Optimal Motion Cueing Algorithm Using the Human Body Model*

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This paper introduces the development of a motion cueing algorithm which produces motion cues from vehicle motion signals. The simulator, a parallel manipulator, has the limitation on the workspace. In order to overcome this problem, the motion cueing algorithm is needed. Here, we suggest a new optimal motion cueing algorithm where the human body model (ISO 2631-1) as well as the human perception model are incorporated. And we show the performance of this algorithm using the computer simulation. In simulation, we produce motion cues from vehicle motion signals through the proposed algorithm and show sensation errors which the human feel between vehicle signals and the simulator motions subjected to motion cues.

Key Words: Motion Cueing Algorithm, Washout Filter, Optimal Control, Human Body Model, Simulator

1. Introduction

The simulator, which is used in the basic design, performance evaluation and training drivers of the aircraft, ship and vehicle, has the limitation on each motion (roll, pitch, yaw, surge, sway, and heave) compared with those of real systems. In other word, when the signal, which is calculated by the vehicle dynamics, is directly inputted to the simulator, it may happen that sometimes the simulator is ordered to reach out of workspace, then it malfunctions or is out of work. The commonly used method to avoid this problem is to change vehicle motion signals into motion cues that are admissible to a given simulator, but the error that the human feel between the vehicle motion and the simulator motion subjected to the motion cues should be diminished. This signal process algorithm is called the motion cueing algorithm and

the studies about this problem can be classified two fold, the algorithm development and studies for the human body development.

Two kinds of variable approaches to motion cueing algorithm have been identified, adaptive washout filters^{(1)-(4),(12),(13)} and optimal motion cueing algorithms^{(5),(6)}. Mostly the human body model used in the motion cueing algorithm is the perception model^{(1),(2),(6),(12),(13)} of the ear, which implies to assume that the human body is rigid. But, through the motion which human feels is the specific force and rotational velocity of perceptual organs, since the simulator motion is transferred through the human body to perceptual organs, the vibration transition of the human body cannot be ignored. So, in this paper, we propose the development of the motion cueing algorithm which uses the optimal control theory and includes not only the perception model but also the human body model in order to consider the human vibration transition.

Three kinds of models for the human vibration have been developed, the mass-spring-damping model⁽⁷⁾⁻⁽⁹⁾, the finite element method model⁽¹⁰⁾ and the transfer function model⁽¹¹⁾. In this work, we take the transfer function model of the human body which is achieved from experiment results.

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2. Human Body Model and Perception Model

2.2 Human body model

Human body model can be modeled as the transfer function, Eq.(1.d), which is given at ISO 2631-1⁽¹¹⁾ and is composed of the band-limiting $H_{BL}(s)$ (Eq.(1.a)), the A-V (Acceleration-Velocity) transition $H_T(s)$ (Eq.(1.b)), and the upward step $H_s(s)$ (Eq.(1.c)). The band limiting transfer function consists of high pass filter $H_{HP}(s)$ and the low pass filter $H_{LP}(s)$. Since the human body has the upward step transfer function of Eq.(1.c) in the only heave direction, the upward step transfer functions are taken as 1 in the other directions.

Therefore, the order of the transfer function of the heave motion is 8th and the other are 6th.

$$H_{HP}(s) = \frac{s^2}{s^2 + w_1\sqrt{2}s + w_1^2}, \quad H_{LP}(s) = \frac{1}{s^2 + w_2\sqrt{2}s + w_2^2}, \quad (1.a)$$

$$H_{BL}(s) = H_{HP}(s)H_{LP}(s) \quad H_T(s) = \frac{1 + s/w_3}{1 + s/(Q_4w_4) + (s/w_4)^2} \quad (1.b)$$

$$H_s(s) = \frac{1 + s/(Q_5w_5) + (s/w_5)^2}{1 + s/(Q_6w_6) + (s/w_6)^2} \left(\frac{w_5}{w_6}\right)^2 \quad (1.c)$$

$$H(s) = H_{BL}(s)H_T(s)H_s(s) \quad (1.d)$$

2.2 Perception model

The human perception organs are the vestibular and otolith organs, which percept the rotational velocity and the specific force that is difference between acceleration and the gravitational acceleration, respectively.

The transfer function of the vestibular organ to the rotational velocity is given as Eq.(2.a) and that of otolith organ to the specific force is given as Eq.(2.b).

$$G_{angular}(s) = \frac{T_L T_{AS}^2}{(T_L s + 1)(T_{SS} s + 1)(T_{AS} s + 1)} \quad (2.a)$$

$$G_{specific}(s) = \frac{k(\tau_{AS} s + 1)}{(\tau_L s + 1)(\tau_{SS} s + 1)} \quad (2.b)$$

3. Motion Cueing Model

Two kinds of technique have been used to process the vehicle signal in the motion cueing algorithm, the adaptive washout and the optimal motion cueing. The adaptive washout algorithm consists of three 2nd order transfer function in each direction motion and refers to the frequency response of perception model (the otolith and vestibular models) in order to find the natural frequency and damping coefficient of the transfer functions so that perception model is not included in the algorithm. In the optimal motion cueing algorithm, the perception model is the part of the structure. This method has 4 modes and applies the optimal control theory to each mode. In our work, the perception model is displaced by perception plus

body model to diminish the sensational error.

3.1 Optimal algorithm

The system including the optimal algorithm $W(s)$ is shown Fig. 1. $u_s(s)$ is the motion cue reproduced by the motion cueing algorithm and $u_v(s)$ is the cue given by the vehicle dynamics. In this method, the motion is divided into 4 modes such as the longitude (pitch/surge), the lateral (roll/sway), the heave, and the yaw mode. And the optimal control theory is applied to the state space equation given by the transfer function of the human body in each mode.

The algorithm of the longitude mode is described as following. The other three modes have similar structures.

The input to this mode, Eq.(3), is composed of the angular velocity of the pitch, $\dot{p}$, and the acceleration of the surge, $\dot{a}_x$. Equations.(4) and (5) display the relation between the angular velocity of the pitch and its sensational signal, $\hat{p}$, and the relation between the specific force, $f_x = a_x + pg$, where p is pitch angle and g is gravitational acceleration, and its sensational signal, $\hat{f}_x$, respectively. The transfer functions, $HG_{pitch}(s)$ and $HG_{surge}(s)$, are given in Appendix.

$$u = \begin{bmatrix} \dot{p} \\ \dot{a}_x \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (3)$$

$$\hat{p} = H_{pitch}(s)G_{pitch}(s)\dot{p} = HG_{pitch}(s)\dot{p} \quad (4)$$

$$\hat{f}_x = H_{surge}(s)G_{surge}(s)f_x = HG_{surge}(s)f_x \quad (5)$$

Equations (4) and (5) can be rewritten in state space equations, Eqs.(6) and (7), that have the observable canonical forms.

$$\dot{x}_{1-9} = A_{pitch}x_{1-9} + B_{pitch}u, \quad \hat{p} = C_{pitch}x_{1-9} \quad (6)$$

$$\hat{f}_x = HG_{surge}(s)f_x = HG_{surge}(s)u_1 + gHG_{surge}(s)u_2/s$$

$$\dot{x}_{10-25} = A_{surge}x_{10-25} + B_{surge}u, \quad \hat{f}_x = C_{surge}x_{10-25} \quad (7)$$

Where $x_{1-9} = [x_1 \cdots x_9]^T$ and $x_{10-25} = [x_{10} \cdots x_{25}]^T$.

Two equations, Eqs.(6) and (7), can be rewritten in one equation as Eq.(8).

$$\dot{x}_{1-25} = A_V x_{1-25} + B_V u, \quad \hat{y} = C_V x_{1-25} \quad (8)$$

Where A_V, B_V and C_V are given in Appendix.

This Eq.(8) describes the relation between $u_s(s)$

Fig. 1 Optimal motion cueing algorithm

and sensation signal as well as the relation between $u_v(s)$ and sensation signal.

$$\dot{x}_{1-25} = A_v x_{1-25} + B_v u_s, \hat{y} = C_v x_{1-25} \quad (9)$$

$$\dot{x}_{1-25} = A_v x_{1-25} + B_v u_v, \hat{y} = C_v x_{1-25} \quad (10)$$

From Eqs.(9) and (10), we can have the error dynamic equation.

$$\dot{x}_e = A_v x_e + B_v u_s - B_v u_v, e = C_v x_e \quad (11)$$

It is assumed that the vehicle signal u_v , which is presented by Eq.(12), the filtered white noise. So total space equation is represented by Eq.(13).

$$\dot{x}_n = A_n x_n + B_n w, u_v = x_n \quad (12)$$

Where w is white noise.

$$x = [x_e \ x_n]^T, \dot{x} = Ax + Bu + Hw, y = e = Cx \quad (13)$$

Where A, B, H and C are given in Appendix.

In the optimal control theory, the cost equation is taken as Eq.(14.a) which can be rewritten in the state variable form as Eq.(14.b).

$$J = E \left\{ \int_{t_0}^{t_1} y^T Q y + u_s^T R u_s dt \right\} \quad (14.a)$$

$$J = E \left\{ \int_{t_0}^{t_1} x^T G x + u_s^T R u_s dt \right\}, G = C^T Q C \quad (14.b)$$

Then, the optimal control input can be found in this form.

$$u_s = -R^{-1} B^T P x = -[F_1 \ F_2] x \quad (15)$$

From Eqs.(11) and (15), we can have the relation between the vehicle signal u_v and simulator motion cue u_s that is given as Eq.(16).

$$u_s = W(s) u_v,$$

$$W(s) = -F_1(sI - A_v + B_v F_1)^{-1}(-B_v - B_v F_2) - F_2 \quad (16)$$

The function $W(s)$ is motion cueing algorithm using the optimal control theory. The lateral mode is similar with the longitude mode and the heave/yaw modes are calculated by Eq.(7) without the gravity g .

4. Simulation and Result

For the optimal motion cueing algorithm $W(s)$ proposed in the section 3, the computer simulation is carried out as following. The rotation motion of the vehicle signal u_v in Fig.1 is taken as a pulse signal with the period 5 sec, the width 2 sec and the amplitude 0.5 rad/s. And the translation motion is taken as a pulse signal with the period 5 sec, the width 2 sec, the amplitude 1 m/s², and the delayed 1 sec start time. Each input of modes (longitude, lateral, heave and yaw) is given by Fig.2(b), Fig.3(b), Fig.4(b) and Fig.5(b).

Figures 2-5 show that sensation errors in 4 modes are all admissible. Though it is difficult to say that our proposed algorithm is better than the precedent ones from these quantitative results, it can be said that some improvement in qualitative respect is achieved since human body model as well as percep-

Fig. 2 Longitude (Surge/Pitch) mode: (a) sensation error (—: surge, - - - : pitch), (b) input (—: surge, - - - : pitch), (c) produced motion cue (surge), (d) produced motion cue (pitch), (e) specific force of human (—: by the produced motion cue $u_s(s)$, - - - : by the vehicle signal $u_v(s)$), (f) angular velocity of human (—: by the produced motion cue $u_s(s)$, - - - : by the vehicle signal $u_v(s)$)

Fig. 3 Laterla (sway/roll) mode: (a) sensation error (—: sway, - - -: roll), (b) input error (—: sway, - - -: roll), (c) produced motion cue (sway), (d) produced motion cue (roll)

Fig. 4 Heave mode: (a) sensation error, (b) input, (c) produced motion cue

Fig. 5 Yaw mode: (a) sensation error, (b) input, (c) produced motion cue

tion model is involved in this algorithm.

5. Conclusion

In this work, we propose a new optimal motion cueing algorithm where the human body model as well as the human perception model are incorporated so that the sensation error that the human feel between vehicle signal and simulator motion subject to the motion cues is more diminished. We address the procedure to design optimal motion cueing algorithm $W(s)$ and show the performance of this algorithm through computer simulations. The simulation results show that some improvement is achieved quantitatively as well as qualitatively.

Appendix

$$HG_{pitch}(s) = \frac{a_1 s^5 + a_0 s^4}{s^9 + b_8 s^8 + b_7 s^7 + b_6 s^6 + b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0} \quad (A1)$$

$$HG_{surge}(s) = \frac{c_2 s^4 + c_1 s^3 + c_0 s^2}{s^8 + d_7 s^7 + d_6 s^6 + d_5 s^5 + d_4 s^4 + d_3 s^3 + d_2 s^2 + d_1 s + d_0} \quad (A2)$$

$$A_{pitch} = \begin{bmatrix} 0_{1 \times 8} & -b_0 \\ I_{8 \times 8} & -b_{1-8} \end{bmatrix}, \quad b_{1-8} [b_1 \cdots b_8]^T, \quad (A3)$$

$$B_{pitch} = \begin{bmatrix} 0_{4 \times 2} \\ a_0 & 0 \\ a_1 & 0 \\ 0_{3 \times 2} \end{bmatrix}, \quad C_{pitch} = [0_{1 \times 8} \quad 1]$$

$$A_{surge} = \begin{bmatrix} A_{surge-u1} & 0_{8 \times 8} \\ 0_{8 \times 8} & A_{surge-u2} \end{bmatrix}, \quad B_{surge} = \begin{bmatrix} B_{surge-u1} \\ B_{surge-u2} \end{bmatrix},$$

$$C_{surge} = [C_{surge-u1} \quad C_{surge-u2}] \quad (A4)$$

where

$$A_{surge-u1} = A_{surge-u2} = \begin{bmatrix} 0_{1 \times 7} & -d_0 \\ I_{7 \times 7} & -d_{1-7} \end{bmatrix}$$

$$B_{surge-u1} = \begin{bmatrix} 0_{2 \times 2} \\ 0_{3 \times 1} & c_{0-2} \\ 0_{3 \times 2} \end{bmatrix}, \quad B_{surge-u2} = \begin{bmatrix} 0_{1 \times 2} \\ g \cdot c_{0-2} & 0_{3 \times 1} \\ 0_{4 \times 2} \end{bmatrix}$$

$$C_{surge-u1} = C_{surge-u2} = [0_{1 \times 7} \quad 1]$$

$$A_v = \begin{bmatrix} A_{pitch} & 0_{9 \times 16} \\ 0_{16 \times 9} & A_{surge} \end{bmatrix}, \quad B_v = \begin{bmatrix} B_{pitch} \\ B_{surge} \end{bmatrix},$$

$$C_v = \begin{bmatrix} C_{pitch} & 0 \\ 0 & C_{surge} \end{bmatrix} \quad (A5)$$

$$A_n = \begin{bmatrix} -1.0 & 0 \\ 0 & -4\pi \end{bmatrix}, \quad B_n = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (A6)$$

$$A = \begin{bmatrix} A_v & -B_v \\ 0 & A_n \end{bmatrix}, \quad B = \begin{bmatrix} B_v \\ 0 \end{bmatrix}, \quad H = \begin{bmatrix} 0 \\ B_n \end{bmatrix},$$

$$C = [C_v \quad 0] \quad (A7)$$

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