NASA Technical Memorandum 100415

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(NASA-TM-100415) EFFECTS OF UPDATE AND REFRESH RATES ON FLIGHT SIMULATION VISUAL DISPLAYS (NASA) 19 p CSCL 01C
N88-22033
Unclas
G3/05 0142321

May 1988

National Aeronautics and
Space Administration

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SUMMARY

An experiment was performed to study the effects of update and refresh rates on dynamic calligraphic CRT displays, particularly those used for visual displays in flight simulators. A moving horizontal line was generated on a CRT and observed at various velocities. Observations were made with both one and two refreshes per update.

The data gathered from these observations are presented on plots of refresh-update rate as a function of display velocity. The display velocity where picture degradation occurs can be found by using these plots. These velocities are related to actual simulated aircraft angular and linear velocities.

Results show that a visual display updated at 30 Hz and refreshed at 60 Hz degrades at very low simulated aircraft angular and linear velocities. These velocities at which degradation occurs can be significantly increased by increasing the update rate of the visual display. Only minor improvements are possible by refreshing the display twice for each update. To display rapidly changing flight scenery without degradation, the display update rate must be far in excess of 60 Hz, typically several hundred Hz.

INTRODUCTION

Various artifacts have been observed in several computer-generated CRT visual displays intended for flight simulation applications. These artifacts usually involve multiple images and jerky motions when high display velocities occur. An experiment was conducted in an attempt to learn more about the nature of these artifacts and the conditions under which they occur. The experiment was not designed to measure the maximum capability of the eye to detect artifacts but rather to estimate the point where the visual display becomes unacceptable. The goal was to determine a relationship between display velocity and CRT refresh and update rates at the point where unacceptable artifacts appear. Although artifacts have been observed on both raster and calligraphic CRT displays, this experiment was limited to the calligraphic case. The intent of this experiment was to develop a simple criterion for estimating the minimum update and refresh rate that produces a calligraphic visual display of a quality acceptable for flight simulators.

Other work on this subject has dealt with constant-velocity lines moving in one direction. This steady motion can be characterized in terms of a combination of spatial and temporal frequency responses (Watson and others, 1983). Because flight simulation displays include unsteady motion (that is, rapid changes in image velocity), the results of this current experiment cannot be directly correlated with the results of previous experiments in which unsteady motion was not studied. To observe the maximum effect of unsteady motion, a display was studied that included substantially infinite accelerations. A line moving at constant velocity in one direction was instantaneously reversed to move at the same velocity in the opposite direction.

This report describes the experiment, discusses the results, relates the data to some actual flight simulation situations, and states some conclusions based on the experiment.

DESCRIPTION OF EXPERIMENT

To study the artifacts observed on visual displays, a horizontal line on an oscilloscope display was moved vertically at various speeds and viewed by several observers. These observers were asked to comment on what they saw. From the observer comments, a map of artifacts was generated. The experiment included lines refreshed once per update and twice per update. A line that is refreshed once per update is drawn on the screen once, has its position recomputed (updated), and is redrawn. A line that is refreshed twice per update is drawn on the screen twice in one position, has its position recomputed, and is redrawn twice in the next position. Lines are frequently refreshed more often than they are updated to avoid flicker in the display.

A block diagram of the setup used in this experiment is shown in figure 1. An oscilloscope is used as the display. A function generator producing a square wave was used to trigger the oscilloscope. The scope was set to trigger on the trailing edge of the pulse. This frequency, which is monitored by a frequency counter, is the refresh rate for the display. The square wave out of the function generator is also connected to a divide-by-two circuit. A microprocessor was used as a counter. The input to the microprocessor is switch-selectable. If the input to the microprocessor is taken directly from the function generator, a display with one refresh per update is obtained. If the input to the microprocessor is taken from the output of the divide-by-two circuit, a display with two refreshes per update is obtained. The microprocessor counted each leading edge of the square wave until reaching 4096, then it reversed and counted down to zero. This count drives a 12-bit digital to analog converter (DAC). The ouput of the DAC drives the vertical input of the oscilloscope. This creates on the oscilloscope screen a horizontal line that moves up and down. The line width was visually measured, and found to be approximately 1 mm. The speed of the line on the oscilloscope is controlled by varying the size of the increment or decrement of the count in the microprocessor as well as by varying the frequency of the function generator. The count is varied by loading the desired increment or decrement into the program of the microprocessor.

The refresh rate was read directly from the frequency counter. The velocity was calculated by taking 8 cm (the height of display), dividing by 4096 (the number of steps per height of the display), multiplying by the increment set into the program, then multiplying by the update frequency. This velocity was cross-checked at various values by using a stopwatch and counting the number of cycles per unit time of the moving line on the display.

This experiment was conducted under office fluorescent lighting of approximately 70 to 100 footcandles. To reduce reflections, a hood was placed around the screen for viewing.

Several people were asked to observe the effects of the moving line, and the data obtained represent the opinions of these observers. The viewing distance of each individual from the screen was maintained at approximately 1 m. Other viewing distances were tried, ranging from approximately 0.3 to 2 m, but the results were not affected.

RESULTS

The results of this experiment are plotted in figures 2 to 5. Figures 2 and 3 are individual plots of the data gathered. Figures 4 and 5 are superimpositions of the straight line approximations of figures 2 and 3. On figure 2, single refresh per update, the graph shows four distinct regions. The "perfect" region of the plot refers to the area where the line appears as intended; that is, it appears to move smoothly without jumping, flickering, blurring, or other artifact. The "flicker" region is where the human eye can detect the actual refresh on the screen. The line blinks in this region. Operation in this region is considered unacceptable. The "multiple line" region of the graph is where the single line appears to become two or more lines. As line velocity increases, these multiple lines are first seen at the top and bottom of the screen where the line reverses direction. The multiple line effect continues to increase as line velocity increases until it persists over the entire screen. The "blurring" region also occurs at the reversal points. The line appears to widen near the top and bottom of the screen (where the line reverses) as the velocity increases until multiple lines are seen.

On figure 3, double refresh per update, two more regions appear where visual artifacts occur. "Flutter" is an artifact where the eye sees the line jump from one position to the next. Flutter closely resembles flicker. "Flutter-multiple lines" is flutter in combination with multiple lines.

The regions for preferred viewing are those marked perfect. The regions marked blurring were judged acceptable for viewing, because this minor degradation was not objectionable to the viewers. Blurring is noticeable only on rapid changes of direction. As the velocity is increased in the area marked blurring, the effect is more pronounced. When multiple lines or flutter are encountered, the display has been degraded enough to be judged unacceptable.

The division line between acceptable and unacceptable viewing regions on both figures 2 and 3 can be approximated with straight lines (shown on these figures). Figure 4 is a combination of the straight line approximations of figures 2 and 3 aligned on the same refresh rate scale. Figure 5 is a combination of the straight line approximations of figures 2 and 3 aligned on the same update rate scale.

The line width of 1 mm used in this experiment reasonably approximates the line width found on 19- through 21-in. display CRTs used for flight simulation visual displays. The results of this experiment can then be directly applied to visual simulation problems that meet these criteria.

IMPLICATIONS

Using the data obtained from figures 2 and 3, and assuming a refresh rate of 60 Hz, the velocity at which the display degrades significantly can be found: for a single refresh per update, the velocity is 5.5 cm/sec. For a double refresh per update, and an update rate of only 30 Hz, the velocity decreases to 1.9 cm/sec.

These maximum acceptable display velocities can be related to simulated aircraft angular velocities, which are seen on simulated visual flight displays. The assumed visual display is a 20-in. CRT. The field of view of the screen is assumed to be 50° horizontal and 37.5° vertical. Sample calculations are shown in appendix A. These calculations compute aircraft angular velocities where the maximum acceptable display velocity occurs somewhere on the screen. In pitch and yaw, the display velocity is nearly constant over the entire screen, while in roll the maximum display velocity occurs at the edge of the screen. Aircraft angular velocities are shown in the following table:

Angular Velocities:

Axis	Refresh, 60 Hz, update, 30-Hz, deg/sec	Refresh, 60 Hz, and update, deg/sec
Roll	5.4	15.5
Pitch and Yaw	2.5	7.2

These maximum acceptable display velocities can also be related to simulated aircraft linear velocities. At lower altitudes, "out the window" displays on the screen result in objects in the near field moving faster than objects farther away. For example, on landing an aircraft, the runway center line moves faster at the bottom of the screen than it does at the center. A derivation and sample calculation are shown in appendix B. These calculations compute aircraft forward velocities at several different altitudes when the maximum acceptable display velocity occurs at the bottom of the screen. Forward velocities at low altitudes are shown in the following table:

Altitude, ft	Refresh, 60 Hz, update, 30-Hz, ft/sec	Refresh, 60 Hz, and update, ft/sec
15	5.4	15.8
50	18.	53.
100	36.	105.

CONCLUSIONS

At relatively low display velocities, artifacts were most readily observed at the reversal points, where acceleration approached infinity. This unsteady motion required very high update rates to eliminate unacceptable artifacts. Steady motion was observed at the center of the display. Steady motion artifacts occurred at higher display velocities for a given update rate. Although these velocities were not precisely measured, they were on the order of double the velocities at the reversal points. These velocities are in general agreement with previous work (Watson and others 1983).

The effective slope of the straight line approximation on figure 2 is approximately 0.93 mm per update. This slope is extremely close to the line width (1 mm) on the display. This comparison strongly suggests that immediately after an abrupt change in velocity, the human observer can see multiple lines any time the next line does not touch the previous line, regardless of the update rate. The eye also detected the lines partially overlapping in the blurring area as the line started to widen. This preliminary conclusion was not verified by additional tests. Such a verification would necessarily involve the study of solid images with different dimensions, and was beyond the scope of this experiment.

The results of this experiment are somewhat pessimistic, because infinite accelerations do not occur in actual simulated out-the-window displays; however, unsteady motion with substantial acceleration does occur, particularly in angular motions. This experiment shows that the study of steady, constant-velocity motion is not sufficient to fully predict the onset of artifacts. This experiment also defines the upper bounds on the onset of unacceptable acceleration-induced artifacts for the given test conditions.

The calculations show that when a simulated out-the-window scene from a maneuvering aircraft is generated at typical update rates (30 and 60 Hz), picture degradation occurs at low angular rates and at low ground speeds when the altitude is low. These rates are well below those actually encountered during simulated aircraft operation. Doubling the update rate from 30 to 60 Hz increases the acceptable maneuvering rates by a factor of approximately three, but they are still too low. Further increases in acceptable maneuvering rates are possible by further increasing update rates; however, the maneuvering rates of modern, high-performance fighter aircraft are very high. For example, roll rates in excess of 60°/sec combined with high accelerations are fairly common. Using this roll rate and the assumptions of appendix A, an extrapolation of the straight line approximation of figure 2 suggests that an update rate of 225 Hz may be required to avoid unacceptable artifacts. A pitch or yaw rate of 60°/sec could require an update rate as high as 480 Hz if substantial accelerations are present. Fortunately, pitch and yaw accelerations are somewhat lower, thus relaxing update rate requirements. These update rates are well beyond the current state of the art for all except the simplest visual displays. Thus other techniques besides update rate must be considered to improve the displays.

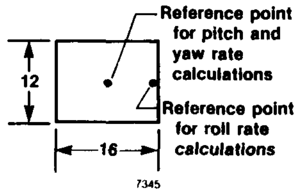
The benefits of doubling the refresh rate over the update rate are relatively small. The most significant benefit of a double refresh per update is to avoid flicker when the update rate is below 50 Hz. At higher update rates, the double refresh provides only a slight improvement. For example, at an 80-Hz update, acceptable screen velocity is about 7.4 cm/sec with one refresh per update. Doubling the refresh rate at the same update rate increases the acceptable velocity to about 8.7 cm/sec an improvement of approximately 18 percent. Therefore, higher refresh rates are, at best, only a small part of the solution of the artifact problem.

Other investigators have suggested other techniques to reduce artifacts, such as computed "smearing" of the picture. (Cook and others, 1984; Dippe and Wold, 1985; Korein and Badler, 1983; and Potmesil and Chakravarty, 1983). It remains to be seen whether it is more difficult to compute a smeared picture or simply increase the update rate.

APPENDIX A — ANGULAR VELOCITY COMPUTATIONS

This appendix relates the velocities of moving objects on a simulated aircraft CRT display to the actual angular rates of the simulated aircraft. The assumption is that the display measures 20-in. diagonally and has a horizontal-to-vertical aspect ratio of 4 to 3. This display is assumed to subtend a horizontal angle from the pilot's viewpoint of 50°. The resulting vertical angle is 38.6°, and the resulting viewer-to-CRT distance is 17.2 in.

The following diagram shows the assumed display:



These sample calculations will compute the aircraft angular velocities that coincide with the maximum acceptable display velocity for two update/refresh conditions. The first condition is a 30-Hz update, with two refreshes per update. According to figure 3, the maximum acceptable display velocity is 1.9 cm/sec. The second condition is a 60-Hz update, with one refresh per update. According to figure 2, the maximum acceptable display velocity is 5.5 cm/sec. These conditions were chosen because they are popular update and refresh rates in current use.

The symbols used are defined as follows:

v_1 — display velocity for 30-Hz update, 1.9 cm/sec
v_2 — display velocity for 60-Hz update, 5.5 cm/sec
r — radius from center of rotation, in.
ω_1 — angular velocity for 30-Hz update, deg/sec
ω_2 — angular velocity for 60-Hz update, deg/sec

The equation used, with conversion factors for in. to cm and rad to deg, is

$$\omega = \left(\frac{v}{r}\right)\left(\frac{1}{2.54}\right)\left(\frac{180}{\pi}\right) = 22.6\,\frac{v}{r}$$

For roll rate, r = 8 in. (horizontal distance from screen center to edge)

$$\omega_1 = 22.6\left(\frac{1.9}{8}\right) = 5.4 \text{ deg/sec}$$

$$\omega_2 = 22.6\left(\frac{5.5}{8}\right) = 15.5 \text{ deg/sec}$$

For pitch and yaw rates, $r = 17.2$ in. (distance from viewer to center of CRT screen)

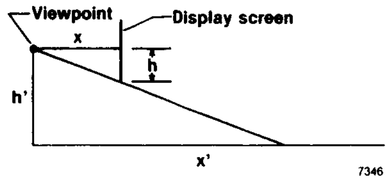
$$\omega_1 = 22.6\left(\frac{1.9}{17.2}\right) = 2.5 \text{ deg/sec}$$

$$\omega_2 = 22.6\left(\frac{5.5}{17.2}\right) = 7.2 \text{ deg/sec}$$

APPENDIX B — LINEAR VELOCITY COMPUTATIONS

This appendix relates the maximum velocity of a moving object on a simulated aircraft CRT display to the actual linear forward velocity of the simulated aircraft. Because the maximum display velocity occurs at the bottom edge of the display, the calculations are limited to that location. The assumptions are that the display measures 12 in. vertically and is located 17.2 in. from the viewpoint. The resulting total vertical viewing angle is 38.6°.

The following diagram shows the assumed display:



The symbols are defined as follows:

- x — distance of viewer from display screen, 17.2 in.
- x' — horizontal distance from viewer to the nearest visible point on the simulated runway in ft
- h — half the height of the display screen, 6 in.
- h' — simulated altitude of the viewer over the runway in ft
- t — time, seconds

To relate display velocity (dh/dt) to simulated aircraft forward velocity (dx'/dt), the following derivation is required:

Using similar triangles,

$$\frac{x'}{h'} = \frac{x}{h}$$

Taking the first derivative with respect to time,

$$\frac{dx'}{dt} = -\frac{h'x}{h^2}\left(\frac{dh}{dt}\right)$$

Because only magnitudes are significant the negative sign can be ignored.

The following sample calculations will compute the aircraft forward velocities that coincide with the maximum acceptable display velocity for two update/refresh conditions. The first condition is a 30-Hz update, with two refreshes per update. According to figure 3, the maximum acceptable display velocity is 1.9 cm/sec, or 0.75 in./sec. The second condition is a 60-Hz update, with one refresh per update. According to figure 2, the maximum acceptable display velocity is 5.5 cm/sec, or 2.2 in./sec. These conditions were chosen because they are popular update and refresh rates in current use.

The following sample calulations are for an assumed altitude of 15 ft, which is typical of a pilot's viewpoint with the aircraft on the runway. Other altitudes will result in proportional changes in maximum acceptable forward velocities.

At 30-Hz update, 60-Hz refresh,

$$\frac{dx'}{dt} = \left(\frac{15 \times 17.2}{6^2}\right) 0.75 = 5.4 \text{ ft/sec}$$

At 60-Hz update and refresh,

$$\frac{dx'}{dt} = \left(\frac{15 \times 17.2}{6^2}\right) 2.2 = 15.8 \text{ ft/sec}$$

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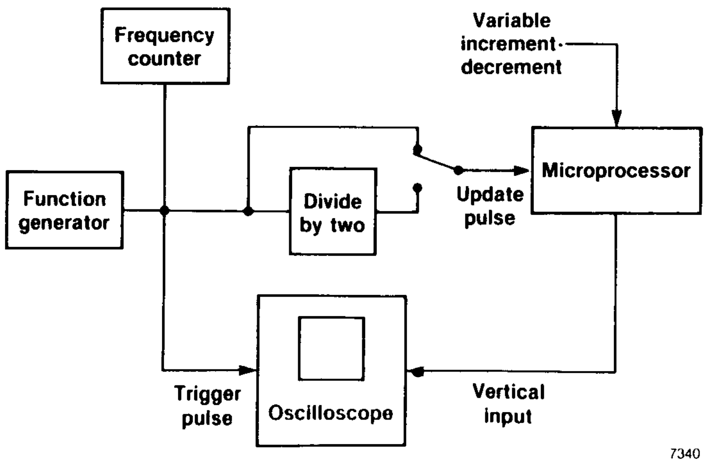

Figure 1. Visual experiment block diagram.

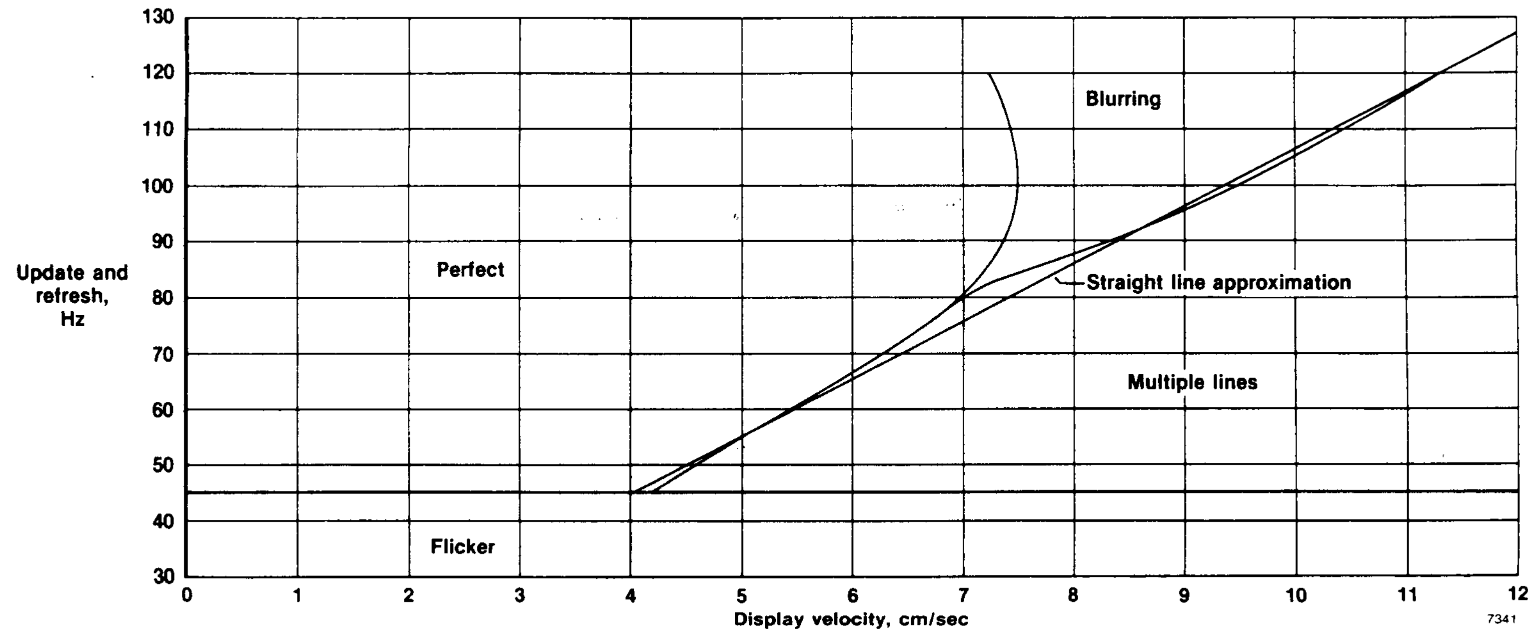

Figure 2. Single refresh per update.

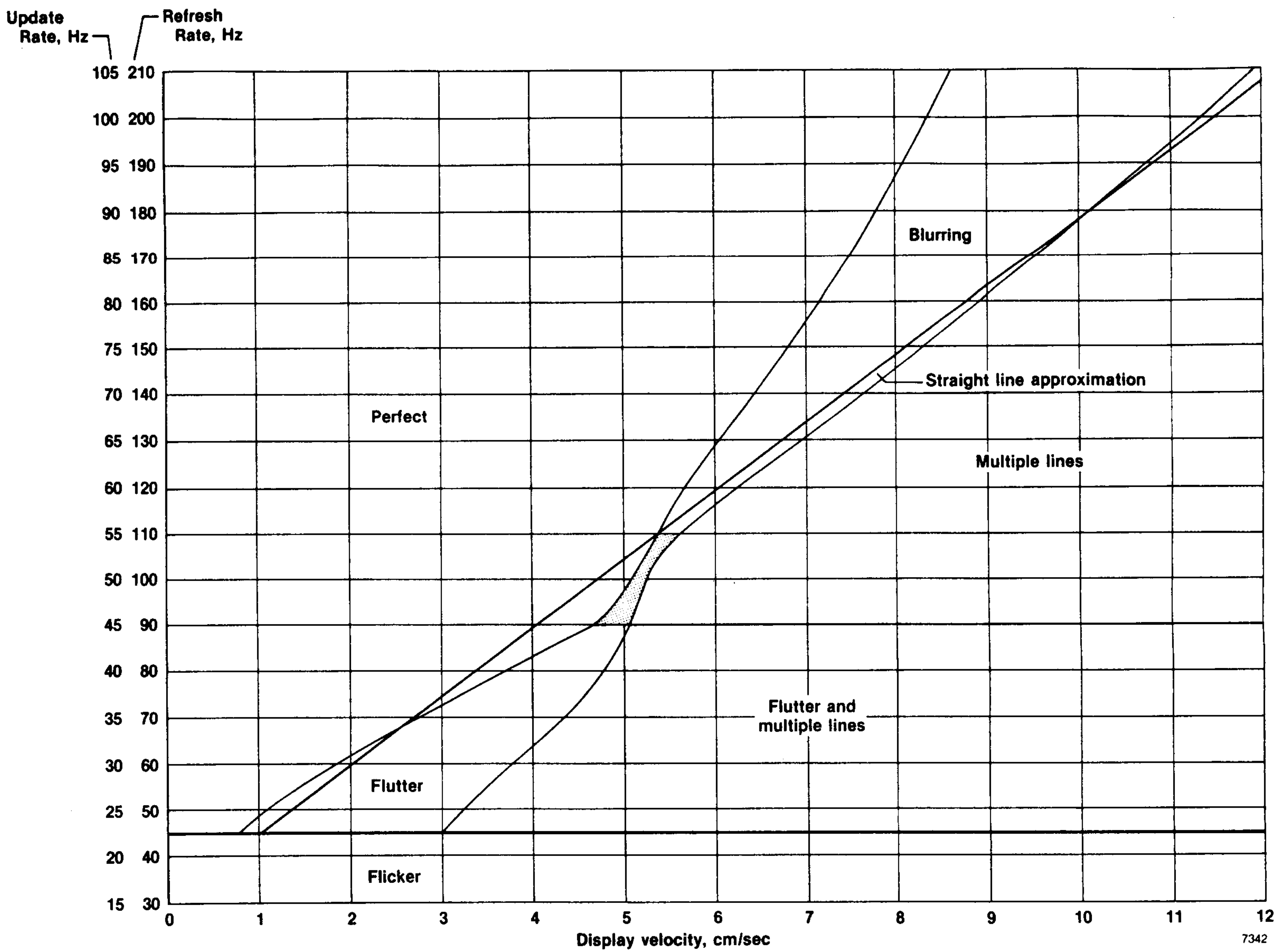

Figure 3. Refresh per update.

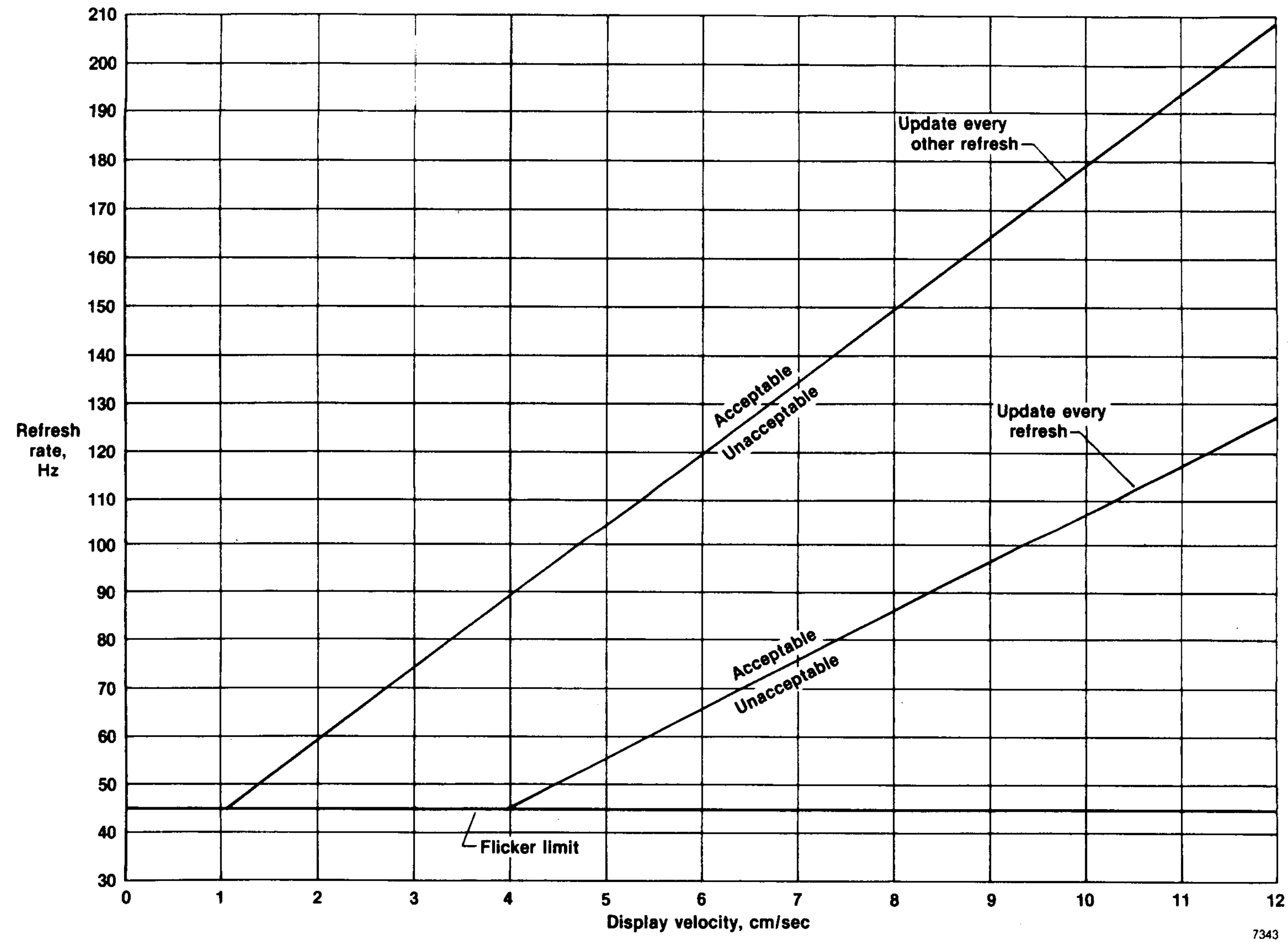

Figure 4. Straight line approximation single refresh per update and double refresh per update on refresh rate scale.

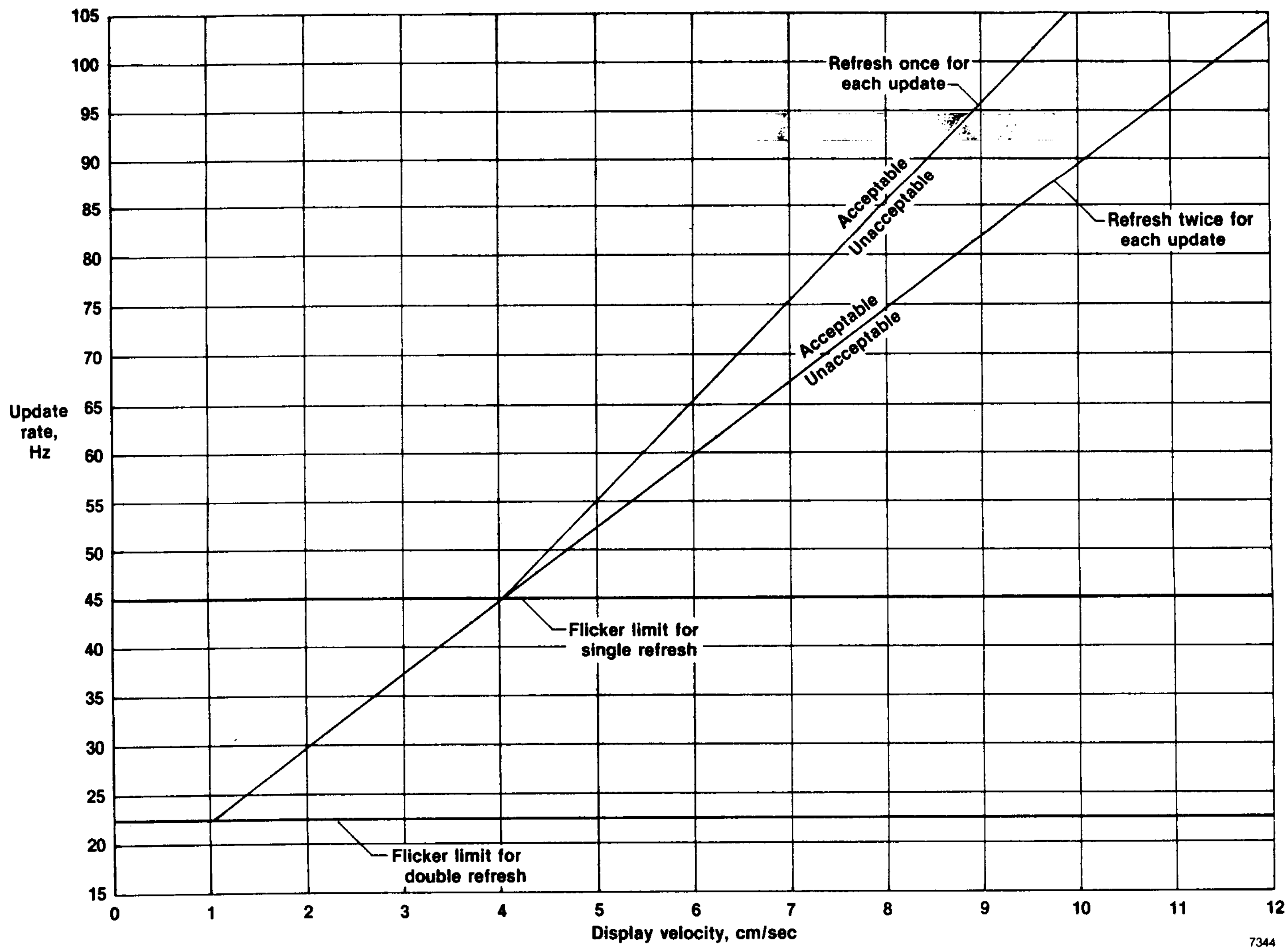

Figure 5. Straight line approximation single refresh per update and double refresh per update on update rate scale.

NASA National Aeronautics and Space Administration	Report Documentation Page	
1. Report No. NASA TM-100415	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Effects of Update and Refresh Rates on Flight Simulation Visual Displays	5. Report Date May 1988
	6. Performing Organization Code
7. Author(s) Gary V. Kellogg and Charles A. Wagner	8. Performing Organization Report No. H-1439
	10. Work Unit No. RTOP-922-22-08
9. Performing Organization Name and Address NASA Ames Research Center Dryden Flight Research Facility P.O. Box 273 Edwards, CA 93523-5000	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	13. Type of Report and Period Covered Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s)) Computer graphics Flight simulation Motion perception Update rate Visual simulation	18. Distribution Statement Unclassified — Unlimited Subject category 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	17	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161.