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16. BANDWIDTH AND SIMDUCE AS SIMULATOR FIDELITY CRITERIA

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Many characteristics define a visual system's quality: the field of view, the resolution, the detail, and, what I will talk about, the delays in response. In addition, I will talk about how to make an overview of the total visual cuing quality.

Bandwidth has been mentioned several times today. I will define it in the context of handling qualities. I will show how the visual delays affect the bandwidth and the handling qualities, and how we could use that to assess the simulation fidelity. The first paper this morning raised many questions about how much fidelity you need for transfer of training. The report the author referred to then (ref. 1) was one I worked on back in 1980. We asked the same questions 11 years ago. My field is handling qualities, not training, so I still do not have the answers. But I will give some hint of how I think you can interpret fidelity.

Figure 1 shows a page out of the handling-quality specification ADS-33 (ref. 2), and defines bandwidth. For a rate-response type, the bandwidth is the lower of the gain margin or the phase margin. For an attitude-command/attitude-hold system, you use the phase margin.

Figure 2 shows the bandwidth boundaries in the handling quality specification. Target acquisition and tracking requirements are not appropriate for many civil aircraft. More appropriate would be the boundaries for "all other MTEs in Usable Cue Environment UCE = 1." UCE is defined in reference 2. Essentially, a UCE greater than 1 implies degraded visibility, and I will limit this discussion to the context of day visual requirements.

Figure 3 shows the UH-60 Black Hawk helicopter's frequency response, gain, and phase. If we put 100 msec of pure delay into the system, it does not affect the gain, but it does affect the phase. Reading the bandwidth (it turns out that the Black Hawk is gain-margin limited), the result can be plotted on the roll bandwidth requirement (fig. 4). With 100 msec of delay, the response moves much closer to the Level 2 boundary. Thus, with an extra 100 msec of delay, the Black Hawk would have changed from a really good (Level 1) almost into the region of degraded handling qualities (Level 2). The levels of flying-qualities concept (ref. 2) is based on the Cooper-Harper Pilot Rating Scale (ref. 3). The Cooper-Harper pilot rating scale provides a measure of subjective evaluations of handling qualities. Ratings from 1 to 3.5 imply that the aircraft is good, has desirable performance, and an acceptable workload. At ratings between 3.5 and 6.5, the aircraft is not so good (Level 2). The pilot can still do the job, but with only adequate performance and the workload is increasing. Above 6.5, the aircraft is so bad that the pilot can no longer do the task, but should not lose control (Level 3).

So, we can see that with an added 100-msec delay the Black Hawk response goes from very good to marginal, that is, almost into the Level 2 region. Now what does that mean in the simulation world? Figure 5 is a timing diagram for the VMS at Ames Research Center. Starting at the pilot's controls, there are some delays or dynamics in the artificial feel system, then there are some measurement delays, then signals go into the main host computer, which has a 20-msec cycle time. Finally, the computed aircraft response comes out to drive the CGI and the motion base. Nominally, the CGI operates at 60 Hz and effectively takes 2.5 cycles, so it adds an 83-msec delay. The motion base can add an equivalent delay of 70 msec in pitch and roll and up to 160 msec in heave. The motion dynamics are not truly a pure delay, but can be represented as such for the frequency range of interest (<3 Hz).

When the pilot moves the control, he can only tell how the helicopter responds by the response of the visual and motion system. As far as he is concerned, this is the airplane. He cannot distinguish delays in the visual and motion cuing from delays in the mathematical model—that is, from the aircraft being simulated. This hypothesis sounds obvious, but we have performed an experiment to demonstrate the fact (ref. 4). The configurations tested are shown in figure 6. The fastest configuration had a roll damping Lp = 4. This would have a bandwidth = 4 with

Phase Delay:

$$\tau_p = \frac{\Delta\Phi 2\omega_{180}}{57.3(2\omega_{180})}$$

Note: if phase is nonlinear between ω_{180} and $2\omega_{180}$, τ_p shall be determined from a linear least squares fit to phase curve between ω_{180} and $2\omega_{180}$

> *CAUTION:*
> *For ACAH, if $\omega_{BW_{gain}} < \omega_{BW_{phase}}$, or if $\omega_{BW_{gain}}$ is indeterminate, the rotorcraft may be PIO prone for super-precision tasks or aggressive pilot technique.*

Rate Response-Types:

ω_{BW} is lesser of $\omega_{BW_{gain}}$ and $\omega_{BW_{phase}}$

Attitude Command/Attitude Hold Response-Types (ACAH):

$\omega_{BW} = \omega_{BW_{phase}}$

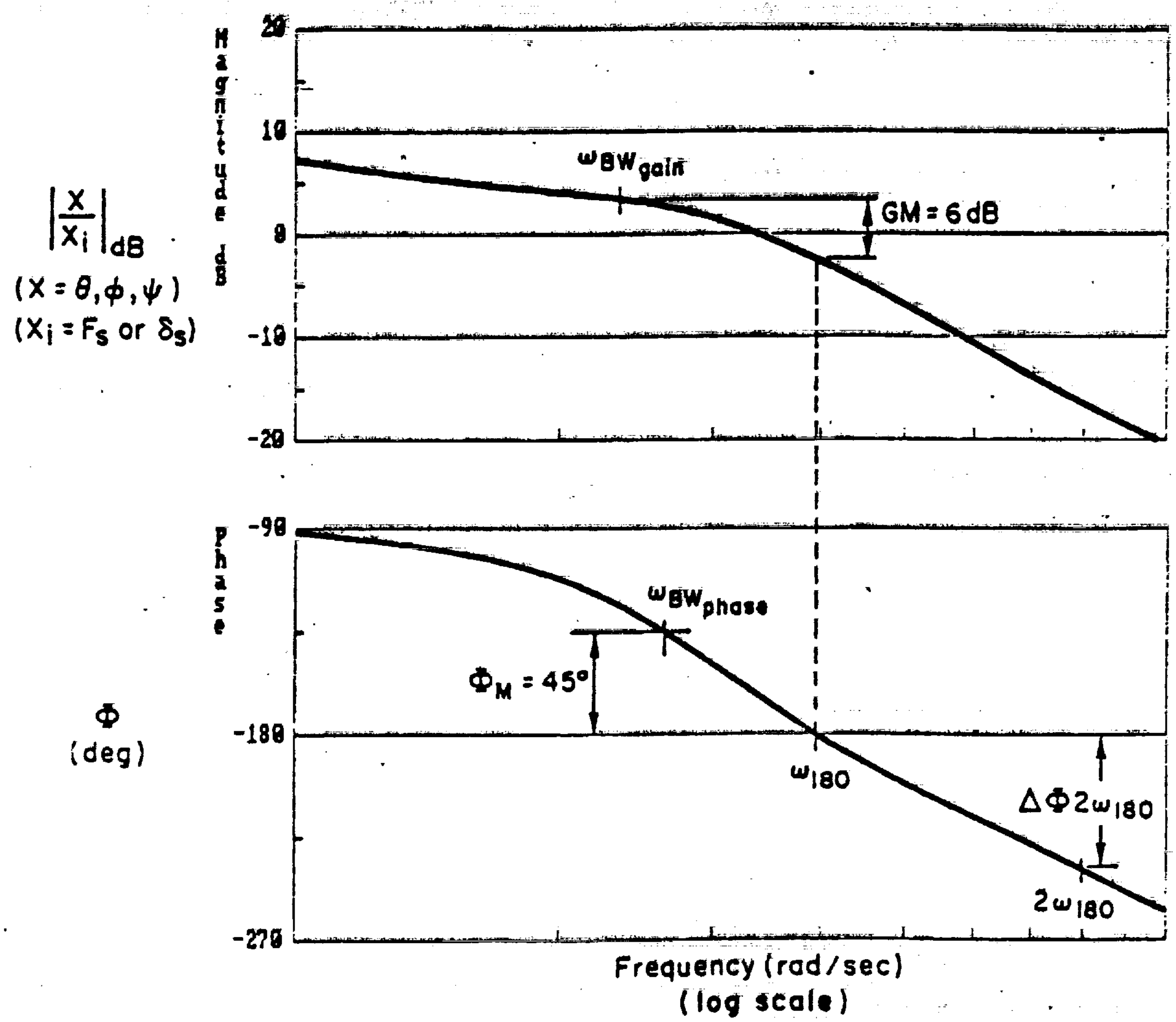

Figure 1. Definition of bandwidth and phase delay.

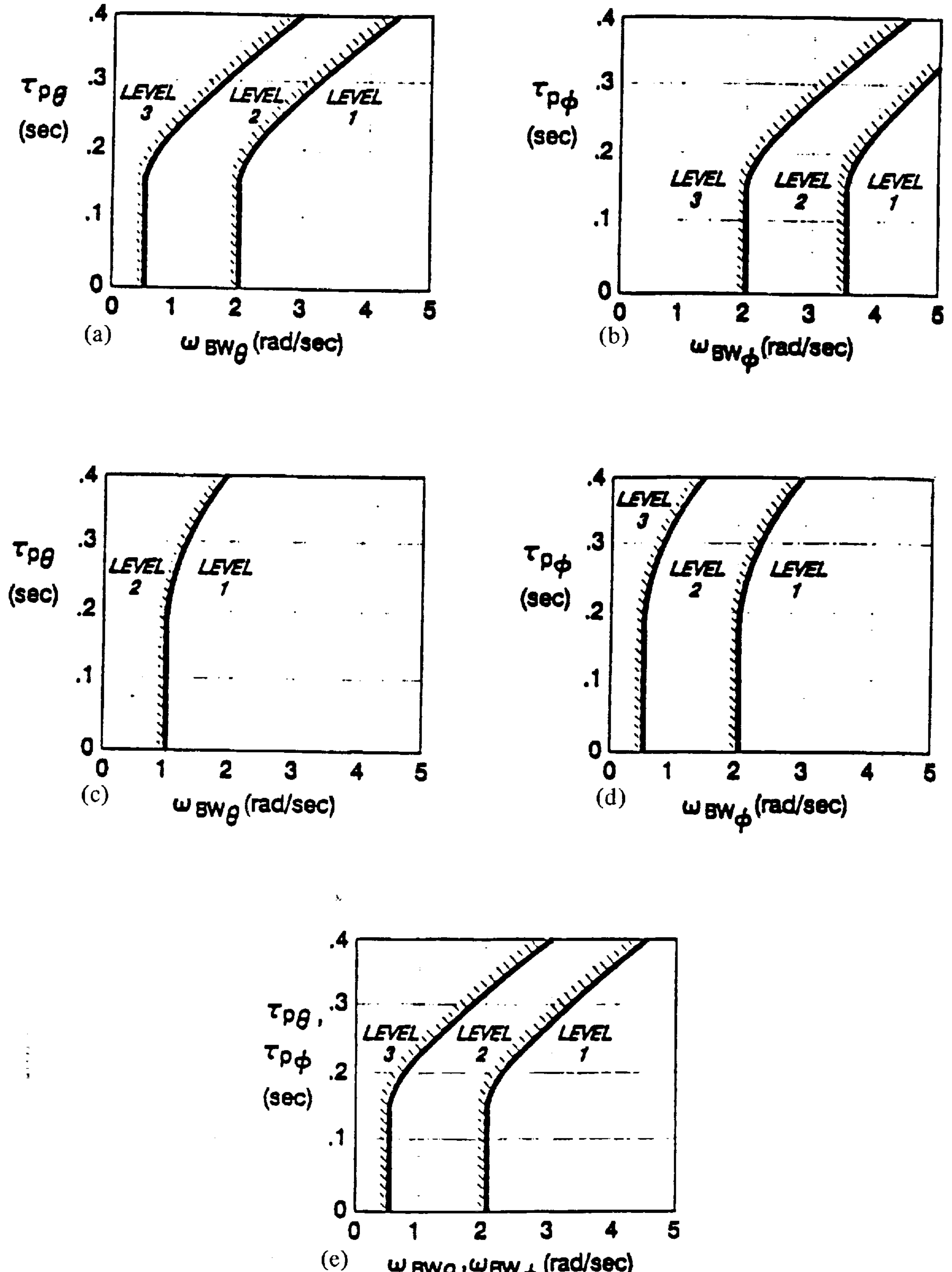

Figure 2. Handling-qualities boundaries for pitch and roll (hover). (a) Target acquisition and tracking (pitch), (b) target acquisition and tracking (roll), (c) all other MTEs - UCE = 1 and fully attended operations (pitch), (d) all other MTEs - UCE = 1 and fully attended operations (roll), (e) all other MTEs - UCE > 1 and/or divided attention operations (pitch and roll).

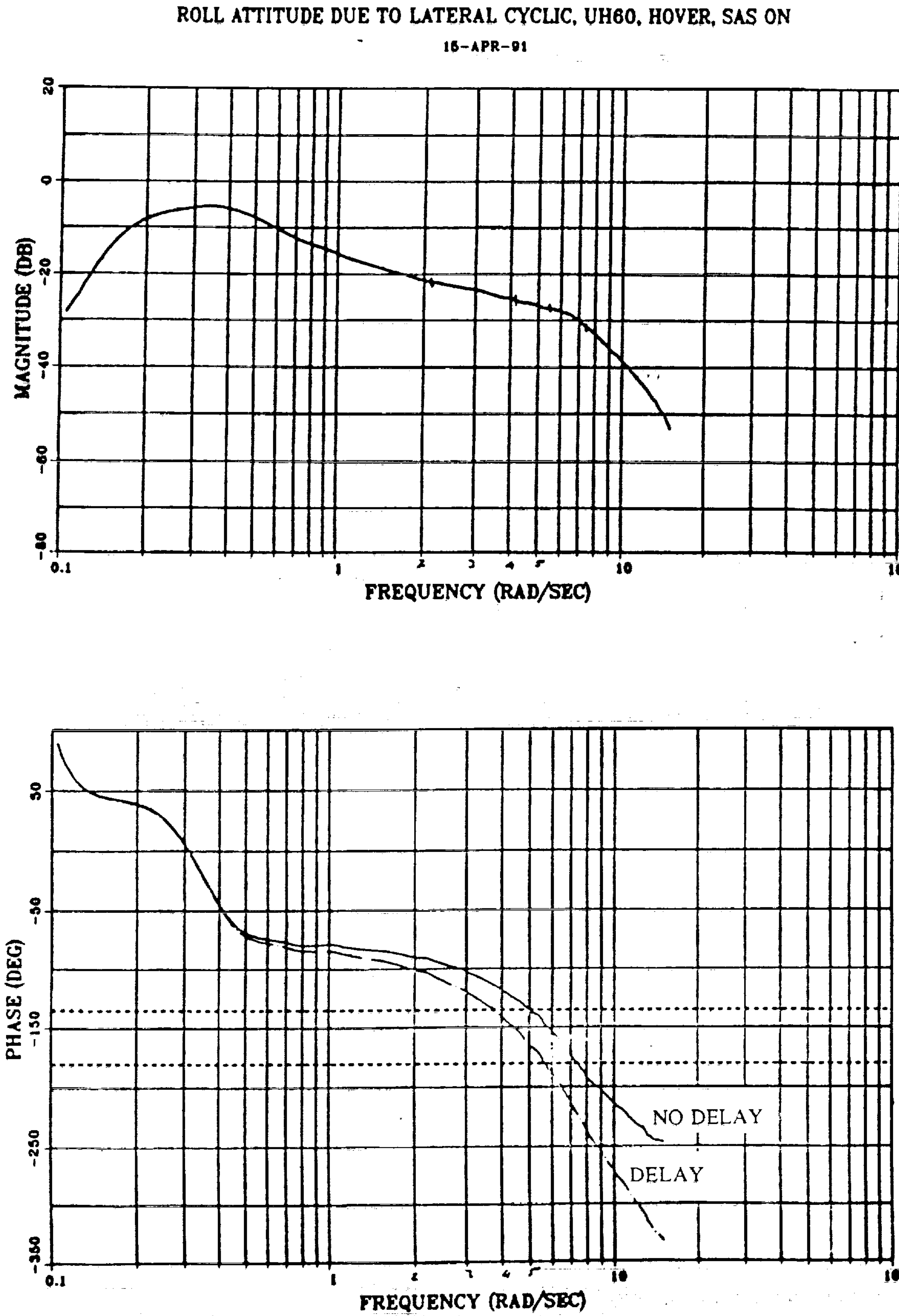

Figure 3. Effect of 100 msec delay on frequency response.

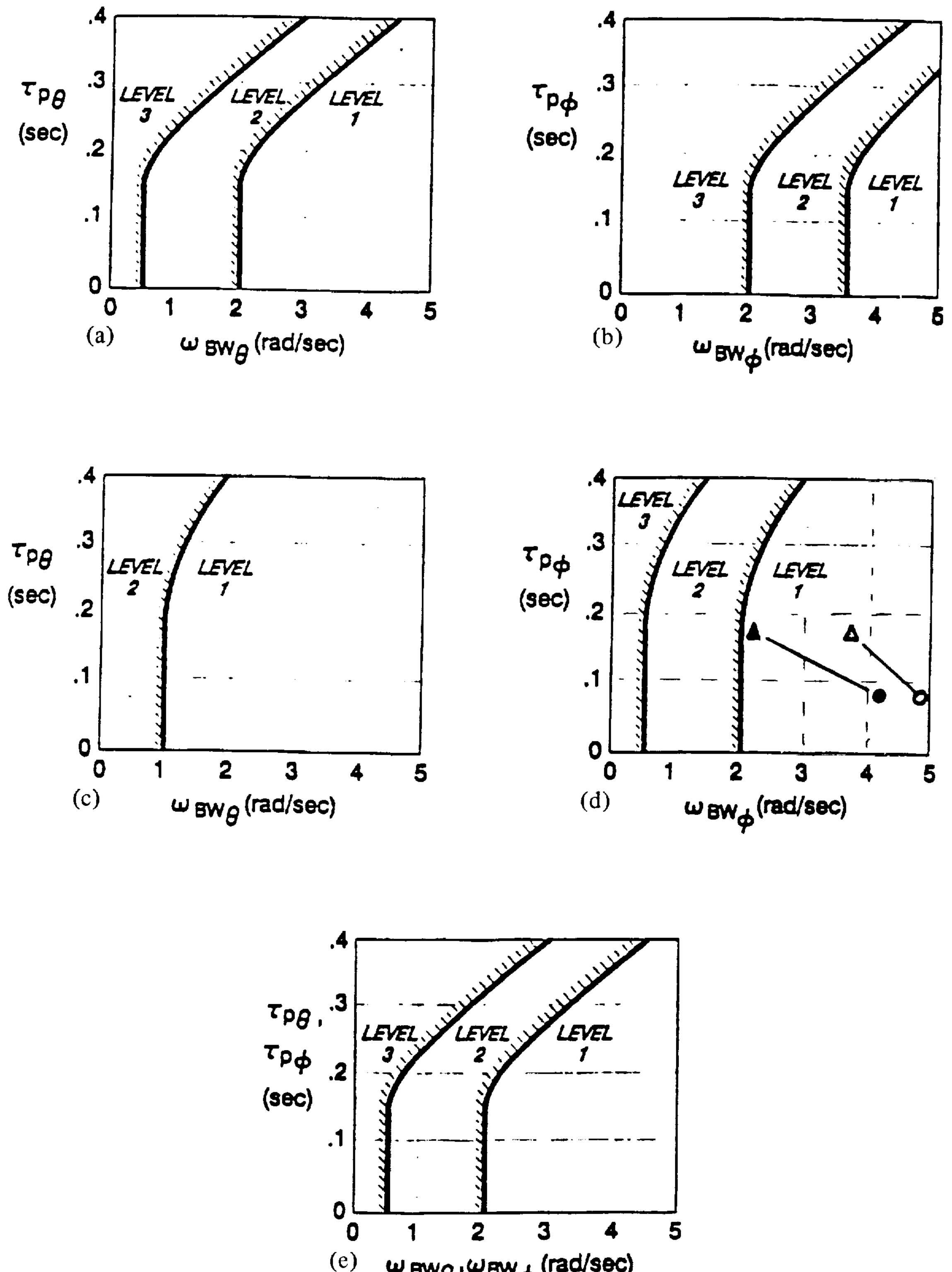

Figure 4. Effect of delay on bandwidth and phase delay. (a) Target acquisition and tracking (pitch), (b) target acquisition and tracking (roll), (c) all other MTEs - UCE = 1 and fully attended operations (pitch), (d) all other MTEs - UCE = 1 and fully attended operations (roll), (e) all other MTEs - UCE > 1 and/or divided attention operations (pitch and roll).

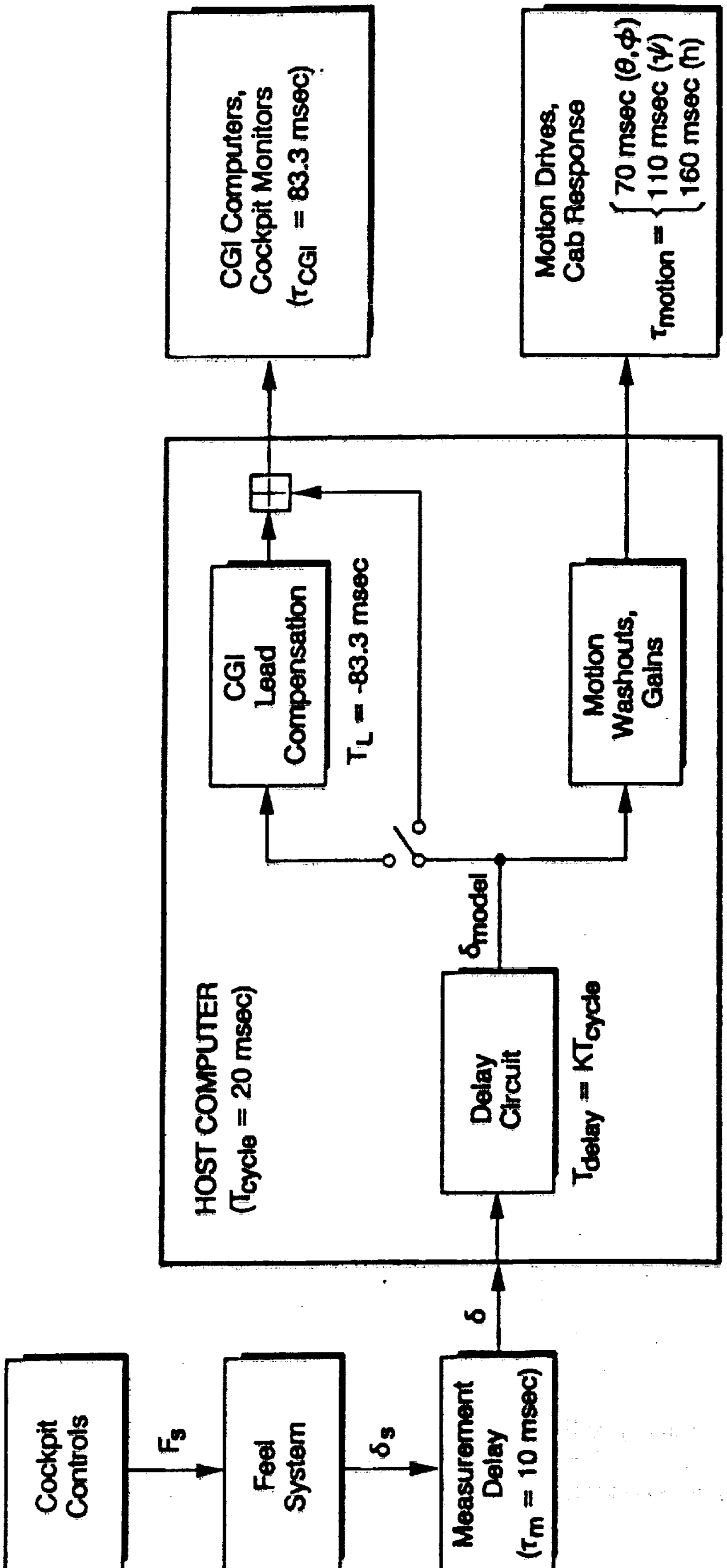

Figure 5. Simulator timing diagram.

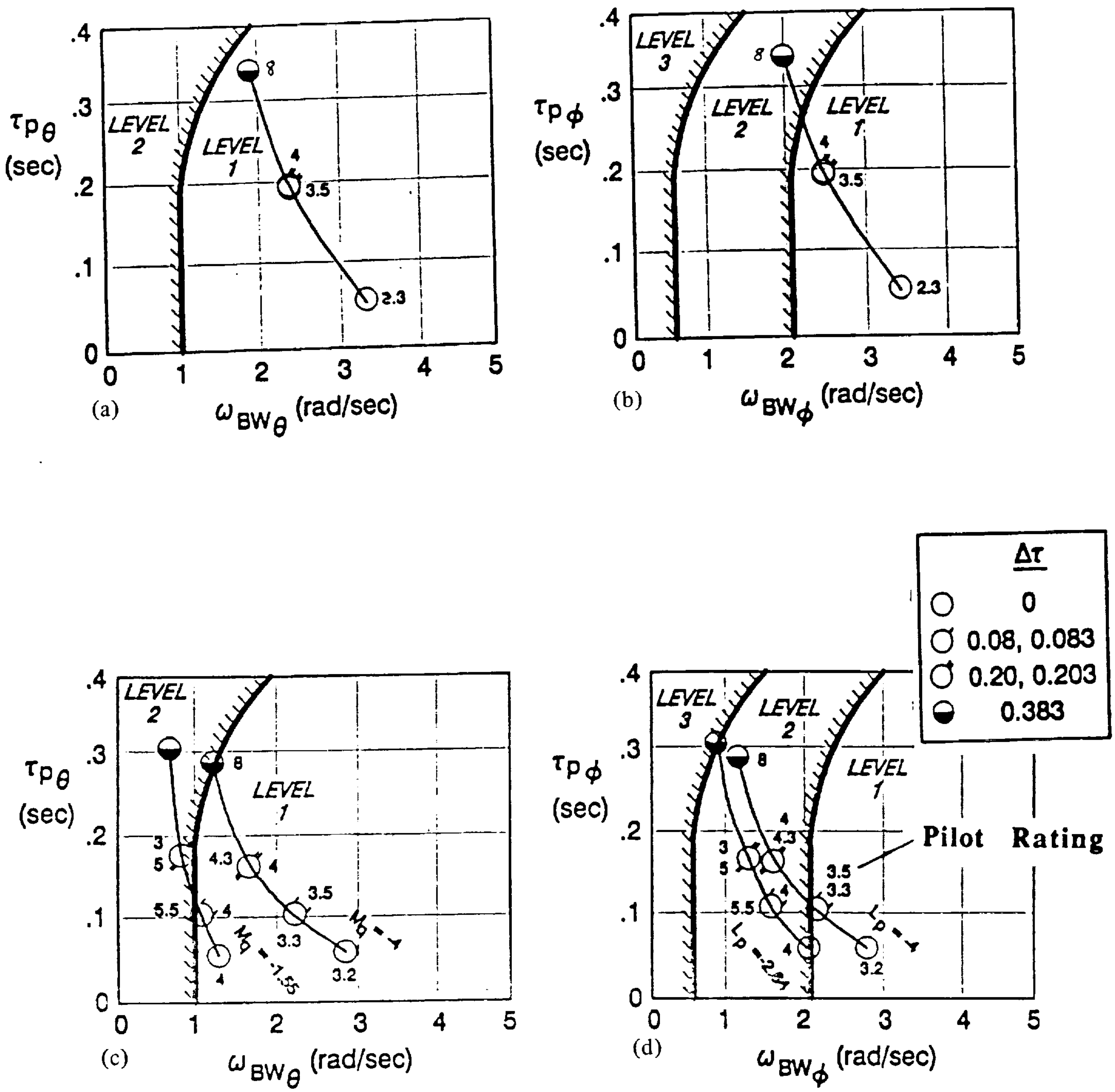

Figure 6. Handling-qualities variations with visual delays. (a) All other MTEs - UCE = 1 and fully attended operations (pitch), (b) all other MTEs - UCE = 1 and fully attended operations (roll). Attitude command response types. (c) All other MTEs - UCE = 1 and fully attended operations (pitch), (d) all other MTEs - UCE = 1 and fully attended operations (roll). Rate response types.

no delay. However, there were some delays from the computation times, so actually it has a bandwidth of about 2.8.

Dick McFarland of Ames has generated a scheme for compensating for the CGI delay (ref. 5) in such a way that the visual delay can be made zero. To investigate the effects of delay in the visual system compared with the mathematical model (aircraft response), the basic visual delay was compensated or, alternatively, a delay was added further downstream as though it was part of the mathematical model. Those two points lie on top of each other on the bandwidth plot (fig. 6). Similar combinations of delays up to 0.383 msec were investigated. The handling-qualities pilot rating was 3.2 (Level 1) with no delay, and with 0.383 delay the pilot rating was 8. So it is clear that the pilot ratings do indeed degrade as delays are increased, and the ratings correlate well with the ADS-33 bandwidth boundaries. Also, as hypothesized, the pilot cannot tell the difference between delays in the visual and delays in the mathematical model.

When we consider motion cues, the situation is a bit more complicated. The helicopter model was a very simple first-order one. Figure 7 shows the Bode plot for the motion. If we add the stick dynamics, the phase and gain are changed as shown. But the motion cue not only has a delay, it has to have washout to limit excursions; this changes the response even more. Consider the cab response between 1 rad/sec and the bandwidth (5 rad/sec), the region that is really of interest. The gain is about 8 dB down (a factor of about 6). Roll would be down by a factor of about 2. Phase matches the model exactly at about 2 rad/sec. At 1.0 rad/sec, there is about 45° of phase lead, and at 5 rad/sec there is about 45° of lag.

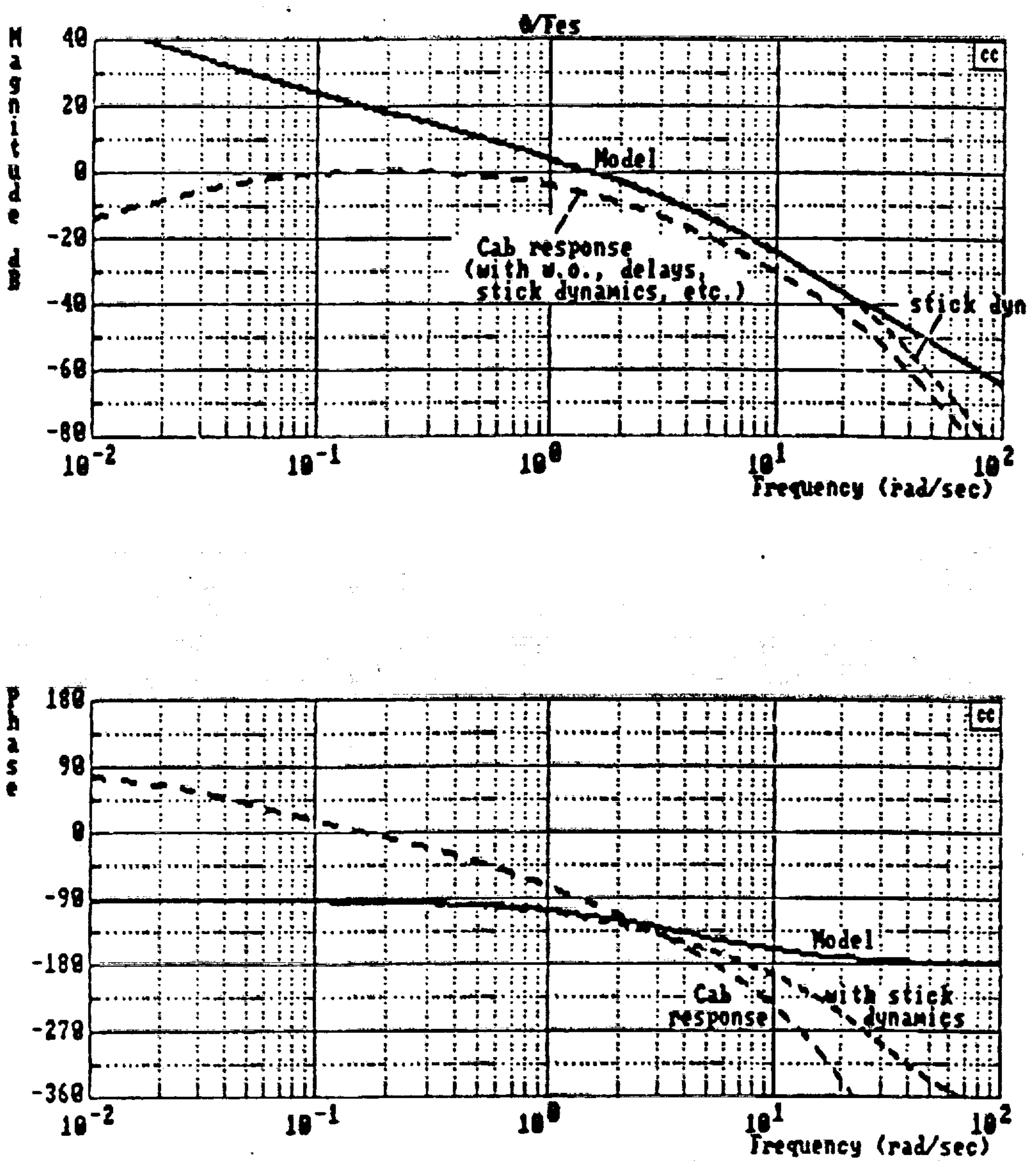

Figure 7. Motion base frequency response (pitch angle response to stick force).

Figure 8 shows pilot ratings obtained with and without 83 msec of delay, with and without motion. The first point to make is that for each of these tasks motion is better than no motion. The next point is a question: How do you combine the visual and motion dynamics? Should the visual and motion be matched or should we try to compensate for the visual time delay? We do not have an answer to this, but do plan an experiment to investigate it later in 1991. In the meantime, it would seem reasonable to set the visual delay to match the fastest axis of motion.

Back to the question of how much delay should be allowed in the visual system? My suggestion is to allow the stick-to-visual bandwidth to degrade to Level 2 (figs. 3(c) and 3(d)), but do not go out of the Level 2 region. Level 3 means the pilot cannot do the task. Presumably, if the handling qualities are so bad a test pilot cannot fly the task, then it is unlikely to give a very good transfer of training. If the helicopter itself is Level 3, you can match the helicopter, but if you are training to fly a Level 3 helicopter, there are other problems that need fixing before routine training starts! These points are summarized in table 1. Note that a fixed value of delay such as 100 ms may or may not cause these boundaries to be violated, depending on the bandwidth of the helicopter being simulated.

Now consider the question of how to assess overall visual cue fidelity. In developing the handling quality specifications (ref. 2) we had to address flying qualities in a degraded visual environment, such as when flying at night with night-vision goggles. Many parameters such as field of view, resolution, scene detail, and response dynamics influence the cue fidelity so that it is currently impossible to compute a cue fidelity. As an alternative we invented a subjective scheme for evaluating how well the pilot could see and called it the usable cue environment (UCE). The procedure is essentially as follows: Take a helicopter with good Level 1 rate response in day visual conditions and assess its capabilities in the degraded visual environment. Thus, on an appropriate dark night with clouds, rain, etc., with the vision aids to be used, perform precisely defined tasks and ask the pilot to rate how precise and aggressive he can be. The process is summarized in figure 9. To get an assessment of the simulator visual cues, we can apply the same procedure (table 2). We call this SIMulator Day UCE; that is where "SIMDUCE" comes from. If the cues are as good as they would be during the daytime, SIMDUCE = 1. If the SIMDUCE = 2 or 3, it is roughly equivalent to having Level 2 or Level 3 handling qualities, so the SIMDUCE number could be treated the same way as the degradation caused by delays. That is, SIMDUCE = 2 is probably satisfactory for training. If SIMDUCE = 3, it is not satisfactory. We applied this routine to the NASA VMS simulator and obtained the data shown in figure 10. This shows the average and standard deviations and an overall UCE of 3. The VMS visual is not inherently that bad; we were trying to get degraded UCE so had put in "fog." For the FAA to incorporate the SIMDUCE concept into an advisory circular, they will have to define a Level 1 rate-response type helicopter mathematical model. This should be a standardized model, and it could be made very simple—I do not expect manufacturers would mind too much.

My conclusions can be summarized as follows:

1. For simulator delays, the visual and motion delays should be set approximately equal. Then the bandwidth from the stick, all the way through to the visual response, should be no worse than ADS-33C Level 2. A single value of delay such as 100 msec will not achieve this and should not be used.

2. Use the SIMDUCE procedure to get an overall calibration of the cue fidelity and it should be 1 or 2, not 3.

Are there any questions?

Questions

MR. McFADDEN: I won't leave you without a question, David. What frequency response was the VMS when you used it there? You showed a frequency response. Do you recall?

MR. KEY: I am not sure I understand your question.

MR. McFADDEN: Where was your 45° phase margin?

MR. KEY: Okay. The 45° phase on the cab response to stick was around 2 rad/sec.

MR. McFADDEN: Thank you.

MR. KEY: That is not the response of the VMS to a pure input to the VMS motion. That response is through the washout. This is the way we had it set up with the washout.

MR. McFADDEN: I understand. You could have made it better.

DR. TISCHLER: Right.

MR. GREEN: The question I have is how do you treat saturation or the limited throw relative to the cab? In other words, of the motion base.

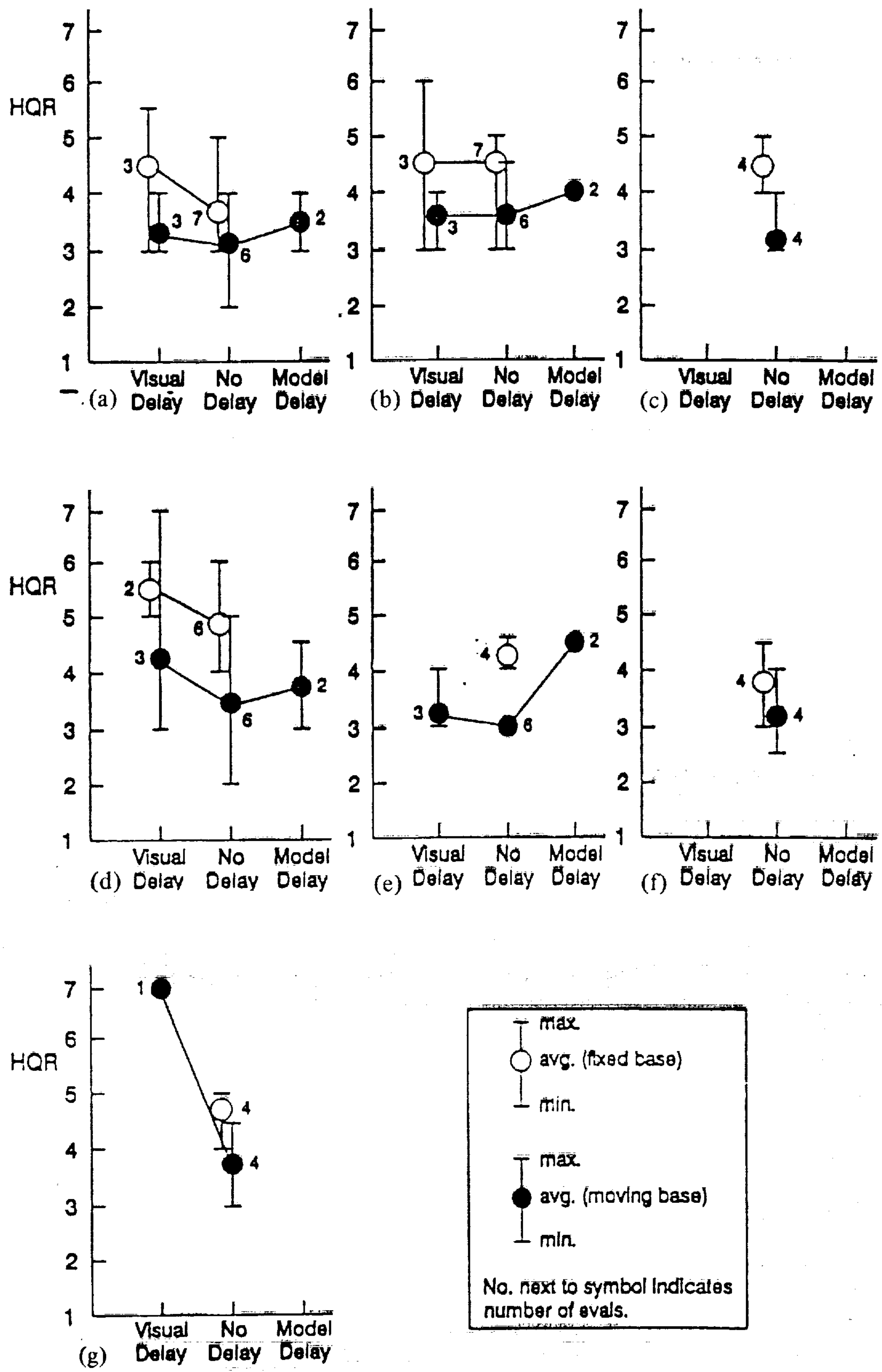

Figure 8. Comparison of handling qualities with and without motion. (a) Hover, (b) vertical translation, (c) pirouette, (d) slalom, (e) bobup, (f) dash/quickstop, (g) sidestep.

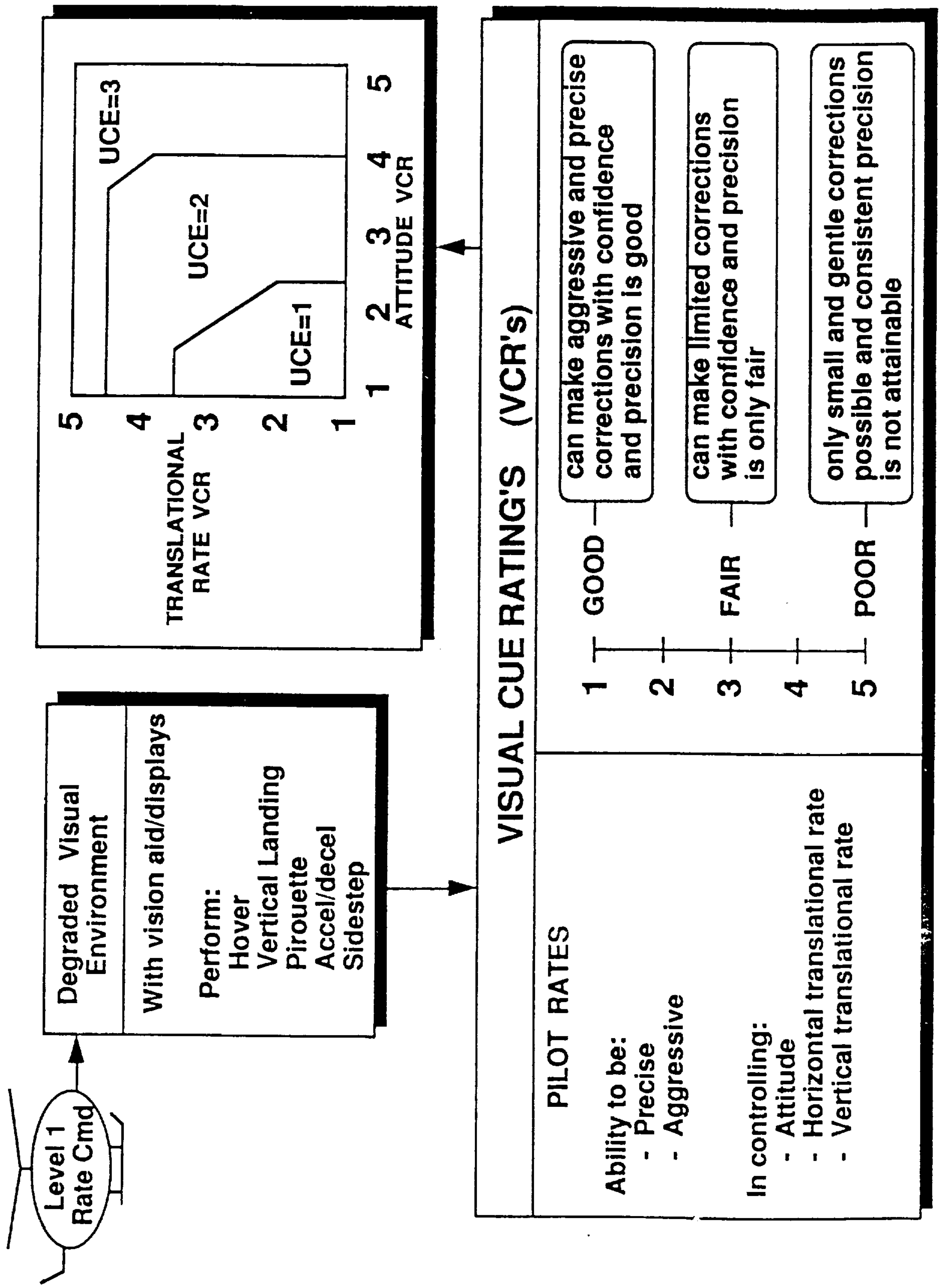

Figure 9. Determination of UCE.

Task	VCR Type	Worst VCR (each pilot)					Average VCR (each task)	Standard Deviation
		A	B	C	D	E		
Hover	Attitude	3.75	3	5	4.5	4.5	4.15	.70
	Translational	4	5	5	4.5	4.5	4.60	.37
Landing	Attitude	3.5	3	5	NR	4.5	4.00	.79
	Translational	4	5	5	NR	4.5	4.63	.41
Pirouette	Attitude	4	3	5	3	4	3.80	.75
	Translational	4.5	5	5	3	4	4.30	.75
Acceleration Deceleration	Attitude	4	3	5	NR	3	3.75	.83
	Translational	4.5	5	5	NR	4	4.63	.41
Sidestep	Attitude	4.5	3	5	4.5	4.5	4.30	.68
	Translational	4	5	5	5	4	4.60	.49

Average Attitude VCR = 4.0

Average Translational VCR = 4.55

UCE = 3

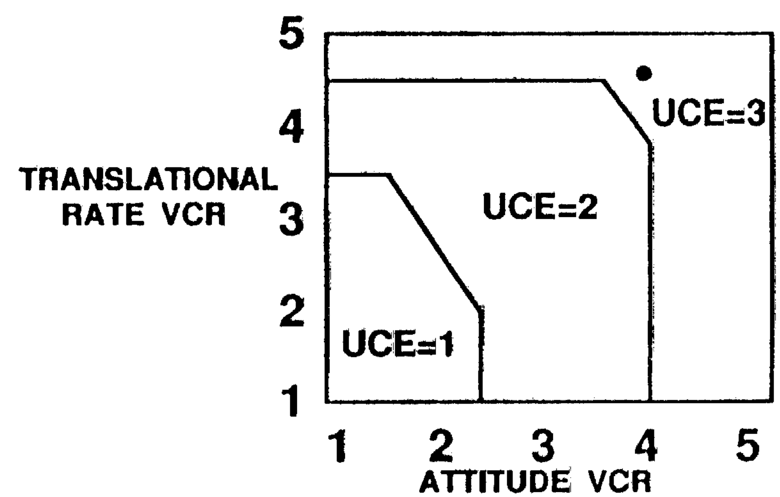

Figure 10. VCR/UCE results.

Table 1. Application of bandwidth to simulation fidelity

Criteria for simulator delay limits:
How to combine visual and motion cues?
Match visual and motion (rather than each as fast as possible)
How much handling-qualities fidelity for transfer of training?
Do not allow stick to visual BW worse than Level 2 (or match the helicopter)

Table 2. SIMDUCE: calibration of visual cue fidelity

Obtain VCR as for UCE except:
Simulator, not flight
Day, not degraded visual environment (DVE)
Task performance standards for day, not DVE
Rating is SIMulatorDayUCE (SIMDUCE)
Should be 1 if cues are as good as flight
If 2 or 3:
Fidelity is equivalent to Level 2 (or 3)
Treat same as degradation due to delays
Disadvantages for FAA application:
Requires a Level 1 rate response model for evaluation
Method requires subjective pilot ratings

MR. KEY: What will happen is if you saturate you will have to drive this gain down, otherwise you will be bumping into the stops all the time when you do maneuvers.

MR. GREEN: Is that self-adaptive, though?

MR. KEY: No, it is not. How do we set these things? Well, until Dick Bray retired, he did it. Now we ask him to do it even though he has retired. One of the motivations for getting these data and doing this experiment is to come up with a more systematic way of setting these washout parameters. I don't think we have good answers yet.

MR. HUTCHINSON: Would you like to suggest a time difference for the approximate cuing between the motion and visual? We all know that motion should precede the visual, but do you have any specific time element?

MR. KEY: You say you know the motion should precede the visual? Well, on the VMS we could make the visual faster than the motion, but would have to slow the visual response to make the motion faster. In terms of pure delay, I do not think visual should be slower than any motion axis. Overall, it would be nice if we could get the phase line to lie along the aircraft model through this region (1 to 3 rad/sec) and increase the gain somewhat. I think we are trying to minimize the phase and gain distortions, that is, to minimize the gain reduction and to minimize the phase lead or lag. So whatever you can do to make the gain and phase of the motion and visual match the model is desirable.

MR. CARDULLO: I was confused by something you said—that the motion was always slower than the visual, yet according to the numbers that you gave, in two degrees of freedom, the motion has actually got less delay than the visual. You quoted 80 msec for the visual, and in pitch and roll I think you quoted 70 msec for the motion.

MR. KEY: That is true. What I thought I said was that we can compensate for the visual. There is a neat scheme for generating lead to drive the CGI. So we can compensate the visual down to zero.

MR. CARDULLO: But the delay is still there; you just compensate the phase, essentially. You could use that in motion too.

MR. KEY: No you can't. You can't do it to the motion.

DR. TISCHLER: Delay compensation will produce side bands at high frequency. Visual electronics is one thing; in fact, in some cases even it will shudder. If we try to put similar lead through a motion system, I think it would go unstable.

MR. CARDULLO: Is that because of the high-frequency anomaly that McFarland predicts?

MR. KEY: Yes. If you take McFarland's prediction and get into very high frequency inputs or turbulence, then things do break up. So there is a limit to the frequency range that you can use it over. And like Mark [Tischler] was saying, when you try to push it through a motion base, that frequency comes down into the usable range. So it can't be done to the motion.

MR. MITCHELL: There is lead compensation already on the VMS, even for those numbers. They compensated what they could to make up for delays to begin with. The numbers are a lot worse without lead compensation.

MR. KEY: At 1 rad/sec we already have 45° of phase lead.

MR. DUVAL: We experimented with a visual lead technique when we tied Flight Lab into the Fort Ord trainer last year. And what we found was that it really did a good job, as long as the pilot's motion was continuous. But you still sense the transport delay at the onset when you had the first discontinuity of something abrupt. The lead certainly could not deal with that. Does that initial discontinuity affect the pilot's perception of what's going on?

MR. KEY: Well, it sure would if it was there. But you were driving a different system through different sets of equations with the different algorithm. A lot of people have used this without noticing too much effect. In the last simulation having a high bandwidth requirement, we only compensated the visual down to match that motion, that is, 70-msec delay on the motion; we did not go all the way to zero. So it is much smoother. But yes, if you push it to far, it will get noisy.

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