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Total Harmonic Distortion and Content Rate of Spatial Modal Information for Haptic Parallel Motion Analysis

In this paper, two kinds of evaluation index for the haptic motion analysis in parallel multiple degrees–of–freedom (MDOF) system are proposed. At first, the spatial modal decomposition method based on discrete Fourier series expansion (DFS) is presented. Spatial modal information expresses a motion element that corresponds to a specific physical action. The spatial modal information can mathematically be defined by the Fourier coefficients. Then, this paper proposes the total harmonic distortion (THD) and the content rate of the haptic modal information as motion evaluation indexes. THD of the spatial modal information can evaluate the complexity of the human motion and/or the deformability of the contact environment. Content rate of the spatial modal information can evaluate the priority of motion element. Some experimental results on the bilateral motion control of a parallel five DOF haptic system are shown, in order to confirm the utility of the proposed indexes.

Key words: Discrete fourier series expansion, Haptics, Modal decomposition, Motion control

Ukupno harmoničko izobličenje i brzina prostorne modalne informacije za analizu haptičkog paralelnog gibanja. U ovom radu predložena su dva indikatora vrednovanja haptičkog gibanja u paralelnom sustavu s više stupnjeva slobode. Prikazana je metoda prostorne modalne dekompozicije zasnovana na proširenom diskretnom Fourierovom redu. Prostorna modalna informacija predstavlja element koji odgovara specifičnoj fizikalnoj radnji. Prostorna modalna informacija matematički se može opisati koristeći Fourierove koeficijente. U ovom se radu kao indikatori za evaluaciju gibanja predlažu ukupno harmoničko izobličenje i brzina haptičke modalne informacije. Ukupnim harmoničkim izobličenjem prostorne modalne informacije može se ocijeniti kompleksnost ljudskog gibanja i/ili deformabilnost kontaktne okoline. Przina prostorne modalne informacije ocjenjuje prioritet elementa u gibanju. Kako bi se potvrdila korisnost predloženih indikatora vrednovanja prikazani su eksperimentalni rezultati dobiveni dvoosnim prostornim upravljanjem paralelnim haptičkim sustavom s pet stupnjeva slobode.

Ključne riječi: proširenje diskretnog Fourierovog reda, haptika, modalna dekompozicija, upravljanje gibanjem

1   INTRODUCTION

The analysis of the dexterity and the flexibility in human physicality is significant for the design and the development of intelligent human support systems. The advanced computer vision technology can realize the human motion capture [1] and the vision–based motion analysis [2]. The sensor and actuator technology can realize the human motion sensing [3] and the physical support based on biological information [4,5]. Biomechanical knowledge about human physicality can enhance the human–system–interaction [6]. For the further comprehension of human physicality, it is expected that not only movement but also strength of force in human motion is analyzed by the engineering approach.

Highly transparent bilateral system can realize not only the transmission of haptic sensation but also the decou-pling detection of the action force and the reaction force [7]. Bilateral motion control has widely been researched as one of the important control methods for the realization of precise teleoperation for more than five decades [8]. In recent years, the acceleration–based bilateral control theory has been proposed [9]. It has been demonstrated that this bilateral control theory can attain high transparency. Then, the applications of the principle of acceleration–based bilateral control are expected to advance the motion control technology for a haptic communication over the network [10], a high precision micro manipulation [11, 12], a novel skill preservation [13], an innovative medical treatment system [14], and so on.

One of the keys for the realization of haptic analysis of human motion is the development of multiple degrees–of–freedom (MDOF) haptic system with high transparency.

If a motion system has much DOF, the whole motion would be quite complicated. Then, how to catch the physical meaning of each motion element in the complicated MDOF motion will be significant for the design of the effective and efficient motion controller. The modal decomposition method is one of the effective motion description methods for a parallel MDOF motion systems. The modal information extracted by the modal decomposition method can express the spatial element of the complicated motion. In the past, the modal decomposition method based on Hadamard matrix was applied to the motion control of the biped robot [15]. However, Hadamard matrix can be applied to the modal decomposition only for a motion system with 2^n DOF. Then, Hadamard matrix was expanded to Quarry matrix [16]. However, Quarry matrix was not mathematically generalized for the arbitrary number of modes. Then, the mathematical approach based on discrete Fourier transformation (DFT) was established [17]. DFT–based modal decomposition method can extract any number of modes. However, an additional information conversion from the complex number to the real number was required for the extraction of motion modes which have physical meanings. In addition, if the arrangement of sensing points does not have spatial linearity and symmetry, these conventional methods cannot easily extract the motion modes. Then, the modal decomposition method based on discrete Fourier series expansion (DFS) has been proposed [18, 19]. This method can mathematically be generalized for the extraction of arbitrary number of motion modes. In addition, this decomposition method can simply extract motion modal information only from the calculation of real number. Even if the arrangement of sensing points does not have spatial linearity and symmetry, DFS–based method can be applied to the modal decomposition. In the modal decomposition based on DFS, the parallel motion can be regarded as the combination of the spatial waves. The modal information is naturally determined by the Fourier coefficients.

The modal decomposition method is so effective for the controller design in a parallel MDOF system. The similar approach in the motion systems with multiple sensors has been reported [20, 21]. Although the modal decomposition for the description of the complicated parallel motion has been researched, there is few researches on how to quantitatively evaluate the motion on the basis of the decomposed modal information. Then, this paper proposes the total harmonic distortion (THD) and the content rate of modal information as the evaluation indexes for the complicated parallel motion. The THD of the spatial modal information can evaluate the complexity of the human motion and/or the deformability of the contact environment. On the other hand, the content rate of the spatial modal information can evaluate the priority of motion element.

This paper describes the details of the proposed indexes which are partly presented at the past conference [19]. The DFS–based modal decomposition is applied to the analysis of human fingertip motion through the parallel five DOF haptic system. Then, the utility of the proposed evaluation indexes is discussed from the newly demonstrated experimental results.

The organization of the paper is as follows. In section 2, acceleration–based bilateral motion control method is briefly introduced. The modal decomposition method based on DFS for a parallel MDOF system is presented in section 3. The proposed indexes based on spatial modal information for the motion analysis in a parallel MDOF system are described in section 4. For the confirmation of the utility of the proposed indexes, some experimental results are shown in section 5. Finally, this paper is summarized in section 6.

2 BILATERAL MOTION CONTROL BASED ON ACCELERATION CONTROL

In order to transmit vivid real haptic information, the master–slave system must attain high transparency. If the precise motion synchronization and the force matching based on "the action and reaction law" between master system and slave system are simultaneously achieved, high transparency would be obtained.

The goal of position control for motion synchronization is represented as (1)

$$
\begin{aligned}
x_m - x_s &= x_{dif} \\
&= 0
\end{aligned}
\tag{1}
$$

where x means the position signal. The subscripts $_m$ and $_s$ express master system and slave system, respectively. The subscript $_{dif}$ means the differential mode signal. On the other hand, the goal of force control for the artificial realization of "the action and reaction law" is represented as (2)

$$
\begin{aligned}
f_m + f_s &= f_{com} \\
&= 0.
\end{aligned}
\tag{2}
$$

Here, f means the force signal. The subscript $_{com}$ means the common mode signal.

In order to achieve these control goals simultaneously, the signal projection from the actuator space to the decoupled modal space based on second order Hadamard matrix H_2 is effective [9]. The signal projection based on Hadamard matrix is given by

$$
\begin{aligned}
\begin{bmatrix} f_{com} & x_{com} \\ f_{dif} & x_{dif} \end{bmatrix} &= \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} f_m & x_m \\ f_s & x_s \end{bmatrix} \\
&= H_2 \begin{bmatrix} f_m & x_m \\ f_s & x_s \end{bmatrix}.
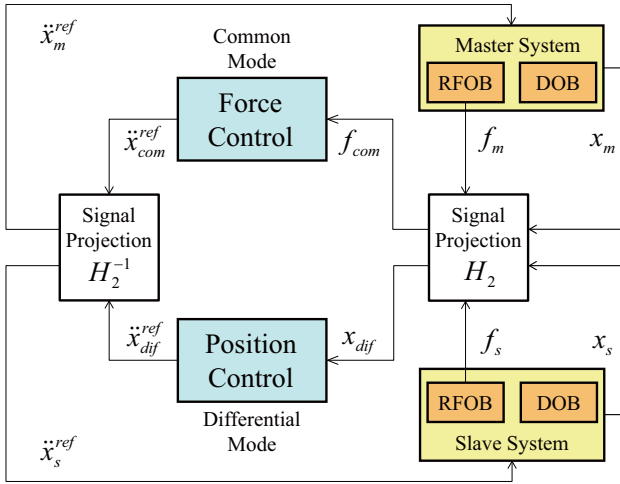\end{aligned}
\tag{3}
$$

Fig. 1. Block diagram of bilateral control based on signal projection

As a result from this signal projection, four kinds of modal signal can be obtained, whereas degrees of freedom of haptic system are two. As shown in (1) and (2), the number of control goals for bilateral control is two. Thus, the only diagonal components f_{com} and x_{dif} in (3) are utilized as the control signals in the modal space. Then, a pure force control and a pure position control can independently be implemented to each decoupled modal space. A force controller can be designed in the common modal space and a position controller can be designed in the differential modal space. The block diagram of the bilateral control method based on signal projection is shown in Fig. 1. In Fig. 1, DOB presents a disturbance observer [22] for the robust acceleration control. RFOB presents a reaction force observer [23] for the wide–band estimation of the reaction force. The acceleration–based bilateral control with high transparency can be realized on the basis of signal projection.

In this paper, the position controller in the differential modal space is designed as (4)

$$
\begin{aligned}
\ddot{x}_{dif}^{ref} &= C_p(s)x_{dif} \\
&= K_p(x_m - x_s) + K_v(\dot{x}_m - \dot{x}_s). \quad (4)
\end{aligned}
$$

$\ddot{x}_{dif}^{ref}$ shows the acceleration reference signal in the differential modal space. $C_p(s)$ denotes a position controller including position feedback gain K_p and velocity feedback gain K_v. On the other hand, the force controller in the common modal space is designed as (5)

$$
\begin{aligned}
\ddot{x}_{com}^{ref} &= C_f f_{com} \\
&= K_f(f_m + f_s). \quad (5)
\end{aligned}
$$

$\ddot{x}_{com}^{ref}$ shows the acceleration reference signal in the common modal space. C_f denotes a force controller only with

(a) Parallel five DOF motion

(b) Grasping (R_{a0})

(c) First–order horizontal manipulation (R_{a1})

(d) First–order vertical manipulation (R_{b1})

(e) Second–order horizontal manipulation (R_{a2})

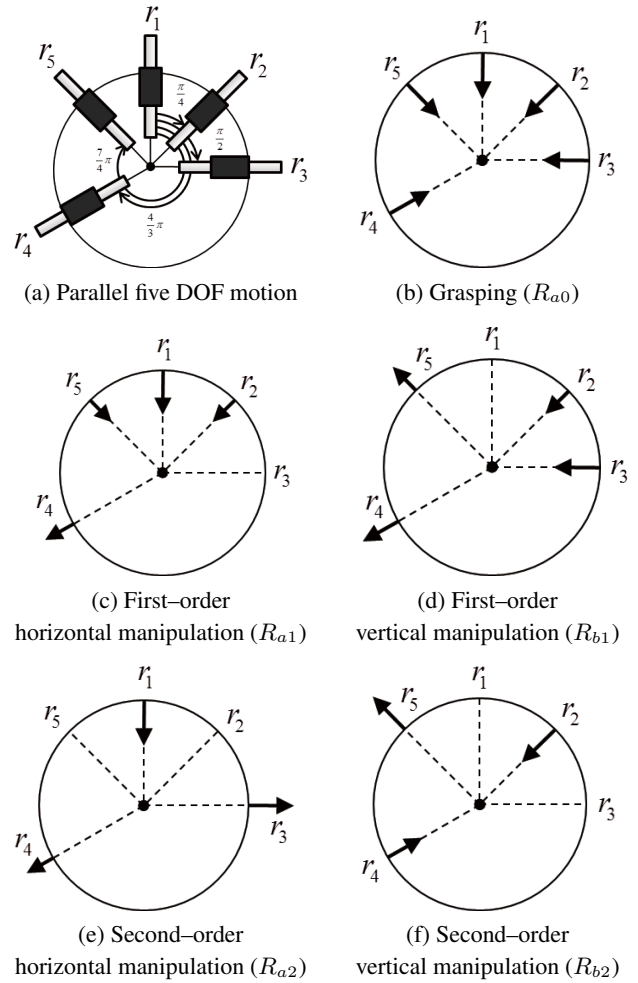(f) Second–order vertical manipulation (R_{b2})

Fig. 2. Motion modal decomposition

force feedback gain K_f.

Finally, the acceleration reference signals for each system $\ddot{x}_m^{ref}$ and $\ddot{x}_s^{ref}$ are obtained by the inverse signal projection based on the inverse Hadamard matrix H_2^{-1} as (6)

$$
\begin{aligned}
\begin{bmatrix} \ddot{x}_s^{ref} \\ \ddot{x}_m^{ref} \end{bmatrix} &= \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} \ddot{x}_{com}^{ref} \\ \ddot{x}_{dif}^{ref} \end{bmatrix} \\
&= \boldsymbol{H}_2^{-1}\begin{bmatrix} \ddot{x}_{com}^{ref} \\ \ddot{x}_{dif}^{ref} \end{bmatrix}. \quad (6)
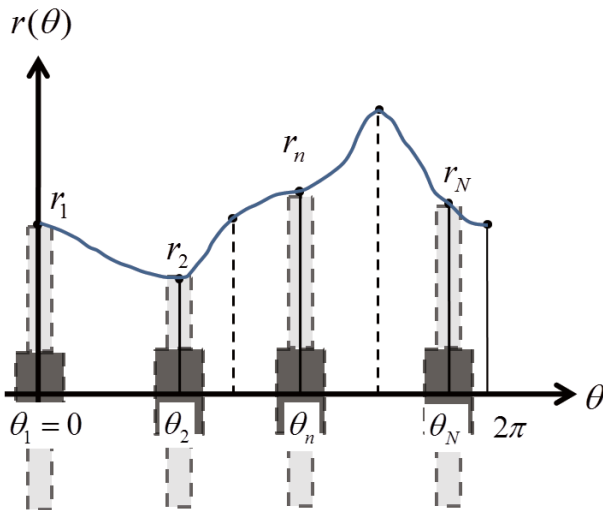\end{aligned}
$$

3 MODAL DECOMPOSITION BASED ON DISCRETE FOURIER SERIES EXPANSION

3.1 Spatial Modal Information

The whole motion of a parallel MDOF system can be decomposed into the motion elements that correspond to
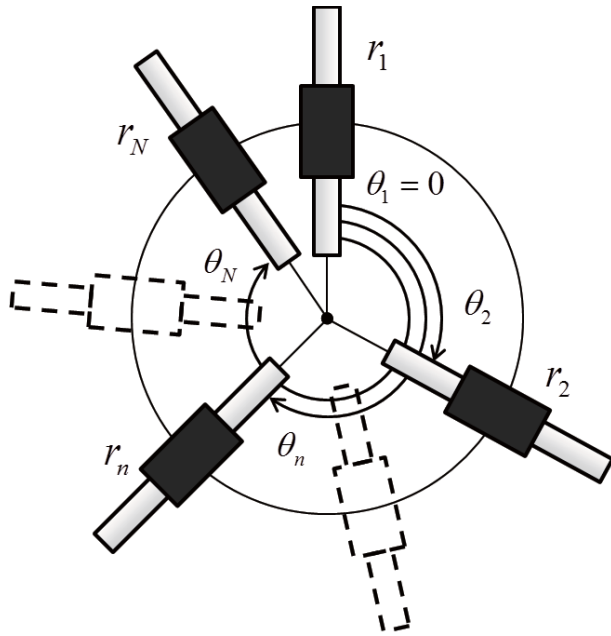
(a) Arrangement of parallel MDOF system

(b) Spatial periodicity

Fig. 3. Spatial periodicity in parallel MDOF system

specific physical action. Fig. 2 (a) shows an example of a parallel MDOF system. It is supposed that this system is composed of five linear motors. Then, those linear motors can be arranged to be suitable for the human fingertip motion. The whole motion can be decomposed into spatial modal information as shown in Fig. 2 (b)–(f). The spatial modal information has a specific physical meaning such as grasping, manipulation. In Fig. 2, r_n ($n = 1, 2, \cdots, 5$) expresses the motion signal of each actuator.

3.2 Modal Decomposition Based on DFS

Discrete Fourier series expansion (DFS) can generally be applied to the decomposition of temporally periodic discrete signal into the direct component and the alternate components. Fig. 3 (a) shows an example of parallel MDOF system composed of N linear actuators. In this figure, r_n ($n = 1, 2, \cdots, N$) determines the motion signal such as position signal x and force signal f. The arrangement of each actuator is represented by θ_n. Then, position signal and force signal of the system can be represented as (7) and (8)

$$\boldsymbol{x}_N = [x_1 \ x_2 \ \cdots x_n \cdots \ x_N] \tag{7}$$
$$\boldsymbol{f}_N = [f_1 \ f_2 \ \cdots f_n \cdots \ f_N]. \tag{8}$$

There is an spatial periodicity whose period is 2π as shown in Fig. 3 (b). Then, DFS can be applied to the spatial motion signal as (9) and (10)

$$\boldsymbol{X}_N = \boldsymbol{T}_N \boldsymbol{x}_N{}^T \tag{9}$$
$$\boldsymbol{F}_N = \boldsymbol{T}_N \boldsymbol{f}_N{}^T \tag{10}$$

where $\boldsymbol{T}_N$ means the Nth order transformation matrix based on DFS. Then, Fourier coefficients $\boldsymbol{X}_N$ and $\boldsymbol{F}_N$ describe the spatial modal information of motion signals. $\boldsymbol{X}_N$ and $\boldsymbol{F}_N$ are determined as follows,

$$\boldsymbol{X}_N = \underbrace{\left[X_{a0} \ X_{a1} \ X_{b1} \ X_{a2} \ X_{b2} \ \cdots\right]}_{N} \tag{11}$$

$$\boldsymbol{F}_N = \underbrace{\left[F_{a0} \ F_{a1} \ F_{b1} \ F_{a2} \ F_{b2} \ \cdots\cdots\right]}_{N}. \tag{12}$$

The spatial modal information corresponds to the specific motion element. In the above equations, subscript $a0$ is the direct component and physically expresses the grasping mode. The other components are the alternate components of the motion. The subscripts $a1$ and $b1$ physically express the first–order manipulation. In particular, $a1$ is the horizontal manipulation mode and $b1$ is the vertical manipulation mode. In addition, higher–order components such as $a2$ and $b2$ can also be extracted, if the parallel system has much DOF.

On the other hand, the transformation from the spatial modal information to the original motion signals can be realized by the inverse transformation matrix $\boldsymbol{T}_N^{-1}$. This inverse transformation is represented as (13) and (14),

$$\boldsymbol{x}_N = \boldsymbol{T}_N^{-1} \boldsymbol{X}_N{}^T \tag{13}$$
$$\boldsymbol{f}_N = \boldsymbol{T}_N^{-1} \boldsymbol{F}_N{}^T. \tag{14}$$

T_N^{-1} is derived as the following equation.

$$\boldsymbol{T}_N^{-1} = \begin{bmatrix} w_{(1,1)} & w_{(1,2)} & \cdots & w_{(1,N)} \\ w_{(2,1)} & w_{(2,2)} & \cdots & w_{(2,N)} \\ \vdots & \vdots & \ddots & \vdots \\ w_{(N,1)} & w_{(N,2)} & \cdots & w_{(N,N)} \end{bmatrix} \quad (15)$$

$$w_{(k,n)} = \begin{cases} 1 & n = 1 \\ \cos\left(\left|\frac{n}{2}\right|\theta_k\right) & n : \text{even} \\ \sin\left(\left|\frac{n}{2}\right|\theta_k\right) & n : \text{odd and } n \neq 1 \end{cases} \quad (16)$$

The modal transformation matrix $\boldsymbol{T}_N$ is calculated from the $\boldsymbol{T}_N^{-1}$.

In the comparison between the conventional modal decomposition methods [15–17] and the proposed DFS modal decomposition method [18,19], the proposed DFS–based method has some advantages. At first, this method has the spatial extendability and the mathematical generality. That is, this method can be applied to a parallel system with any number of degrees of freedom. In addition to that, even if the arrangement of a parallel MDOF system does not have the spatial linearity and symmetry, this method can decompose the whole motion into the spatial modal information. Secondly, it is easy to grasp the physical meanings. In this method, spatial modal information is naturally determined by the Fourier coefficients. The whole motion is regarded as the combination of the waves. Moreover, the modal transformation can be achieved only by the simple calculation of the real numbers.

4 TOTAL HARMONIC DISTORTION AND CONTENT RATE OF SPATIAL MODAL INFORMATION

In the modal decomposition based on DFS, the whole motion of the parallel MDOF system is regarded as the combination of spatial waves. Fourier coefficients determine the amplitude of spatial modal information. In the analysis of the electrical signal, total harmonic distortion (THD) is one of the effective evaluation indexes. THD is a kind of ratio between the fundamental waves and the harmonic waves.

This paper firstly proposes an evaluation index for the parallel motion analysis. The THD of the spatial modal information is proposed. The proposed THD is determined as (17)

$$THD = \frac{\sqrt{\sum_{i=2}\left(R_{ai}^2 + R_{bi}^2\right)}}{\sqrt{R_{a0}^2 + R_{a1}^2 + R_{b1}^2}}. \quad (17)$$

R means the spatial modal information. The denominator in (17) expresses the fundamental motion elements; grasping modal information, 1st–order horizontal manipulation modal information, and 1st–order vertical manipulation modal information. The numerator in (17) expresses the higher–order manipulation modal information.
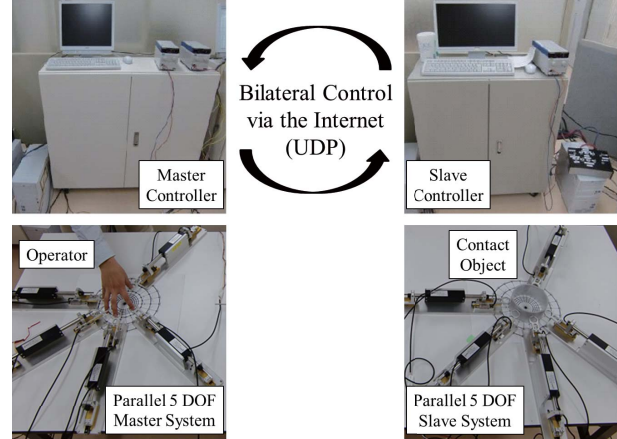

Fig. 4. Experimental system

Table 1. Experimental parameters

Nominal mass	M_n	0.500 [kg]
Nominal force coefficient	Kt_n	33.0 [N/A]
Position feedback gain	K_p	1.00×10^4
Velocity feedback gain	K_v	2.00×10^2
Force feedback gain	K_f	1.00
Cut-off frequency of DOB	g_{dis}	6.00×10^2 [rad/s]
Cut-off frequency of RFOB	g_{env}	6.00×10^2 [rad/s]
Sampling time	st	0.100 [ms]

In the free motion, THD of the motion modes can evaluate the motion complexity of a parallel MDOF system. In the contact motion, THD of the motion modes can evaluate the deformability of the contact object.

Moreover, this paper additionally proposes a content rate of the spatial modal information as an evaluation index for the parallel motion analysis. The content rate of the spatial modal information can be represented as follows,

$$\tilde{R}_{a0} = \frac{R_{a0}}{R_{a0} + \sum_{i=1} R_{ai} + \sum_{i=1} R_{bi}} \quad (18)$$

$$\tilde{R}_{an} = \frac{R_{an}}{R_{a0} + \sum_{i=1} R_{ai} + \sum_{i=1} R_{bi}} \quad (19)$$

$$\tilde{R}_{bn} = \frac{R_{bn}}{R_{a0} + \sum_{i=1} R_{ai} + \sum_{i=1} R_{bi}}. \quad (20)$$

The content rate of the spatial modal information determines the percentage of the specific modal information. This index can evaluate the priority of the specific spatial modal information.
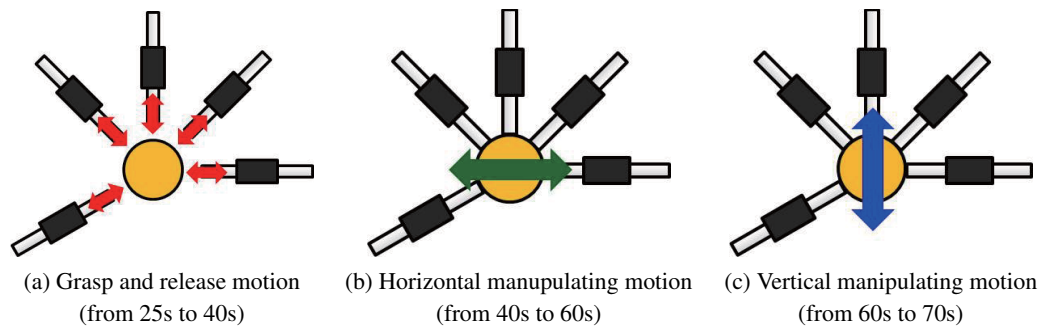
(a) Grasp and release motion　　　(b) Horizontal manupulating motion　　　(c) Vertical manipulating motion
(from 25s to 40s)　　　　　　　　　(from 40s to 60s)　　　　　　　　　　(from 60s to 70s)

Fig. 5. Schematic of experimental motion

5 EXPERIMENT

5.1 Experimental System

Fig. 4 shows the parallel MDOF haptic system in the experiment. Ten linear actuators are totally utilized in this system. Five of ten linear actuators are used as the parallel five DOF master system. The other five are used as the parallel five DOF slave system. The acceleration–based bilateral motion control is applied to this haptic system. The actuators are arranged as shown in Fig. 2(a). The master system and the slave system are communicated via network. In the experiment, the time delay is so small that the effect of it can be neglected. Table 1 shows the experimental control parameters. The control software of this system is written in C language under RTAI3.6.1. In the experiment, an operator directly manipulates the master system by his five fingertips. Then, the slave system grasps the rubber ball and manipulates it.

5.2 Experimental Result

In the experiment, the operator firstly grasps the rubber ball twice from 25s to 40s. Then, while grasping the ball, he manipulates it in the horizontal direction twice from 40s to 60s. Finally, he manipulates the grasped ball in the vertical direction from 60s to 70s. This experimental motion is illustrated in a schematic way as shown in Fig. 5.

Fig. 6(a) and (b) show the bilateral control performance of the acceleration–based bilateral control. These figures indicate the position response and the force response of each actuator. Thus, the movement and the force strength of each fingertip can be found. These results demonstrate that the acceleration–based bilateral control can realize the position tracking and the artificial "law of action and reaction" well. The highly transparent bilateral control is achieved.

Fig. 6(c) and (d) show the results on DFS modal decomposition. The whole motion of five fingertips is decomposed into five kinds of the spatial modal information; grasping mode (R_{a0}), first–order horizontal manipulation mode (R_{a1}), first–order vertical manipulation mode

(R_{b1}), second–order horizontal manipulation mode (R_{a2}), and second–order vertical manipulation mode (R_{b2}). From these figures, it can be found that the DFS–based modal decomposition method can realize the transformation between the actuator information and the spatial modal information. The precise tracking of modal information corresponding to the position signal is achieved. It is also found that "the law of action and reaction" is realized. It can be said that the transparency is highly obtained in the spatial modal information as well.

Fig. 7(a) and (b) show the THD of spatial modal information corresponding to the position and the THD of spatial modal information corresponding to the force, respectively. When the haptic system just grasps the rubber ball (from 25s to 30s, and from 35s to 40s), THD indicates the relatively high value. This is because that the rubber ball is soft and deformable. In the free motion from 30s to 35s, it turns out that the operator can smoothly open and close his fingers, since the THD corresponding to position shows low value. When the operator grasps the soft rubber ball from 35 to 70s, the THD corresponding to position shows relatively high value again, since the soft rubber ball is deformable. It can be said that the THD in the contact motion can evaluate the deformability of the object. Fig. 7(b) shows the THD of spatial modal information corresponding to the force. This index can evaluate the waste force in the fundamental motion. Especially, it is found that much waste force is generated when the operator changes the direction of the manipulation.

Fig. 7(c) and (d) show the content rate of spatial modal information. From the results, it can be said that this index can demonstrate which motion element is the most activated. When the operator only grasps the object (from 25s to 30s, and from 35s to 40s), the content rate of the grasping mode ($\tilde{R}_{a0}$) is highest. In the free motion from 30s to 35s, it seems that the content rates of modal information corresponding to force are oscillated. This is because that the system is not constrained by the object and the every force responses are quite low. Thus, it can be said
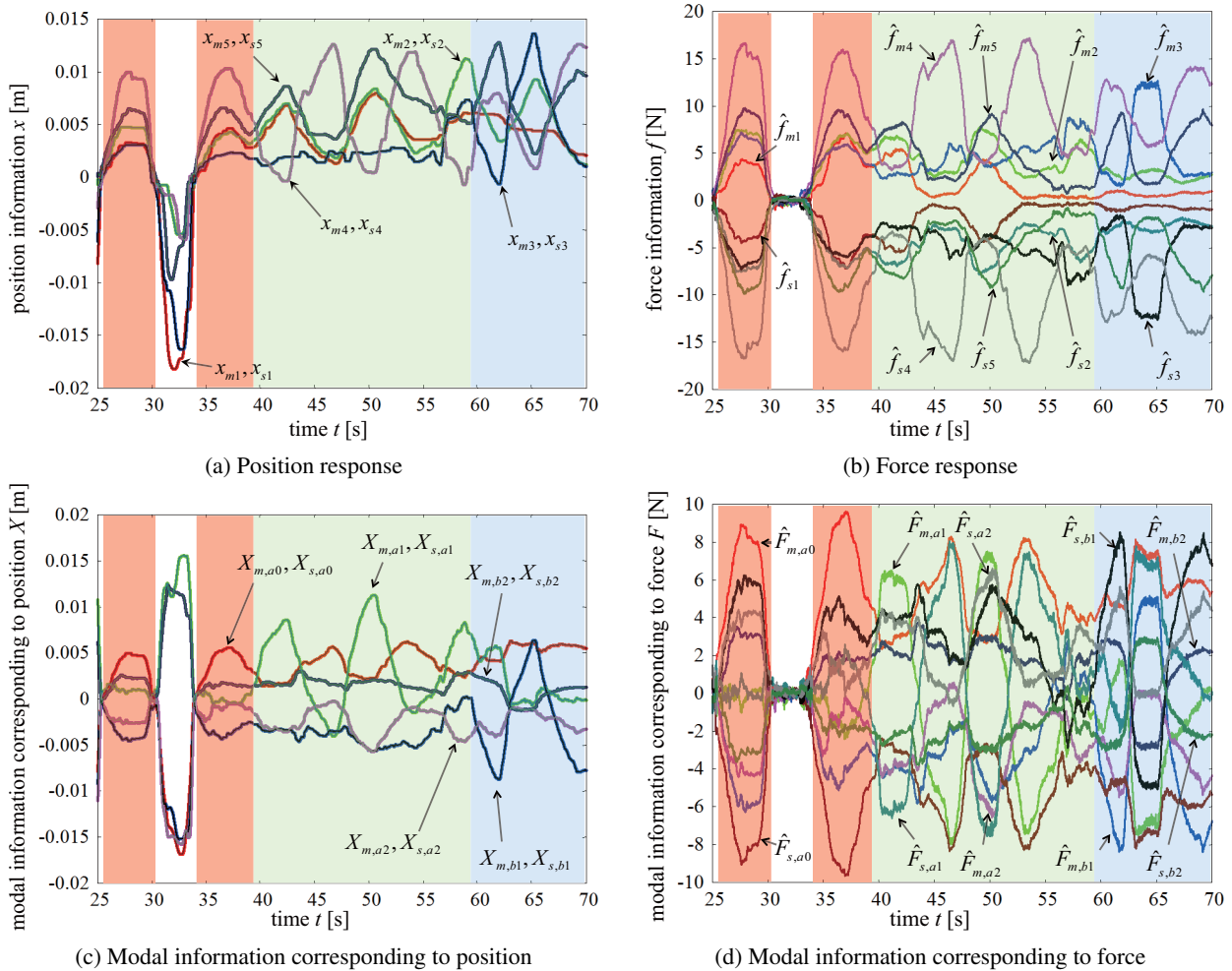
(a) Position response

(b) Force response

(c) Modal information corresponding to position

(d) Modal information corresponding to force

Fig. 6. Experimental results on bilateral motion control and DFS–based modal decomposition

that this index is more effective for the motion evaluation of the contact motion. In the manipulating motion of the grasped object in the horizontal direction from 40s to 60s, the content rate of the grasping mode ($\tilde{R}_{a0}$) and the content rate of the first–order horizontal manipulation mode ($\tilde{R}_{a1}$) show the high value. Moreover, in the manipulating motion of the grasped object in the vertical direction from 60s to 70s, the content rate of the grasping mode ($\tilde{R}_{a0}$) and the content rate of the first–order vertical manipulation mode ($\tilde{R}_{b1}$) show the high value. It is found that the content rate of the spatial modal information can evaluate the priority of the specific modal information.

6   CONCLUSION

In this paper, the spatial modal decomposition method based on discrete Fourier series expansion (DFS) was firstly presented. The DFS–based modal decomposition method was effective for the motion description of a parallel multiple degrees–of–freedom (MDOF) system. The

spatial modal information can mathematically be determined by Fourier coefficients. Then, the total harmonic distortion (THD) and the content rate of spatial modal information were proposed, as the evaluation indexes for the complicated motion of the parallel MDOF system. The THD of the spatial modal information can evaluate the complexity of the human motion and/or the deformability of the contact environment. The content rate of the spatial modal information can evaluate the priority of motion element. The experimental results demonstrated that the proposed indexes were effective for the motion analysis of a parallel MDOF motion systems. In the paper, the human fingertip motion through a haptic parallel five DOF was analyzed by utilizing the proposed evaluation indexes, as an example of the applications.

(a) THD of modal information corresponding to position

(b) THD of modal information corresponding to force

(c) Content rate of modal information corresponding to position

(d) Content rate of modal information corresponding to force

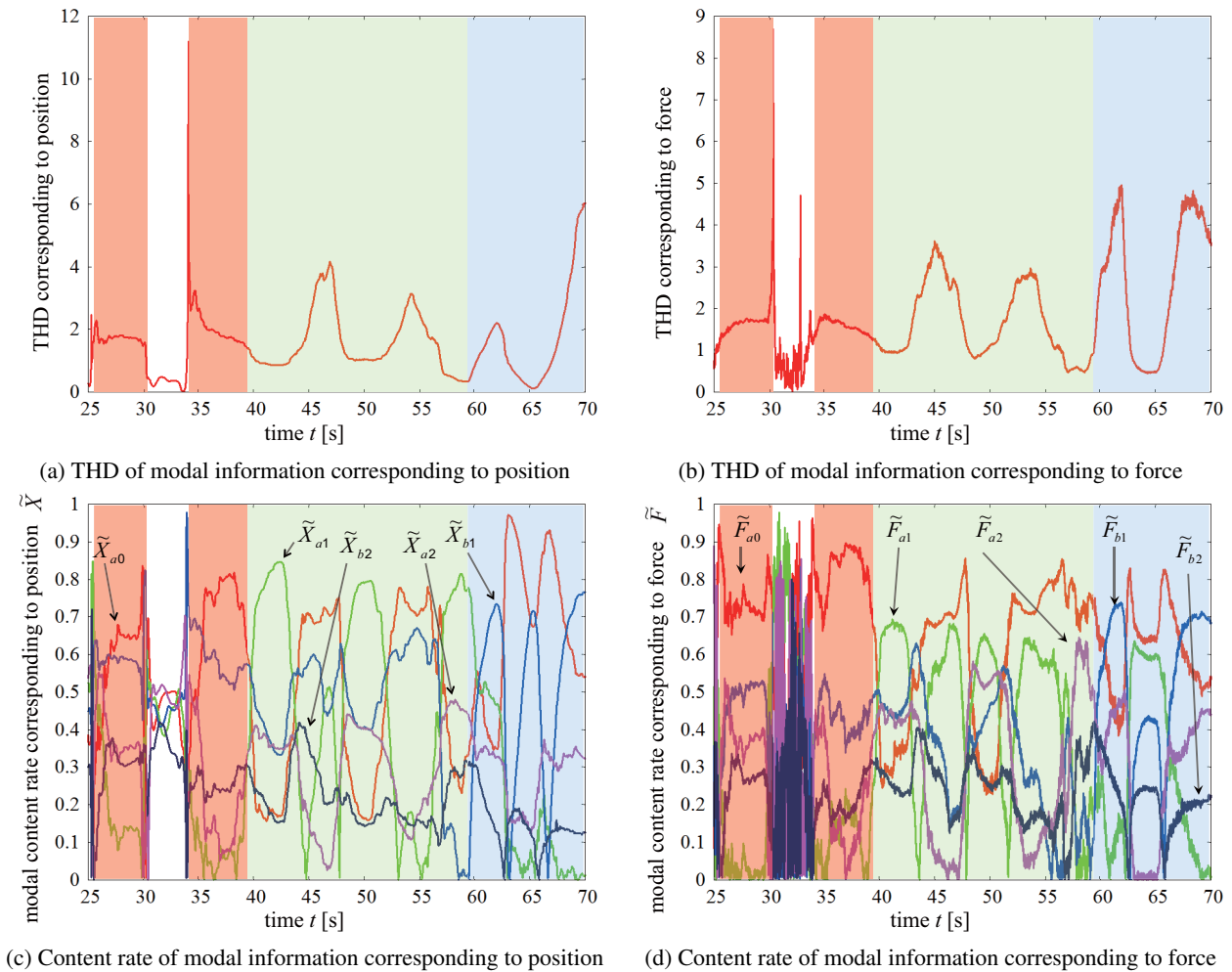*Fig. 7. THD and content rate of spatial modal information*

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