An Analytical Comparison of the Fidelity of "Large Motion" vs "Small Motion" Flight Simulators in a Rotorcraft Side-Step Task

Ronald A. Hess
Dept. of Mechanical and Aeronautical Engineering
University of California
Davis, CA 95616

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Introduction

Reference 1 presents an analytical and experimental methodology for studying flight simulator fidelity. The task was a rotorcraft bob-up/down maneuver in which vertical acceleration constituted the motion cue. The task considered here is a side-step maneuver that differs from the bob-up one important way: both roll *and* lateral acceleration cues are available to the pilot. It has been communicated to the author that in some VMS studies, the lateral acceleration cue has been found to be the most important.[2] It is of some interest to hypothesize how this motion cue associated with "outer-loop" lateral translation fits into the modeling procedure discussed in Ref. 1 where only "inner-loop" motion cues were considered. This Note is an attempt at formulating such an hypothesis and analytically comparing a large-motion simulator, e.g., the VMS, with a small-motion simulator, e.g., a hexapod.

The Hypothesis

As discussed in Ref. 1, inner-loop motion cues have a relatively small effect upon pilot/vehicle dynamics and performance, especially in target tracking (as opposed to disturbance regulation). An example of such inner-loop cues is the vertical acceleration cue in the bob-up/down maneuver of Ref. 1. In the pilot/vehicle analyses of Ref. 1 (and those which preceded it, e.g., Refs. 3 and 4), the central hypothesis was that activity in the "primary control loop" was the most important in determining simulator fidelity. By "primary" loop is meant the inner-most control loop that the pilot uses to control the vehicle. For example, in the bob-up/bob-down task of Ref. 1, the primary control loop was hypothesized to be a vertical velocity loop. In the side-step task of Ref. 3, it was the roll-attitude loop.

Figure 1 compares the bob-up/down and side-step tasks and indicates the motion cues assumed to be employed by the pilot in the primary control loop as defined using the Structural Pilot Model discussed in Ref. 1. The pilot control loop structures are also indicated in the figure. Note that although $\dot{\phi}(t)$ is not an acceleration, per se, it has been assumed to be sensed by the vestibular system in past modeling experiments, e.g., Ref. 5. In the bob-up/down task, vertical acceleration provided the motion cue for the Structural Model of the pilot in the primary control loop. The question now becomes: How would the lateral acceleration cue $\ddot{y}(t)$ be employed in the Structural Model as applied to the side-step task, given that it is associated with the outer-control loop? The answer to this question forms the principal hypothesis of this Note, namely

> *In the side-step task, lateral acceleration $\ddot{y}(t)$ provides the pilot with information about roll-attitude, $\phi(t)$. This information reduces the pilot's dependency upon visually-sensed roll attitude and, in essence, allows operation upon the roll variable with reduced gain. This implies less visual workload in the control of attitude and allows more attention to be paid to lateral displacement and velocity.*

The impact of this hypothesis upon simulator fidelity, particularly upon large vs small motion simulators will be addressed using the modeling methodology of Ref. 1.

Modeling the Side-Step Maneuver

Consider the simple model of a the lateral dynamics of hovering helicopter below.

Helicopter Model

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$x(t) = \begin{Bmatrix} p(t) \\ \phi(t) \\ \dot{y}(t) \\ y(t) \end{Bmatrix} \tag{1}$$

$p(t)$ = *roll rate rad/s*; $\phi(t)$ = *roll attitude rad*

$\dot{y}(t)$ = *lateral velocity m/s*; $y(t)$ = *lateral displacement m*

$u(t) = \delta_A(t)$ *lateral cyclic displacement cm*

$$A = \begin{bmatrix} -9.2 & 0 & -0.21 & 0 \\ 1 & 0 & 0 & 0 \\ -0.53 & 9.8066 & -0.03 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1.04 \\ 0 \\ -0.096 \\ 0 \end{bmatrix} \qquad (2)$$

all dimensions in SI units

Figure 2 compares the Bode diagrams of a pair of vehicle transfer functions, namely a $0.1 \cdot \frac{\ddot{y}}{\delta_A}(s)$ and $\frac{\phi}{\delta_A}(s)$. Note the similarity between the diagrams, particularly in the frequency range of interest for manual control, i.e., $0.1 \le \omega \le 10$ *rad*/sec. As a point of departure, we will assume that the vestibular and visual sensing of roll attitude will be split evenly. This is shown in Fig. 3. Note that any simulator motion limitations, i.e., washout and/or gain attenuation will affect the vestibular feedback. Also note, that for simplicity, we have neglected any inner-loop motion feedback, i.e., $\dot{\phi}(t)$, in the pilot/vehicle analyses to follow.

Nominal Configuration

Using the procedure for pilot model generation and the inverse dynamic analysis described in Ref. 1, and assuming roll-attitude is sensed as in Fig. 3, the response of the closed-loop pilot/vehicle system to a desired side-step of 15 m is shown in Fig. 4. Note the excellent response characteristics.

Configuration with VMS-Like Motion System

Following the methodology described in Ref. 1, we now "freeze" the pilot model and employ it in a computer simulation using PVD_{NL}[6] in which we incorporate a VMS-like motion system, here modeled as

$$\frac{\ddot{y}_{motion}}{\ddot{y}_{command}}(s) = \frac{0.5s^2}{s^2+2(0.707)0.521+0.521^2} \qquad (3)$$

Plots of the Handling Quality Sensitivity Functions (HQSF's) for the nominal and VMS-motion configurations are shown in Fig. 5. As demonstrated in Ref. 1, differences in these two plots as quantified by the shaded area between the HQSF's can be a measure of simulator fidelity limitations. Note the relatively small shaded area.

Configuration with Hexapod-Like Motion System

We now employ a computer simulation again using PVD_{NL} for the nominal and a hexapod-like motion system,[7] here modeled as

$$\frac{\ddot{y}_{motion}}{\ddot{y}_{command}}(s) = \frac{0.45s^2}{s^2+2(0.707)(0.9)s+0.9^2} \tag{4}$$

Figure 6 compares the HQSF's for the nominal and hexapod motion configuration. Note the shaded area which is considerably larger than that of Fig. 5, indicating significantly reduced simulator fidelity as compared to the VMS system.

Summary

The brief pilot/vehicle analysis just described is obviously somewhat speculative in nature, particularly as regards the assumption of lateral acceleration being employed as a surrogate cue for roll attitude. Nonetheless, the assumption can be justified on the basis of the similarity of the two signals and in the payoff in terms of reduced pilot workload. Of course, the assumption of a 50/50 split in utilization of the two signals was somewhat arbitrary. Nonetheless, the methodology of Ref. 1 could be used to point to the apparent superiority of the VMS motion system as compared to that of a hexapod system for the task at hand.

References

[1]Zeyada, Y., and Hess, R. A., "A Methodology for Evaluating the Fidelity of Ground-Based Flight Simulators," AIAA Paper No. 99-4034, AIAA Modeling and Simulation Conference and Exhibit, Aug. 9-11, Portland, OR.

[2]Franklin, J., Personal communication.

[3]Hess, R. A., and Malsbury, T., "Closed-Loop Assessment of Flight Simulator Fidelity," *Journal of Guidance, Control, and Dynamics*, Vol. 14, No. 1, 1991, pp. 191-197.

[4]Hess, R. A., Malsbury, T., and Atencio, A., Jr., "Flight Simulator Fidelity Assessment in a Rotorcraft Lateral Translation Maneuver," *Journal of Guidance, Control and Dynamics*, Vol. 16, No. 1, 1993, pp. 79-85.

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[6]Zeyada, Y., and Hess, R. A., "PVD_{NL} Pilot/Vehicle Dynamics $_{Nonlinear}$, An Interactive Computer Program for Modeling the Human Pilot in Single-Axis Linear and Nonlinear Tracking Tasks," Dept. of Mechanical and Aeronautical Engineering, University of California, Davis, CA, 1998.

[7]Schroeder, J. A., Chung, W. W. Y., Tran, D. T., Laforce, S., and Bengford, N. J., "Pilot-Induced Oscillation Prediction with Three Levels of Simulation Motion Displacement," AIAA Paper No. 98-4333, AIAA Atmospheric Flight Mechanics Conference, August 10-12, 1998, Boston, MA.

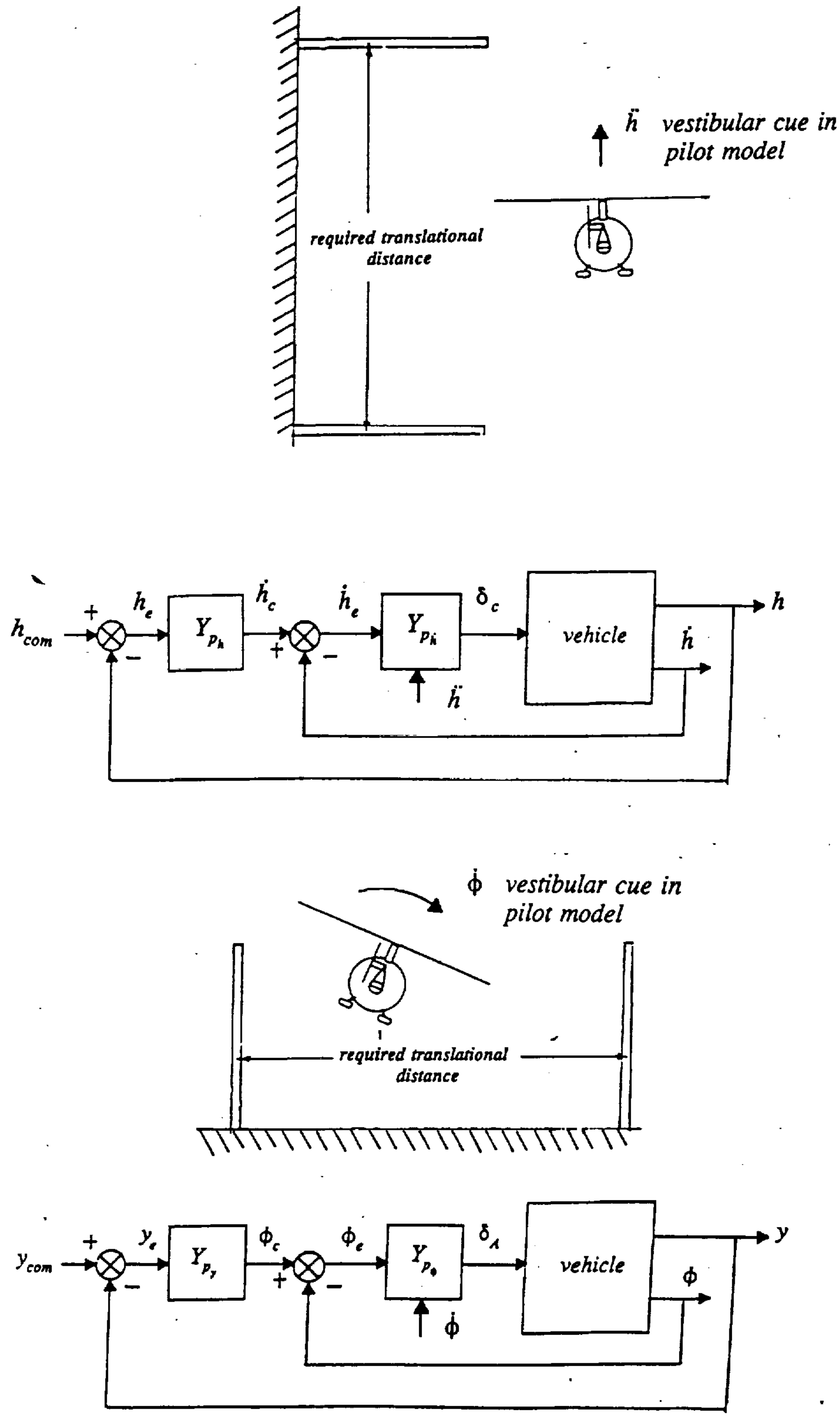

Figure 1 Bob-up/down and side-step tasks with pilot model from Ref. 1

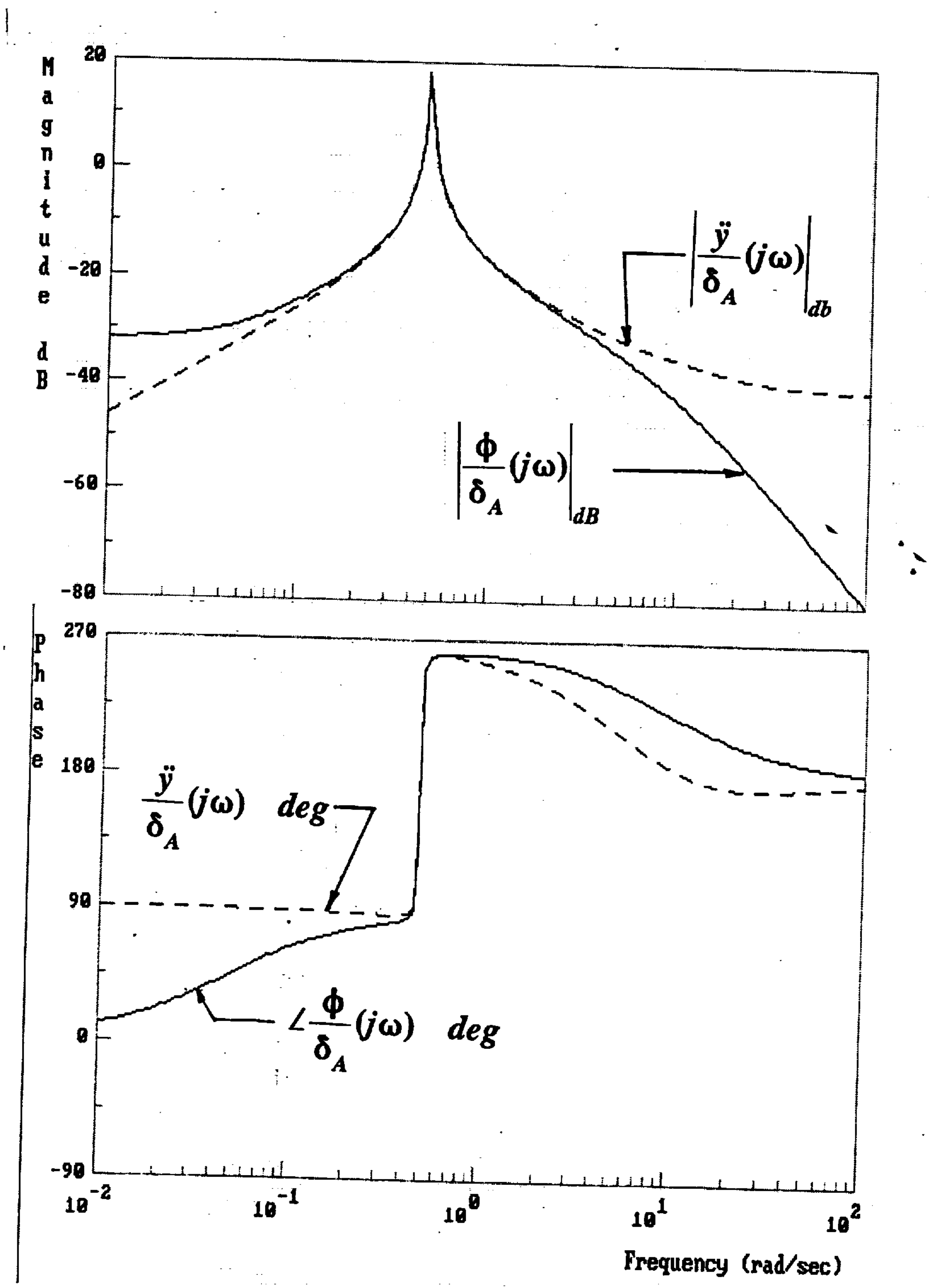

Figure 2 Comparison of Bode plots for ϕ/δ_A and $0.1 \cdot \ddot{y}/\delta_A$ for example rotorcraft

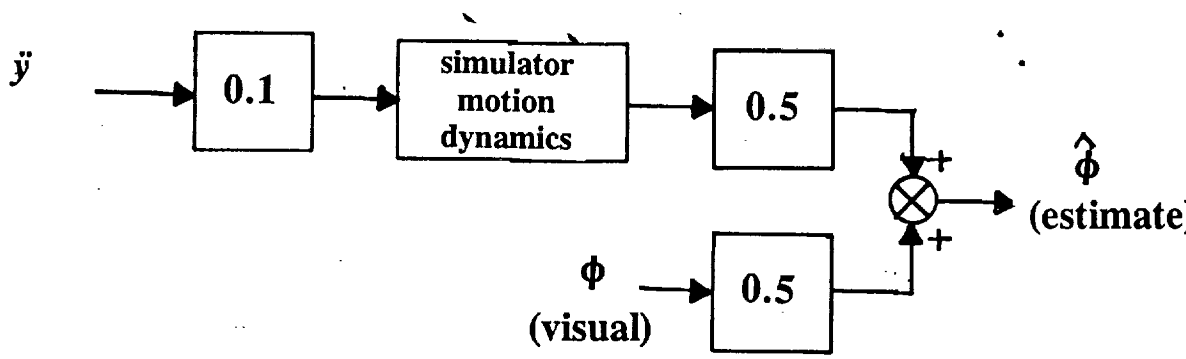

Figure 3 Hypothesized pilot sensing of $\ddot{y}$ and ϕ for generating $\hat{\phi}$

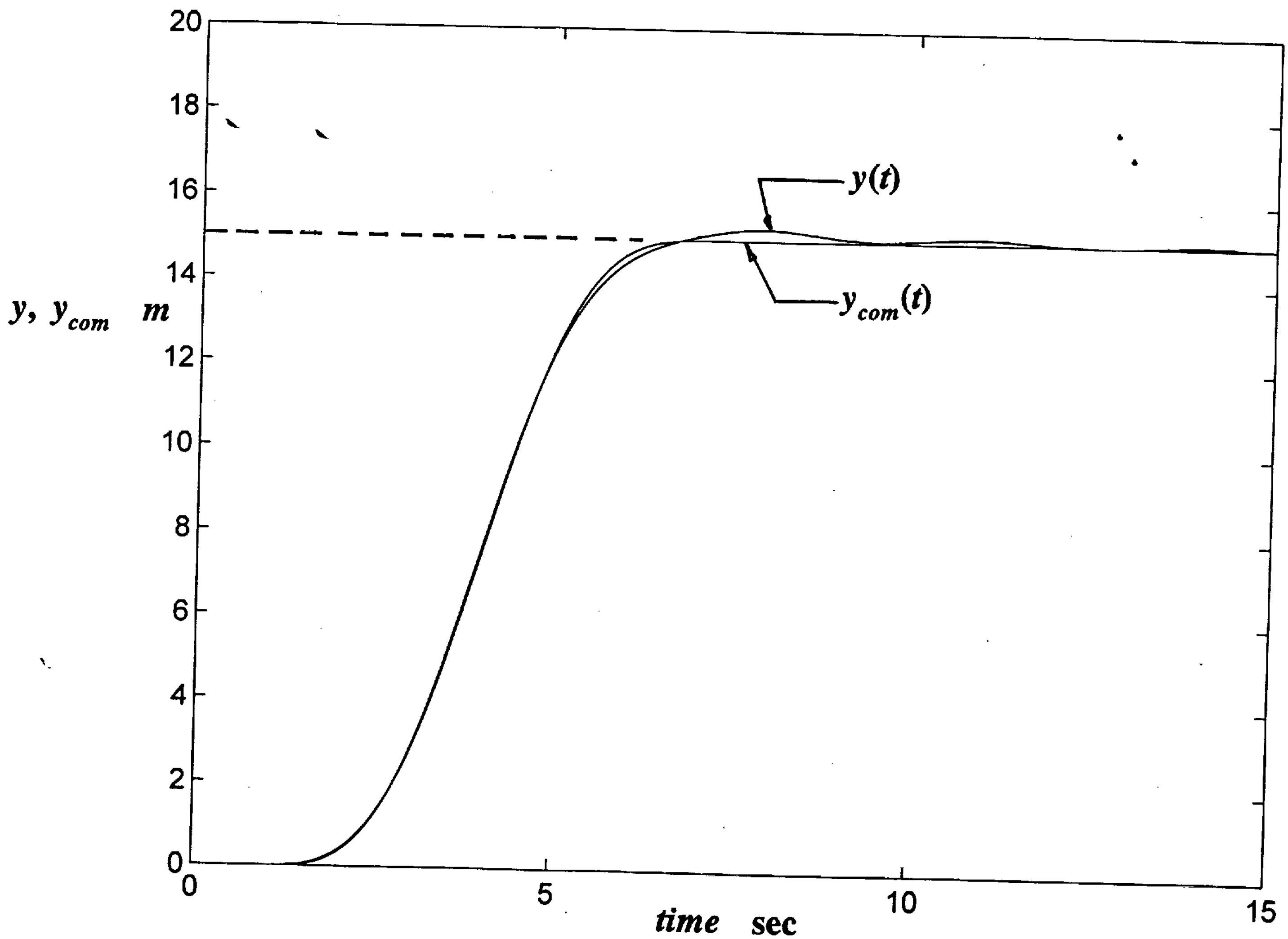

Figure 4 Computer simulation of side-step maneuver for "nominal" vehicle employing inner-loop feedback of $\hat{\phi}$ from Fig. 3

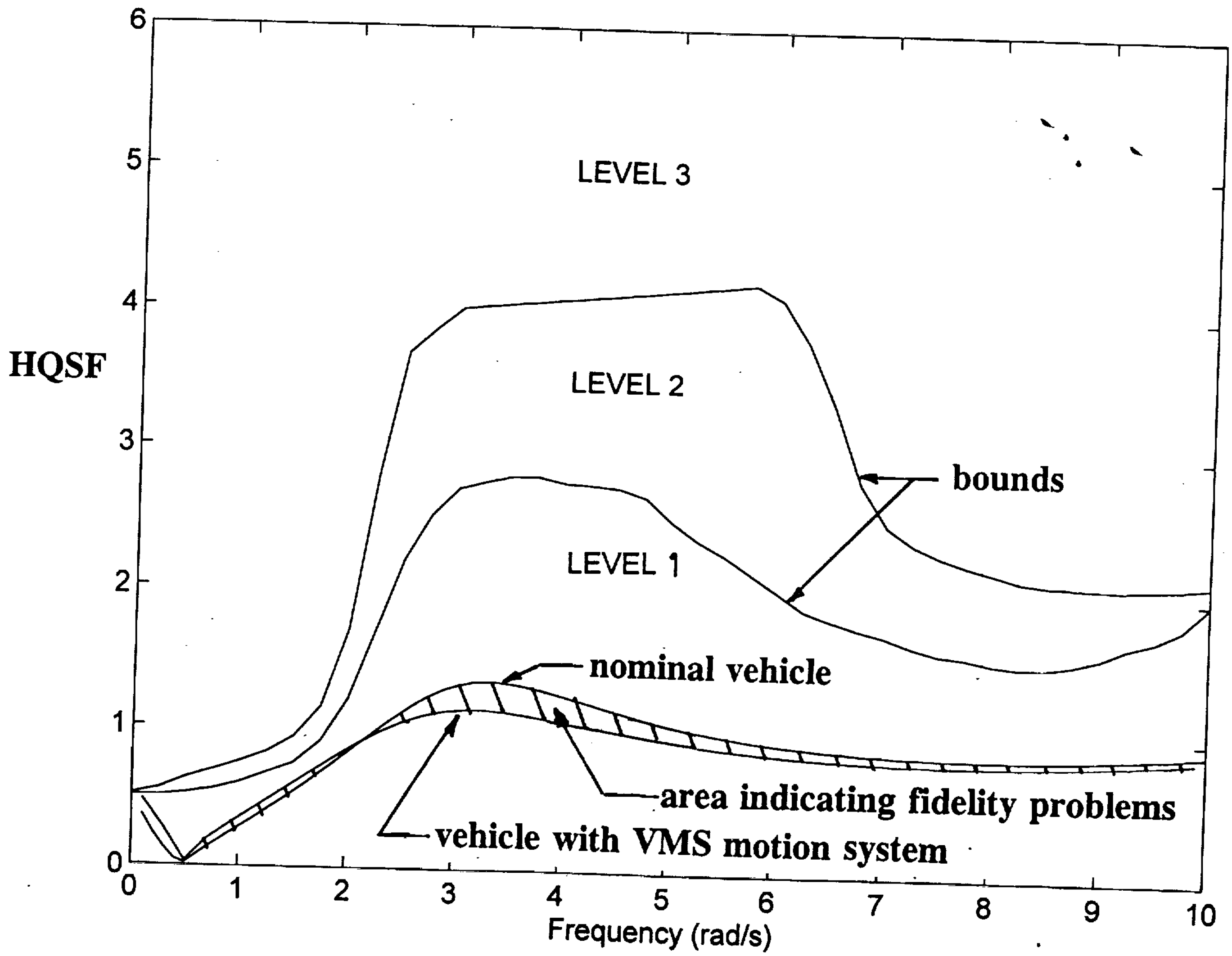

Figure 5 Handling Qualities Sensitivity Functions for "nominal" vehicle and simulated vehicle with VMS motion dynamics of Eq. 3

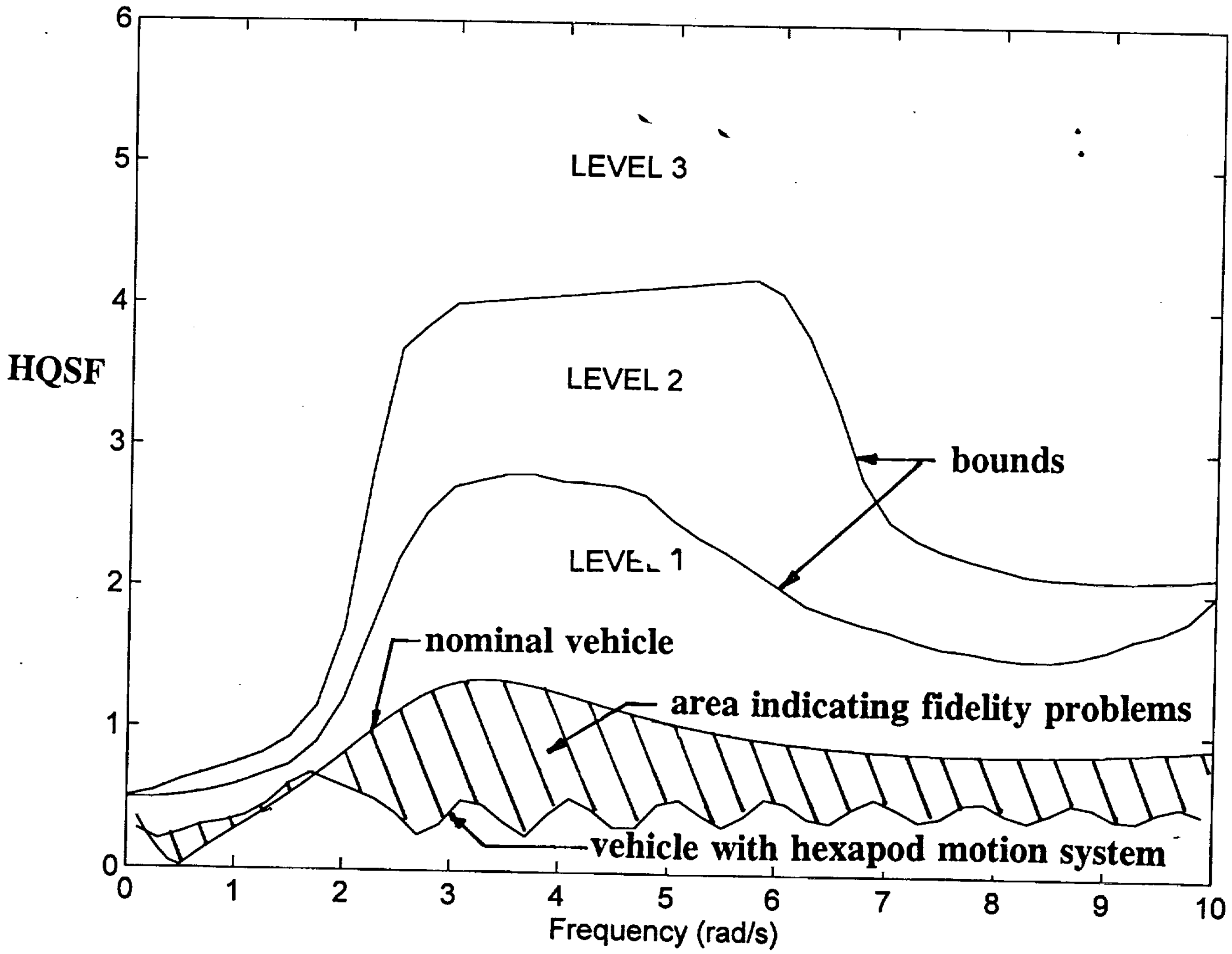

Figure 6 Handling Qualities Sensitivity Functions for "nominal" vehicle and simulated vehicle with hexapod motion dynamics of Eq. 4