P_{nc1} = P_{nc1}^T > 0 \quad (35)$$

$$P_{nc3} = P_{nc3}^T > 0 \quad (36)$$

(c) From Eqs. (19) and (20), the matrix Q is determined.

$$\begin{aligned} Q &= -(A^T P_{nc} + P_{nc} A) \\ &= \begin{bmatrix} 0 \\ -P_{nc1} - P_{nc3}(A_{21} + F_{21}) \\ -P_{nc1} - (A_{21}^T + F_{21}^T)P_{nc3} \\ -(A_{22}^T + F_{22}^T)P_{nc3} - P_{nc3}(A_{22} + F_{22}) \end{bmatrix} \end{aligned} \quad (37)$$

For the positive definite Q , the following two equations must be satisfied.

$$P_{nc1} + P_{nc3}(A_{21} + F_{21}) = P_{nc1} + (A_{21}^T + F_{21}^T)P_{nc3} = 0 \quad (38)$$

$$(A_{22}^T + F_{22}^T)P_{nc3} + P_{nc3}(A_{22} + F_{22}) < 0 \quad (39)$$

The condition under which the above two equations can be solved is represented by the following two equations.

$$A_{21} + F_{21} = A_{21}^T + F_{21}^T < 0 \quad (40)$$

$$A_{22} + F_{22} = A_{22}^T + F_{22}^T < 0 \quad (41)$$

In other words, if P_{nc3} calculated based on these equations satisfies Eqs. (32) and (33), Eqs. (40) and (41) are the sufficient conditions for the existence of a Lyapunov function and for the system stability in the sense of Lyapunov. These are also the condition required to make the first term of Eq. (18) nonpositive and the sum of the second term through the sixth nonpositive. This indicates that the derivative of the Lyapunov function is smaller in the case which considers collision than that which does not. In other words, the collision phenomena contribute to the stability of the system.

2.3 Example of stable control law

We consider a system such as is represented in Fig. 2. One example of this kind of system is a linear

manipulator positioned on a deformable wall. The manipulator consists of a number of so-called Voigt models, or mass-spring-damper elements, and actuators set parallel to springs and dampers, and the wall also consists of a mass-spring-damper-actuator element. This problem considers collision between the manipulator and the wall during positioning and thus becomes a nonlinear problem. We discuss the conditions required for stability or the control law of this system.

In this problem, the system matrix in Eq. (5) is written as in Eq. (42).

$$A_{21} = -M^{-1}K, A_{22} = -M^{-1}C \quad (42)$$

where,

$$K = K^T > 0, C = C^T > 0 \quad (43)$$

Linear state feedback is assumed to be the control law, and is formulated in the following manner:

$$F_{21} = -M^{-1}K_p, F_{22} = -M^{-1}K_v \quad (44)$$

From Eqs. (40) and (41), the following two matrices are the solution for the stable control law.

$$K_p = K_p^T \geq 0, K_v = K_v^T \geq 0 \quad (45)$$

In this case, there exists a Lyapunov function which is defined in quadratic form with the partial matrices described by Eq. (46).

$$P_{nc1} = K + K_p, P_{nc3} = M \quad (46)$$

Here, Eq. (46) satisfies all the stable conditions.

From the physical point of view, with this control law, every mass has an actuator and the force is controlled with coupling other mass displacements and velocities. This control law is effective only in the case where many of the masses have actuators. The applicability of the law is limited, if the number of actuators is small in comparison to the number of the masses. Another control law will be discussed for the case where only one mass has the force control actuator considering the stability condition.

The manipulator model shown in Fig. 2 is modified and employed. The manipulator has only one actuator between the base and the mass (f_n) which is closest to the base. The other actuators are neglected. This is considered to be a model of a cue for billiards. In this problem, a Lyapunov function can be defined with the following matrices as the control law.

Fig. 2 Linear manipulator model

$$K_p = \begin{bmatrix} & 0 & 0 \\ 0 & \vdots & \vdots \\ 0 \cdots 0 & k_{p(n-1)} & k_{pn} \end{bmatrix} \neq K_p^T \quad (47)$$

$$K_v = \begin{bmatrix} & 0 & 0 \\ 0 & \vdots & \vdots \\ 0 \cdots 0 & k_{v(n-1)} & k_{vn} \end{bmatrix} \neq K_v^T \quad (48)$$

These matrices are rewritten as the following formula.

$$f = -k_{p(n-1)}x_{n-1} - k_{pn}x_n - k_{v(n-1)}\dot{x}_{n-1} - k_v\dot{x}_n \quad (49)$$

According to the above equation, the system stability in the sense of Lyapunov is guaranteed. However, in this case, the system, or the control law, must satisfy the following conditions to comply with Eqs. (35) and (36).

$$k_{n-1} - k_{(n-1)} > 0 \quad (50)$$

$$k_n + k_{p(n-1)} + k_{pn} > 0 \quad (51)$$

$$c_{n-1} + c_n + k_{vn} > 0 \quad (52)$$

$$\frac{c_{n-1}k_{n-1}(c_{n-1} + c_n + k_{vn})}{k_{n-1} - k_{p(n-1)}} - \left\{ \frac{k_{n-1}(c_{n-1} - c_{n-1} - k_{v(n-1)})}{2(k_{n-1} - k_{p(n-1)})} \right\}^2 > 0 \quad (53)$$

In the above discussion, the possibility has been shown to exist theoretically for the stable control problem with nonlinearity due to collision between the manipulator and the object, and a methodology has been proposed for the determination of control feedback gains.

3. Simulation

Transient response of the system is as important for control as the stability. In this section, we will verify the analytical results mentioned in the previous section and discuss the transient behavior of the system using numerical simulations. In the simulations, a 3-degrees-of-freedom (D.O.F.) system is treated as the numerical model, shown in Fig. 2 and explained in the last example of the previous Lyapunov analyses.

3.1 Simulation method

Eq. (1) is directly integrated using the 4th order Runge-Kutta method with the consideration of Eqs. (5), (6), (7), (42), (44), (47) and (48). Here, the manipulator and the wall are treated as independent systems. They are not considered to be connected in structure, but apply impact/contact forces to each other. The force is determined by the relative displacement and the relative velocity between the two systems.

3.2 Boundary condition

Judgment of the state as being either contact or noncontact in nature is based on the relative displacement and the relative velocity in between the manipulator and the wall. Namely, both at the beginning and

the end of each increment during Runge-Kutta integration, the nature of the states as contact or non-contact is judged. If the states are the same, the boundary condition on the state is fixed. However, if they are different, the exact time of the state change is approximated by linear interpolation of the two states at the beginning and the end of the increment, and the condition is switched from contact to non-contact and vice versa at the estimated changing time. Throughout the integration, the only difference in the boundary condition is whether or not the impact/contact force is zero.

3.3 Simulation results

The dynamic parameters of the system are shown in Table 1, and the simulation results are plotted as shown in Fig. 3 through Fig. 6.

The plot in Fig. 3 represents stable behavior of the manipulator under a certain feedback control which does not satisfy the control law expressed by Eqs. (44) and (45) in the absence of collision. The manipulator is understood to be controlled to be stable by the conventional feedback determination. The plot in Fig. 4 shows the behavior of the manipulator when collision occurs. The control law is the same as in the previous simulation. The plot shows that the system diverges and stable positioning is not achieved using the feedback gains. The Lyapunov method essentially provides the sufficient condition, and it is possible to control a system stably, even if the control

Fig. 3 Manipulator response in the absence of collision not satisfying stable conditions

law does not satisfy the sufficient stability condition. However, if such a control law is used, the system sometimes shows instability due to collision as indicated above. On the other hand, Fig.5 shows an example of the system behavior under the control law which satisfies the stability condition derived from

Tfble 1 Simulation parameters

Sub-script	Mass	Spring Const.	Damping Coef.
	m (kg)	k (N/mm)	c (Ns/mm)
1	1.0	10.0	0.1
2	1.0	10.0	0.05
3	0.5	5.0	0.1
b	5.0	200.0	0.05
Hertz Coef.		H	10000.0

Fig. 4 Response in case of collision not satisfying stable conditions using the same manipulator as in Fig. 3

Eqs.(44) and (45). As estimated by the theoretical analysis in the former section, the stable transient response is obtained. The plot of Fig.6 shows the response of the same manipulator as in Fig.5 using the same control law in the absence of collision. When comparing these two figures, we observe the superior convergence in the collision case during overshooting and recovering to the desired position. This difference indicates that the collision phenomena can be used in the control of manipulator positioning to shorten the convergence time, if the appropriate control law is employed.

From the results discussed above, a system which satisfies the conditions defined by Eqs. (44) and (45) is guaranteed to be stable, and the collision phenomena sometimes have stabilization effects on the system under the stability condition.

4. Conclusions

In this paper we discussed theoretically the stability of positioning of a multi-degrees-of-freedom

Fig. 5 Response in case of collision satisfying stable conditions

Fig. 6 Response in the absence of collision satisfying stable conditions using the same manipulator as in Fig. 5

manipulator on the wall using the Lyapunov method, and discussed the transient response of positioning by means of numerical simulations. The following results are obtained:

(1) The Lyapunov direct method is effective for analyzing the stability of a multi-D.O.F. manipulator system even in the case of collision.

(2) Stable contact control of a multi-D.O.F. manipulator can be guaranteed by linear feedback control, and the methodology for determining the control law is proposed.

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