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Inertia Reduction in Haptic Devices Using Force Feedback Method

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*Abstract--**In haptic devices the problem of major concern is the inertia offered by the haptic device. When using it in unconstrained space, it should offer the least inertia. Depending on the interaction mechanism we are required to adapt different control algorithms to maintain transparency. This paper investigates force feedback method of inertia reduction and analyses its advantages over the feed forward method of inertia reduction in impedance interaction of haptic devices.***

*Keywords--**feedback system, feedforward systems, frequency response, haptic system, human operator, hybrid systems, impedance interaction, virtual environment***

I. INTRODUCTION

Humans have been provided with five sense organs to assist them in enjoying the beauty of nature but as well live their life comfortably. These senses are the sense of vision, taste, touch, hearing and smell. Loss of any of the senses may result in severe loss in living. To deal with the virtual world we generally use our sense of vision and most often sense of hearing. Haptics technology focuses on using sense of touch in addition to these senses to make virtual interaction livelier. The term “haptics” arises from the Greek root *haptikos*, meaning “able to grasp or perceive”. A haptic device is a robot that uses the human’s sense of touch as advantage to interface human operator with the virtual environment so that the user can feel the environment. Haptic interaction with computers implies the ability to use our natural sense of touch to feel and manipulate computed quantities. Being able to touch, feel, and manipulate objects in an environment, in addition to seeing (and/or hearing) them, gives a sense of compelling immersion in the environment that is otherwise not possible. This is done by interface by providing a feedback to user. The haptic feedback interface sense the position and orientation of the user and then provides feedback forces and torques to the user, on the bases of what user interacts and manipulates in the virtual environment. Haptic research attempts to solve this feedback in two different fields: Kinesthetic feedback and tactile feedback.

Kinesthetic haptic devices use actuators to apply forces to the user which deals with interaction with muscles and tendons and are often large as compared to tactile devices.Tactile perceptions are caused by stimulating human skin by e.g. vibration, electric voltage or current [1]. Many devices have developed in recent years, including but not limited to fields such as surgery training [2, 4], space applications [5], flights [6], driving simulators [7], virtual maintenance and prototyping [8, 9]. Ideally, a haptic interface should provide full transparency of motions and forces of the virtual world. To maintain transparency control strategies are required. Understanding movement and manipulation and how they may best be controlled is a basic endeavour in haptics. There are basically 4 types of control that may be used. Impedance control, Admittance control, hybrid control & Energy based control.

The various impedance and admittance control strategies that may be used in haptic devices are given in [10]. Feedforward method of inertia reduction in an impedance type haptic device is given in [11] and [12], and successfully used in [13], [14] and [15] for friction reduction, gravity compensation and for teleoperation system. Stability issues related to the feedforward method has been discussed in [16, 33]. Effect of sampling and digital filtering has also been discussed in that brief.This paper compares feedforward and force feedback methods of inertia reduction. Section II discusses about the various modelling taken into account for user, haptic device and environment. In section III the feedforward method along with their advantages and disadvantages has been discussed. In section IV positive feedback method and their effects on haptic rendering has been investigated. Finally paper has been concluded in part V

II. SYSTEM DESCRIPTION

Haptic system essentially comprises of user, haptic device or interface and virtual environment as shown in Fig. 1.

We generally assume that link between user and interface is rigid, and therefore, the displacements of them, both are same. This assumption is valid as long as the finger pulp is sufficiently compressed, which occurs for forces greater than about 2N [17, 18].

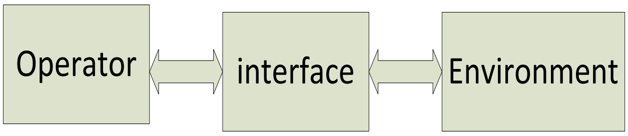

Fig.1. Block diagram of haptic System

There are many factors that affect the quality of the human-tool interaction. From the knowledge of the human hand and tool impedances we can infer how well the human will interact with the tool. As an example, higher damping makes manipulation more stable, but at the same time more fatiguing. Usually, higher stiffness makes position control easier, but force control more difficult. Mechanical impedance elegantly includes all these factors in a compact symbolic representation. For this reason, its determination is of paramount importance.

The human tool interaction is thus highly dependent on the device being used and user grasping method [19]. Mechanical impedance characterizes the relationship between limb motion and externally applied task or constraint forces, and is comprised of both a static component relating forces and displacements and a dynamic component relating forces to velocities and accelerations.

Strictly speaking, according to force voltage analogy in which mechanical force is equivalent to voltage and position is related to charge and hence velocity is related to current, the impedance is the relationship between velocity and force, not the position [20].

$$Z(s) = \frac{F(s)}{v(s)} \qquad (1)$$

where Z is the impedance, F is the force and v is the velocity.

In literature we will find impedance taken as relationship between position and force. In this paper also relation between position and force is assumed as the impedance.

A. User Modeling

Many sources have supported the validity of modeling human joint dynamics as linear about an operating point, with second-order models being common [21]-[26].

A linear second order model is assumed to represent the translational relationship between applied force f(t) and resulting displacement x(t), velocity $\dot{x}(t)$, and acceleration $\ddot{x}(t)$ of the hand. The parameter m_h represent the effective point mass (kg), b_h represent the viscous damping (N-s/m) and k_h is the stiffness (N/m) of the hand. Obviously although this characterization has been successfully used in many theoretical studies, it is only an approximation [27] so that conclusion using this model should be interpreted with caution [28]. The user model can be written as:

$$Z_u(s) = \frac{F(s)}{X(s)} = m_h s^2 + b_h s + k_h \qquad (2)$$

where Z_u is known as user impedance.

B. Interface modeling

The most important feature required from a haptic interface is transparency. Transparency implies:

1) Free space must feel free
2) Solid virtual object must feel stiff
3) Virtual constraint must not be easily saturated (actuator must provide enough forces to feel solid objects)

The general characteristics of all actuators used in haptic device are: high force/torque to weight ratio, high bandwidth, large stroke, low internal friction, low inertia and high level of safety.

The dynamic model of haptic device can be represented as

$$Z_m(s) = \frac{F(s)}{X(s)} = M_m(x)s^2 + V_m(x)s + G_m(x) \qquad (3)$$

where M_m is the mass matrix, V_m is the centrifugal and coriolis forces and G_m is the gravitational force. X represents task space coordinates and Z_m is the impedance of haptic interface.

C. Environment modeling

Virtual environment in haptic rendering can be of two type (1) Impedance type and (2) Admittance type. The virtual contact can be modeled by spring damper system and represented as

$$Z_e(s) = B_e s + K_e \qquad (4)$$

where Z_e is the impedance of virtual environment represented by spring damper system with damping constant B_e and stiffness K_e

There can be either Impedance interaction or admittance interaction in haptic system. Impedance interaction refers to the situation where virtual environment sense the position and control the forces applied by the haptic device. Admittance interaction is when the device sense forces commanded by the user and control the motion (velocity or position) of the device. Sometimes force is used as an additional input to the impedance controller or displacement is used as an additional input to the admittance controller. Such type of interaction is known as Hybrid interaction. In this paper only the impedance interaction has been discussed. An impedance interaction continuous model of haptic device can be represented as shown in Fig. 2.The transfer function of the system becomes

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s)+Z_m(s)+Z_e(s)} \qquad (5)$$

Every application requires certain workspace and as the workspace becomes larger, it becomes difficult to keep the inertia of the device low. If the mechanical interface is non back drivable, admittance type of control is required as in Haptic-Master [29] and WYSIWYF [30]. With moderate inertia it can be controlled with any of the impedance or admittance method as in Excalibur [31]. If the system is back drivable we use impedance type of control as applied in LHIfAM [32].

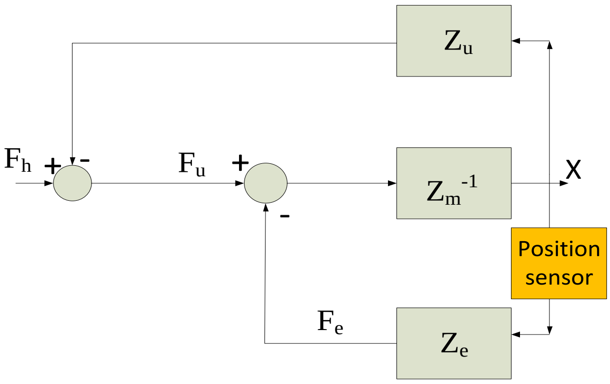

Fig.2. Impedance interaction of haptic device

III. IMPEDANCE INTERACTION WITH FEEDFORWARD COMPENSATION

There are number of control schemes that can be applied in different situation to decrease the perceived inertia. One of the methods is the impedance interaction with feedforward compensation. In order to apply this method we need to sense the force using force sensor and exert an additional force in the direction of user. This type has already been implemented to reduce the friction at the University of Colorado [13]. Also it has been used to compensate gravity and reduce the friction of the ViSHaRD6 [14].

In [34] author has modeled the haptic interface with m_m=0.86 kg and a viscous damping b_m =3.03 Ns/m. Thus resulting impedance of the interface is

$$Z_m^{-1}(s) = \frac{1}{0.86s^2+3.03s} \qquad (6)$$

The user dynamics has been considered as one proposed by Hogan [27].

$$Z_h(s) = 0.8s^2+5.5s+568 \qquad (7)$$

In this paper we have considered the same interface model as given in (6) and user model as given in (7) and the environment or virtual contact has been modeled with a spring-damper system with stiffness K_e and damping B_e with values as proposed in [31] as K_e=12000 and B_e=18 and thus environment is represented as

$$Z_e(s) = 18s+12000 \qquad (8)$$

Thus for system as shown in Fig. 2, the transfer function becomes

$$\frac{X(s)}{F(s)} = \frac{1}{1.66s^2+26.53s+12568} \qquad (9)$$

If we neglect environment in Fig. 2, the transfer function will become

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s)+Z_m(s)} = \frac{1}{1.66s^2+8.53s+568} \qquad (10)$$

Now applying feedforward gain without considering environment as shown in Fig. 3, the transfer function becomes

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s)+\frac{Z_m(s)}{1+K_f}} = \frac{1}{1.09s^2+6.51s+568} \qquad (11)$$

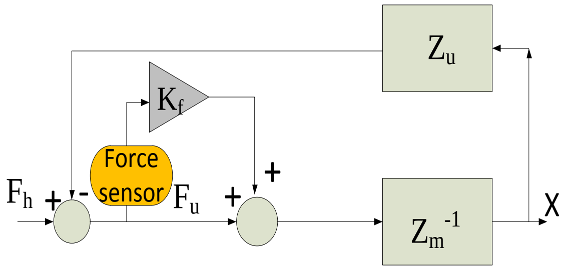

Fig.3. Impedance interaction with feedforward gain without environment

The frequency response of the systems given by (10) and (11) is given in Fig. 4 and as expected the gain Bode diagram increases approximately 4 dB and the inertia felt is three times smaller.

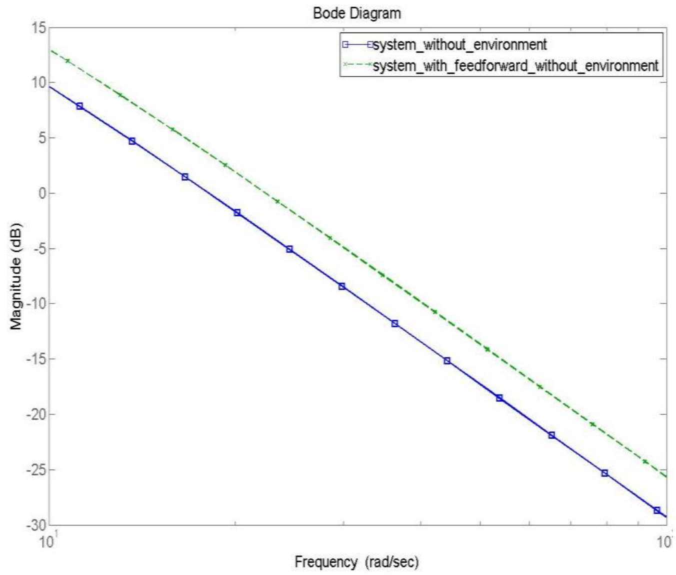

Fig.4. Bode response of a system with feedforward and system (without environment)

But as the feedforward gain is introduced in system with environment as shown in Fig. 5 the transfer function of the system becomes

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s)+\frac{Z_m(s)+Z_e(s)}{1+K_f}} = \frac{1}{1.09s^2+12.51s+4568} \qquad (12)$$

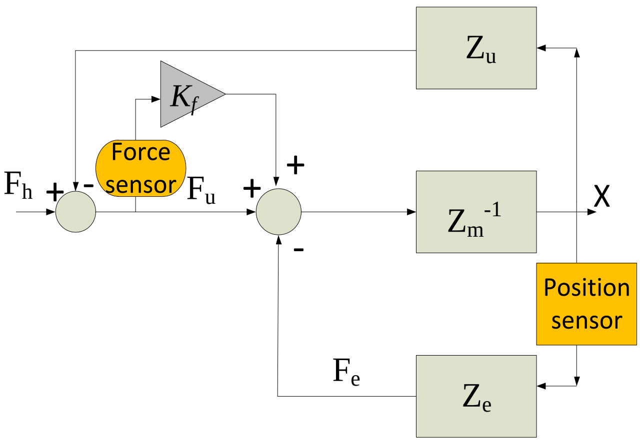

Fig.5. Impedance interaction with feedforward gain and environment

The frequency response for (12) as compared to (9) is given in Fig. 6. Unexpectedly the bode gain of the system decreases instead of increasing with the introduction of environment. This occurs because inertia felt by the user is $1+K_f$ times smaller than the real one but the impedance of the environment is also reduced by the same amount and hence the user does not feel the stiffness from the environment but instead reduced stiffness.

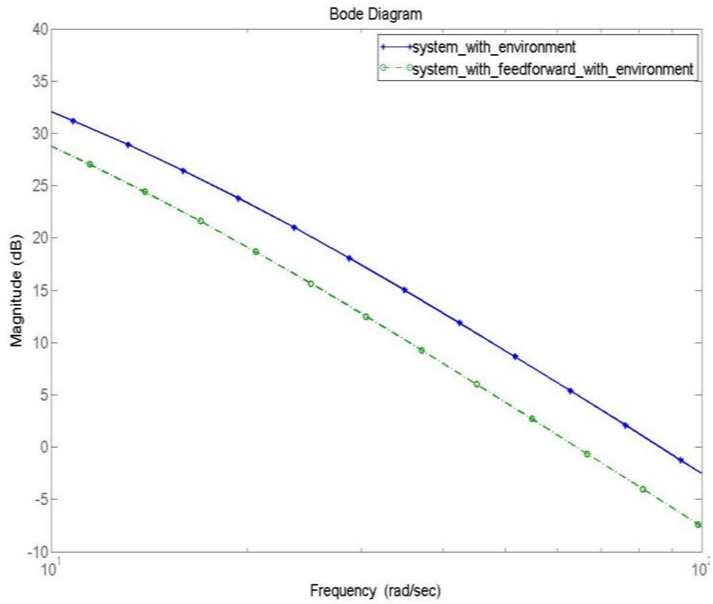

Fig.6. Bode response of system with feedforward compared to system without feedforward (including environment)

To avoid the situation the virtual impedance is increased by $1+K_f$ times, as shown in Fig. 7

The transfer function is thus modified and becomes

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s)+\frac{Z_m(s)}{1+K_f}+Z_e(s)} = \frac{1}{1.09s^2+24.51s+12568} \qquad (13)$$

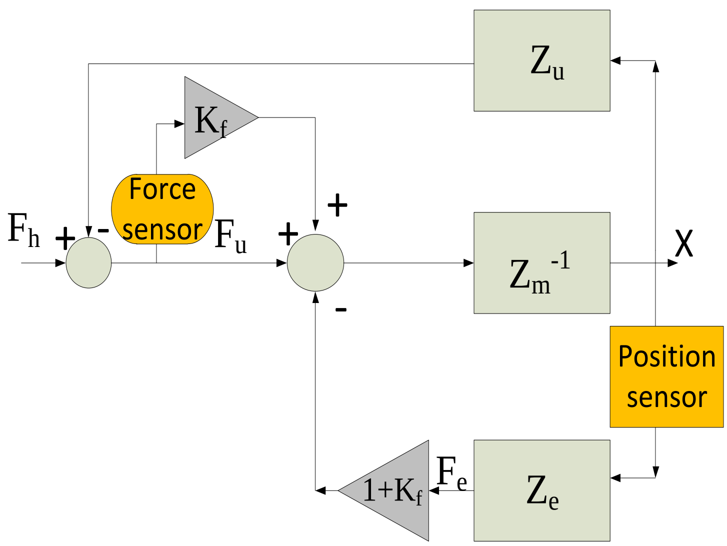

Fig.7. Impedance interaction with feedforward and environment with modification

System is further modified as shown in Fig. 8 to gang up two different gains shown in Fig. 7 into one so that developer does not forget to change the gain in both the loops. However, the transfer function remains the same as (13). The frequency response shown in Fig. 9 clearly indicates that this method increases the gain of the system even with the environment and the environment is felt without modification whereas device inertia is reduced to $1+K_f$.

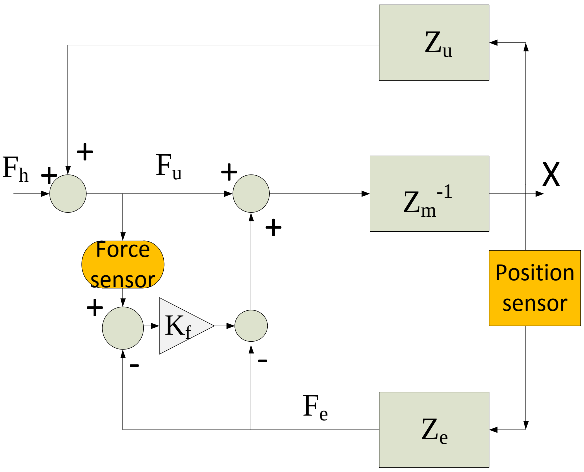

Fig.8. Impedance interaction with feedforward and environment with gain blocks ganged together

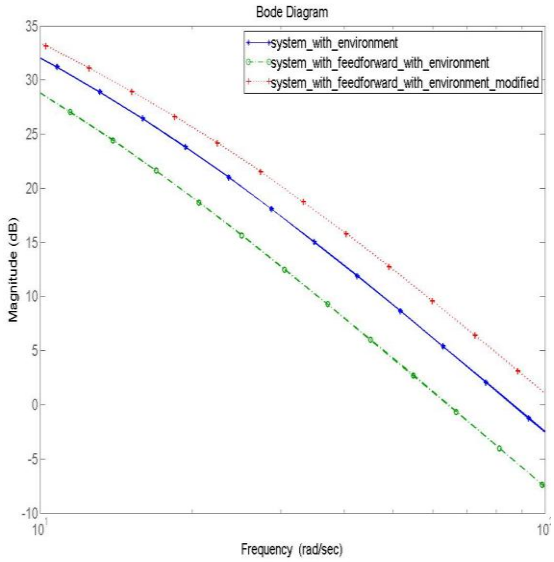

Fig.9. Frequency response of feedforward system with modified environment compared to feedforward system without modification and simple system with environment without control strategy

IV. IMPEDANCE INTERACTION WITH POSITIVE FEEDBACK COMPENSATION

A different way to reduce the inertia of the mechanical interface is to include feedback compensation.
From Fig. 10

$$F_m(s) = -Z_e(s)X(s) + Z_c(s)X(s) + F(s) - Z_u(s)X(s) \quad (14)$$

$$F_m(s) = Z_m(s)X(s) \quad (15)$$

From (14) and (15):

$$Z_m(s)X(s) = (Z_c(s) - Z_e(s) - Z_u(s))X(s) + F(s) \quad (16)$$

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s) + Z_m(s) - Z_c(s) + Z_e(s)} \quad (17)$$

If $Z_m(s) = m_m s^2 + b_m s$ (18)

$$Z_h(s) = m_h s^2 + b_h s + k_h \quad (19)$$

And $Z_e(s) = b_e s + k_e$ (20)

Then taking $Z_c(s) = m_c s^2$ (21)

Gives

$$\frac{X(s)}{F(s)} = \frac{1}{(m_h + m_m - m_c)s^2 + (b_h + b_m + b_e)s + (k_h + k_e)} \quad (22)$$

According to routh-hurwitz criteria for stability, the system becomes unstable if

$$m_c > m_m + m_h \quad (23)$$

Thus there is a compromise between stability and transparency here. If we don't take dynamics of user, the condition for stability becomes $m_c > m_m$ and system becomes critically stable as we completely compensate tool impedance. This stability is further reduced if quantization, sampling, filtering, etc are taken into account [27].

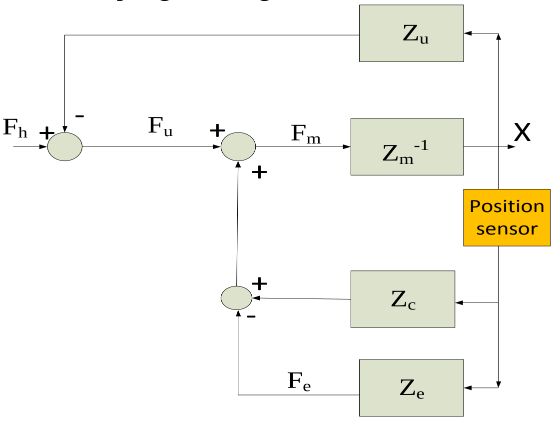

Fig.10. Impedance interaction with positive feedback compensation

The block diagram for this method has been given in Fig.10. The transfer function of the system with feedback impedance $Z_c = 0.57s^2$ becomes

$$\frac{X(s)}{F(s)} = \frac{1}{Z_u(s)+Z_m(s)-Z_c(s)+Z_e(s)} = \frac{1}{1.09s^2+26.53s+12568} \quad (24)$$

The frequency response of the system is shown in Fig. 11.

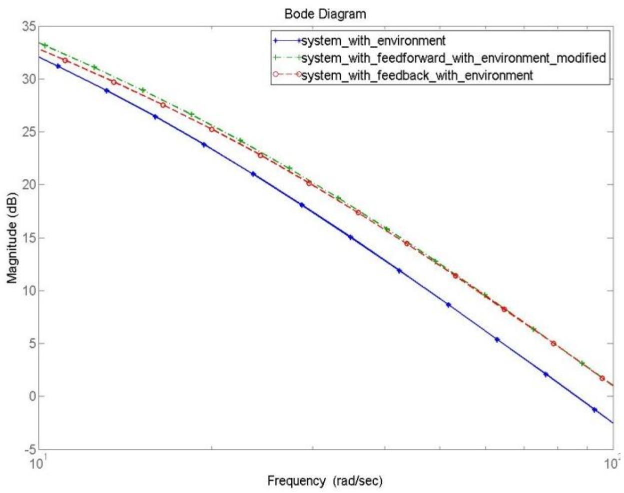

Fig.11.Frequency response of force feedback system compared to system with feedforward with environment modified and system with environment

Fig. 11 shows that although force feedback method reduces the inertial mass to the same extent but failure to improve the damping, results in a lower gain than feedforward method. Also in range of haptic operating frequency i.e. between 30 Hz to 100 Hz the difference between system with feedforward gain and with force feedback having same inertial reduction is negligible. Thus force feedback can be implemented instead of feedforward. One of the major advantages of using force feedback is that modification of environment is not required.

Another advantages of this approach over feedforward method is that it does not need force sensor and hence possible to obtain a simpler and cheaper final implementation. However there are a few disadvantages that restrict its usability as we need to know the dynamics of the interface to adjust the compensator. Also no force change can be done until we have the position readings. Thus where the dynamic compensation is possible it's hard to reduce static friction.

V. CONCLUSION

The force feedback method has been proposed for inertia reduction in haptic devices. Condition for stability in force feedback method has also been derived in this paper. It has been shown that both of the methods, feedforward and force feedback method had got their own set of advantages and disadvantages. The force feedback method may be applied in haptic devices without any modification in environment. Hence a simple and cheaper compensator than feedforward compensator is achieved. However, as both the methods has certain advantages and disadvantages, the advantages of both can be combined together overcoming their individual disadvantages using hybrid method of inertia reduction.

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BIOGRAPHIES

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