Compensatory tracking in disturbance tasks and target following tasks. The influence of cockpit motion on performance and control behaviour.

December 1987

J.C. van der Vaart / R.J.A.W. Hosman
Compensatory tracking in disturbance tasks and target following tasks. The influence of cockpit motion on performance and control behaviour

J.C. van der Vaart / R.J.A.W. Hosman
Summary

Manned, moving base simulator experiments, reported by the authors and many others, show improved tracking performance (lower error RMS) in disturbance tasks as well as in target following tasks when cockpit motion is added to a basic, visual, artificial horizon display. For so-called disturbance tasks, where the disturbing signal acts on the controlled element and where system output is presented on the display, improved performance due to cockpit motion is accompanied by measured increases in crossover frequency while phase margin remains fairly constant. Improved performance is, in this case, readily explained by larger overall controller gain and greater bandwidth. For target following tasks, where the error between disturbing signal and system output is presented visually, improved performance due to cockpit motion is correlated with large increases in phase margin, whereas crossover frequency is hardly influenced. These findings were reported over and again in literature, yet without satisfactory explanation.

The present report clarifies these experimental findings both qualitatively and quantitatively by analysing the differences of the two tasks in terms of classic control theory and by using experimental data on vestibular motion perception obtained earlier by the present authors.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of symbols</td>
<td>3</td>
</tr>
<tr>
<td>1. Introduction. Disturbance and target following compensatory tracking tasks</td>
<td>4</td>
</tr>
<tr>
<td>2. Summary of experimental results</td>
<td>6</td>
</tr>
<tr>
<td>3. Closed-loop stability and performance of the operator-controlled system</td>
<td>8</td>
</tr>
<tr>
<td>4. Closed-loop transfer functions and performance calculated from measured human operator describing functions</td>
<td>13</td>
</tr>
<tr>
<td>5. The influence of human controller simplified model parameters on performance</td>
<td>15</td>
</tr>
<tr>
<td>6. Why large phase margin improves tracking performance in target following</td>
<td>16</td>
</tr>
<tr>
<td>7. Vestibular motion perception in compensatory tracking tasks</td>
<td>18</td>
</tr>
<tr>
<td>8. Concluding remarks</td>
<td>21</td>
</tr>
<tr>
<td>References</td>
<td>22</td>
</tr>
<tr>
<td>Tables</td>
<td>24</td>
</tr>
<tr>
<td>Figures</td>
<td>26</td>
</tr>
</tbody>
</table>
List of symbols

- $H(s)$: transfer function
- $H_c(s)$: transfer function, controlled element
- $H_{\text{closed}}(s)$: closed-loop transfer function
- $H_p(s)$: human pilot transfer function
- $H(\omega)$: frequency response, describing function

- $j = \sqrt{-1}$: gain factor
- $K_c$: gain factor in $H_c(s)$
- $K_p$: gain factor in $H_p(s)$
- $s$: Laplace variable
- $\text{RMS}$: root mean square
- $l/r$: error amplification factor
- $w_i$: noise input, disturbance signal, driving function

- $\delta$: control deflection
- $\epsilon$: error (angle)
- $\sigma_x^2$: variance of $x$
- $\tau$: time constant
- $\tau_e$: effective time delay
- $\phi$: roll angle
- $\phi_i$: input, reference roll angle
- $\phi_m$: phase margin
- $\Phi_{xx}(\omega)$: power spectral density of $x$
- $\omega$: angular frequency (rad/sec)
- $\omega_c$: crossover frequency
- $\omega_{ec}$: error crossover frequency
- $\omega_i$: (effective) input power spectrum bandwidth

Subscripts

- $c$: controlled element
- $D$: disturbance task
- $i$: input, disturbing signal, forcing function
- $L$: lead
- $p$: human pilot
- $T$: target following task
- $\text{vest. v}$: vestibular
- $\text{vis}$: visual
1. Introduction. Disturbance and target following compensatory tracking tasks

Tracking tasks are well established experimental tools in research on human control behaviour (Refs. 1 and 2). This report is concerned with compensatory tracking tasks in which the operator sees only the error between input and output and where his task is to null it. This is different from so-called pursuit tracking tasks where the operator sees input and output independently and tries to match them (Ref. 1).

A general block diagram of compensatory tracking is given in Fig. 1. The human operator follows a moving target while the controlled system is being disturbed by an external noise signal. Such a task has many real-world equivalents, for instance when a human pilot follows a moving target while the aeroplane (the controlled system) is perturbed by atmospheric turbulence. Most laboratory tasks used in human controller research, however, fall into one of the following categories, which are particular cases of the one depicted in Fig. 1.

i) Disturbance tasks in which a disturbance signal acts on the controlled element and where the reference input variable in Fig. 1 is set to zero. System output is displayed to the controller.

ii) Target following tasks where the disturbance signal (or 'forcing function') is the reference signal and where the disturbance on the controlled element in Fig. 1 is set to zero. Here the error between disturbance input and system output is displayed to the controller.

In the present report, only pure disturbance and pure target following tasks are considered, see Fig. 2.

Since task nomenclature tends to differ among authors, the most current denominations and the references in which they occur, have been summarized in Table 1.

The most important differences between the two tasks will be illustrated by taking single axis roll control tasks (see Ref. 3) as examples, see Fig. 2.

The blocks denoted by \( H_d(s) \) and \( H_c(s) \) are transfer functions of human controller and controlled element respectively. The control signal is the stick deflection \( \delta \), system output is the roll angle \( \varphi \). The error signal \( \varepsilon \) is displayed on the artificial horizon. For the sake of simplicity human control behaviour is here taken to be purely linear and time independent, no remnant noise (see Refs. 9 and 11) is supposed to be present.

In the disturbance task of Fig. 2b, the disturbing signal \( w_i \) acts on the controlled element, the error signal to be nulled by the human operator is

\[
\varepsilon_D = \varphi_i - \varphi = -\varphi
\]  

since the reference input signal \( \varphi_i \) is zero. The subject's task is like keeping an aeroplane wings level during flight in turbulence. In target following, Fig. 2b, the disturbing signal (forcing function) acts on the display directly, the error to be nulled is

\[
\varepsilon_T = \varphi_i - \varphi = w_i - \varphi
\]  

since the reference input signal is equal to the disturbing signal \( w_i \).
In most experiments, the disturbance $w_i$ is a quasi-random one consisting of the sum of a number of sinusoids (usually between 8 or 13, see Refs 3, 4, 6, 7, 11 and 13).

In either task, subjects are required to keep the error $e$ as small as possible and performance is expressed by the measured RMS of the error signal $e$, often perhaps less appropriately called the standard deviation $\sigma_e$.

If the disturbance signal $w_i$, is identical in either case, as in the experiments of Refs. 3 and 4, a first distinction is that in disturbance tasks the disturbing signal cannot be perceived directly. Only the response of the controlled element (Fig. 2a) to the disturbance signal is perceived. This is in contrast with target following, where $w_i$ is fed directly to the display (Fig. 2b).

Simulated controlled elements, like real world systems, are usually of second or higher order and therefore the disturbing signal will be low-pass filtered before being displayed to subjects in disturbance tasks. As a consequence, the displayed error signal will have a much lower high frequency content if compared to the error signal in target following where the disturbance signal is fed to the display directly and unfiltered.

A next distinction is, that in disturbance tasks the visually presented error is identical with the output of the controlled element, whereas in target following tasks such a direct connection is lacking, see eq. (2). The latter distinction becomes still more important when cockpit motion is present. System angular acceleration $\dot{\phi}$ is then sensed by the subject's vestibular apparatus, see Fig. 3. In disturbance tasks, the vestibular information is much more directly related to the error signal displayed visually (Fig. 3a) than in target following tasks (Fig. 3b).

Of course a similar important distinction exists when roll rate ($\dot{\phi}$) information is made perceivable to subjects for instance by providing peripheral visual field displays (Refs. 3 and 4).
2. Summary of experimental results

Experiments by the present authors where done in the three-degrees-of-freedom moving base flight simulator of Delft University of Technology. The influence of various combinations of central display (artificial horizon, C) peripheral visual field displays (P) and cockpit motion (M) were studied for disturbance and target following tasks in which roll angle was the variable to be controlled. The dynamics of the controlled element were those of a double integrator with

\[ H_c(s) = \frac{K_c}{s^2} \quad \text{where } K_c = 4.0 \text{ sec}^{-2} \]

No motion filtering was applied in the simulator motion generation, the dynamic characteristics of the motion system hardware were compensated for such that over the frequency range of interest, a one to one simulation of roll motion was obtained. For details, the reader is referred to Refs. 3 and 4.

In the context of the present Report only tasks with central display only (C), or central display combined with peripheral displays (CP), with cockpit motion (CM) or both (CPM) will be considered. Results of performance, as expressed in error signal standard deviation are summarized in Fig. 4. Addition of peripheral visual field displays, of cockpit motion or both decrease the measured error standard deviation significantly for both classes of tasks.

Some examples of measured open loop describing functions are shown in Fig. 6 where the measured modulus (or gain) and the phase of the open loop describing functions

\[ H_P(\omega) \cdot H_C(\omega) \]

are plotted together with the open loop phase \( \varphi \).

The frequency where the modulus (or gain) is

\[ |H_P(\omega) H_C(\omega)| = 1 \]

called the crossover frequency \( \omega_c \). For \( \omega = \omega_c \) the phase lag of the open loop transfer function should be less than 180° according to the classic Nyquist criterion for closed loop stability.

The phase margin \( \varphi_m \), defined by

\[ \varphi_m = 180 + \varphi_{H_P H_C}(\omega_c) \]

see Fig. 6, gives an indication of the margin of closed-loop stability. In general, higher \( \omega_c \) implies a higher overall controller gain, a more tight control and better closed-loop error compensation. Well-motivated subjects would, heuristically, choose as high a gain (and crossover frequency) as would be compatible with a certain minimum phase margin.

**Disturbance tasks**

Fig. 5 illustrates the changes in measured crossover frequency and phase margin due to changes in display configuration. For disturbance tasks crossover frequency increases from 3.18 rad/sec to 5.03 rad/sec due to the addition of peripheral displays and motion to the basic central display, while phase margin is between 14 and 19 degrees for all configurations. All relative improvements
in performance can be easily explained by higher crossover frequencies and, as a consequence, higher overall controller gains. 
The question why cockpit motion and peripheral displays enable a human controller to generate higher overall gains will be dealt with in more detail later on in this Report.

Target Following tasks

In target following, crossover frequency remains fairly constant around 2 rad/sec and even tends to decrease due to the presence of motion, see Fig. 5, while phase margin increases from around 19 degrees for central visual display (C) only to almost 60 degrees for the case with peripheral displays and motion added (CPM). For some reason, subjects do not trade the extra available phase margin for a higher gain, although performance is significantly better.

When comparing open loop describing functions \( H_p(\omega) \), \( H_c(\omega) \) in the two classes of tasks, some other remarkable features emerge, see for instance Fig. 6. Overall controller gains are much lower in target following, and the phase angles show typically more phase lead in the frequency range below the crossover region. Similar findings were reported by others, see for instance Refs. 5, 6 and 7. Displays, dynamics of the controlled element and motion generation are sometimes different in other experiments but the reported changes in control behaviour are similar.

More recently, results of simulated helicopter hovering experiments, featuring variations in vertical motion fidelity (Ref. 5), also revealed a quite similar influence of cockpit motion on crossover frequency and phase margin for the two types of tasks.

Experimental evidence as mentioned above has been published during several decades, and a number of hypotheses have been proposed as possible causes for subjects to behave differently in different tasks. 
The present authors suggested that, due to the fact that in their experiments test-subjects were experienced civil airline pilots, they intuitively restrained from aggressive control in target following. 
In the experiments of Ref. 6, subjects were non-pilots but were trained and required to minimize an error-score which was of the weighted sum of the RMS tracking error \( e \) and angular acceleration \( \dot{\phi} \), which possibly invoked a similar non-aggressive control strategy.

In Ref. 5, it was suggested that certain visual display characteristics 'tend to inhibit the control bandwidth exercised by the pilot' in the case of target following with motion.

Another explanation could be that since, in target following the visual feedback signal is contaminated with quasi random input noise, subjects are unable to fully profit from the cockpit motion cues available to them.

In Ref. 3, the present authors concluded that 'more complete mathematical descriptions of human control behaviour would be needed to explain the experimental findings'.

In the next Sections of this Report both categories of tracking tasks are analyzed in terms of classic control theory, using simplified linear controller transfer functions. It will be shown that, given the task of minimizing the error score, the measured control behaviour characteristics in fact reflect the most sensible controller strategies in either task and that trends in performance can fairly accurately be predicted from measured controller describing functions.

Finally, the markedly different influence of cockpit motion on controller behaviour in the two tasks, is made plausible by including a simple vestibular motion feedback loop in the human operator model.
3. Closed-loop stability and performance of the operator-controlled system

In this Report, human control behaviour will, just for the sake of clarity and brevity, be treated as if the human controller were a linear, time-independent regulator. Therefore, no remnant noise is supposed to be injected in the block diagrams of Figs. 2 and 3.
Moreover, in the present Section, the disturbance noise signal power spectrum is, for the same reasons, supposed to be continuous rather than discrete.
In the case of system linearity, frequency response functions \( H(\omega) \) are directly related to transfer functions \( H(s) \). Strictly speaking, conclusions based on these simplifying assumptions can only be related to the linear part of the partly linear (or quasi-linear) behaviour in actual practice. However, as will become apparent later on in this Report, some important conclusions derived from linear system theory (and a continuous disturbance noise power spectrum) can be applied to actually measured describing functions.

The closed-loop transfer function relating input \( \Phi_i(s) \) and output \( \Phi(s) \) is in either task, see Fig. 2,

\[
H_{\text{closed}}(s) = \frac{\Phi(s)}{\Phi_i(s)} = \frac{H_p(s) H_c(s)}{1 + H_p(s) H_c(s)}
\]

(3)

Closed loop stability

Closed loop stability can be analysed by considering the 'open loop' frequency response characteristics \( H_p(\omega) \cdot H_c(\omega) \) corresponding to \( H_p(s) \cdot H_c(s) \). As mentioned earlier, application of the well-known Nyquist stability criterion leads to the widely used parameters crossover frequency \( \omega_c \) and phase margin \( \phi_m \) (see Fig. 6).

Performance

When assessing performance, however, it is more appropriate to consider the particular closed loop function that relates the error signal \( \varepsilon \) to the disturbance input signal \( \omega_i \)

\[
H_{c\omega_i}(s) = \frac{\varepsilon(s)}{\omega_i(s)}
\]

If the power spectral density of the disturbance signal is

\[
\Phi_{\omega_i\omega_i}(\omega)
\]

then the power spectral density function of the error signal is, see Ref. 16
\[ \phi_{\epsilon \epsilon}(\omega) = |H_{\epsilon w_i}(\omega)|^2 \phi_{w_i w_i}(\omega) \] (4)

Since the error signal variance is given by (see Ref. 16)

\[ \sigma^2_{\epsilon} = \frac{1}{2\pi} \int_{0}^{\infty} \phi_{\epsilon \epsilon}(\omega) \, d\omega = \frac{1}{2\pi} \int_{0}^{\infty} |H_{\epsilon w_i}(\omega)|^2 \phi_{w_i w_i}(\omega) \, d\omega \] (5)

the variance \( \sigma^2_{\epsilon} \) of the error signal is completely determined by the modulus of \( H_{\epsilon w_i}(\omega) \) and the power spectral density of the disturbance signal. Whichever the task may be (target or disturbance), a well motivated subject should choose his control strategy such as to keep the modulus

\[ |H_{\epsilon w_i}(\omega)| \]

as small as possible over the entire frequency range of the input spectrum in order to minimize \( \sigma^2_{\epsilon} \).

A similar analysis was done by Mc Ruer et al for target following tasks, they approximated the input spectrum by a rectangular one and derived the so-called 'one-third law' (Ref. 11).

In disturbance tasks, see Fig. 2a, the error signal to be minimized is, see eq. (1)

\[ \epsilon(s) = -\varphi(s) \] (1)

and the controller output is then

\[ \delta(s) = H_p(s) \cdot \epsilon(s) = -H_p(s) \cdot \varphi(s) \] (6)

Since

\[ \varphi(s) = H_c(s) \cdot \delta(s) + H_c(s) w_i(s) \] (7)

it follows by combining eqs. (6) and (7) that

\[ H_{\epsilon w_i}(s) = \frac{\epsilon(s)}{w_i(s)} = \frac{H_c(s)}{1 + H_p(s) H_c(s)} \] (8)

where the subscript D denotes disturbance task.
For target following tasks, see Fig. 2b, the error signal is, see eq. (2)
\[ \varepsilon(s) = \varphi_i(s) - \varphi(s) = w_i(s) - \varphi(s) \]  
(2)

The controller output is here
\[ \delta(s) = H_p(s) \cdot \varepsilon(s) = H_p(s) \cdot w_i(s) - H_p(s) \varphi(s) \]  
(9)

and
\[ \varphi(s) = H_c(s) \delta(s) \]  
(10)

Combining eqs. (9) and (10) yields
\[ \varphi(s) = \frac{H_p(s) H_c(s)}{1 + H_p(s) H_c(s)} \cdot w_i(s) \]  
(11)

Finally, by combining eqs. (11) and (2) it follows that
\[ H_{e \varphi_{wi}}(s) = \frac{\varepsilon(s)}{w_i(s)} = \frac{H_p(s) H_c(s)}{1 + H_p(s) H_c(s)} = \frac{1}{1 + H_p(s) H_c(s)} \]  
(12)

where the subscript T denotes target following task.

It is remarked here that the closed-loop transfer function according to eq. (12) is different from the one used by Neil and Smith in their analysis. Their tracking performance standards (see Ref 12) are based on the closed-loop transfer function that directly obtains from eq (3):
\[ \frac{\varphi(s)}{w_i(s)} = \frac{H_p(s) H_c(s)}{1 + H_p(s) H_c(s)} \]

If it is assumed that subjects in either task will indeed try to minimize the error variance, as they were required in the experiments of Refs. 3 and 4, then it may be expected, by comparing eqs. (8) and (12), that their control strategies as characterized by $H_p(s)$ will be different in target following tasks when compared to disturbance tasks. This may be illustrated by a very simplified example where the human operator transfer function is taken to be a pure gain without time-delay:
\[ H_p(s) = K_p \]

If the dynamics of the controlled element are those of a double integrator as in Refs. 3 and 4, then
\[ H_c(s) = \frac{K}{s^2} \]

For the disturbance task it follows that, see eq. (8)

\[ H_{\varepsilon w_D}(s) = \frac{\frac{K}{s^2}}{1 + \frac{K}{p} \frac{K}{s^2}} = \frac{K}{s^2 + k_p K_C} \]

or

\[ H_{\varepsilon w_D}(s) = K_D \frac{1}{1 + \left(\frac{s}{\omega_o}\right)^2} \]  \hspace{1cm} (13)

where \( K_D = \frac{1}{K_p} \) and \( \omega_o = \sqrt{K K_c} \).

Similarly, the relevant closed-loop transfer function for the target following task becomes, see eq. (12)

\[ H_{\varepsilon w_T}(s) = \frac{\frac{K}{s^2}}{1 + \frac{K}{p} \frac{K}{s^2}} = \frac{s^2}{s^2 + k_p K_C} \]

or

\[ H_{\varepsilon w_T}(s) = K_T \frac{s^2}{1 + \left(\frac{s}{\omega_o}\right)^2} \]  \hspace{1cm} (14)

where \( K_T = \frac{1}{K_p K_c} \) and \( \omega_o = \sqrt{K K_c} \).

The frequency response functions obtained from eqs. (13) and (14) are respectively:

\[ H_{\varepsilon w_D}(\omega) = K_D \frac{1}{1 + \left(\frac{j \omega}{\omega_o}\right)^2} \]  \hspace{1cm} (15)
\[ H_{\infty}^{\ell}(\omega) = K_T \frac{(j\omega)^2}{1 + (j\omega/\omega_o)^2} \] (16)

The asymptotes of the moduli according to eqs. (15) and (16) have been schematically given in Fig. 7. The closed loop characteristics determining closed-loop performance for the disturbance task are typically low pass whereas those for target following are high pass.

Note that the asymptote of the modulus of eq. (15) for \( \omega \to 0 \) is \( K_D = \frac{1}{K_p} \), whereas the asymptote of the modulus of (16) for \( \omega \to \infty \) is unity. Also schematically shown is the influence of changes in controller gain \( K_p \) on the position of the asymptotes and on the corner frequency \( \omega_o \). Increasing controller gain \( K_p \) decreases the modulus of \( H_{\infty}^{\ell}(\omega) \) over the entire frequency range whereas for \( H_{\infty}^{\ell}(\omega) \) for target following this is only the case for low frequencies.
4. Closed-loop transfer functions and performance calculated from measured human operator describing functions

The experiments described in Refs. 3 and 4 featured all combinations of central artificial horizon display (C), peripheral visual field displays (P) and cockpit motion (M). For the present analysis, only the following combinations, all featuring the central visual display, are considered.

C : Central visual display only
CP : Central visual display combined with peripheral visual displays
CM : Central visual display and cockpit motion
CPM: Central visual display, peripheral displays and cockpit motion.

Measured operator describing functions have been plotted in Figs. 8 through 11 for the disturbance task and in Figs. 12 through 15 for the target following task.
A very simplified 'extended crossover' human pilot transfer function $H_p(s)$ (see Ref. 11) was used to fit to the data points in the crossover region (from 1 to 10 rads/sec):

$$H_p(s) = K_p (1 + \tau_L \tau_e^s)$$

where $K_p$ is the human controller gain, $\tau_L$ a lead constant and $\tau_e$ an effective time delay, a lumped parameter taking into account all time-delays caused by perception, decisionmaking and the generation of the control output, including delays due to the neuro-muscular system. As can be seen in the Figs. 8 through 11 a reasonable fit can be obtained, in the mid-frequency region, by using eq. (17). The parameters of the fitted models are summarized in Table 2. From the model parameters and the dynamics of the controlled system, the crossover frequency $\omega_c$ and phase margin $\phi_m$ were calculated. They are also listed in Table 2 together with the values directly measured from the experimental data.

When comparing the model parameters for the two tasks, it is seen that controller gains and crossover frequencies both increase due to cockpit motion and peripheral displays in the disturbance task. Due to the fact that these changes in display configuration cause decreases in effective time delay $\tau_L$, more phase lead is available at high frequencies which allows the human controller to generate a higher overall gain $K_p$.

It is remarkable that the effective time delay is 0.35 sec for all display configurations in the target following task. Apparently, the control process in target following is more difficult and more time consuming than in disturbance tasks. The value of .35 sec. corresponds well with the classic results obtained by Mc Ruer et al, see Refs. 11 and 14. Controller gain $K_p$ decreases in target following due to the addition of peripheral displays and/or cockpit motion, but these additions induce higher lead constants $\tau_L$, resulting in more phase lead below crossover frequency.

The parameters from Table 2 and the controller model according to eq. (17) were used to calculate the closed loop transfer functions according to eqs. (8) and (12). The moduli of these closed loop frequency response functions are given in Figs. 16 and 17.

The asymptotic behaviour is indeed as sketched in Fig. 7. Also, the influence of increasing controller gain for the disturbance task is exactly as predicted by
Fig. 7. For target following, the trend for increasing controller gain $K_p$ is also predicted for low frequencies, see Fig. 17. Moreover it can be seen from Fig. 17 that for all display configurations, there is a frequency range where the modulus of the closed loop transfer function is greater than unity, signifying that within this frequency range, input errors are amplified rather than compensated.

The parameters from Table 2, the controller model according to eq. (17) and the closed loop transfer functions according to eqs. (8) and (12), were used to calculate the variance and the standard deviation of the error signal from the discrete frequency equivalent of eq. (5) and the data of the discrete forcing function power spectral density, see Table 3.

The results are shown in Fig. 18 for the disturbance, and in Fig. 19 for the target following task. Also shown are the contributions to the error variance at each of the ten forcing function frequencies. Especially for the disturbance task, a very good agreement is seen between measured and calculated performance. That the measured error standard deviation for target following is, in particular for the configuration with central display only (C), is larger than calculated may well be caused by highly non-linear pilot control behaviour in this particular (difficult) case.

The diagrams showing the contributions at the single input forcing function frequencies reflect the different influence of cockpit motion and peripheral displays on task performance: an overall decrease in error contributions in the disturbance task in contrast with only a reduction in the high frequency range (frequency nos 6, 7 and 8) in the target following task.
5. The influence of human controller simplified model parameters on performance

It was shown in the former Section that measured performance and especially changes in performance due to changes in display configurations could fairly accurately be predicted from measured describing functions using a simple controller model.

One of the pitfalls of modelling human operator behaviour is that a good fit of experimental data may always be obtained by specifying a sufficiently large number of parameters and an obvious question of course is how sensitive the calculated results are for changes in model parameters. A related question would then be whether the parameter values reflect specific control strategies.

In order to answer these questions, the parameters in the simple model according to eq. (17) were varied around the values as given in Table 2, and the crossover frequency \( \omega_c \), the phase margin \( \phi_m \) and the error standard deviation, based on the experimental input power spectrum were calculated. For the disturbance task the results are given in Fig. 20. The circles denote measured data. It is seen that error standard deviation is sensitive to controller gain \( K_p' \). At constant \( K_p' \), phase margin increases with decreasing effective time-delay \( \tau_e \). A small time-delay \( \tau_e \) allows the controller to choose a higher gain \( K_p' \) to maintain a comfortable phase margin \( \phi_m \) and to decrease the error standard deviation. That the controller releases the generation of lead (as witnessed by slightly lower values of \( \tau_L \) ) when provided with a larger phase margin due to a smaller \( \tau_e \), is to be considered as a very human trait.

Summarizing, the control strategy in disturbance tasks can be formulated as choosing as high a gain \( K_p \) as is compatible with a minimum phase margin of around 20\(^\circ\), given the constraints of a particular value of \( \tau_e \).

A similar variation of model parameters was carried out for the target following task and the results are shown in Fig. 21. Here a quite different picture emerges: low error standard deviations are obtained with small controller gains \( K_p \) and high values of \( \tau_L \). Since from the experiments no changes of \( \tau_e \) were apparent in target following tasks, \( \tau_e \) was taken constant at 0.35 sec.

It is seen here that motion and peripheral displays dramatically increase phase margin, but it also becomes apparent that decreasing phase margin by choosing a higher controller gain \( K_p \), would only increase the error standard deviation in the configurations CP, CM and CPM. Moreover, given the values for \( \tau_L \) in the configurations CP, CM and CPM, the values for \( K_p \) as obtained form the measurements, approximately reflect the best possible choice to obtain minimum error standard deviation. Control strategy in target following is, in summary, typified by retaining as large a phase margin as possible, crossover frequency being determined by the striving for large phase margin.
6. Why large phase margin improves tracking performance in target following

Apparently, good compensatory control performance in target following is strongly related with large phase margin. In order to analyze this phenomenon into more detail, consider the frequency response equivalent of eq. (12)

$$\frac{e(\omega)}{w_i(\omega)} = \frac{1}{1 + H_p(\omega) H_c(\omega)}$$  \hspace{1cm} (17)

For error compensation at a particular frequency, see also eq. (5), it is necessary that

$$\left| \frac{1}{1 + H_p(\omega) H_c(\omega)} \right| < 1$$  \hspace{1cm} (18)

It follows from eq. (18) that for error compensation

$$\left| 1 + H_p(\omega) H_c(\omega) \right| > 1$$  \hspace{1cm} (19)

Since $H_p(\omega) H_c(\omega)$ can be represented as a vector in the complex plane (the well known Nyquist plot of $H_p(\omega) H_c(\omega)$), the denominator $1 + H_p(\omega) H_c(\omega)$ can be considered as the vectorial sum of $H_p(\omega)$, $H_c(\omega)$ and the unity vector $(1, oj)$ see Fig. 22. For error compensation at a given frequency, the end of this sum vector should be outside the unit circle with $(0, oj)$ as its centre. This is equivalent to stating that for error compensation at all frequencies in target tracking the Nyquist plot of $H_p(\omega) H_c(\omega)$ should remain outside the unit circle with $(-1, oj)$ as its centre, see Fig. 22.

From Fig. 23, where the Nyquist plots for $H_p(\omega) H_c(\omega)$ are shown, it is evident that, because of the dynamics of the controlled element and the inherent limitations of the human operator, this is not possible for any of the configurations tested. For each configuration, there is a frequency range within which there is error amplification rather than error compensation.

In analogy with the crossover frequency $\omega_c$ (which corresponds with the intersection of the Nyquist plot with the unit circle around $(0, oj)$), the lower of the two frequencies where the Nyquist plot intersects the unit circle around $(-1, j)$ is proposed here to be called "error crossover frequency $\omega_{ec}$", see Fig. 23.

Finally, Fig. 23 also illustrates why larger phase margin improves performance. Apparently for the target following tasks considered, it is not possible for a human controller to keep outside the "error amplification circle". However, when larger phase margins can be maintained, as in the configurations CP, CM and CPM, the adverse effect of error amplification can be decreased by keeping $H_p(\omega)$ $H_c(\omega)$ as far away as possible from the point $(-1, oj)$.

This is in accordance with one of the criteria that Neil and Smith, Ref. 12, propose for good tracking performance (in target following tasks) i.e. "a phase
margin of 60 to 110 degrees". However they state this in connection with "good high frequency stability", which seems to be somewhat beside the point in view of the foregoing.

As remarked earlier, crossover frequency gives, for target following tasks, no indication of performance.

This typical phenomenon occurring with target following tasks with a double integrator as controlled dynamics, was also mentioned by McReur et al in Ref.11. What they refer to as "crossover regression" occurs if the bandwidth $\omega_i$ of a (rectangular) input spectrum is close to, or greater than, the crossover frequency $\omega_c$. By comparing tables 2 and 3 it can be seen that the effective bandwidth $\omega_i$ of the input spectrum of around 2 rad/sec was indeed greater than the crossover frequency $\omega_c$ for all the configurations of the target following task.

Because of the "crossover regression", better indicators of performance would here be phase margin or gain margin, see Fig. 24 or better still, the maximum error amplification, see Figs. 23 and 24.
7. Vestibular motion perception in compensatory tracking tasks

In the preceding sections, the role of cockpit motion on pilot control behaviour and tracking accuracy was analysed by using a "simplified extended crossover model"

\[ H_p(s) = K_p (1 + \tau_L s) e^{-\tau_1 s} \]  
(17)

It was shown by closed loop analysis, that pilot behaviour, as measured in either of the tasks and characterized by the parameters in (17) reflect the subjects' strategies to minimize tracking error under the limitations set by the experimental configurations. It was shown that cockpit motion added to a central visual display caused \( \tau_1 \) to decrease in disturbance tasks, whereas in target following tasks \( \tau_L \) increased by the addition of cockpit motion.

Since the parameters of the dynamics of the human vestibular apparatus are well known, see Ref. 15, it would be interesting to know whether including the semicircular canal dynamics for the perception of angular motion, could shed some light on the role of cockpit motion in the tasks considered.

Therefore, two tentative vestibular feedback models are formulated for the two tasks, see Fig. 25. In both tasks the vestibular apparatus senses angular acceleration and the vestibular feedback paths are somewhat similar to those proposed in Ref. 13 for a disturbance task.

Since the forcing function in disturbance tasks acts on the controlled element, visual and vestibular feedback loops are parallel and hence,

\[ H_D(s) = \frac{\delta(s)}{\epsilon(s)} = H_{p_{vis}}(s) + s^2 H_{p_{vest}}(s) \]  
(20)

In the target following tasks, the disturbance acts on the display and although the block diagram is, in principle, similar to that for the disturbance task, the vestibular loop can be considered as an inner, stabilization loop. After some elaboration, it follows that

\[ H_T(s) = \frac{\delta(s)}{\epsilon(s)} = \frac{H_{p_{vis}}(s)}{1 + H_{p_{vest}}(s) H_c(s) s^2} \]  
(21)

Equations (20) and (21) reflect the models for the describing functions as measured in the two tasks.

Next, very simple models are formulated for \( H_{p_{vis}} \) and \( H_{p_{vest}} \)

\[ H_{p_{vis}}(s) = K_p (1 + \tau_L s) e^{-\tau_1 s} \]  
(22)
\begin{equation}
H_p^{\text{vest}}(s) = K_v \frac{1 + \tau_{v1} s}{1 + \tau_{v2} s} e^{-\tau_{e2} s}
\end{equation}

The visual feedback model according to (22) is similar to the pilot model used up to now. The vestibular feedback model according to eq. (23) features the lead and lag time constants \(\tau_{v1}\) and \(\tau_{v2}\) of the semi-circular canal dynamics, see Ref. 15, a gain factor \(K_v\) and an effective time-delay \(\tau_{e2}\). In the pilot model, the control output is simply taken as the sum of the output of the subsystems described by (22) and (23). The parameters \(\tau_{v1}\) and \(\tau_{v2}\) were taken as constants and set at \(\tau_{v1} = 0.1\) sec. and \(\tau_{v2} = 6.0\) sec, see Ref. 15.

For the disturbance task, \(\tau_L\) was chosen at .7 sec, and the effective time delay for the visual feedback was set at .28 sec, just as in the model for the central display only configuration, see Table 2. The effective time delay for the vestibular feedback loop was set at .18 sec, the value for the configuration CM, see Table 2.

For target following, \(\tau_L\) was set at 1.0 sec, \(\tau_{e1}\) at .35 sec and \(\tau_{e2}\) at .35 sec. or .15 sec.

Although the choice of most parameters in eqs. (20), (21), (22) and (23) was based on prior data, the resulting vestibular feedback models are somewhat speculative, since two new "free" parameters \(K_p\) and \(K_v\) are to be specified. The only intention is to see whether the typical trends in control behaviour due to addition of cockpit motion could be explained by some form of vestibular feedback, taking into account prior experimental data.

When starting from the central display only configuration (C) for the disturbance task, \(K_v = 0\) and when increasing \(K_v\), see Fig. 26, the trend of increasing \(\omega_c\) and slightly increasing \(\phi_m\) as witnessed by the measured data, is clearly replicated by the model. Choosing \(K_p\) and \(K_v\) so as to match the measured \(\phi_m\) and \(\omega_c\), gives a reasonable fit over the entire frequency range for the measured pilot describing function, see the dotted lines in Fig. 10.

When starting at \(K_v = 0\) for the target following task, see Fig. 27, a clear trend towards larger phase margin is seen, both for \(\tau_{e2}\) at .35 and .15 sec, for increasing \(K_v\), just as measured for the addition of cockpit motion. If \(K_p\) and \(K_v\) are chosen such as to cover the measured values of \(\phi_m\) for the CM configuration, the increased phase lead at lower frequencies is also very well replicated, see the dotted lines in Fig. 14.

No noticeable differences in the calculated frequency response characteristics were found due to setting the vestibular time delay at .35 or .15 secs.

A final test of the validity of the proposed vestibular feedback loops is of course a calculation of the performance. It is shown in Figs. 28, 29 and 30 that, when matching \(K_v\) and \(K_p\) so as to obtain the measured \(\omega_c\) and \(\phi_m\), measured performance is also replicated rather accurately.
As can be seen from the results of Figs. 27, 29 and 30 no definite conclusions can be drawn as to the influence of vestibular delay time (.35 or .15 secs) on human control behaviour and performance.

It is interesting to mention here a similar analysis using an optimal control model for the calculation of pilot transfer functions and performance for the joint use of visual and vestibular motion cues, (Ref. 13). It was concluded there, that vestibular dynamic response characteristics were not required to obtain a good model fit. In the first place this is not amazing since a good model fit was also obtained in section 4 of this Report without using any vestibular dynamics. Secondly, supplying a pilot model with motion information on roll angle and its first three derivatives, as in Ref. 13, means implicitly including some important aspects of vestibular system dynamics, see eq. (23) and the block-diagrams of Fig. 25.
8. Concluding remarks

By analyzing distinctions of disturbance tracking tasks on the one hand and target following tasks on the other in terms of classic control theory, it was shown that the closed loop transfer function relating the error signal and the disturbing signal in disturbance tasks is a low pass one, whereas this closed loop transfer function in target following is of a high pass nature. Trends in tracking error RMS could very well be predicted from measured describing functions. By varying the parameters in a simplified extended crossover model, it was shown that measured parameters reflect the best possible subject control strategy, given the limitations of the experimental setting and the limitations imposed by human motor control.

In disturbance tracking tasks, crossover frequency $\omega_c$ is a good indicator of performance and control behaviour.

In the target tracking tasks considered, however, crossover frequency had virtually no significance as an indicator of performance or control behaviour. The analysis showed that, above a certain "error crossover frequency", error amplification rather than error compensation occurs. Phase margin, gain margin or low frequency lead are indicators for performance in this case, rather than crossover frequency. The implications of 'crossover regression' as reported by McRuer et al, seem to have been overlooked by several authors, including the present ones. A better indicator of target following performance would be the "maximum error amplification", which can readily be found from a Nyquist plot of the open loop transfer function $H_p H_c$.

By formulating a very simple vestibular feedback loop, which features known parameters of semi-circular canal dynamics, it was shown that cockpit motion as sensed via the vestibular organs, indeed brings about the typical changes in control behaviour and performance as measured in the two distinct tasks.
References

1. Th. B. Sheridan
   W.R. Ferrell

2. E.C. Poulton

3. R.J.A.W. Hosman
   J.C. van der Vaart

4. R.J.A.W. Hosman
   J.C. van der Vaart

5. R.S. Bray

6. W.H. Levison
   A.M. Jonker

7. W.H. Levison

8. W.H. Levison
   G.L. Zacharias

9. W.H. Levison
   G.L. Zacharias

10. A.M. Junker
    W.H. Levison

11. D.Mc Ruer
    D. Graham
    E. Krendel
    W. Reisener, jr.

12. T.P. Neil
    R.E. Smith
    An in-flight investigation to develop control system design criteria for fighter airplanes. AFFDL-TR-70-74, 1970.
13. G.L. Zacharias  
    L.R. Young  

14. D. McRuer  
    E.S. Krendel  

15. R.J.A.W. Hosman  
    J.C. van der Vaart  

16. A. Papoulis  
Table 1 Nomenclature of compensatory tracking tasks

<table>
<thead>
<tr>
<th>Disturbance on controlled element only</th>
<th>Disturbance signal as reference input only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance task</td>
<td>Target following task</td>
</tr>
<tr>
<td>Disturbance input task</td>
<td>Target input task</td>
</tr>
<tr>
<td>Vehicle disturbance task</td>
<td>Commanded input task</td>
</tr>
<tr>
<td>Disturbance regulation task</td>
<td>Target following task</td>
</tr>
<tr>
<td>Holding against disturbance</td>
<td>Following target</td>
</tr>
</tbody>
</table>

Compensatory: Only error visible Operator tries to null the error

Pursuit: Input and output visible Operator tries to match them
Table 2  Measured (exp) and calculated (calc) performance, crossover frequency, phase margin and parameters of fitted controller model

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\sigma_\phi$ (deg)</th>
<th>$\omega_c$ (rad/sec)</th>
<th>$\phi_m$ (deg)</th>
<th>fitted model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>exp</td>
<td>calc</td>
<td>exp</td>
<td>calc</td>
</tr>
<tr>
<td>C</td>
<td>1.94</td>
<td>1.80</td>
<td>3.18</td>
<td>3.22</td>
</tr>
<tr>
<td>CP</td>
<td>1.80</td>
<td>1.70</td>
<td>3.55</td>
<td>3.35</td>
</tr>
<tr>
<td>CM</td>
<td>0.78</td>
<td>0.89</td>
<td>4.76</td>
<td>4.58</td>
</tr>
<tr>
<td>CPM</td>
<td>0.70</td>
<td>0.69</td>
<td>5.03</td>
<td>5.27</td>
</tr>
</tbody>
</table>

Target Following Task

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\sigma_\phi$ (deg)</th>
<th>$\omega_c$ (Rad/sec)</th>
<th>$\phi_m$ (deg)</th>
<th>fitted model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>exp</td>
<td>calc</td>
<td>exp</td>
<td>calc</td>
</tr>
<tr>
<td>C</td>
<td>2.23</td>
<td>1.66</td>
<td>2.3</td>
<td>2.38</td>
</tr>
<tr>
<td>CP</td>
<td>1.63</td>
<td>1.21</td>
<td>2.3</td>
<td>2.41</td>
</tr>
<tr>
<td>CM</td>
<td>1.32</td>
<td>1.18</td>
<td>2.4</td>
<td>2.17</td>
</tr>
<tr>
<td>CPM</td>
<td>1.26</td>
<td>1.20</td>
<td>1.7</td>
<td>1.81</td>
</tr>
</tbody>
</table>

Table 3  Input frequencies and amplitudes

<table>
<thead>
<tr>
<th>Frequency no.</th>
<th>Frequency $\omega_1$ (rad/sec)</th>
<th>Amplitude $A$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.153</td>
<td>1.106</td>
</tr>
<tr>
<td>2</td>
<td>0.230</td>
<td>1.099</td>
</tr>
<tr>
<td>3</td>
<td>0.383</td>
<td>1.083</td>
</tr>
<tr>
<td>4</td>
<td>0.537</td>
<td>1.058</td>
</tr>
<tr>
<td>5</td>
<td>0.997</td>
<td>0.957</td>
</tr>
<tr>
<td>6</td>
<td>1.457</td>
<td>0.842</td>
</tr>
<tr>
<td>7</td>
<td>2.378</td>
<td>0.646</td>
</tr>
<tr>
<td>8</td>
<td>4.065</td>
<td>0.428</td>
</tr>
<tr>
<td>9</td>
<td>7.440</td>
<td>0.247</td>
</tr>
<tr>
<td>10</td>
<td>13.567</td>
<td>0.136</td>
</tr>
</tbody>
</table>
Fig. 1. Block diagram of compensatory tracking

Fig. 2. Disturbance task and target following task
Fig. 3. Disturbance and target following task with cockpit motion feedback
Fig. 4. Measured performance in disturbance and in target following tasks, Ref. 3 (C: central display, P: peripheral displays, M: cockpit motion)

Fig. 5. Measured crossover frequency and phase margin, Ref. 3. (C: central display, P: peripheral displays, C: cockpit motion)
Fig. 6. Examples of measured open-loop describing functions. Ref. 3. Configuration CPM for both tasks.
Fig. 7. Asymptotic characteristics of simplified closed-loop frequency response moduli
Disturbance Task, C

\[ H_p(s) = 1.05 (1+0.7s) e^{-0.28s} \]

Measured data

Fig. 8. Measured human operator describing function, central display only. Disturbance task
Fig. 9. Measured human operator describing function, central and peripheral displays. Disturbance task
Fig. 10. Measured human operator describing function, central display and cockpit motion. Disturbance task

\( H_p(s) = 2.1 (1 + 0.5 s) e^{-0.18 s} \)

Visual-vestibular feedback model

Measured data
Fig. 11. Measured human operator describing function, central and peripheral displays and cockpit motion. Disturbance task
Fig. 12. Measured human operator describing function, central displays only. Target following task
Fig. 13. Measured human operator describing function, central and peripheral displays. Target following task
Fig. 14, Measured human operator describing function, central display and cockpit motion. Target following task.
Fig. 15. Measured human operator describing function, central and peripheral displays and cockpit motion. Target following task
Fig. 16. Calculated closed-loop frequency response moduli, disturbance task (C: central display, P: peripheral displays, M: cockpit motion)
Fig. 17. Calculated closed-loop frequency response moduli, target following task
(C: central display, P: peripheral displays, M: cockpit motion)
Fig. 18. Calculated and measured error standard deviation and calculated variance contributions at discrete forcing function frequencies. Disturbance task.
Fig. 19. Calculated and measured standard deviation and calculated variance contributions at discrete forcing function frequencies. Target following task.
Fig. 20. Influence of model parameters on calculated crossover frequency, phase margin and error standard deviation. Disturbance task. Circles denote measured data.
Fig. 21. Influence of model parameters on calculated crossover frequency, phase margin and error standard deviation. Target following task. Circles denote measured data.
Fig. 22. The denominator of the closed-loop transfer function (target following task) in the complex plane.
Fig. 23. Nyquist plots of $H_p H_c$ (target following task) showing crossover frequency $\omega_c$, error crossover frequency $\omega_{ec}$, phase margin $\varphi_m$ and $H_{p,c}^{\varphi=-180}$.
Fig. 24. Performance in target following tasks as a function of phase margin \( \varphi_m \), gain margin \( 1/H_p H_c \), and maximum error amplification \( \frac{1}{r_{\text{min}}} \).
Fig. 25. Block diagrams for compensatory tracking tasks including vestibular feedback loops.
Fig. 26. Phase margin $\phi_m$ as a function of crossover frequency $\omega_c$. Visual-vestibular feedback model for the disturbance task. Circles denote measured data.
Fig. 27. Phase margin $\varphi_m$ as a function of crossover frequency $\omega_c$. Visual-vestibular feedback model for the target following task. Circles denote measured data.
Fig. 28. Crossover frequency $\omega_c$, phase margin $\phi_m$ and error standard deviation as a function of visual-vestibular feedback model parameters. Disturbance task. Circles denote measured data.
Fig. 29. Crossover frequency $\omega_c$, phase margin $\varphi_m$ and error standard deviation as a function of visual-vestibular feedback model parameters. Target following task, $\tau_{e2} = .35$ secs. Circles denote measured data.
Fig. 30. Crossover frequency $\omega_c$, phase margin $\phi_m$, and error standard deviation as a function of visual-vestibular feedback model parameters. Target following task, $\tau_{e2} = .15$ secs. Circles denote measured data.