Experimental Studies of the Use of Phase Lead Filters to Compensate Lags in Head-Coupled Visual Displays

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***Abstract*—Display lags degrade performance when using the head to track a target presented on a helmet-mounted display. These lags originate from delays in measuring the position of the head and the time required to generate the image of the target. This paper presents two laboratory studies on the use of phase lead filters to improve head tracking performance in the presence of display lags. In the preliminary study, the benefits of lag compensation by a phase lead filter were impeded by associated changes in filter gain. The frequency responses of two phase lead filters were then optimized to have near unity gain at frequencies below 0.7 Hz where there was most head motion. The main study showed that these optimized filters significantly improved head tracking performance with a system having a total lag of 140 ms. At frequencies above about 0.7 Hz, a greater than unity filter gain caused jittery image movement. Although this jittering degraded head tracking performance it was removed by an alternative lag compensation technique involving 'image deflection'. This deflection shifted the displayed image to its correct horizontal and vertical position relative to the head. Image deflection, combined with the phase lead filters, produced a tracking performance unaffected by lag.**

I. Introduction

The purpose of a head-coupled visual display system is to present visual images appropriate to the instantaneous orientation of the head. A head-coupled system consists of a helmet-mounted display, a helmet-pointing system, and a graphics-generator. Time delays (i.e., lags) in such systems became evident during head movement. The lags cause the visual image field of the head-coupled system to be presented at an incorrect position on the display. This type of lag will hereafter be referred to as 'display lag': it includes the time taken to measure head position and generate the visual image.

Effects of lags on human performance with head-coupled systems have been studied in the field of simulation training (e.g., [2], [5] and [17]). Previous studies by the present authors showed that imposed display lags of 40 ms or more significantly degraded head tracking performance. The lags were imposed on a head-coupled system with a baseline display lag of 40 ms [9] and [10].

It was hypothesised that the effect of display lag on tracking performance would be reduced by inserting a phase lead element at an appropriate location within a head-coupled system. There are many types of phase lead elements, for example: (i) phase lead filters [12], (ii) adaptive least-mean-square predictors [1] and [15], (iii) model based Kalman predictors [4], (iv) self-learning neural net predictors [16] and (v) nonlinear predictors [7]. Among the five types of phase lead elements, only a phase lead filter has a time-invariant characteristic. Such a characteristic enables the amount of phase lead to be studied as an independent variable. This paper reports two experiments conducted to optimize the benefits of lag compensation with phase lead filters. The effects of filter gain were investigated in a preliminary experiment and lag compensation with two optimized phase lead filters was studied in a main experiment.

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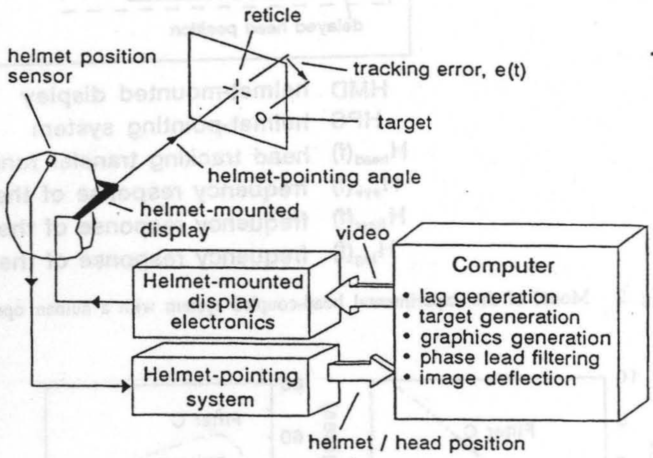

Fig. 1. Configuration of apparatus used in the experiments.

II. Materials and Methods

A. Apparatus

The general arrangement of experimental apparatus is summarized in Fig. 1. The helmet-pointing system (HPS) was a Ferranti SPASYN system type 101 capable of detecting helmet orientation in the pitch and yaw axes with about 0.1° accuracy. Helmet (i.e., head) position in the pitch and yaw axes was measured at 50 samples per second. The sensor was mounted on an experimental flying helmet (Hughes Aircraft Co. HMD-001) carrying a collimated Hughes helmet-mounted display (model RC/HMD-212). The display was monocular with a

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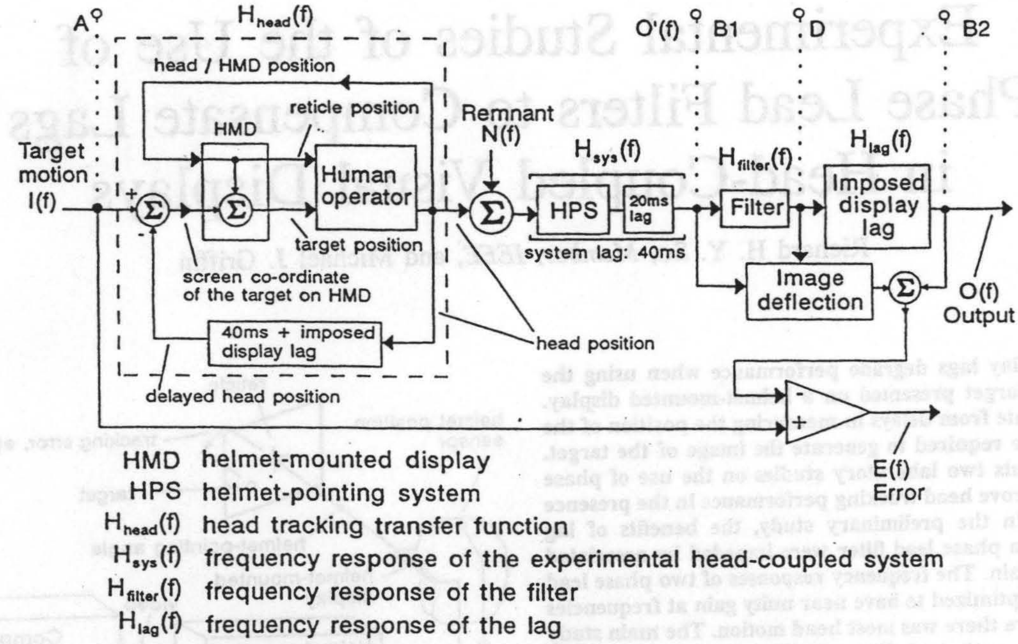

Fig. 2. Model of the experimental head-coupled system with a human operator in the loop.

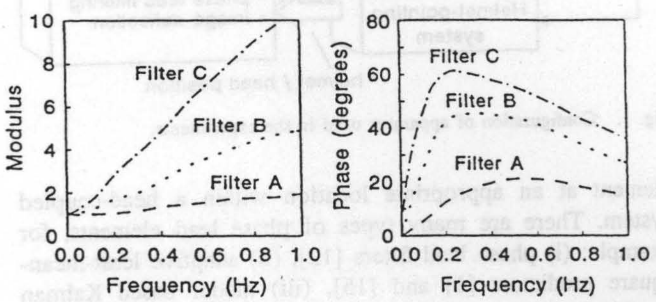

Fig. 3. Frequency responses of the three phase lead filters (Filters A, B and C).

field-of-view of 17° by 17°. An open-cross reticle with an inner diameter of 1.2° and an outer diameter of 3.6° was permanently displayed at the centre of the helmet-mounted display. The position of the reticle was stationary relative to the head and was not affected by display lag. A circle of 1° diameter was displayed as the target. The target position relative to the reticle was updated every 20 ms. This relative position depended on the target motion and the measured head position. The head positions were calibrated to be 0° in both pitch and yaw axes at the beginning of each run when subjects were instructed to sit in an upright posture with head facing forward.

The head-coupled system used in both studies had a baseline display lag of 40 ms. Imposed display lags in steps of 20 ms were added according to the appropriate lag condition. The 40 ms baseline display lag of the experimental head-coupled system included: (i) a 20 ms lag in the helmet-pointing system [14]; (ii) a 3.5 ms computation time; (iii) a 0 to 16.7 ms presentation delay for an image to appear on the raster scan system of the helmet-mounted display; and (iv) a 0 to 16.7 ms lag introduced by the asynchronization between the helmet-pointing system, updating at 50 frames per second, and the graphics output of the host computer refreshing at 60 frames per second. Imposed display lags were purposefully generated through a data buffer in the host computer. These lags would correspond to the time taken to generate more complex computer images in a head-coupled simulator.

The experiments reported in this paper were approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research. All subjects were fully informed about the experiments and their right to withdraw at any time without prejudice during the experiments.

B. Theories of Phase Lead Filters

A model of the head tracking system is shown in Fig. 2. The frequency response equations of the phase lead filters and their implementation in this study can be found in Appendix A. To compensate a display lag with a phase lead filter, the frequency response of the filter should be the opposite of the display lag response. Ideally, a phase lead filter should have a unity gain and a linearly increasing phase lead with increasing frequency. A filter with such response at all frequencies is impossible to achieve because an increasing phase lead will always be associated with some form of amplification. Fortunately, the ideal filter response is only required at low frequencies, because lags within the human operator restrict useful tracking to frequencies below about 1 Hz [13]. At higher frequencies, attenuation will be desirable to reduce the effect of any head movement or background noise in the system.

C. Dependent Variables

Tracking performance was measured in terms of transfer functions, squared coherency functions, error spectra and mean radial error. Their definitions are included in Appendix B.

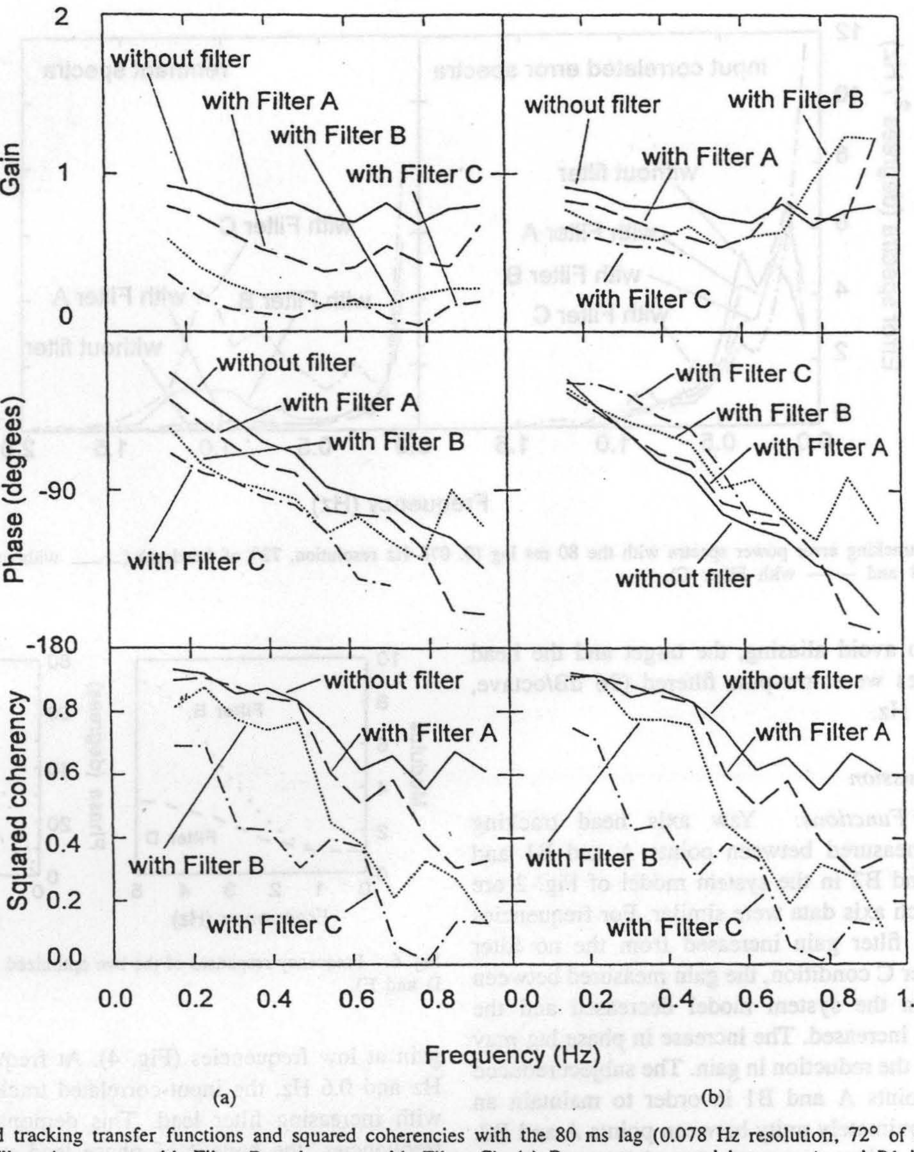

Fig. 4. Yaw-axis head tracking transfer functions and squared coherencies with the 80 ms lag (0.078 Hz resolution, 72° of freedom) (——— without filter; – – – – with Filter A; ...... with Filter B and —·— with Filter C). (a) Response measured between A and B1 in the system model; (b) response between A and B2 in the system model.

III. Preliminary Study: Benefits of Lag Compensation with Phase Lead Filters

A. Introduction and Hypotheses

This preliminary study investigated lag compensation by phase lead filters with greater than unity filter gains. It was anticipated that the filter gain amplification would degrade tracking performance while the filter phase lead would improve tracking performance. The amount of gain and phase lead of a filter would vary with frequency. It was hypothesised that at some frequencies, the benefits of the phase lead would be greater than the detrimental effects of the amplification.

B. Methods and Design

One male subject participated in this preliminary experiment. He was a University researcher of 24 years of age and had previous experience of tracking with the experimental head-coupled visual display system. The subject was asked to move his head to track a circular target with an open-cross reticle for 120 s. Both the target and the reticle were presented on the Hughes helmet-mounted display at optical infinity. The yaw axis target motion was a Gaussian random function integrated once and low-pass filtered at 0.7 Hz (24 dB/octave) and at 1 Hz (120 dB/octave). Butterworth low-pass filters were used. The pitch axis target motion was produced by reversing the yaw axis target motion in the time domain. (i.e., starting from the end of the yaw axis target time history and progressing backward). Target motions were scaled to a maximum displacement of ±16° for both axes. One display lag (80 ms imposed on a 40 ms system lag) and four filtering conditions were used (no filter, filtering with Filters A, B and C). The frequency responses of Filters A, B and C are shown in Fig. 3.

Both the target motion and the head motion time histories were re-sampled at 5 samples per second to reduce the size

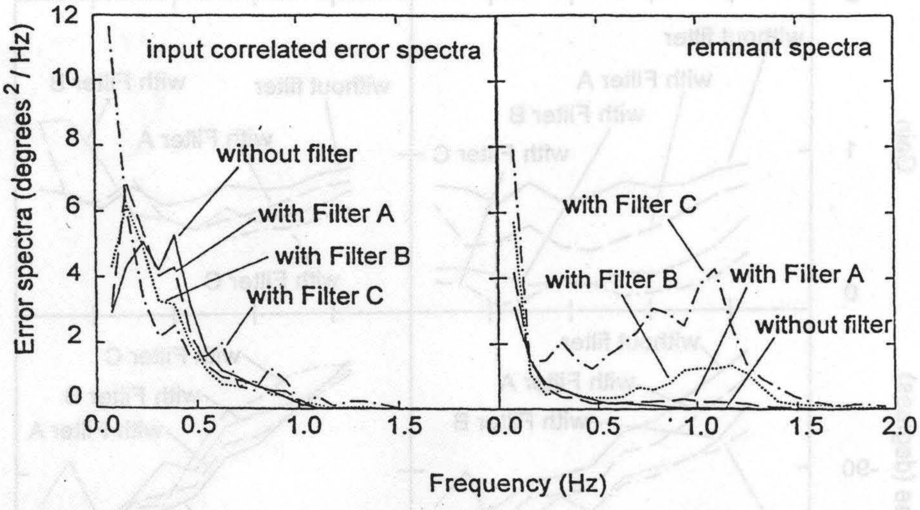

Fig. 5. Yaw-axis head tracking error power spectra with the 80 ms lag (0. 078 Hz resolution, 72° of freedom) (——— without filter; - - - with Filter A; ...... with Filter B and —·— with Filter C).

of the data files. To avoid aliasing, the target and the head motion time histories were low-pass filtered (96 dB/octave, Butterworth) at 2.2 Hz.

C. Results and Discussion

Tracking Transfer Functions: Yaw axis head tracking transfer functions measured between points A and B1 and between points A and B2 in the system model of Fig. 2 are shown in Fig. 4. Pitch axis data were similar. For frequencies up to 1 Hz, as the filter gain increased from the no filter condition to the Filter C condition, the gain measured between points A and B1 in the system model decreased and the associated phase lag increased. The increase in phase lag may have been caused by the reduction in gain. The subject reduced the gain between points A and B1 in order to maintain an overall gain of approximately unity between points A and B2. This overall gain of unity was required to follow the target with the reticle. This suggests that a filter gain close to unity within the frequency range of possible head movement would be desirable.

Input-Correlated Error: Fig. 2 shows that the overall phase lag measured between points A and B2 is the sum of the phase lag measured between points A and B1, the filter lead and the 80 ms imposed display lag. For frequencies between about 0.3 Hz and 0.6 Hz, as the filter lead increased, the phase lag between A and B1 increased but the overall phase lag between A and B2 decreased (Fig. 4). This suggests that, at these frequencies, the phase leads provided by the filters were greater than the associated increases in the phase lag measured between A and B1. (For example, at 0.4 Hz, Filter B provided a phase lead of about 42° whilst the associated increase in the phase lag between A and B1 was about 32°, Figs. 3 and 4).

Yaw axis error power spectra with the 80 ms imposed display lag and the four filtering conditions are shown in Fig. 5. At frequencies around 0.1 Hz, the input-correlated error spectrum with Filter C was much greater than the input-correlated error spectra with the other conditions: this was because the subject failed to maintain a near unity overall gain at low frequencies (Fig. 4). At frequencies between 0.3 Hz and 0.6 Hz, the input-correlated tracking error decreased with increasing filter lead. This demonstrates that at these frequencies, the benefit of phase lead was greater than the detrimental effect of the filter amplification.

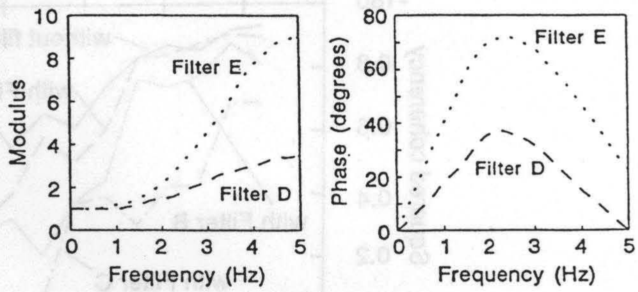

Fig. 6. Frequency responses of the two optimized phase lead filters (Filters D and E).

IV. Main Study: Lag Compensation by Optimized Phase Lead Filters and Image Deflection

A. Introduction

Optimization of Phase Lead Filters: From a consideration of the results of Study 1 it was decided to optimize the frequency response of two phaselead filters. The aim of the optimization was to produce filters with unity gains and phase leads within the frequency range of the target motion (0 to 0.7 Hz). The optimization utilized the 'ARMAX' program, a modeling routine in the PC-MATLAB package [11]. Two optimized filters were produced and their frequency responses are shown in Fig. 6. Filters D and E had a time lead of 48 ms and 117 ms respectively. These time leads were not multiples of 20 ms (the sampling period) because of the optimization.

The Need for Image Deflection: Although the two optimized filters had near unity gains below 0.7 Hz, they had greater than unity gain above 0.7 Hz (Fig. 6). This will amplify any signal above 0.7 Hz and produce jittery image movements.

The results of Study I suggest that jittering increased tracking remnant: the effect was certainly disturbing to the subject. The jittering may be removed by deflecting images back to their correct positions [9]. The image position error caused by the imposed lag was calculated using the pre-filtered head position measured at B1, filtered head position measured at D, and the duration of the lag (Fig. 2). This position error was scaled into horizontal and vertical offsets which were used to deflect the video image on the helmet-mounted display (Fig. 1). Previous work has shown that the use of image deflection alone improves head tracking performance but reduces the field-of-view [9].

B. Aims and Hypotheses

The objective of the study was to investigate any benefit of lag compensation by phase lead filters optimized to have unity gain responses below 0.7 Hz. The combined use of lag compensation and image deflection was also investigated. The hypotheses were:

1) Lag compensation by optimized phase lead filters would improve head tracking performance but introduce jittery image movements;
2) With image deflection, the jittery image movements produced by phase lead filters would be removed and tracking performance would be further improved.

C. Methods and Design

Six male volunteers participated in the experiment. They were University researchers with ages between 21 to 28 years. Similar to Study I, the subjects were asked to move their heads to track a circular target with an open-cross reticle. In this study, tracking was performed for 90 s. The yaw axis target motion was a Gaussian random function integrated twice and then band-pass filtered between 0.01 Hz (48 dB/octave) and 0.63 Hz (48 dB/octave). The pitch axis target motion was produced by reversing the sequence of yaw axis motion in the time domain. The target motions were scaled to a maximum displacement of $\pm 40°$ for the yaw axis and $\pm 30°$ for the pitch axis. Six display lags (0, 20, 40, 60, 80 and 100 ms) and six lag compensation conditions were used. The six compensation conditions were combinations of three filtering conditions (none, Filter D, and Filter E) and two image deflection conditions (with and without). There was therefore a total of 36 conditions.

The frequency response equations of Filters D and E can be found in Appendix A. The display lags were imposed on a 40 ms system display lag. Six similar target motions were used to balance the sequence of presentation of the conditions. Each of the target motions was used once in each condition. The order of presentation of the conditions among the six subjects was balanced with a Latin square design. Previous study has shown that, with an 80 ms imposed display lag, head tracking performance of a target moving randomly at frequencies up to 0.7 Hz is not significantly affected by practice [10]. Five practice runs were presented to the subjects. Their conditions were: (i) 60 ms lag, (ii) 0 ms lag with Filter D, (iii) 80 ms lag with Filter D, (iv) 40 ms lag with Filter D and image deflection and, (v) 0 ms lag with Filter D and image deflection. The target motions used in the practice were similar to, but different from, the six target motions used in the 36 experimental conditions. These six target motions were generated by starting the yaw axis target motion at different instants in relation to the pitch axis target motion. Subjects performed all 41 runs in one session. Both the target motion and the head motion time histories were re-sampled at 10 samples per second to reduce the size of the data files. To avoid aliasing, the target motion and the head motion were low-pass filtered (96 dB/octave, Butterworth) at 4.8 Hz.

D. Results and Discussion

Effects of Lags: Fig. 7 shows that, without compensation, the mean radial error increased as the lag increased. The data in Fig. 7 are median values of the six subjects mean radial errors. Imposed lags greater than, or equal to, 40 ms significantly degraded head tracking performance ($p < 0.05$, Wilcoxon matched-pairs signed ranks test). This agrees with previous studies [9] and [10]. In this experiment, the effects of display lag on head tracking transfer functions without lag compensation were similar to those previously reported [10].

Lag Compensation by Phase Lead Filters:

a) Time domain analysis of mean radial error: Both Filter D and Filter E significantly reduced the mean radial tracking error with the 100 ms imposed display lag ($p < 0.05$, Wilcoxon matched-pairs signed ranks test, Fig. 7). With the 80 ms lag, both filters reduced the mean tracking error, but the reduction was statistically significant only with Filter D ($p < 0.05$, Wilcoxon). With the 40 ms and the 60 ms lags, the mean tracking error decreased with Filter D but increased with Filter E. Including the 40 ms system lag, the total display lag with the 40 ms and the 60 ms imposed lags was 80 ms and 100 ms respectively. Both the total lags were less than the 117 ms lead of Filter E. This suggests that too much phase lead can degrade tracking performance. Not surprisingly, with imposed display lags less than 60 ms, the use of Filter E increased the mean radial error, and the increase was statistically significant with the 0 ms and the 20 ms imposed display lag ($p < 0.05$, Wilcoxon).

   With the 80 ms lag, Filter D reduced tracking error more than Filter E, even though Filter E had a larger lead. This could not be due to an excess of phase lead because both filters had leads less than the total lag of 120 ms. A convincing explanation could not be deduced from the time domain analysis.

b) Frequency domain analyses of input-correlated outputs: Yaw axis head tracking transfer functions and error power spectra are shown in Figs. 8 and 9. Pitch axis data were similar. Inspection of Fig. 9 shows that, with an 80 ms lag, the input- correlated error spectrum decreased with Filter D but increased with Filter E. This is consistent with the above finding that with the 80 ms lag, Filter D reduced tracking error more than Filter E. Wilcoxon tests were performed to test the difference

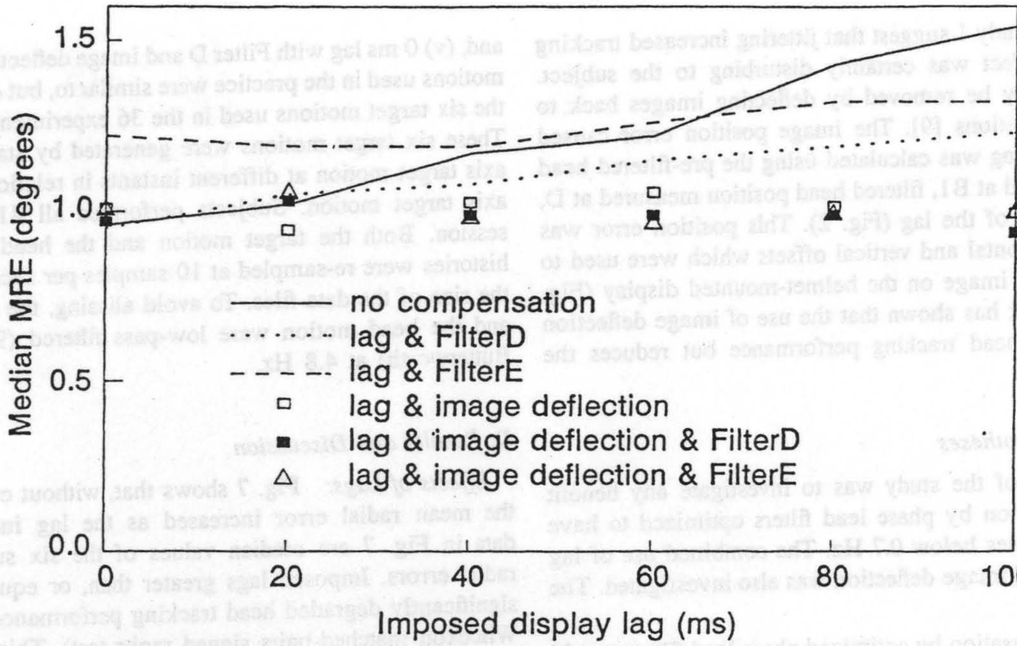

Fig. 7. Mean radial error (MRE) with different lag compensation conditions as a function of imposed display lags (median of 6 subjects).

between the input-correlated error with and without filters. The increases in input-correlated error with Filter E were statistically significant while the decreases in the input-correlated error with Filter D were marginally significant (at 0.3 Hz, $p < 0.05$ with and without Filter E; $p < 0.1$ with and without Filter D).

With Filter E, the increases in input-correlated error at about 0.3 Hz were associated with increases in the overall tracking phase lag measured between points A and B2 in the system model (Fig. 8(b)). The increases of phase lag with Filter E were significant (at 0.3 Hz, $p < 0.05$, Wilcoxon). Unlike the preliminary experiment, the increases in overall tracking lag at about 0.3 Hz were not caused by a reduction of tracking gain in response to the gain of the filter. At these frequencies, Filter E had a unity gain (Fig. 6). With 80 ms lag, a Wilcoxon test showed no significant difference between the tracking gains with and without Filter E ($p < 0.5$, 0.3 Hz).

Jittery movements of the images at frequencies above 1 Hz were observed during the use of Filter E. At these frequencies, Filter E had a greater than unity gain that amplified the head movement (Fig. 6). When image deflection was applied with Filter E, the jittery images were removed. In addition, the increased overall phase lag with Filter E was also reduced. With Filter E and 80 ms lag, the phase responses with and without image deflection were significantly different (Fig. 8(b); at 0.3 Hz, $p < 0.05$, Wilcoxon). This suggests that, with Filter E, jittering images might have caused the increased overall tracking phase lag measured between points A and B2.

c) Frequency domain analyses of remnant outputs: With the 80 ms lag, at frequencies above about 0.4 Hz, remnant spectra decreased significantly with both Filters D and E (at 0.7 Hz, $p < 0.05$, Wilcoxon). There was an appreciable amount of remnant around 0.1 Hz. It is thought that the subjects would not have generated remnant at such low frequencies (Fig. 9). Examination of the procedure for calculating the remnant spectra revealed that tracking error around 0.1 Hz may have been incorrectly classified as remnant; this was because the display lag reduced the coherency function, $\gamma^2_{io}(f)$, measured between the head tracking output, $O(f)$, and the target input, $I(f)$, (see Appendix B for remnant measurement). It has previously been reported that a lag between an input signal and an output signal decreases their measured relative coherency and therefore increases the calculated input-uncorrelated output (i.e., remnant) [3]. In this case, at 0.078 Hz, the imposed lag of 80 ms reduced the squared coherency function, $\gamma^2_{io}(f)$, by less than 0.1% (Fig. 8). However, because the target motion had most energy at frequencies around 0.1 Hz, the resulting increase in calculated remnant was not negligible.

The reduction of the squared coherency function depends on both the duration of the lag and the time segment used during spectral estimation (i.e., the Fast Fourier Transform, FFT, length). The longer the time segment used, the smaller the reduction in coherency and, hence, the smaller the remnant [3]. However, a long FFT length lowers the degrees of freedom. A FFT length of 128 samples was used in the data analysis (12.8 s duration with 10 samples per second). With a FFT length of 256 samples (25.6 s with 10 samples per second), the remnant around 0.1 Hz was found to decrease while the input-correlated error at these frequencies increased. This seems reasonable as a target motion with most energy around 0.1 Hz should produce input-correlated tracking error at the same frequencies. However, the spectra were erratic due to

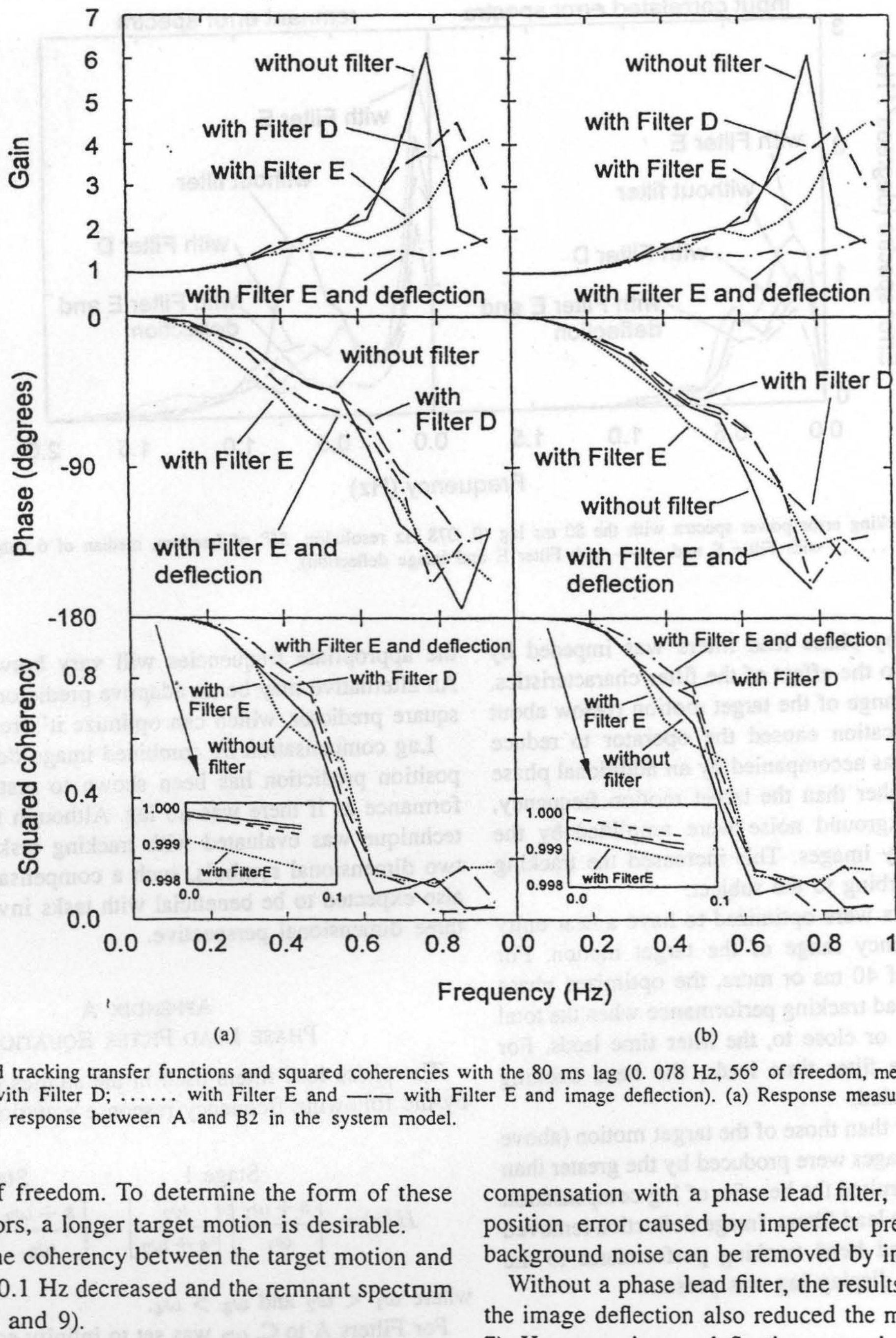

Fig. 8. Yaw-axis head tracking transfer functions and squared coherencies with the 80 ms lag (0. 078 Hz, 56° of freedom, median of 6 subjects) (——— without filter; – – – with Filter D; . . . . . . with Filter E and —·— with Filter E and image deflection). (a) Response measured between A and B1 in the system model; (b) response between A and B2 in the system model.

the low degrees of freedom. To determine the form of these low frequency errors, a longer target motion is desirable.

With Filter E, the coherency between the target motion and the output around 0.1 Hz decreased and the remnant spectrum increased (Figs. 8 and 9).

At frequencies around 1.4 Hz, the remnant spectrum with Filter E and the 80 ms lag had a magnitude of about 0.2°^{2}/Hz (Fig. 9). This indicates target oscillations relative to the subjects at these frequencies which may have been responsible for the jittery images.

Lag Compensation by Combined Phase Lead Filter and Image Deflection: For lag compensation by both Filters D and E, the use of image deflection resulted in a performance which was unaffected by the imposed display lags up to 100 ms (Fig. 7; $p > 0.1$ Filter D with image deflection; $p > 0.1$ Filter E with image deflection, Friedman two-way analyses of variance performed to test the effects of lags on tracking error). In addition, jittery image movement disappeared with image deflection. These results show that when providing lag compensation with a phase lead filter, any remaining image position error caused by imperfect prediction or magnified background noise can be removed by image deflection.

Without a phase lead filter, the results show that the use of the image deflection also reduced the mean radial error (Fig. 7). However, image deflection caused parts of the image to be displaced beyond the field-of-view of the display [9]. With large image displacements, deflection may also cause parallax distortion when it is applied to images of 3-dimensional objects. The amount of deflection required should therefore be minimized. Both Filter D and Filter E significantly reduced the required image deflection when the imposed display lag was close to, or greater than, the time lead provided by the filters ($p < 0.05$, Wilcoxon, both axes).

V. Conclusion

Display lags of 40 ms or more degraded tracking performance with head-coupled visual displays when the lags were imposed in a system with a 40 ms baseline display lag.

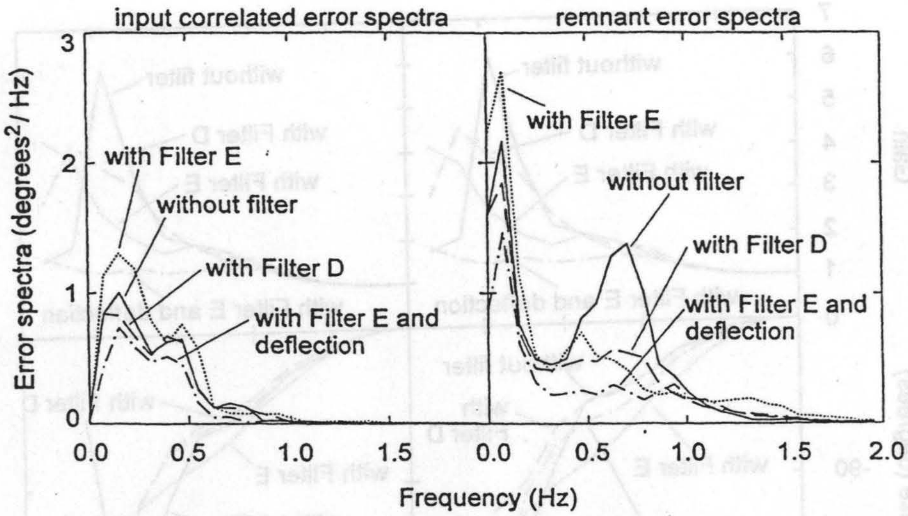

Fig. 9. Yaw-axis head tracking error power spectra with the 80 ms lag (0. 078 Hz resolution, 56° of freedom, median of 6 subjects) (—— without filter; - - - with Filter D; ...... with Filter E and —·— with Filter E and image deflection).

Lag compensation by phase lead filters was impeded by the operator response to the effect of the filter characteristics. Within the frequency range of the target motion (below about 0.7 Hz), filter amplification caused the operator to reduce control gain and this was accompanied by an additional phase lag. At frequencies higher than the target motion frequency, head motion and background noise were amplified by the filters to produce jittery images. This increased the tracking remnant and was disturbing to the subject.

Two phase lead filters were optimized to have a near unity gain within the frequency range of the target motion. For imposed display lags of 40 ms or more, the optimized phase lead filters improved head tracking performance when the total lags were greater than, or close to, the filter time leads. For total lags less than the filter time leads, the head tracking performance was degraded.

At frequencies higher than those of the target motion (above about 0.7 Hz), jittery images were produced by the greater than unity filter gains. This limited the benefits of lag compensation with the optimized phase lead filters. Image deflection removed the jittering and restored head tracking performance to the level when no imposed display lag was present.

VI. Final Remarks

Updating complex computer-generated graphics scenes on a head-coupled system can involve lags in the order of 80 to 100 ms. The finding that an imposed 40 ms lag can degrade head tracking performance suggests that lag compensation can be highly desirable when using head-coupled systems.

When a phase lead filter is used to predict head position during a tracking task, it is important to maintain a unity filter gain within the frequency range of the target movement. A greater than unity filter gain may cause operators to reduce their tracking gain and increase their tracking phase lag, which will cause more tracking error. Phase lead filters can be optimized to have unity gain at appropriate frequencies, although the appropriate frequencies will vary between applications. An alternative may be an adaptive predictor, like least-mean-square predictor, which can optimize it's response.

Lag compensation by combined image deflection and head position prediction has been shown to restore tracking performance as if there was no lag. Although the compensation technique was evaluated with tracking tasks involving only two dimensional symbols, such a compensation technique is also expected to be beneficial with tasks involving images in three dimensional perspective.

Appendix A
Phase Lead Filter Equations

The phase lead filters used in the studies can be described by the following frequency response equation

$$H(s) = \underbrace{\left[\frac{s+\omega_1}{\omega_1}\right]\left[\frac{\omega_2}{s+\omega_2}\right]}_{\text{Stage 1}} \times \underbrace{\left[\frac{s+\omega_3}{\omega_3}\right]\left[\frac{\omega_4}{s+\omega_4}\right]}_{\text{Stage 2}}$$

where $\omega_1 < \omega_2$ and $\omega_3 > \omega_4$.

For Filters A to C, ω_3 was set to infinity so that Stage 2 of the above equation became

$$\left[\frac{\omega_4}{s+\omega_4}\right]$$

Stage 1 of the frequency response equation described a high-pass filter and Stage 2 described a low-pass filter. The former had a phase lead response and the latter had a phase lag response.

The filter parameters for Filters D and E were optimized to produce a filter with unity gain and phase lead below 0. 7 Hz. Above this frequency, the gain was kept as low as possible. An amplification greater than unity was inevitable at frequencies higher than 0.7 Hz.

TABLE I
FILTER PARAMETERS FOR FILTERS A TO E (SAMPLING PERIOD = 0.02 S)

Parameter	Filter A	Filter B	Filter C	Filter D	Filter E
a_0	5.722	13.174	33.500	14.632	3.102
a_1	0.333	0.261	0.333	-24.746	4.336
a_2	-5.389	-12.913	-33.167	10.724	1.630
a_3	0.091	0.091	0.091	0.062	1.000
a_4	0.091	0.091	0.091	0.124	-1.735
a_5	0.000	0.000	0.000	0.062	0.765
b_1	0.333	0.261	0.333	-0.007	0.408
b_2	-0.667	-0.739	-0.667	-0.383	-0.390
b_4	-0.818	-0.818	-0.818	-1.184	-1.309
b_5	0.000	0.000	0.000	0.431	0.579

The frequency response equation was transformed to the discrete time domain through the bi-linear z-transform (sampling period = 0.02 s)

$$H(z) = \overset{\text{Stage 1}}{\left[\frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}}\right]} \overset{\text{Stage 2}}{\left[\frac{a_3 + a_4 z^{-1} + a_5 z^{-2}}{1 + b_4 z^{-1} + b_5 z^{-2}}\right]}.$$

The filter parameters (a_0 to b_5) for Filters A to E are shown in Table I. The filters were implemented in direct-form II [8].

APPENDIX B
DEPENDENT VARIABLES

A. Head Tracking Transfer Functions

The quasilinear model of the head tracking system shown in Fig. 2 was adapted from Krendal and McRuer [6]. Head tracking was modeled as pursuit tracking behavior [10]. From Fig. 2, the transfer function measured between points A and B1 is

$$H_{\text{head}}(f) \cdot H_{\text{sys}}(f) = \frac{G_{io'}(f)}{G_{ii}(f)}$$

where $G_{io'}(f)$ is the cross spectrum between the target motion $I(f)$ and the pre-filtered and pre-lag head motion measured at $B1, O'(f)$; $G_{ii}(f)$ is the power spectrum of the target motion, $I(f)$.

A transfer function was also measured between points A and B2. This transfer function is

$$H_{\text{head}}(f) \cdot H_{\text{sys}}(f) \cdot H_{\text{filter}}(f) \cdot H_{\text{lag}}(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

where $G_{io}(f)$ is the cross spectrum between the target motion $I(f)$ and the output at B2, $O(f)$.

This transfer function represents the overall gain and phase.

B. Squared Coherency Functions

A squared coherency function, $\gamma_{io}^2(f)$, between a target input and a head tracking output may be calculated

$$\gamma_{io}^2(f) = \frac{|G_{io}(f)|^2}{|G_{ii}(f)| \cdot |G_{oo}(f)|}$$

where $G_{io}(f)$ is the cross spectrum between the input and the output; $G_{ii}(f)$ and $G_{oo}(f)$ are the power spectra of the input and the output respectively.

C. Error Power Spectra

The tracking error power spectrum, $G_{ee}(f)$, consists of an input-correlated component and a remnant component

$$G_{ee}(f) = G_{ee}(f) \cdot \gamma_{ie}^2(f) + \text{Remnant}$$

where $G_{ee}(f)$ is the power spectrum of the tracking error; $\gamma_{ie}^2(f)$ is the squared coherency function between the target motion, $I(f)$, and the tracking error, $E(f)$.

The remnant spectrum can also be calculated with the following equation

$$\text{Remnant} = G_{oo} \cdot (1 - \gamma_{io}^2(f))$$

where $G_{oo}(f)$ is the power spectrum of the tracking output, $O(f)$, measured at point B2; $\gamma_{io}^2(f)$ is the squared coherency between the target motion, $I(f)$, and the tracking output, $O(f)$.

D. Mean Radial Error

The mean radial head tracking error (MRE) is

$$\text{MRE} = \frac{1}{N}\sum_{i=1}^{N}(p_i^2 + y_i^2)^{\frac{1}{2}}$$

where p_i is the ith value of the pitch axis error time history; y_i is the ith value of the yaw axis error time history; N is the number of values in each time history.

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