Filtration of Feedback Signal to Human Operator in Active Sensory Feedback System

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Abstract

In many manufacturing processes, the human operator could perform its task well and swiftly, if it could acquire sensory information helpful to the performance effectively. In such situations, high frequency components contained in the sensory information (feedback signal to the operator) must be suppressed, because the operator cannot recognize and respond them. In this research, the cut-off frequency of low pass filter in active visual feedback system has been investigated. The objective manufacturing operation is to make a small-diameter hole onto an aluminum workpiece with a carbide drill and the feedback information is cutting force. As the results, from the points of operating efficiency, workload and fatigue of the operators, it is found that the optimum cut-off frequency exists.

1 Introduction

In recent years, the role of human operators is still indispensable from the viewpoints of flexibility to a wide range of objective operation and adaptability in emergency situation. The abilities of human operators are closely related to the information acquisition ability through their sense organs. If the operators could acquire sensory information relevant to the operation actively by using a special device, they could improve their ability further more. The authors have been investigating the behavior of sensory feedback so far and developed several devices for active auditory, force sensory and visual feedback of minute cutting force in manufacturing with manual machine tools[1-4]. In active sensory feedback systems, high frequency components contained in the feedback signal to the operator must be suppressed, because the operator cannot recognize and respond them. To suppress them, a low pass filter is applied. However, the optimum filtering condition has not been clarified yet. Hence, in this paper, the effect of filtration in active visual feedback system has been investigated.

2 Objective task and active visual feedback system

The objective task is to make a small-diameter blind hole onto an aluminum workpiece with a carbide drill. The cutting conditions are shown in Table 1. This is a difficult task for even skilled operators as well as unskilled ones, because the drill flutes are apt to be choked with the cutting chip and the drill often breaks. As a machine tool, an NC milling machine in manual operation mode was adopted in order to remove the influence of force sensory feedback. That is to say, since its handwheel is just connected with a pulse generator for spindle feed, the operator cannot feel cutting force through the handwheel at all. In addition, no auditory feedback exists either, because loud sound of the main spindle motor prevents the operator from hearing cutting sound. Accordingly, only the visual feedback, or view of the cutting chip flow, drill breakage, etc., exists basically in this task.

Figure 1 shows the active visual feedback system of cutting force for drilling. As the feedback information, the force signal is selected because it is very important for the operator to complete the task safely and swiftly. The force is detected with a strain gauge type

Table 1 Conditions of objective task

Cutting tool	Carbide drill (ϕ1 mm)
Workpiece	Easy machinable aluminum (ϕ5 mm)
Approach distance	5 mm
Depth of hole	5 mm
Rotational speed	500 rpm
Machine tool	NC milling machine MAKINO AV III NC-85 (Manual operation mode with a handwheel)

dynamometer and input to a personal computer. The computer processes the force information and displays it as a sector chart on a screen of a monocular HMD (Data glass, Shimazdu Corporation) which the operator wears. The operator can see the drill and workpiece themselves through HMD because it is a see-through see-around type one.The cutting force displayed by sector chart on HMD is either thrust (axial) component or torque (rotational) component. In this paper, only thrust component has been discussed, because envelope calculation is necessary in the feedback of torque signal [4] and the calculation itself has low pass filtering effect. The right photo in Fig.1 shows a sample image which the operator get while drilling. The sector chart is selected because it is effective in improvement of operating efficiency [4]. The sector angle corresponds to the cutting force. The chart size and position in the display screen can be adjusted as the operator likes. The sector angle of 135^{o} corresponds to the critical cutting (thrust) force 40N at which the tool breakage often occurs. The pattern color is changed into 3 steps as shown in Table 2 and the operator can roughly recognize the magnitude of cutting force by the color change too. In addition, the high operating efficiency without drill breakage will be achieved if the sector angle is near the middle of yellow area, or sector angle 112.5^{o}.

Figure 2 shows the cutting force signal detected with the dynamometer. Though a second order Batterworth low pass filter of 1 Hz inside a strain amplifier is used for the measurement, the fluctuation caused by rotation of the drill (8.33r/s) still appears because of dominant component in the signal. To suppress the high frequency component sufficiently, FIR low pass filter[5] was examined in this research. The filtration is done in PC by a software. Figure 3 shows the transmissibility of FIR low pass filter examined. The filter cuts off sharply the component over the double cut-off frequency, though the gain at the cut-off frequency is only -7dB.

3. Influence of cut-off frequency on performance

By preliminary experiments, 1,2,3 and 5Hz have been chosen as the cut-off frequency of FIR low pass filter to be examined. Subjects were 6 twenties- or thirties-aged male adults. The time of completing a task was about 8 to 20 seconds for all subjects. Before the real experiment, all subjects had practiced the tasks under various conditions many times in order to accustom themselves to the vi-

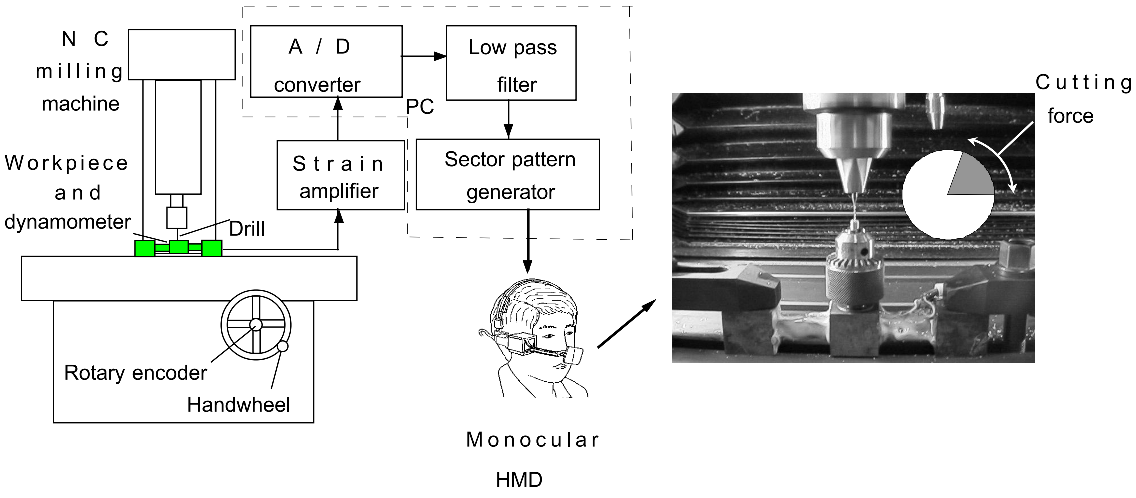
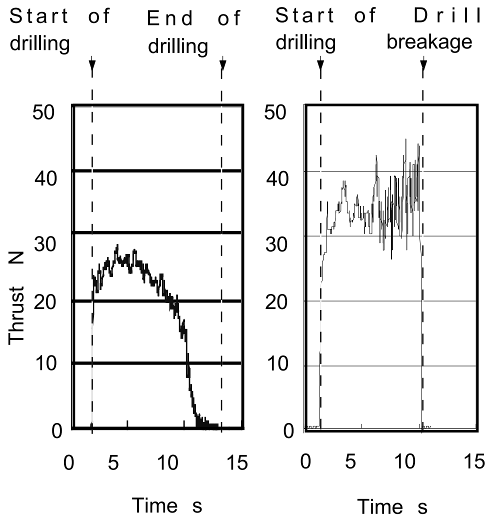


Fig.1 Active visual feedback system using using monocular HMD for minute drilling



(a) Completed task (b) Failed task

Fig.2 Cutting force signal

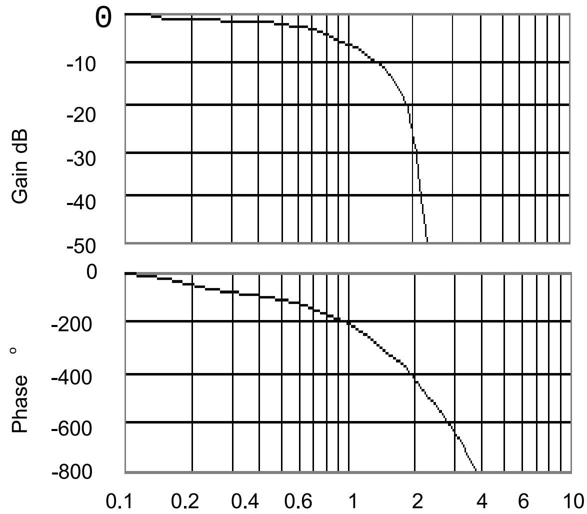


Fig.3 Transmissibility of FIR low pass filter

sual feedback with HMD. As a set of experiments, a subject executed 20 tasks one after another under the same filtering condition. A set of experiments under a filtering condition followed another set of experiments under different filtering condition with over ten minutes recess. The filtering condition was selected in random order. For each task, the subject is requested to complete it as swiftly as possible without drill breakage.

The performance of a task is evaluated by the following index; where *r* represents the distance from the drill point position at time *t* to its final position, and *T* represents total time consumption for the task.

$$I=\int_0^T |r|\cdot t\,dt \qquad (1)$$

For measuring the distance *r*, a rotary encoder is attached on the handwheel as shown in Figure 1. When the drill happened to break, the task was regarded as "failed" and the index value was not evaluated. Besides the performance, the subjective symptom of the tasks as workload was evaluated using NASA-TLX [6] after each set of experiments. As the indexes of mental stress and fatigue, electromyogram (EMG) of forehead of the operator in eye closing state

Table 2 Display pattern color

Sector angle	0^o-110^o	110^o-135^o	135^o-360^o
Pattern color	Green	Yellow	Red

and critical fricker fusion value (CFF) were measured before all tasks and every five tasks.

Figures 4 to 7 show the experimental results. Figure 4 shows average performance index *I* of the 6- to 20-th tasks. The reason why the data of the first to fifth tasks were omitted in calculation of the average is that the index *I* goes to an steady value at the sixth task for almost all subjects and filtering conditions. As seen in this figure, the cut-off frequency f_c=2Hz provides the best operating efficiency for all subjects and f_c=1Hz provides the worst operating efficiency. In addition, it should be noticed that the performance of f_c=1Hz is quite worse than that of f_c=3Hz, though the frequency difference from f_c=2Hz is the same. This result comes from the difference of the time delay corresponding to phase shift; 0.8 s for f_c=1Hz and 0.18 s for f_c=3Hz. Large time delay naturally leads to low maneuverability.

Figure 5 shows the average weighted workload by NASA-TLX. Low value of the workload indicates comfortability of the subject while task, and high value does difficulty of the task. In the figure, the minimum value appears in the case of f_c=2Hz for almost all subjects, similarly to that of the average performance index. This fact means that the condition which improves the operating efficiency can reduce the workload. Figure 6 shows the variation ratio of CFF[7]. Positive value of the ratio indicates the increase of mental fatigue by the tasks and negative value does the increase of arousal level without fatigue. In this figure, the minimum value also appears in the case of f_c=2Hz. Figure 7 shows the average EMG of forehead while 20 tasks. From this figure, it is seen that the mental tress increased with the cut-off frequency for almost all subjects. It

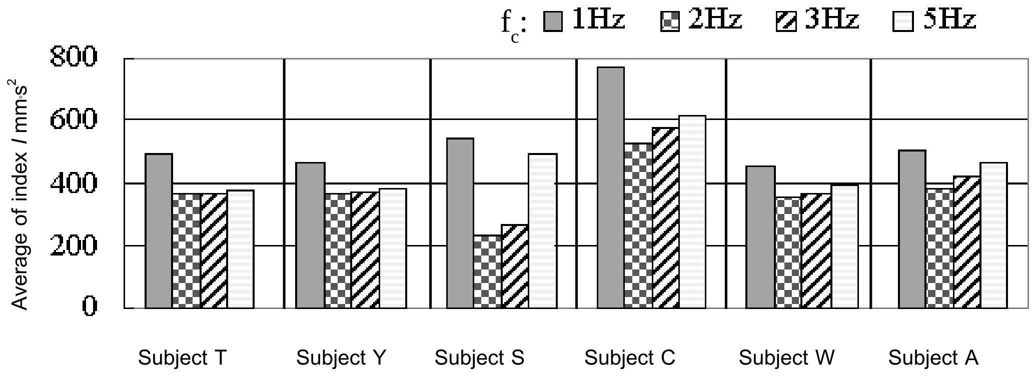


Fig.4 Average performance index

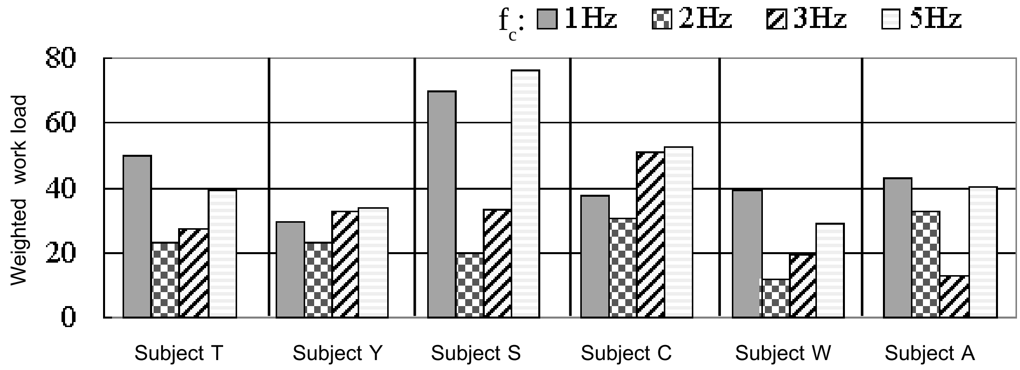


Fig.5 Subjective symptom by NASA-TLX

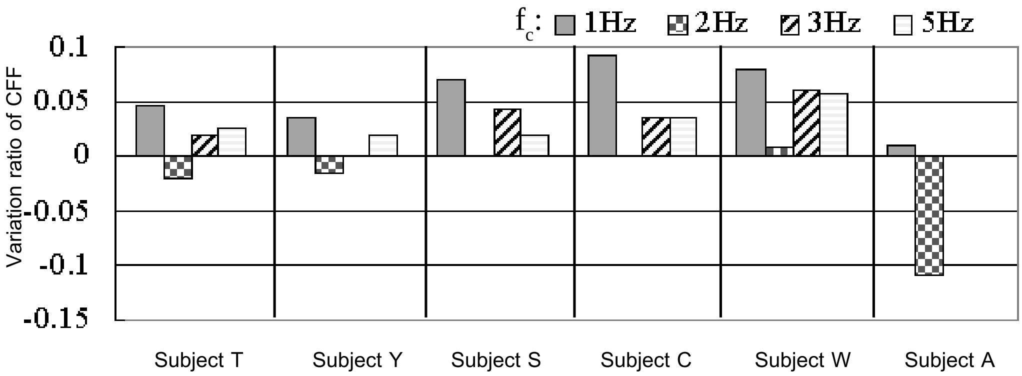


Fig.6 Variation ratio of CFF

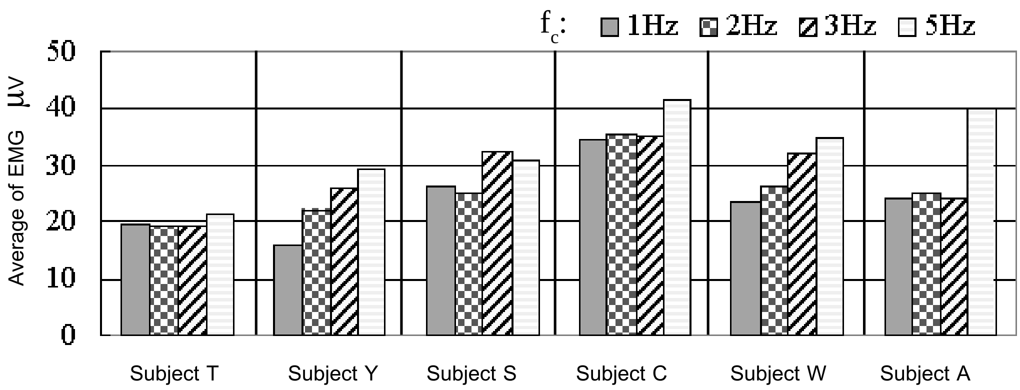


Fig.7 Comparison of average of EMG of forehead

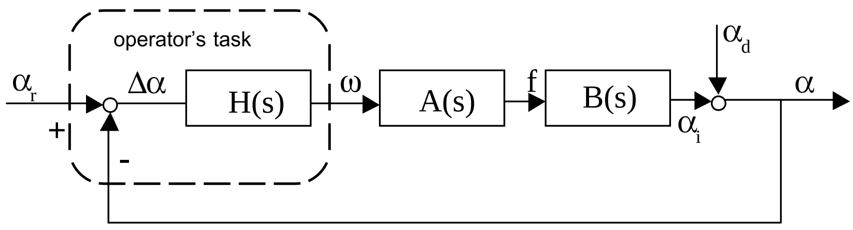


Fig.8 Block diagram of active visual feedback system for the objective task.

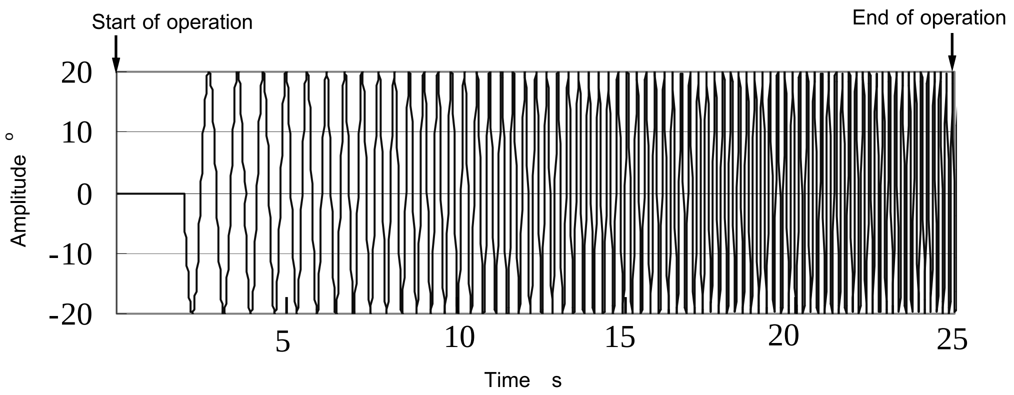


Fig.9 Applied noise signal.

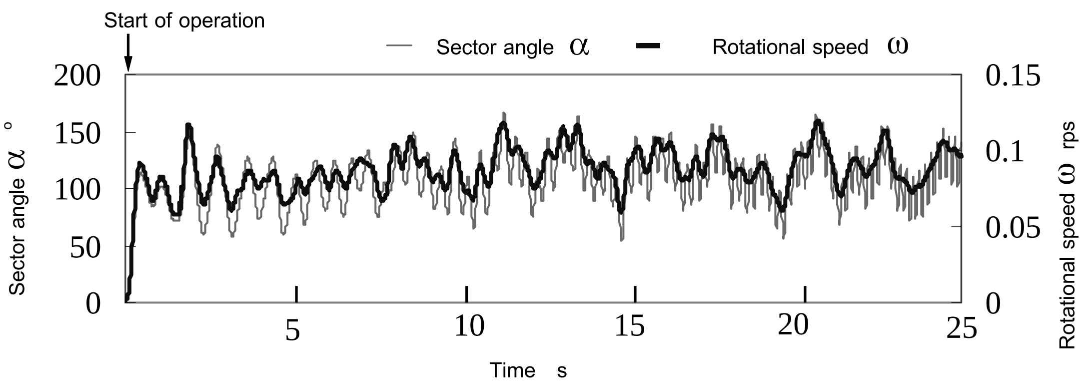


Fig.10 Example of changes in sector angle a and rotational speed ω.

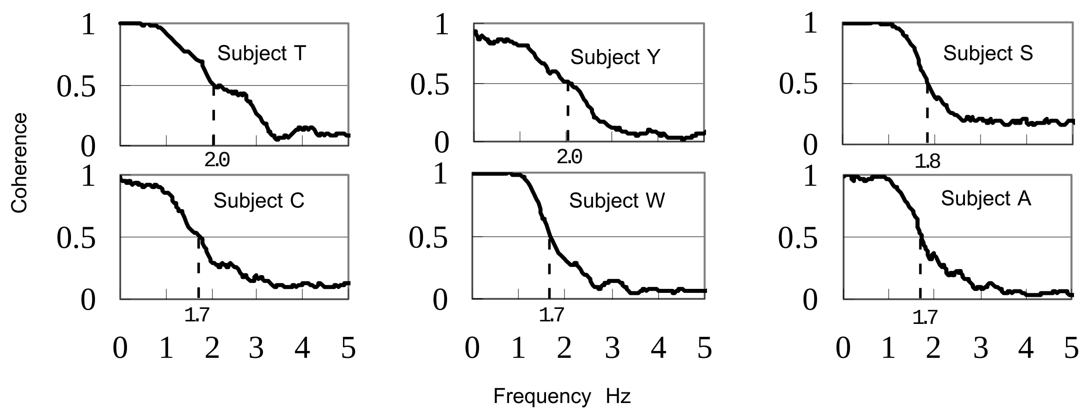


Fig.11 Coherence plots between Δα and ω.

is considered that the fast variation of sector angle might cause the increase of mental stress.

From the results mentioned above, it can be concluded that the optimum cut-off frequency for the objective task with active visual feedback is 2Hz.

4. Evaluation of human characteristic in active visual feedback

The active visual feedback system for the objective task can be expressed in the form of block diagram as shown in Fig.8. The nomenclatures used are as follows:

α_r : Target angle of sector chart (=122.5°)

$\Delta\alpha$:Sector angle error (=α_ρ-α)

ω : Handle rotation speed (rps)

f : Cutting force (N)

α_i : Sector angle to be displayed (°)

H(s) : Human characteristics

A(s) : Cutting process (relation between handle rotation speed and cutting force (N/rps))

B(s) : Visual feedback process (relation between cutting force and sector angle (°/N))

α_d : Noise signal (°)

α : Actual sector including noise signal (°)

s : Laplace operator

The operator's task is to detect the difference between the target and current sector angles, and to rotate the handwheel so as to reduce the difference. There must be some relation between the optimum cut-off frequency derived in the previous section and the human characteristics in operator's task. To investigate it, the human characteristics H(s) or the coherence function related with it was evaluated by simulating the cutting process A(s) with a constant 367.7 [N/rps] and applying 0.5-5Hz charp signal as the noise. The constant and range of charp signal were determined on the basis of experimental results. As shown in Fig.9, the charp signal was put into the system after 2 seconds from the start of the operation. The example of changes in the sector angle a and the rotational speed ω of one subject is shown in Fig.10. The data from 2 s to 25 s were Fourier-transformed and the human characteristics was evaluated. Figure 11 shows the coherence plots between $\Delta\alpha$ and ω of all subjects. Since the coherence is a correlation coefficient between the input and output, the human characteristics can be evaluated by the frequency at which the value crosses 0.5. From this figure, it is obvious that the frequency is 1.7 to 2.0 Hz. In other words, each subject can be a controller for the frequency range below about 2 Hz. Therefore, the cut-off frequency of low pass filter for the objective task should be 2 Hz.

5. Conclusions

In this study, the cut-off frequency of low pass filter in active visual feedback system has been investigated. The objective task is small-diameter drilling with sector chart type visual feedback of cutting force. Main conclusions obtained are summarized as follows.

(1)The optimum cut-off frequency which provides the maximum operating efficiency exists.

(2)The optimum cut-off frequency can minimize the mental workload and the fatigue.

(3)The human characteristics measured by using a simply simulated cutting process and charp noise explains the existence of the optimum cut-off frequency very well.

References

[1]. H. Kato and T. Sato, Effect of Auditory feedback on Operating Efficiency and Fatigue --In the Case of Manual Cut-Off Turning with Virtual Lathe, Int. J. of Japan Soc. for Precision Eng.,30,4,(1996) 325.

[2]. H. Kato, K. Kobayashi and Liu S., Skill Learning in Manual Machine Tool Operation --Development of New Virtual Lathe and Study on Minute Grooving by Using It, Int. J.of Japan Soc. for Precision Eng., 31,3,(1997) 221.

[3]. H. Kato and N. Taoka, Active Sensory Feedback in Manual Machine Tool Operation --Effect of Auditory and Force Sensory Feedback of Cutting Force in Fine Machining, Int. J.of Japan Soc. for Precision Eng., 64,3,(1998) 455.

[4]. N.Depaiwa, H. Kato, Yang Y. and S. Ochiai, Active Visual Feedback Using Head Mounted Display in Human Directed Manufacturing System, Human Friendly Mechatronics (ICMA2000), 49.

[5]. T. Takebe, Design of ditital filter, Tokai University Publishing Co.,(1986) 51 (in Japanese)

[6]. e.g. S. Miyake and M. Kumashiro, Subjective mental workload assessment technique --An introduction to NASA-TLX and SWAT and a proposal of simple scoring methods, J. of Japan Ergonomics Soc.,29,6,(1993)399 (in Japanese).

[7]. e.g. Ergonomics Handbook, Kanehara Publishing Co.,(1966) 441 (in Japanese).