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DIGITAL ANALYSIS OF THE VOLUNTARY HEAD MOVEMENT-INDUCED
VESTIBULO-OCULAR REFLEX, WITH SACCADE EXTRACTION

Ralph M. Jell, Gene T. Turnipseed, and Fred E. Guedry, Jr.

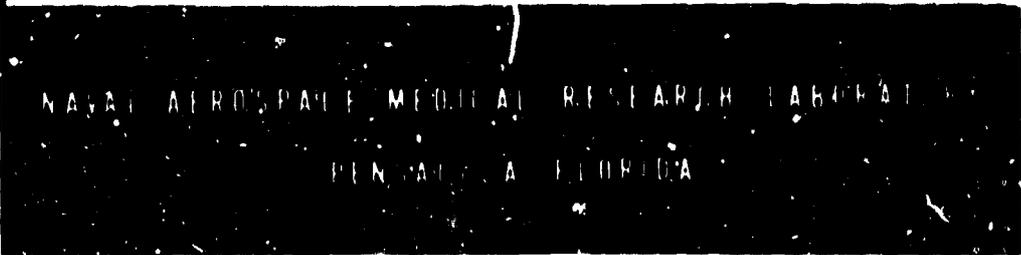
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SUMMARY PAGE

THE PROBLEM

Failures in visual pursuit, in ocular stabilization during head movement, and in visual suppression of the vestibulo-ocular reflex (VOR) are characterized by saccadic (high velocity) corrections for errors in the smooth pursuit velocity required to maintain foveation of targets. Measures of the ratio of pursuit eye velocities to velocities required by the stimulus situation together with counts of saccadic corrections are required to quantitatively characterize the over-all response which is crucial to performance in many operational situations and in neuro-otological examinations for equilibration disorders.

FINDINGS

A signal processing algorithm utilizing available equipment was developed to detect, count, and remove saccades from oculomotor responses generated by head oscillation and to provide estimates of the "response gain" under several conditions of visual stimulation. After saccade removal, the velocity of "smooth" pursuit or slow phase eye velocity may be plotted with respect to stimulus velocity automatically if desired. A linear regression least squares fit of the data provides a quantitative estimate of the "response gain" (ratio of eye to stimulus velocity), and the correlation coefficient provides an index of the goodness of fit. This procedure may be used to assess the oculomotor response during either cyclic vestibular or visual stimulation.

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INTRODUCTION

Stabilization of visual fixation during natural head movement is necessary for maintained high visual acuity. Two neural pathways send control messages to the motor nuclei which drive the eyes smoothly during head movements: One pathway carrying information about visual target movement in the visual fields attempts to maintain foveation by a "tracking" or "smooth pursuit" process; a second pathway originates in the inner ear sensors of head angular and linear acceleration - the vestibular organs - and sends signals which are compensatory for the resultant head movement, the vestibulo-ocular reflex (VOR). Failure to maintain foveation may produce a rapid compensatory movement (saccade) of the eyes to a new fixation point. These two separate systems normally operate over different ranges of target velocity, tracking being optimum from frequencies close to zero up to 1 Hz, and the VOR being effective from below 0.1 Hz to at least 4 Hz.

In order to test the function of the VOR, it is common practice to record eye movements electrically by detecting with skin surface electrodes the changing potentials produced across the eyes by the moving corneoretinal potentials of the eyes. Analytical determination of the relationship between head velocity and eye velocity during passive whole-body rotation or voluntary head movements then characterizes the VOR (3-5,7,9). The presence of saccades in the eye position record complicates the analysis since it represents a different process from that involved in smooth eye movement.

This report describes a computer-based procedure for determining, in the time domain, the output (eye velocity) versus input (head velocity) relationship during voluntary head oscillation, including algorithms to detect and remove saccades before analysis. The procedures, developed for use with equipment available at the time, provide a basis for further advances in automated scoring as updated equipment becomes available.

PROCEDURE

Head and eye position signals were obtained from human subjects according to procedures described elsewhere (6), and recorded in analog form on magnetic tape, along with calibrations of head and eye signal channels for 20 deg of left and right movement with respect to center gaze position.

For analysis, the magnetic tape was replayed for analog-to-digital conversion and digital storage of data on diskettes. Analysis was then carried out on these diskette data files.

APPARATUS

Analog recordings were made on a Philips Mini-Log 4 four-channel cassette recorder. Recording mode was frequency modulation at a tape speed of 0.75 inch per sec, giving a signal channel bandwidth of d.c. to 250 Hz. Eye and head position signals were simultaneously recorded on

paper chart, using a Hewlett-Packard Model 7754A thermal strip chart recorder.

The Hewlett-Packard Model 3582A Spectrum Analyzer is capable of simultaneous two-channel analog-to-digital conversion and storage of preselected time epochs of data under remote control via the standard Hewlett-Packard interface bus (HP-IB). The input circuits of the 3582A incorporate appropriate anti-aliasing filters for the chosen sampling rate. Programs were written in BASIC to run on a Hewlett-Packard 9830A calculator which was interconnected via the HP-IB with the spectrum analyzer. Under program control, the spectrum analyzer first was commanded to acquire the two channels of data present at its inputs, generating two corresponding 512-sample blocks of 16-bit digital data in its 1024 word memory. A typical time epoch was 12.5 sec, during which time 512 samples each of head and eye position data were obtained, at a sampling rate of 40.96 samples per sec.

At the end of each acquisition epoch, the contents of the spectrum analyzer memory were transferred via the HP-IB and under 9830A control to the memory of the 9830A, and thence to permanent mass storage on an Infotek Model FD30A diskette unit.

Analysis was done on the 9830A calculator, using BASIC programming. Data plots were made by the Hewlett-Packard Model 9862A X-Y plotter and printouts by the Hewlett-Packard Model 9871A printer, both operating as peripheral devices under the control of the 9830A calculator.

METHOD

A typical time record of head and eye position data is shown in Figure 1 and will be used as the basis for this discussion. In this case, voluntary head oscillation at approximately 1 Hz over an angle of about 40 deg was the forcing function, and the VOR, with partial suppression by attempted fixation on a spot of light moving with the same angle and phase as the head, was the response. Perfect suppression would produce a flat eye position trace, as the eye would not move in the head. Zero suppression would result in an eye trace matching the head waveform, but 180 deg out of phase with it. At 1 Hz, fixation was only partially able to suppress the VOR and resulted in sporadic saccades to catch the target.

The objective was to relate eye velocity to head velocity throughout the epoch, without contamination from the high velocity saccades. The saccade detection and removal procedure are outlined in block form in Figure 2. The operation was performed only on the eye movement record which started out as the raw displacement data from the diskette file. This 512-point record was digitally differentiated by the procedure:

$$Y'_i = (Y_{i+1} - Y_i) \cdot r$$

where Y_i is the i th displacement sample, Y_{i+1} is the $i+1$ st sample, Y'_i is the i th velocity sample, and r is the sampling rate. Figure 3 shows velocity data (head and eye) corresponding to Figure 1. The eye

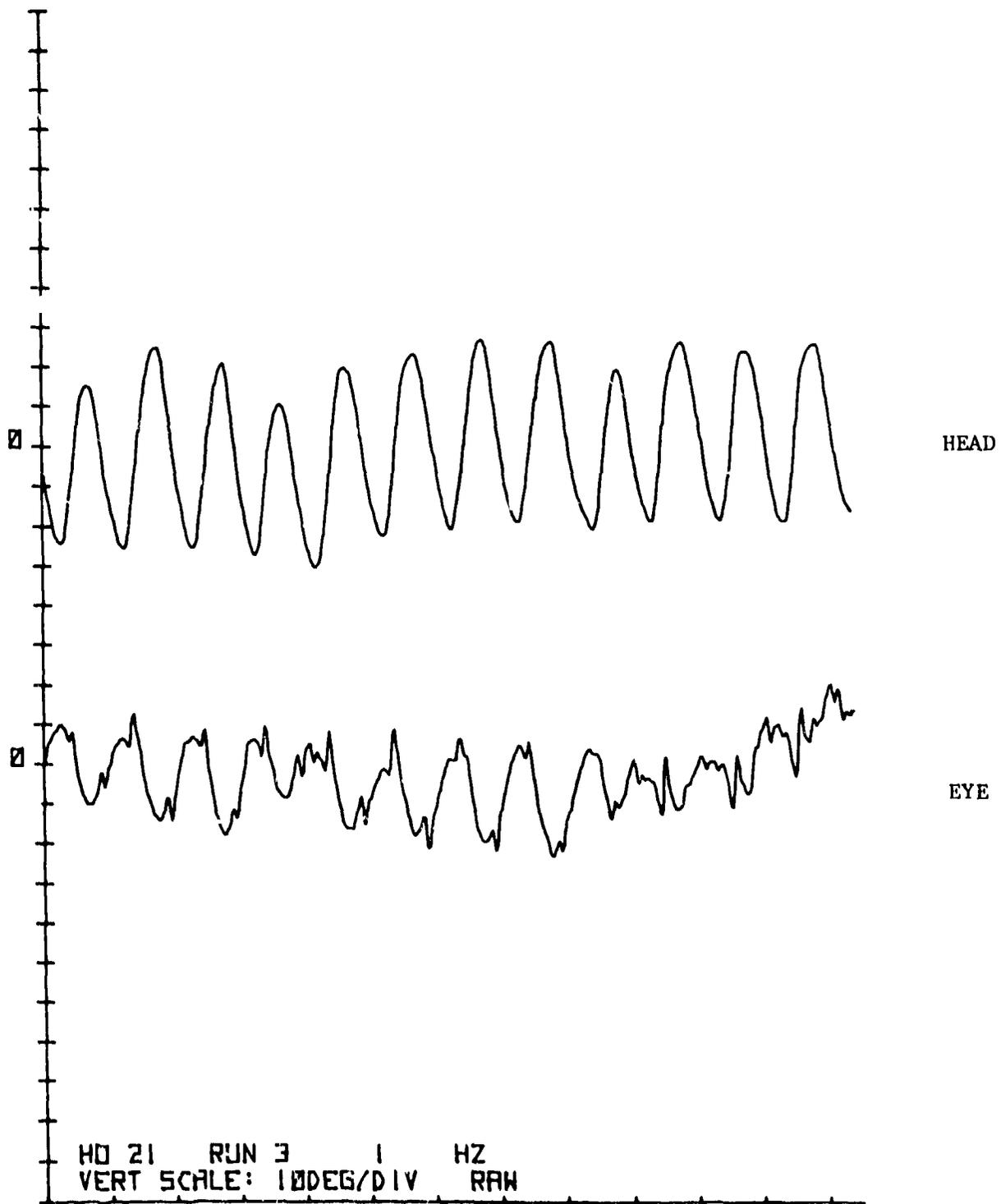


Figure 1

Time record showing head and eye position data. (Horizontal scale is in this and all subsequent time records.)

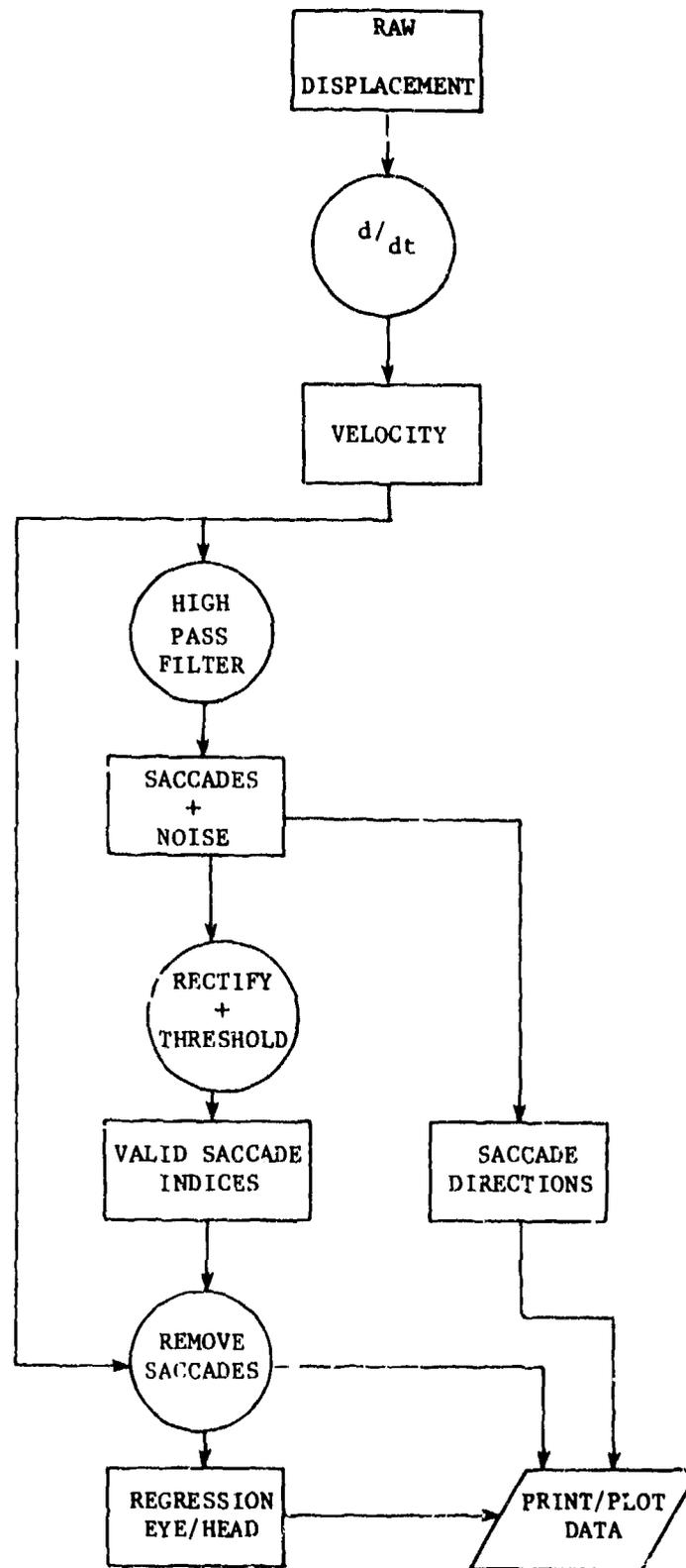


Figure 2

Block diagram of the saccade detection and removal procedure

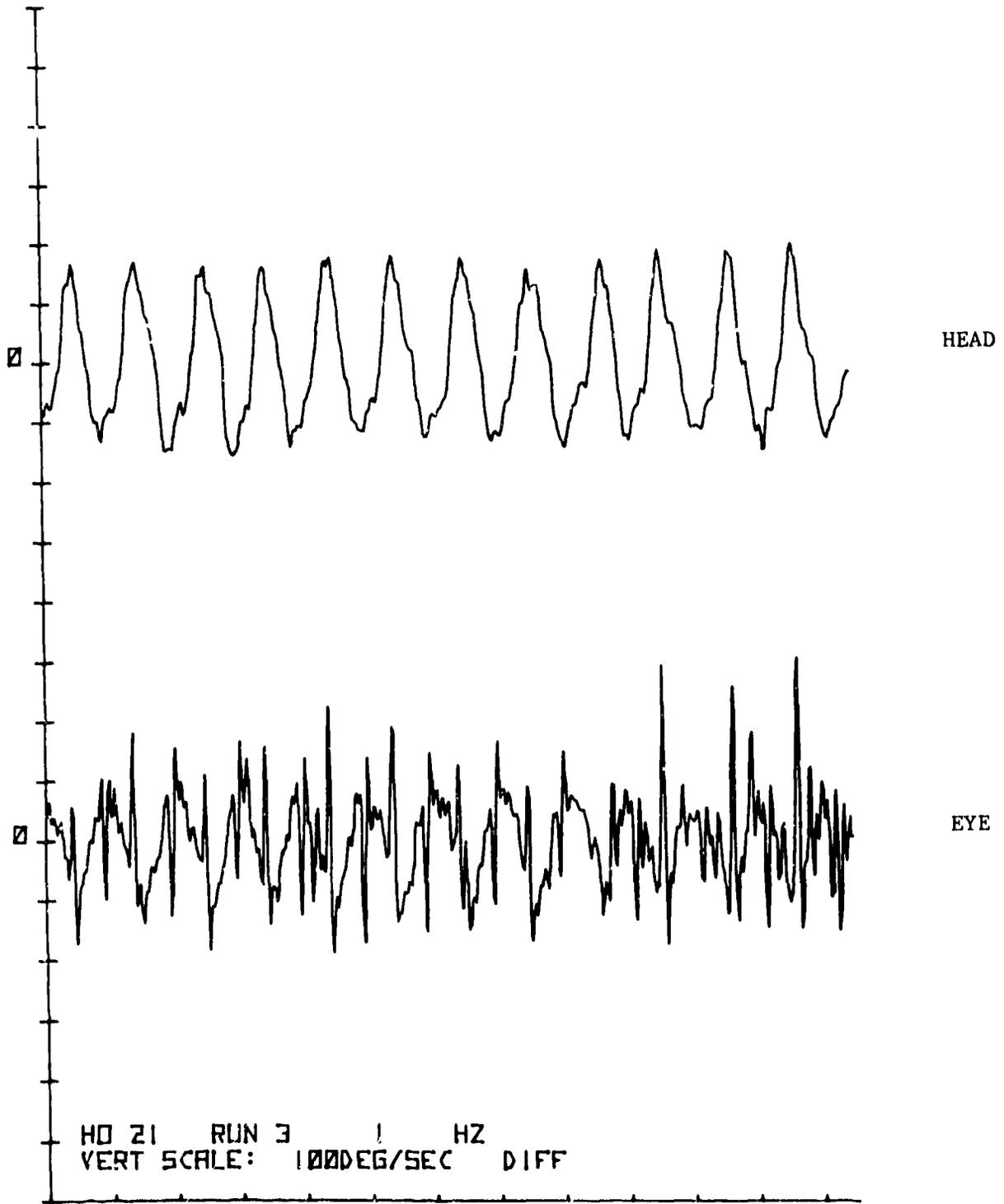


Figure 3

Time record showing head and eye velocity data

velocity record was saved for future removal of saccades, and its duplicate was then used for saccade detection.

The saccade detection process consisted of a digital high pass filter, which removed all but the high velocity saccades and differentiation noise, followed by full wave rectification and elimination of subcriterion peak velocities. The remaining peaks were taken as valid pointers to saccades in the velocity record. Implementation of the digital high-pass filter was achieved by subtracting from the original velocity record a low-pass filtered version of itself. The low-pass filter equation was the 3-point moving average

$$Y'_i = \frac{Y_{i-1} + Y_i + Y_{i+1}}{3}$$

where Y_i is the i th sample of the velocity record which is replaced in the filtered record by Y'_i , and Y_{i-1} and Y_{i+1} are the preceding and next velocity samples, respectively. Four iterations of this equation were applied to produce a low-pass filter with a cutoff frequency of approximately 4 Hz, slope 12 dB/octave and zero phase shift (8). Figure 4 (lower tracing) shows the resulting eye velocity record, which was then subtracted from the record of Figure 3 and full wave rectified simply by the process of taking absolute values of all points. From the full wave rectified record, as shown in Figure 5, the saccades could be located by detecting the largest peaks in each group. This process was facilitated by first smoothing the record by low-pass filtering with two passes of the 3-point moving average already described, resulting in the record shown in Figure 6. The peaks of the record were then determined by detecting positive to negative slope transitions. All peaks below a preassigned threshold were rejected and the indices of the rest were held in a saccade index matrix. At this point, each saccade index was used to find the direction of the corresponding saccade by referring back to the record containing saccades before rectification. The sign of the indexed sample in this record indicated whether the saccade was upgoing or downgoing, and a saccade direction matrix was formed to contain direction information for all accepted saccades.

Saccade removal from the eye displacement or velocity record was performed by replacing five sample points for each saccade, as indexed by the saccade index matrix. A satisfactory result was obtained by removing the indexed sample, three previous and one following; these samples were removed by replacing their values with an unlikely one, in this case the value 999. Subsequent processing always tested each sample for the value 999, and ignored such samples. An example of a displacement record with saccades removed is shown in Figure 7, which should be compared with the raw data of Figure 1. Removal of saccades from the velocity record is shown in Figure 8, which should be compared with Figure 3.

The true relationship between eye velocity and head velocity was then obtained by plotting the eye velocity record with saccades removed against the corresponding head velocity record. An example of this is

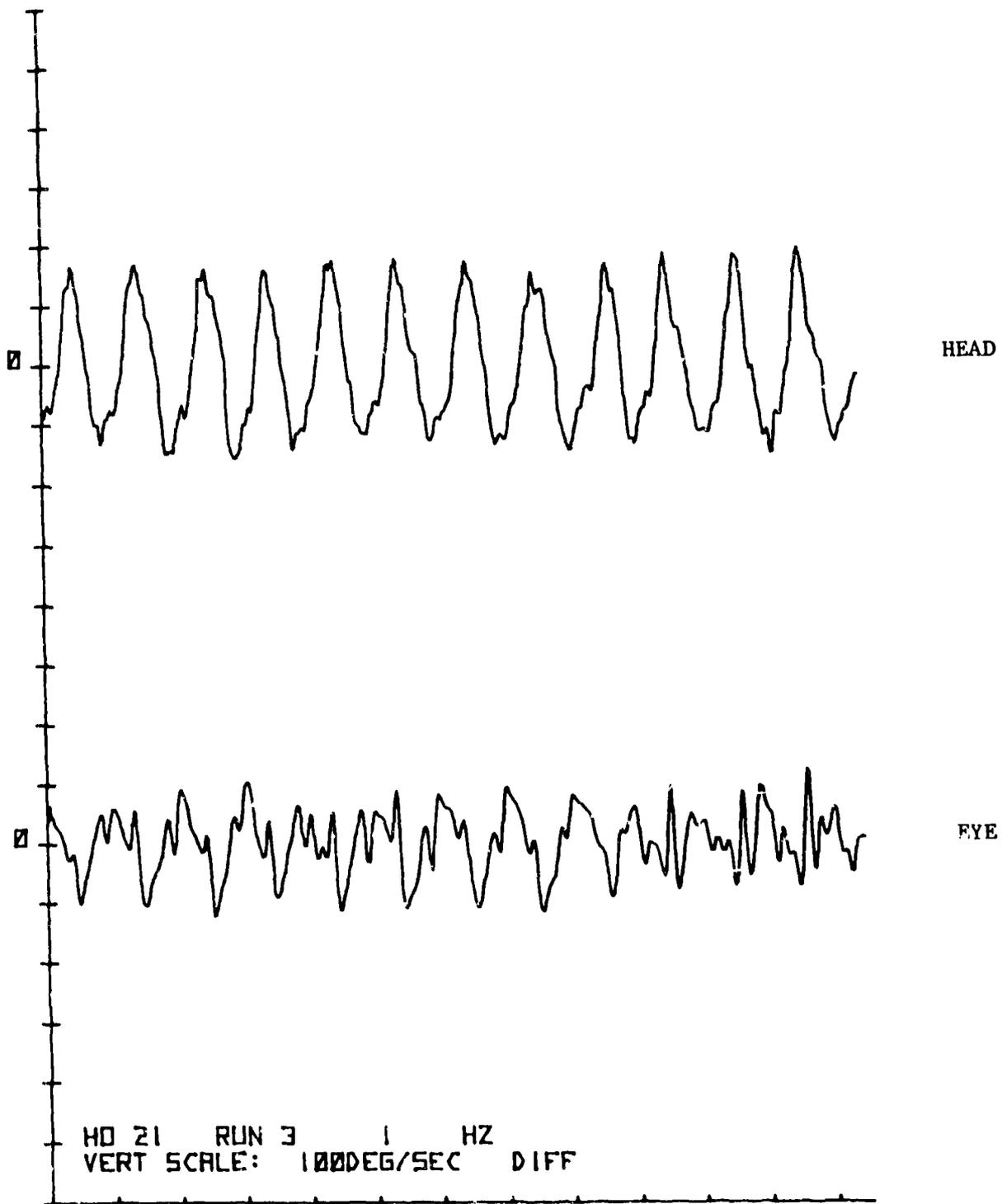


Figure 4

Time record of head and eye velocity data after the eye velocity
has been filtered

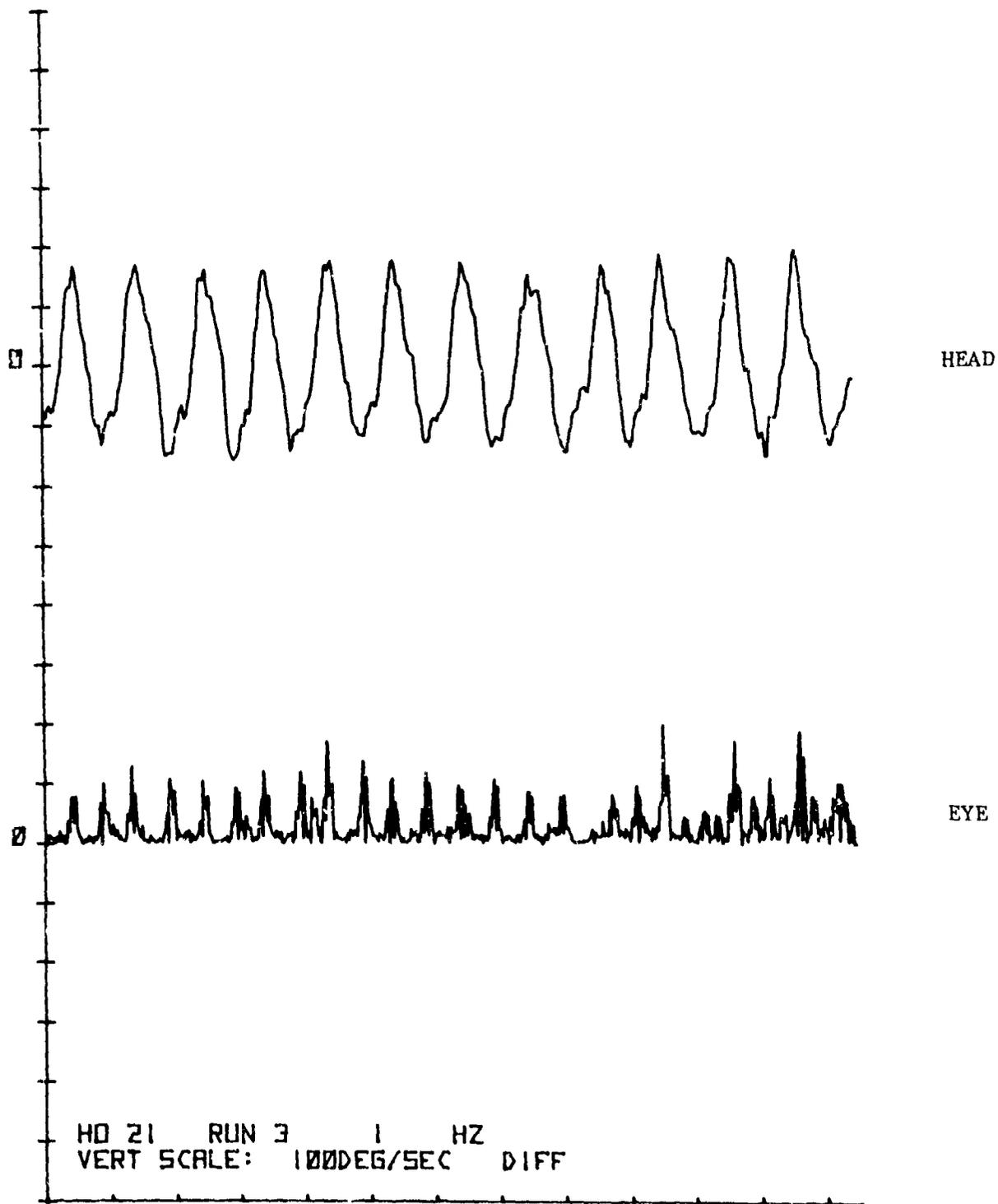


Figure 5

Eye velocity after the filtered data were subtracted from
velocity data and rectified

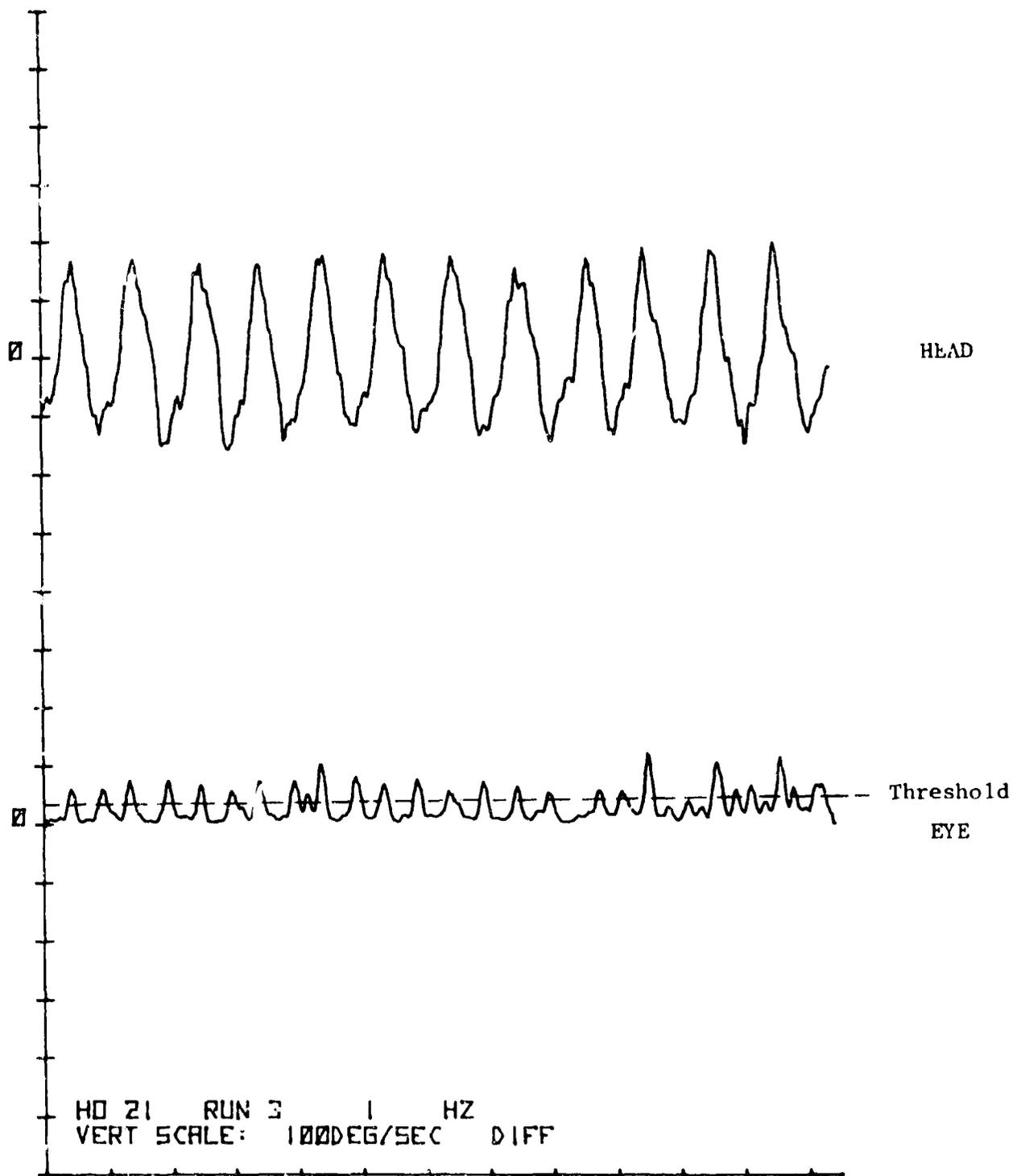


Figure 6

Rectified eye velocity data after filtering, showing
saccade peaks and a saccade detection threshold

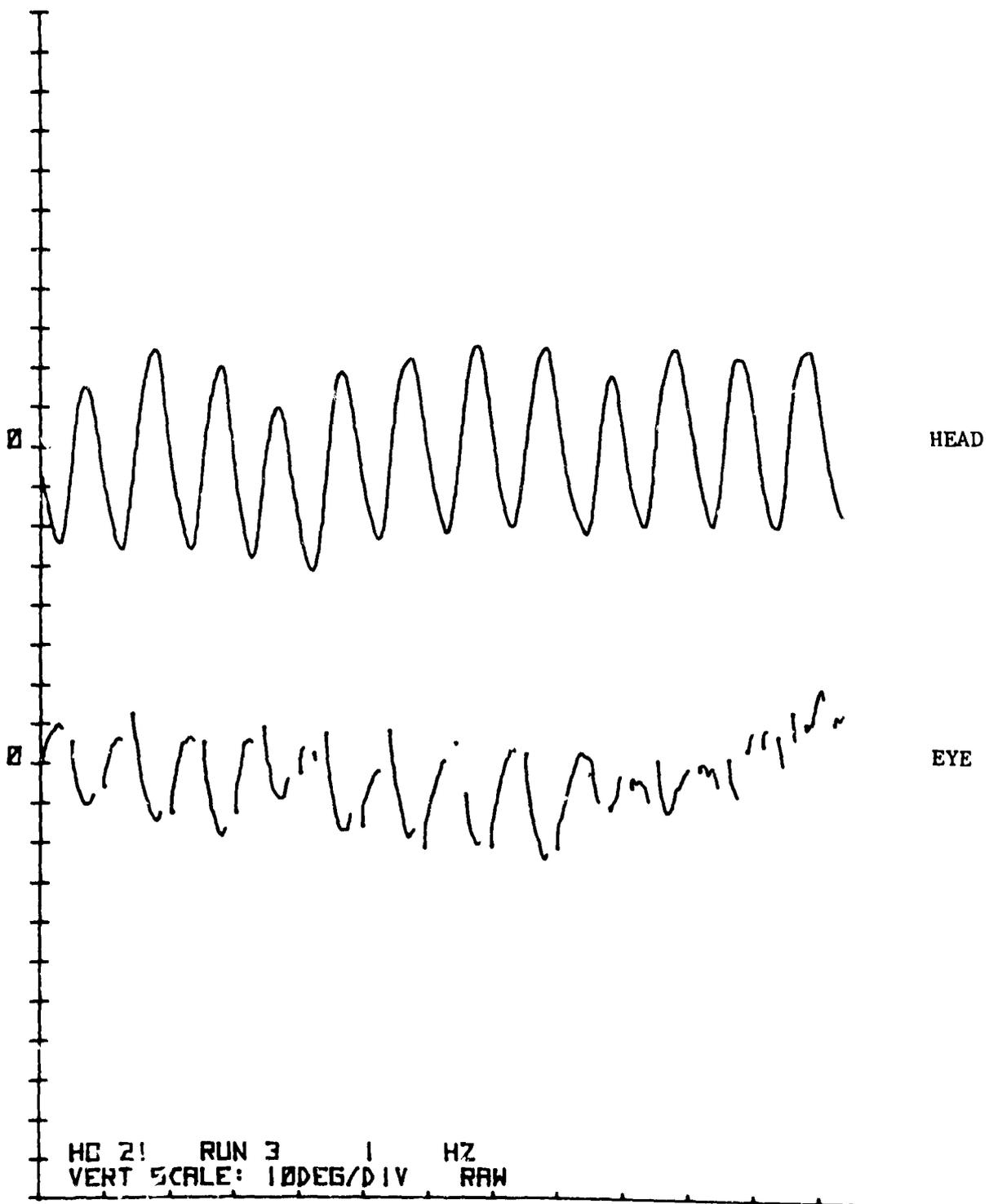


Figure 7

Time record of head and eye displacement data with saccades removed

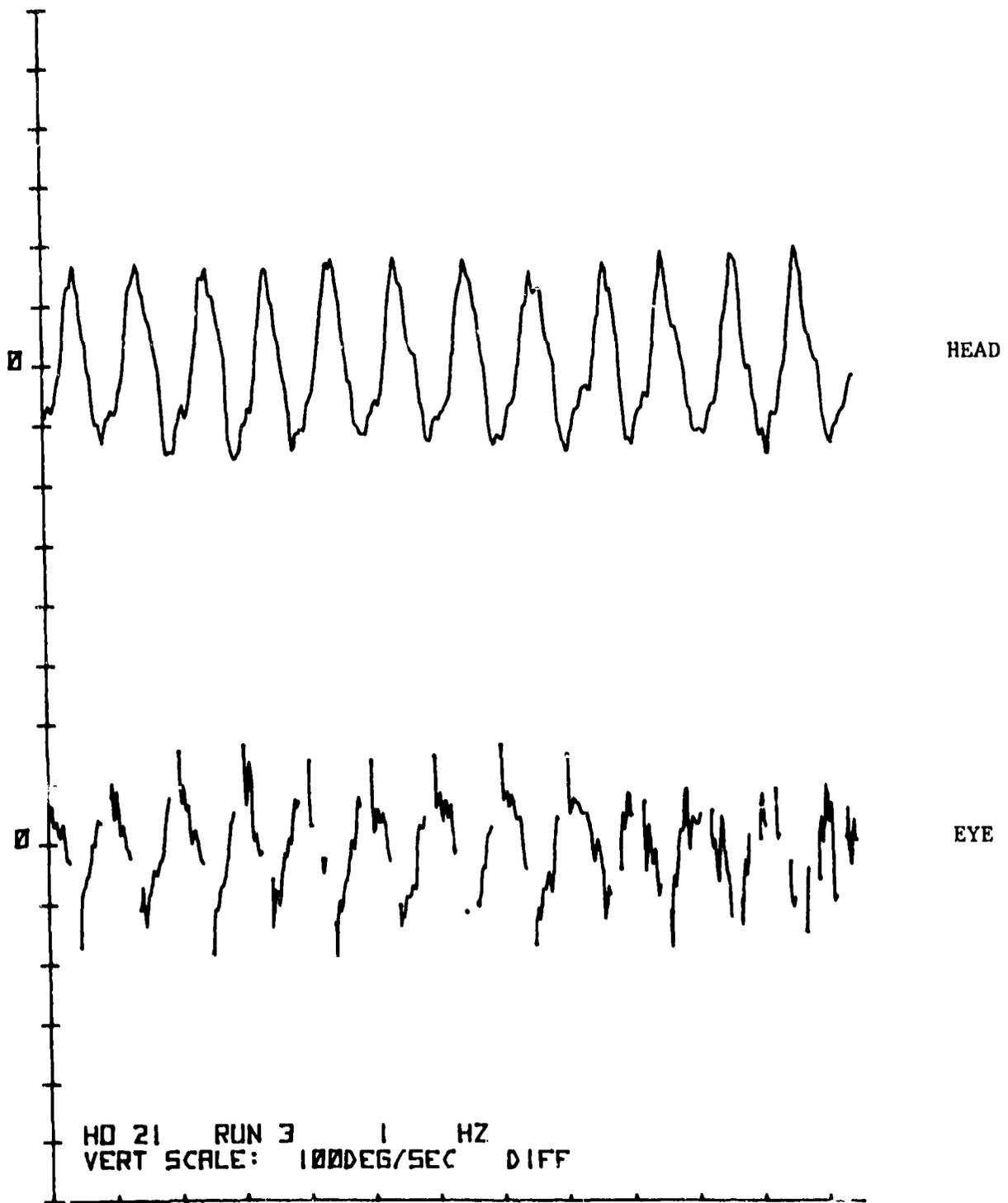


Figure 8

Time record of head and eye velocity with saccades removed

given in Figure 9, where movements to the right yield positive velocities. Each point represents a head velocity and the corresponding eye velocity at that point in time, with no saccades represented. The slope of the best fitting line for positive head velocities yields the gain of the VOR for head movements to the right, and similarly the slope of the best fitting line for negative head velocities yields VOR gain for leftward head movements.

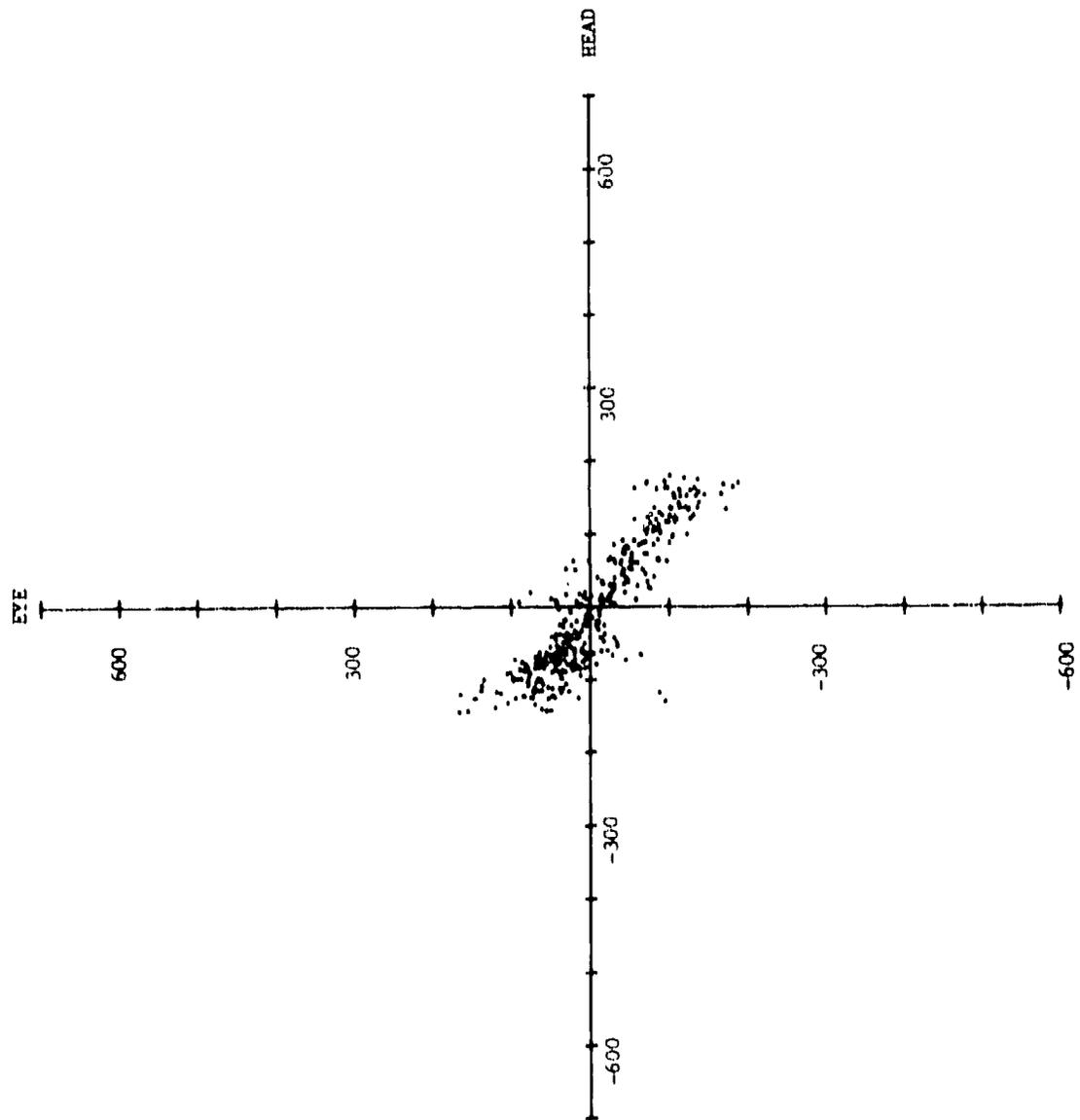
Best fitting lines by the method of least squares for both leftward and rightward head movements have been computed and plotted on the data of Figure 9, and are shown in Figure 10. A line was also computed and plotted for the whole record. Equations of the best fitting lines and regression coefficients were printed out, along with saccade number and direction subtotals.

RESULTS AND DISCUSSION

Comparison of Figures 1 and 7 reveals the success of the saccade extraction procedure. Twenty-nine saccades were detected and removed from the data of Figure 1, leaving a displacement record consisting primarily of the slow component of the VOR. When the same saccades were removed from the velocity data of Figure 3, the result shown in Figure 8 was obtained. Eye velocity was then plotted against head velocity, and the result is shown in Figure 9, where each dot represents one eye velocity sample and the head velocity corresponding to it. Most of the dots are clustered about lines through the origin in the second and fourth quadrants, and would all fall on the bisectors if the gain was unity with zero phase shift. The actual gain was determined by fitting a regression line, by the method of least squares, to the data in each side of the vertical axis; data on left side represent head movements toward the left while those on the right side are representative of head movements to the right. Results of the linear regression for these data are shown in Figure 10. A slightly higher gain with head movements to the right is indicated (0.777 vs. 0.671), although the spread is higher with leftward head movements. A regression line fitted to all data produces an intermediate value of gain (0.689) with better fit ($r = 0.884$) than either directional line.

In order to assess the value of saccade extraction in determining these parameters, linear regressions were computed for the eye velocity record without removal of saccades. These data are shown in Figure 11, where the dots have been connected with lines to show the saccade trajectory more clearly. Regression analysis produced unusable gain data in this case, with slopes skewed by high saccade velocities, and low coefficients of correlation as a result of the spread.

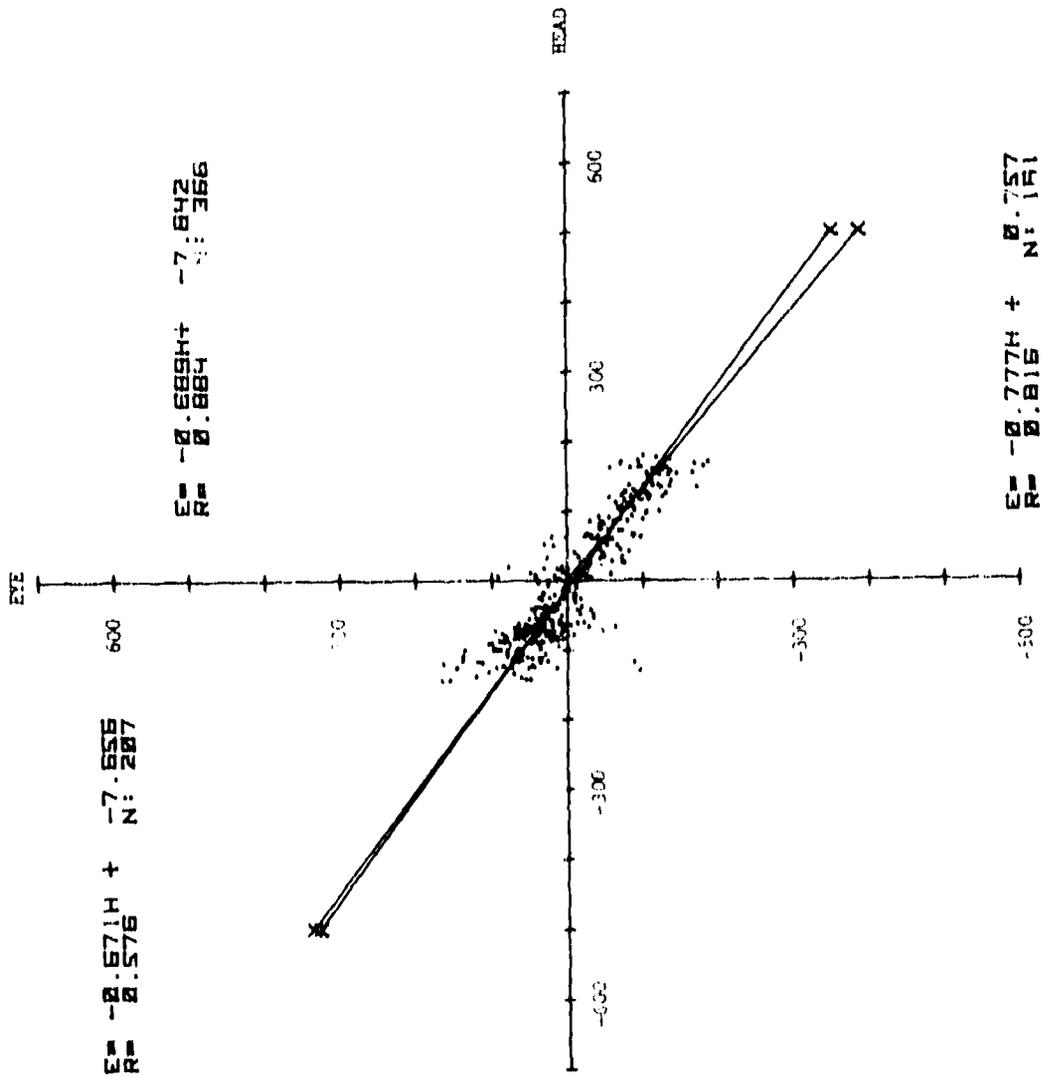
The procedures described have thus been shown to be successful in producing a meaningful analysis of eye versus head velocity relationships under the circumstances given. Two aspects of the procedures are empirical and could give rise to less optimum analyses under certain other circumstances. These are the value of the threshold level for peaks used to identify valid saccades (dashed line in Figure 6), and the number of samples



HD 21 RUN 3 1 HZ SCALES: 100 DEG/SEC/DIV SACCADES: 29

Figure 9

Plot of eye velocity versus head velocity with saccades removed



HD 21 RUN 3 1 HZ SCALES: 100 DEG/SEC/DIV SACCADES: 29

Figure 10

Plot of head velocity versus eye velocity, with saccades removed. Regression lines were fitted to the data as follows: top left for head movements toward the left, bottom right for head movements toward the right, top right for combined data.

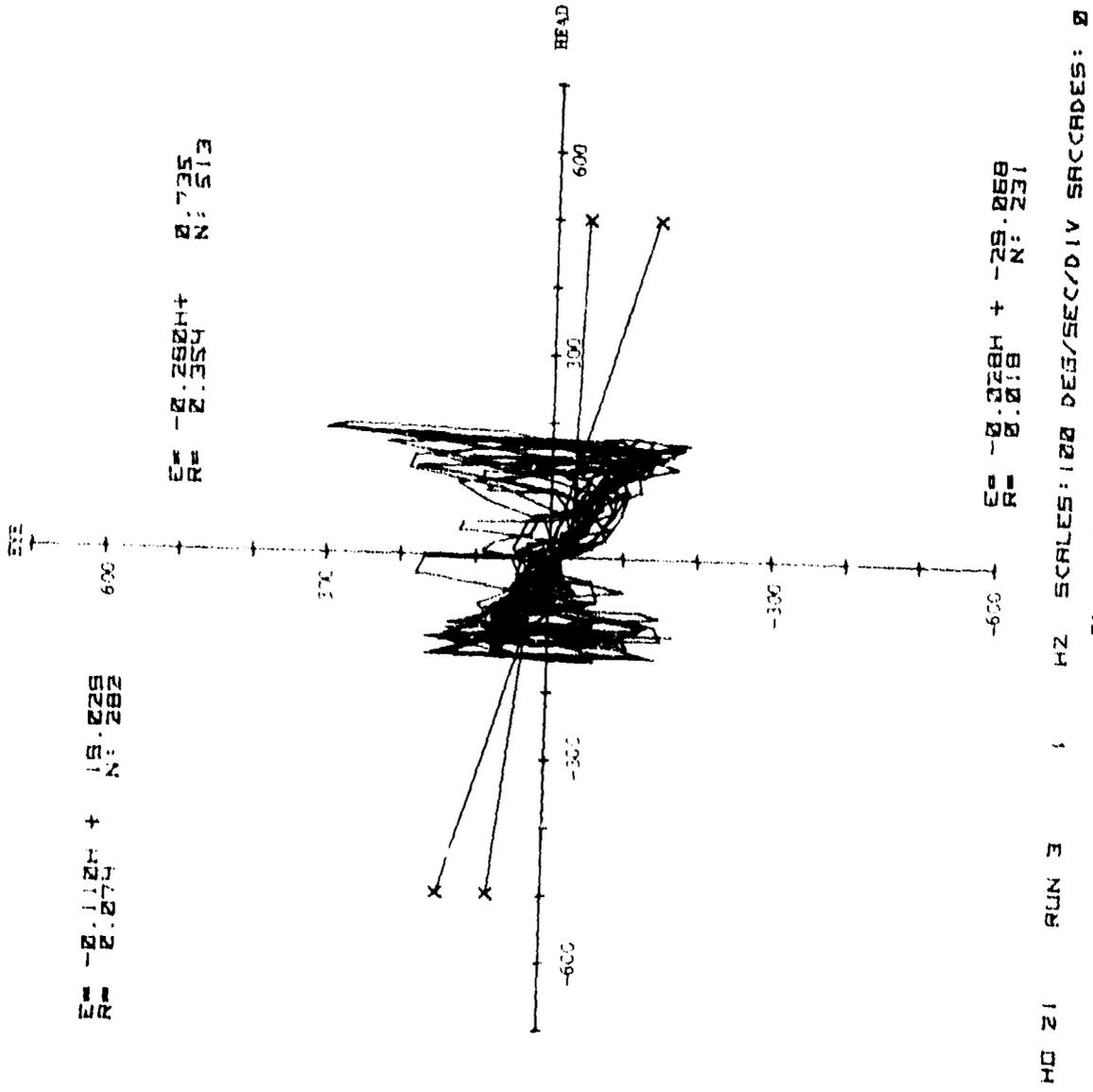


Figure 11

Plot of head velocity versus eye velocity, without saccade removal, with lines of best fit and their coefficients added as in previous figure

removed before and after the peak index from the velocity record. The former is related to saccade velocity which, under unchanging conditions of input to the VOR (head movement), might be expected to be reasonably constant for each saccade as long as it occurs at the same head velocity in each cycle. Any head velocity or eye amplitude dependence (2) of the saccade velocity may cause errors to occur in which true saccades are not eliminated because their velocities are too low for the chosen threshold. The effectiveness of saccade removal in producing a close-fitting regression line is also related to how well each saccade is removed once it is detected by the program, and this boils down to how many samples before and how many samples after the peak index are eliminated. Clearly, if some samples during the saccade are left in, a few straggling points will remain to lessen the regression line goodness of fit. Such is obviously the case in Figure 10. Alternatively, if too many samples are eliminated before and/or after each saccade index, valid points will be lost from the analysis. This could be of importance in evaluating the VOR in vestibular disorders which may involve high velocities in particular (1) since the saccades predominantly occur during the highest velocities of head movement. Careful assessment of this factor is therefore necessary in the application of the technique reported here.

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